Integration of Remote Sensing and GIS for Groundwater Resources Assessment in Moyale-Teletele Sub-Basin, South Ethiopia

A Thesis Submitted to the School of Graduate Studies,

Addis Ababa University

in Partial Fulfillment of the Requirements for the

DEGREE OF MASTER OF SCIENCE IN GIS AND REMOTE SENSING

By:

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March 2007

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DEDICATION

May this thesis is dedicated to my father Ato Getachew Mamo and my mother W/ro Tsige Asfaw with love.

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First of all, I give thanks to the glorified GOD, who has created me and provided me his good wills in all my activities. Secondly, I send my heartfelt thanks to my Mom and Dad, and all my family who have contributed the lions share in the success of my life yet.

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ABSTRACT

An integrated approach with remote sensing and Geographic Information Systems (GIS) was adopeted to assess the groundwater potential in the southern lowlands of Ethiopia, Moyale-Teltele sub-basin of the Genale Dawa river basin. Six geologic, physiographic, and hydrologic factors were applied namely: lithology, structure, geomorphology, slope, land cover, and drainage. Digital Elevation Model (DEM) acquired from Shuttle Radar Topography Mission (SRTM) was used to derive contour and geomorphology, where contour is also used to generate slope. Landsat ETM scenes covering the area were classified for landcover. Other maps were digitized from different sources. Water point inventory was done in selected wells and springs to collect data on location, depth, water level, and yield. Satty's Analytical Hierarchy Process was utilized in giving ranks and weights to the layers and different classes in them. Weighted Overlay Analysis was implemented in ArcGIS to combine the thematic layers and produce the groundwater potential map of the area. This result was further verified by groundwater yield data of boreholes and springs collected in the field and from previous reports. The validation revealed that the result was in well conformity with the actual yield of the wells and springs.

The spatial distribution of groundwater potential zones showed regional patterns related to geologic, physiographic, and hydrologic characteristics of the area. Quaternary alluvium deposits and Quaternary volcanics were obtained to be situated in very good groundwater potential zones. The SE-NW trending geological structures affected most of the tertiary volcanics which appeared in the very good to good potential zones. Plain landforms and very low slope areas dominate the very good to good groundwater potential zones. The very good groundwater potential zones have very low drainage density. Agricultural lands and wood lands cover most of the very good to good groundwater potential areas. Groundwater potential zones demarcated through the model are in good agreement with borehole and spring yield data. The result demonstrate that the integration of remote sensing and GIS

provide a powerful tool in the assessment and management of water resources.

Key Words

Geographic Information Systems, Remote Sensing, Multicriteria Decision Evaluation, Groundwater, Rank, Weight, Moyale-Teltele

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ACRONYMS

AHP	Analytical Hierarchy Process
C R	Consistency Ratio
DEM	Digital Elevation Model
DSS	Decision Support System
EMA	Ethiopian Mapping Authority
ETM	Enhanced Thematic Mapper
GIS	Geographic Information Systems
GSE	Geological Survey of Ethiopia
LVIA	Lay Volunteers International Association - Ethiopia
MCDE	Multi-criteria Decision Evaluation
MC-SDSS	Multi-criteria - Spatial Decision Support System
MoWR	Ministry of Water Resources
NMA	National Meteorological Agency
RS	Remote Sensing
SDSS	Spatial Decision Support System
SRTM	Shuttle Radar Topography Mission

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1. INTRODUCTION

1.1. Background

After air, water is indispensable for survival of mankind and life on the earth. The amount of water on, under, and above the earth's surface remains essentially constant. Although a minor amount of water vapor may escape into space, additional new water is constantly created as juvenile water by chemical reactions during volcanic emanations. Out of the estimated 1,385,984,610 km^3 water on the earth, fresh water makes up only 2.5%. But not all of this water is available for human use; the water in polar ice caps, other forms of ice and snow, soil moisture, marshes, biological systems, and the atmosphere are not readily available. As a result, only the 10,530,000 km^3 of groundwater, 91,000 km^3 of fresh water in lakes, and the 2,120 km^3 of water in rivers are considered attainable for use and comprise a total of 10,623,120 km^3. Consequently, groundwater comprises 99% of the earth's available fresh water. (Leap, 1999).

Groundwater constitutes an important source of water for various purposes like domestic needs, supply for industries and agriculture etc. Particularly in semi-arid areas of low rainfall, groundwater is the prime source of fresh drinking water. Its occurrence and movement in an area is governed by a variety of factors mainly topography, lithology, geomorphology, geological structures, slope, drainage, land use and interrelationships between them.

Ethiopia has abundant water resources potential of which groundwater has a lion-share. The estimated amount of yearly groundwater recharge of the country is about 28,000 Mm^3 (MoWR, 1998). Most of the developed groundwater resources is mainly used for domestic and industrial water supply. So far, only 20.4% of the Ethiopian landmass has been mapped at 1:250,000, 36.8% at one million scale and the whole country at two million scale.

In the Ethiopian context, different types of ground water are available within the sediments (sandstones, alluvium, karstic limestones, etc); from the very best potable water for domestic use to exceptionally saline water. Poor groundwater

quality in the south, southeast and northeastern regions of the country is the major problem for its utilization due to the presence of gypsum and rock salt in most of the sedimentary formations of the Mesozoic, Tertiary and Quaternary (Tesfaye, 1989).

The shortage of fresh drinking water is acute in lowland and in some highland areas. To feed the ever increasing Ethiopian population on a sustainable basis, traditional rain-fed agricultural practices must shift to irrigated agricultural practices. Likewise, the huge livestock potential of the country has to get reliable water supply. Therefore, it is essential to explore water resources of the country for sustainable water supply and food self-sufficiency.

In developing countries like Ethiopia most of hydrogeological investigations have been done using the conventional techniques with the absence of the application of Remote Sensing and Geographic Information System. The conventional approaches for groundwater investigation like ground based surveys and exploratory drilling are understood to be time consuming and uneconomical. Systematical organization of data on the aforementioned terrain characteristics, evaluation of interthematic and interclass dependencies and variability operating in nature, analyzing their cumulative effect on the development of groundwater regime is the best approach which the current decade requires. This can be achieved by generation of the thematic information on the governing factors through remote sensing, and integration in GIS for evaluation using Multi-Criteria Decision Making techniques.

Satellite remote sensing provides efficient data and effective method for groundwater exploration. Satellite remote sensing data are useful because they provide up-to-date information on the area under investigation particularly, geology, land cover/land use, general topography, the presence of surface water and drainage system. The use of remote sensing data allows effective delineation of aquifers and reducing costs and time spent during geological and geophysical, components of field work prospecting for groundwater.

GIS, as a computer-based data capture, analysis and management system, its main purpose is to provide support and evidences for decisions using spatial data integrations. This purpose can be achieved through organizing, visualizing, querying, combining, or generally analyzing data, and by making predictions with the data (Bonham-Carter, 1994). The concept of integrated remote sensing and GIS techniques has proved to be an efficient tool in groundwater studies (K.S.R. Murthy, 1999, Amaresh et al, 2003, Jeryam et al, 1999)

The study area is covered by hard rock terrain so that the occurrence of groundwater in such an area can be effectively mapped using the integration of thematic maps generated from remotely sensed data on a model developed based on GIS techniques. The thematic maps include lithology, geological structures, geomorphology, drainage density, slope, and landcover. The integration of the thematic layers is performed using the techniques of overlay analysis.

1.2. Problem Definition

Ethiopia is often referred as the "rooftop of Africa" because its extensive highlands capture a major portion of the precipitation that falls on the continent. Indeed, modern hydrogeological studies reveal that fully 80 percent of all the water flowing down the Nile River into Egypt has its source in Ethiopia.

The abundance of water in the highlands, however, contrasts sharply with the acute scarcity afflicting the vast low-lying region stretching south from the central Rift Valley to the border with Kenya. Here, the search for water is a constant element of survival for the semi-nomadic herders who populate the area.

Both the climate and the geology are working against a good water resource potential of the semi-desert Moyale-Teltele region. However, in this unsuitable location, there is significant density of population which mainly depend on livestock for livelihood. In order to make the best use of the available resources, herd owners have accustomed to facilitate the mobility of their stocks from place to place in search of water and pasture.

Wherever basic life resource are so scarce, human conflict appears inevitable, and the study area is no exception. In a part of the world where the contrast between urban and rural lifestyles couldn't be stronger, it's little wonder that nomads and town dwellers are engaged in a political struggle over water.

The hydrogeology of Moyale is yet not well studied except a pre-feasibility study for water supply for the town of Moyale by Associated Engineering Ltd, as part of the programme of work for the International Drinking Water Supply and Sanitation Decade (IDWSSD) in Ethiopia on 1982. At that time, there was no community water supply in the area. Attempts were made to provide community water supply but failed.

As Moyale is one of the agro-pastoralist areas of the country which are most vulnerable to drought, the water resources should be studied in detail and developed to insure the food security of the population. Keeping this in view, the present study attempts to integrate remote sensing and GIS through multi-criteria analysis of decision support for evaluation of groundwater potential in Moyale-Teltele sub-basin.

1.3. Objectives

- General:

- To apply techniques of Geographic Information System and Remote Sensing data for groundwater resources assessment using Multi-criteria Decision Evaluation and to reveal the importance of their integration.

- To show the advantage, with respect to effectiveness and efficiency, of the Remote Sensing, GIS, and MCDE technologies over the conventional approaches of ground water exploration.

- Specific:

- To assess groundwater potential of the study area,

- to develop a Geodatabase as a Spatial Multi-criteria Decision Support System for use by the responsible authorities as a baseline for planning, and

- to forward recommendations to any plans and programs targeted on meeting the increasing demand of the population of the study area with safe drinking water.

1.4. Methods of Study

The study demonstrates the capabilities of using remote sensing and GIS for demarcation of different ground water zones, especially in diverse geological setup. This gives more realistic groundwater potential map of the area which may be used for any groundwater development and management programme. Therefore, an effort is made to utilize all these techniques in every step of the research as possible.

The application of GIS technology in water resource investigation requires the design and development of a methodology to analyse water resources and its components with its complex ecological and socio-economic inter-relationship.

The methodology adopted in the research study is designed to integrate the modern techniques of remote sensing, GIS, and MCDE in the groundwater potential zone demarcation.

Primarily the problem has been identified and the scope of the research study and the extent of the study area has been defined. Water as a scarce resource in the world, is the prime need for the agro-pastoralist community in the Ethiopian southern plains. One of the areas categorized as driest zone in the country, as a result properly unexplored hydrogeologically is located in the southern most extreme as Moyale-Teltele sub-basin of Genale Dawa river basin.

In such crystalline hard rock terrains, rock type, geological structures, and geomorphology influence the presence of water in the underground. Drainage

system, landcover, and slope are the other factors to be considered in assessing groundwater resources of an area. After setting the criterion of the factors for groundwater occurrence in the area, different types of data had been collected and entered into the GIS environment through scanning, digitizing, and Key-board entering. See table 1.1 for the type and sources of different data collected and used for the research study.

Data Type	Method of Input	Data Source
Lithologic Map	Digitized from Analog Geological Maps	Geological Survey of Ethiopia
Structural Map	Digitized from Analog Geological Maps	Geological Survey of Ethiopia
Contour Map	Generated from SRTM DEM data	Ministry of Water Resources
Drainage	Digitized from Analog Topo-sheets	Ethiopian Mapping Agency
Land cover	Classified from Satellite Imageries	Ministry of Water Resources

Table 1.1: Identified data types and possible sources

As summarized in table 1.1, Satellite imageries have been classified in ERDASImagine 8.6 to generate land-cover map of the area. Geologic, structural, and drainage maps were digitized from 1:250,000 analog maps obtained from GSE and EMA. 90m resolution SRTM digital elevation model data has been used to generate contour map of the study area in Global Mapper 6, which in turn used to generate the slope map in ArcGIS 9.1.

The input datasets have passed through different remote sensing and GIS analysis processes to derive the datasets needed for analysis. The derivation of analysis maps utilized different spatial analysis functions in ArcGIS 9.1.

Pair-wise comparison of different map layers and classes using the WEIGHT module in IDRISI 32 resulted in the weights and ranks to be assigned to the datasets. Finally, overlaying the weighted and ranked datasets in ArcGIS 9.1 brought the resultant of the different factors considered in the analysis.

Reclassifying the combined result revealed the final groundwater potential map of the study area. A geodatabase containing the map layers used as input and the final groundwater potential map is a complement out put together with the text report of the research study. Figure 1.1 shows the overall flow chart of the research methodology.

1.5. Thesis Layout

The thesis has comprised six separate chapters. The first chapter gives general introduction on the background of the problem, objectives of the research study, the methodology utilized and layout of the thesis.

The physical and socioeconomic characteristics of the study area, its location and accessibility are well described in the second chapter. Chapter three covers literatures on the concepts of Multicriteria Analysis in Groundwater Assessment. Different international experiences of using RS, GIS, and MCDE in integration for groundwater assessment and previous works in the study area are also reviewed in this chapter.

The main part of the research study, data analysis is presented in the fourth chapter while the results are discussed in chapter five. Finally conclusion and recommendation is given in the sixth chapter. Different tables and additional information are collected in the annexes.

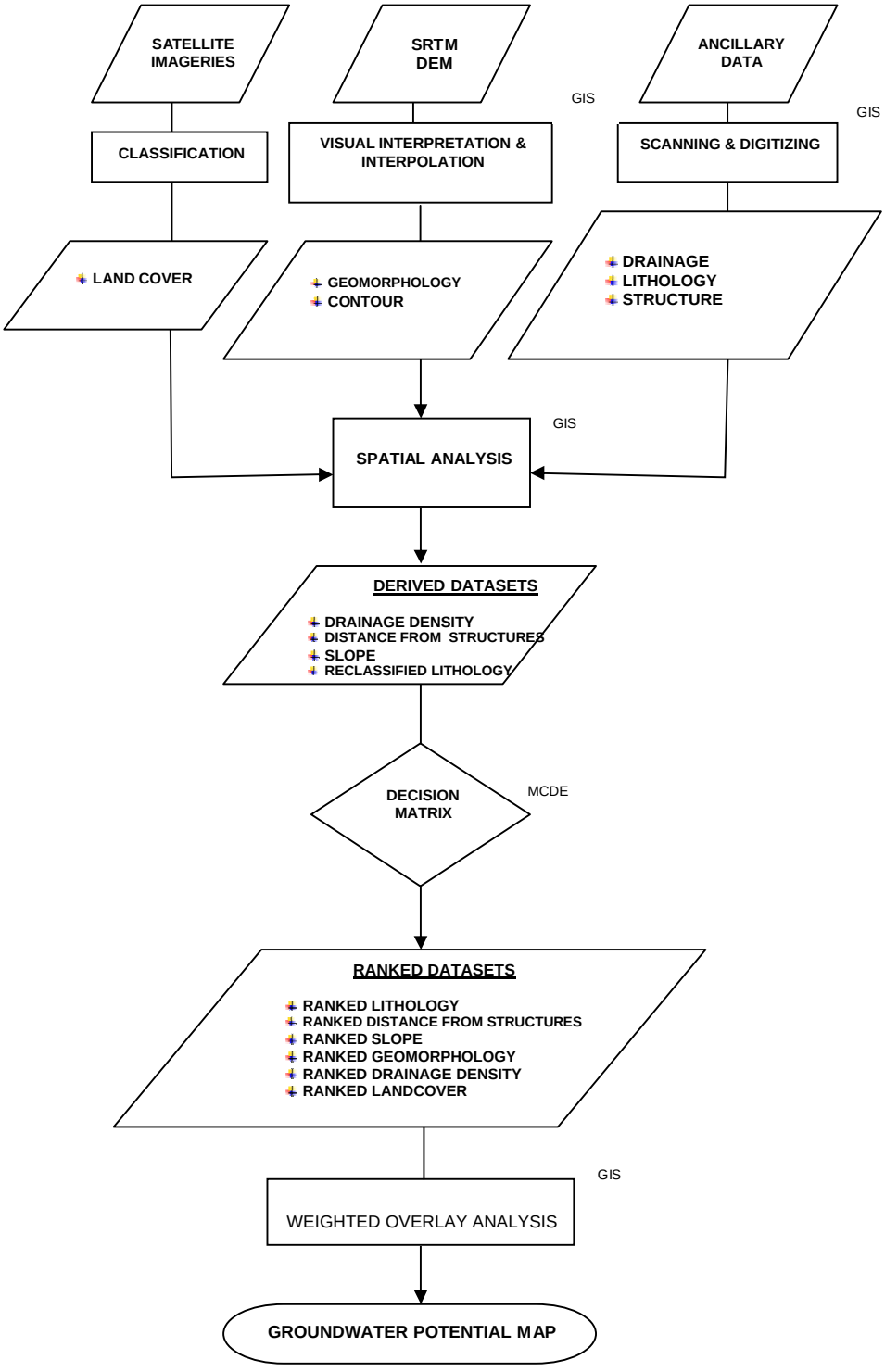

Figure 1.1: Methodology flow chart

2. STUDY AREA DESCRIPTION

2.1. Location and Accessibility

2.1.1. Location

The research area is located in the Moyale-Teltele sub-basin of Genale Dawa river basin in the southern extreme of Ethiopia (Figure 2.1). The area is internationally bordered with Kenya in the south and with Somalia in the east. It is bounded by latitude 3°24'4'' N – 5°2'6'' N and longitude 37°1'40'' E - 40°14'34'' E. In general, it includes the southern parts of NB 37-13, NB 37-14, and NB 37-15 and the upper parts of NA 37-2 and NA 37-3 covering a total area of 30,825 km^2.

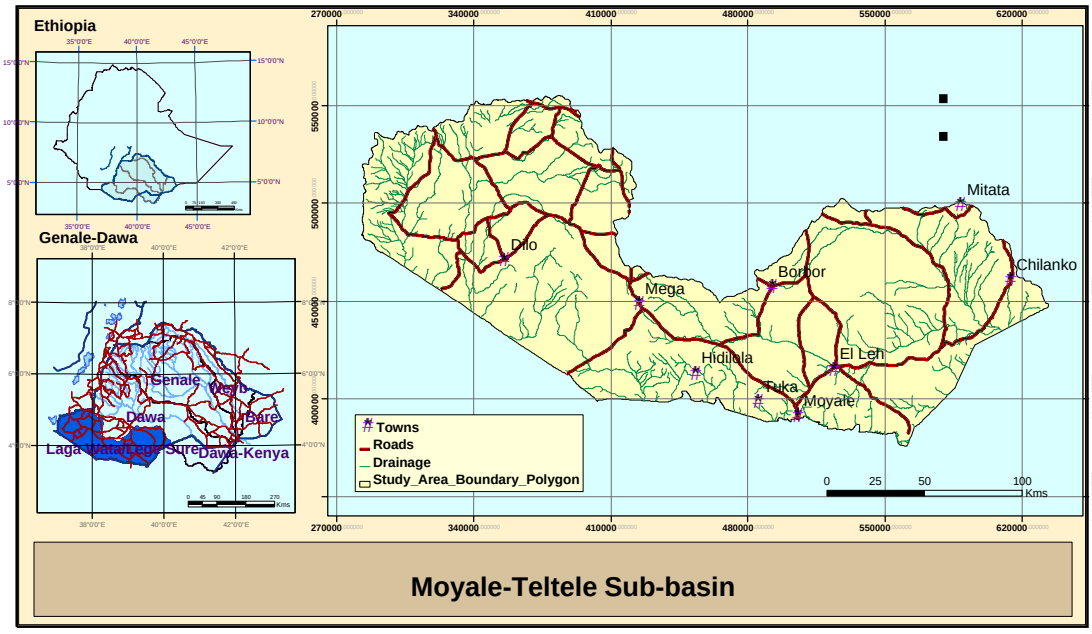

Figure 2.1 Location Map of the Study Area

2.1.2. Accessibility

The study area is included in the Moyale, Dire, Arero, and Teltele Woredas, Borena Zone of Oromia Administrative Regional State and Moyale Woreda, Liben Zone of Somali Administrative Regional State (Figure 2.2). Except the southern part which is rugged, the rest are accessible by four-wheel drive vehicles. The

775 Km Addis Ababa-Moyale international asphalt road runs north-south across the central part of the part of the study area. The Moyale-Katama dry weather road, which passes through Dokisso crosses the area across the lower east side. Dry weather roads join Moyale to Chilanko via Leh; Moyale to Kedaduma via Dokisso & Katama; Moyale to Wachile. There are also other roads which join this E-W running road. Besides this, there are foot paths from different villages that join Moyale-Katama road.

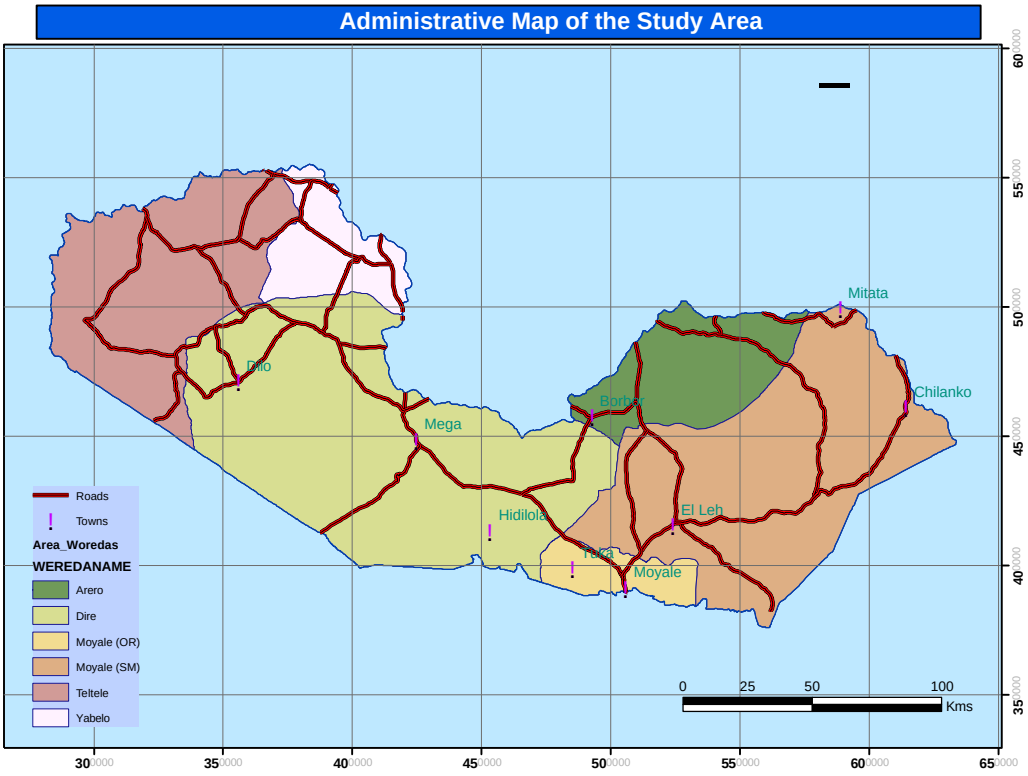

Figure 2.2: Administrative Map of the Study Area

2.2. Physiography, Climate and Hydrology

2.2.1. Physiography

i) Topography

In the southern, north western and western parts of the area exist mountaneous land forms relatively rugged and ranging from 2000 to 2400 meters above sea

level with associated river gorges; while the rest part is flat lying with maximum elevation of 1740. Altitude decrement is observable from west to east (Annex 4).

About 50% of the basin is below 1380m; while some 25% of the sub-basin area ranges in altitude between 1380m and 2000m.

ii) Geomorphology

Geomorphology of a region is controlled mainly by structures, rock types, denudational activities, and climate. The main geomorphological features that characterize the study area are described below. See figure 4.5 for geomorphological map of the study area.

A) Highly Rugged Terrain (Major Scarps)

The north western and western part of the area is highly rugged and dissected by parallel and sub-parallel drainages. The rocks in the area are mainly amphibolite, gneiss and schist. Erosion is very intensive in this terrain. There is a morphological difference between the low lying plain bordering Kenya and relatively elevated land in this unit; this difference in topography favours erosion at higher elevation and formation of alluvial fans in the low land.

B) Isolated Hills (Foot Hills)

These are few intrusives forming a prominent topography in a flatter terrain. These hills are composed of ultramafic rocks. The core is hard-silicified ultrabasic (serpentinite) which is resistant to weathering and erosion. The outer part is dominantly schist.

The ultramafic hills are elongaed in the E-W direction, which makes it clear that, they are intruding in the E-W trending structure.

C) Sharp Crested Ridges (Minor Scarps)

These are mainly N-S trending structurally controlled ridges; lithologically they are granite and granitic gneiss. They are very resistant to erosion and weathering. Some of the ridges in the central part of the area are deviating towards NNW direction.

D) Peneplained Flat Terrain (Plains)

The vast majority of the area is categorized in this unit. It is a plain with very few inselberges. Since this flat terrain is covered with soil, the underlying rock can not be identified but it is expected to be rocks of low resistant types. In the entire region this is the only unit which is covered by soil. The streams show meandering courses due to extremely low gradient.

Piedmont Plains and Plateaus are also the geomorphological features that cover little portion of the study area.

iii) Soils and Vegetation

The type in texture and thickness of soils is important in determining the degree of infiltration in an area. Silty and sandy soils occur in the alluvial, metamorphic and intrusive areas while clayey soils are common in the volcanic areas. Similarly, the type and extent of coverage of the vegetation cover can have significant effect on the infiltration.

The soil occurring in the area are similar to those found on arid moisture regime having calcric and gypsic horizons lacking other diagnostic horizons (Haplic-Xerosols). They are reddish in color and very thin. These soils, which are constituted by unconsolidated material and possess weak or no development of soil horizons (Eutric Regosols) cover the southern part of the area (Zenaw et al, 2000).

Generally, there is no well developed soil horizon with significant thickness; except the soil horizon developed in the lacustrine deposits, in a locality of El-Gof and El-Leh, which has got considerable thickness. It is fine to medium grained in texture and can be seen forming termite hills of light color, thus demarcating the boundary between the reddish soil and that of lacustrine deposits. (Zenaw et al, 2000).

2.2.2. Climate

The area is characterized by hot semi-arid climate experiencing high-temperature, low rain fall and high evapotranspiration. This climatic condition is favorable to sustain grasses and acacia trees. (Zenaw et al, 2000).

i) Precipitation/Rainfall

In the study area, there are two meteorological stations, which are located in Mega ($38^0$20'E, $4^0$05'N) and Moyale ($39^0$04'E, $3^0$31'N). 21 years of rainfall data was collected from the National Meteorological Agency for the stations from 1985 to 2005. Summary of the mean rainfall (mm/month) data is given in the table 2.1 and 2.2 below and the detailed climatological data for each year is given in the Annex - 1.

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Rainfall	16.7	41.3	80.6	142	74.7	17.1	14.7	5.0	7.3	74.5	57.9	41	572.8

Table 2.1: Summary of mean rainfall data of Mega Station, Year 1985-2005

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Rainfall	17.5	22	42	148.9	65.6	13.4	7.4	4.9	13.5	83.5	82.2	30.2	531.1

Table 2.2: Summary of mean rainfall data of Moyale Station, Year 1986-2005

From the rainfall data of the stations two short rainy seasons are observed in the study area. The first rainy period lasts from March to May. The second rainy period lasts from October to November, which is torrential in October. The main cause of the rainfall in this region is the southward migrating Inter Tropical

Convergence Zone (ITCZ) and westward propagating disturbance from the Indian Ocean (Zenaw et al, 2000).

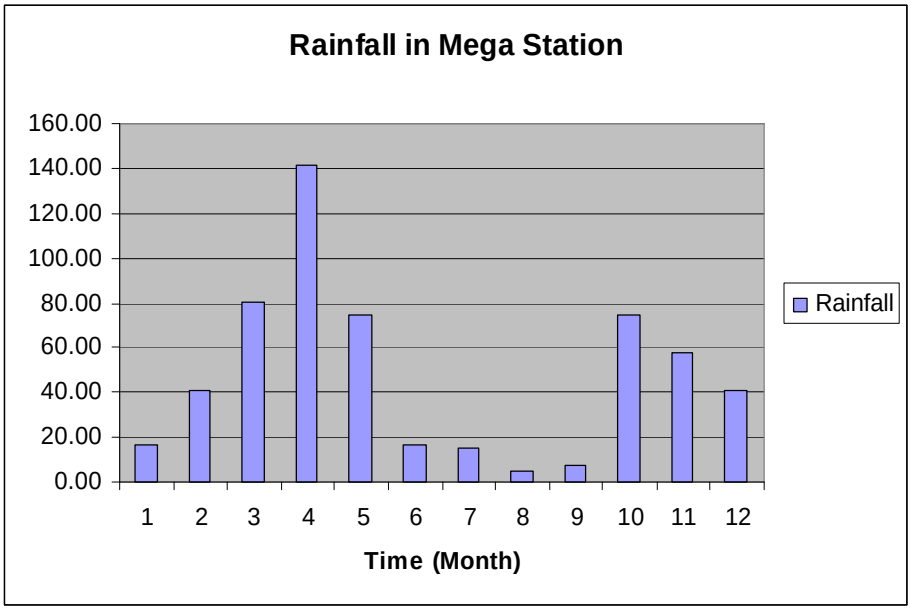

Figure 2.3: Mean Annual Rainfall Chart of Mega Station

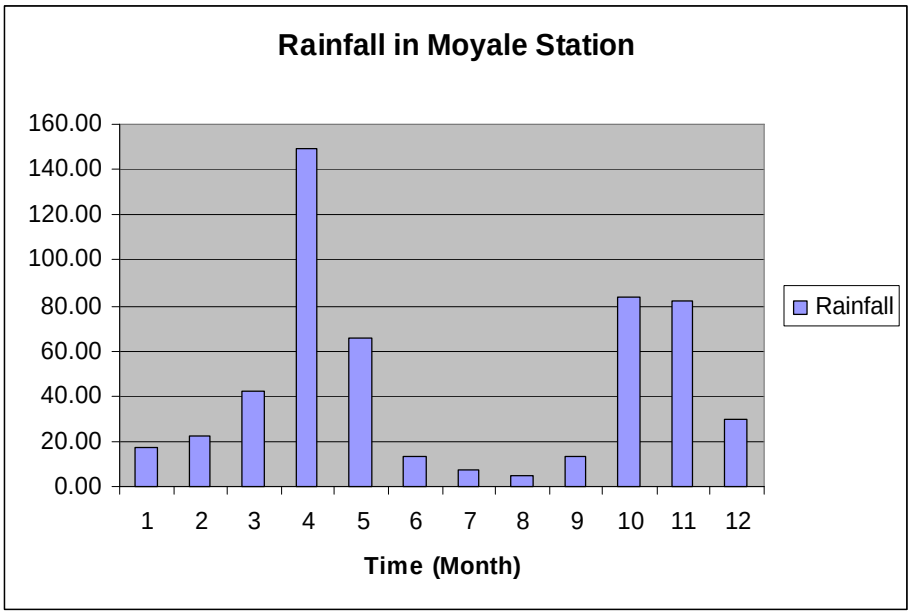

Figure 2.4: Mean Annual Rainfall Chart of Moyale Station

The above charts clearly show that the area has uniform rainfall pattern which is relatively low. Since there is no variation in the mean annual rainfall of the two

stations, it is not possible to consider rainfall as input factor layer for the analysis.

ii) Temperature

The temperature of the study area is typical of tropical monsoon lands. In most cases the mean monthly temperature exceeds 20^{o}C. The daily average minimum temperature registered is 11.4^{o}C in the month of July in Mega Station and the daily average maximum temperature is 35.3^{o}C registered in Moyale Station. The hottest season extends from December to late March.

The summary of mean monthly air temperature of the stations is given below.

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
T (^{o}C)	20.6	21.0	20.3	19.5	18.3	16.8	16.1	16.9	18.3	18.9	19.2	19.8

Table 2.3: Mean Monthly temperature of Mega Station

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
T (^{o}C)	24.9	25.5	25.0	23.0	21.8	20.6	19.9	20.5	21.6	22.0	22.5	24.9

Table 2.4: Mean Monthly temperature of Moyale Station

iii) Potential Evapotranspiration

In tropical regions, where there is little change in temperature or duration of sunlight, potential evapotranspiration is likely to be constant through out the year. The peneplained part of the area is characterized by tall savannah grass with shrubs accacia and thorn bushes. The southern rugged terrain bordering Kenya is composed of continuous dense shrubs with scattered small trees. The vegetation cover over some part of the study area has contributed to increasing evapotranspiration.

The average evapotranspiration of the study area is 1633 mm/yr at 1000 m.a.s.l. (Zenaw et al, 2000). In this report, the evapotranspiration has been estimated according to penman method. High potential evapotranspiration values known in

the lowlands exceed 1500mm/year (up to 2300 mm/year) with no water surplus through out the area. The moisture deficits in the area reach 1047mm.

2.2.3. Hydrology

The Genale-Dawa basin, the third largest basin in the country, may be sub-divided into five sub-basins as:

The main river sub-basins:

- The Genale sub-basin
- The Weyb sub-basin
- The Dawa sub-basin

The sub-basins with ephemeral streams that do not drain to the main rivers inside Ethiopia:

- The Moyale-Teltele (Lege Sure-Laga Wata) sub basin in the south west
- The Hargele sub-basin in south east.

The Moyale-Teltele (Lege Sure-Laga Wata) sub basin includes the Lega-sure and Lega-wata rivers to the east and west respectively. Both streams flow towards the south to Kenya across the general structure and both are intermittent. Generally the drainage pattern is dendritic-paralel type, with medium-coarse texture.

Due to inaccessibility of the area and the seasonal nature of the streams, both are not guaged and there is no flow and stage data. But from field observation, the Lega Sure will fill its channel in the summer and dries in mid winter.

2.3. Geological Setting

2.3.1. Regional Geology

The area is covered by the different rock groups in the sub-basin may be approximated as follows:

- Precambrian rocks with associated intrusives

- Mesozoic sediments
- Tertiary Volcanic Successions
- Quaternary Volcanics and Sediments

The gneisses and metamorphosed granites of the Lower complex are the oldest rocks and they are located in the southern and south western parts of the basin. When the movements in the granite-gneisses basement (Lower Complex) are established, a long quiet period commenced and during this period the Wadera clastics derived from older granite-gneiss were accumulated, and later the Wadera rocks were strongly altered and partly granitized (Kazmin, 1972). This Middle Complex occurred between approximately 2500 million years and 1600 million years before the time of the Upper Proterozoic geosynclinal succession.

Table 2.5 summaries the stratigraphic succession of the rock units known in the sub-basin.

Stratigraphy		Lithology	
Era	Period	Name	Description
Quaternary	Holocene	Alluvium, Eluvium, and Basalt	Quaternary Volcamics and Sediments
Tertiary	Oligocene to Middle Miocene	Alaji Formation	Tertiary Volcanic Successions
Mesozoic	Juriassic	Hamanlei Formation	Bioclastic limestone
Precambrian	Early Paleozoic	Biotite and Hornblende Granites	Intrusives
	Upper Proterozoic	Metagranites	Intrusives
		Adola Group	Mafic-Ultramafic-Volcano-Sedimentary Assemblages
	Lower to Middle Proterozoic	Mormora Group	Gneissic and Migmatitic Complexes
		Awata Group	
		Algehe Group	

Table 2.5: General Stratigraphy of the Study Area

The upper Proterozoic geosynclinal deposition occurred with subsequent light degree of metamorphism of the greenshist facies. This began more than 1000 million years and 1600 million years ago with the formation of major geosynclinal trough approximately in the Red Sea Zone (Kazmin, 1972). These geosynclinal rocks exist in the north, west, and south of the country, but they are very abundant in the north. The Adola and Mormora groups were formed in the geosyncline. As part of the geosynclinal rocks, one finds both metavolcanics and metasediments. The Adola Group has amphibolites of intrusive and volcanic origin while the Mormora Group has biotite and graphite phylites with carbonaceous schist, sandstone and rare marble.

The main trends in Precambrian history may be summarized as:

1. Formation of ancient craton with thin sedimentary cover (2500-1600my)
2. Mozambique rejuvenation which had two aspects
    a. Formation of geosynclinal troughs on the broken granite-gneiss basement
    b. Formation of mobile belts built of rejuvenated cratonic material

In the beginning of the Mesozoic Era, Jurassic Period, marine transgression occurred resulting from tectonic subsidence, and the Adigrat sandstones were deposited. During this transgression and subsequent regression of the sea, Lower to Upper Hamanlei was deposited. In shallower sea of the regression, the Middle Hamanlei Formation, gypsum, anhydrites, and dolomites were deposited. Then sandy limestones of Upper Hamanlei were deposited in shallow transgressing sea. Next the deep water shales of Urandab Formation were deposited. The sea then became shallower and the carbonates of Gabredarre Formation were deposited. Finally, in another transgression, the Mustahil Formation was deposited consisting of limestones, shales and marls.

In the Cainozoic Era, extensive Tertiary volcanism occurred together with formation of the Rift valley. The volcanism and tectonism continued into the Quaternary, Continental environment prevailed during this era up to present in the Genale Dawa basin with formation of alluvial and eluvial deposits.

2.3.2. Local Geology

Basement rocks of different groups associated with intrusives as well as undifferentiated quaternary sediment comprise the major lithological units. (Tolossa, et al, 1990)

Good exposures of Precambrian rocks are found in the southern part of the area, following the main stream valleys. The basement rocks are mostly associated with intrusives of Precambrian to phanerozoic age. The intrusives are mainly gabro, tonalite, and pretectonic, syntectonic, and post tectonic granites. Further more, the crystalline rocks deeply affected by multi-oriented faults and folds. Locally, there exist major fault lines aligned NW to SE while minor fault lines nearly perpendicular to the main fault systems.

The rest part of the area is predominantly covered by flat lying undifferentiated quaternary alluvial and lacustrine deposits compositionally sand, silt, clay, diatomite, limestone and beach sand.

2.4. Settlement and Population

Very low annual rainfall and lack of perennial streams have limited wider settlements in the area. Moyale is the major town with a population of about 100,000. Apart from this, villages such as Elgof, Leh, Chilanko, Ketema, Dokisso, Kedaduma, Elder, Elkur have got very limited number of population which depend on dug wells (locally called Ela) as well as borehole for water supply. The borehole, in basement rocks yields insignificant amount of water. Large group of population or settlement is therefore, not anticipated in areas covered by basement rocks.

Two major tribes dwell in the area namely, Borena belonging to the Oromo and the Geri to the Somali. The Borenas inhabit the western side where as the Geri the eastern. Oromifa is widely spoken besides the Somali language, which is mainly bounded to the eastern frontier of the study area. The basic means of

subsistence (livelihood) is livestock. The camel population is larger in the east than in west.

3. LITERATURE REVIEW

3.1. Spatial Multicriteria Decision Analysis

A decision is a choice between alternatives. The alternatives may represent different courses of action, different hypotheses about the character of a feature, different classifications, and so on. Broadly speaking a Decision Support System (DSS) is simply a computer system that helps you make a decision. DSS provide a means for decision-makers to make decisions on the basis of more complete information and analysis. Decision makers historically have indicated that inaccessibility of required geographic data and difficulties in synthesizing various recommendations are primary obstacles to spatial problem solving. Studies have shown that the quality of decisions (i.e., the ability to produce meaningful solutions) can be improved if these obstacles are lessened or removed through an integrated systems approach, such as a spatial decision support system (SDSS), particular and important types of DSS.

SDSS refers to those support systems that combine the use of GIS technology with software packages for selection of alternatives of location for different activities. In addition, multicriteria decision making (MCDM) and a wide range of related methodologies offer a variety of techniques and practices to uncover and integrate decision makers' preferences in order to solve "real-world" GIS-based planning and management problems. However, because of conceptual difficulties (i.e., dynamic preference structures and large decision alternative and evaluation criteria sets) involved in formulating and solving spatial decision problems, researchers have developed multicriteria-spatial decision support systems (MC-SDSS).

Spatial multicriteria decision problems typically involve a set of geographically-defined alternatives (events) from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria (Malczewski, 1999).

3.2. Integration of Remote Sensing and Geographic Information Systems in Hydrogeology

Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become a very handy tool in assessing, monitoring and conserving groundwater resources. Satellite data provides quick and useful baseline information on the parameters controlling the occurrence and movement of groundwater like geology, (lithology and structure), geomorphology, soils, landuse/cover, lineaments etc. However all the controlling parameters have rarely been studied together because of non-availability of data, integrating tools and modeling techniques. Hence a systematic study of these factors leads to better delineation of prospective zones in an area which is then followed up on the ground through detailed hydrogeological and geophysical investigations. Visual interpretation has been the main tool for evaluation of groundwater prospective zones for over two decades.

It has also been found that remote sensing besides helping in targeting potential zones for groundwater exploration provides inputs towards estimation of the total groundwater resources in an area, the selection of appropriate sites for artificial recharge and the depth of the weathering area. By combining the remote sensing information with adequate field data, particularly well inventory and yield data, it is possible to arrive at prognostic models to predict the ranges of depth, the yield, the success rate and the types of wells suited to various terrain under different hydrogeological domains. Based on the status of groundwater development and groundwater irrigated areas (through remote sensing), artificial recharge structures such as percolation tanks, check dams and subsurface dykes can be recommended upstream of groundwater irrigated areas to recharge the wells in the downstream areas so as to augment groundwater resources.

Apart from visual interpretation, digital techniques are used by many researchers for deriving geological, structural and geomorphological details. The various thematic layers generated using remote sensing data like lithology/structural,

geomorphology, landuse/cover, lineaments etc, can be integrated with slope, drainage density and other collateral data in a Geographic Information system (GIS) framework and analysed using a model developed with logical conditions to derive at groundwater zones as well as artificial recharge sites. Digital enhancement techniques are found to be suitable since they improve the feature sharpness and contrast for simple interpretation.

Typical examples of GIS applications in groundwater studies are site suitability analyses; mapping information such as water table depths, aquifer type and material, and aquifer recharge; managing site inventory data; computing statistics to estimate spatial correlation of a process occurring over a region such as non-point source pollution; estimating vulnerability of groundwater to pollution potential from non-point sources of pollution; integrating groundwater quality assessment models with spatial data to create spatial decision support systems; modeling groundwater movement: advection and dispersion modeling, developing flow field or vector fields representing groundwater seepage velocities, tracking particle movement, and particle retardation; modeling solute transport and leaching; and evaluating soil salinity and salt loading into groundwater.

3.3. Previous Works

There are a variety of preveous researches undertaken in the application of Remote Sensing, GIS, and MCDE in groundwater resources assessment. Very few of the relevant literatures reviewed are summarized below.

Amaresh et al, 2003 used integrated approach of Remote Sensing, geophysics and GIS to evaluation of groundwater potentiality of Ojhala Subwatershed, Mirzapur district, U.P., India. In order to delineate the groundwater potential zones, in general, different thematic layers viz: hydrogeomorphology, lineaments, slope, drainage and overburden thickness are used to be integrated without considering aquifer thickness. This provides a broad idea about the groundwater prospect of the area. Then groundwater potential zones have been demarcated by integration of aquifer thickness derived from surface electrical

resistivity survey and drilling data with above thematic layers, using a model developed through GIS technique. The groundwater potential zones map generated through this model was verified with the yield data to ascertain the validity of the model developed and found that it is in agreement with the bore wells yield data. This illustrates that the approach outlined has merits and can be successfully used elsewhere with appropriate modifications. The study has demonstrated the capabilities of using remote sensing, geoelectrical data and Geographical Information System for demarcation of different ground water potential zones, especially in diverse geological setup. This gives more realistic groundwater potential map of an area which may be used for any groundwater development and management programme.

Sandeep et al, 1999 attempted to use remote sensing, GIS and multi-criteria analysis of decision support for evaluation of groundwater in watersheds of Rawasen and Pili rivers which are the tributaries of Ganga, U.P., India. The groundwater exploration in the study area involved thematic map generation and their integration through GIS. Geology, Landuse, Geomorphology and Lineament maps were derived from interpretation of Satellite Images and Aerial Photographs supported by selective ground truth verification. Drainage map was prepared using Survey of India toposheet on 1:50,000 scale. Slope map was obtained by creating DEM after interpolation of spot height and contour in GIS. For integration all the maps were converted into digital format in the GIS. Prior to integration of different information, individual class weights and map scores were assessed based on Satty's Analytic Hierarchy Process. In this method a pairwise comparison matrix was prepared for each map using Satty's nine point importance scale and this matrix was solved using Eigon Vector method. This resulted in individual class weights. The map scores were also calculated by same method. These weights were multiplied with map scores and applied to linear summation equation. This resulted in a unified weight map containing due weights of all input variables. This map was further logically classified to arrive at groundwater potential zone map.

Jeyram et al, 1999 developed a Ground water potential model for Uma-Kalhar watershed in northwestern part of Chandrapur district of Nagpur. Maharashtra,

India,based on Index overlay method using hierarchical weightage. Depending upon the perceived importance of maps and its classes, hierarchical weightages are accepted as map score and class score. The interface generates ground water potential map with five potential classes. Ground water reserve estimation GIS model is tasted on Groundwater Estimation Committee of India which estimate phreatic ground water reserve. Static ground water reserve and dynamic reserve calculation was done separately.

In order to produce the ground water potential map of the Langat Basin area, Malaysia, a GIS model has been used, to integrate thematic maps such as annual rainfall, lithology, lineament density, land use, topography elevation, slope steepness, drainage density and soil type (Khairul et al, 2000). Each thematic layer consists of a number of polygons, which correspond to different features. The polygons in each of the thematic layers have been categorized, depending on the suitability/relevance to the ground water potential, and suitable weights were assigned. Finally, all the thematic layers were integrated using the ground water potential model to derive the final derived layers of ground water potential. The output is then reclassed into five groups using the Quantile classification method. The output that is produced is capable of being used for further investigations and assessments, especially at larger scale.

A groundwater assessment model allows engineers and planners to assess the groundwater more efficiently, accurately and at a faster pace. In the GIS based groundwater assessment model of S.M.Kharad et al, 1999, ground water assessment is based on the water table fluctuation method and calculated based on the norms recommended by National Groundwater Estimation Committee of India. The parameters used include: normal yearly and monsoon rainfall data, depth to water table for pre and post monsoon water level, specific yield data for the zone of water table, geomorphology, surface water irrigation data (For monsoon and non-monsoon), landuse/landcover, slope etc. The database of the parameters listed above (ie Spatial and Non-Spatial database) was created and imported into ARC/INFO as coverage. The required non-spatial database was attached to respective coverage. The module is designed to select the relevant coverages and calculate the recharge or seepage of individual

component/coverages. The module then combines the results of individual components and displays value of groundwater balance and the categorization of the watershed under investigation.

A number of reports have been produced on the geology and mineral resources as well as the groundwater of the sub basin. The main literature encountered is listed in References. These are reports and maps dealing with the geology, hydrogeology and related fields and they are found mainly in the libraries of the Geological Survey of Ethiopia and the Ministry of Water Resources.

Some reports and maps are more important and closely related to the objective of the groundwater study in the sub-basin. A reconnaissance phase study was carried out in 1998 on the Genale-Dawa River Basin Integrated Master Plan Project by the Ministry of Water Resources. This report of the Reconnaissance phase provides a general overview on the hydrogeology of the Basin based on previous works.

In the Moyale area, regional hydrogeological mapping was carried out at 1:250,000 scale for the sheet NA 37-3 by Zenaw Tessema et al. (2000). This mapping covers about 30% of the sub-basin area and also done in GSE.

The previous works, especially those concerned with the hydrogeology of the sub-basin, are used as source of basic data on aspects as water points and aquifer characteristics as viewed by the respective authors. The present study required reviewing all available information for a common interpretation of the hydrogeology.

4. ANALYSIS

The integrated approach methodology of assessing groundwater potential in the study area involved analysis of data in RS, GIS, and MCDE techniques. The techniques are applied in every stages of analysis, starting from data organization to final out put modeling/generation. After defining the objectives of the research, the factors to be considered in order to solve the stated problem were determined. This has led to identify the data needed and its sources.

The research geodatabase is designed in order to archive the collected data and the analysis results in a logical arrangement. The factors involved were examined according to their relative importance towards solving the stated problem and assigned weights. The classes in each factor layers were also compared one another and ranked by their contribution to the output. This has derived the input map to ranked analysis maps.

Finally, the derived maps were also multiplied by their weights and combined in raster calculator. The detailed description of the analysis is presented in the following sections.

4.1. Dataset Organization

The main objective of the research is to characterize the study area in terms of its groundwater potential by applying the integrated techniques of RS, GIS, and MCDE.

To achieve the above stated objective, the study area was assessed whether or not it fulfills the criteria that are commonly applied in hydrogeology to select best groundwater potential areas. Based on the criteria, those factors that have to be considered for delineating groundwater potential zones were selected. All the necessary data were identified with their possible sources, collected by different means and organized in to layers of criteria factors.

4.1.1. Setting Criteria and Determining Factors

From hydrogeological point of view, an area with promising groundwater potential should be covered in a rock outcrop with high primary permeability that developed from intergranular connected porosity. If the area in concern is hard-rock terrain, there must be abundant network of connected fractures that will make the rock a groundwater reservoir.

Flood channels, alluvial fans, piedmonts, and pediplains are known to be good physiographic zones that facilitate infiltration of precipitated water to the underground.

Groundwater follows similar pattern of flow as surface water. Therefore, low and flat slopes are favourable sites of groundwater discharge.

The natural cover of the land surface is indicative of the subsurface condition. Trees favour wet soil surface to sustain their permanent growth. In areas where the number of streams is more in a unit area, the most proportion of the water coming from precipitation goes to runoff. Unless there are sufficient interconnected pores, there is no chance of water to percolate to the ground.

The aforementioned relations of groundwater with the natural factors that determine its occurrence were used as criteria to select best groundwater potential zones in the study area.

These criteria imply the governing factors of occurrence of groundwater in the study area. Accordingly the following six factors were selected for consideration in the analysis:

- Lithology
- Geological structures
- Geomorphology
- Slope
- Landcover, and
- Drainage.

Table 4.1 describes the property of each factor and its relationship to groundwater potential.

Factor	Property Considered	Implication to Groundwater	
		Value	GW
Lithology	Type	Mesozoic and Quaternary Deposits	High
		Prec. Basement And Intrusives	Low
Structure	Proximity	Nearest	High
		Farthest	Low
Geomorphology	Type	Peneplained Flat Terrain, and	High
		Hills and Ridges	Low
Slope	Degree	Very Low	High
		Very High	Low
Landcover	Vegetation Cover	Woodland, Cultivated Land	High
		Bareland, Open Grassland	Low
Drainage	Density	High	Low
		Low	High

Table 4.1: Characteristic of factors in relation to groundwater occurrence

4.1.2. Input Datasets Identification

The first step in every research is to identify the information/data needed to solve the problem justified earlier. The data needed to support the analysis functions in this research and the providers of such geographic information were

identified (see table 1.1). The data is then collected from the corresponding sources and automated.

Individual entities were assigned and a characteristic spatial representation format was selected for each entity (table 4.2) that will make it suitable for handling in the research geodatabase.

Entity	Format
Geological Factors	
Lithology	Shape File (Polygon)
Structure	Shape File (Line)
Soil	Shape File (Polygon)
Hydrological Factor	
Drainage	Shape File (Line)
Physiographic Factors	
Geomorphology	Shape File (Polygon)
Slope	Raster
Land use/cover	Raster

Table 4.2: Entity representations in the research geodatabase

4.1.3. Research Geodatabase Design and Building

The collected data were automated (scanned, digitized, and clipped by the study area boundary) and organized into logical groupings of the factors. The six factor layers that are grouped into three according to their nature as:

A. Geological Factors:

1. Lithology
2. Structure

B. Physiographic Factors:

3. Geomorphology
4. Slope
5. Landuse/Cover

C. Hydrological Factor:

6. Drainage

The research geodatabase is then designed to include the input datasets, their derived datasets, the weighted analysis maps, and the final result. Verification layers are also included in the geodatabase in tabular and shape-file format. The vector files are exported to the corresponding feature data sets and the raster files are exported as individual rater datasets in the geodatabase.

The coordinate system selected to be used for analysis is projected coordinate system, UTM (table 4.3). Thus the geodatabase is set to this spatial reference and all the maps were projected to it while exporting to the geodatabase.

Projected Coordinate System:	Adindan_UTM_Zone_37N
Projection:	Universal Transverse Mercator
False Easing:	500000.000000
False Northing:	0.000000
Central Meridian:	39.000000
Latitude of origin:	0.000000
Linear Unit:	Meter (1.000000)

Table 4.3: Spatial reference of data used in the research

4.2. Data Processing

The study area boundary was digitized from a scanned sub-basin description map of Genale- Dawa basin obtained from the Ministry of Water Resources. This boundary map was used to clip different maps in order to prepare them as data layers used for analysis.

4.2.1. Data Input and Deriving Analysis Maps

Geologic Factors

Five 1:250,000 geologic maps of NB37-13 (Istifanos Hayk), NB 37-14 (Yabello), NA 37-15 (Wachile), NA 37-2 (Sololo), and NA 37-3 (Moyale) were collected inhard-copy format from Geological Survey of Ethiopia; then scanned, georeferenced, mosaiced, clipped and digitized in to shape files of polygon (lithology) and line (structure) as input layers.

i) Lithology

The lithologic units that used to classify the lithology (Figure 4.1) were grouped according to their importance for groundwater in to hydrogeologic units. The reclassified lithologic map contains the following hydrogeologic units: Quaternary Alluvial Deposits, Quaternary Volcanics, Tertiary Volcanics, Mesozoic Sediments, Gneissic and Migmatitic Complexes, Mafic Ultramafic Assemblages, and Precambrian Basements. The Old Classification according to lithology and the new grouping is shown in table 4.4. Refer the Annex-6 for the description of the codes used to represent the lithological units. This resulted to the reclassified lithological map (Figure 4.2).

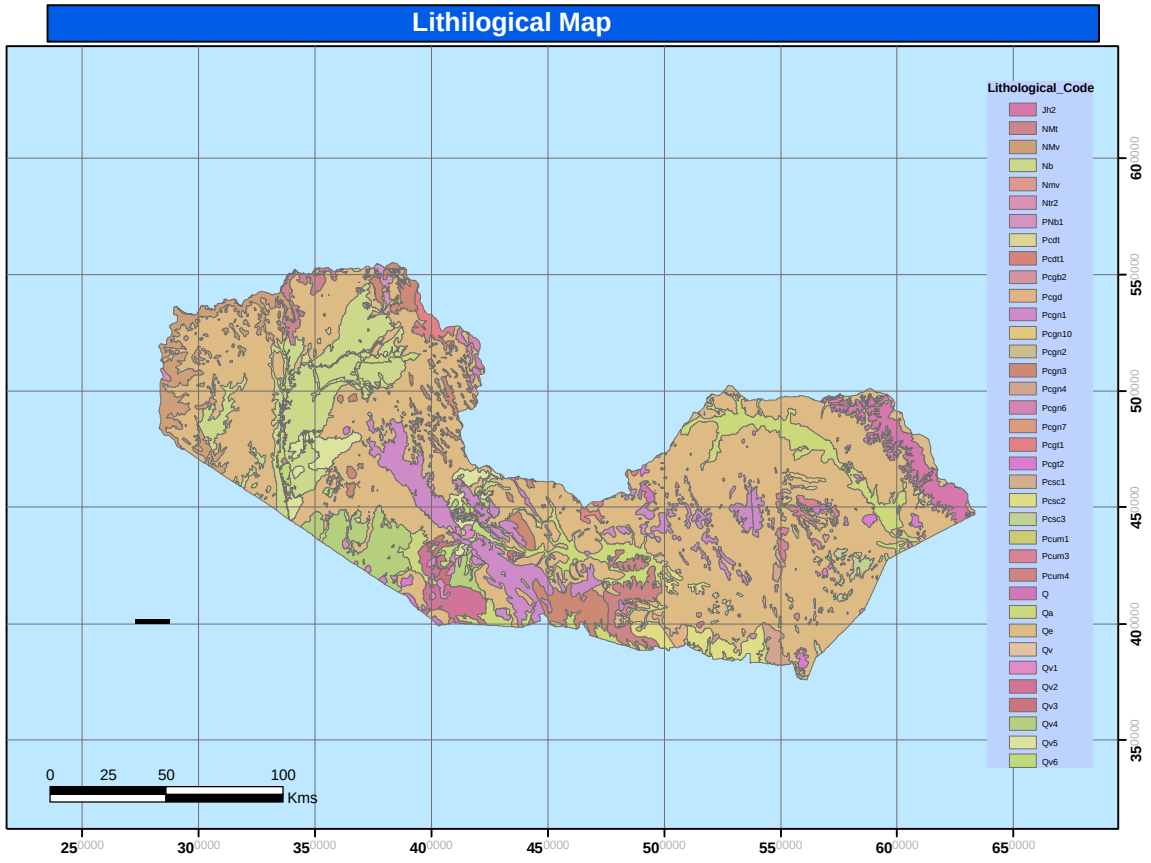

Figure 4.1: Lithological Map

Old Code	New Class
Q	Undivided Quaternary Alluvium, Eluvium and Lacustrine
Qa	Quaternary Alluvium Deposits
Qe	Quaternary Eluvium Deposits
Qv6	Quaternary Volcanics and Sediments
Qv5	
Qv4	
Qv3	
Qv2	
Qv1	
Qv	
Ntr2	Tertiary Volcanics and Sediments
Nb	
NMv	
NMt	
PNb1	
Jh2	Mesozoic Sedimentary Successions
Pcgt2	Precambrian-Early Paleozoic Basement Complexes
Pcdt	
Pcgd	
Pcgt1	
Pcdt1	
Pcsc1	Mafic-Ultramafic-Volcano-Sedimentary Assemblages
Pcsc2	
Pcsc	
Pcum2	
Pcgb	
Pcum3	
Pcum4	
Pcum	
Pcgn1	Gneissic and Migmatitic Complexes
Pcgn7	
Pcgn6	
Pcgn4	
Pcgn3	
Pcgn2	
Pcgn1	

Table 4.4: Reclassification of Lithologic Units

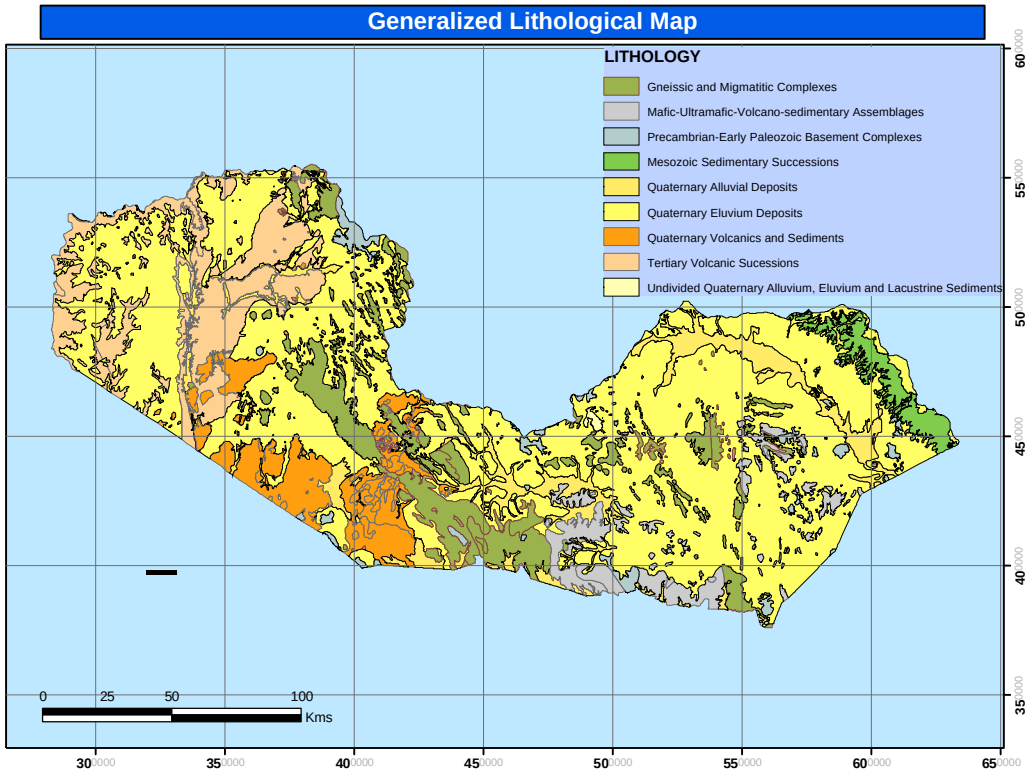

Figure 4.2: Generalized Lithological Map

ii) Structure

The linear structures which are important for increasing the permeability of the bed rock are lineaments (faults, fractures, and joints). These structural features are digitized separately from the analog geological maps and a line feature class of structures is prepared (Figure 4.3). The distance from structures map (Figure 4.4) is derived using the distance function of spatial analyst in ArcGIS and then reclassified into five classes described in table 4.5.

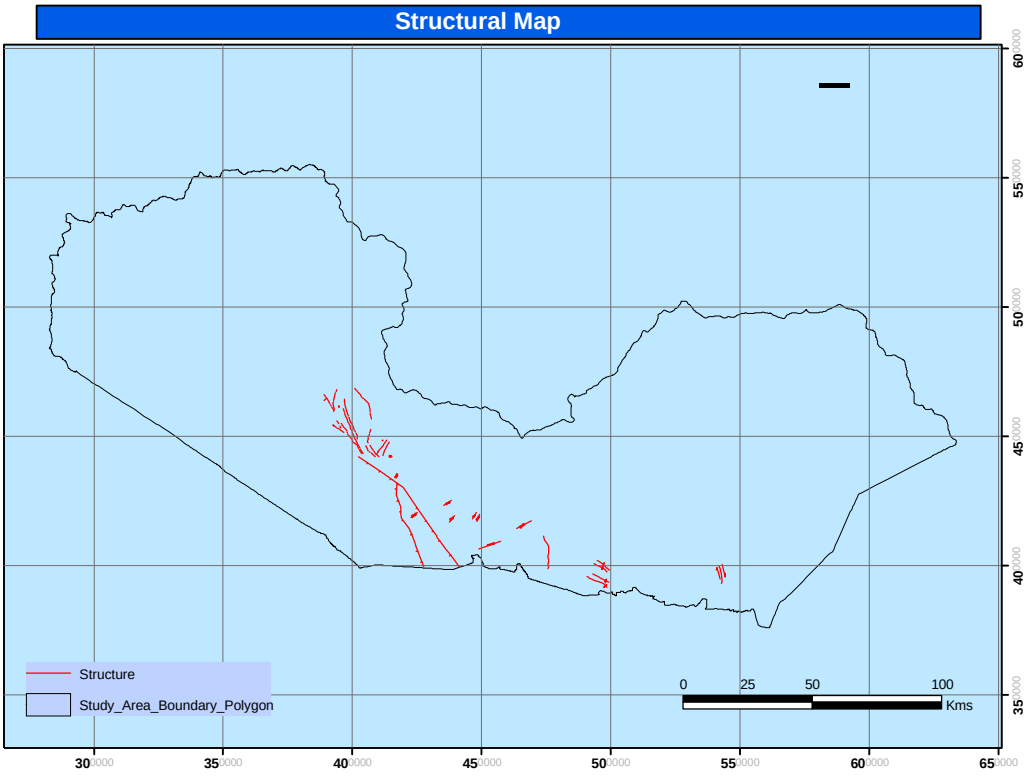

Figure 4.3: Structural Map

Distance from Structures (Km)	Class
0 - 1.8	Nearest
1.8 - 4	Near
4 - 7.2	Medium
7.2 - 30.4	Far
>30.4	Farthest

Table 4.5: Reclassification of Structure Classes

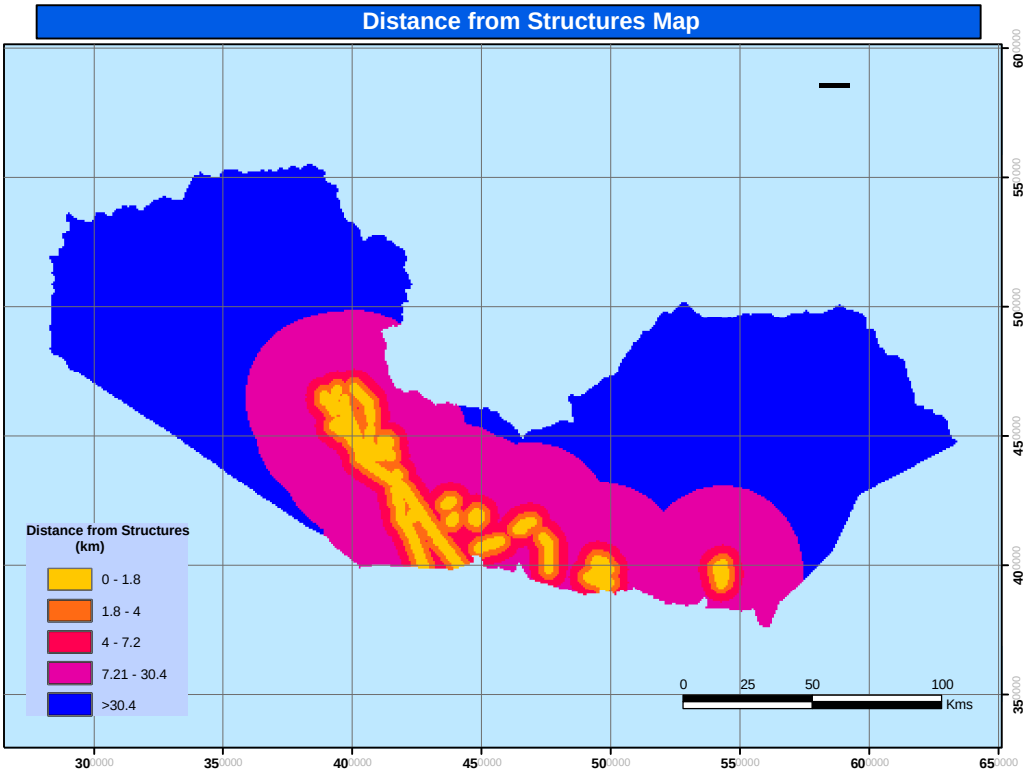

Figure 4.4: Distance from Structures Map

Physiographic Factors

iii) Geomorphology

SRTM DEM of 90m resolution of the study area was examined in 3D format in Global Mapper 6 to delineate the different geomorphological features in the study area. The vector file is exported as polygon shape file of geomorphology (Figure 4.5) and attribute information has been populated to the table.

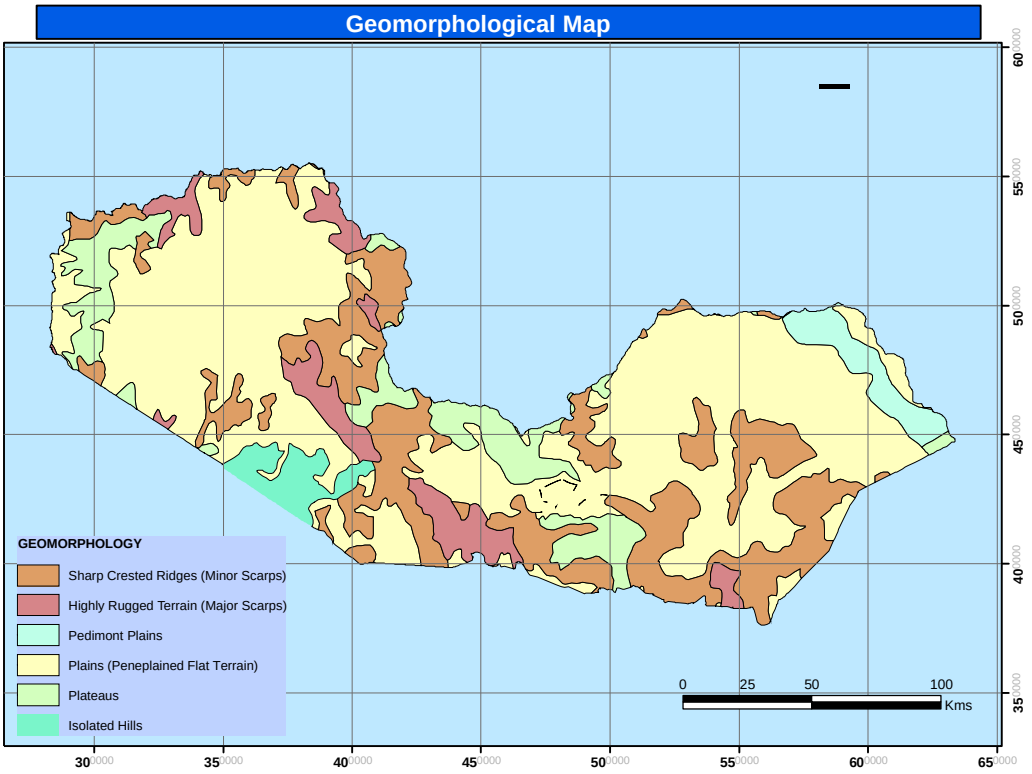

Figure 4.5: Geomorphological Map

iv) Slope

Contour map of 20m intervals (Annex 4) is generated from the SRTM DEM in Global Mapper 6 from which TIN (Annex 5) is generated and rasterized in ArcGIS. Slope is then interpolated from the TIN grid and clipped by the study area boundary (Figure 4.6).

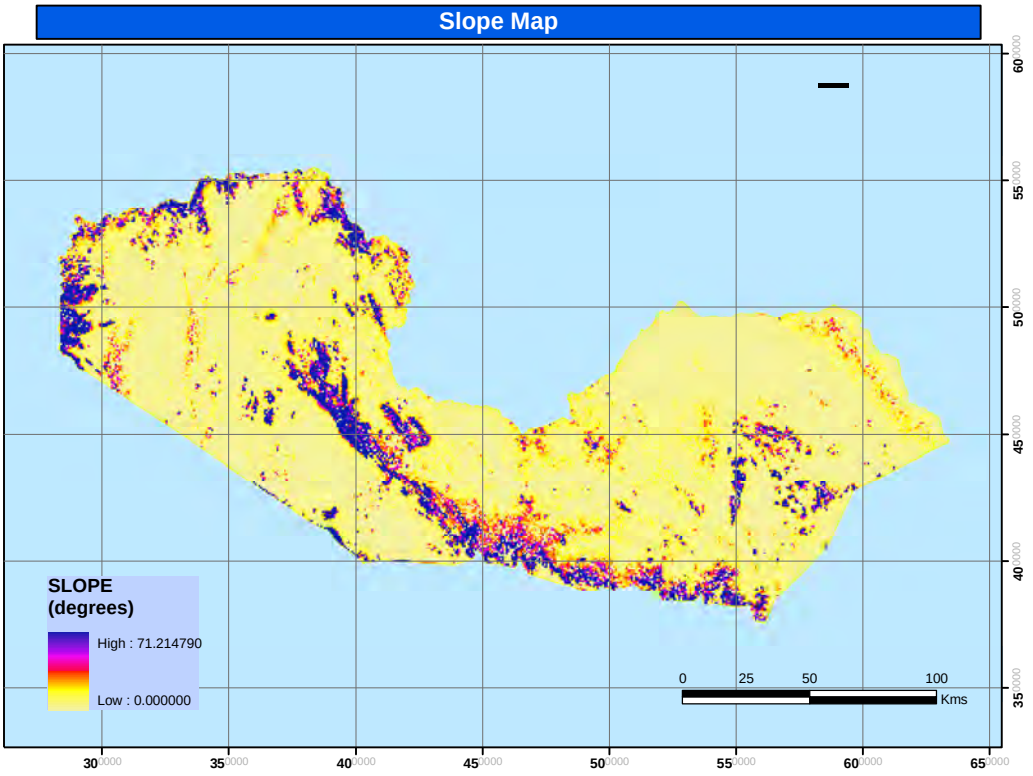

Figure 4.6: Slope Map

The slope map is reclassified manually in to five classes of slope degree examining the value and the frequency of slope degrees in the study area on the histogram.

Although most of the area has very flat-to-flat slope, it is classified in to five slope degree classes for the purpose of analysis.

The break values and the description of the new slope classes are given in table 4.6 while figure 4.7 shows the reclassified slope map.

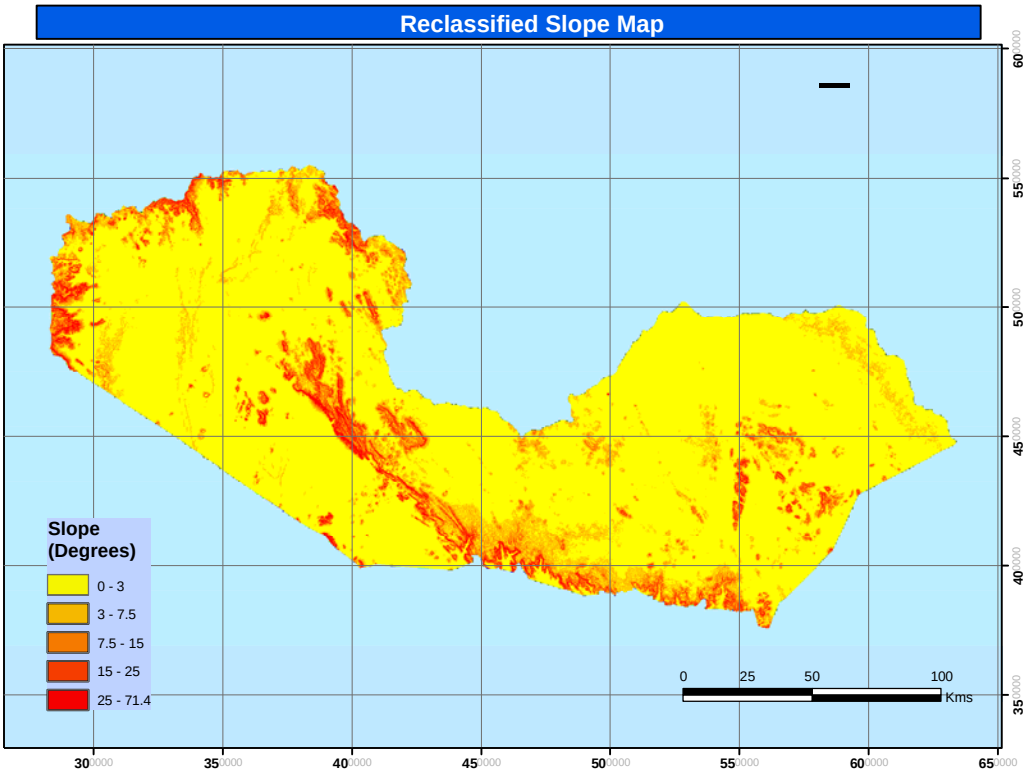

Figure 4.7: Reclassified Slope Map

Slope (deg)	Class
0-3	Very Flat
3-7.5	Flat
7.5-15	Gentle
15-25	Steep
>25	Very Steep

Table 4.6: Reclassification of Slope

v) Land Cover

Five adjacent scenes of 2002 were selected and acquired from Landsat ETM with path and row 167/57, 167/58, 168/57, 168/58, 169/57. The wide areal extent of the area of study and the purpose of the research make the satellite images with 30 pixel resolution suitable to easily extract the natural vegetation cover of the area. Images were georeferenced to Projection: Universal Transverse Mercator, Grid: UTM 37 N, Datum: Adindan.

The individual images have undertaken unsupervised classification for preliminary land cover information in ERDAS Imagine. After collecting ground-truthing data from the field, a supervised classification, guided by a number of control points (signatures) from the in situ observations is done using maximum likelihood parametric decision rule with very high accuracy (> 83-85%). Classified pixels were clustered into five general categories: Shrubland, Cultivated land, Woodland, Grassland, and Bare land. The resulting thematic raster layers were mosaiced to form a contiguous dataset and subset by the study area boundary to produce landcover map of the area (Figure 4.8).

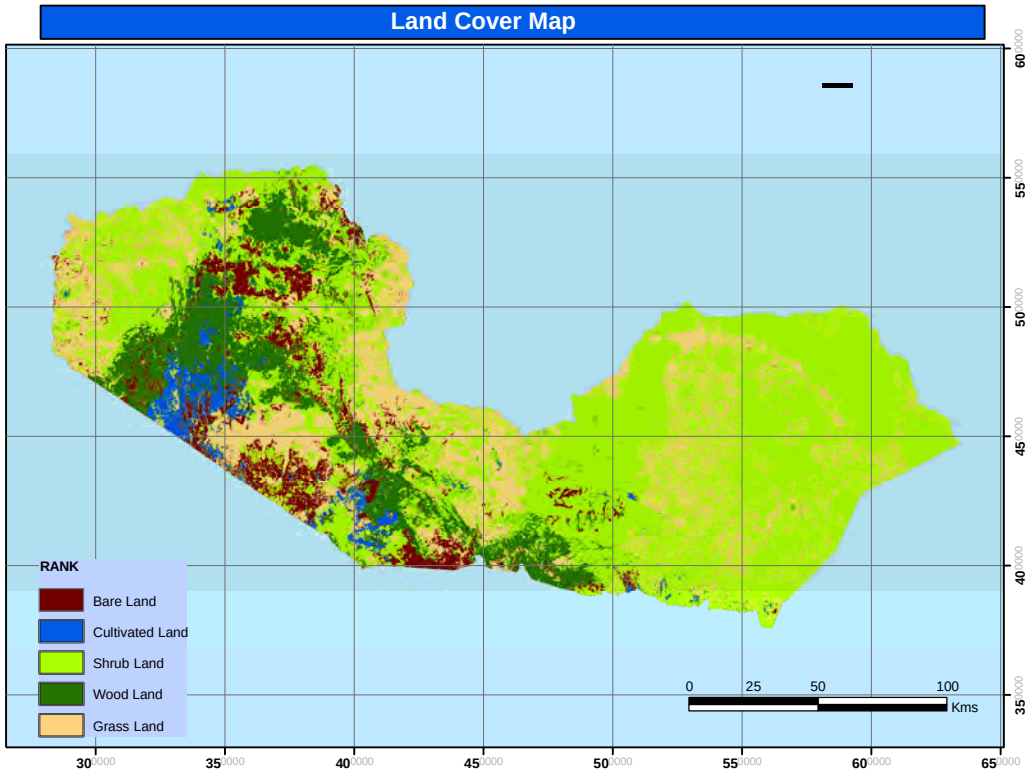

Figure 4.8: Landcover Map

Hydrologic Factor

vi) Drainage

Five topographic maps of 1:250,000 NB 37-13 (Istifanos Hayk), NB 37-14 (Yabello), NB 37-15 (Wachile), NA 37-2 (Sololo), and NA 37-3 (Moyale) were collected from EMA, scanned, georeferenced and mosaiced then clipped by the study area boundary. From the mosaiced topo-map, stream courses are digitized and saved as drainage shape file (Figure 4.9).

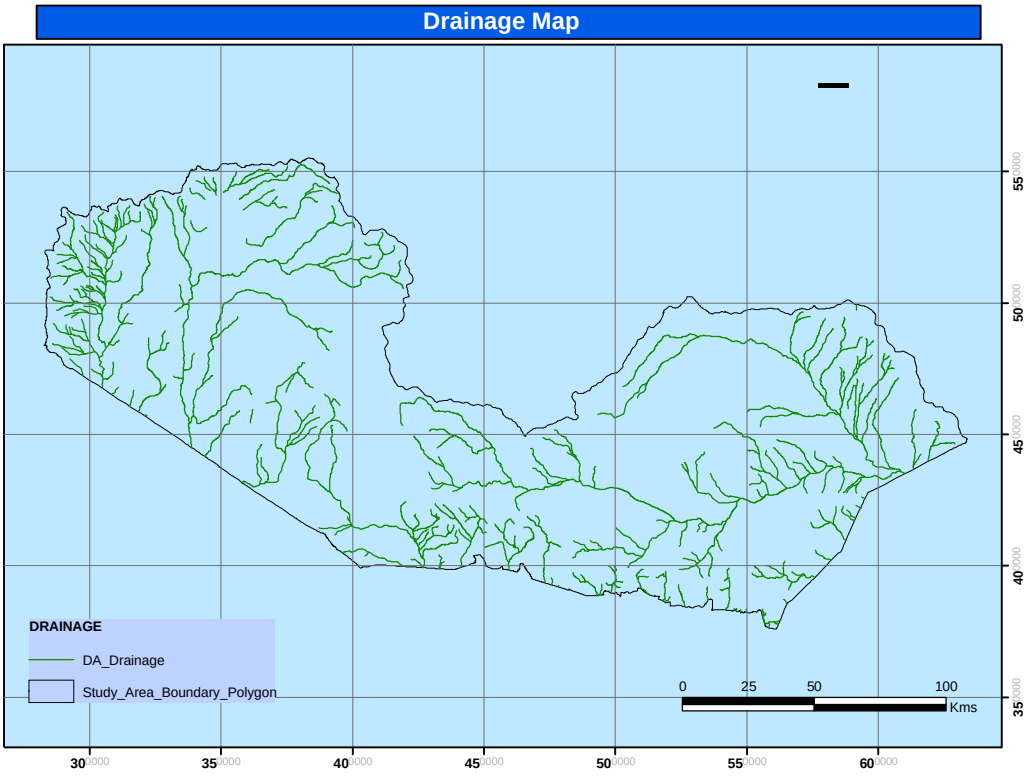

Figure 4.9: Drainage Map

To analyze groundwater occurrence focusing on areas influenced by intermittent streams, deriving the drainage density is of paramount importance. From the drainage map, drainage density map (Figure 4.10) is derived and classified in to five classes of drainage density as described in table 4.7.

Drainage Density (m/m^2)	Class
0 - 0.75	Absent
0.75 - 1.5	Rare
1.5 - 2.75	Open
2.75 - 4	Light
>4	Dense

Table 4.7: Reclassification of Drainage Density

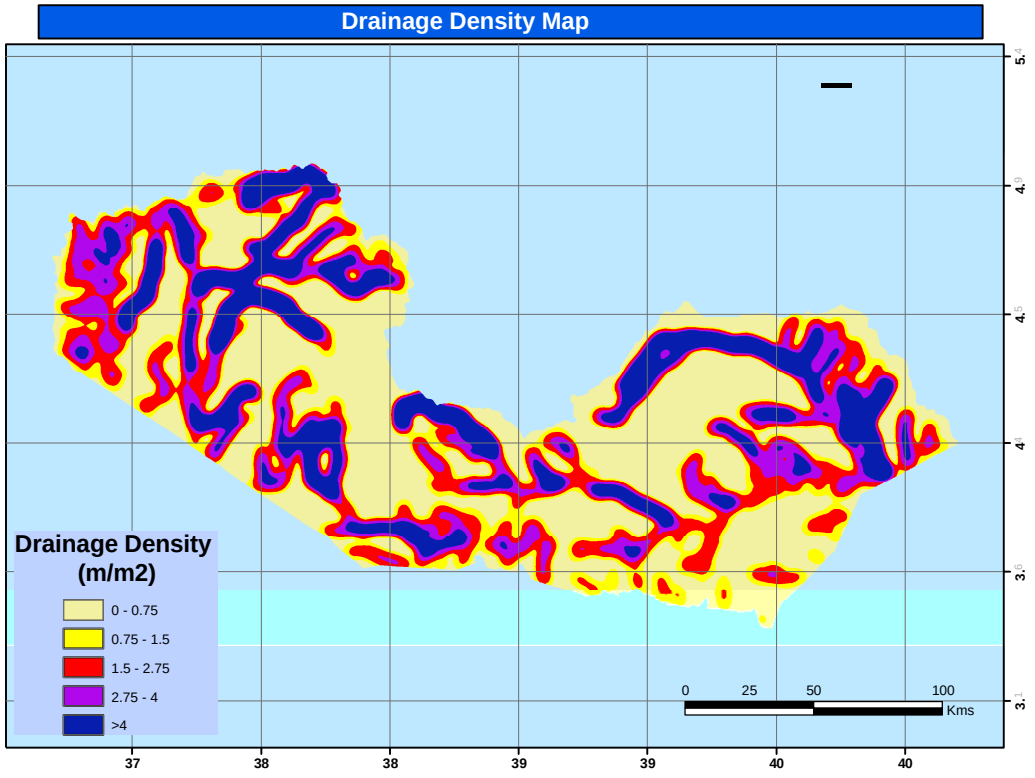

Figure 4.10: Drainage Density Map

4.3. Multicriteria Analysis

4.3.1. Determining Factor Weights

Prior to integration of the factors weights and map scores have to be assessed based on Satty's Analytic Hierarchy Process (AHP) where a pair-wise comparison matrix will be prepared for each map using a nine point importance scale (table 4.9).

One of the problems in decision theory of multi-parameter analysis is the determination of the relative importance of each parameter. The technique used here and implemented in IDRISI software is that of pair wise comparisons in the context of the decision-making process of AHP.

Pair wise Comparison of the six parameters based on geological, physiographical, and hydrological factors for groundwater availability was carried out to develop the pair wise comparison matrix in table 4.8.

	Lithology	Structure	Geomorphology	Slope	Drainage	Landcover
Lithology	1					
Structure	1/3	1				
Geomorphology	1/3	3	1			
Slope	1/5	1/3	1/3	1		
Drainage	1/7	1/5	1/5	1/3	1	
Landcover	1/9	1/7	1/7	1/5	1/3	1

Table 4.8: Pair-wise comparison of factor layers

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very Strongly	Strongly	Moderately	Equally Important	Moderately	Strongly	Very Strongly	Extremely
Less Important					More Important			

Table 4.9: Nine-point importance scale of Satty

To produce the best fit set of weights, the principal eigon vector of the above pair wise comparison matrix was computed in IDRSI software by a special module named Weight. The resulting eigon vector (table 4.10) is then taken as the weight of corresponding factors in each row in the comparison matrix.

Factor	Weight
Lithology	0.4199
Structure	0.1689
Geomorphology	0.2475
Slope	0.0913
Drainage	0.0486
Landcover	0.0259

Consistency Ratio (CR) is 0.06, Acceptable

Table 4.10: Principal Eigon vector of the pair wise comparison matrix

Since the complete pair wise comparison matrix contains multiple paths by which the relative importance of criteria can be assessed, it is also possible to determine the degree of consistency that has been used in developing the ratings. The consistency ratio (CR) indicates the probability that the matrix ratings were randomly generated so that matrices with CR ratings greater than 0.10 should be re-evaluated. In this study the consistency ratio calculated as 0.06 which is acceptable. Therefore each of the parameters can be assigned by these weights.

4.3.2. Ranking Classes of Factors

Geologic Factors

i) Lithology

Tesfaye Chernet (1993) explained that The quaternary alluvials have very good potential since they are recent deposits and have better permeability and productivity. If fractured, quaternary volcanics will yield good amount of fresh water. The Mesozoic sediments in this area are the Hamaniel formations of

limestones, which are have good productivity but with high depth to groundwater table. The gneissic-migmatitic complexes, mafic-ultramafic volcano-sedimentary assemblages and the Precambrian basement are poor aquifuges (Tesfaye, 1993). The class ranks are therefore assigned according to the aforementioned characteristics of the hydrogeological units (see table 4.11 for the ranking and figure 4.12 for the ranked lithological map).

Lithological Group	Relative Value	Rank
Quaternary Volcanics and Sediments	Very Good	5
Quaternary Alluvium Deposits		
Tertiary Volcanics and Sediments	Good	4
Undivided Quaternary Alluvium, Eluvium and Lacustrine Sediments		
Mesozoic Sedimentary Successions	Moderate	3
Quaternary Eluvium Deposits	Poor	2
Mafic-Ultramafic-Volcano-Sedimentary Assemblages	Very Poor	1
Gneissic and Migmatitic Complexes		
Precambrian-Early Paleozoic Basement Complexes		

Table 4.11: Ranking of Lithology

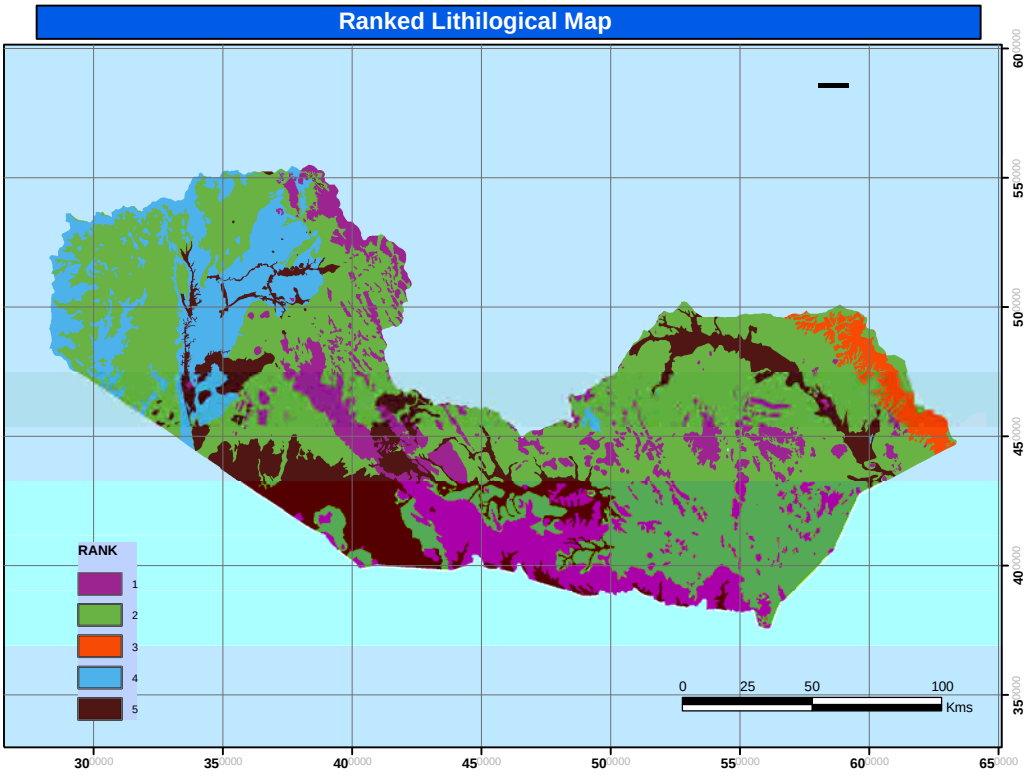

Figure 4.11: Ranked Lithological Map

ii) Distance from Structures

Areas close to structures develop a secondary porosity that will help them to percolate water better than those far from structures. Therefore, areas proximal to geological structures have better groundwater potential than areas farthest from structures. This is the base to assign higher ranks to areas very near to structures and vice versa (table 4.12). Figure 4.12 shows the ranked distance from structures map.

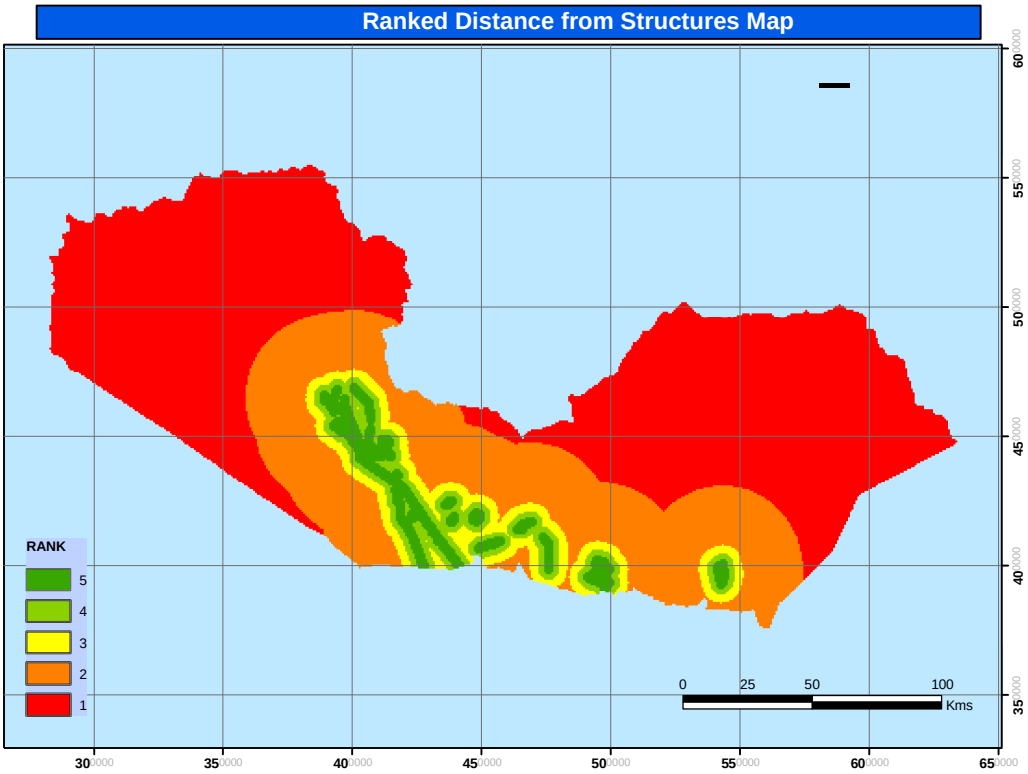

Figure 4.12: Ranked Distance from Structures Map

Distance from Structures (Km)	Relative Value	Rank
0 - 1.8	Nearest	1
1.8 - 4	Near	2
4 - 7.2	Medium	3
7.2 - 30.4	Far	4
>30.4	Farthest	5

Table 4.12: Ranking of Distance from Structures

Physiographic Factors

iii) Geomorphology

Pediments and Plains are the gentle to flat and flat land forms respectively where the groundwater recharged up hill is accumulated and discharged. Those areas have higher water level surface, so they are the best land forms for groundwater prospecting. If rainfall is high, plateaus favor groundwater percolation than sharp crested hills and often groundwater may occur there. Sharp-crested hills and ridges facilitate runoff than infiltration. Thus there is unlikely to find groundwater in such geomorphological units. The following ranks are given to geomorphological units considering their contribution to groundwater availability and the corresponding ranked geomorphological map is shown in Figure 4.13.

Geomorphological Group	Relative Value	Rank
Piedmont Plains	Very Good	6
Plains (Peneplained Flat Terrain)	Good	5
Plateaus	Good	4
Isolated Hills	Moderate	3
Sharp Crested Ridges (Minor Scarps)	Poor	2
Highly Rugged Terrain (Major Scarps)	Very Poor	1

Table 4.13: Ranking of Geomorphology

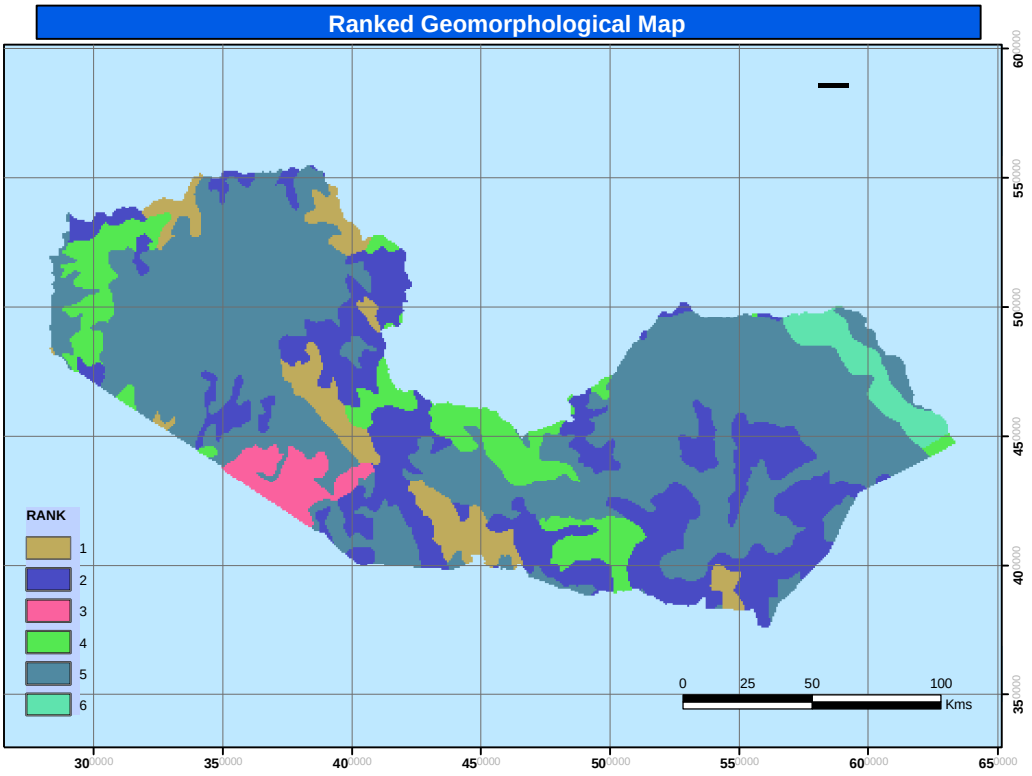

Figure 4.13: Ranked Geomorphologic Map

iv) Slope

Slope steepness/gradient is important since it is related to groundwater potential of an area by its factor to ease runoff or subsurface flow. Flat areas are capable of holding the rainfall and facilitate groundwater replenishment in contrast to steep areas which instigate runoff. The area is situated in a topographically low plain so the difference in elevation is minimal (i.e. slope is very low). Therefore; in order not to highly tradeoff the other factors, the weight given to the slope factor is low. The ranks given to individual slope classes are shown in table 4.14 and the ranked slope map is given in Figure 4.14.

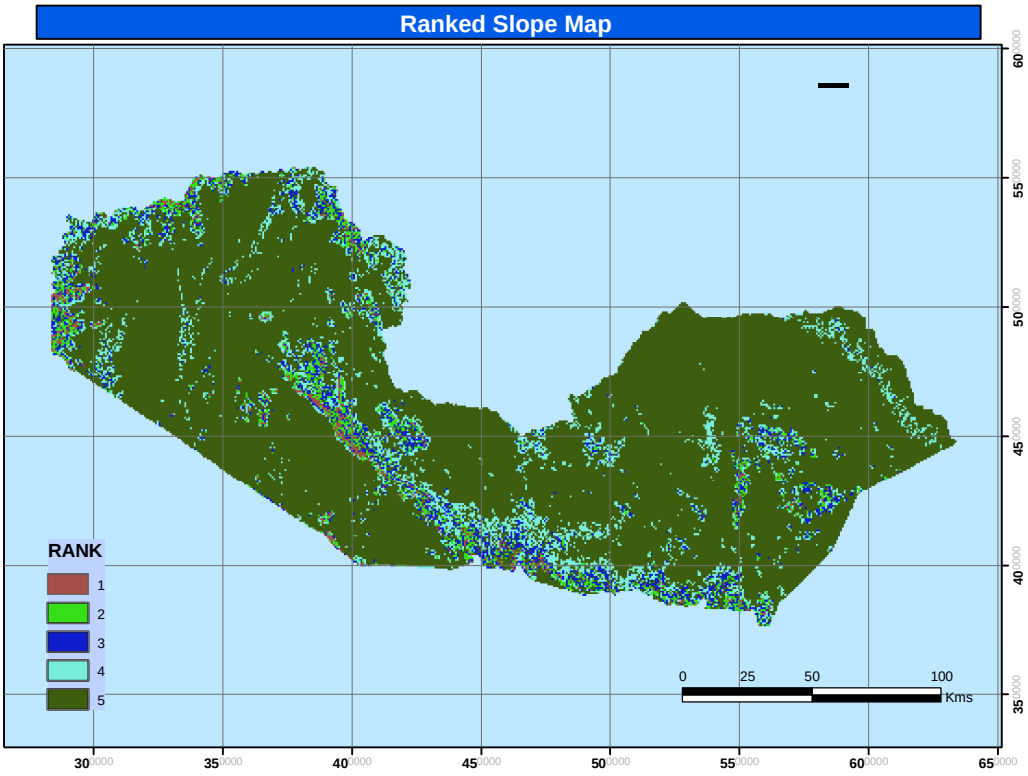

Figure 4.14: Ranked Slope Map

Slope(degrees)	Relative Value	Rank
0-3	Very Flat	5
3-7.5	Flat	4
7.5-15	Gentle	3
15-25	Steep	2
>25	Very Steep	1

Table 4.14: Ranking of Slope

v) Land Cover

The present condition of landcover of the area influences the occurrence of groundwater. Agricultural or cultivated lands are ploughed highly and the pore spaces between the soil particles are improved so that they have high potential to infiltrate water to the subsurface. This increases the potential of groundwater

under the cultivated surface. This makes cultivated lands high prospect to groundwater availability.

The effect of tree cover to groundwater recharge is both negative and positive. Trees may increase water loss by evapotranspitation or they may facilitate recharge by reducing runoff and by intercepting water and infiltrating its droplet slowly. For the problem in concern, it is assumed that evapotranspiration and interception are constant so that only the positive effects of vegetation to groundwater potential are considered. Therefore, cultivated lands are given higher rank and open grass-lands the lowest (table 4.15). See Figure 4.15 for the ranked landcover map.

Landcover	Relative Value	Rank
Bare Land	Bad	1
Grassland	Poor	2
Shrubland	Good	3
Woodland	Ideal	4
Cultivated Land	Excellent	5

Table 4.15: Ranking of Land Cover

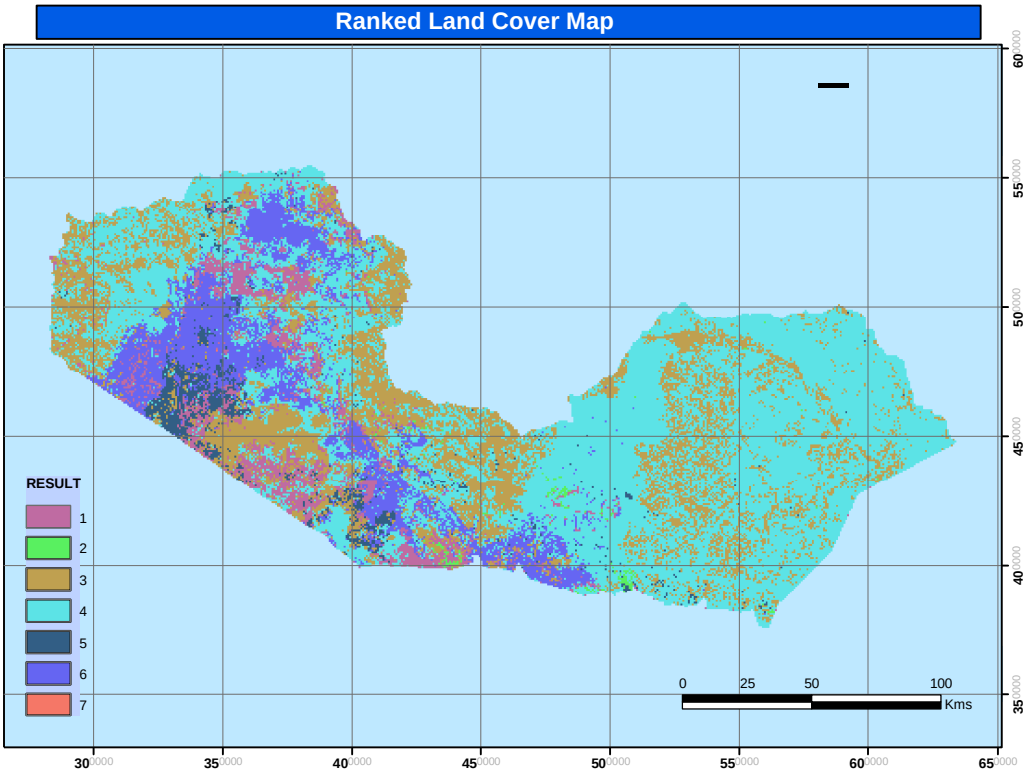

Figure 4.15: Ranked Landcover Map

Hydrologic Factor

vi) Drainage Density

In areas where the number of streams is more in a unit area, the most proportion of the water coming from precipitation goes to runoff. This is indicative of the subsurface condition of porosity. Unless there are sufficient interconnected pores, there is no chance of water to percolate to the ground. In other words, high drainage density implies low groundwater potential. As shown in table 4.16 and figure 4.16, high ranks are given to low drainage density area and vice versa.

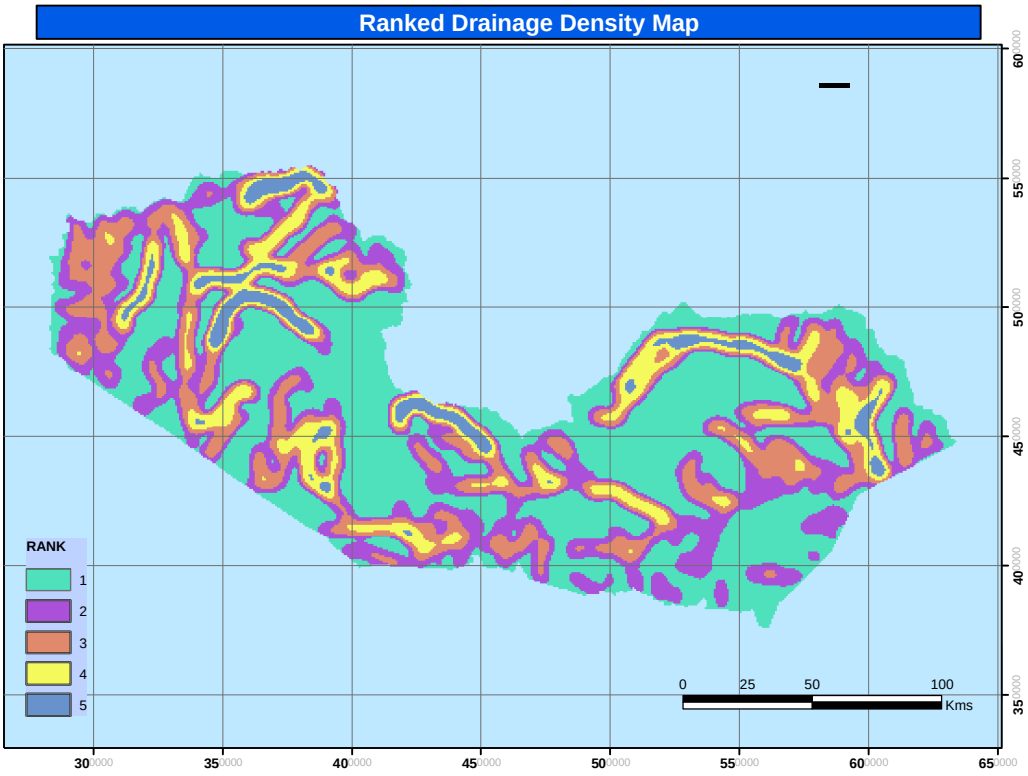

Figure 4.16: Ranked Drainage Density Map

Drainage Density (m)	Relative Value	Binary form
0 - 0.75	Very Low	5
0.75 - 1.5	Low	4
1.5 - 2.75	Medium	3
2.75 – 4	High	2
>4	Very High	1

Table 4.16: Ranking of Drainage Density

4.3.3. Weighted Overlay Analysis

At this stage, all the factor layers are ready to be combined in order to reveal the groundwater potential of the study area. If all datasets were equally important, it could be possible to combine them simply; however, from the principal eigenvector calculation, the relative importance of each parameter has been determined (see table 4.10). Therefore the higher the weight, the more influence a particular factor will have in the suitability model. Accordingly the factor layers are combined by applying the following formula in the raster calculator of spatial analyst extension of Arc GIS by the following equation.

Lithology] * 0.4199 + [Distance from Structures] * 0.1689 +

[Geomorphology] * 0.2475 + [Slope] *0.0913 +

[Drainage Density] * 0.0466+ [Land Cover] * 0.0259 = GWP

Where GWP is for Groundwater Potential

Figure 4.17 illustrates diagrammatically the weighted overlay analysis undertaken on the analysis maps to produce the final resultant map.

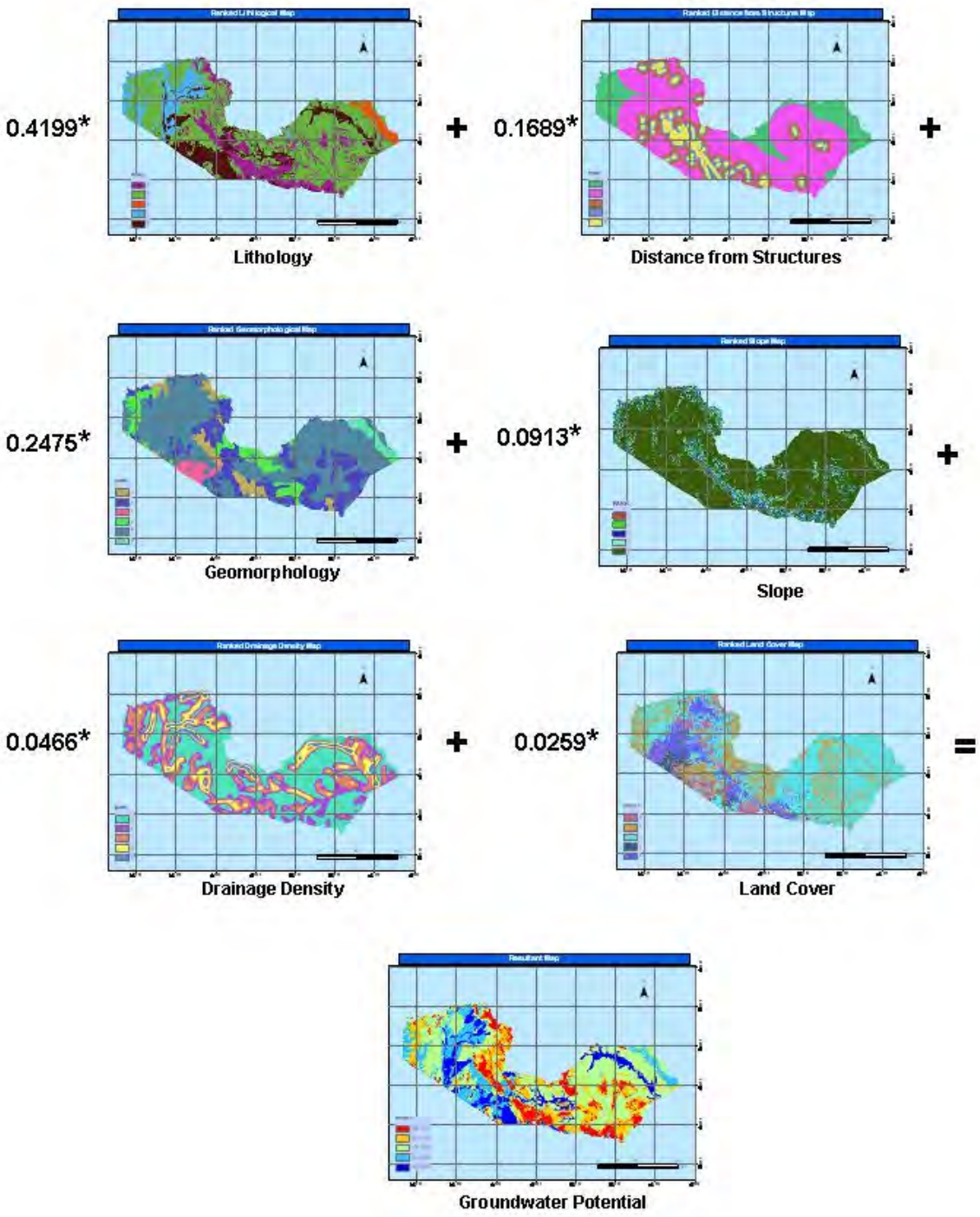

Figure 4.17: Diagram showing the Weighted Overlay Analysis

5. RESULTS AND DISCUSSION

5.1. Result Description

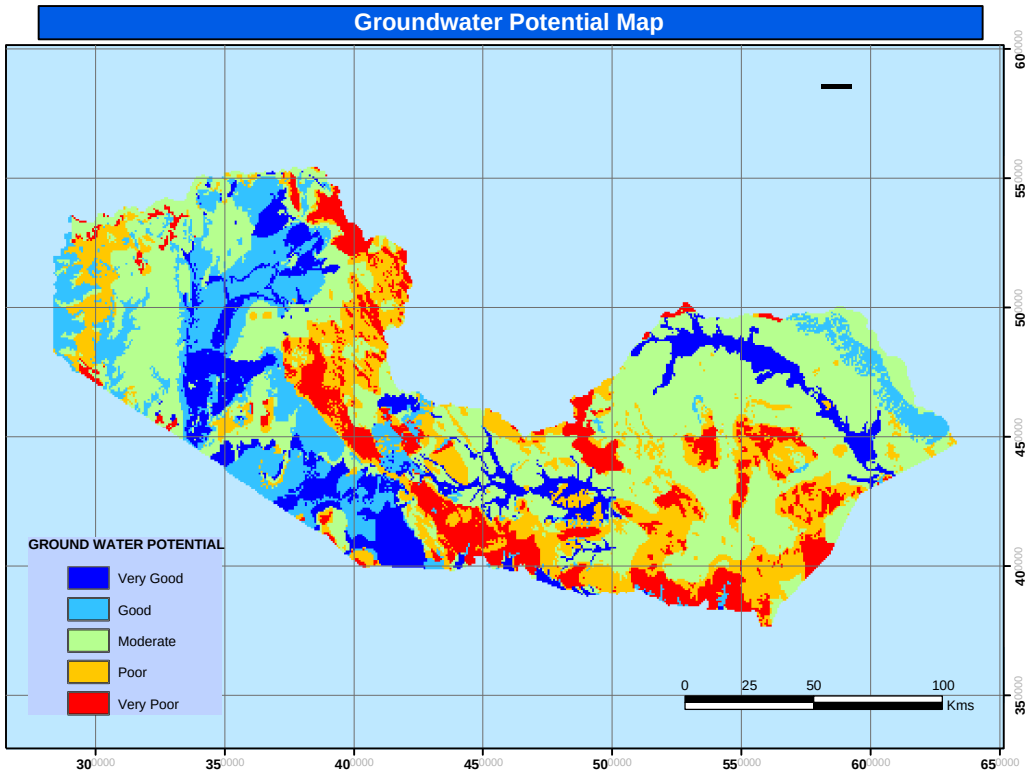

Figure 5.1: Groundwater Potential Map

The values of final combined resultant map obtained after the weighted overlay analysis has been reclassified as in table 5.1 to demarcate the study area in to five groundwater potential zones.

Value	Class
108-173	Very Poor
173-228	Poor
228-264	Moderate
294-361	Good
361-458	Very Good

Table 5.1: Reclassified groundwater potential zones after the resultant map

5.2. Model Validation

The groundwater potential map produced confirmed the reliability of the criterion formerly set for prospecting groundwater in the study area using the selected factors. The poor potential areas appear in areas which are unfavorable for groundwater in most of the background factors and the very good areas occur in areas suitable according to most of the factors.

Validation of the output map is tested by overlaying the yield data of boreholes and springs collected from field and reports. Out of the collected and reviewed 90 water points, 44 have measured and estimated actual yield data. In general, the data indicated high yield (•3 l/s) in the very good potential areas while very low yield (•0.8 l/s) in the very poor potential areas. Intermediate values appear in the zones between these extremes. Water points with yield 1-2 l/s occur in the poor, with 2-2.24 l/s in the moderate, and 2.5-2.78 l/s in the good zones of groundwater potential respectively.

Therefore the groundwater potential map produced is in good agreement with well yield data. Table 5.2. compares the actual yield data and the groundwater potential assigned by the analysis for each water points used for validation.

No.	SITE_NAME	EASTING	NORTHING	YIELD (l/s)	GW_Potential
1	15km W of Yabelo	419188	434910	0.11	Very Poor
2	Areallo (Dololo Mekala	558222	384691	0.35	Very Poor
3	Cheriliche	424006	448721	0.50	Very Poor
4	Chilanko	389737	541642	0.50	Very Poor
5	Chilano2	537618	446577	0.50	Very Poor
6	Dawa South2	504515	392687	0.60	Poor
7	Dawa South1	482360	395165	0.60	Very Poor
8	Dololo Merkala1	378646	539472	0.66	Very Poor
9	Dubluk1	453002	408270	0.80	Very Poor

No.	SITE_NAME	EASTING	NORTHING	YIELD (l/s)	GW_Potential
10	El Gof_irr2	451896	449530	1.00	Poor
11	Elder	428683	461192	1.00	Poor
12	Elleh	525025	416796	1.00	Poor
13	Finchawa1	561593	381738	1.00	Poor
14	Elder1	434955	420232	1.00	Very Poor
15	El-leh	400413	524294	1.00	Very Poor
16	Gimbe	451923	449071	1.20	Poor
17	Gofgedo	524361	416770	1.20	Poor
18	Gololcha	524466	416770	1.20	Poor
19	Hidi Lola_2	429649	441856	1.25	Moderate
20	Higole6	584196	427695	1.33	Poor
21	Kadale2	600580	475106	1.40	Moderate
22	Kadale1	504000	390600	1.40	Poor
23	Kagofa	612863	462303	1.47	Moderate
24	Kedaduma	442832	431243	1.67	Poor
25	Mega1	467618	429505	1.92	Poor
26	Melbana	614327	461702	1.93	Moderate
27	Melbana	406748	457612	2.00	Moderate
28	Melbana3	506691	426258	2.00	Moderate
29	Menesoda	506669	426216	2.00	Moderate
30	Mormora	349378	538949	2.00	Moderate
31	Moyale SW	520779	416940	2.00	Moderate
32	Mudiambo (Boru jirmo)	423607	449990	2.13	Moderate
33	Orbati1	347744	535635	2.17	Moderate
34	Sake (20km SW of Mega)	428974	460458	2.24	Moderate
35	Shewaber	410758	442763	2.50	Good
36	Siru1	531398	417460	2.78	Good
37	Sourupa1	339570	463166	3.00	Very Good
38	Tessoma	433776	430135	3.00	Very Good
39	Tuka	441558	429517	3.00	Very Good
40	Tuka3	507383	425649	3.00	Moderate

No.	SITE_NAME	EASTING	NORTHING	YIELD (l/s)	GW_Potential
41	Wachile	615724	462495	3.00	Good
42	Wachile1	440787	429211	3.33	Very Good
43	Wachile2	613302	461257	3.33	Very Good
44	Yabelo1	420480	463572	6.00	Very Good

Table 5.2: Comparison of actual yield data of water point with result

A map showing the validity of the model by overlay of water points yield data on the resultant map is included in Annex-7.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The research study has investigated that application of Remote Sending, GIS, and MCDE in integration is very important to aid the exploration of groundwater specially in larger, inaccessible, and hard rock areas like the area under investigation.

Remote Sensing is applied to generate land cover map for input as one of the factors determining groundwater occurrence. The other thematic maps; geology, structure, and drainage are automated from existing paper maps while SRTM data is used to generate geomorphology, contour and slope from Digital Elevation Model (DEM) of the study area. Data is collected and organized from different sources and properly organized in the designed project database. The classes in individual factors are ranked according to their contribution for groundwater occurrence. The thorough examination of the interrelationship of the factors yields in an acceptable eigon vector of weights for evaluation. The ranked and weighted factor maps are then combined by weighted overlay analysis to produce the final groundwater potential map as an out put.

In the final groundwater potential map, the very good groundwater potential area is comprised of quaternary alluvium deposits and Quaternary volcanics and sediments. Most of the tertiary volcanics and sediments and undivided quaternary alluvium, eluvium and lacustrine sediments and the mesozoic sedimentary successions fall in the good to moderate potential areas. The quaternary eluvium deposits and all the metamorphic basements (mafic-ultramafic-volcano-sedimentary assemblages, gneissic and migmatitic complexes, precambrian-early paleozoic basement complexes) are together categorized in the poor to very poor groundwater potential zones.

The very good and good groundwater potential areas are characterized by very near distance to geological structures. This is better manifested in the central rift system which trends SE –NW and in the north western part of the area where the tertiary volcanics are affected by linear structures. Areas very far and

farthest from geological structures result in poor to very poor groundwater potential. However, some areas that are farthest from geological structures are found to have good potential. These are: the tertiary volcanics in the western and Hamanelei formation in the eastern part of the study area.

The piedmonts and plains are categorized in to very good and good potential zones, while most of the plateaus, minor hills, and major hills are grouped into moderate to poor, poor to very poor, and very poor zones of groundwater potential respectively.

Since the area is dominantly flat, all the very good, good and moderate groundwater potential zones are included in the very low slope area. The higher slope areas are typically characterized to reveal poor to very poor groundwater potential zones.

It is clearly visible from the resultant map that the very good groundwater potential zones are in the very low drainage density areas and the very poor groundwater potential zones in higher drainage density areas. This implies in the study area, drainage density and groundwater potential are inversely related except in alluvium where both drainage density and groundwater potential are high.

Most part of the bare land is situated in the good groundwater potential zones which implies the underlying geology is favorable (it is found to be quaternary volcanics), whereas some part of the bare land, which is situated in the precambrian basement lied in the very poor groundwater potential zones. The grass land resulted in poor to very poor potential area, while the bush land in moderate to very poor potential areas. The inclusion of these classes in bush land may be due its wide areal extent. In southern and south western parts of the study area, the wood land is clearly seen to fall in the very good groundwater potential zone. This strengthens the hypothesis that most of the natural vegetation (wood land) follow geological lineaments and are indicators of higher groundwater table. The trend of the wood land in the study area is SE-NW which follows the trend of the major escarpment proving the underlying hypothesis.

Agricultural lands are also seen to appear in the very good groundwater potential zones, specially in the western and central western parts of the study area. In the central south, the agricultural lands are categorized in to moderate groundwater potential zones.

In addition to comparison with the different input datasets, the out put is further verified by actual well yield data collected from field and other sources. From the verification, it can be concluded that the final output is insured to be an interesting groundwater potential map that can be used at higher level of confidence.

6.2. Recommendations

The application of spatial decision making techniques in natural resources management in general and in groundwater resources in particular should be encouraged and there is a need of effort to increase the type and quantity of research in the subject.

There is a high shortage of geographic data, which limits the quality and detail-ness of the investigations being undertaken in the geo-spatial science in the country. This research study has faced this problem during the data collection phase. Much efforts are expected from graduates of the stream, the University, and responsible institutions to increase the quantity and standard of the geographic data of the nation.

If an appropriate geophysical survey is undertaken in selected areas of very good to moderate potential zones, the groundwater potential in the subsurface will be inferred quantitatively.

The output of this research should be integrated with other researches to insure the food security of the population of the area under investigation.

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ANNEXES

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Annex 1 - Climatological Data

Station: Mega

Element: Monthly Rainfall in mm

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	5.5	13	88		103.2	16.1	6.7	4.4	9	46.7	23.5	0.8
1986	0	1.5	51.4	259.7	31.7	18.5	12.4	0	12.5	127.2	51.3	95
1987	5.9	41.4	94.5	127.9	245.7	14.8	0	15.5	1.5	0	19.9	8.8
1988	0	0	20.6	251.4	41.8	35.1	14.8	15.6	23.8	35.4	112.2	62.4
1989	49.4	73.6	120.3	146.5	50.9	19	21.6	7			123.1	19.2
1990	29.7	233.6				7.3	3.7	0.1	1.6	50.7	29.7	30.8
1991	24.3	55.4		108	70.4		24.4	4.7	0.7			
1993			68.5	110	162.1	35.3	15	0.7	1.4		44.5	4.2
1994	0	0	56.6	100.3	51.1	5.4		2.1	6.7	107	79.2	0
1995	0	82.5	132.5	167.9	18.3	3.7	24.3	9.6	25.4	59.1	11.3	39.6
1996	18.4	5.5	134.6	40.2	113.6	18.1	27.8	0.9		21.8	52.6	0
1997		0	75.3	284.5	27.7	7.8	36	0.1	4	276.6	159.7	22.9
1998	115.2	70.6	43.4	105.7	90	46.3	32.4	8.4	3.7	4.6	5.7	8.5
1999	0.4	10.8	196.4	70.9	21.6	33.5	17.7		2.6	103	23.6	
2000	0		3.7	29	118.3	3.6	11.6	4.6	8.5	39.9	35.9	49.6
2001	9.5	29.3	177.2	162.7	19.7	1.4	4.5	0.7	0	0	119.5	155.4
2002	0	0	40.2	117	18.4	17.7	5.5	5.3	20.6	121.6	18.1	142.4
2003	8.5	38.9	48.7	218.1	137.9	20.7	0.5	10.2	2.6	34.6	92.6	51.9
2004		47.5	8.9		21.9	3	5.6	0.5	0	163.2	40.2	5.6
2005			90	113.8								

Station: Moyale

Element: Monthly Rainfall in mm

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	0	4.5	33.5	327.4	67	19.7	29.7	0	0	92	126.9	26.9
1987	17.3	53	39.5	149		4	1.4		8.9	15.7	71.2	13.9
1988	0		91.9	399.5			0		90.5	73	61.4	27
1989	30	29.1	60.8	187.9	50.6	20.9	3.6	3.4	4.3	35.7		54.9
1990	4.6	70.8	34	130.4	79.5	0	1	0	0.3	88.5	45.3	
1991	16	27	34.8	68.3			25	0	0	33.5	45.4	16.8
1992	0		27.5	25.8	43.4	0	1.5		50	72		
1993					11.6	18.9	0.6	0	1.7	50.2	13.2	16
1994		0	26.6	96.9	84.6	17.1	10.2	0.2	8.2		198.6	25.5
1995	0	18	67.5	70.6	30.8	0.7	12.9		3.6	59.2	31.5	28.8
1996	0.7	27	82	102.4	130	6.8	11.6	0.3	7.4	19.7	27	0
1997	0	0	24.7	228.3	6.1	14.4	8	2.4	10	504.7	254	39.5
1998	129	68.1			129.8	47.7	11.1	15.8	0.9	12.4	38.4	29.9
1999	0.5	0	44.2			25.2	3.1	8.5	1.1	97.6	55.4	20.5
2000	23	0	0	48.5	105.9	2.5	10.2	11.6	16.9	81.8	71.6	64.8
2001	2	33.5	51.7	133.4	19.4	10.1	5.8	14.5		24.2	65.1	14.6
2002	19.2	0	35.6	148.3		16.3	0.1	2.4	24.9	117.3	34.6	90.9
2003	17	4.9		93.5	52.8	13.1	0.8	13.1	2.2	4	159.5	23.8
2004	38.5	16.5	26.7	172.2	15	10.5	3.1	0.7	12.6	121.4	98.3	19.9
2005			32.6	148.8	158.3							

Station: Mega

Element: Maximum Monthly Temperature in ^{o}C

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984			20.8	22.4	20.6	21.4						
1985											25	27
1986	28.5	28.4	27.1	24.5	22.7	22.3	20.5	23.6	24.5	24.9	24.6	25.6
1987	27.8	27.9	26.8	24.5	23.4	20.7	21.6	22.4	24.9	26.4	26.9	29.4
1988	29.4	29.3	29.5	25.8	23.9	21.6	22.1	22.6	26.1	25.7	26	23.8
1989	25.3	25.2	24.9	21.3	20.4	17.7	17.6	19.2	21.7	22.1	22.6	23.7
1990	25	24.4	22.7	22.5	20.7	19.7	19.1	20.6	23	23.1	22.5	24.5
1991	25.8	26.8	25.1	23.5	21.7		18.6	20.5	23.4			
1993	24.2	24.4	26	25.7								
1994			27.3	23.6	21.6	21.7	20.7	21.7	23.7	23.5	23.3	25.4
1995	27.2	26.9	24.3	23.6	23.3	22.3	21	21.1	23.2	23.6	24.8	25.7
1996	27.6	28	25.4	23.9	22.2	19.7	19.4	21.8	23.2	23.5	24.6	26.8
1997	28.2	29.2	28.4	23	23	22.3	20.8	22.7	23.9	21.5	21.7	22.2
1998	23.1	25	25.2	24.1	22.4	20.1	18.4	19.6	22.3	23.3	24.6	26.2
1999	26.9	28.2	23.6	22.6	21.6	20.5	19.4	22	22.4	22.3	24.2	
2000	27.2	27.7	27.9	25	22.4	20.3	20.2	21.7	23.2	23.8	24.1	25.7
2001	26.2	26.7	25.7	23.6	22.2	21	21.5	22	23.2	23.3	22.6	23.1
2002	25	24.4	22.9	24.9	24.4	19.9	20.7	21.2	23.4	22.9	24.3	23.6
2003	25.2	27.6	27.5	25.7	23.4	20.3	21.4	21.9	23.4	25	24.5	24.8
2004		27.1	28.5	23.6	23	21.7	22.4	23.6	27.2	24.4	24.2	26.5
2005			27.1	27	22.6							

Station: Moyale

Element: Maximum Monthly Temperature in ^{o}C

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	33.2	35.3	34	29.6	28.1	27	25.1	26.9	27.5	27.8	27.8	29.6
1987	31.5	32.1	31.4	27.4	26	23.8	24.9	25.7	27.5	27.5	29	31.1
1988									26.2	27.1	26.8	28.5
1989	30.7	30.8	30.7	26.9	25.5	24	22.4	23.9	27	26.4		27.3
1990	29.6	29.5	28.1	26.2	24.7	24.2	23.1	24.6	26.3	26	26	
1991	30.1	31.7	30.8	28.4	25.5		22.6	26	26.2	27.6	27.6	27.7
1992	32.1		27.6	27	25.5	23.1	23.7	24.8	26.1	26.5		
1993					25.8	22.9	22.6	23.2	26	27.7	29.7	30
1994		32.8	31.5	27.2								
1995	32.4	31.7	28.8	26.6	25.8	27.2	24.9		26.2	26.4	26.6	29.4
1996	31.1	32.1	28.5	26.2	25.8	23.7	23.4	25.1	26.2	26.5	27.7	30.2
1997	31.5	32.7	31.2	26.2	24.8	25.2	24.8	25.7	27.2	24.4	25.4	26.9
1998	27.1	29.2		27.8	25.4	24.2	22.7	24.1	26.4	27.7	27.8	29.7
1999	31.1	32.1	29.2			25.1	23.6	25.3	26.7	25.1	26.7	28.7
2000	31.3	32.8	32.1	29.3	26.1	24.5	23.7	25.1	27.1	27	28.5	30.2
2001	31.9	31.6	31.2	26.7	27.1							
2002			31	27.6		23.7	24.9	25	26.9	25.9	27.4	27.8
2003	30.8	33		28.6	25.7	24.6	24.8	25.3	26.9	28.8	26.7	28.5
2004	30.9	31.8	32	26.6	25.9	25.2	24.7	25.2	27	25.6	25.6	29.4
2005			32.7	28.8	26.5						27.3	

Station: Mega

Element: Minimum Monthly Temperature in ^{o}C

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984			15.6	14.2	13.4	14.3						
1985											15	15.5
1986	16	16.7	15.4	14.4	13.7	12.9	11.4	13.4	12.4	13.7	13.1	13.4
1987	13	12.1	10.7	15.4	14.6	13.4	12.3	12.7	14	15.5	14.8	14.7
1988	15.5	16	13	14.8	14.7	13.7	13	13.1	13.4	14.4	15	14.5
1989	14.6	15.6	15.6	14.9	14.3	12.4	11.5	11.5	12.9	14	14.6	15
1990	15	14.8	15.6	14.8	14.7	12.5	11.9	12.5	13	14.3	14.8	15.2
1991	15.6	16.3	16.1	15.5	15.2		12.3	11.8	13.1			
1993	18	17.6	17.3									
1994			15.8	15	14.5	12.4	11.9	12	12.6	14.3	14.5	13.5
1995	14	14.7	15.3	15.3	14.7	12.7	12	11.6	11.9	13.4	14.1	14.3
1996	14.9	15.4	15.3	14.7	14.3	12.5	11.2	11.8	12.4	13.4	13.8	13.6
1997	14.6	14.6	14.4									
1998				15.9	14.4	13	12.2	12	12.5	13.5	14.1	14.1
1999	15.3	15.6	15.2	14.8	13.5	12.9	11.8	12.3	12.7	13.3	14.5	
2000	14.8	14.6	14.4	14.6	14.2	12.7	12.1	12.3	12.8	14	15.1	15.2
2001	14.3	15.1	15.3	14.9	14.2	12.3	12	11.6	12.3	12.8	11.3	11.6
2002	13.8	13.2	12.3	12.4	12.4	12.4	12	12.1	13.3	14.6	14.7	15.1
2003	13.3	14	14.6	15	14.4	13.1	11.9	12	12.9	14.5	14.9	13.7
2004		14.3	14.3	15.5	14.3	12.6	11.7	11.7	14.6	14.5	14.8	15.1
2005			16.2	15.5	14.6							

Station: Moyale

Element: Minimum Monthly Temperature in ^{o}C

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	16.9	17.2	17	18.2	17.8	16.4	16.1	16.1	16.2	16.2	16.2	
1986	16.3	17.2	17.1	16.9	17.1	16.6	15.8	15.6	15.5	17.1	18.9	20.6
1987	23.4	17.6	20.3	19.1	18.3	16.9	14.6	12.5	13.7	16.3	18.7	17.5
1988									16.5	17.6	17.7	17.5
1989	18.7	19.2	19.3	18.1	17.8	15.8	15.6	17.2	16.6	16.3		18
1990	18.2	18.7	18.3	18.2	17.6	16.1	15.7	15.9	16.5	16.6	16.8	
1991	18.2	19.4	19.6	18.4	15.5		15.1	15.1	15.8	16.4	17.7	17.2
1992	19		18	17.1	17	16.8	16.1	15.7	16.5	17.7		
1993					17.2	16.5	15.7	15.6	16.1	17.6	16.1	18.1
1994		19.4	19.6	18.7								
1995	18.2	20	19.3	19	18.3	16.6	16.6		17.1	18.1	17.9	18.5
1996	19.3	20.1	19.1	18.8	18	17.1	16	15.9	16.9	17.7	18.3	18.5
1997	19.3	19.7	20.1	18.3	17.7	17.3	16.4	16.6	17.5	17.9	18.1	17.9
1998	18.3	19.1		19.5	18.5	17	16	16.4	16.7	17.4	17.4	18
1999	18.6	18.9	19.4			16.4	16.6	16.6	16.8	17.4	17.3	17.5
2000	18.3	19.6	19.9	19.3	18	16.7	16.3	16.4	16.9	18	18.5	19.1
2001	19.8	19.4	19.9	18.8	18.5	16.9	16.3	16.3	17.4	18.4	18.4	18.7
2002	19.7	20.2	20.4	18.6		16.5						
2004			20	18.1	17.7	15.9	15.5	15.9	16.7	17.6	17.5	17.5
2005			21	19.9	18.9							

Annex 2 - Database Water Points

NO.	SITE_NAME	EASTING	NORTHING	ALTITUDE	REGION	ZONE	WOREDA	DEPTH	SWL	YIELD	EC	TEMP
1	Arbele	386975	452305	929	Oromia	Borena	Dire					
2	Chafa Sadeqa (Gombisa)	467846	402128	1124	Oromia	Borena	Dire	19				
3	Didibe	415810	436190	1510	Oromia	Borena	Dire					
4	Didmega	425994	445668	1498	Oromia	Borena	Dire	42			1293	22
5	Dillo	356561	467007	937	Oromia	Borena	Dire					
6	Gincho (Gombisa)	465821	404062	1135	Oromia	Borena	Dire	38				
7	Gofgedo	418265	434756	1580	Oromia	Borena	Dire	49	35	0.11	405	22
8	Gololcha	406748	457612	1594	Oromia	Borena	Dire	77		2		
9	Gololcha	402826	467063	1540	Oromia	Borena	Dire	84				
10	Goray	339570	463166	805	Oromia	Borena	Dire	250		3		
11	Gorille	452435	449530	1350	Oromia	Borena	Dire	65		1		
12	Gorille	452550	449071	1319	Oromia	Borena	Dire	56	44	1.2		
13	Madhocho	420413	459078	1579	Oromia	Borena	Dire	69				
14	Mega	424058	448740	1732	Oromia	Borena	Dire				755	19
15	Mega2	423911	448517	1710	Oromia	Borena	Dire					
16	Mega3	423910	448489	1711	Oromia	Borena	Dire					

NO.	SITE_NAME	EASTING	NORTHING	ALTITUDE	REGION	ZONE	WOREDA	DEPTH	SWL	YIELD	EC	TEMP
17	Mega5	424072	448744	1721	Oromia	Borena	Dire					
18	Menesoda	428683	461192	1490	Oromia	Borena	Dire	72	57	1		
19	Menesoda	429440	460941	1482	Oromia	Borena	Dire	63				
20	Romso	418492	444585	1580	Oromia	Borena	Dire	57			1103	21
21	Areallo (Dololo Mekala	429440	460941	1482	Oromia	Borena	Miyo	150		2.24		
22	Boku Lugoma (Did Chena	459954	432024	1294	Oromia	Borena	Miyo					
23	Boku Lugoma (147Millit	466907	428666	1270	Oromia	Borena	Miyo					
24	Boku Lugoma (Did Chena	458741	431255	1292	Oromia	Borena	Miyo					
25	Boku Lugoma	464356	427471	1278	Oromia	Borena	Miyo	64			1138	24
26	Cheriliche	434955	420232	1400	Oromia	Borena	Miyo	56	15	1		
27	Didchena	464459	427727	1276	Oromia	Borena	Miyo					
28	Didchena	458741	431255	1292	Oromia	Borena	Miyo	65				
29	Didmele	435396	431255	1421	Oromia	Borena	Miyo	58			1765	
30	Dikicha	457246	411294	1197	Oromia	Borena	Miyo					
31	Erder	485162	433053		Oromia	Borena	Miyo	50				
32	Gimbe	433776	430135		Oromia	Borena	Miyo	73	32	3		
33	Hidi Lola_1	453189	407918	1209	Oromia	Borena	Miyo					
34	Hidi Lola_2	453002	407846	1210	Oromia	Borena	Miyo	23		0.8		
35	Mechana (Silala1)	451669	430503	1324	Oromia	Borena	Miyo					
36	Mechana (Silala2)	452258	430930	1324	Oromia	Borena	Miyo					

NO.	SITE_NAME	EASTING	NORTHING	ALTITUDE	REGION	ZONE	WOREDA	DEPTH	SWL	YIELD	EC	TEMP
37	Melbana	442725	430406	1360	Oromia	Borena	Miyo	40	20	1		
38	Melbana	440821	429927	1372	Oromia	Borena	Miyo	98				
39	Melbana	442120	430449	1368	Oromia	Borena	Miyo					
40	Tesso (Galgelo)	450181	406942	1237	Oromia	Borena	Miyo	21				
41	Argene	482425	399295	1230	Oromia	Borena	Moyale	58	40	1		
42	Dembi_3 (Araa)	489102	398445	1198	Oromia	Borena	Moyale					
43	Dembi_2 (Araa)	489076	398432	1198	Oromia	Borena	Moyale					
44	Dembi_1 (Araa)	489874	398882	1210	Oromia	Borena	Moyale					
45	Did Guchi	496564	426811	1151	Oromia	Borena	Moyale					
46	El Gof_irr1	506691	426258	1134	Oromia	Borena	Moyale	40	18	2		
47	El Gof_irr2	506669	426216	1137	Oromia	Borena	Moyale	40	18	2		
48	El Gof				Oromia	Borena	Moyale	50			1170	23
49	Mormora	482357	408822	1283	Oromia	Borena	Moyale	62		0.3		
50	Mudiambo (Boru jirmo)	482360	395165	1261	Oromia	Borena	Moyale	27		0.6		
51	Mudiambo (Boru jirmo)	481868	395368	1260	Oromia	Borena	Moyale					
52	Sebante	500304	398028	1077	Oromia	Borena	Moyale					
53	Shewaber	504515	392687	1162	Oromia	Borena	Moyale	39		0.6		
54	Tuka	485139	398483	1194	Oromia	Borena	Moyale					
55	Tuka	485065	398553	1197	Oromia	Borena	Moyale					
56	Tuka	485620	398239	1197	Oromia	Borena	Moyale					

NO.	SITE_NAME	EASTING	NORTHING	ALTITUDE	REGION	ZONE	WOREDA	DEPTH	SWL	YIELD	EC	TEMP
57	Bururi	557742	384697	1105	Somali	Liben	Moyale	39	33		1594	26
58	Bururi	557752	384691	1105	Somali	Liben	Moyale	40	37	0.35	1594	26
59	Chilanko	614327	461702	1039	Somali	Liben	Moyale	130	110	1.93		
60	Elder	584424	427048	975	Somali	Liben	Moyale	120		5.56	4310	27
61	El-leh	525226	416549	1032	Somali	Liben	Moyale	42		4.17	2200	23
62	El-leh	525242	416464	1040	Somali	Liben	Moyale	55		6.67		
63	El-leh	524361	416770	1041	Somali	Liben	Moyale	43	19	1.2		
64	El-leh	524466	416770	1041	Somali	Liben	Moyale	43	19	1.2		
65	El-leh	525025	416796	1042	Somali	Liben	Moyale		21	1		
66	Katama	549624	397862	1083	Somali	Liben	Moyale	72		3.4		
67	Quedaduma	561829	381808	973	Somali	Liben	Moyale	24	19	8.33		
68	Tessoma	531398	418015	1022	Somali	Liben	Moyale	55.5		2.78	2860	30

Annex 3 - Database of Landcover

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
1	Elnyapo	601709	503572	Wooded Shrubland		

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
2	Elnyapo	608354	492642	Wooded Bushland		Wayama
3	Gelgalo	608840	492019	Farmland	Obru	Wayama
4	Gelgalo	609345	491183	Woodland	Adama	Wayama
5	Halobirti	639229	487833	Wooded Grassland		Koticha
6	Halobirti	639257	487360	Bush Shrubland		Koticha
7	Halobirti	639294	486830	Shrub Grassland		Koticha
8	Chilanko	615542	461528	Farmland	Obru	Wayama
9	Chilanko	615547	461371	Bareland	Kolkolo	Wayama
10	Chilanko	616166	461658	Wooded Bushland	Uor	Wayama
11	Chilanko	615044	461554	Bushland		Boyi
12	Chilanko	611805	460045	Wooded Bushland		Wayama
13	Elkur	576369	424155	Wooded bushland		Wayama
14	Elkur	572955	420986	Bareland		Wayama
15	Elkur	573137	421095	Bareland		Wayama
16	Elkur	573146	421197	Bushland		Wayama
17	Boji-korbessa	543125	418241	Bushland		Koticha
18	Boji-korbessa	541538	418782	Bareland		
19	Gaio	448456	466735	Wooded Grassland		
20	Das	468410	465821	Wooded Shrubland		
21	Romso	418492	444585	Grassland		

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
22	Gofgedo	418265	434756	Bushland		
23	Didmega	425994	445668	Farmland		
24	Boku Lugoma	464356	427471	Wooded Shrubland		
25	Didmele	435396	451255	Wooded Grassland		
26	Chereliche	434955	420232	Bareland		
27	Melbana	442739	430381	Wooded Grassland		
28	Tuka	485139	398483	Woodland		
29	Sebante	500304	398028	Wooded Bushland		
30	Elkur			Wooded Bushland		
31	Elnyapo	601711	503519	Wooded Bushland		
32	Chilanko	614327	461702	Farmland		
33	Elder	584424	427048	Open grassland		
34	Tessoma	531398	418015	Bushland		
35	El-leh	524361	416770	Farmland		
36	El-leh	524466	416770	Farmland		
37	Kojowa	536712	451702	Wooded Bushland		
38	Kojowa	538336	452510	Wooded Grassland		
39	Katama	549624	397862	Grassland		
40	Sabante	496237	400542	Bush?shrubland		Chaari
41	Sabante	496200	400110	Farmland		Chaari

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
42	Sabante	497034	401428		Gamogi	Kooticha
43	Sabante	496490	403357		Gamogi	Sandy Wayama
44	Sabante	495729	405249	Wooded bushland	Gamogi	Wayama
45	Sabante	495328	406008	Wooded grassland	Gamogi	Kooticha
46	Sabante	495094	406949	Wooded bushland	Gamogi	Wayama
47	Tuka	484147	401356	Farmland	Gamogi	Wayama
48	Tuka	483790	401696	Bush?shrubland	Gamogi	Wayama
49	Tuka	482497	402492	Farmland		Kooticha
50	Tuka	485039	402817	Wooded bushland		Ashawa Mansa (Sandy
51	Tuka	485204	401335	Wooded grassland	Gamogi	Wayama
52	Tuka	485199	401955	Bush?shrubland	Gamogi	Biye bor
53	Tuka	485273	404301	Bush?shrubland	Gamogi	Kooticha
54	Tuka	485444	398933	Wooded bushland	Badda	Wayama
55	Tuka	485603	398156	Wooded bushland	Badda	Biye bor
56	Mormora	483406	410049	Wooded bushland	Gamogi	Wayama/Kooticha
57	Mormora	481850	411134	Wooded bushland	Gamogi/Badda	Chaari
58	Mormora	480247	414733	Bush?shrubland	Gamogi	Wayama
59	Mormora	482064	415952	Bush?shrubland	Gamogi	Kooticha/Biye adhi
60	Chamuk Oromia	502995	396941	Grassland	Gamogi	Kooticha
61	Chamuk Oromia	502701	395093	Bush?shrubland	Gamogi	Sandy Wayama/Biye d

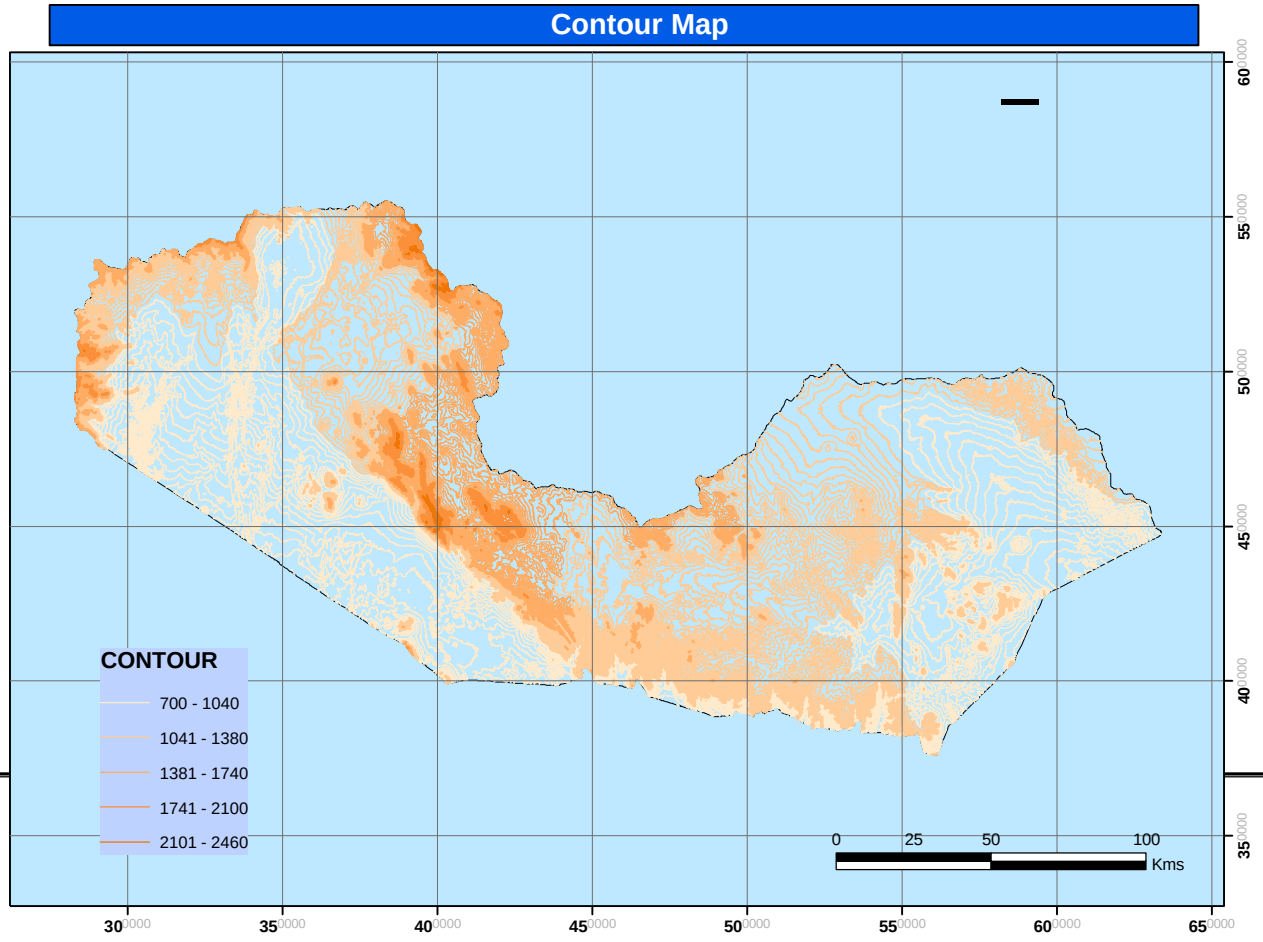
ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
62	Chamuk Oromia	502242	395195	Bush?shrubland		Chaari
63	Chamuk Oromia	500767	395234	Wooded bushland		Chaari
64	Chamuk Somali	506869	399852	Bush?shrubland	Gamogi	Wayama
65	Chamuk Somali	509551	402913	Wooded bushland	Gamogi	Kooticha
66	Chamuk Somali	506736	397366	Eroded bushland	Badda	Chaari/Maansa adhi
67	Chamuk Somali	505929	396387	Bush?shrubland	Badda	Chaari
68	Chamuk Somali	505957	397175	Bush?shrubland	Badda	Chaari
69	Chamuk Somali	517231	403683	Wooded bushland	Gamogi	Wayama
70	Chamuk Somali	508617	397571	Wooded bushland	Badda	Maansa adhi
71	Chamuk Somali	508273	396830	Grassland	Badda	Chaari
72	Dukusu	536012	395191	Bush?shrubland	Gilbabo	Wayama
73	Dukusu	538320	397344	Wooded bushland	Badda	Wayama
74	Dukusu	535677	394957	Wooded bushland	Gamogi	Kooticha
75	Dukusu	532114	388450	Wooded bushland	Badda	Wayama
76	Bede	524423	394074	Bush?shrubland	Badda	Borborki
77	Bede	524096	391776	Wooded bushland	Badda	Biye dalach
78	Bede	524269	392058		Gamogi	Biye adhi
79	Bede	524178	393128		Badda	Wayama
80	Bede	527537	398219			Kooticha
81	Arda-Ola	517039	401479	Wooded bushland	Gilbabo	Borborki

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
82	Arda-Ola	515451	403048	Wooded bushland	Gamogi	Ramata
83	Arda-Ola	514613	396362	Wooded bushland	Badda	Charri
84	Erder	485203	434085	Bush-shrubland	Gam/Gilbabo	Wayama
85	Erder	485712	436491	Wooded shrubland	Gam/Gilbabo	Wayama
86	Erder	485718	440334	Wooded shrubland	Gam/Dirre	Biye adhi
87	Erder	487216	446167	Bush-shrubland	Gam/Dirre	Wayama
88	Erder	488296	448611	Farmland	Gam/Gilbabo	Wayama
89	Erder	485142	433636	Abandoned area	Gam/Gilbabo	Biye adhi
90	Erder	483180	431891	Bush-shrubland	Gam/Gilbabo	Biye adhi
91	Erder	481720	430456	Wooded shrubland	Gilbabo	Way/Biye adhi
92	Erder (Mogori)	481232	430196	Farmland	Gilbabo	Way/Biye adhi
93	Erder	480397	429209	Grassland	Gilbabo	Way/Biye adhi
94	Erder	478371	425383	Wooded grassland	Gilbabo	Kooticha
95	Erder	476774	424961	Bush-shrubland		Chaari
96	Erder	476043	424063	Bush-shrubland		Chaari/Wayama
97	Bokulugoma	465093	427621	Grassland	Gam/Gilbabo	Biye adhi
98	Bokulugoma	463718	428422	Wooded grassland	Gam/Gilbabo	Biye bor
99	Bokulugoma	462367	429750	Open grassland	Gam/Gilbabo	Kooticha
100	Bokulugoma	463033	430795	Bush?shrubland	Gam/Gilbabo	Wayama
101	Bokulugoma	462808	431177	Farmland	Gam/Gilbabo	Wayama

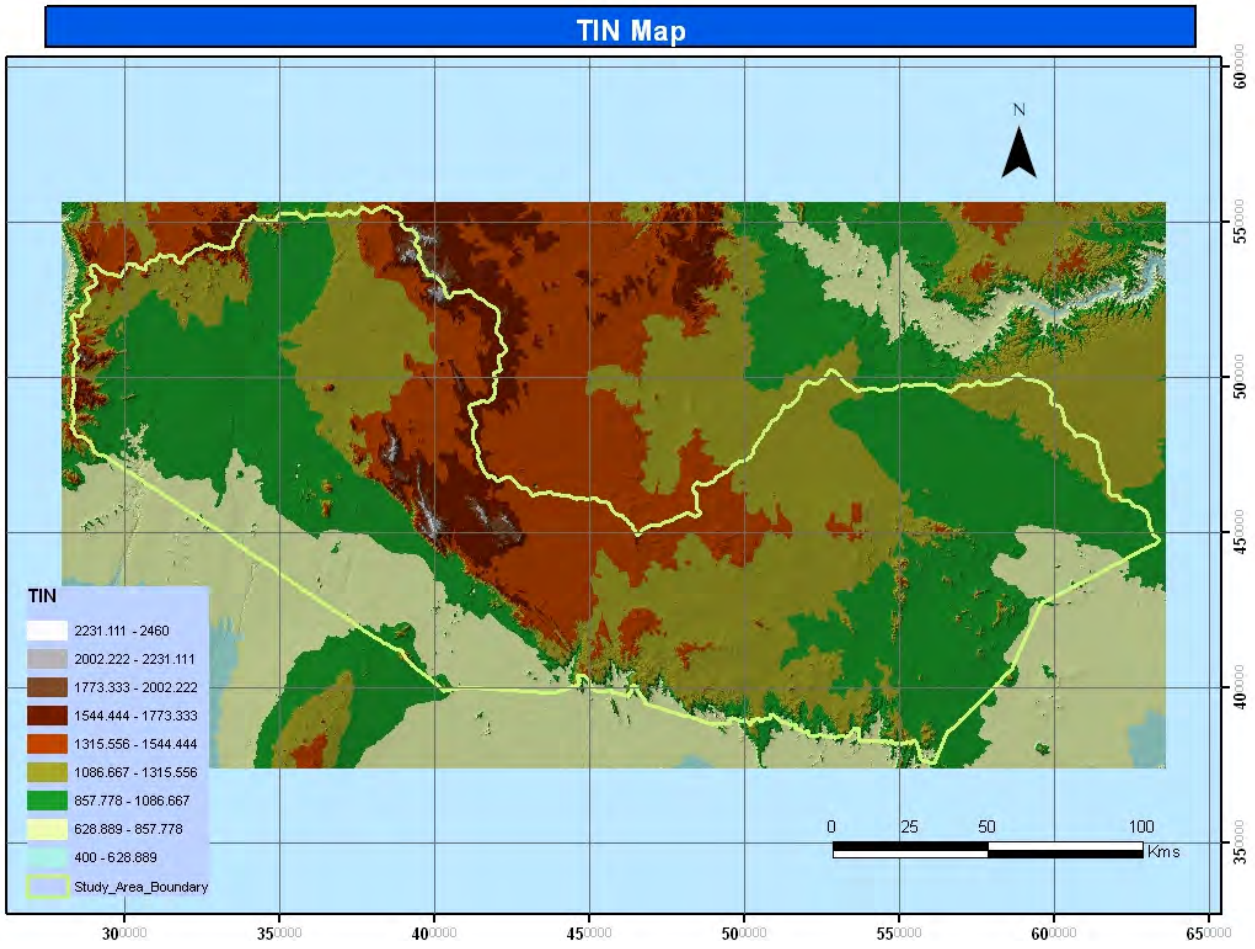
ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
102	Bokulugoma	461706	432089	Bush-shrubland	Gam/Gilbabo	Biye adhi
103	Bokulugoma	461088	431948	Wooded grassland	Gam/Gilbabo	Biye adhi
104	Bokulugoma	460591	431736	Abandoned grassla	Gam/Gilbabo	Biye bor
105	Bokulugoma	460477	428568	Abandoned grassla	Gam/Gilbabo	Biye adhi
106	Bokulugoma	461887	427598	Bush-shrubland	Gam/Gilbabo	Wayama
107	Bokulugoma	463240	427923	Wooded grassland	Gam/Gilbabo	Kooticha
108	Meleb Somali/ Legesu	502976	402622	Bush-shrubland	Gamogi	Wayama
109	Meleb Somali/ Legesu	500198	407308	Wooded shrubland	Gamogi	Kooticha
110	Meleb Somali/ Legesu	502843	397970	Bushy grassland	Gamogi	Biye bor
111	Meleb Oromia	502312	395081	Bush?shrubland	Gamogi	Charri
112	Meleb Oromia	503033	396325	Bush?shrubland	Gamogi	Kooticha
113	Kadadouma	563820	382244	Wooded shrubland	Badda	Byie bor
114	Kadadouma	559938	382030	Wooded grassland	Badda	Byie bor
115	Kadadouma	562583	383594	Eroded bushland	Gamogi	Byie bor
116	Kadadouma	563323	386908	Bush?shrubland	Gamogi	Wayama
117	Boji	552716	395246	Wooded shrubland	Badda	Byie bor
118	Boji	554631	394033	Bush?shrubland	Badda	Wayama
119	Boji	557357	392718	Farmland	Badda	Wayama
120	Boji	560377	390172	Wooded shrubland	Badda	Wayama
121	Ketema	542376	402206	Wooded shrubland	Badda	Kooticha

ID	KEBELE	EASTING	NORTHING	LAND_COVER	TRAD_CLASS	TRAD_SOIL
122	Ketema	544633	400749	Wooded shrubland	Gamogi	Wayama
123	Ketema	556034	401948		Badda	Koothica
124	Ketema	540331	396780		Badda	Koothica
125	Ketema	553603	394690	Woodland	Badda	Charri

Annex 4 - Contour Map of the Study Area



Annex 5 - TIN of the Study Area


TIN Map
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TIN
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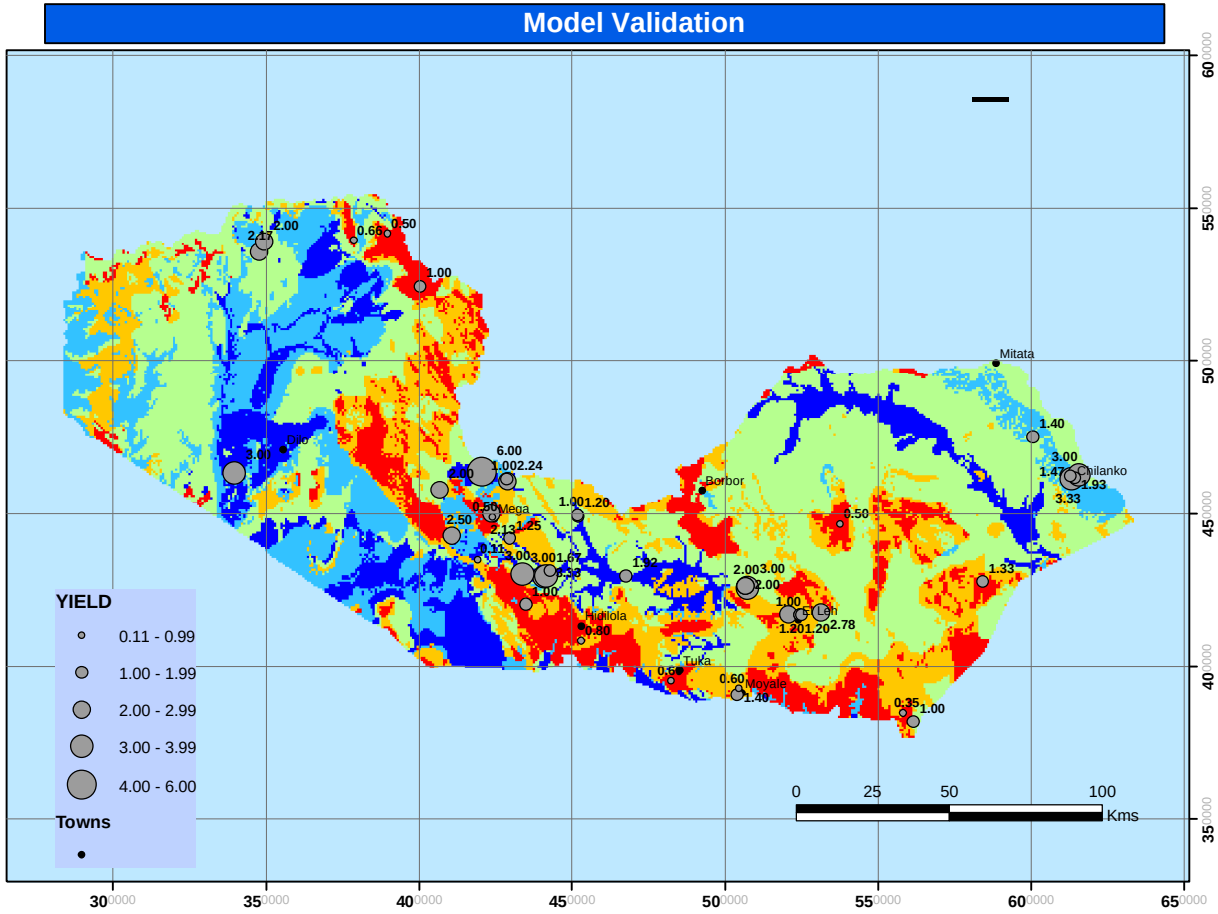
2002.222 - 2231.111
1773.333 - 2002.222
1544.444 - 1773.333
1315.556 - 1544.444
1086.667 - 1315.556
857.778 - 1086.667
628.889 - 857.778
400 - 628.889
Study_Area_Boundary
0 25 50 100
Kms
30 35 40 45 50 55 60 65
60 55 50 45 40 35

Annex 6 - Description of codes used for geological units

Code	Description
Q	Undivided alluvium, eluvium, and lacustrine deposits
Qa	Alluvial deposits: gravel, sand, silt, and clay
Qe	Eluvium: Red to reddish brown sandy soil, black cotton soil, calcrite, minor ferricrite, silt and clay
Qv6	Augite-olivine-phyric-basalt, scoraceous-vesicular with xenoliths of mantle nodules
Qv5	Pyroclastic surge deposits: Lapilli tuff
Qv4	Olivine-phyric-basalt
Qv3	Pyroclastic surge deposits: Lapilli tuff
Qv2	Augite-labradorite-phyric-basalt
Qv1	Pyroclastic surge deposits: mainly bedded fall deposits, scoria, rock fragments
Qv	Scoraceous-vesicular-olivine-phyric basalt
Ntr2	Alkali trachyte and basalt flows
Nb	Bulal basalt flows
NMv	Upper basalt flows
NMt	Teltele basalt flows
PNb1	Lower flood basalts
Jh2	Hamaniel Formation: micritic to microcrystalline and oolitic limestones
Pcgt2	Biotite and hornblende granites
Pcdt	Quartz metadiorite

Code	Description
Pcgd	Metagranodiorite
Pcgt1	Biotite metagranite
Pcdt1	Melka Guba diorite gneiss
Pcsc2	Metavolcanics: Amphibolite and plagioclase-chlorite-actinite schist
Pcsc1	Subvolcanic amphibolite
Pcsc	Metasediments: Phylite, metasiltstone, metasandstone, micashists, quartz-graphite-muscovite, kyanite-muscovite schists
Pcum2	Serpentinite
Pcgb	Metagabbro
Pcum3	Talc, tremolite-chlorite-talc, chlorite, chlorite-actinolite and actinolite schists
Pcum4	Metahornblendite
Pcum	Undifferentiated metaultramafics
Pcgn1	Granulite-quartzofeldspathic gneiss
Pcgn7	Oligoclase-hornblende-biotite-quartz, biotite-hornblende, biotite and calcsilicate gneiss (paragneisses)
Pcgn6	Quartzofeldspathic gneiss, minor biotite-feldspar-quartz gneiss and biotite gnanite pods
Pcgn4	Wadera mylonite and mylonitic gneiss
Pcgn3	Hornblende-biotite-quartz-feldspar and biotite-quartz-feldspar gneiss
Pcgn2	Biotite-hornblende gneiss
Pcgn1	Granulite-quartzofeldspathic gneiss

Annex 7 - Map showing the validity of the model



DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other University, and all sources of material used for the thesis have been duly acknowledged.

Name : Abiy Getachew Mamo

Signature : _____

Place and Date of Submission: Addis Ababa,
23 March 2007