Integrated Approach Using Remote Sensing and GIS Techniques for Delineation of Groundwater Potential Zones in Dire Dawa Rivers Catchment, Eastern Ethiopia.

Thesis submitted for Partial Fulfillment of the Requirements for the Award of the Degree of

MASTER OF SCIENCE

In

Remote Sensing and Geographical Information Systems (GIS) of Addis Ababa University, Addis Ababa, Ethiopia.

By

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Under the guidance of

Dr.K.V. Suryabhagavan

School of Earth Sciences
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JUNE, 2013

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SCHOOL OF GRADUATE STUDIES

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D E C L A R A T I O N

I hereby declare that the thesis entitled "Integrated Approach Using Remote Sensing and GIS Techniques for Delineation of Groundwater Potential Zones in Dire Dawa Rivers Catchment, Eastern Ethiopia" has been carried out by me under the supervision of Dr. K. V. Suryabhagavan, School of Earth Sciences, Addis Ababa University, Addis Ababa during the year 2012-2013 as a part of Master of Science programme in Remote Sensing and GIS. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Place: Addis Ababa

Date: June, 2013

(Mohammed Yusuf)

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A C K N O W L E D G M E N T S

First of all I am thankful to Allah for the divine blessing showered up on me to complete this work.

I express my deep sense of gratitude and indebtedness to my advisor Dr. K.V. Suryabhagavan, Department of Earth Sciences, Addis Ababa University for his guidance and valuable suggestions during the research work.

I am also grateful indebted to Water Works Design and supervision Enterprise (WWDSE) for providing me groundwater data; National Meteorological Agency (NMA) for providing me meteorological data and Geological survey of Ethiopia for provide me geological map and related literatures.

I am also greatly thanks to Ato Iliyas Abdi Ali, Eastern Harrerge water, mineral and Energy office, Irrigation and land observation process owner, for providing me GPS during field study.

I also wish to thank Ato zelalem, staff of Water Works Design and supervision Enterprise for providing me groundwater data of dire dawa Administration.

I am greatly indebted to all my family members for their helpful nature throughout my study period and my wife Firontu Aliye for the care and support and their cooperation during the work.

My whole hearted thanks are also to all my friends in Fejrul-Islam, whose names could not be mentioned separately because of limitations; for their constant encouragement and cooperation.

Abstract

Groundwater is one of the very precious natural resource of earth that sustains all human activities. It is essential not only for sustenance of the human life but also for the economic and social progress of a region. Integration of remote sensing data and the geographical information system (GIS) for the exploration of groundwater resources has become a advance in the field of groundwater research, which assists in assessing, monitoring, and conserving groundwater resources. Present paper is an attempt to delineate groundwater potential zone in Dire dawa rivers catchment, eastern Ethiopia using integrated approach of remote sensing and GIS techniques. The Ethiopia geological survey of NC 37-12 and NC 38-9 Geological map, Landsat (2011), SRTM, FAO soil data and Meteorological data are used to prepare various thematic layers such as lithology, slope, land-use, lineament, drainage, soil, rainfall, geomorphology and water level depth maps. They were transformed to raster data using feature to raster converter tool in ArcGIS and again to IDRISI raster for weight calculation. Digital image processing of Landsat ETM+ was carryout and interpreted to produce thematic map of land use/cover in ERDAS Imagine. Lithology and lineaments for lineament density were digitized from geological map. Contours for elevation, drainage lines for drainage density, slope and geomorphology were prepared from SRTM and soil map from FAO (the Digital Soil and Terrain Database). The rainfall map and depth to water level are interpolated from point data. Multi-criteria evaluation technique is used to integrate all the thematic layers. Individual themes and their corresponding categories are assigned a knowledge base ranking depending on their suitability to hold groundwater and their weights are calculated. Using weighed overly analysis in Arc GIS software; all thematic maps are integrated to produce a composite groundwater potential map of the study area. This map was further classified into five categories which represents Very poor to Very potential zones. The result indicated that large part of the study area is classified under good category and the groundwater potential of the study area is related mainly to geology, geomorphology, slope and lineaments. Spatially the very good and good categories are distributed along plain geomorphic units, near to lineaments, less dense drainage density and where the lithology is affected by secondary structure and having interconnected pore spaces. The validity of the model was checked against borehole, dug well, spring data distribution and bore hole yield which reflects the actual groundwater potential of the area; where out of 90 borehole data collected, 81 are on very good and good zones, 9 on moderate zones. From all of 27 dug wells and 23 springs covering the entire catchment area, 22 and 11 of them are located in very good and good groundwater potential zone and the other 5 and 12 are in the moderate and poor zone respectively. Moreover out of 47 bore holes with yield between 0.4-10l/s, 41 bore holes are on the very good and good zones and 3 on moderate zone; out of 14 bore holes with yield between 10-20l/s all of them are in very good and good zone and from 18 bore holes with yield between 20-60l/s 13 are in very good and good zone. Even though, dug wells exist in all groundwater potential zones, the best yielding wells lie in the very good and good groundwater prospect zone.

Key word

Groundwater potential, Geographic Information System, Remote Sensing, multi criteria decision evaluation, Weight, Dire Dawa, Eastern Ethiopia

ACRONYMS

GIS	Geographic Information System
WWDSE	Water Work Design and Supervision Enterprise
IRS	Indian Remote Sensing
Msc	Master of Science
DDPA-TIDCB	Dire Dawa Provisional Administration Trade & Industry Development Coordination Bureau
SRTM	Shuttle Radar Topographic Mission
ERDAS	Earth Resources Data Analysis System
ETM	Enhanced Thematic Mapper
FAO	Food and Agricultural Organization
AAU	Addis Ababa University
EMA	Ethiopian Mapping Agency
NMA	National Meteorological Agency
DEM	Digital Elevation Model
GCP	Ground Control Point
DIP	Digital Image Process
WGS	World Geodetic System
TCC	True Color Composition
FCC	False Color Composition
LULC	Land Use Land Cover
MCA	Multi-criteria Analysis
MM^3	Million Meter Cub
BM^3	Billion Meter Cub
BH	Borehole
TW	Test Well
RGB	Red Green Blue
UNESCO	United Nations Educational Scientific and Cultural Organization
EIGS	Ethiopian Institute of Geological Survey

1. INTRODUCTION

1.1 Background of the Study Area

Groundwater is one of a very valuable natural resources and an important source for sustenance and maintenance of human life activities as well as for economic and social progression of the country. It is the major and most reasonable source of water supply predominantly in areas of semi-arid zones and it is a resource on which the society are mostly dependent and must be exploit for development and improvement of socio-economic and cultural well being of the country.

According to Murthy (2000) groundwater is very important resource for different social-economic activities as agriculture, domestic water supply and industry when the water bearing formation of the area is permeable enough in which the water is easily percolate through them and can yield adequate amount of water through various discharge mechanisms. The amount of water draw out from the aquifer must be replaced in the form of recharge, this allow the formation to give continues supply of water.

It is also the single largest and most productive source of irrigation and it plays a critical role in maintaining agricultural production during droughts. There for groundwater can be effectively exploited if potential area is identified as much as possible. Since it is difficult to now the occurrence of groundwater potential zone from the surface and the use of geophysical and geo-electrical method to exploit the groundwater is very expensive, time consuming and not efficient for large area. So Systematic planning of groundwater development using new technologies of remote sensing and Geographical information system (GIS) in the exploration of groundwater is essential for proper utilization and management of this natural resource. (Sener *et a*l., 2005).

Geospatial technology is a rapid and cost-effective tool in producing valuable data on geology, geomorphology, lineaments, slope, etc. that helps in interpreting groundwater potential zone. A systematic integration of these data with follow-up of hydrogeological investigation provides rapid and cost-effective delineation of groundwater potential zones. Although it has been possible to integrate these data visually and delineate groundwater potential zones, however, it becomes time consuming, difficult, and introduces manual error. In recent years, digital technique is used to integrate various data to delineate not only groundwater potential zone but also solve other problems related to groundwater. These various data are prepared in the form of a thematic map using geographical information system (GIS) software tool. These thematic maps are then integrated using Spatial Analyst tool (Kavitha *et al.,* 2011). Remotely Sensed data by its wide area coverage and multispectral nature help in identification and mapping of different factors like Drainage Density, Slope Steepness, Land use/Land cover, Soil, Rainfall, Geological, Structures/Lineaments, Landforms/Geomorphology and Geology with selective ground checks in a cost-effective manner. An integrated analysis of these factors together with the available well and ancillary data in the GIS environment helps in identifying the potential groundwater zones.

In order to determine the location of aquifer, quality of groundwater, physical characteristics of aquifers, etc., in any basin, test drilling and stratigraphy analysis are the most reliable and standard methods. However, such an approach for groundwater investigations is very costly, time-consuming and requires skilled manpower (Basavaraj and Nijagunappa, 2011). In contrast, remote Geo-informatics technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a very useful tool for the assessment, monitoring and management of groundwater resources, (Jha *et al.,* 2007).

Dire dawa rivers catchment is found in semi arid region at the south east margin of the Awash River basin. The study area contains rural and town of dire dawa and shinile zone. In these and surrounding area there is rapid development of irrigation and industry in addition to high population growth. Because of Lake Haromaya which is previously potential source of water supply of Harrar, Haromaya and Awady is dried out and stabilization of new factories, the demand of water supply in the area is become increasing and increasing.

1.2 Statement of problem

Several studies have been attempted in the area with different approaches as Groundwater Regime Monitoring Work in Dire dawa Area, Dire dawa Administrative Council Integrated Resource Development Master Plan Study Project, Volume-III, Part 2 Hydrogeology report, Harrar Water Supply and Sanitation Project (WWDSE, 2004, 2007 2008). In this projects groundwater in escarpment and Dire dawa basin, groundwater quality, geology and hydrogeology are studied by using water point inventory, geophysical investigation, drilling and pumping tests.

The need to delineate the groundwater potential zone in Dire dawa rivers catchment is because of increasing water demand in Dire dawa, Harrar, Shinile zone and their surrounding areas for drinking, irrigation and industrial purpose. In the study area there are different well field as Sabiyan, Dire jarra and Haseliso. Even though there are number of projects which are conducted and many pumps drilled in millions birr, but there is no study conducted to delineate groundwater potential zones. Due to this reason we can't easily identify groundwater potential zone in this catchment. So that it is very important to identify and Delineating Groundwater Potential Zone in Dire dawa rivers catchment which cross western Dira dawa and south of Shinile zone by applying Integrated Approach using Remote Sensing and GIS Techniques.

1.3 Objectives

1.3.1 General Objectives

To contribute towards systematic groundwater studies utilizing Remote Sensing, field studies and Geographic Information Systems (GIS) in the delineation of groundwater potential Zone, in Dire dawa rivers catchment.

1.3.2 Specific Objectives

- To prepare thematic maps of the area such as lithology, lineaments, landforms, soil, rainfall, depth to water level, drainage and slopes from remotely sensed data, field studies and secondary data.
- To identify and delineate groundwater potential zones through integration of various thematic maps with GIS techniques.
- To validate the Model results with borehole, dug well and spring distribution and yield data.

2. LITERATURE REVIEW

2.1 Groundwater studies using GIS and remote sensing techniques

Now a day there are many researches done on groundwater potential delineation using coast effective and time saving methods of GIS and remote sensing approaches by integrating different factors which contribute a great role to identify the potential area.

According to Nag and Anindita (2011) integrated approach using remote sensing and GIS techniques for delineation of groundwater potential zones in Dwarakeswar watershed, Bankura district, west Bengal is carried out by using datas like contours, drainage, geological map, Indian remote sensing data (IRS P6) for different hydro-geomorphological units as structural and denudation hill buried pediments (BPM) and dissected pediment and valley fills lineament and lineament density. From the above data different thematic maps are generated and interpreted with respect to their water potential.

It is possible to predict the range of depth, yield, success rate and types of wells matched to different litho-units under different hydro-geological domains using remote sensing information combined with the adequate field details; as well inventory and dug well yield data (Gurugnanam *et al*., 2008 and Wath, 2008).

Hydrogeologists and geologists are used the modern techniques as Remote sensing and GIS approach to understand and solve the complex and confusing problems about the identification of groundwater occurrence considering different factors. In recent years, Satellite remote sensing data has been widely used in locating groundwater potential zones due to its cost-effective, reliable, and timely and also meets the essential requirements of data in the geographical Information System (GIS) domain, which are current, sufficiently accurate, comprehensive and available to a uniform standard. Integration of the information on the different groundwater controlling parameters as geology, lineament, geomorphology, hydrogeology, land use land cover is best achieved through GIS which is an effective tool for storage, management and retrieval of spatial and non-spatial data as well as for integration and analysis of this information for meaningful solutions. Because of satellite remote sensing provide an opportunity of better observation and systematic analysis and interpretation of various groundwater controlling factors due to its synoptic and multi-spectral coverage of the earth surface. The integration of remote sensing data and GIS techniques is very useful for groundwater studies. Investigation of remotely sensed data for drainage map, geological, geomorphological and lineament characteristics of terrain in an integrated way was facilities effective evaluation of ground water potential zones (Biswas *et al.,* 2012).

Digital technique is used to integrate various data for delineation of groundwater potential zone and also solve other problems related to groundwater. These various data are prepared in the form of a thematic map using geographical information system (GIS) software tool. These thematic maps are then integrated using Spatial Analyst tool to develop a model depending on the objective of problem at hand, such as delineation of groundwater potential zones (Mailvaganan *et al*., 2011).

The type and number of themes used for the assessment of groundwater resources by remote sensing and GIS techniques varies considerably from one study to another. In most studies, local experience has been used for assigning weights to different thematic layers and their features (Chowdhury *et al.,* 2009).

Several researchers have used remote sensing and GIS techniques for the delineation of groundwater potential zones with successful results (Jugran and Srinivasa, 2003, Gezahegn Lemecha, 2007, Sisay Libasse, 2007, Abiy Getachewm, 2007, Chowdhury *et al*., 2009, Sreedhar *et al.,* 2009, Singh, 2009, Akramja and Mushtaqhussainwani, 2009, Gouri *et al.*, 2012, Kadam and Sankhua, 2012, Sharma *et al*., 2012, Nezar *et al.,* 2012, David *et al.,* 2012, Prabir *et al.,* 2012, Nag and Ghosh, 2012, Subagunasekar and Sashikkumar, 2012 and Sethupathi *et al*., 2012). In these studies, there are several thematic layers used which are different from each other, these includes lithology, geomorphology, drainage pattern, lineament density, soil and topographic slope, land use land cover groundwater recharge, surface water body, rain fall, vegetations types of flooded area, runoff. On the other hand, some researchers have integrated remote sensing, GIS and geoelectrical techniques to delineate groundwater potential zones (Basudeo *et al.,* 2005, Awad, 2008, Girish *et al.,* 2009, Nagarajan *et al.,* 2011 and Srivastava *et al.,* 2012). They used geoelectrical surveys (VES) for deriving additional thematic layers of subsurface parameters such as delineate the detailed aquifer geometry, aquifer resistivity, aquifer thickness, thickness of the top layer or depth to bedrocks and resistivity of the expected water bearing zone. Except for (Awad, 2008) all the studies have been carried out in India. The details about the applications of remote sensing and GIS in groundwater hydrology, including groundwater prospecting can be found in (Awad, 2008, Girish *et al.,* 2009 and Srivastava *et al.,* 2012).

2.2 Previous work

The investigation carried out so far in the area are either to general (on a regional scale) or hydrogeological and geophysical investigations for specific institutions, organizations, private limited companies and town water supply for locating borehole sites without considering all the catchment areas.

Among the important regional geological and hydrogeological investigations within the catchment and its surrounding area are: Hydrogeology of Dire dawa area by (Tesfamichael Keleta, 1974), Hydrogeology of Dire dawa area by (ketama Tadesse, 1982), Hydrogeology and Hydrochemistry of Dire dawa area by (Habteab Zeray and Sima Jiri (1986) and contamination of hydrogeological system in Dire dawa area by (Taye Alemayahu, 1988). Dire dawa Administrative and catchment based studies are: Unpublished Dire Dawa Administrative Council Integrated Resource Development Master Plan Study Project Phase II – Data Collection Site Investigation Survey and Analysis part 2 – Hydrogeology Report by (WWDSE, 2004), Msc thesis on GIS-based Vulnerability and Hazard Mapping for the Protection of Dire Dawa Groundwater Basin, Ethiopia by (Meresa Kiros, 2006), Resource Potential Assessment, Project Identification & Selection, and Profile Preparation Study by (DDPA-TIDCB, 2006), Msc thesis on Assessment of Flood Risk In Dire Dawa Town, Eastern Ethiopia, Using Gis By (Daniel Alemayehu, 2007), numerical groundwater flow modeling of the dire dawa area By (Minalah Bushra, 2007), Master Thesis in Geosciences Anthropogenic Impacts on Groundwater Resources in the urban Environment of Dire Dawa, Ethiopia by (Abate Eyilachew, 2010) and various specific hydrogeological and geophysical investigations which done within the catchment are explain as follow: Dire Dawa Provisional Adminstration Dire Dawa Water Supply And Sewerage Authority Well Completion Report Of Dire Dawa University & Melka Jebdu Kebele Production Bore Holes, Dire Dawa Water Supply & Sewerage Authority Supplementary Three Deep Wells Drilling & Construction Completion Report, groundwater regime monitoring work in Dire dawa area, Dire dawa administrative council integrated resource development master plan study project volume I - natural resources, Dire dawa water supply well drilling completion report and Harrar water supply and sanitation project water wells drilling and construction final well completion report (WWDSE, 2003, 2005, 2007, 2008) are specific project carried out for limited objectives like sewerage, wells drilling, sanitation, ground water regime monitoring and so on. Therefore this study is proposed to give detail picture on Groundwater potential zone with respect to geology, geomorphology, structures, slope, recharge area, soil, aquifer thickness, depth to water level and land use/land cover in the Dire dawa rivers catchment.

3. DESCRIPTION OF THE STUDY AREA AND METHODS

3.1 Descriptions of the Study Area

3.1.1 Location of the Study Area

Dire dawa rivers catchment is geographically located in the eastern part of the country at the south east of the awash river basin specifically lying between latitude 9°26'00" - 9°45'30"N and longitude 41° 41'0" - 42°6'30"E in Universal Transverse Mercator (UTM) and lie in zone 37 north covering total area of 810 km^2 (Fig 3.1). Dire dawa town is 515 km from Addis Ababa the capital city of Ethiopia and 333 km from the international port of Djibouti.

Except the south and south east part which is rugged the rest of the area accessible by taxi, hose-wheel. The main road from Addis to Djibouti crosses in the centre of the study area and there are also other asphalt roads which join this main road. Beside these there are so many foot paths from different villages that join the asphalt roads.

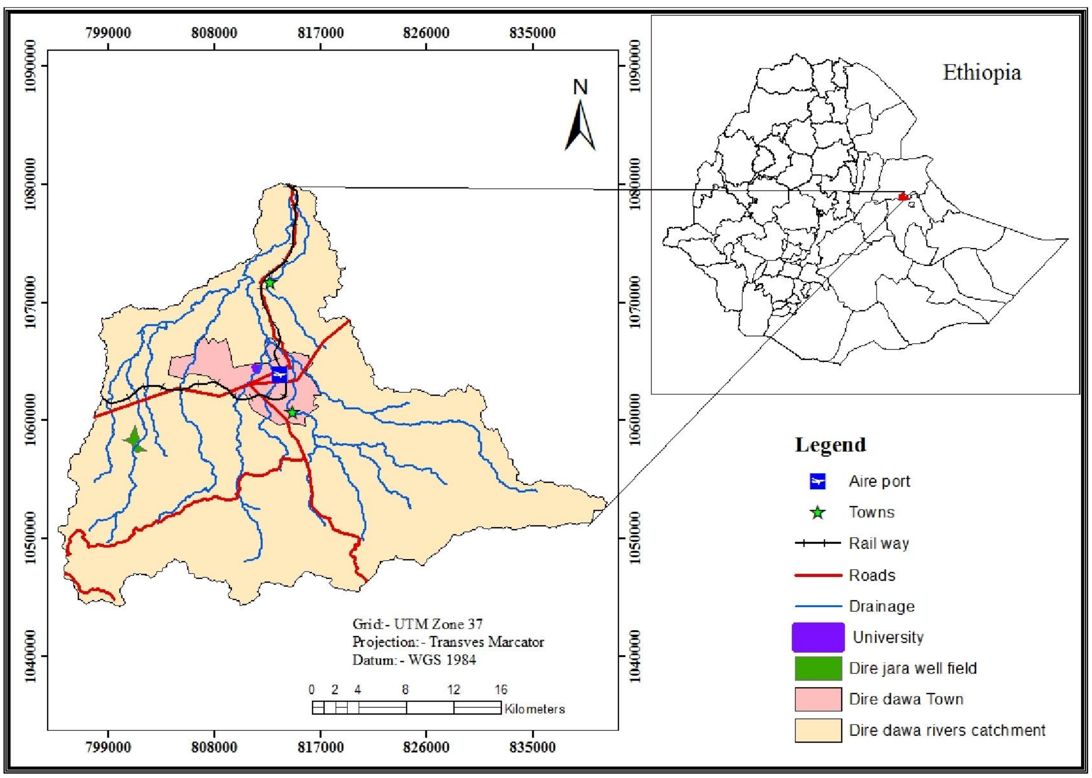

Figure 3.1. Location Map of the study area

3.1.2 Physiography and Drainage

The Dire dawa rivers catchment is located in Awash river basin at the southern margin of the afar depression so that physiography of the area is mainly controlled by volcano-tectonic rather than erosional activities. The area has very diverse spatial variation of topographic features. It ranges from very steep high mountains to flat plains with the general topography direction from south towards the north. According to Minalah Bushra (2007) it is characterized by successive short running E-W oriented step faults forming half graben and horsts. The aggregates come from the higher graben by the runoff is dropped at the toe of the horst towards the north. The elevation of the area is varies from more than 2300m at Dangago to below 1000m at the north part of Shinile (Fig.3.2). Geomorphologically the area is categorized into three major features as escarpment, the transitional and the alluvial plains.

The escarpment area is characterised by steep slopes, gullies and dry wadies mainly underlain by sedimentary and basement rocks. In these areas runoff is high due to the steep slope and the rock surfaces permitting low retention period.

The transitional areas are mainly characterised by small outcrops of sedimentary rocks, basalts and some recent coarse alluvial sediments. In this area the topography is gentle and the rocks are close to the surface.

The alluvial plains are characterised by gentle to flat topography. Except some volcanic hills of younger age, the Mesozoic and the tertiary rocks are buried deep inside the sediment.

In Dire dawa rivers catchment there is no large rivers which flow throughout the year. The presence of high relief in the area made it dissected by many tectonically controlled small intermittent rivers, which are tributaries to the main perennial river Awash. All rivers run from the southern high lands of Kulubi and Dengego towards the low land of northern Shinile town. Because of the faults and faulted blocks the drainage has generally rectangular drainage pattern in the mountains but the overall drainage pattern of the study area is dendritic drainage pattern. The most important intermittent and perennial streams that drain the Dire Dawa region are Dechatu, chacho, Lege Hare, Dube, Goro and lege Oda. Among the main intermittent streams in the Dire dawa region; Dechatu, cherecha and lege Oda are the major one where most of the precipitation as run-off from the south (escarpment zone) drains into it. Although this stream is dry for the most part of the year, it carries very large flow in the rainy season (WWDSE, 2004).

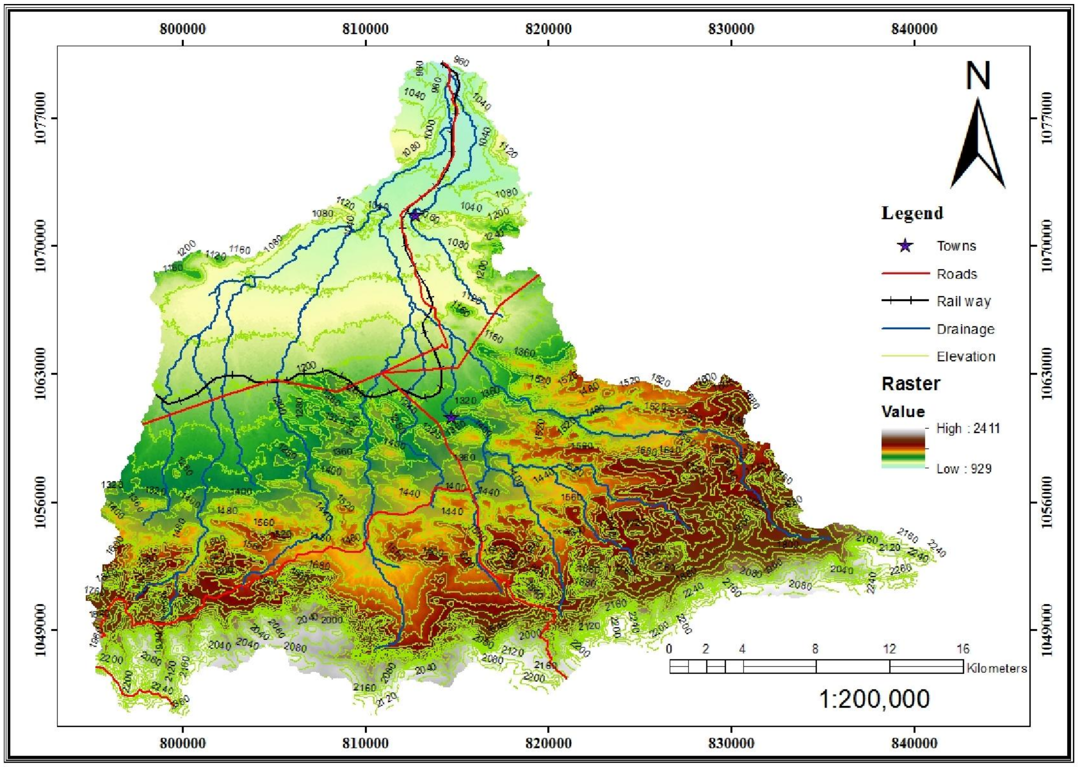

Figure 3.2. Elevation and Drainage map

3.1.3 Climate

Dire dawa rivers catchment is situated in Kola agro-climatic region; the temperature of the area is increasing from south margin of mountainous area towards northern flat alluvial plains. Generally the temperature of the area is hot throughout the year with small seasonal variations. The mean monthly maximum temperature is varies from 28.9°C to 35.7°C in January and June respectively. The mean monthly minimum temperature is varies from 15.3°C to 22.5°C in January and June respectively. June, May and July are the hottest month of the year; whereas January, February, November and December are the coldest (Fig. 3.3).

The area gets rainfall in two seasons as 'Meher'(autumn) and 'Belg' (winter) which separated by a short dry spell in June and seasonal rainfall has a bimodal distribution with peak in April and August. The mean annual rainfall of Dire dawa station is 49.2mm and mean monthly values varies between 6.06mm (February) and 120.26mm (August), which indicate poor temporal distribution of rainfall (Fig. 3.4). As shown in the (Fig.3.5) the trends of rainfall in the Dire dawa for 15 years shows that there is high precipitation in

1996 but in 2000, 2005, 2008 and 2009 minimum precipitation is recorded. In Dengago station there is higher precipitation in 1997 and 2001; but in Kersa station the highest and lowest precipitation is recorded in 1996, 2001 and 1997, 2002, 2004 respectively. Generally the graph shows there is decreasing in precipitation areal wise from high land to low land and from 1995 to 2009; this is due to decreasing in elevation from Kersa to Dire dawa and fast climatic change occurring throughout the world.

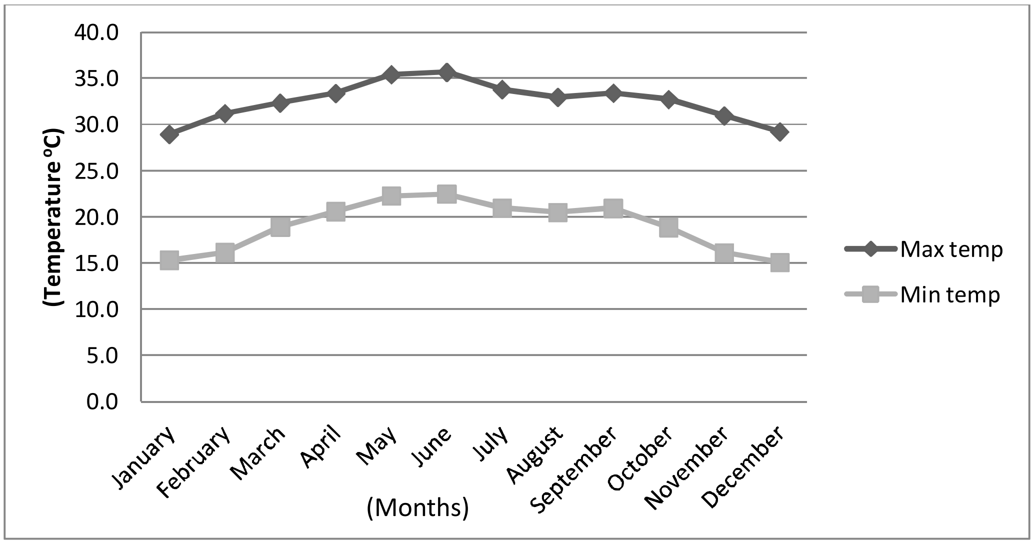

Figure 3.3. Mean monthly temperature of Dire dawa station from (1995-2009)

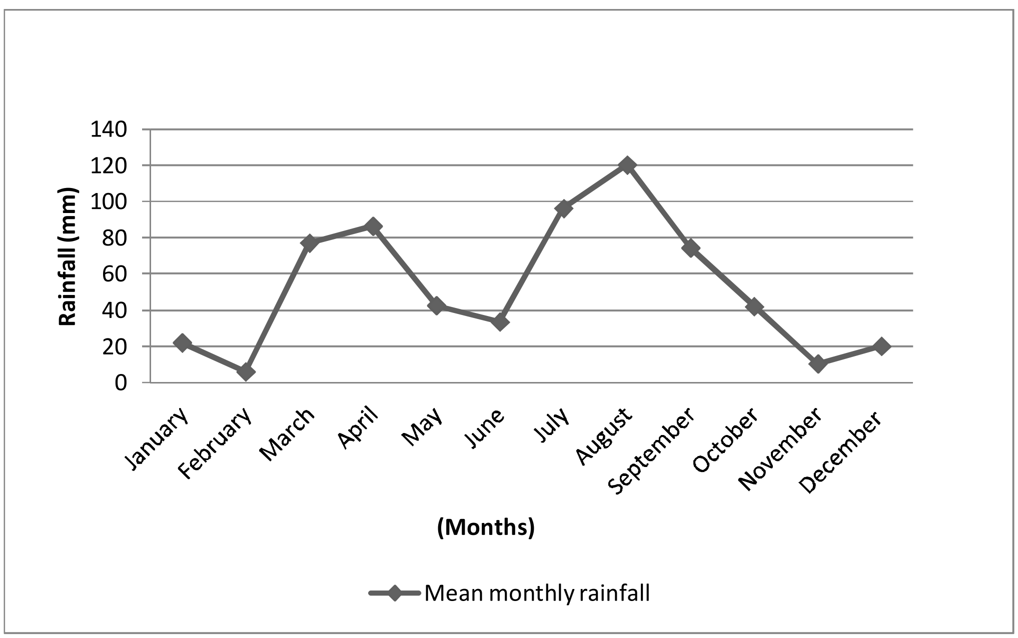

Figure 3.4. Mean monthly rainfall at Dire dawa station (1995-2009)

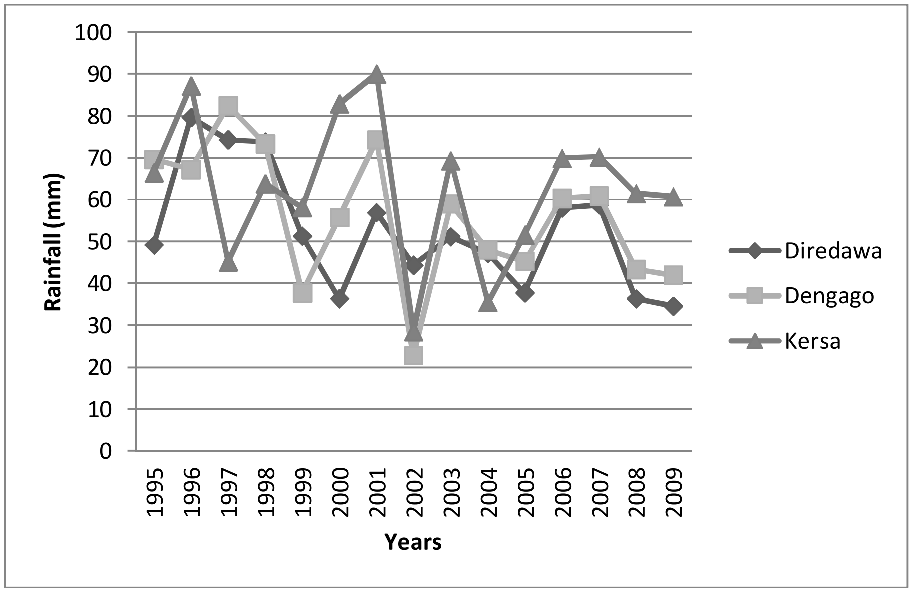

Figure 3.5. Mean annual rainfall trends of Dirw dawa, Dengago and Kersa station (1995-2009)

3.2 Material and Methods

The methodology employed to achieve the above objectives is summarized in the flow chart in (Fig.3.6). It involves extraction of the study are, slope and drainage from SRTM using spatial analysis tools in arc GIS, digital image processing using ERDAS Imagine 9.2 software and visual interpretation of ETM+ data for the extraction of lineament and land use / land cover. Soil and lithology are extracted from FAO and geological map done by Geological survey of Ethiopia respectively, but depth to water levels are prepared from log data and well inventory. Field studies are conducted for collection of GCP points and ground truth data for accuracy assessment of different land use classification and geographic correction of satellite image. All data were integrated in a Geographic Information System (GIS) using ArcGIS 10.1 software and analyzed to assess the groundwater controlling features. Finally groundwater potential maps were prepared based on the GIS analysis. The data and material used in this study are generalized in the (Table 3.1).

Table 3.1. Data, their sources and material used

Area	Data	Data type	scale	Data sources
Dire dawa Rivers Catchment	1. Boundary, drainage, geomorphology and slope	SRTM	30m	AAU
	2. Top- sheet	NC 37-12 and NC 38-9	1:250,000	EMA
	3. Land use/ Land cover	Landsat ETM+ 2011(166/053)	28.5m	Private sell
	4. Rainfall	Rainfall records	1995-2009	NMA
	5. Lithology	Geological map	1:250,000	EMA
	6. Soil	Soil map		
	7. Log and well discharge	drilling core record and well inventory	-	WWDSE
	Material Used			
	1. ArcGIS10.1	-	-	AAU
	2. ERDAS Imagine 9.2	-	-	AAU
	3. IDRISI Andes 15.0	-	-	AAU
	4. Global Mapper 11	-	-	AAU
	5. 3DEM	-	-	AAU

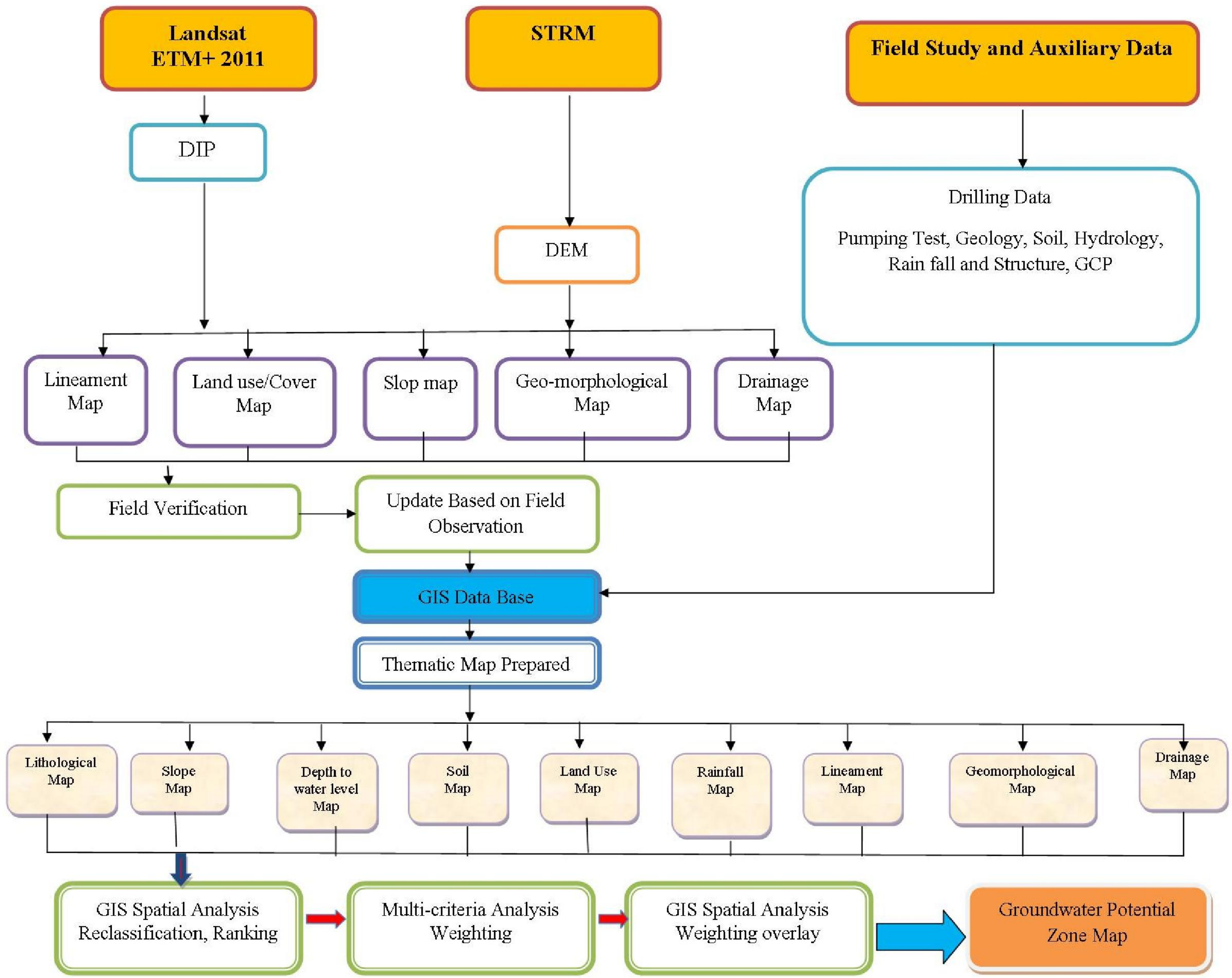

Figure 3.6. Methodology flow chart

3.3 Remote Sensing and Application of GIS Analysis for Groundwater Exploration

3.3.1 Remote Sensing Analysis

3.3.1.1 Study Area Delineation

The study area shape is prepared through different stages by GIS platform from SRTM data of 30m resolution. In this process the SRTM is exported to DEM using Global mapper 11 and then patched for missing data on 3DEM. After data conversion hydrological analysis is takes place to delineate river basin following these stapes: - raster to flow direction to basin to polygon finally Dire dawa rivers catchment extraction.

3.3.1.2 Image Processing

Image processing is a vital part of most remote sensing operations. All digital imagery must be processed in some way in order to be used in the vast majority of applications. Digital image processing involves the manipulation and interpretation of digital images with the aid of a computer (Lillesand *et al.,* 2000).

In this study only three types of digital image processing operations were used: layer stacking, image rectification and restoration (preprocessing), image enhancement and image classification. The first part of image processing is usually known as pre-processing, since it must precede most other image processing operations. The amount of pre –processing required will vary with the sensor type and the quality of the digital data, and also for which application the imagery will used. Pre-processing is aimed at correcting distorted or degraded data to create a more faithful representation of the original scene. This typically involves the initial processing of raw image data to correct for geometric distortions, to calibrate the data radiometrically and to eliminate noise present in the data (Fundamentals of Remote Sensing). During layer stacking, the Universal Traverse Mercator (UTM) system with WGS 84 as a datum was assigned as a preference as far as projection is concerned. All seven bands of ETM+ were considered for Layers stacking. After layer stacking, all the scenes have the same co-ordinate system UTM Zone 37 North using WGS 84 as a datum.

3.3.1.3 Image Enhancement

Image enhancement is one of the image processing techniques which make an image ready for more interpretation in a particular application and also makes important features of raw, remotely sensed data more interpretable to the human eye.

The following image enhancement techniques where used before image classification was performed.

I. **Contrast Enhancement: -** is used to increasing the contrast between targets and their backgrounds by changing the original values using more available range. From contrast enhancement techniques linear contrast stretch where used to identify the lower and upper bounds from the histogram and applying a transformation to stretch this range to fill the full range. This makes the contrast in the area having light tone appears lighter and dark areas appears darker which implies visual interpretation much easier.

II. **Spatial Filters**: - are used to highlight specific features in an image based on their spatial frequency. The types of spatial filters applied in this study are low-pass and high-pass filter. Low-pass filter reduce the smaller detail in the image and give stress to larger, homogeneous areas of similar tone and results to smooth the appearance of the image. In the opposite the high-pass filter sharpens the appearance of fine detail in the image.

III. **Directional or Edge Detection Filter**: - is used to highlight linear features, such as roads or field boundaries and also be to enhance features which are oriented in specific directions. These filters are mostly useful in applications as extraction of geological structures (fundamental of remote sensing).

3.3.1.4 Image Interpretation and Classification

Different image interpretation elements were used to distinguish variations among features. For instance pattern, tone, shape, size association and texture ware used for effective of land use/cover classification.

Classification is one of the digital image processing that is very useful for different land use land cover mapping. The analyst that is classifying an image must distinguish between spectral classes and information classes. Spectral classes are groups of pixels that have nearly uniform spectral characteristics. Information classes are the various groups that the analyst is trying to identify in an image. Information classes may include classes such as deciduous and coniferous forests, various agricultural crop types, etc. Each object has unique and different characteristics of reflection or emission in different environment as a result an object can be identified using reflected /emitted electromagnetic radiation from that object (Billah *et al.,* 2004).

Remotely sensed datasets provide useful thematic information and extracting thematic information from the data is obtained through image classification. There are variety of techniques for extracting thematic information from an image. From these Unsupervised and supervised image classifications are the most frequently applied classification techniques in remote sensing.

For accurate image classification, band selection also crucial since one feature which is not discriminated apparently may be clearly differentiated on another band. For this purposes Interpretation and classification was carried out by utilizing FCC and TCC. The Landsat ETM+ 2011 image has seven bands with a spatial resolution of 28.5 m and additional one panchromatic band which is merged to improve a spatial resolution of the features to 15m and similar color composite (4:3:2 FCC and 3:2:1 TCC band combination) has been used for the LULC classes mapping (Fig.4.5). The false color composite and object based supervised classifications were done using ERDAS Imagine 9.2 software. Ground truth data which were collected during field survey were used for supervised image classification using the algorithm of Maximum likelihood classifier.

3.3.2 Data Integration and Analysis in GIS Environment

Various favorable groundwater thematic maps have been integrated into a single groundwater prospect zone with the application of GIS techniques. It required mainly three steps.

1. Spatial data base building
2. Spatial data analysis
3. Data integration

3.3.2.1 Spatial Data Base Building

In the Arc GIS software catalogue, tools have been provided to create the features data sets, tables, geometric network and other items in data base. Following methods have been used to create thematic map.

I. Digitization of scanned maps (geological map)
II. Editing for errors
III. Topology building
IV. Attributes assignment
V. Projection

3.3.2.2 Spatial Data Analysis

It is an analysis technique using study of locations of geographic phenomena together with their dimension and associated attributes, table analysis, classification, polygon classification and weight classification. All thematic maps like geology, geomorphology, lineaments, drainage, slope, rainfall, soil, aquifer thickness and depth to water levels have been converted into raster. Each thematic map is considered and assigned a weight depending on its influence on groundwater recharge and storage. For example geology plays a prominent role in groundwater prospect than lineament hence higher weight given to geology.

3.3.2.3 Data Integration

Each thematic map such as geology, geomorphology, lineaments, drainage, slope, rainfall, soil, aquifer thickness and depth to water levels provide certain clue of groundwater occurrence. Each theme is overlain on other theme to find the intersecting polygons. By this method a new map is obtained which is an integrated feature of two thematic maps. This composite map is overlaid by a third map, then fourth and so on, so that final composite map is obtained. In the final weight of the polygons, the final integrated layer was obtained using simple arithmetic model which has been adopted to integrate various thematic maps.

3.3.2.4 Interpolation

Interpolation is Geostatistical Analysis in which point source collected was interpolated and thematic map was prepared. The data for rainfall and temperature was interpolated using inverse distance weighing method and depth to water level by kriging, as this method is more appropriate in the data sparse regions. IDW assigns weights to neighboring observed values based on distance to the interpolation location and the interpolated value is the weighted average of the observations. IDW is applied in many precipitation mapping methods (e.g. Rudolf and Rubel, 2005; Frei and Schar, 1998). The IDW method is an example of a deterministic interpolation method. Statistical interpolation methods like Kriging are optimal in a statistical sense, but not strong in data sparse regions.

The main objective of the study is to generate groundwater potential zone of Dire dawa rivers catchment by assessing groundwater controlling features and preparing different thematic maps considering their relevance to groundwater occurrence. In order to produce the potential groundwater zone map, detailed GIS analysis of nine thematic maps was conducted. Using GIS environment all maps were rasterized, reclassified and given appropriate rank based on the weight generated on IDRISI 15.0 Andes platform and weighted overly in order to get groundwater potential map of the area.

To generate the final map various steps have been followed, these stapes are explained as follow:

i. Selection of data for an input, based on their groundwater controlling parameters.
ii. Each data set that was produced from previous work, remote sensing imagery, digital elevation model (DEM) and field observation were imported into geodatabase to have the same spatial reference.
iii. All data sets were then converted into raster in order to perform different GIS analysis between data layers such as reclassification, data conversion for weighing analysis on IDRISI platform and overlay analysis.
iv. All data sets were reclassified based on their importance to groundwater occurrence and integration of the data sets, individual class weights and map scores were assessed based on Satty's Analytic Hierarchy Process (AHP) (Table 3.1); in this method the relative importance of each individual class with in the same map and factor maps are compared each other and important matrices are produced with calculated weight using decision support of IDRISIS 15.0.
v. After a pair-wise comparison of each factor maps based on their influence to groundwater occurrence a single matrix (Table 6.1) with calculated weight of each factor map was produced.

vi. Finally weighted overly in GIS spatial analysis is used to overly all factor maps based on their weights to delineate groundwater potential zone of Dire dawa rivers catchment.

3.4 Multi Criteria Analysis

3.4.1 Weighting and Map Score

In MCA techniques numerical analysis apply to a performance matrix in two stages such as scoring and weighing. Scoring is the process of assigning the numerical scale for each option on the bases of strength of the preference of each criterion. More preferred options score higher on the scale, and less preferred options score lower. Weighting is assigning the predefined numerical scales to the computer according to their preference to achieve the objective of the study and leave the decision to the computer. After processing is takes place the weight of each options are given with their consistence ratio. (Multi-criteria analysis: a manual)

According to Eastman (2001) Multi-Criteria Evaluation is the process of applying a decision rule to a set of alternatives. A decision rule is a procedure by which criteria are combined to arrive at a particular evaluation, and by which evaluations are compared and acted upon.

To determine the relative importance or weights of each thematic map and with another, paired-comparison matrix was prepared by pair wise comparison on Satty’s importance scale (Table 3.2). These matrices have the property of consistency known as consistency ratios (CR). Satty indicates that the matrices with CR ratings greater than 0.1 should be re-evaluated. This way it helps to analyses the matrix to determine the inconsistency in defining the interrelationships. The weights were normalized by multiplying with 100 to avoid complexities of computation. These weights were applied in linear summation equation to obtain a total weight of each input factor map, which was further reclassified to arrive at groundwater potential map.

In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. For example, a decision may need to be made about which areas are the most suitable for groundwater exploration. Criteria might include drainage density, slope gradient, land use land cover, geology, and so on.

Suitable weights were assigned to all themes and their individual features after understanding their importance in causing groundwater occurrence in the study area. The normalized weights of the individual themes and their different features were obtained through the Satty's analytical hierarchy process (AHP). The weights assigned to different themes are presented in (Table 6.1) and the process of obtaining the normalized weights of the themes is presented. The weights assigned to different features of the individual themes and their normalized weights are presented under each factor map.

Table 3.2. Pair-wise comparison of 9 point continuous rating scale developed by (Satty, 1977)

1/9	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
Less important					More important			

4. GEOLOGY AND HYDROGEOLOGY

4.1 Geological Setting

4.1.1 Regional Geology

Ethiopia has different geomorphic setting in which various lithological unit exposed throughout the country. It varies from place to place by their formation, age and degree of the process applied on them. Based on stratigraphy and tectonic activities of surface exposure the regional geological units of the eastern part of the country as well as the study area can be classified in to four main geological units (Minaleh Bushra, 2007) and the geological events are summarized in (Table 4.1). Outcrops of Precambrian rocks, Adigrat sandstone, Hamanalei limestone, Upper sandstone and Basalts mostly covered the escarpment while the down thrown plain is dominantly covered by alluvial deposits. Both the plains and the escarpment are highly dissected by east-west trending faults as it observed from (Fig 4.2) (Abate Eyilachew, 2007).

In terms of their surface exposure, the main lithologic units of the eastern part of the country have been grouped as follows (Tamiru Alemayehu, 2006).

- i Precambrian metamorphic basement rocks
- ii Mesozoic sedimentary rock
- iii Tertiary volcanic rocks (largely basalts) and
- iv Quaternary volcanic rocks, largely ignimbrites and sediments

Generally the regional geology is described based on their regional stratigraphic position, form the older to younger as follow:

4.1.1.1 Precambrian Metamorphic Basement Complex Rocks

Precambrian rocks are the oldest of all rocks present in our country and the study area. It exposed in southern, south western and south eastern part of the area and composed of high grade gneisses and migmatite of lower complex. Practically this type of rock is impervious but it can hold little amount of water in their fracture and weathered part (Habteab Zeray and Sima Jiri (1986).

4.1.1.2 Mesozoic Sedimentary Rock

The complete sedimentation is takes place from the end of Precambrian to Jurassic. The crust was uplifted at the end of Precambrian and the pre-existing rocks are weathered, eroded and deposition of very few sedimentary rocks. In Cenozoic period the shallow sea starts to spread over the Ogaden region and extended to northern and western part of the country. The sand stone which deposited in shallow water on old land is overlaid by shale and limestone as depth increased during transgression and the upper sand stone (Amba Aradam sand stone) is deposited during regression events (Minaleh Bushra, 2007). Generally Mesozoic sediments of the study area are grouped in to three formations as Jurassic Adigrat sandstones, Jurassic Hamanlei limestone and Cretaceous Amba-aradam sandstones.

4.1.1.3 Tertiary Volcanic Rocks

The Tertiary volcanic rocks mapped in the study area are trap volcanoes of transitional basalts, which comprise Alaji basalts and the upper part of Stratoid basalts of the Afar group (Seife Mikael Keleta, 1985).

4.1.1.4 Quaternary Volcanic Rocks

In quaternary is dominated by fluvial activities and young volcanic eruption events which lead to the formation of alluvial deposits and basic volcanic rocks. The area has undergoes several tectonic events. After the volcanic ash is erupted and deposited the lower part is compacted, as a result it changes to welded tuff and at last to ignimbrites. The study area consists of three tectonic events as escarpment, plateau and depressions. Due to the weathering process of exposed escarpment rocks, the sediments are eroded and transported by the rivers and streams downward from escarpment. These built large alluvial deposits. Course grained sediments are deposited at the foot of the escarpment, while the fine grains in the plain areas of the catchment. From quaternary rocks it is only sediments which are exposed in the area; they consists of alluvial sediments, lacustrine deposit (travertine) and river sand deposit (WWDSE, 2003).

Table 4.1. The generalized geological events of the study area.

Chronology		**Events**	**Litho-logical formation**
Cenozoic	Quaternary	Fluvial activities and young volcanic eruptions	Alluvial deposits and basic volcanic rocks
	Pliocene	Volcanic eruptions and rift formation	Pyroclastic and lava deposits
	Tertiary	Uplifting	Trap volcanoes
	Miocene	erosion	
	Eocene		
	Paleocene		
Mesozoic	Cretaceous	Regression	Upper sandstone
		Transgression	Antalo Limestone
	Jurassic		Adigrat sandstone
	Triassic		
Paleozoic			
Precambrian		Intrusion and metamorphism	High grade metamorphic rocks

(Source: Minaleh Bushra, 2007)

4.1.2 Geology of the Study Area

As explain above local geology of the area is also described based on their regional stratigraphic position, form the older to younger as follow and (Fig.4.1) shows nine geological formations that exposed in the area.

4.1.2.1 High Grade Gneisses and Migmatite

This formation is the metamorphic rocks of Precambrian age underlies with Adigrat sandstone and also Hamanlei limestone at the absence of sand stone. It is mainly exposed the southern margin and south eastern parts of the study area (Plate 4.1).

Plate 4.1. Basement rocks exposed at southern escarpment along the road from Dengago to Dire dawa.

4.1.2.2 Adigrat Sandstones (Lower Sandstones)

Adigrat sandstone is a Triassic to lower Jurassic in age which can be formed by transgression events of the sea from Ogaden to north and southern part of the country. This formation is underlie by basement complex and overlie by Hamaneli lime stone. It is fractured, medium to course grained and red to brown in color with a thickness of not more than 20 meter (Abate Eyilachew, 2007) and exposed in southern part under the foot of escarpment as well as in the transitional area of the catchment (Plate 4.2).

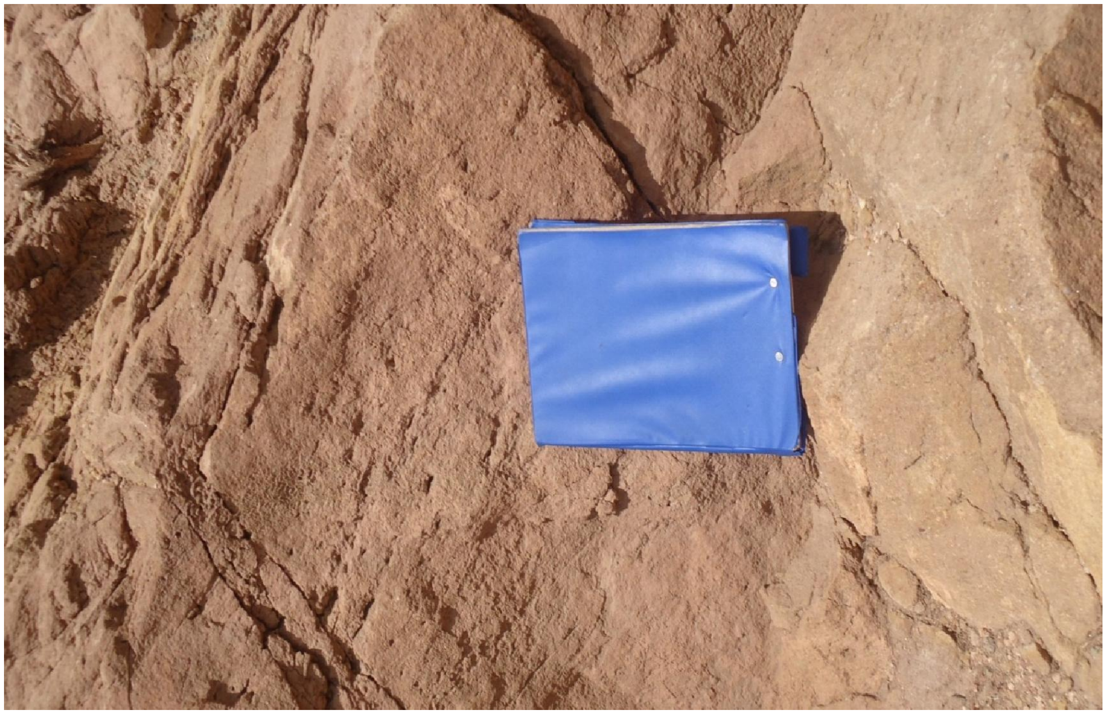

Plate 4.2. Adigrat sandstone

4.1.2.3 Hamanlei Limestone

Hamanlei lime stone is formed during Jurassic period as the sea transgressed and the depth increased and varies in thickness up to 200 meter. This formation is underlies by Adigrat sand stone and overlie by upper sand stone which created because of the sea regressed (WWDSE, 2003). Mainly it is exposed in the central, south west and south east part of the study area and highly fractured by normal fault of Precambrian and tertiary period (plate 4.3). The Hamanlei lime stone together with Upper sand stone, they make the main water bearing horizon of the study area. It composed of alternating layers of Shales and Chocks at the lower part and brown to grey color in the upper part and unconformably overlies Precambrian rock in the area where Adigrat sand stone absent (Minaleh Bushra, 2007).

Plate 4.3. Limestone exposed around national cement factory

4.1.2.4 Amba-Aradam (Upper) Sandstones

The Amba aradam sand stone/ upper sandstone/ is the upper Jurassic and lower cretaceous formation which is unconformably overlies the Hamanlie limestone and underlies with alaji basalt. It has various thicknesses from 150 to 200 meter and composed of quartz sandstone (Minaleh Bushra, 2007). This formation is exposed in the central, north eastern and south western margin of the study area (plate 4.4). It is the main water bearing horizon of the area.

Plate 4.4. Amba-aradam (upper) sandstones formation

4.1.2.5 The Alaji basalt

Alaji basalt a Tertiary basalt and unconformably overlying the Amba Aradam sandstone and mainly consists of a phyric flood basalts associated with rhyolites and subordinate trachytes (Kazmin, 1979). This formation is exposed in the western, northeast southwestern margin of the catchment.

4.1.2.6 The stratoid basalt

This formation is exposed in northern and north western part of the study area and represented by the upper part of Afar series of recent age (Minaleh Bushra, 2007). It is most likely fissural eruptions and serves as a barrier for the surface run off and cover small area of the catchment.

4.1.2.7 Alluvial Sediments

The alluvial sediment is the quaternary age deposits which mainly cove the lower elevation of the area (WWDSE, 2003) (Plate 4.5). It is the product of weathering of exposed rocks in the area and eroded and transported by the means of river and stream flow and finally deposited in gentle plain mostly at the northern half of the catchment.

This deposit consists of boulder, coarse grain gravel, sand, silt to clay size rock of metamorphic (basement), sedimentary, sandstone, limestone and basalts with variable thickness.

Plate 4.5. Alluvial Deposit at the Melka Jebdu

4.1.2.8 Travertine

Travertine is a lacustrine deposit of quaternary rock out cropped in Dire Dawa and Melka Jebdu area. This rock is associated within the alluvial sediments and occupies small areal extent. Mostly it is used for construction of houses and fences (WWDSE, 2003).

4.1.2.9 River Sand Deposits

River sand is the weathered producers of the rocks within the catchments of the main stream and their tributaries. It is the most recent sediments which deposits in the flood plain of the large rivers and significant deposits are associates with Goro, Dechatu and Lega Hare intermittent stream (Plate 4.6). This sediment is exposed in the river plain crossing the middle of the catchment flowing towards in the north direction.

Plate 4.6. River sand at the right side of the road from Dengago to Diredawa

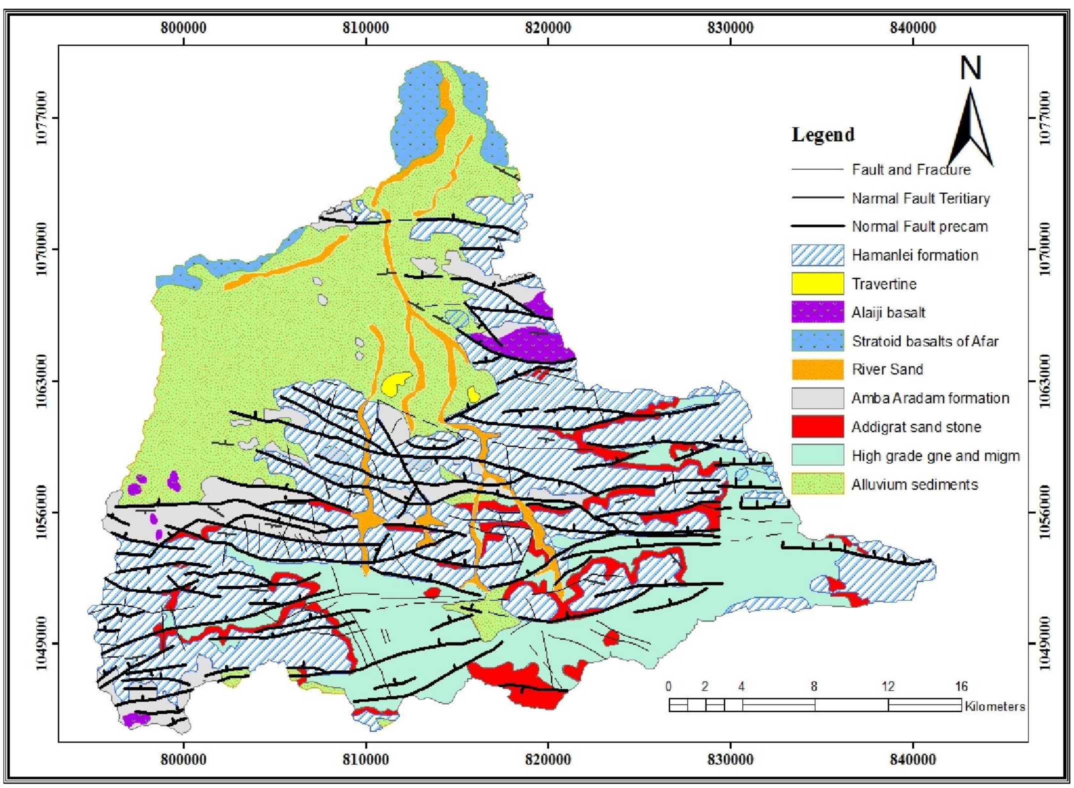

Figure 4.1. Geological map

4.1.3 Geological Structure set up

In Miocene the great East African Rift System started to develop from the Red Sea and Gulf of Aden Rifts and join with the younger and continental Main Ethiopian Rift (MER) at Afar Triple Junction (Afar Depression) Huchon (1989, as cited in Minaleh Bushra, 2007). The study area is located in the south-eastern escarpment of the Afar Depression. The structural features which are dominantly found in this area are fault. There are various faults which strike east west forming normal faults down-thrown towards north with steep to gentle dips. The general trend of these faults is related to the main rift system. These faults are visible only in the escarpment and transitional area; there is no visible fault indication in the northern plain. As explain above the area consists of three tectonic units: the plateau, the escarpment and the depression. Most of study area faults are easily visible in Hamanlei limestone (Fig.4.1). The escarpment is dominated by E-W or ENE-WSW trending faults. They strike east west in the south and east, gradually change to ESE-WNW towards the NW and W. Some NW-SE trending cross faults are common in the central part of the basin. These structures are grouped in to three; E-W strike Precambrian faults, E-W and NW to SE strike tertiary fault and small fracture and faults which are exposed in central, south and south west part of the study area. E-W strike Precambrian faults are visibly exposed in north eastern, central, south, south eastern and south western part forming the series of graben and horse down to the north direction while E-W and NW to SE strike tertiary fault are distributed in north east and transitional area between escarpment and plain dipping towards north, south and north east of the catchment (Fig.4.2). The presence of structures as fault in the rock optimizes the storage, transmissivity and recharge, particularly when they occur adjacent to or within surface drainage system.

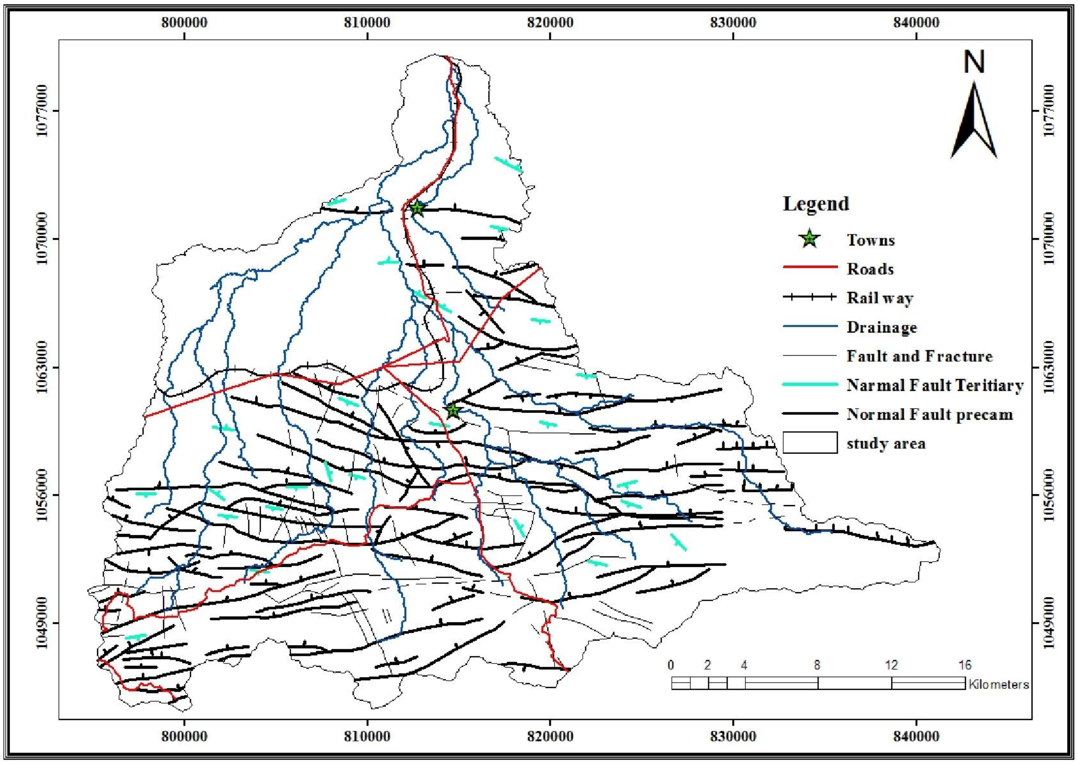

Figure 4.2. Structural map

4.2 Hydrogeology

The hydrogeological study mainly attempts to obtain the general groundwater condition of the area. The Dire dawa rivers catchment is found at the eastern margin of the Awash River Basin. The geological formation and hydrogeological conditions of the area is a function of geomorphology, on the escarpment outcrops as pre-Cambrian Basement rocks, Adigrat sandstone, Hamanalei limestone, Amba-aradam sandstones, Alaji and Stratoid basalts, the down thrown plain (foot of the escarpment) is dominantly covered by alluvial deposits. Both the plains (down thrown block) and the escarpment are highly dissected by east-west trending faults. The groundwater occurrence, distribution and flow regime is highly governed by topography, tectonics, geological formation and aerial relationship of the geological formation (Fig. 4.3). Based on these major factors, Dire dawa rivers catchment can be classified into two groundwater systems i.e. the escarpment and the foot of the escarpment (down thrown plain) (WWDSE, 2004).

I. The Escarpment Groundwater

The escarpment occupies the southern, southeastern, southwestern and central parts of the catchment. It is highly rugged areas and intensively faulted by east-west trending Precambrian normal faults (Plate 4.7). Geologically the Hamanei formation is exposed in southwestern, central, eastern and southeastern part, basalt rocks are distributed in Northwestern, northeastern and small areas of western and southwestern part, sandstones are dominantly occupied in southwestern, southeastern and northern parts and the basement rock is occupied south and southeastern parts of the catchment. From analysis of the ground water point inventory, which was carried out from (August to September 2002) the groundwater potential of the escarpment is estimated to be about (4.8 MM^3/year) (WWDSE, 2004). This area is dominated by the spring and hand dug well and cannot provide potential water for the society.

Plate 4.7. Escarpments at the right side of the road from Dengago to Dire dawa

II. The down thrown plain (foot of the escarpment)

The foot of the escarpment (down thrown plain) occupies the northern part (plains) of the catchment from the center of the study area, Dire Dawa town along Melka Jebdu and Haseliso (Plate 4.8). This area is considered to have high groundwater potential, where Dire Dawa town water supply source is found and the future water supply source of Harare town is located. Distribution and the groundwater occurrence in the basin is mainly a function of the geological units, geomorphology and tectonics. This is because of the basin is covered by alluvial deposited, limestone and sandstone which is pores to store and permeable to transmit water through them.

The groundwater recharge of the basin is estimated about (31BM^3/year) (WWDSE, 2004) for both alluvial, upper sandstones and limestone aquifers but the basement rocks are limited to the fractured zones and used only for shallow hand dug well.

Plate 4.8. Foot of the Escarpment around Harilla Village.

4.2.1 Alluvial Sediment Aquifers

The alluvial aquifer extensively occupies the North of the catchment and composed of varies size sediment deposit as clay, silt, sand, gravel and rock fragments. The occurrence of groundwater in this formation is limited along the alluvial fans and river channel deposits. The thickness of the alluvial sediment varies from 8.5 to 237 meters and the ground water depth varies from 5 to 45 meters. The discharge of wells from this formation varies from dry to a specific well discharge of 7.2 l/s/m at Unive oil of BH-124. The transimissivity of the alluvial formation varies from 8 to700 m2/day, and the maximum transimissivity is registered at Shinile (WWDSE 2004).

4.2.2 Tertiary Volcanic Rocks

Tertiary volcanic rocks in the study area are mainly Stratiod basalts and Alaji basalts outcrops that occupy the elevated areas at the north, northeastern and with very small area extent at west and southwestern part. Most of boreholes drilled on the basalts are practically dry except some areas as Cheremiti and Jeldesa having 0.4 l/s.

4.2.3 Upper Sandstones

The upper sandstone outcrops in a small aerial extent at Haseliso, north of Dire Dawa at the airport and Northwest of Dire Dawa town. The investigation results of the drilled test wells showed that the upper sandstone forms a strip aquifer extending from Serkama (outcrops) to Dire Jara (overlain by alluvium and basalts). The width of the strip in north direction from the foot of the escarpment is estimated in average about five kilometers. As the drilled well data shows the thickness of this aquifer is various from 36meter at dire Jara (w-4) wall field to 108 at TW4. At TW4 the groundwater was strike at 98 meters depth and the static water level stabilized at 31 meters, in the Dire Jara well groundwater was strike from 100-120 meters and the static water level is stabilized at 50 to 60meters below the ground surface. The static water level of the catchment is varies from 9.3 meters at Sabiyian to 69.3 meters at Dire Jara with the specific well discharge of 0.13 to 68.97 l/s/m. In general from the information gathered from drilled well about the aquifer is that it is confined aquifer (WWDSE 2004).

4.2.4 Hamanalei Lime Stones

The Hamanlei limestone outcrops in the Dire dawa rivers catchment at the central, southwestern, south eastern and northeastern part having larger aerial extent. Drilling results show that the limestone unconformably underlies the upper sandstone. The limestone at Dire Jara area is highly fractured and karsted and forms complex water bearing formation together with the upper sandstone, whereas at the Dire Dawa town area the lime stones are massive of low groundwater productivity.

Hydrodynamic condition of the geological formations

As explained above groundwater resource distribution in the area is governed by the topography, in addition to the water bearing lithology. The aquifers are categorized in to two classes:

Group 1: Aquifers on the escarpment

Group 2: Aquifers in the Rift Valley

The hydrodynamic parameters of the two groups of the aquifers are summarized in (table 4.2).

Table 4.2. Hydrodynamic Parameters of Aquifers in Dire dawa rivers catchment

a) On the escarpment (characterized by springs yields)

Aquifer	**Aerial extent**	**Type of aquifer**	***Yield l/s***		**Productivity**
			Range	**Mean**	
Alluvial sediments	Localized along river channels	Intergranular, unconfined	1.0-25.3	7.5	Moderate
Basalts	Localized	Fractured, unconfined	0.3-3.0	1.7	Very Low
Upper sandstones	Localized	Fractured	2.0	2.0	Low
Hamanalei lime stones	Extensive	Fractured, confined	0.2- 30	14.0	Moderate
Basement rocks	Localized	Weathered and fractured, unconfined	0.4-4.0	1.6	Very Low

b) In the down thrown plain (foot of the escarpment)

Aquifer	Aerial extent	Type of aquifer	Hydrodynamic parameters						Productivity of aquifer
			Yield l/s		*Specific capacity l/s/m*		*Transimissivity m2/day*		
			Range	Mean	Range	Mean	Range	Harmonic - mean	
Alluvial sediments	Extensive	Intergranular, unconfined	0.0-6.5	3.1	0.0-3.19	0.68	7.8-712.8	27.5	Moderate
Basalts	Localized	Fractured, unconfined	0.0-1.9	0.73	0.0-0.01	0.01	2.4-9.9	5.7	Very Low
Sandstones and lime stones	Extensive	Fractured, confined	0.6-45.4	14.0	0.13-68.97	7.7	9.0-5512.0	88.0	High

(Source: WWDSE, 2004)

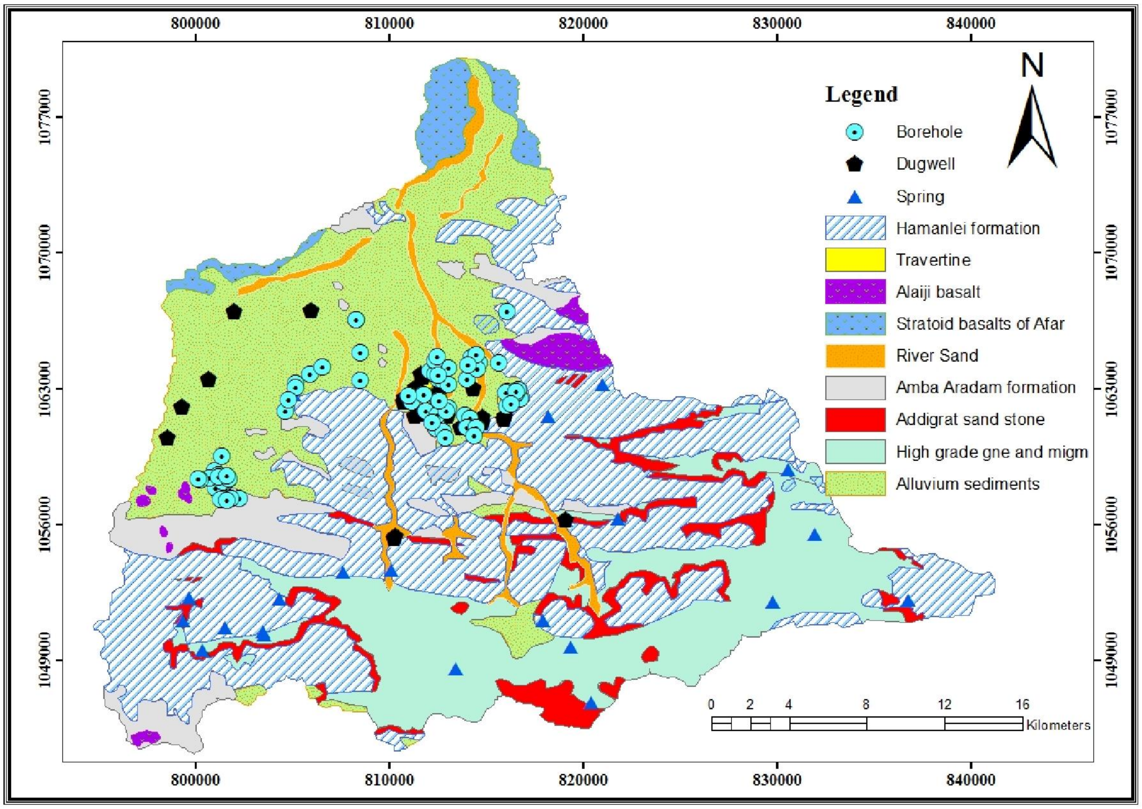

Figure 4.3. Location of water points

4.3 Groundwater Recharge Mechanism

Recharge may occur naturally from precipitation, rivers, canals, lakes, as man induced phenomena; irrigation, urban recharge...etc. The groundwater recharge varies in a wide range governed by the rainfall distribution, topography, land use and geology. In the study area two types of recharges are identified;

4.3.1 Direct Recharge

Direct recharge from precipitation which widely varies with the position of wind ward and lee ward, it take place in all areas except where at the steep slope (at the escarpment) and in areas where there is wide coverage of clay around northern part of the area and where the volcanic rocks are fresh around the northern and northeastern margin of the catchment.

4.3.2 Indirect Recharge

Indirect recharge into the water table from the surface water sources such as Lege Hare river, Dechatu river, Chacho river, Dube river and Kerkera river where the water table is below river channel, along the fracture zone and fault areas.

4.4 Groundwater Flow

On the basis of the potentiometer head and water table distribution from various shallow to deep wells drilled in unconfined and confined aquifer system, groundwater contour map has been constructed and groundwater flow direction is indicated (Fig 4.4). The general trend of groundwater flow is toward north from the southern mountain range along which the general potentiometer head or water table decline as observed from the groundwater contour distribution map.

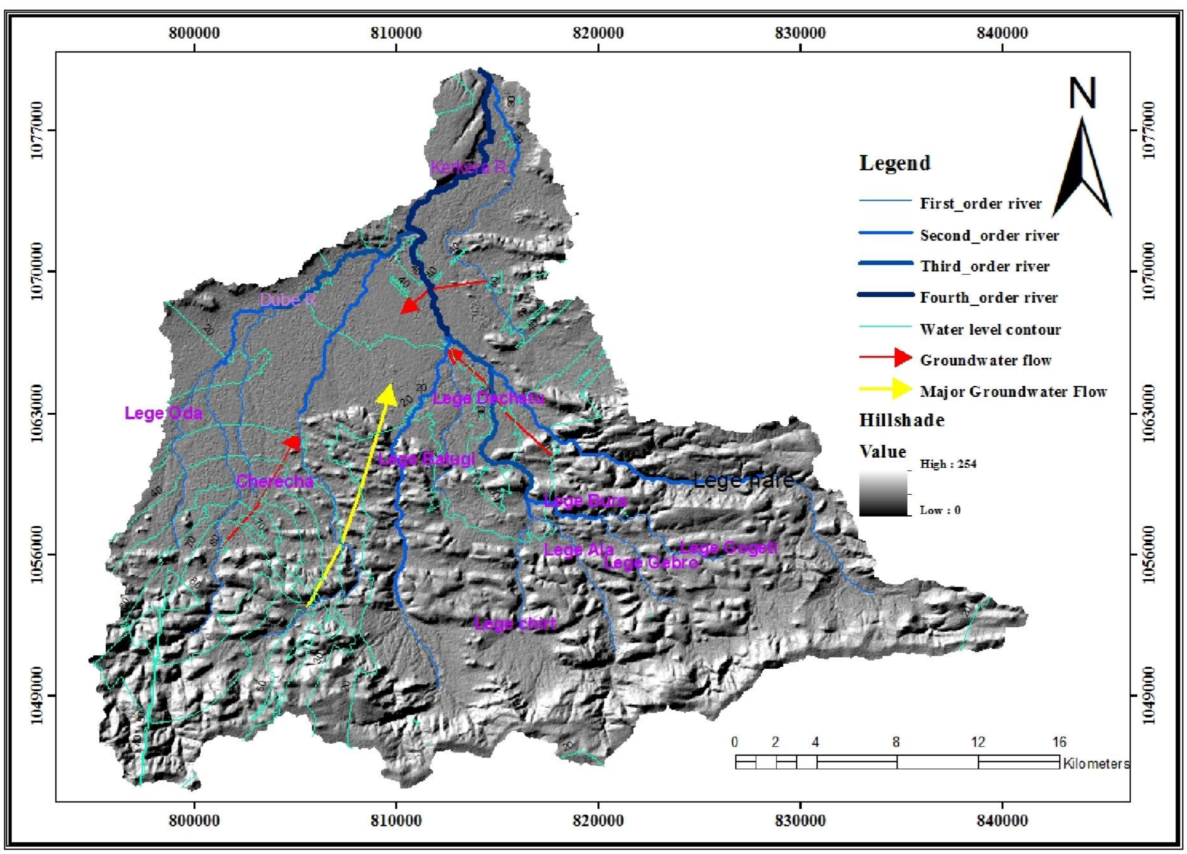

Figure 4.4. Groundwater flow Direction

5. DATA ANALYSIS AND INTERPRETATION

5.1 Factors Governing Groundwater Occurrence and Movement in the Study Area

Nine factors that have significant influence in groundwater occurrence and distribution are identified in the study area. Each factor is analyzed independently with respect to the groundwater occurrence and finally, they are integrated together to delineate groundwater potential zones area. All factors are discusses one by one as follow:

5.1.1 Slope

Slope is an important factor for the identification of groundwater potential zones, this is because of it controls the infiltration of groundwater into subsurface. In the gentle slope area, the surface runoff is slow allowing more time for rainwater to percolate, whereas, steep slope area facilitates high runoff allowing less residence time for rainwater and hence comparatively less infiltration. The slope map of the study area was prepared from SRTM data using the spatial analysis tool. Slope of an area plays a major role in groundwater availability. This is because of slope steepness/gradiant influences groundwater recharge. Flat areas are capable of holding the rainfall and facilitate groundwater replacement in contrast to steep areas which activate runoff. Based on the slope amount, the study area can be divided into five slope classes, with slope 0^{o} to 64^{o} in flat and mountainous areas respectively (Fig.5.1).

The areas having 0^{o}-5^{o} slope fall into the 'very good' category because of the nearly flat terrain and relatively high infiltration rate. The areas with 5^{o}-11^{o} slope are considered as 'good' for groundwater storage due to slightly undulating topography with some runoff. The areas having a slope of 11^{o}-18^{o} cause relatively high runoff and low infiltration, and hence are categorized as 'poor' and the areas having a slope>18^{o} are considered as 'very poor' due to higher slope and runoff (Fig 5.2). Therefore the 1^{st} rank is given to the areas which have low slope area (Table 5.1)

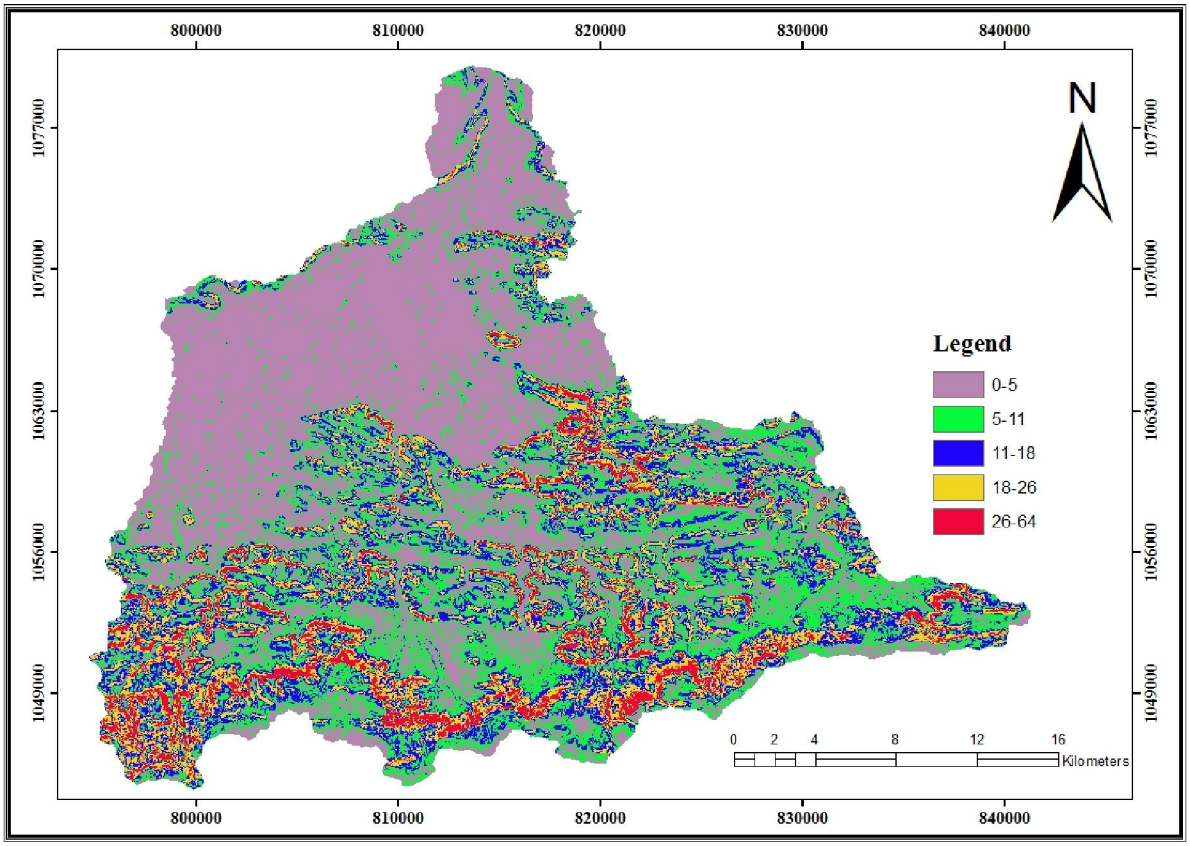

Figure 5.1. Slope map

Table 5.1. Weight for slope map of the study area

Slope	**Flat**	**Gentle**	**Moderate**	**Steep**	**Very Steep**	**Weight**	**Weight *100**
Flat	1					0.5128	51
Gentle	1/3	1				0.2615	26
Moderate	1/5	1/3	1			0.1290	13
Steep	1/7	1/5	1/3	1		0.0634	6
Very Steep	1/9	1/7	1/5	1/3	1	0.0333	3

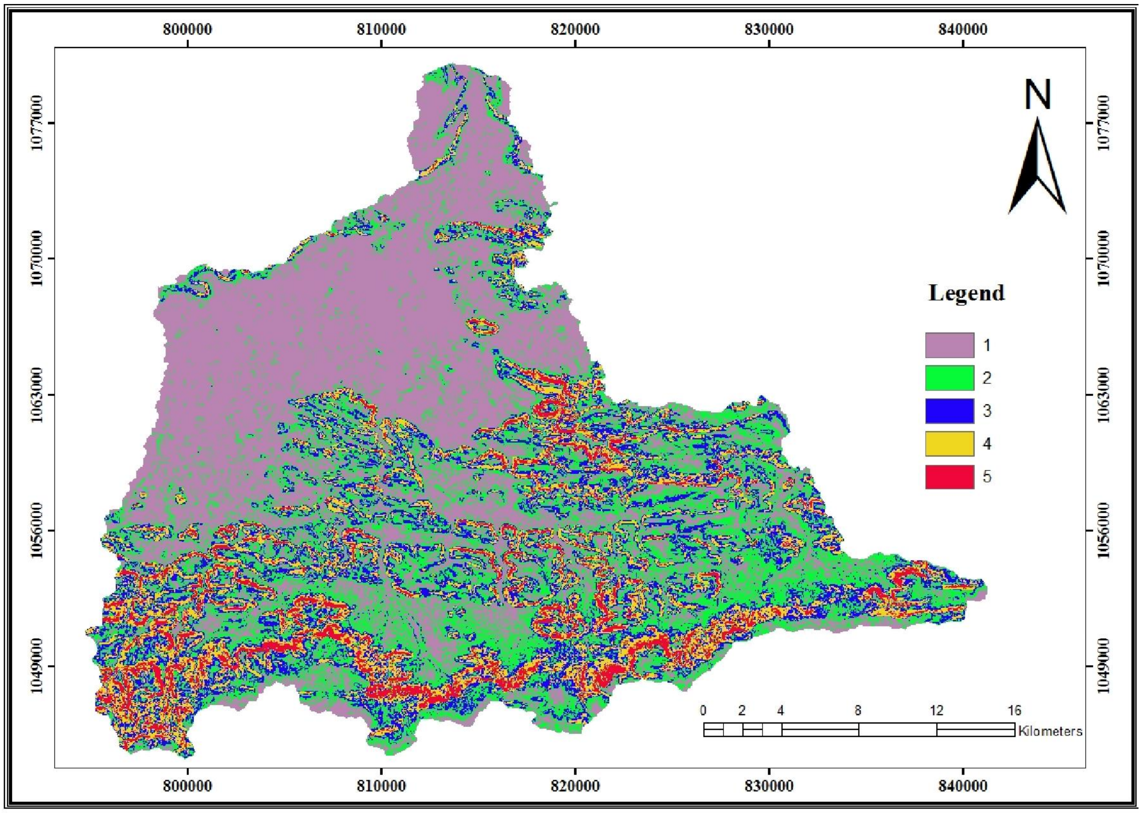

Figure 5.2. Reclassified slope map

5.1.2 Drainage Density

The drainage system of any area always plays an important role in various ways. They reflect the lithology and structure of a given area. The drainage network of the study area was extracted from SRTM and density was calculated directly using spatial analyst extension. In the study area, mainly 4 drainage density categories have been identified and mapped as shown in (Fig 5.3). These are further reclassified and 1st rank is given to low density (Fig 5.4) (Table 5.2).

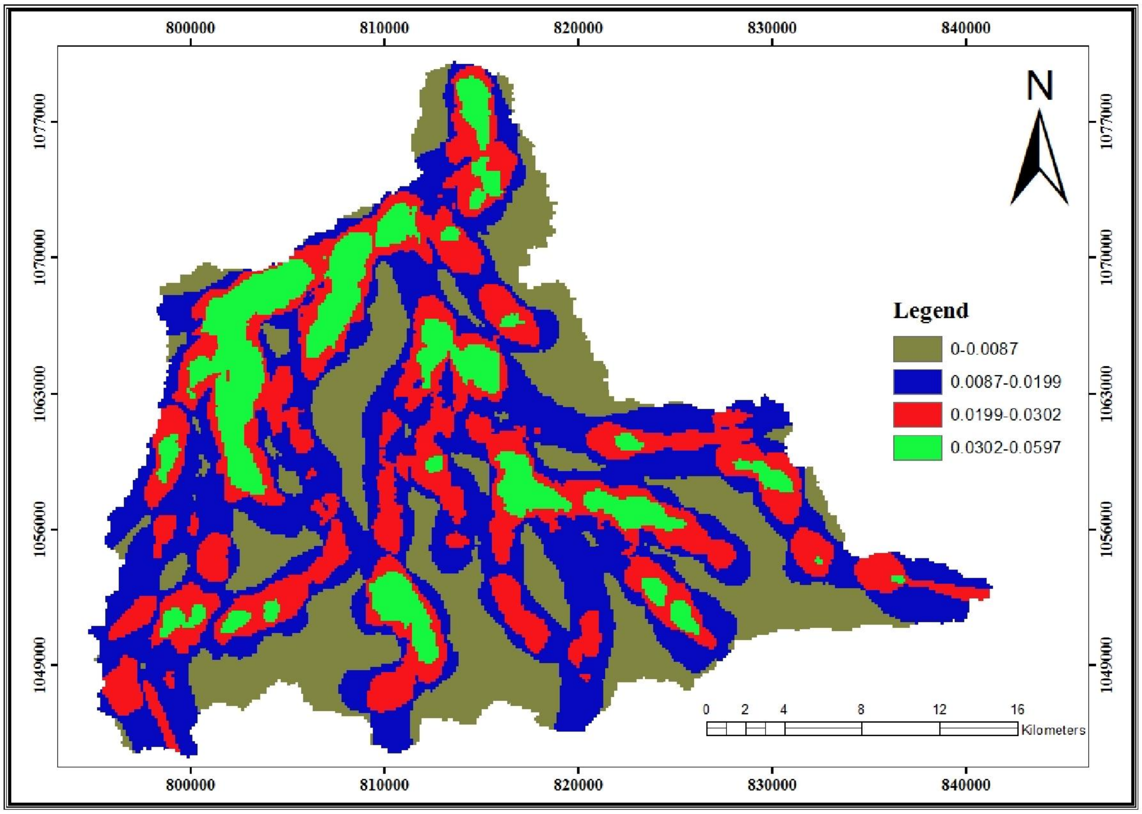

Figure 5.3. Drainage density map

The surface water infiltration is found to be more in the sheet wash than in channel flow. The area of very high drainage density represents more closeness of drainage lines and vice-versa. Groundwater potential is found to be poor in very high drainage density areas as major part of the water poured over them during rainfall is lost as surface runoff with little infiltration to meet groundwater. On the contrary low drainage density areas permit more infiltration and recharge to the groundwater and therefore have more potential for groundwater occurrence.

Table 5.2. Weight for drainage density map

Drainage	**Low**	**Moderate**	**High**	**Very high**	**Weight**	**Weight *100**
Low	1				0.4686	47
Moderate	1/2	1			0.2968	30
High	1/3	1/2	1		0.1664	17
Very high	1/5	1/5	1/3	1	0.0682	7

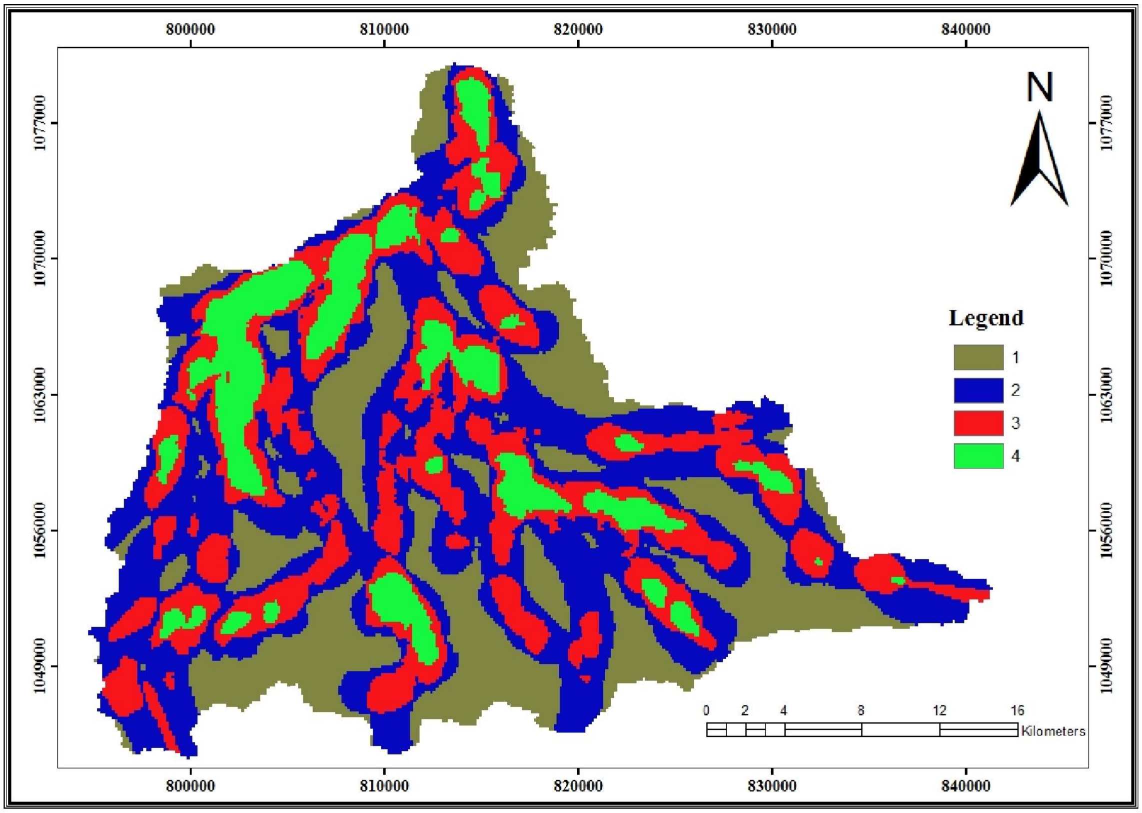

Figure 5.4. Reclassified drainage density map

5.1.3 Land use Land cover

Land use/land cover plays important role in the occurrence and development of groundwater. Therefore, the land use/cover map of the area was visually interpreted from Landsat ETM+ 2011 data and supervised classification of band combination 4, 3, 2 in RGB is done using field visit (Fig.5.5) and previous background of the area and finally five land use classes are identified in the entire study area namely physiographic vegetation (371.7482 km^2), agricultural land (309.843 km^2), Bare land (98.4726 km^2), Urban built-up (11.9538 km^2) and River sand (17.3088 km^2) (Fig. 5.8). Physiographic vegetation, Agricultural land and forest cover and Bare land are the prominent land use types in the study area (Fig 5.6).

The present condition of land covers of the area influence the occurrence of groundwater. The effect of land cover to groundwater recharge is both negative and positive. Trees may increases water loss by evapotranspiration or they may facilitate recharge by reducing runoff and by intercepting water and infiltrating its droplet slowly (Murthy and Abiy Gatachew, 2009). For the problem under discussion, even if evapotranspiration and interception are assumed constant and only positive effects of vegetation are considered because of most of the Physiographic vegetations are occupied the escarpment area and sloppy. From water resource point of view, it has high runoff and low probability to infiltrate into subsurface except preferentially along the geological structures. Therefore vegetation covers are given 5th rank and Agricultural lands the highest (Table 5.3). For identification of vegetation cover band ration of band 4 to band 3 was done (Fig 5.7).

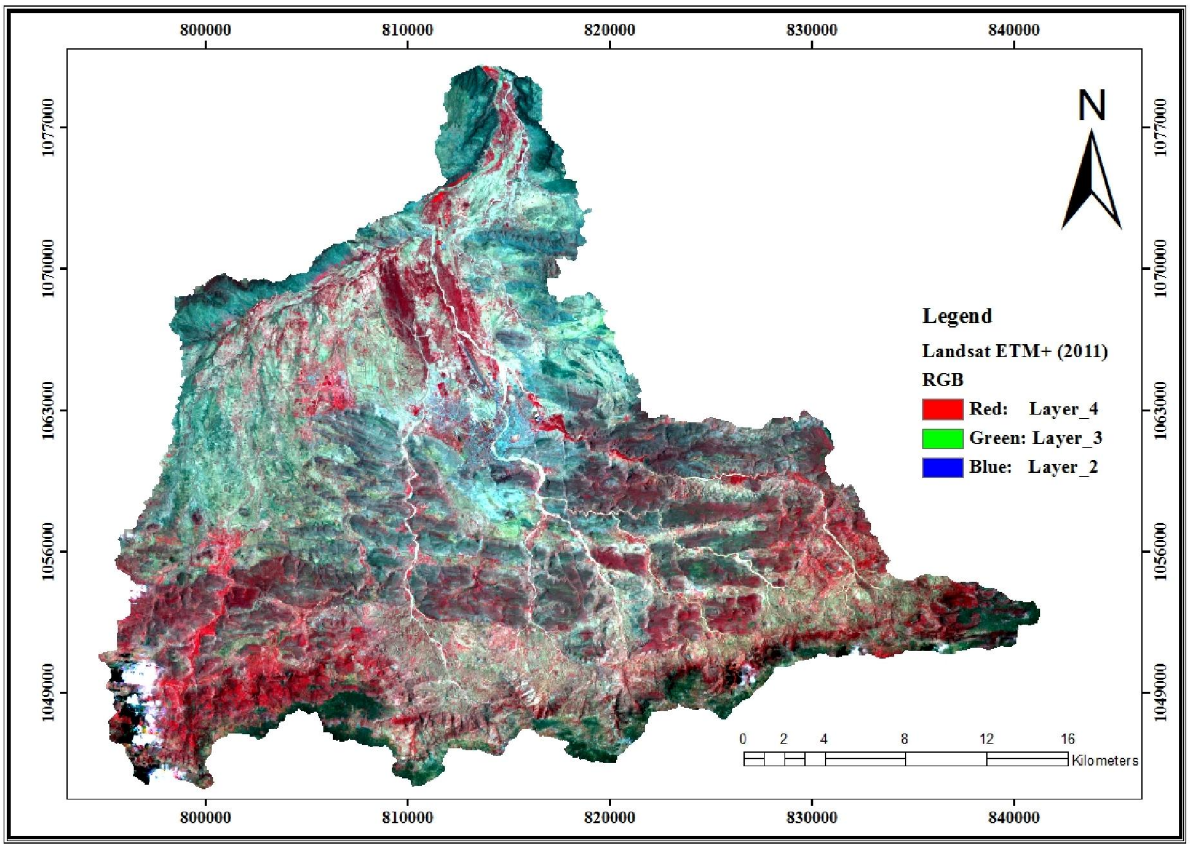

Figure 5.5. False color composition of 4, 3, 2 landsat (2011).

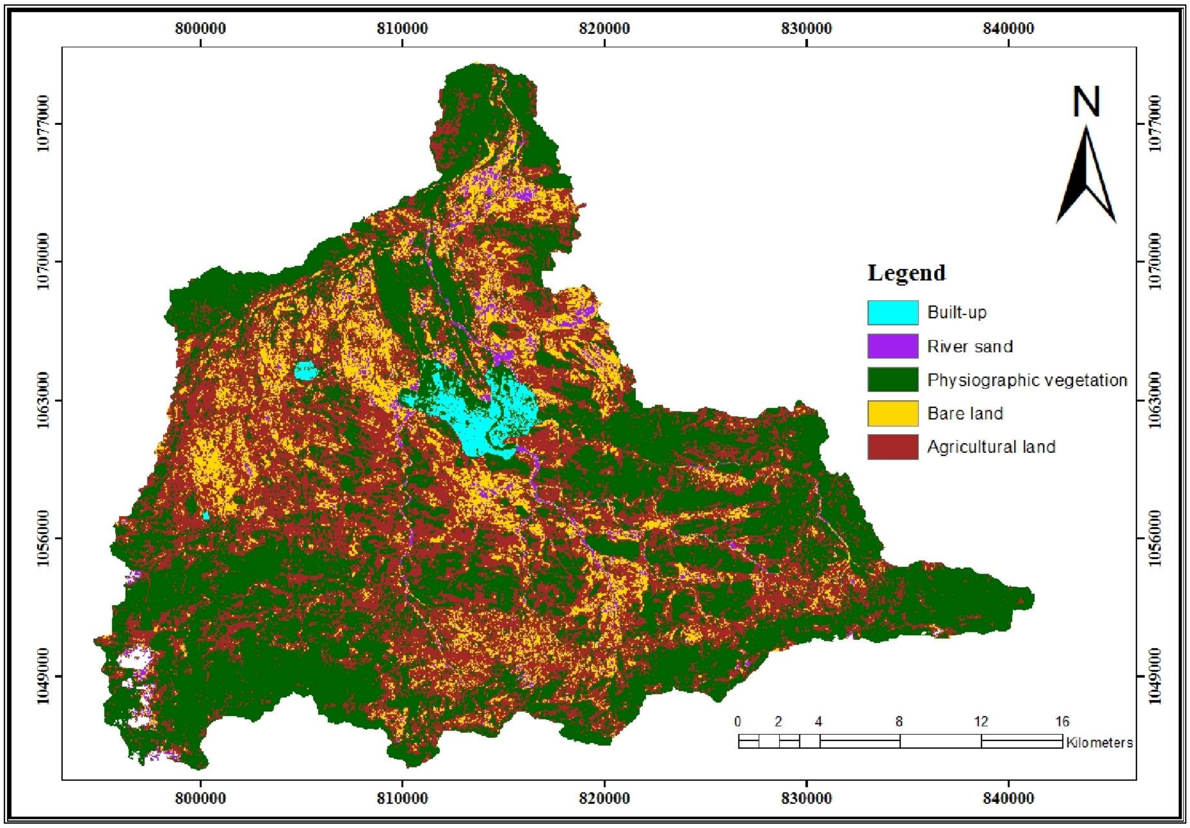

Figure 5.6. Land use/Land cover map (2011)

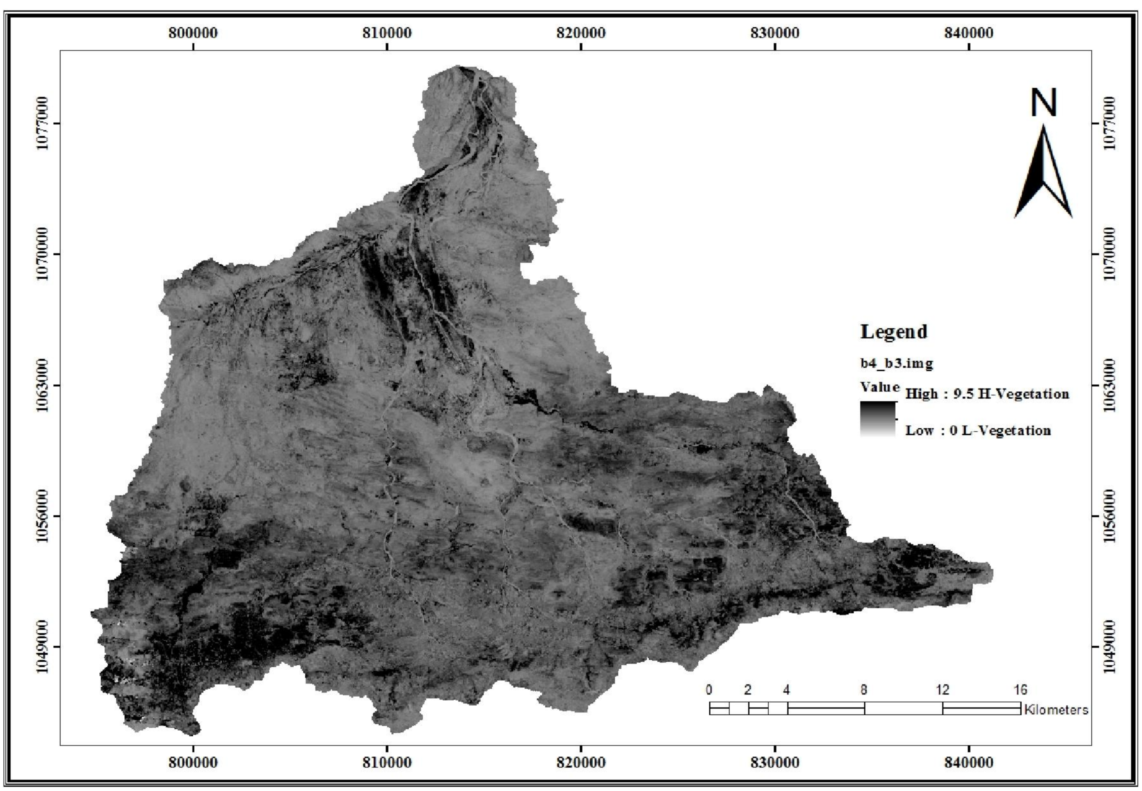

Figure 5.7. Band4/Band3 ratio map

Table 5.3. Weight for land use land cover map of the study area

Land use/Land cover	**Agricultural land**	**Bare land**	**River sand**	**Built-up**	**Physiographic vegetation**	**Weight**	**Weight * 100**
Agricultural land	1					0.4188	41.9
Bare land	1/2	1				0.2737	27.4
River sand	1/3	1/2	1			0.1739	17.4
Built-up	1/4	1/4	1/3	1		0.0883	8.8
Physiographic vegetation	1/7	1/5	1/4	1/3	1	0.0452	4.5

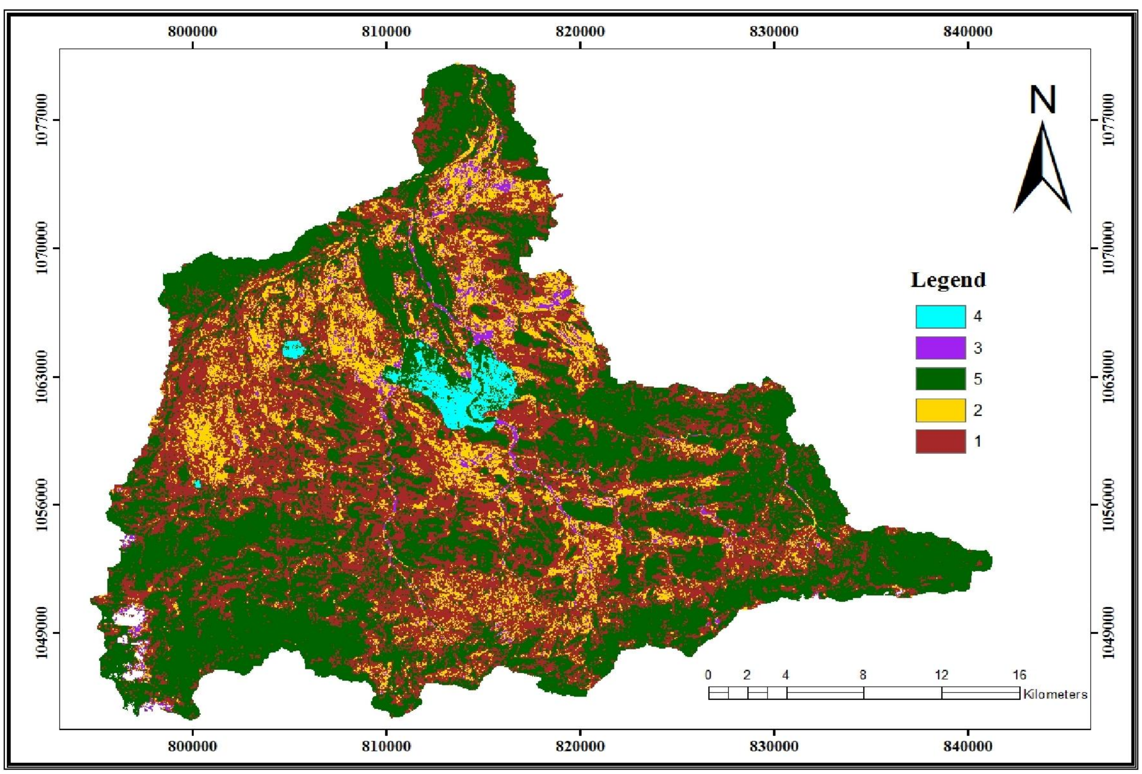

Figure 5.8. Reclassified land use/ Land cover map

Physiographic vegetation is mostly included the desert wood and bushes, dominantly found at the south western and eastern part of the study area. Eucalyptus plantation around the home is also growing for energy and changing the weather condition of the area as well as construction purposes are categorized under this category. This land cover is not that much importance for groundwater occurrence, this is because of it occupies largely escarpment and around river canals. Agricultural land incorporates Sorghum, Maize and Chats are the major crops grown below the escarpment at valley bottoms and in the valleys. Bare land is also distributed thought the study area and includes rock exposed along escarpment and valley plain. This area is weathered and fractured so it is very good from ground water point of view. The river sand along river canals and that deposited by overflow of the river is good for groundwater occurrence but, the urban land is poor due to the asphalt and roof of the house are reduce the infiltration and facilitate the runoff.

5.1.4 Soil

Soil is natural bodies which form through some natural process whether external or internal process as weathering and decomposition of parent materials, climatic change, relief, organism and human activities on different geomorphic surfaces. These results the formation of various soil types over a period of time (Meresa Kiros, 2006).

Soil map was prepared from soil database of FAO (1997, the digital Soil and Database of East Africa), the study area soil map was clipped from this database and six soil types were identified: Lithic leptosols, Eutric fluivesols, Eutic planosols, Chromic luvisols, Haptic phaeozems and Humic Nitosols (Fig 5.9). Description of soils was made based on FAO/UNESCO “World reference base for soil resources, 2006; a framework for international classification, correlation and communication”.

According to Ethiopian Road Authority, Drainage Design Manual (2002) Soil properties influence the relationship between runoff and rainfall since soils have differing rates of infiltration. Permeability and infiltration are the principal factors required to classify into hydrologic groups (Table 5.5). Reclassification of soil types in relation to groundwater was done based on the soil texture (Table 5.4 and Fig. 5.10).

According to WWDSE (2004) study report, the interaction of the different soil forming factors is determined and still forming various soils in the study area. Because of most of the area are being continuously weathered and eroded by different factors the soil is relatively younger, since most of the soils are not fully develop. These are especially seen at the mountainous/hilly areas and foot of the escarpment. The most important factor in the soil formation is time.

The soil units have been grouped together into the following classes for a generalized description of their soil morphology:

- **Chromic Luvisols(Lvx):** is deep soil formation, moderately well-to-well drained soils. The soils are brown to dark clay loams to clay type, strongly calcareous and wide spread over the whole Melka-Jebdu area occurring on flat to very gently undulating topography under laying Lithic Leptosols in this area. Soils within siliceous material, yellowish brown color and strongly calcareous are occurring on the foot of slopes of hill/mountains but, dominantly they are exposed at the southern and south eastern hill/ mountain margin of the study area.

- **Lithic Leptosols(Lpq):** is Very shallow-to-shallow soils, these soils occur throughout the study area and are mostly widespread in areas of steep slopes to flat plain. They are produced from crystalline limestone and grain rich sand stone occupying complex land forms to plain.
- **Eutric Leptosols(Lpe):** Moderately deep to deep, poorly drained soils; these soils occur at receiving sites of runoff from the surrounding elevated terrain. They are imperfectly to poorly drain, heavy clay soils and occur in the north eastern and north western margin of Melka Jebdu plain area to shinile. This soil type is formed from basic and ultra basic parent materials such as basalt rocks and occupies bare land, agricultural and alluvial plain physiographic vegetation areas.
- **Eutric fluvisols (Fle):** is deep alluvial soil; these soils are characterized by their highly heterogeneous nature (along the valley) down the Shinile. It is found on exposed surface of unconsolidated sediment. They are very diverse and young soils that are often found on low-lying plains and near river stream courses.

- **Humic Nitosols (NTu):** is a deep soil formation, covering the south and south eastern margin of the area occupying escarpment plateaus. This soil type is derived from basement rocks characterized by clayey to very clayey texture and this results that low permeability of the formation.
- **Haplic Phaeozems(PHh):** is Moderately deep to deep, poorly drained soil formation covering the central southern of foot slope or pediment plains and characterized by clayey to very clayey texture.

Different land/soil degradation types were encountered within the basin area. They are mainly evident as moderate to severe erosion, flooding and weathering. The main contributors for the phenomena are steep slopes, very little vegetation cover, etc. All these situations aggravate (accelerate) the degradation processes (Meresa Kiros, 2006). Based on their infiltration capacity the weight is given for each class and the 1st rank is given to higher permeable formation compared to the other (Table 5.6).

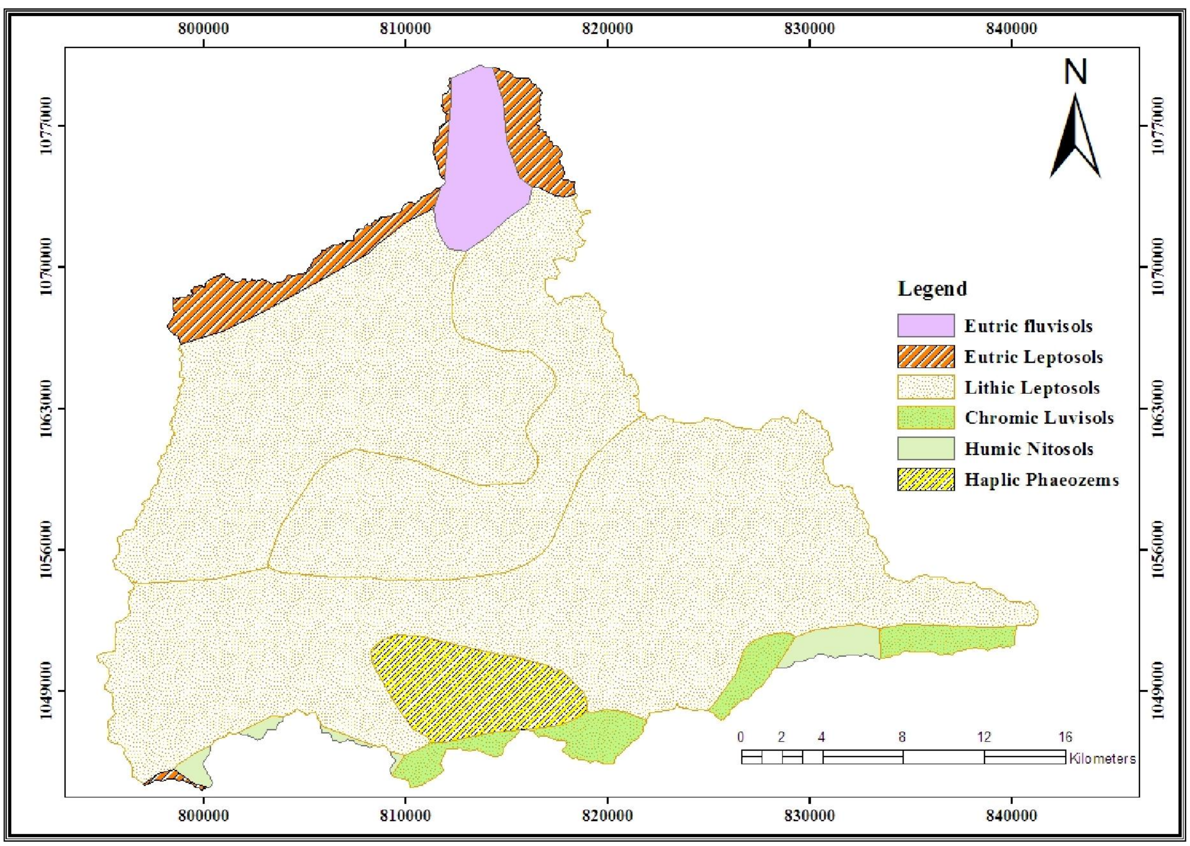

Figure 5.9. Soil map

Table 5.4. Soil information of the Dire dawa rivers catchment

	Soil-Type	Texture	Landscape	Geology	Depth
S1	Eutric fluivesols	Loam	Plains	Unconsolidated sediments	>120cm
S2	Lithic Leptosols	Sandy	Mountain	Crystalline limestone and grains relatively rich sand stone	<30cm
S3		Sandy	Mountain	Crystalline limestone	
S4		Sandy	Complex land forms	Varies parent material	
S5	Haplic Phaeozems	Very Clayey	Foot slopes	Varies parent material	30-90cm
S6	Chromic Luvisols	Clayey	Hill/Minor escarpment	Varies parent material	>120cm
S8		Very Clayey	Plateaus	Calc-Silicate gneisses	
S7	Humic Nitosols	Very Clayey	Plateaus	Undifferentiated basement system gneisses/rocks	>120cm
S9		Very Clayey	Plateaus	Undifferentiated basement system gneisses/rocks	
S10	Eutric Leptosols	Clayey	Mountain	Varies parent material	30-90cm
S11		Loam	Complex land forms	Basic and ultrabasic rocks	
S12			Complex land forms	Basic and ultrabasic rocks	

(Source: The Digital Soil and Terrain Database Of East Africa (SEA), 1997)

Table 5.5. Permeability of Soil types in the catchment

No.	Soil type	Code	Texture	
1	Lithic leptosols	2	Sandy	Increasing Permeability ↑
2	Eutric fluivesols	3	Loam	
3	Eutic planosols	3	Loam	
4	Chromic luvisols	4	Clayey	
5	Haptic phaeozems	5	Very Clayey	
6	Humic Nitosols	5	Very Clayey	

Table 5.6. Weight for soil map

Soil	**Lithic leptosols**	**Eutric fluivesols**	**Eutic planosols**	**Chromic luvisols**	**Haptic phaeoze**	**Humic Nitosols**	**Weight**	**Weight * 100**
Lithic leptosols	1						0.3265	32.7
Eutric fluivesols	1/2	1					0.2608	26.1
Eutic planosols	1/2	1/2	1				0.2083	20.8
Chromic luvisols	1/3	1/3	1/3	1			0.1175	11.8
Haptic phaeozems	1/5	1/5	1/5	1/4	1		0.0596	6.0
Humic Nitosols	1/7	1/7	1/7	1/5	1/5	1	0.0273	2.7

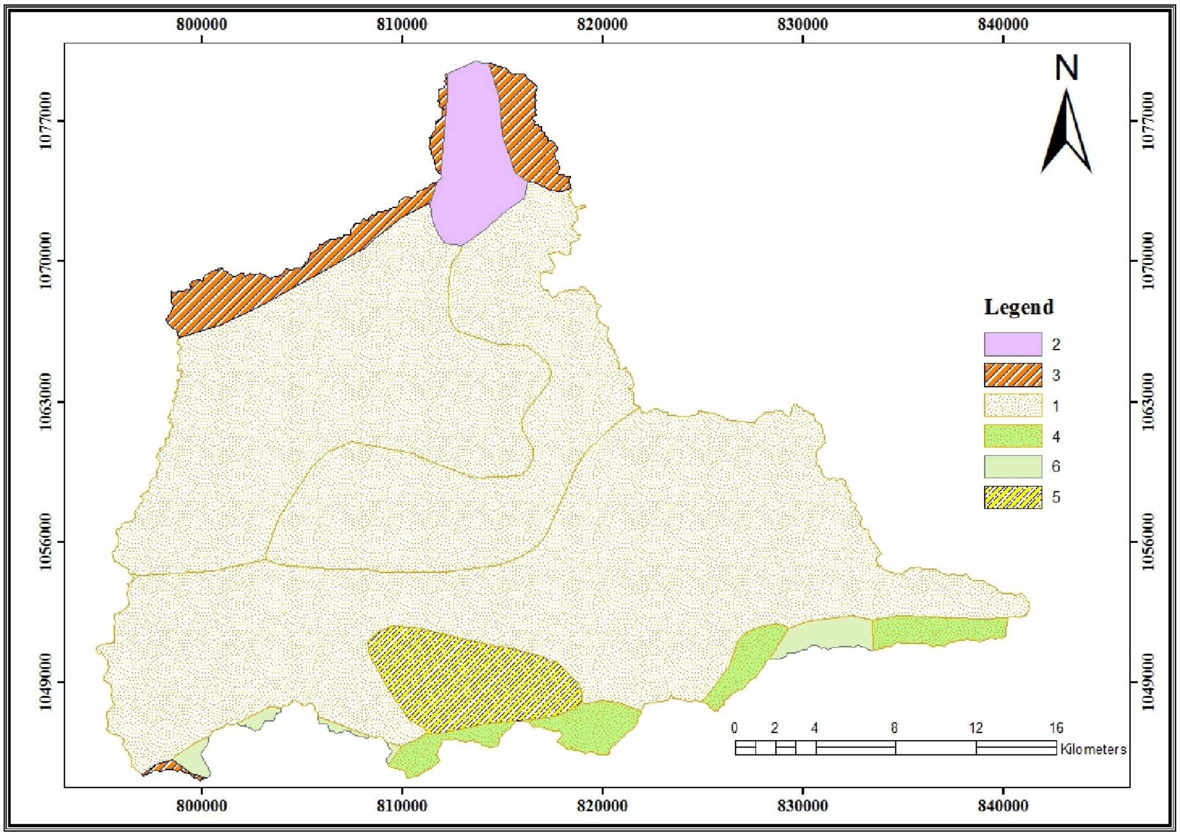

Figure 5.10. Reclassified soil map

5.1.5 Geomorphology

An integrated study of the geology and evolution of landforms is useful to understand the occurrence of porous and permeable zones Karanth (1987, as cited in Sharma and Kujur, 2012). Slope, soil, land use, etc are plays an important roles in defining the groundwater regime of the area. In view of this geomorphological map of the study area has been prepared. The geomorphology of the study area can be classified into three major features: the escarpment, the transitional and the alluvial plains (Fig 5.11). From groundwater point of view the escarpment is very low; this is because of the steepness of the area the rainfall flows over it rather than infiltrating to the sub-surface. In transitional area as foot slope ridge and minor escarpment, there is moderate infiltration of precipitation through fractures and faults, so that it has moderate contribution for groundwater occurrence in the area. Transitional zone and alluvial pains are the gentle to flat landforms respectively where the uphill groundwater recharge is accumulated and discharged. These areas have higher water level surface, so they are the best land forms for groundwater prospecting. In high rainfall conditions, the escarpments facilitate runoff rather than infiltration. The ranks are given to geomorphological units considering their contribution to groundwater infiltration (Table 5.7) (Fig. 5.12).

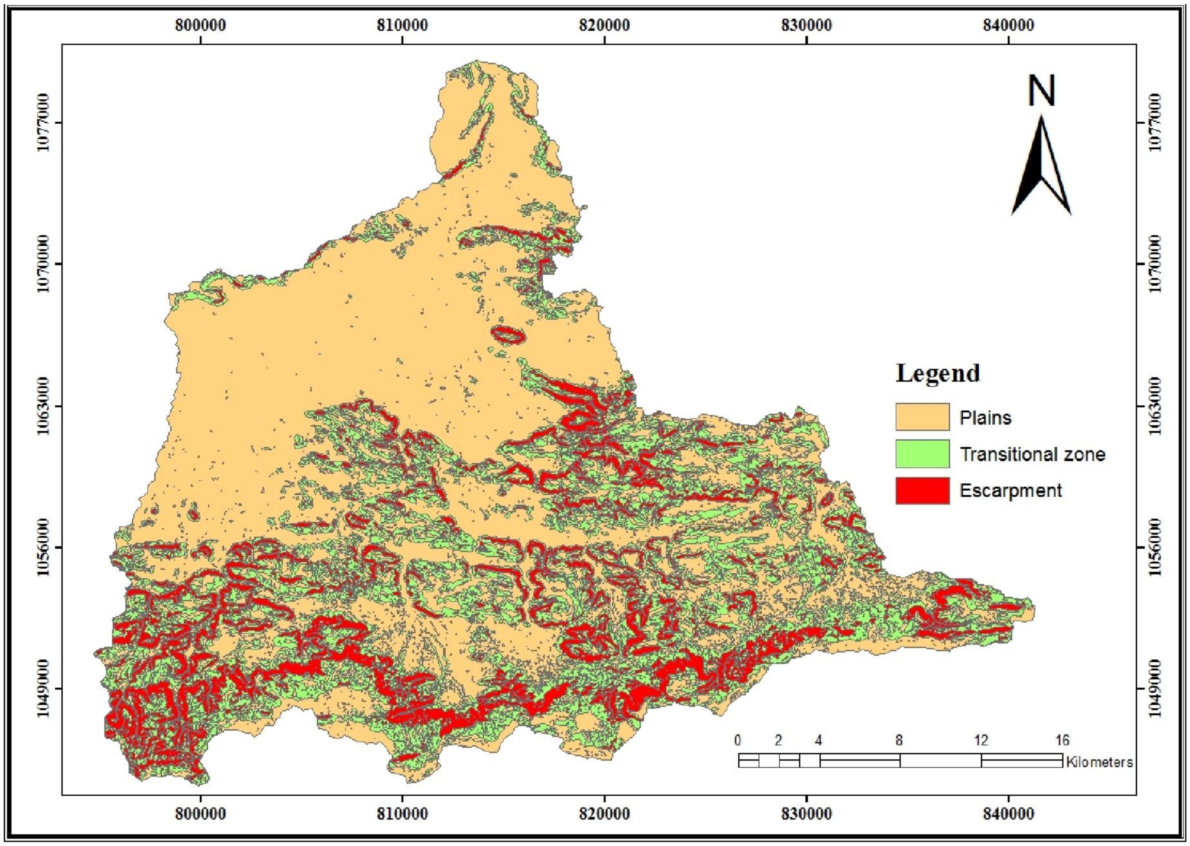

Figure 5.11. Geomorphology map

Table 5.7. Weight for geomorphology of the study area

Geomorphology	Plains	Transitional	Escarpment	Weight	Weight * 100
Plains	1			0.6694	66.9
Transitional zone	1/3	1		0.2426	24.3
Escarpment	1/7	1/3	1	0.0879	8.8

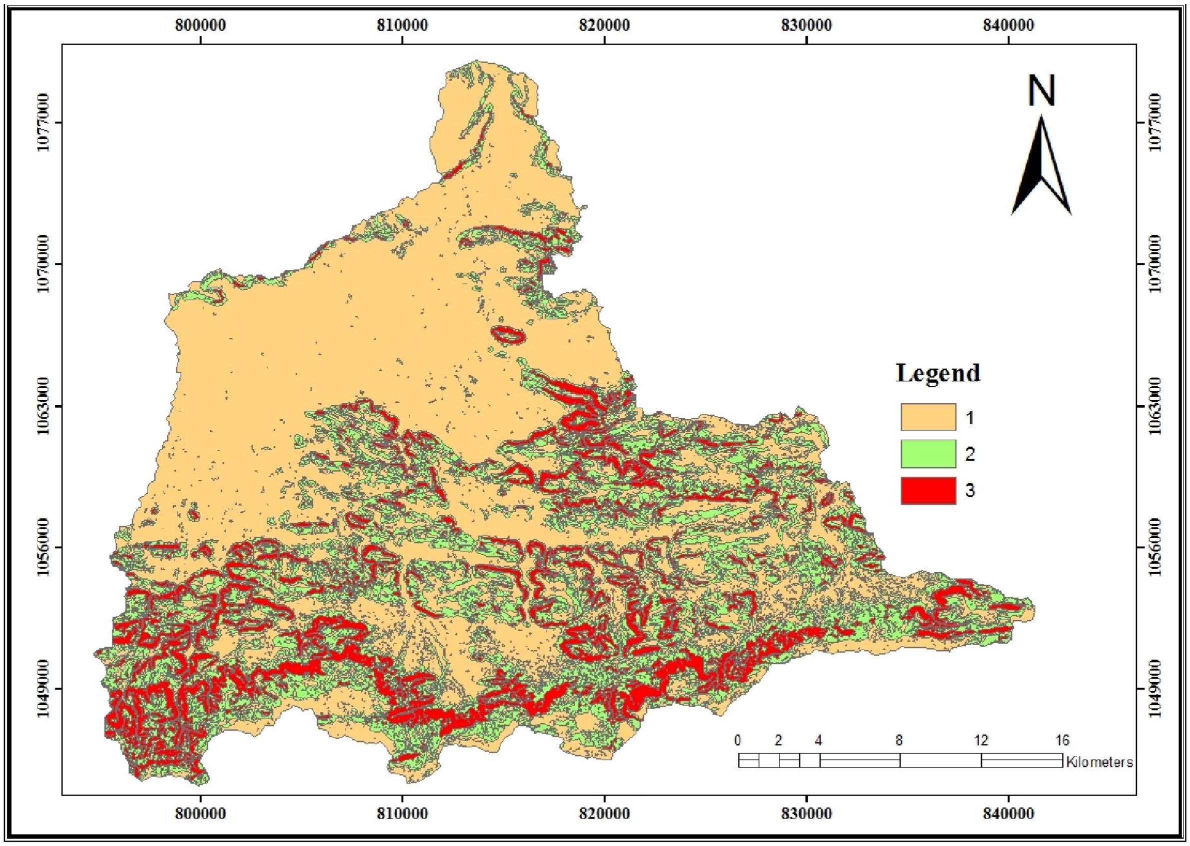

Figure 5.12. Reclassified Geomorphology map

5.1.6 Lithology

According to Stanley et *al*. (1966, as cited in Gezahegn Lemecha, 2007) Lithology is one of the factors that indicate the groundwater potential of an area. Different litholgic units have different porosity and permeability (Fig. 5.13). The porosity of each unit is determined by the amount of water which can be storage in it and the permeability determines the transmisivity of the water through that unit. Intergranular is the dominant porosity which exists in unconsolidated sediments and fractures in consolidated rocks. The other types of porosity is called double porosity, mostly it is present in some consolidated volcanic and sedimentary rocks.

Sand stone have high productivity at the foot of escarpment because they have fractured permeability and can have extensive aquifers. Alluvial sediments have also moderate potential because they are recent deposits and have better productivity and permeability (WWDSE, 2004). Alluvial sediments with localized area along river channel and Hamanlei limestone having large areal extent are good potential aquifers in the escarpment because of better permeability. If highly fractured, basaltic rocks will yield better amount of water. Basalts and basement rocks have low productivity aquifer (Fig. 5.14). The class ranks are therefore assigned according to abovementioned characteristics of the hydrogeological units (Table 5.8).

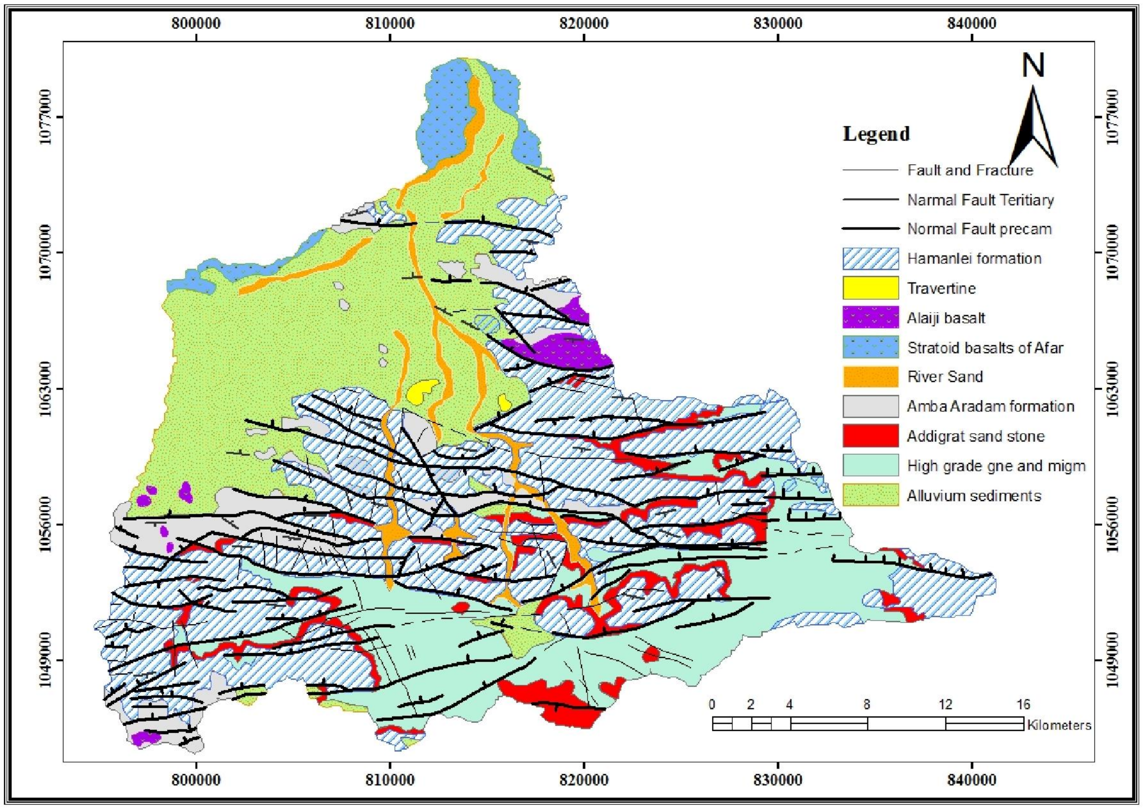

Figure 5.13. Lithology map

Table 5.8 Weight for lithology map

Lithology	Alluvium sedment	Hamanlei formation	River sand	Addigrat sand stone	Amba Aradom formation	Travertine	Alaji basalt	Stratoid basalt	Basement rock	Weight	Weight * 100
Alluvium sedment	1									0.2582	25.8
Hamanlei formation	½	1								0.2172	21.7
River sand	1/2	1/2	1							0.1861	18.6
Addigrat sand stone	1/3	1/3	1/3	1						0.1222	12.2
Amba Aradom formation	1/4	1/4	1/4	1/3	1					0.0907	9.1
travertine	1/5	1/5	1/5	1/4	1/4	1				0.0573	5.7
Alaji basalt	1/7	1/6	1/5	1/5	1/5	1/4	1			0.0331	3.3
Stratoid basalt	1/8	1/7	1/7	1/6	1/6	1/5	1/3	1		0.0209	2.1
Basement rock	1/9	1/8	1/9	1/7	1/7	1/7	1/5	1/3	1	0.0142	1.4

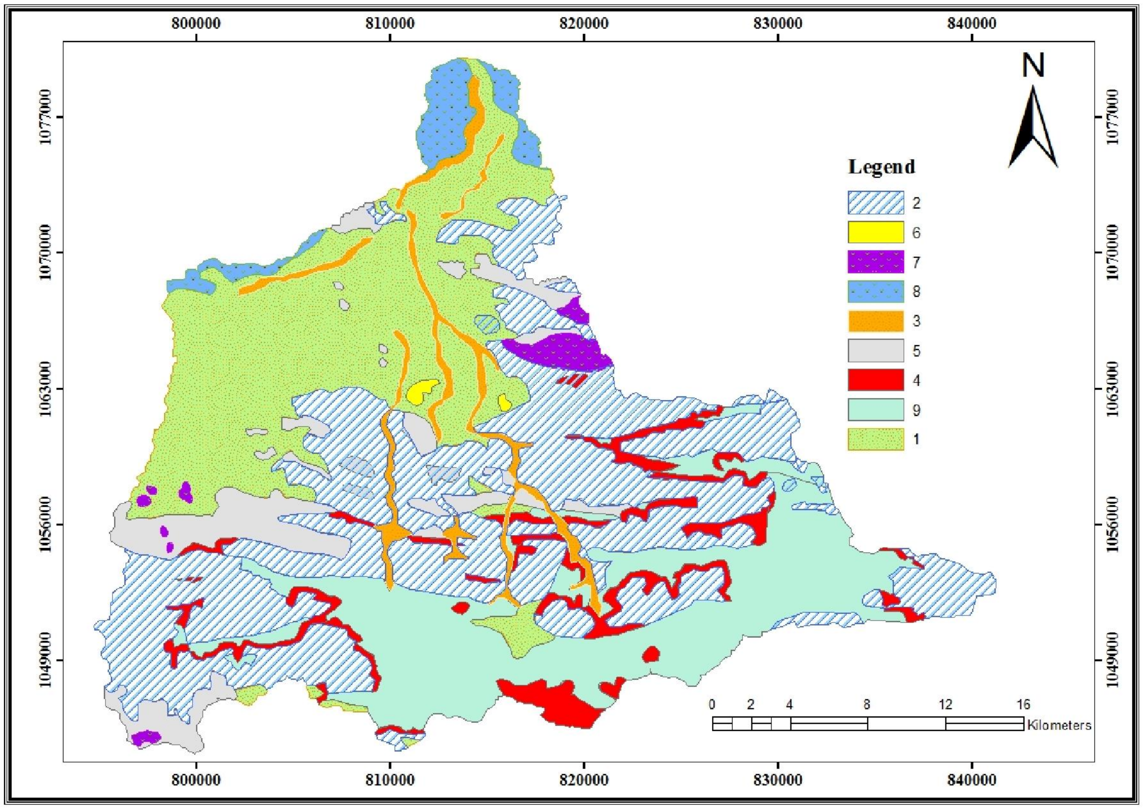

Figure 5.14. Reclassified lithology map

5.1.7 Lineament Density

Lineaments are linear or curvilinear structures on the earth surface; it depicts the weaker zone of bed rocks and is considered as secondary aquifer in hard rock regions (Sharma *et.al*, 2012). According to Koopmans (1986, Kar, 1994 and Philip, 1996) lineament analysis provides an important leading factors for the studies related to tectonics, engineering, geomorphology and in the exploration of natural resources such as groundwater, petroleum and minerals.

The linear structures which are important for increasing the permeability of the bed rock are lineaments, faults, fractures and joints (Murthy and Abiy Gatachew, 2009). These data sets were processed to have a uniform projection system and stored in raster format for further analysis. These data sets are going to be scored and weighted to describe their contribution in the natural occurrence of groundwater (Table 5.9). The density of the lineament mostly high at the south and central part of the study area as shown in the (Fig 5.15). The formations with higher lineament density develop a secondary porosity that will help them to percolate water than that very low density. Therefore 1st rank is given to area which has highest lineament density (Fig 5.16).

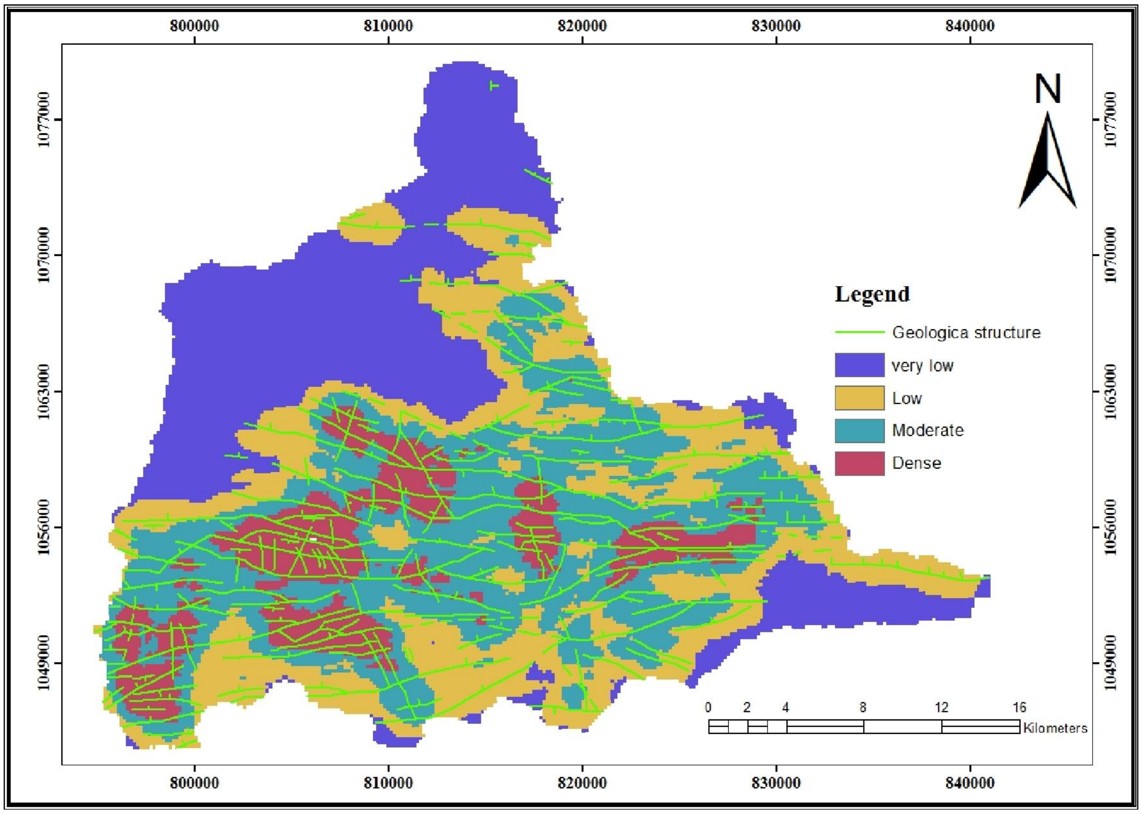

Figure 5.15. Lineament density map

Table 5.9. Weight for Lineament density map

Lineament	**Very Dense**	**Dense**	**moderate**	**Low**	**Very low**	**Weight**	**Weight * 100**
Very Dense	1					0.5128	51.3
Dense	1/3	1				0.2615	26.2
moderately	1/5	1/3	1			0.1290	12.9
Low	1/7	1/5	1/3	1		0.0634	6.3
Very low	1/9	1/7	1/5	1/3	1	0.0333	3.3

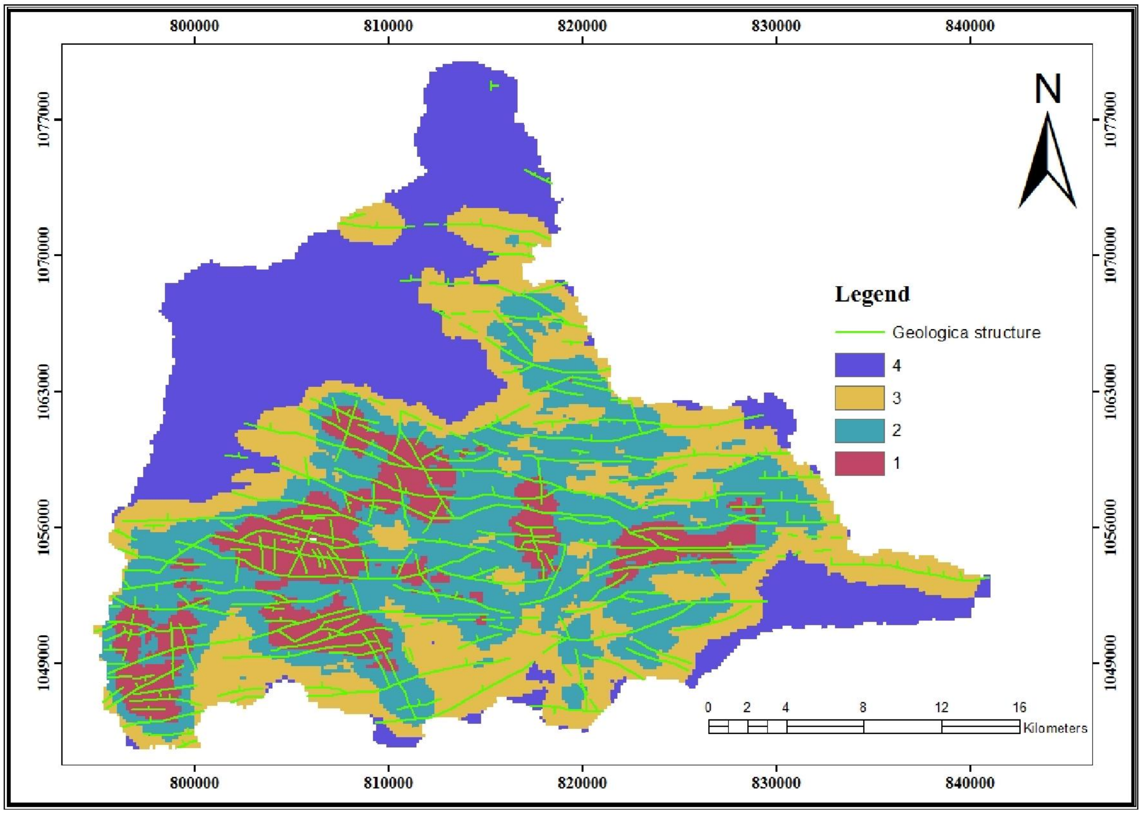

Figure 5.16. Reclassified Lineament density map

5.1.8 Rainfall

Rainfall is the most vital input in the hydrological cycle and fluctuations in quality and distribution strongly influence surface and sub-surface water sources (Gouri *et al.,* 2012). Part of the rain water, which falls on the ground is infiltrated into the soil. This infiltrated water is utilized partly in filling the soil moisture deficiency and part of it is percolated down reaching the water table. This water reaching the water table is known as the recharge from rainfall to the aquifer.

Rainfall distribution along with the slope gradient directly affects the infiltration rate of runoff water hence increases the possibility of groundwater potential zones. The relationship of rainfall to groundwater occurrence is modified by many factors as topography, vegetation, surface geology and lineament; all these factors affect the quantity of water that gets underground (Sisay Libasse, 2007). With respect to different surface condition which affect the amount of water that goes to the ground, annual rainfall should be taken in order to average the amount of water that percolates in to the ground regardless of surface condition.

In general the high rainfall amounts imply the possibility of high groundwater potential zone (Fig 17). The river catchment has been divided into three rainfall zones (Fig 18). Out of the total area, 500 - 642.8mm, 642.8-745.7mm and 745.7-851.4mm rainfall zone covered 179.03, 268.69 and362.13km^2 respectively. On the other hand, highest rainfall zone was found on southern part of the area and lowest rainfall zone was in the northern part of the study area. For each class weight is given with respect to groundwater occurrence (Table 10).

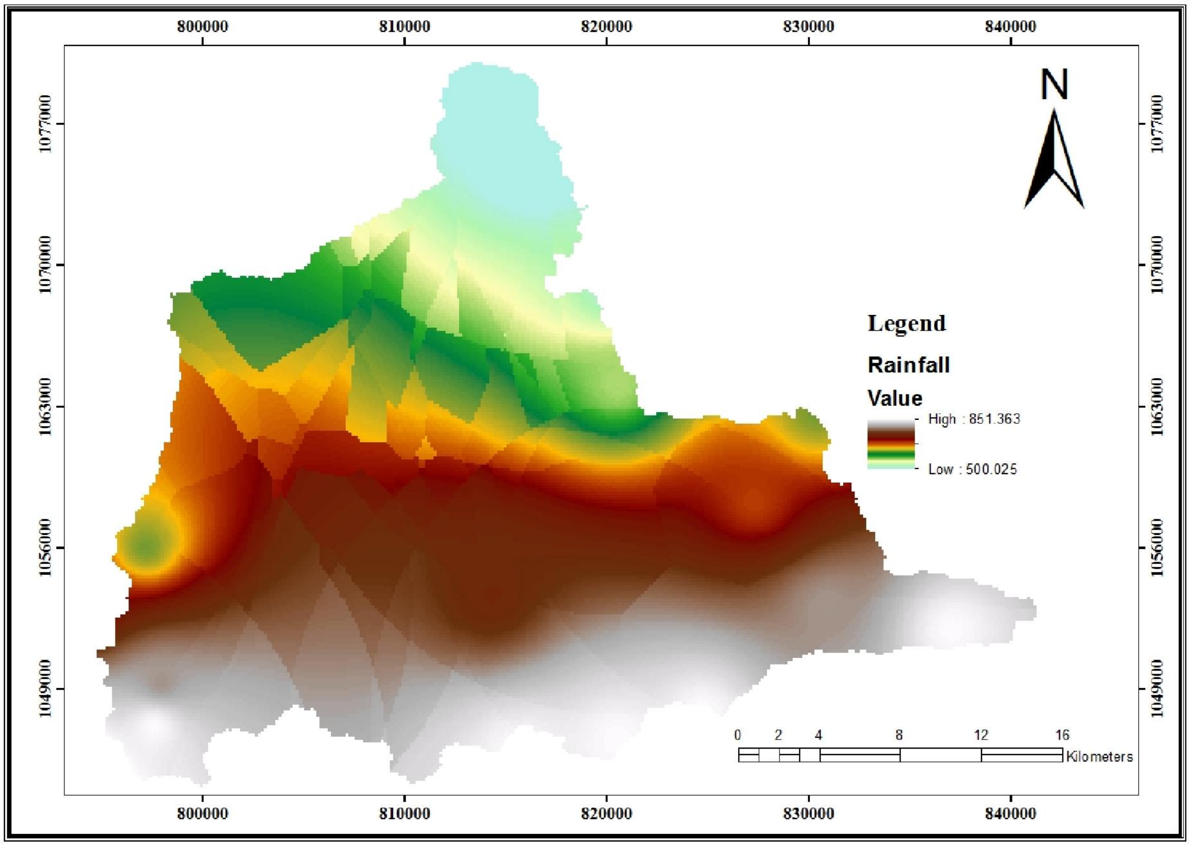

Figure 5.17. Rainfall map

Table 5.10. Weight for Rainfall map

Rainfall	500 - 642.8mm	642.8-745.7mm	745.7-851.4mm	**Weight**	**Weight * 100**
500 - 642.8mm	1			0.6370	63.7
642.8-745.7mm	1/3	1		0.2583	25.8
745.7-851.4mm	1/5	1/3	1	0.1047	10.5

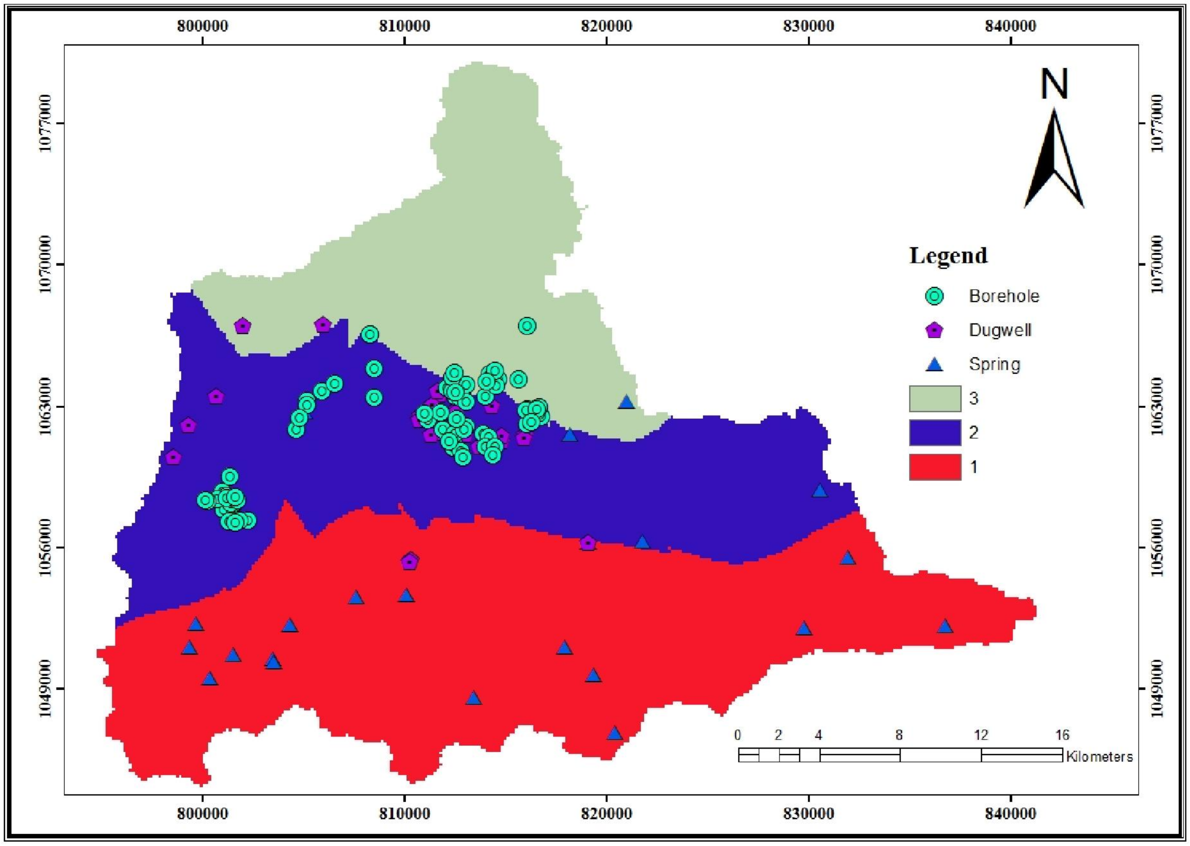

Figure 5.18. Reclassified Rainfall map

5.1.9 Depth to Water Level

Depth to Water represents the depth of the topographic surface over the water level or the depth where the water pressure head is equal to the atmospheric pressure and it gives an idea of the distance that the water infiltrates to reach the saturated zone (<*en.wikipedia.org/wiki/**Water table***<). Groundwater infiltrates from precipitation or from surface flow and passes through this depth until it reaches saturated zone. While depth to water level increases the depth from the surface to the saturated zone increases and vise verse (Fig.5.19). Water level data was collected from over 70 wells (WWDES Organization); Mean water level was worked out and plotted in their respective geographical positions and contours were generated. The map shows that the value ranges between 9 meter and 88 meter below ground level. As far as water level is concern lower the value then water is available at shallow depth while higher value means water is at deeper level. Accordingly classified into five groups (Fig 5.20), and the weight of each class is explained in the (Table 5.11) with respect to groundwater occurrence.

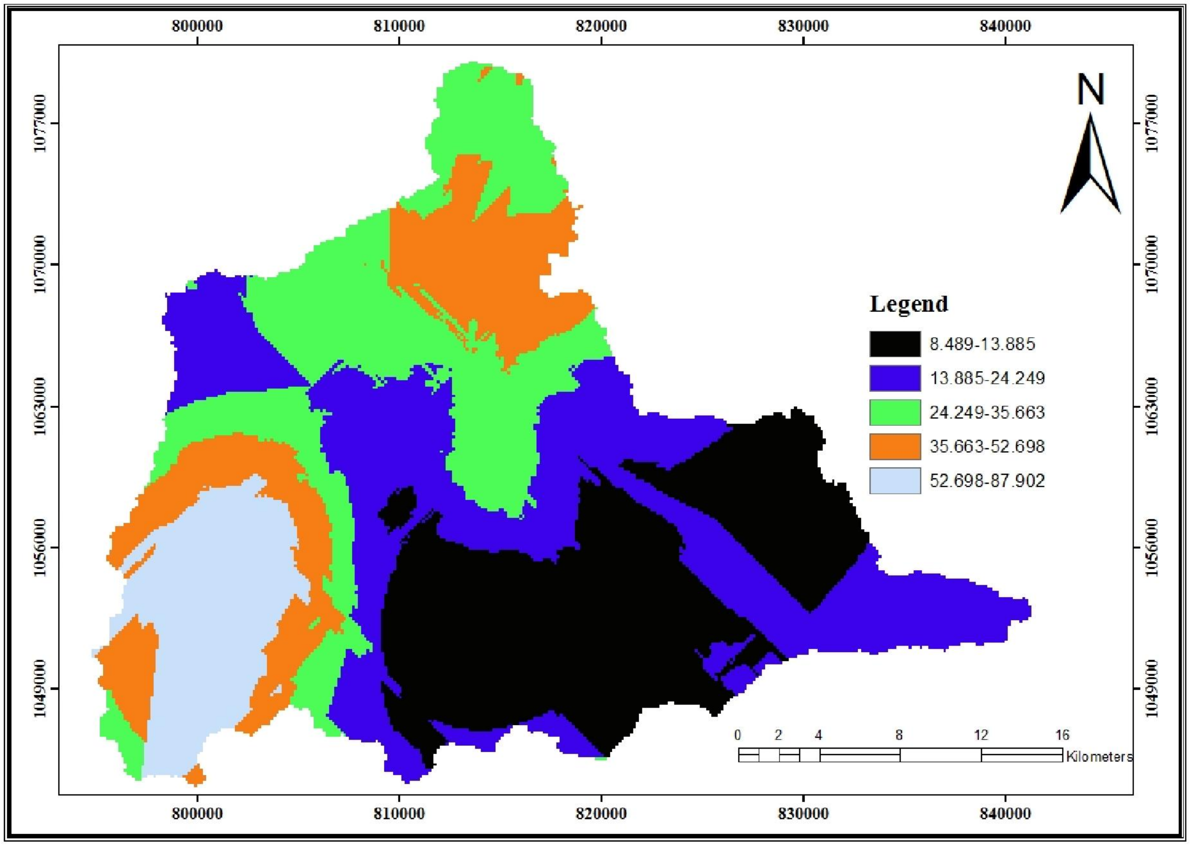

Figure 5.19. Depth to water level map

Table 5.11. Weight for depth to water level map

Depth to water level	Very shallow	Shallow	moderate	Deep	Very Deep	Weight	Weight * 100
Very shallow	1					0.3188	31.9
shallow	0.9	1				0.3737	37.4
moderate	1/2	1/3	1			0.1804	18
Deep	1/3	1/5	1/3	1		0.0873	8.7
Very Deep	1/7	1/7	1/5	1/3	1	0.0398	4

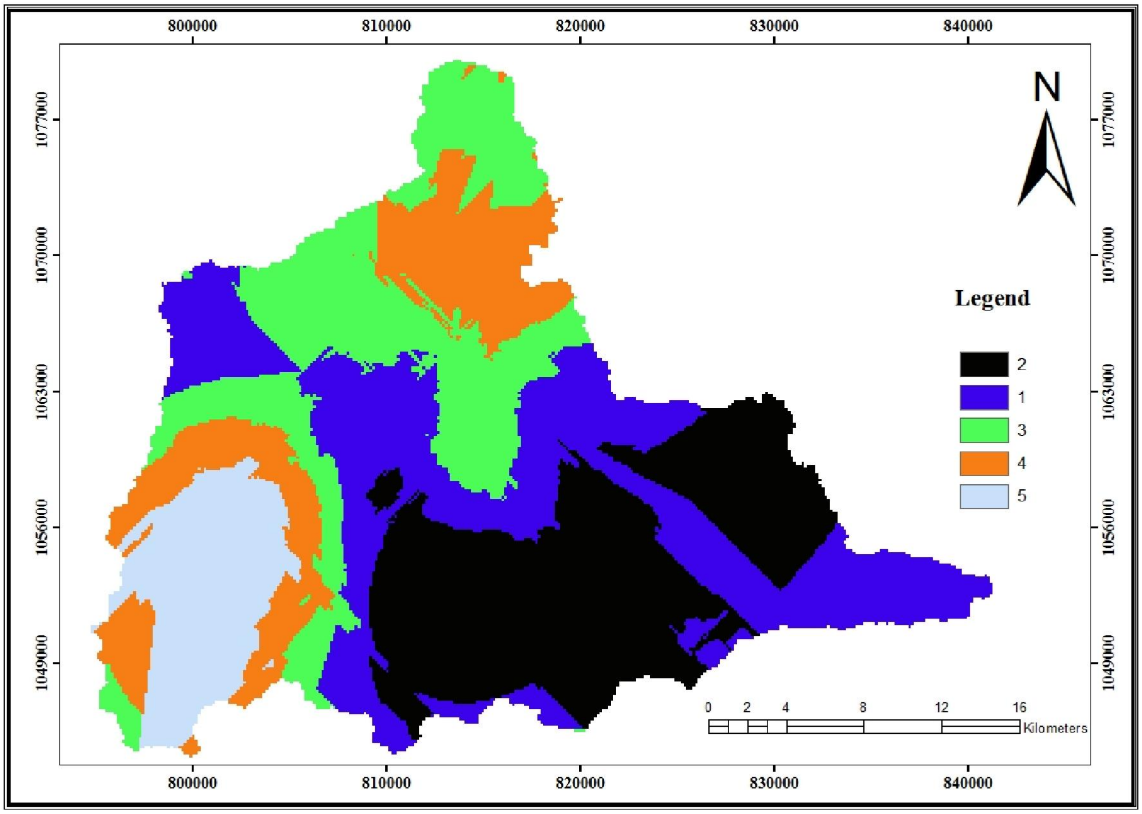

Figure 5.20. Reclassified depths to water level map

6. RESULT AND DISCUSSION

6.1 Result

In order to categorize the study area into different groundwater prospect zone different factor maps are developed. The datasets derived have different degree of influence of groundwater occurrence. From the weight calculation, the relative importance of each parameter has been determined for all thematic layers, lithological map, geomorphological map, slope map, soil map, lineament density map, rainfall map, drainage density map, land use/cover map and depth to water level maps. Therefore the higher the weight, the more influence a particular factors will have in the groundwater occurrence model. The factors involved were examined according to their relative importance in solving the stated problem and weights are assigned (Table 6.1). Accordingly all the reclassified factor layers are used in weighed overlay analysis (Fig. 6.1) by applying equation (1), and a final groundwater potential map of Dire dawa rivers catchment has been produced.

The resulting groundwater potential zone map was categorized in to different potential zones as Very good, Good, Moderate, Poor and very poor (Fig.6.2). The result indicated that large part of the study area is classified under good category and the groundwater potential of the study area is related mainly to geology, geomorphology, slope and lineaments.

$GW = \sum_{i=1}^{9}(\mathrm{R_i}W_i)$ (1) Where: **GW: Groundwater potential**

Ri: Factors under consideration

Wi: Corresponding weight for factors

[(Lithology) × 24 + (Geomorphology) × 22 +(Slope) × 18 +(Lineament) × 13 +(Soil) × 10 +(Rainfall) × 6 +(Drainage) × 4 +(Land use/ cover) × 2 +(Water level depth) × 1] = Groundwater potential

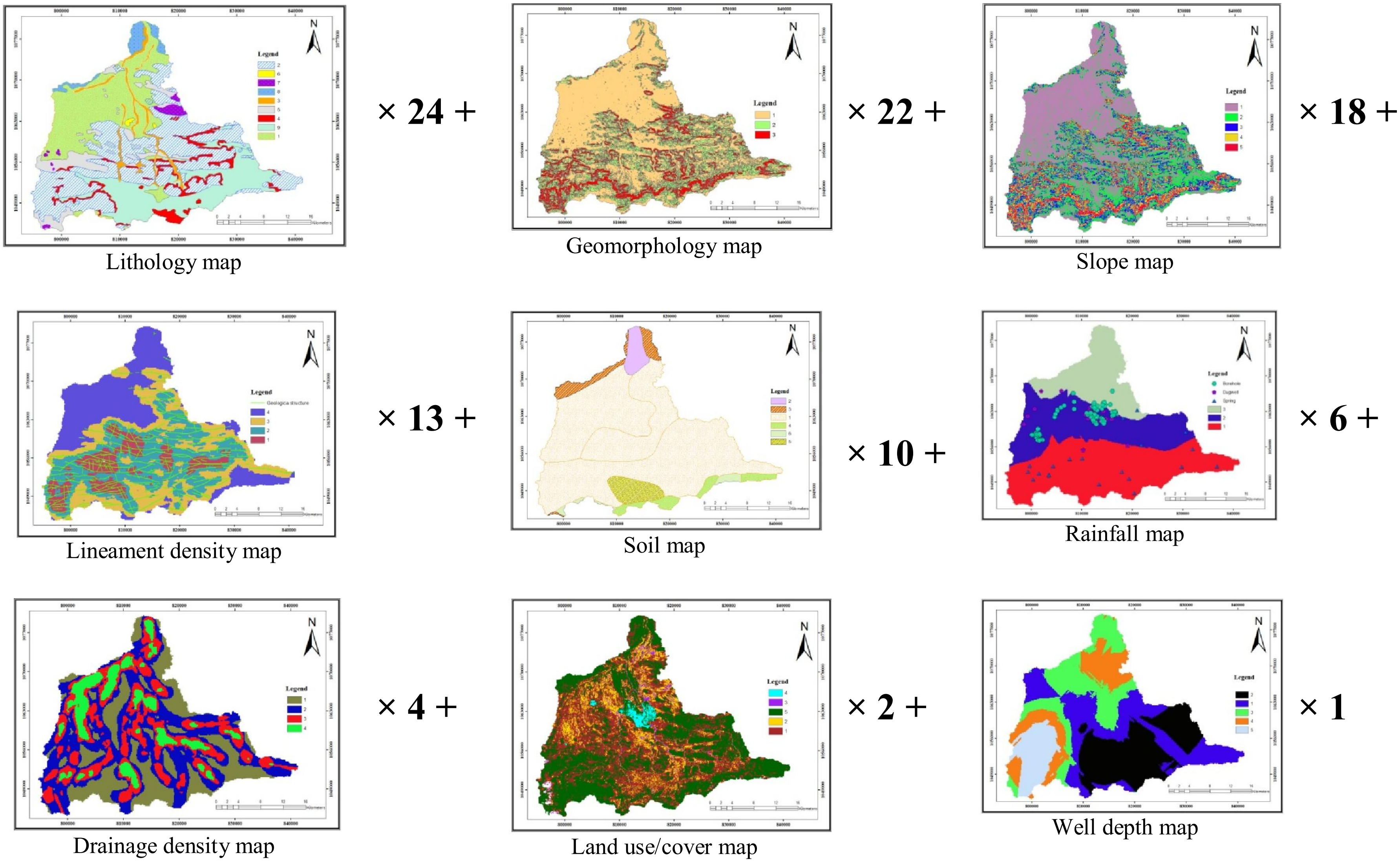

Figure 6.1. Integration of reclassified thematic layers.

Table 6.1. Weight for all factor maps

Layers	Lithology	Geomorphology	Slope	Lineament density	Soil	Rainfall	Drainage density	LU/LC	Wl_Depth	Weight	Weight * 100
Lithology	1									0.2442	24
Geomorphology	1/2	1								0.2238	22
Slope	1/2	1/2	1							0.1774	18
Lineament density	1/3	1/3	1/3	1						0.1273	13
Soil	1/3	1/4	1/3	1/3	1					0.0969	10
Rainfall	¼	1/5	1/4	1/4	1/3	1				0.0587	6
Drainage density	1/6	1/6	1/5	1/5	1/5	1/3	1			0.0350	4
LU/LC	1/7	1/7	1/7	1/6	1/7	1/5	1/3	1		0.0228	2
Wl_Depth	1/9	1/8	1/9	1/7	1/9	1/7	1/5	1/4	1	0.0138	1

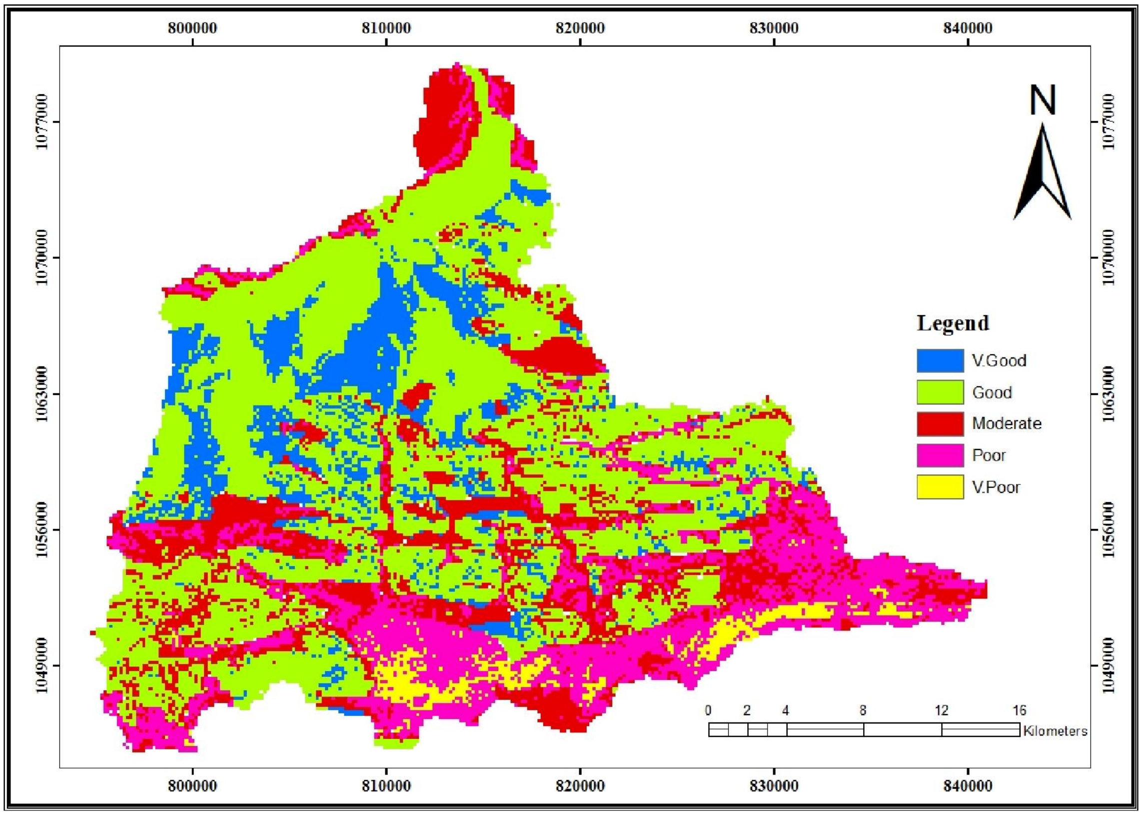

Figure 6.2. Groundwater potential zone map

6.1.1 Model validation

The validity of the model was checked against borehole, dug well, spring data distribution and bore hole yield which reflects the actual groundwater potential of the area; where out of 90 (With and without yield value) borehole data collected from (WWDSE, 2003) 81 are on very good and good zone, 9 on moderate zone, but in poor and very poor zone there is no any borehole drilled. From all of 27 dug wells and 23 springs covering the entire field area, 22 of them are located in very good and good groundwater potential zone and the other 5 dug wells are in the moderate zone. In poor and very poor zone there is no any dug well which observed in the area. From 23 springs distributed on the area 11 of them are located in very good and good zone and 12 are in moderate and poor zone. The (Fig. 6.3) shows that there exists a good correlation of borehole, dug wells and springs distribution with the potential zone.

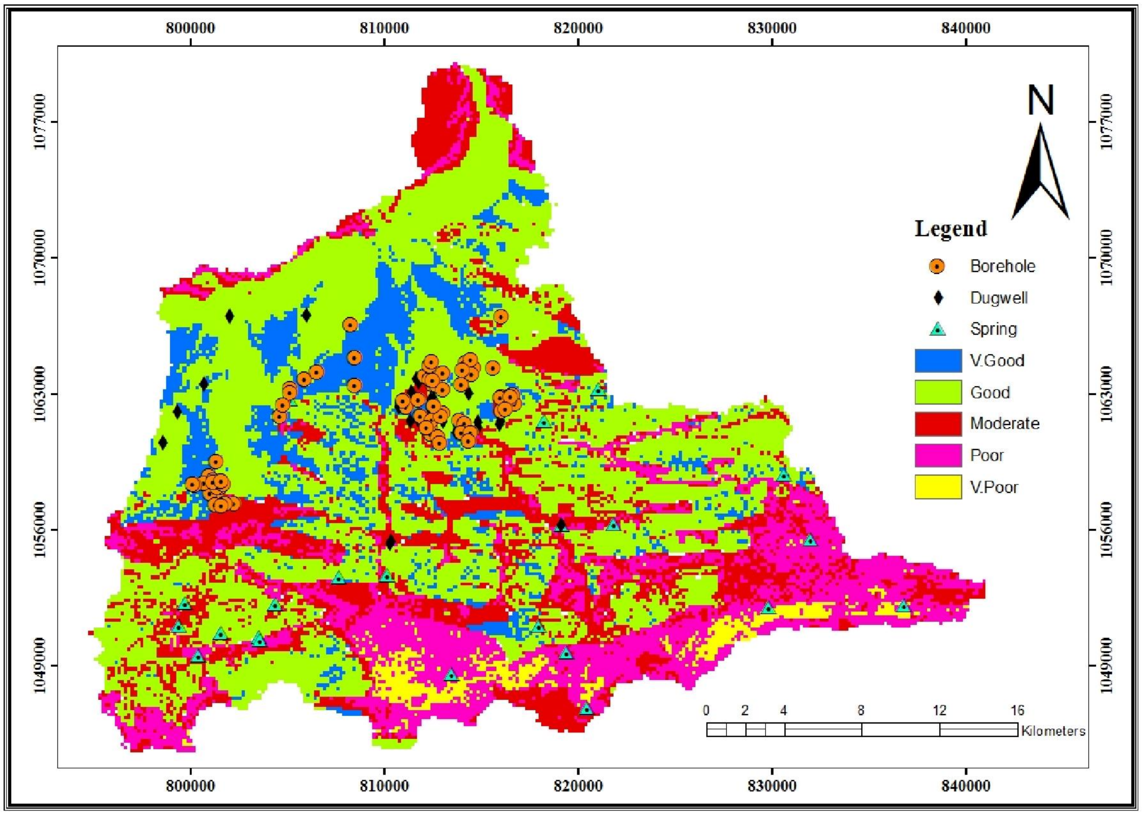

Figure 6.3 Comparison of water point locations with Groundwater potential zone map

Moreover out of 47 bore holes with yield between 0.4-10l/s, 41 bore holes are on the very good and good zones and 3 on moderate zone; out of 14 bore holes with yield between 10-20l/s all of them are in very good and good zone and from 18 bore holes with yield between 20-60l/s 13 are in very good and good zone, only 5 are in moderate area (due to deep drilling from 214m – 250m) which reflects the actual groundwater potential (Fig. 6.4). Although some wells exist in all groundwater potential zones, the best yielding wells lie in the very good and good groundwater prospect zones. Table 6.2 shows the comparison of actual yield data of Boreholes with resulting groundwater prospect zone.

The result generated will help as a guideline for designing a suitable groundwater exploration plan in the future. The spatial distributions of the various groundwater potential zones obtained from the result generally show regional patterns of lineaments, lithology, slope and geomorphology.

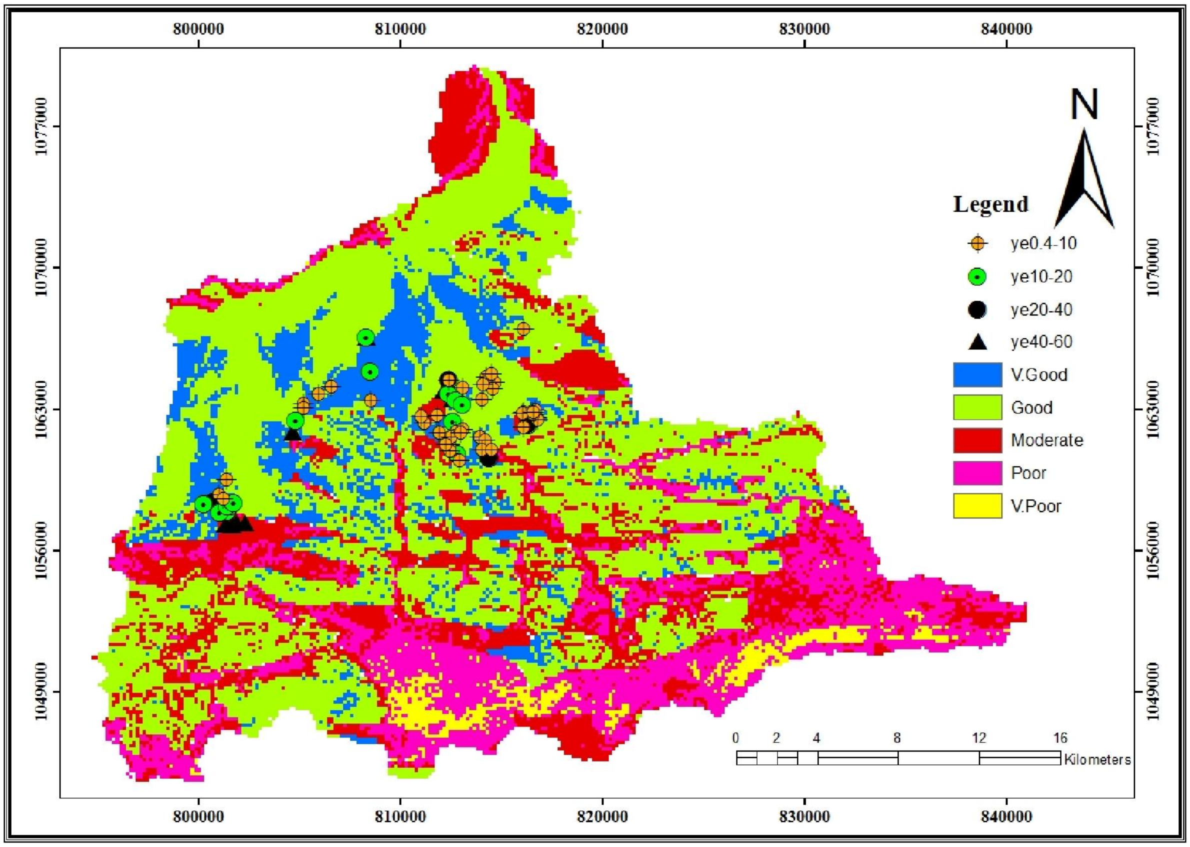

Figure 6.4 Comparison of well yield with Groundwater potential zone map

Table 6.2 Comparison of actual yield data of Boreholes with result

No.	Site Name	Easting	Northing	Yield (l/s)	Groundwater potential Model result
1	Melkajebdu(old)	806549	1064183	0.40	Very good
2	Police training	812730	1061950	0.60	Good
3	High way author	813073	1062031	0.78	Good
4	Cement Fac. NPW-1	812515	1061646	1.00	Good
5	Textil Old W-11	816677	1062984	1.00	Very good
6	Textile Old W-5	816090	1062140	1.00	Moderate
7	Dire Jara W-2	801394	1059555	1.00	Very good
8	Textile Old W10	816025	1062825	1.50	Good
9	Pig farm	810987	1062681	1.87	Moderate
10	Textile No. 4	816792	1062510	1.90	Good
11	Textile-1(old)	816702	1062643	2.00	Good
12	Well drilling c	811900	1061880	2.20	Good
13	D/D R.R.C.	814072	1064275	2.58	Good
14	Melka Jebdu-3	805167	1063299	3.00	Good
15	Amdael #2	814239	1064632	3.00	Good
16	Genderige BH-6	805945	1063792	3.00	Very good
17	Textile A.W. 4	814522	1064772	3.30	Good
18	Prison	814010	1063530	3.30	Good
19	East Afri Bot#2	814020	1061049	3.30	Good
20	Dire Jara W-9	801238	1058620	3.41	Very good
21	Palace	814172	1061499	3.80	Good
22	Locust control	811806	1062708	4.00	Good
23	Textile-2(old)	816573	1062781	4.10	Very good
24	Textile Old W-3	816481	1062864	4.30	Very good
25	Cement old BH-2	811170	1062350	4.40	Moderate
26	East Afri Bot#3	814520	1061049	4.50	Good
27	Municipality#1	812440	1061310	4.50	Good
28	Cement Fac. NPW-4	812248	1061295	4.50	Good
29	Genderige BH-3	805170	1063115	5.00	Good
30	Airport (erer)	813060	1064100	5.00	Good
31	Textile O.W-14	816103	1067017	5.17	Good
32	Textile A.W 3	814531	1064064	5.20	Good
33	Textile Old W-9	816080	1062886	5.42	Good
34	Textile N.W 3	816584	1062892	6.00	Very good
35	Rail way statio	813936	1061662	6.00	V.Good
36	Genderige BH-5	808532	1063462	6.50	Very good
37	Municipality#2	812460	1060990	6.70	Good
38	Unive Oil	812952	1061856	7.20	Good
39	Textile A.W-1	814343	1064427	7.70	Good

40	Cement Fac. NPW-3	812898	1060504	8.00	Very good
41	Textile A.W-2	814652	1064390	8.20	Good
42	DDU	812384	1064499	9.31	Good
43	Dire Jara W-1	801010	1058803	10.00	Very good
44	Dire Jara W-8	801047	1057939	10.74	Good
45	Al-Falath -Melka	804805	1062481	11.00	Good
46	Sabian Pw-7	813081	1063268	13.00	Good
47	Sabian Pw-6	812767	1063462	13.30	Good
48	Sabian Pw-8	812573	1062411	13.30	Good
49	DDU	808291	1066600	13.87	Very good
50	Sabian Pw-5	812362	1063793	14.00	Good
51	Cement Fac. NPW-2	812786	1060805	14.00	Very good
52	Industry village -Pw11	808515	1064885	15.00	Very good
53	Dire Jara W-7	801409	1057966	18.70	Very good
54	Dire Jara W-15	801425	1058252	19.00	Very good
55	Dire Jara W-17	801738	1058408	19.00	Very good
56	Dire Jara W-16	800276	1058325	19.80	Very good
57	Dire Jara w-10	801606	1058257	19.80	Very good
58	Lege Hare	816277	1062258	20.00	Very good
59	Sabian	812384	1064499	20.00	Good
60	Dire Jara W-5	801225	1058126	20.01	Very good
61	Dire Jara W-4	800965	1058414	20.30	Very good
62	Dire Jara W-11	800722	1058418	20.30	Very good
63	Dire Jara W-14	801484	1058356	20.30	Very good
64	Dire Jara W-6	800965	1058414	22.80	Very good
65	Addis Ketema	814415	1060601	33.00	Very good
66	Sabian Pw-4	812527	1063543	40.80	Good
67	Sabian Pw-2	812097	1063961	42.00	Good
68	TW1-2006	808291	1066600	45.00	Very good
69	Sabian Pw-1	812491	1063930	45.40	Good
70	Melka	804646	1061899	50.00	Very good

6.2 Discussion

The full potential of remote sensing and GIS can be utilized when an integrated approach is adopted. Integration of the two technologies has proven to be an efficient tool in groundwater studies (Kavitha *et al.,* 2011). Spatially, the very good and good categories occupies large area of the Dire dawa rivers catchment and they are distributed mostly along areas near to lineaments in the complex morphology of the central and escarpment, where the lithology is affected by secondary structure and having interconnected pore spaces and less drainage density towards the north in the alluvial plains. These highlight the importance of lineaments, lithology and geomorphological units for groundwater investigations.

Lineaments, landform, rock type and weathered zone conditions are the major controlling parameters in assessment of groundwater potential zones (ObiReddy *et al.,* 2000). Areas with moderate groundwater prospects are attributed to contributions from combinations of the high drainage density, lineament density, land use/cover, lithology and soil. The poor to very poor categories of groundwater potential zones are spatially distributed mainly along escarpment where slope class is steep to very steep; the lithology is compact/massive, clay soil composition and very low to low lineament density. Groundwater potential map clearly indicate that alluvial plain which is composed of sand, silt and clay with gentle slope, very low drainage density and double recharging area from precipitation and main rivers has Very good and good groundwater potentiality.

The foot of escarpment with gentle slope and low drainage density poses good to very good potential while alluvial plain with silty clay to fine sand has moderate to poor potential due to less water transmisivity of the formation. Structural hill at the center and linear escarpment on the southern part of the catchment with very steep slope and high drainage density; but due to presence of high lineament density and shallow depth to water level offer poor to moderate potential. Most of the southern margin, south eastern and small areas along the northern margins of the catchment with low lineament density, very steep slope and very high drainage density lie in very poor potential zones. Thus the generated groundwater potential map serves as a base line for future exploration.

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The objective set out was accomplished. In this work the utility of geospatial technologies in estimating the groundwater potential in Dire dawa rivers catchment has been demonstrated. This was achieved through preparation of land-cover maps from classification of Landsat (ETM+ 2011) imagery, generation of lineament density maps, drainage density map, Lithological map, geomorphological map, soil map and depth to water level map and evaluation of the various parameters using the Arc MAP 10.1, IDRISI 15.0 and ERDAS Imagine 9.2 and delineation of groundwater potential zones map. Contour and DEM maps have been developed from SRTM. The highest and lowest elevations were found to be 2411m at the southern margin and 929m at the northern part of the area respectively. Slope map was prepared from the DEM map. Slopes of the study area were found to vary between 0 to 64^{o}. The various soil units obtained from soil map are Eutric fluvisols (Fle), Eutric Leptosols (Lpe), Lithic Leptosols (Lpq), Chromic Luvisols (Lvx), Humic Nitosols (NTu) and Haplic Phaeozems (PHh) with coverage percentages of 27.4, 33.3, 670.2, 30.1, 10.8 and 38 km^2 respectively. The soil unit Lithic Leptosols (Lpq) is found to be predominant, covering 82.8 % in the study area. In order to gather information from the images, image pre-processing, directional or edge detection filter, contrast and spatial filtering enhancements were performed. Different false color composite images were generated and Study area has been classified for Land Use / Land Cover into five classes as agricultural land, physiographic vegetation, bare land, and urban built-up and river sand with areal extents of 309.843, 371.7482, 98.4726, 11.9538, and 17.3088 km^2 respectively. physiographic vegetation class in the study has been found to be predominant with 45.9% of the total area. Various geomorphologic units such as alluvial plains, transitional area and escarpment were generated in the area. Accordingly lineament density and lithology were digitized from geologic maps. The digitized lithologic units were reclassified in to 9 class based on their relative significance for the occurrence of groundwater. Field survey was conducted to collect point data (ground truth point) for image Classification and accuracy assessment. GIS analysis was conducted on the input dataset to get new derived information. All resulting maps were reclassified to common scale and class weight was assigned using pair-wise comparison matrix.

These maps have been overlaid in terms of weighed overlay method using Spatial Analysis tool in Arc GIS 10.1 version. During weighed overlay analysis, the ranking has been given for each individual parameter of each thematic map and weights of 24%, 22%, 18%, 13%, 10%, 6%, 4%, 2% and 1% were assigned according to their influence for lithology, geomorphology, slope, lineament, Soil, rainfall, drainage density, Land use/Land cover and static water level depth maps respectively and obtained five groundwater potential zones in terms of Very good, Good, Moderate, poor and very poor zones. Finally, the respective areal extents of very good, Good, Moderate, poor and very poor zones were calculated and found to be 95.58, 375.46, 171.96, 142.56 and 24.3 km^2 respectively. The groundwater potential zone map generated through this model was verified using borehole, dug well, spring data and borehole yield collected from (WWDSE) datas.

These techniques have been successfully used and demonstrated for evaluation of groundwater potentiality of the area. The groundwater potential map (Fig.6.2) around main alluvial deposit and in some parts of central and north-eastern region shows very good potential whereas greater part of the area shows good groundwater potential. Whereas moderate potential is dominantly cover the central, northern, north east and south western part; Poor and very poor groundwater potentials are confined mostly in the hilly terrain (Escarpment) area. Generally the most suitable areas for groundwater prospecting were shown to be those in the central and northern half of the catchment. While many of the existing boreholes yielding between 0.4-60 l/s and dug wells with good discharges are lie in these areas, there are some boreholes falling outside these areas, but these are still in the moderately suitable areas.

7.2 Recommendations

Based on the present study the following recommendations are made:

Remote sensing data are powerful tools to improve our understanding of groundwater systems and provide continuous detailed terrain information and allow the mapping of features significant to groundwater development in shorter time and lesser cost. Therefore integration of these data with ground based information in GIS environment is recommended for groundwater development projects.

It is recommended that Selection of drilling sites for ground water was based on spectral reflectance from multispectral high-resolution satellite data for identification of interconnected fractures exposed and hidden within the soil and vegetation cover.

For the current groundwater potential zone map generated from different groundwater controlling factors based on the datas collected from previous studies and Input data as satellite images and ground control points for accuracy assessment, water point datas (borehole, dug wells and spring) and yield data plays great role for the validation of the map. It is also highly recommended to conduct further validation of the maps using groundwater modeling, geophysical investigation and additional seasonal well discharge.

Despite various satellite data with different spectral and spatial resolutions together with digital image processing techniques help to produce detailed maps, ground verification is crucial to increase the accuracy of the interpretation results.

For more realistic result detailed ground verification of thematic layers generated from satellite images and GIS model output needs to be done.

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ANNEX S

Annex -1 Water point Data Base

Annex -2 Climatological Data Base

Annex -3 Geological map of Dire dawa and Harrar area

Annex -4 Landsat ETM+ (2011) path 166 and Row 053

Annex 1. Water points Data Base

Boreholes data

No.	Well ID	Location	x	y	Well depth	SWL	Well yield
1	BH-04	Cheremiti-#2	864535	1079607	101	21.42	0.4
2	BH-09	Melka Jebdu-3	805167	1063299	106	23	3
3	BH-52	Rail way statio	813936	1061662	62	29.77	6
4	BH-54	Textile-1(old)	816702	1062643	45.7	25.1	2
5	BH-12	Palace	814172	1061499	48.8	34.1	3.8
6	BH-26	Dire Jara W-1	801010	1058803	163.5	49.6	10
7	BH-27	Dire Jara W-2	801394	1059555	161.5	88.22	1
8	BH-29	Dire Jara W-4	800965	1058414	123.4	56.6	20.3
9	BH-30	Dire Jara W-5	801225	1058126	156.5	64.5	20.01
10	BH-31	Dire Jara W-6	800965	1058414	105.5	59.6	22.8
11	BH-32	Dire Jara W-7	801409	1057966	172	67.45	18.7
12	BH-33	Dire Jara W-8	801047	1057939	187.6	69.8	10.74
13	BH-34	Dire Jara W-9	801238	1058620	176	52.08	3.41
14	BH-35	Dire Jara w-10	801606	1058257	150.45	58.45	19.8
15	BH-36	Dire Jara W-11	800722	1058418	126	57.71	20.3
16	BH-39	Dire Jara W-14	801484	1058356	154	50.12	20.3
17	BH-56	Textile Old W-3	816481	1062864	61	25.9	4.3
18	BH-57	Textile No. 4	816792	1062510	62.5	27.4	1.9
19	BH-17	Amdael #2	814239	1064632	124	24	3
20	BH-25	Jeldesa	842515	1076753	90	23.7	0.4
21	BH-10	East Afri Bot#2	814020	1061049	120	36.5	3.3
22	BH-11	East Afri Bot#3	814520	1061049	125	36.5	4.5
23	BH-80	Genderige BH-3	805170	1063115	80	11.55	5
24	BH-91	Hurso mil.camp	788387	1057037	115	23.84	20
25	BH-40	Dire Jara W-15	801425	1058252	175	60.56	19
26	BH-41	Dire Jara W-16	800276	1058325	198.5	54.64	19.8
27	BH-42	Dire Jara W-17	801738	1058408	141.7	54.63	19
28	BH-43	Sabian Pw-1	812491	1063930	72.4	13.5	45.4
29	BH-44	Sabian Pw-2	812097	1063961	98.8	9.3	42
30	BH-46	Sabian Pw-4	812527	1063543	104.6	19.7	40.8
31	BH-47	Sabian Pw-5	812362	1063793	101.8	15.9	14
32	BH-48	Sabian Pw-6	812767	1063462	86.2	22.8	13.3
33	BH-49	Sabian Pw-7	813081	1063268	82.7	23.7	13
34	BH-50	Sabian Pw-8	812573	1062411	87.7	15	13.3
35	BH-55	Textile-2(old)	816573	1062781	61	18.8	4.1
36	BH-77	Bore TW4(2002)	796050	1058100	160	31.06	21.3
37	BH-95	Prison	814010	1063530	47.8	21.7	3.3
38	BH-98	Airport(erer pr	813060	1064100		16	5

39	BH-99	Municipality#1	812440	1061310	33.5	25.3	4.5
40	BH-100	Municipality#2	812460	1060990	35	21.9	6.7
41	BH-101	Municipality#3	812460	1060990	32.5	10.3	6.7
42	BH-83	Genderige BH-5	808532	1063462	80	18.68	6.5
43	BH-84	Genderige BH-6	805945	1063792	50	18	3
44	BH-105	Police training	812730	1061950	65.6	22	0.6
45	BH-106	Well drilling c	811900	1061880		41.1	2.2
46	BH-58	Textile Old W-5	816090	1062140	70.1	35	1
47	Bh-62	Textile Old W-9	816080	1062886	50	39	5.42
48	BH-63	Textile Old W10	816025	1062825	50	41	1.5
49	BH-64	Textil Old W-11	816677	1062984	59	17	1
50	BH-65	Textile O.W-14	816103	1067017	78	42.2	5.17
51	BH-66	Textile A.W-1	814343	1064427	116	37.3	7.7
52	BH-67	Textile A.W-2	814652	1064390	82.3	32.13	8.2
53	BH-68	Textile A.W 3	814531	1064064	91	26.42	5.2
54	BH-69	Textile A.W. 4	814522	1064772		35.71	3.3
55	BH-70	Textile N.W 3	816584	1062892		14.86	6
56	BH-85	Cement old BH-2	811170	1062350	25	12.8	4.4
57	BH-86	High way author	813073	1062031	47.2	30.5	0.78
58	BH-87	D/D R.R.C.	814072	1064275	63	27.5	2.58
59	BH-88	Locust control	811806	1062708	48.7	21	4
60	BH-113	Melkajebdu(old)	806549	1064183	125.9	43.4	0.4
61	BH-89	Pig farm	810987	1062681		20.74	1.87
62	PW1	Melka	804646	1061899	86	25.65	50
63	PW1	DDU	808291	1066600	150	33.25	13.87
64	PW2	DDU	812384	1064499	118	18.35	9.31
65	PW-19	Addis Ketema	814415	1060601	110	45.59	33
66	PW-20	Lege Hare	816277	1062258	266	39.55	20
67	PW-21	Sabian	812384	1064499	221	64.05	20
68	BH-102	Cement Fac. NPW-1	812515	1061646	120	19.24	1
69	BH-103	Cement Fac. NPW-2	812786	1060805	110	28.8	14
70	BH-104	Cement Fac. NPW-3	812898	1060504	137	25	8
71	BH-105	Cement Fac. NPW-4	812248	1061295	168	24	4.5
72	BH-124	Unive Oil	812952	1061856	45	23.14	7.2
63	BH-127	TW1-2006	808291	1066600	221	45.58	45
64	BH-128	Industry village - Pw11	808515	1064885	108		15
75	BH-129	Al-Falath -Melka	804805	1062481	102	27	11
76	TW-1	Haseliso	801859	1057371	220	80.12	43
77	NPW-1	Haseliso	802293	1057401	220	73.57	57
78	NPW-2	Haseliso	801838	1057385	214	80.93	57
79	NPW-3	Haseliso	801309	1057318	252	89.54	54
80	NPW-4	Haseliso	801632	1057297	218	90.13	54

Dug well data

N0.	Well Index	Local Name	UTM north	UTM east
1	DW-14	D/DEdible oil f	1061925	812941
2	DW-30	Tony farm #1	1063611	811769
3	DW-31	Christos school	1061283	814820
4	DW-32	Ras hotel	1061030	813690
5	DW-17	Pigtry	1062750	812380
6	DW-33	Lime factory	1062590	810820
7	DW-34	Old Italian wel	1061720	811710
8	DW-35	Lime fact.Kemal	1061620	811350
9	DW-36	Malaria Control	1061560	814800
10	DW-37	Abdela Ahmed	1061825	814630
11	DW-38	Asefa Adefres	1062740	812520
12	DW-39	Abdurahman hus	1061625	815980
13	DW-40	She Ismael mosq	1061450	815930
14	DW-41	Belewa #2	1053804	840942
15	DW-42	Kanchara #2	1055427	810324
16	DW-01	Jeldesa	1075928	841574
17	DW-02	Garba Anano	1072551	857203
18	DW-27	Goro(Mohamed)	1062334	810738
19	DW-03	Kalicha	1059032	833527
20	DW-23	ELFORA	1062365	811200
21	DW-04	Tsehay Hotel	1061596	813009
22	DW-06	Kenchera #1	1055328	810272
23	DW-07	Ejaneni	1056268	819113
24	DW-08	Belewa#1	1058278	840894
25	DW-09	Gende Sur	1062084	799308
26	DW-10	Bore	1060531	798554
27	DW-12	Grba Anano	1072675	857182
28	DW-11	Koran Goga	1063496	800714
29	DW-15	Goladeg	1067013	802030
30	DW-16	Arsho Adele	1067040	806000
31	DW-21	Cement Factory	1061937	812282
32	DW-24	WFP(ABIKIAN)	1063061	814317
33	DW-28	Tony Farm #3	1063118	811366
34	DW-29	Tony farm #2	1063807	811633

Spring Data

N0.	Index	Local Name	UTM_N	UTM_E	Spring type
1	SP-7	Belewa	1057346	842176	Joint
2	SP-8	Medekedjima	1052194	804366	Contact
3	SP-9	Gende Boru	1050527	803501	Contact
4	SP-10	HARAWATU	1050333	803522	Contact
5	SP11	Borte	1049534	800391	Joint
6	SP-12	Wahil Muluke	1050728	801534	Depression
7	SP-13	Fechase	1055546	831945	Depression
8	SP-14	Cement Factory	1061280	812255	Depression
9	SP-15	Eftua	1054557	843185	Joint
10	SP-30	Legahrtu(hotsp)	1085780	847988	Depression
11	SP-1	Legemeda	1053559	807621	Depression
12	SP-2	Halobusa(Legego	1053690	810084	Joint
13	SP-3	Keche	1046854	820449	Dyke
14	SP-4	Adada	1056268	819112	Joint
15	SP-16	Serkama	1057387	845129	Joint
16	SP-17	Gendesale	1055943	835486	Contact
17	SP-18	Awale Roresa	1052144	836775	Joint
18	SP-19	Bishambaye	1058862	830595	Depression
19	SP-5	Biyoawale	1052057	829794	Contact
20	SP-6	Gende kurto	1057243	837595	Joint
21	SP-20	Harla	1049728	819375	Joint
22	SP-21	Legehare	1061625	818219	Depression
23	SP-22	Mudi Anano	1063252	820995	Joint
24	SP-23	Jarso sp.#1	1049999	855079	Joint
25	SP-24	Jarso-Gendelege	1049830	852823	Joint
26	SP-25	Legedomirga	1048587	813438	Joint
27	SP-26	Jelobelina	1051086	817946	Dyke
28	SP-27	Jarso Sebelo	1050555	858960	Joint
29	SP-28	Koriso	1051072	799366	Joint
30	SP-31	Hulul mojo	1052250	799700	Joint
31	SP-32	Lega bira	1056305	821822	Contact
32	SP-29	Melka(Fuad Haji	1062727	805106	Depression

(Source: WWDSE, 2003-2008)

Annex 2 Climatological Data Base

The Mean annual rainfalls in (mm) at Dire dawa, Dengago and Kersa station from (1995-2009)

Year	**Mean Annual Precipitation**		
1995	49.2	69.6	66.44
1996	79.64	67.2	87.2
1997	74.3	82.5	45.2
1998	73.77	73.3	63.8
1999	51.31	37.7	58.2
2000	36.38	55.8	82.9
2001	56.93	74.3	90
2002	44.39	22.8	28.5
2003	51.19	59	69.3
2004	47.15	48	35.5
2005	37.78	45.3	51.6
2006	58	60.33	69.88
2007	58.8	60.96	70.19
2008	36.36	43.39	61.43
2009	34.56	41.99	60.73

(Source: NMA and Daniel Alemayehu, 2007)

Mean monthly rainfalls (mm) of Dire dawa station from (1995-2009)

Year	January	February	March	April	May	June	July	August	September	October	November	December
1995	0	0	131.3	124.5	56.5	16.8	100.4	70.8	76.3	8.7	0	4.7
1996	29.3	1	161.1	133.8	132.4	64.7	189.5	155.4	54.9	1	32.6	0
1997	56.7	0	95.2	142.4	34.4	75	81.1	102.9	16.2	266.9	20.8	0
1998	93.9	29.3	75.2	64.7	87.3	17.1	100.2	134.1	215.2	59.1	9.1	0
1999	0	1.3	158.3	28.3	21.8	17.5	97.1	174.6	40.1	71.4	3.6	1.7
2000	0	0	13.8	26.5	7.1	20	71.9	112.4	93	24.7	23.6	43.6
2001	0	0	128.7	28	49.5	22.3	111.7	241.5	74.9	15.8	4.7	6
2002	34.8	0	80.9	83.1	33.3	9.7	49.4	126.8	65.8	18.7	0	30.2
2003	14.4	11.3	37	98.5	2.2	65.2	136.3	53.1	63.6	2.1	0.8	129.8
2004	39.3	0	44.3	130.1	0.3	12.6	54.5	111	59.1	85.6	23.3	5.7
2005	2.5	3.4	78.5	40.9	28.3	48.3	84.7	76.9	89.9	0	0	0
2006	10.7	4.9	94.2	163.4	29.4	5.1	87.3	145.8	70.2	13.3	0	71.7
2007	0	27.8	27.3	180	21	67.5	128.7	91.4	129.1	30.2	2.7	0
2008	10.5	0	0.2	53.3	112.8	10.2	79	124.4	43.9	2	0	0
2009	38.9	12	31.8	0	24.2	51.6	72	82.8	25.7	31.4	35.8	8.5
Mean	22.06	6.06	77.186	86.5	42.7	33.573	96.253	120.26	74.526	42.06	10.46	20.126

Mean monthly Max. Temperature (^oC) of Dire dawa station from (1995-2009)

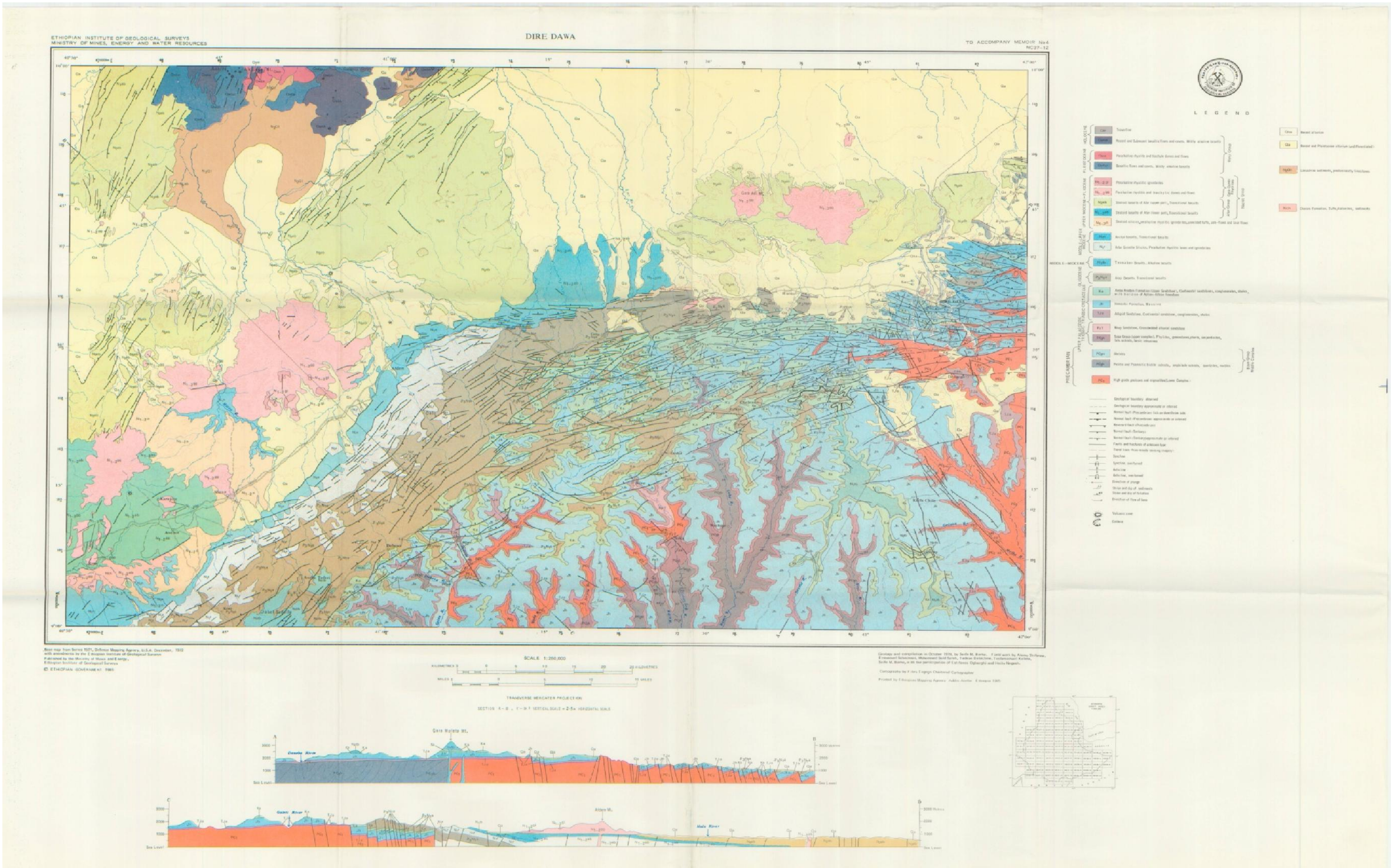
Year	January	February	March	April	May	June	July	August	September	October	November	December
1995	28.7	0.0	30.2	31.4	35.1	36.1	33.5	33.0	34.0	33.2	31.2	29.6
1996	28.9	31.2	31.8	32.0	32.7	32.9	32.7	33.1	32.9	33.2	30.1	29.1
1997	28.4	29.7	32.2	31.3	34.6	34.4	33.0	33.6	34.9	30.2	29.2	29.5
1998	28.2	29.5	31.9	34.4	34.5	37.2	33.9	32.2	32.1	31.7	30.6	29.2
1999	29.7	32.0	30.0	34.3	35.4	35.7	33.2	32.5	32.8	30.9	30.5	28.9
2000	29.6	31.4	33.1	34.5	35.8	36.1	34.6	32.3	32.8	32.2	29.9	28.7
2001	27.9	30.7	31.6	34.8	35.5	36.0	34.1	31.4	32.6	33.7	31.1	29.8
2002	28.0	31.6	32.0	33.4	36.7	36.4	35.4	33.6	33.4	34.1	32.0	28.8
2003	29.2	32.0	32.8	33.7	36.3	35.1	33.3	32.3	33.2	33.9	31.4	28.5
2004	29.2	30.4	32.5	32.4	36.6	35.5	33.4	33.6	33.4	31.5	31.0	29.2
2005	29.7	32.6	33.0	34.2	34.6	35.6	33.1	33.6	33.6	33.5	32.1	29.6
2006	29.4	31.8	32.2	31.7	35.1	36.2	34.5	32.5	33.2	32.7	31.7	28.4
2007	28.8	31.8	34.3	34.1	36.5	35.3	32.9	32.3	32.7	33.5	31.0	29.5
2008	29.6	30.1	34.1	35.0	35.0	35.6	34.6	33.7	34.4	33.3	0.0	0.0
2009	28.8	32.2	33.6	0.0	36.5	36.9	34.9	34.8	35.2	33.2	31.8	30.3
Mean	28.9	31.2	32.3	33.4	35.4	35.7	33.8	33.0	33.4	32.7	31.0	29.2

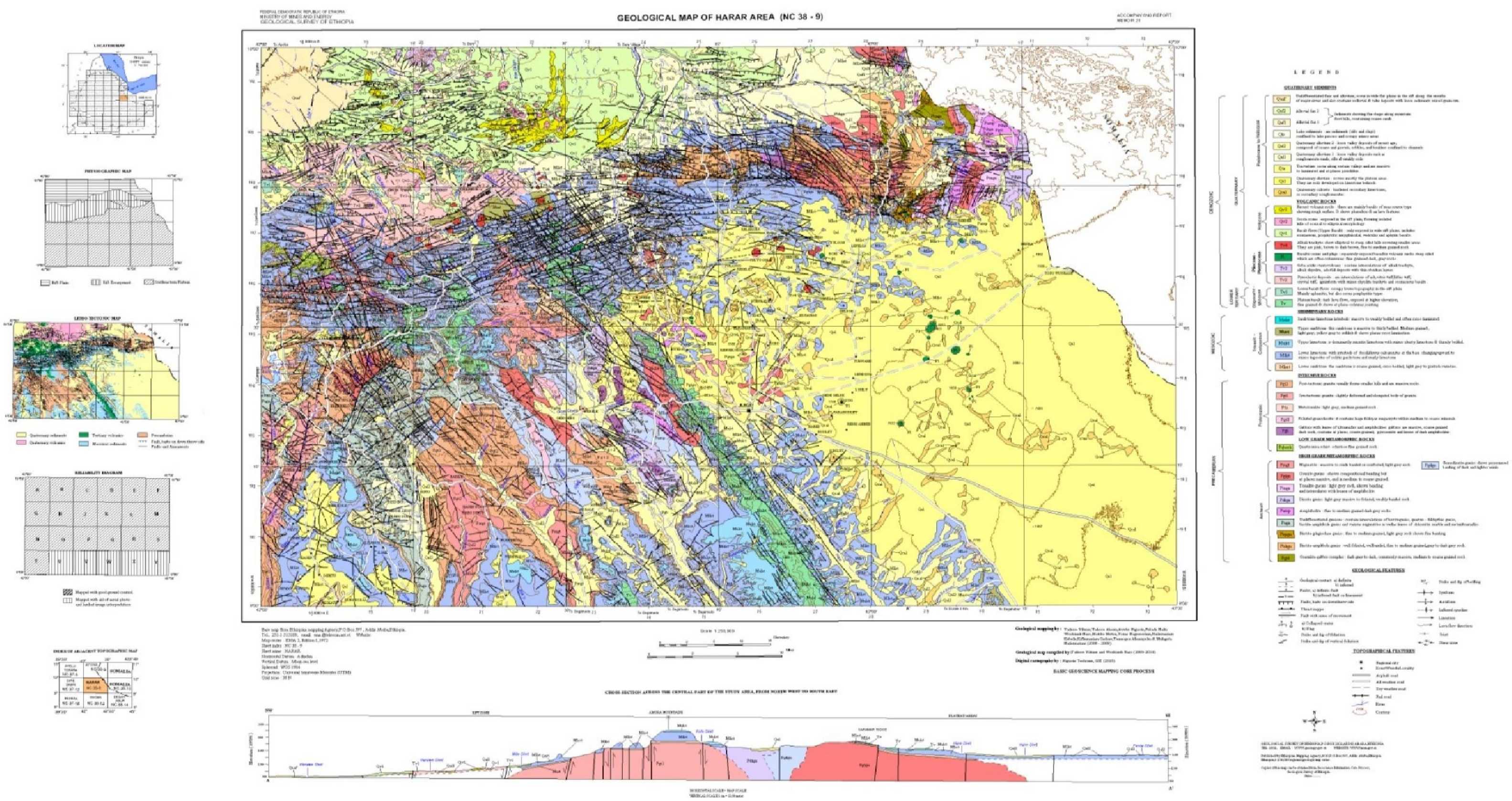
Mean monthly Min. Temperature (^oC) of Dire dawa station from (1995-2009)

Year	January	February	March	April	May	June	July	August	September	October	November	December
1995	13.1	0.0	18.8	20.5	22.1	22.9	20.8	20.6	21.3	19.6	16.2	16.8
1996	16.6	16.2	20.0	20.1	20.3	20.9	20.6	20.7	21.1	18.1	16.0	13.9
1997	15.3	14.6	19.6	19.7	20.8	21.3	20.5	20.1	21.9	17.9	17.0	14.8
1998	16.9	18.0	20.3	22.0	22.3	23.4	20.8	20.5	19.7	19.2	15.4	13.4
1999	14.5	15.9	18.5	20.9	22.2	22.4	20.4	20.2	21.1	18.5	15.1	13.8
2000	13.9	15.0	17.3	20.2	22.7	22.7	21.4	20.3	21.1	19.0	16.8	15.1
2001	14.1	15.9	19.5	20.6	22.5	22.5	21.4	19.7	20.1	19.4	15.3	15.0
2002	15.7	15.3	19.2	20.6	23.4	22.9	22.2	20.9	21.2	19.5	16.4	17.5
2003	16.2	18.2	19.1	21.0	22.8	22.5	20.9	21.2	21.2	19.2	17.0	15.5
2004	17.4	15.9	18.2	20.8	23.2	23.2	21.5	21.1	20.7	17.4	16.1	15.6
2005	15.8	16.4	19.9	20.1	22.2	22.8	21.1	21.3	21.3	19.3	16.5	13.6
2006	15.7	17.8	18.8	20.0	21.9	23.4	21.1	19.3	20.4	20.0	16.1	15.8
2007	15.2	17.4	19.2	20.4	22.5	22.1	20.6	20.1	20.1	17.8	15.5	13.3
2008	14.4	13.3	16.1	21.4	22.5	21.2	20.2	19.8	21.0	18.7	0.0	0.0
2009	15.0	16.1	18.9	0.0	22.6	22.9	21.0	21.4	22.0	19.1	16.2	16.7
Mean	15.3	16.1	18.9	20.6	22.3	22.5	21.0	20.5	20.9	18.9	16.1	15.1

(Source: National Meteorological Agency)

Annex 3. Geological map of Dire dawa and Harrar area





(Source: Geological Survey of Ethiopia, 1985)

Annex 4. Landsat ETM+ (2011) path 166 and Row 053