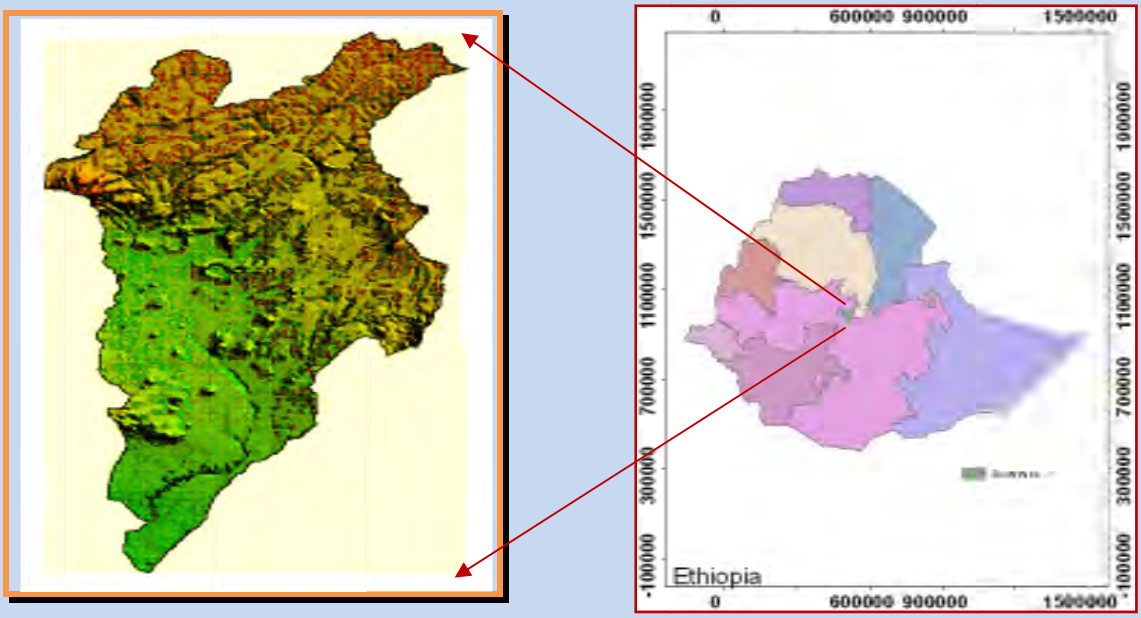
AQUIFER VULNERABILITY ASSESSMENT IN MODJO RIVER CATCHMENT (CENTRAL MAIN ETHIOPIAN RIFT)

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the Degree of MASTER of SCIENCE

In



HYDROGEOLOGY

By

EWNETU BEDANE

November 2008.

Ewnetu Bedane, 2008

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FACULTY OF SCIENCES

DEPARTMENT OF EARTH SCIENCES

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HYDROGEOLOGY

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ABSTRACT

The thesis entitled Aquifer Vulnerability Assessment In Modjo River Catchment is a study of the hydrogeological factors pertaining to the DRASTIC system and covers an area of 1527sq km in the Upper Awash River Basin, particularly Modjo River Catchment, northwestern shoulder of the Central Main Ethiopian Rift system bounded in the Zone 37 UTM grids of 930000meter N to 1005000meter N and 490000meter E to 535000meter E.

With increasing demand and reliance on groundwater from a growing population and agricultural activity comes the need to increase efforts to protect and manage the resources.

Urban, and Industrial development, as well as agricultural activities, are potential sources of groundwater contamination in the study area. The general objective of the research work is to identify and produce aquifer vulnerability map to pollution in Modjo River catchment and to assess the risk for groundwater pollution by adopting Geographic Information System (GIS) based DRASTIC system through producing thematic maps of pertinent hydrogeological factors within the catchment and finally to prepare both Intrinsic and Pesticide Vulnerability Maps and determine aquifer Vulnerability Classes based on DRASTIC Index values. Accordingly, high and very high vulnerable areas are found to occupy most of the gentle and plain terrains in the central and southern parts of the study area whereas low and very low vulnerable area occupy the elevated lands in the eastern, northeastern and northwestern parts of the catchment. Unfortunately the high and very high vulnerable areas occupy also the high and moderate groundwater potential zones identified by Sisay, 2007. This gives additional stimulus to the need to protect the groundwater in the study area.

The final use of such a study is to help planners and regulators make environmentally sound decisions regarding land use and groundwater protection.

Keywords: DRASTIC Model, Aquifer, Vulnerability, Intrinsic Vulnerability, Pesticide Vulnerability, Modjo River Catchment, Central Main Ethiopian Rift

CHAPTER ONE
1. INTRODUCTION

1.1. Background

The impact of human population on surface and groundwater is increasing with the development of industry, agricultural activity, uncontrolled urbanization, poor sanitation situation and population size in Modjo River Catchment.

Water quality degradation is one of the major environmental problems of these days. Most pollution originates from the disposal of wastewater following the use of water for any variety of purposes. According to (Todd, 1980) quoted by (Belema, 2004), a large number of sources and causes can modify groundwater quality, ranging from septic tanks to agricultural activities. The physical, chemical and biological quality degradation can limit the intended use of water. So, the quality of groundwater is receiving wide spread attention all over the world; and hydrogeological information is essential to the effective protection and management of groundwater quality (Assaminew, 2007).

The quality of groundwater can affect not only our health, but also society and the economy. Groundwater contamination can adversely affect property values, the image of a community, economic development, and overall quality of life we all share. Once groundwater has been contaminated, its effect may continue for indefinite periods since natural dilution is slow and artificial flushing or treatment is generally impractical or too costly. For many years, it was thought that groundwater was protected from contamination by the layers of rock and soil that act as filters, but contaminants do make their way into the groundwater and affect its quality (Dereje, 2003).

"By the time subsurface pollution is conclusively identified, it is too late to apply remedial measures.... Degradation of groundwater often requires long periods of time before the true extent of the problem is readily detectable. Long periods of groundwater flow are often required

for pollutants to be flushed from contaminated aquifers. Groundwater pollution often results in aquifers or parts of aquifers being damaged beyond repair" (Freeze and Cherry, 1979).

One of the major potential sources of groundwater contamination in the study area is agricultural activity. Even though the flower farm impacts on the groundwater quality is not yet detected as being practiced recently, it remains one of the potential threats to the groundwater due to uncontrolled discharge of the chemical effluents.

To be more specific, Groundwater is an important resource in much of Modjo River catchment. It supplies drinking water and other domestic and agricultural use for both rural and urban dwellers in the study area. Protection of the groundwater in the country has become a significant concern.

Therefore, it is crystal clear that there should be a protection of the groundwater resource from any pollution threat. To supplement the policy makers on groundwater resources management in this catchment, there must be map-based information that indicates spatial distribution of relatively vulnerable areas. Hence, this study is initiated to make available this information for the decision/policy makers and professionals who are interested to work on related issues.

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against the natural and human impacts, especially with regard to contaminants entering the subsurface environment.

1.2. Statement of the problem

With increasing demand and reliance on groundwater from a growing population and agricultural activity comes the need to increase efforts to protect and manage the resources.

The impact of human on surface and groundwater is increasing with the development of agricultural activity and population size in the Modjo River catchment. The currently identified problem, which is going to be applied in the indicated geological set-up and hydrogeological settings, is believed to meet the objectives mentioned.

There is a need to compile the groundwater data into information to enable more effective management decision-making regarding the resource. As well, a method of identifying and prioritizing aquifers for different types of management attention is becoming essential in an era of limiting budget resources.

This work is, therefore, planned to address and cater groundwater degradation by anthropogenic sources of pollutants which is critical problem to the society's resources and which is consistently facing development planners with regard to groundwater management. Furthermore, in order to conduct development in harmony with groundwater regime in particular, and the environment in general, the concerned development needs to have such comprehensive groundwater vulnerability map, which is used easily by other professionals.

1.3. Location, Aerial Extent, and Accessibility

Modjo River catchment is located in the northwestern shoulder of the Central Main Ethiopian Rift, at about 45-70kms road distance from Addis Ababa in the southeasterly direction, in Oromia Regional National State, East Shoa Administrative Region. It is located in the Zone 37 UTM grids of 930000meter N to 1005000meter N and 490000meter E to 535000meter E .The area is bordered with Yerer Mountain and Kesem River in the northwestern and northeastern limits respectively. Modjo River that flows from northeast to southwest is the main stream draining the area.

The catchment is delineated based on surface water divide using topographic maps of scale 1:50,000. It comprises parts of the four administrative woredas: Gimbichu, Ejere, Ade'a and Lume with a total surface area of 1527.34sq km and perimeter 301km. The area is traversed by the main high way from Addis Ababa to Djibuti. Most parts of the area are accessible from all directions by a number of all weathered roads, dry season roads and footpaths as well asphalt road.

It is accessible from Addis Ababa by main asphalt road running to Modjo town via Dukem and Debrezeit towns. There are secondary roads leading to Chefe Donsa and Ejere Towns respectively from Debrezeit and Modjo. (Figure1.1)

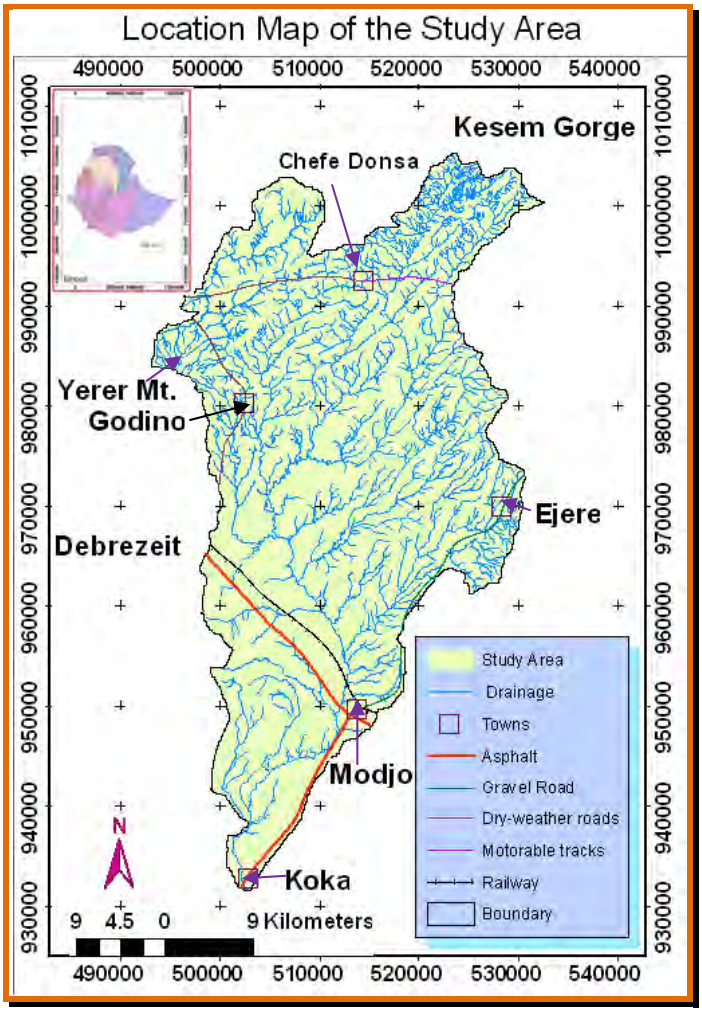


Figure 1.1 Location Map of the Study Area

1.4. Objectives

1.4.1General Objective

The general objective of the research work is to identify and produce aquifer vulnerability map to pollution in Modjo River catchment and to assess the risk for groundwater pollution by adopting Geographic Information System (GIS) based DRASTIC system through mapping the pertinent hydrogeological factors within the catchment.

1.4.2. Specific objectives

- To identify areas which are more likely to be susceptible to groundwater contamination relative to one another.
- Identifying the possible potential sources of pollutants in the study area.
- Characterizing the aquifers in the catchment.
- To study the hydrogeology, and groundwater flow direction within the catchment.
- To produce the Intrinsic and Pesticide vulnerability map.

1.5. Methodology

To meet the above specified objectives of the research project, the empirical model known as the DRASTIC model developed by the National Water Well Association under a cooperative agreement with the United states Environmental protection Agency(Aller et.al,1987; Evans and Meyers,1990) to assess relative groundwater pollution susceptibility using hydrogeologic factors with GIS was adopted.

Evaluating and mapping the seven parameters in the DRASTIC model, named:

D=**D**epth to water table,

R=Net **R**echarge,

A=**A**quifer media,

S=**S**oil media,

T= **T**opography/Slope,

I= **I**mpact of Vadose Zone media, and

C= Hydraulic **C**onductivity of the aquifer.

The following approaches related to the above method have been used to assess the aquifer vulnerability.

- Characterization of the meteorological elements and hydrological conditions of the catchment and its surroundings.
- Plotting all developed water schemes on 1:50,000 topographic maps.
- Characterization of various contaminants with in the catchment.
- Understanding the geologic and hydrogeologic set-ups of the catchment and adjacent catchments through observation of borehole logs from well completion reports, water well sitting reports, pumping test reports, irrigation scheme study reports, and water scheme inventory reports.

1.5.1. Data integration

The following flow chart (figure 1.2) shows data flow and procedures followed to prepare the seven DRASTIC maps for the aquifer vulnerability analysis.

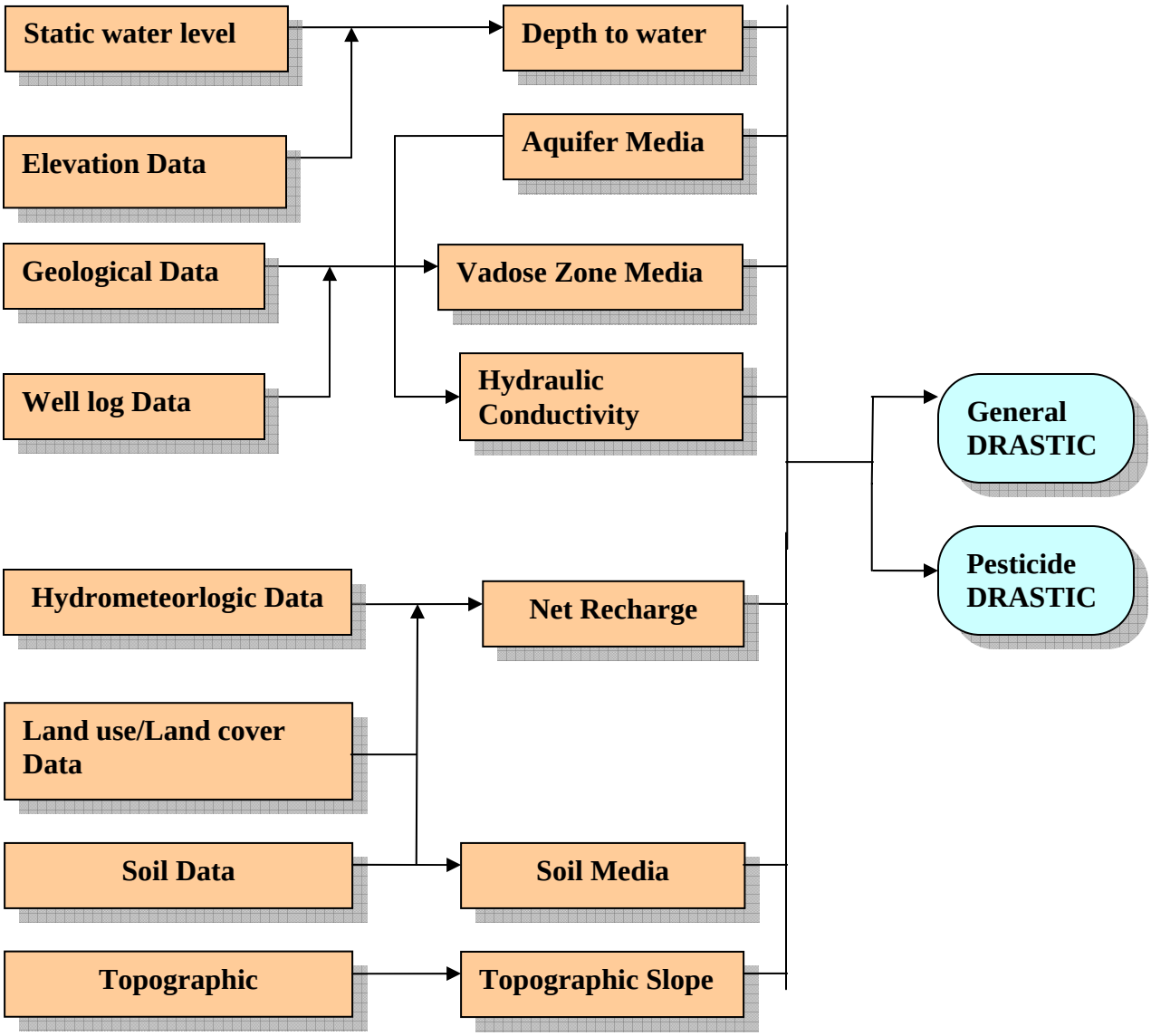


Figure 1.2.Flow Chart Showing Procedures Followed for Aquifer Vulnerability Mapping

In this thesis GIS (Arc GIS Version 9.2 software) is used as a tool for aquifer vulnerability mapping. Groundwater vulnerability is determined by assigning a weight based on rating for different ranges of the values. The typical ratings range from 1to 10 and the weights from 1to5.

1.5.2. Procedure to Evaluate Groundwater Vulnerability

First of all the seven thematic maps are produced for each hydrogeological settings which make up the acronym DRASTIC, and each DRASTIC factor is assigned a relative value of Ratings shown in Table 7.1

The value obtained is multiplied by its respective weight, and the seven layers or products are summed to obtain the DRASTIC index (D_I)(equation1.1). That means the additive-overlay processes in the corresponding data layer values(ratings) for a particular cell are multiplied by an important coefficient (weight) to produce a composite score called vulnerability index (Dereje Nigussa,2003). The equation for determining the DRASTIC index is:

$$\mathbf{D_I = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w} \text{ ---------- (1.1)}$$

Where, D, R, S, T, I, and C are the seven parameters stated before, and r=rating value W= weight.

Once a DRASTIC index has been computed, it is possible to identify areas which are more likely to be susceptible to groundwater contamination relative to one another. The higher the DRASTIC Index, the greater the groundwater pollution potential. The DRASTIC Index provides only a relative evaluation tool and is not designed to provide absolute answers. Therefore, the numbers generated in the DRASTIC index and in the pesticide DRASTIC cannot be equated (Aller et.al., 1987).

1.6. Application of Results

- Vulnerability maps can help planners and regulators make informed, environmentally sound decisions regarding land use and groundwater protection.
- Vulnerability maps are a good tool to make local assessment of groundwater vulnerability potential, to identify areas susceptible to contamination, to design monitoring networks, and evaluate groundwater contamination, particularly non-point contamination.

- They are also helpful for educating and informing planners, managers, and decision- and policy-makers about groundwater protection, risk of contamination, and contamination prevention.
- Assist decision and policy makers, (land use) planners and researchers to direct and prioritize resource for conservation of groundwater aquifers that are more vulnerable to pollution, and;

- The results can also be used to educate the public in the study area about groundwater being part of a large, interconnected ecological system.
- It also helps for similar studies in the adjacent areas and region which possess similar geological, hydrogeological and climatic conditions.
- The result will also be used as a data source for the feature researchers.

1.7. Previous Works

In Debre Zeit the majority of water used for domestic purposes comes from groundwater sources. Several groundwater related studies have been conducted in Debre Zeit which includes the whole Ada`a plain. Tamiru and Antonio (1995) (in Sisay 2007) have used all possible geological and hydrogeological methods for evaluation of groundwater potentiality together with chemical characteristics and their interactions with the country rocks. They have also explained that the area is part of the Ethiopian rift System that is characterized by a Plio-Quaternary volcanism which gave rise to trachytic domes, rhyolitic lava flows and rhyolitic ignimbrites in the upper part of the area and successive olivine basaltic lava flows, surge deposits and alluvial deposits. In their result of investigation the basaltic lava flows, occurring as alternative layers of amygdaloidal, fractured, vesicular and scoraceous basalts are found to be the best and the most productive aquifers in the area. In addition,

they pointed out that groundwater occurs within the basaltic layers under unconfined; semi confined or confined conditions, where the thick clayey and pyroclastic layers play an important role of aquitards. In their analysis of lake level fluctuation, they have shown that there is a good hydraulic connection between the explosion crater lakes and the groundwater circulation. Tibebe (2006) carried out Integrated Geophysical Investigation for the Evaluation of Groundwater Resources at Ada`a Plain Near Debre Zeit, in his MSc thesis. According to the author, the research was conducted to verify the inferred groundwater barrier and its possible connection to the linear structures. In his geophysical interpretation results, the magnetic survey was found to be useful in lithological mapping and identifying linear geologic features. On the magnetic map, NW-SE trending anomalies are in conformity with the anticipated groundwater barrier and the inferred groundwater barrier was not detected and mapped by resistivity method.

Alem (2004) carried out Hydrogeology of Modjo River, in his Msc thesis. In his research he has carried out conventional hydrogeological investigation in order to define the basic hydrogeological factors controlling the occurrence, movement and storage of groundwater in the Modjo river basin. In his research result he pointed that alluvial deposits, basaltic flows and domes are important permeable units, while fractured ignimbrite and rhyolitic ignimbrite are considered as medium permeability group and are also good water bearing units. The rest of geological units such as massive ignimbrites and lacustrine deposits are considered to be low permeable units.

Studies about Surface Water and Groundwater Pollution Problems in The Upper Awash River Basin, Ethiopia carried out by Adane (1999) show that the scoracious and vesicular basalts that out crop in the vicinity of

Debre Zeit and Akaki are highly permeable due to interconnection of pore space and high fracture system.

Studies about Natural Hydrochemical Variations and Anthropogenic Influences on Surface and Groundwater Systems in the Selected Urban Centers in the Upper Awash Basin carried out by Belema (2004), MSc thesis, shows high concentration of nitrate in some groundwaters above the standard limits in some boreholes like in Debrezeit Airforce,Blue Nile Plastics, Hora Tannery,Almaz Doro,CIM-Mission,Kalehiwot,Ade'Pasta and Macaroni and Debrezeit Management Institute. He also indicated considerable concentration of nitrate in some of the boreholes around Modjo Town like in Modjo Ethiopian Food Corporation and in some shallow wells. According to Belema's work, the high concentration of nitrate in shallow hand dug and boreholes indicate the interaction of surface water and groundwater.

Very recently (April, 2007), the Ministry of Water Resources has conducted studies on Evaluation of Water Resources of Ade'a and Becho Plains Groundwater Basin for Irrigation Development Project.

CHAPTER TWO
2. OVERVIEW OF THE STUDY AREA

2.1. Climate

Climatic elements such as precipitation, temperature, humidity, sunshine, and wind are affected by geographic location and altitude. Seasonal classification over the study area is thus mainly based on the average rainfall distribution pattern over the year, and the seasonal distribution of rainfall over the area is governed by the position of the Inter-Tropical Convergence Zone (ITCZ).

According to this, the study areas is characterized by three distinct seasons and are locally known as "Bega" (October-January), "Belg" (February-May), and "Kiremt" (June-September).Therefore, the rainfall

pattern in the area has two distinct peaks during a year that is a short rainy seasons in months of February / March-May and long Rainy Seasons in moths of June/ July-September (fig. 2.1) and has the mean annual rainfall of **922.75mm**.

Mean Monthly Rainfall (mm) Over the Catchment Area

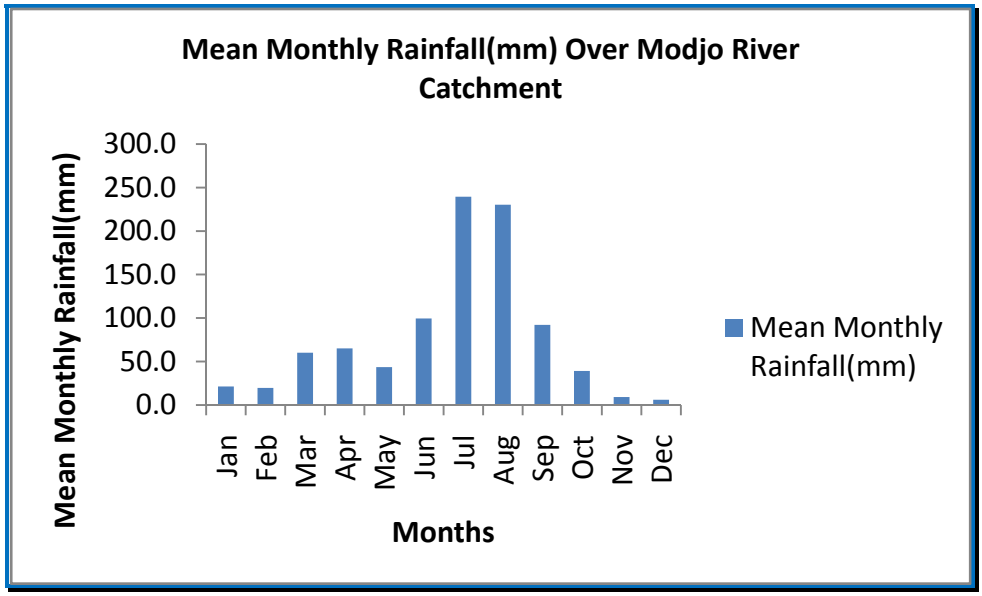


Figure 2.1 Rainfall Pattern over Modjo River Catchment

From the fact that altitude in the catchment ranges between below 1600m to 3050m, it is possible to classify the study area into Temperate (Woina Dega) of72% and cool temperate (Dega) of 28% Climatic zones.

The annual mean maximum, the annual mean and the annual mean minimum air temperatures over the catchment area are taken respectively as 27.6^{o}c, 19.8 ^{o}c and 12.2 ^{o}c. These are taken as the average values recorded by Debrezeit Air Force and Modjo Meteorological Stationns for the years 1996-2006.

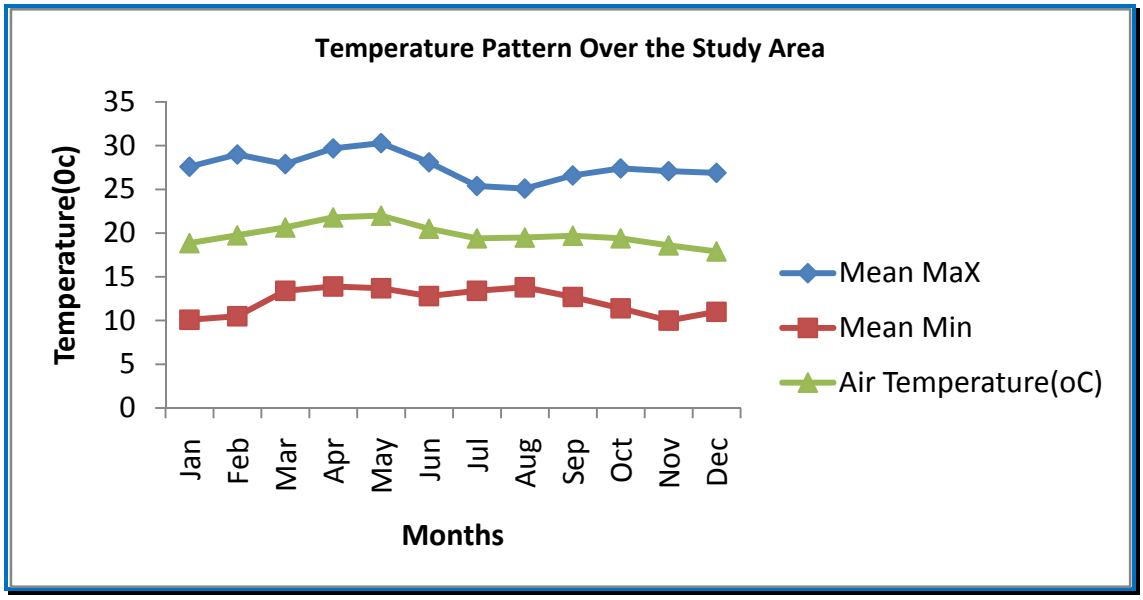


Figure 2.2 Temperature Pattern over the Study Area

2.2. Physiography, Drainage, and Land use/land cover

2.2.1 Physiography

Ethiopia is broadly divided into three major physiographic regions- the Western Highland and associated lowlands; the Eastern Highland and associated lowlands; and the Rift Valley. Modjo River catchment, a sub-catchment of Upper Awash Basin, is located in the western shoulder of the central Main Ethiopian Rift. The present physiographic setting of the catchment is the result of volcano-tectonic activity that forms the plateau and the rift in general. Later erosion and river dissection has contributed to the existing rugged landform. Two major types of land forms generally characterize the study area: volcanic ridges and hills surrounding the catchment at its northern and eastern, with flat land forms in central and southern part. Modjo river catchment has an elevation range of less than 1600m.a.s.l. to 3050m.a.s.l. (topographic map of scale 1:50, 000, EMA) at Koka area and Yerer Mountain respectively (Figure 2.3.1a).

The general slope of the area is towards the south and ranges between 0-75.80(degrees) (Figure 2.3.1b).

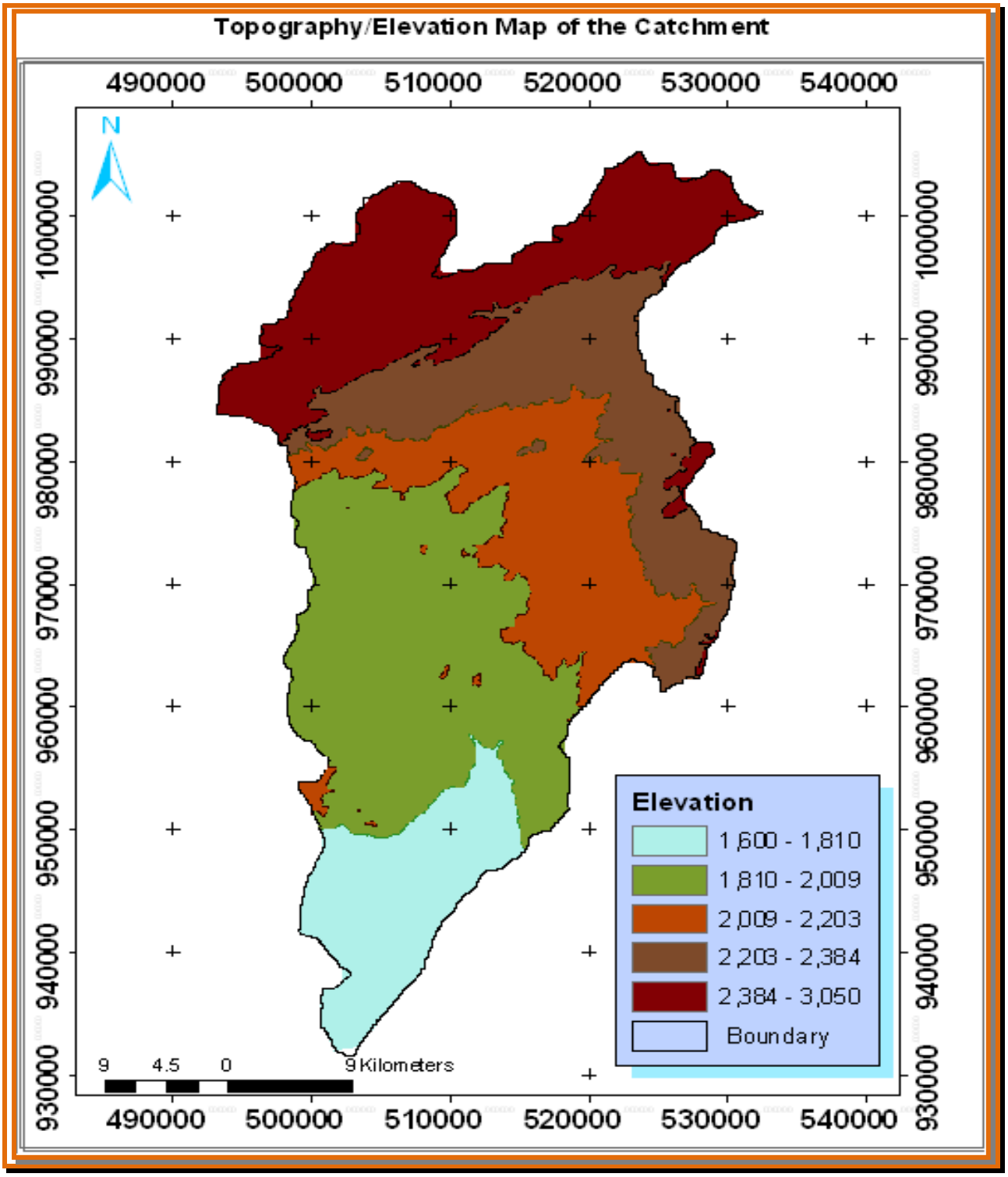


Fig.2.3.1a Elevation Map of the Area

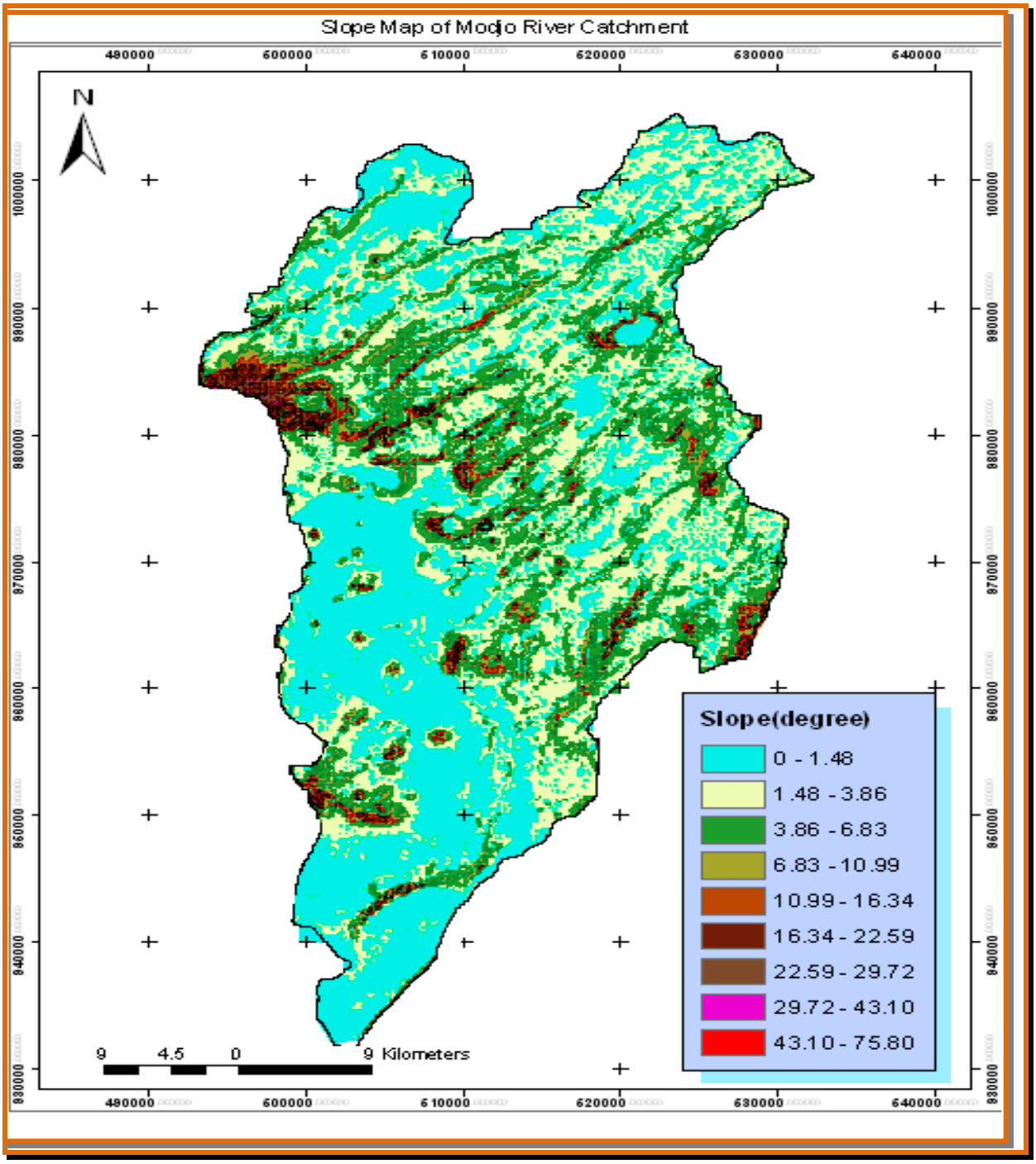


Fig.2.3.1b Slope Map of the Area

2.2.2. Drainage

Modjo River with its tributaries forms Modjo River catchment or Hydrographic basin. This river is one of the tributaries of Awash River.

Various factors affect the pattern and density of drainage in the study area. Among these are: rainfall, slope, vegetation, rock type and tectonics are important ones.

It is commonly known that the higher the permeability the lower the drainage density, and higher the drainage density higher the surface runoff.

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 has been digitized using 1:50000 topographic maps (Fig.2.3.2a). The major rivers present in the study area are Wedecha, Tiliku Modjo and Modjo river (Plate1). Both Wedecha and Tiliku Modjo are tributaries for Modjo river. Modjo River is considered to be the principal drainage system of the study area.



Plate 1. Modjo River the principal drainage system, southern part (Adapted from Sisay, 2007).

All the small river and large rivers, which are found in the study area drain from north to south following the topographic drops.

Comparison of the drainage system of the area and structure has shown that the drainage system is structurally controlled following lineaments directions (Fig.2.3.2b). In the study area dendritic and parallel drainage pattern are recognized, which are indicative of the presence of structures that act as conduits or storage for sub-surface water. Structurally controlled drainage patterns are observed in NE part of the study area.

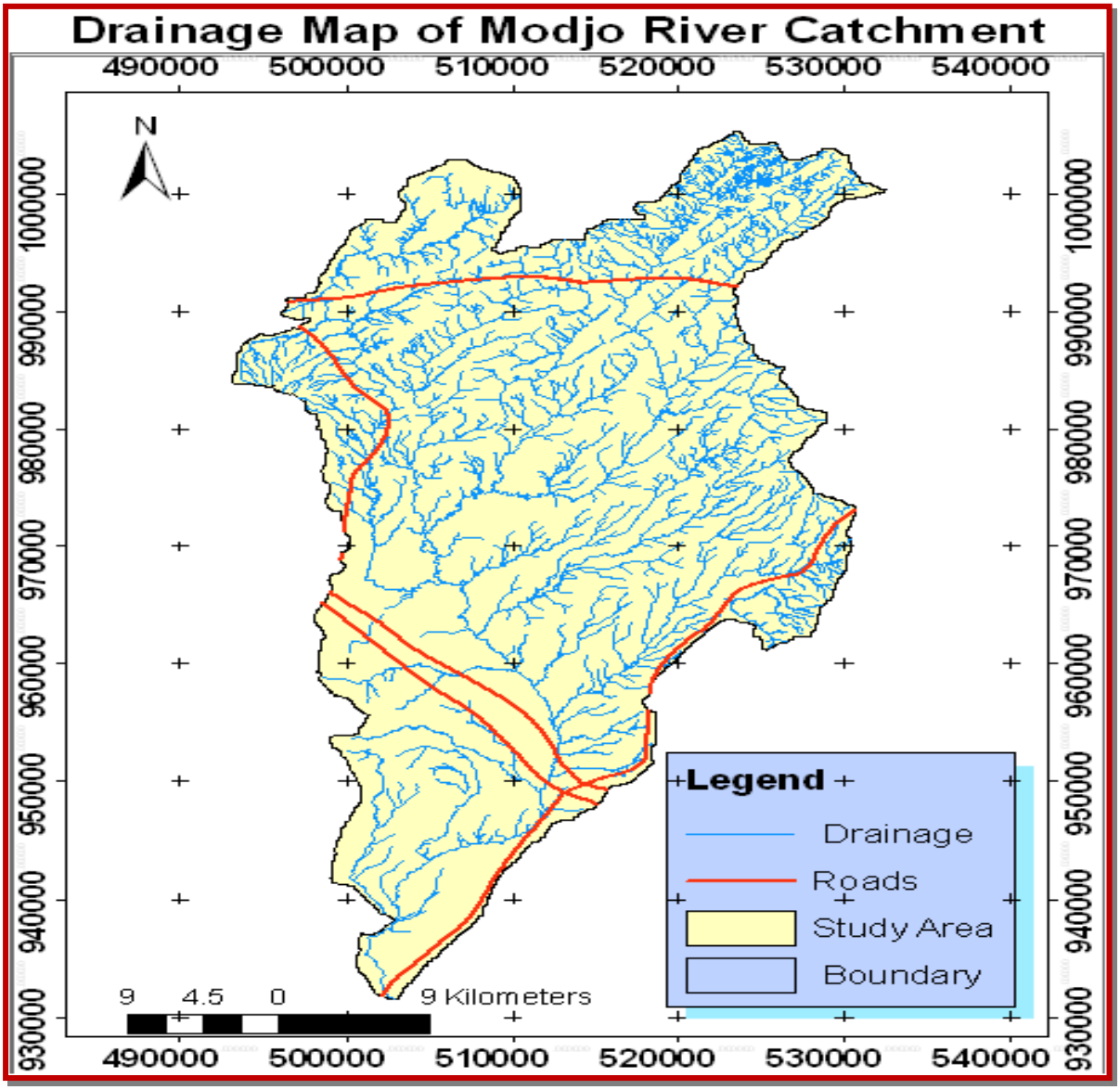


Figure 2.3.2a Drainage Map

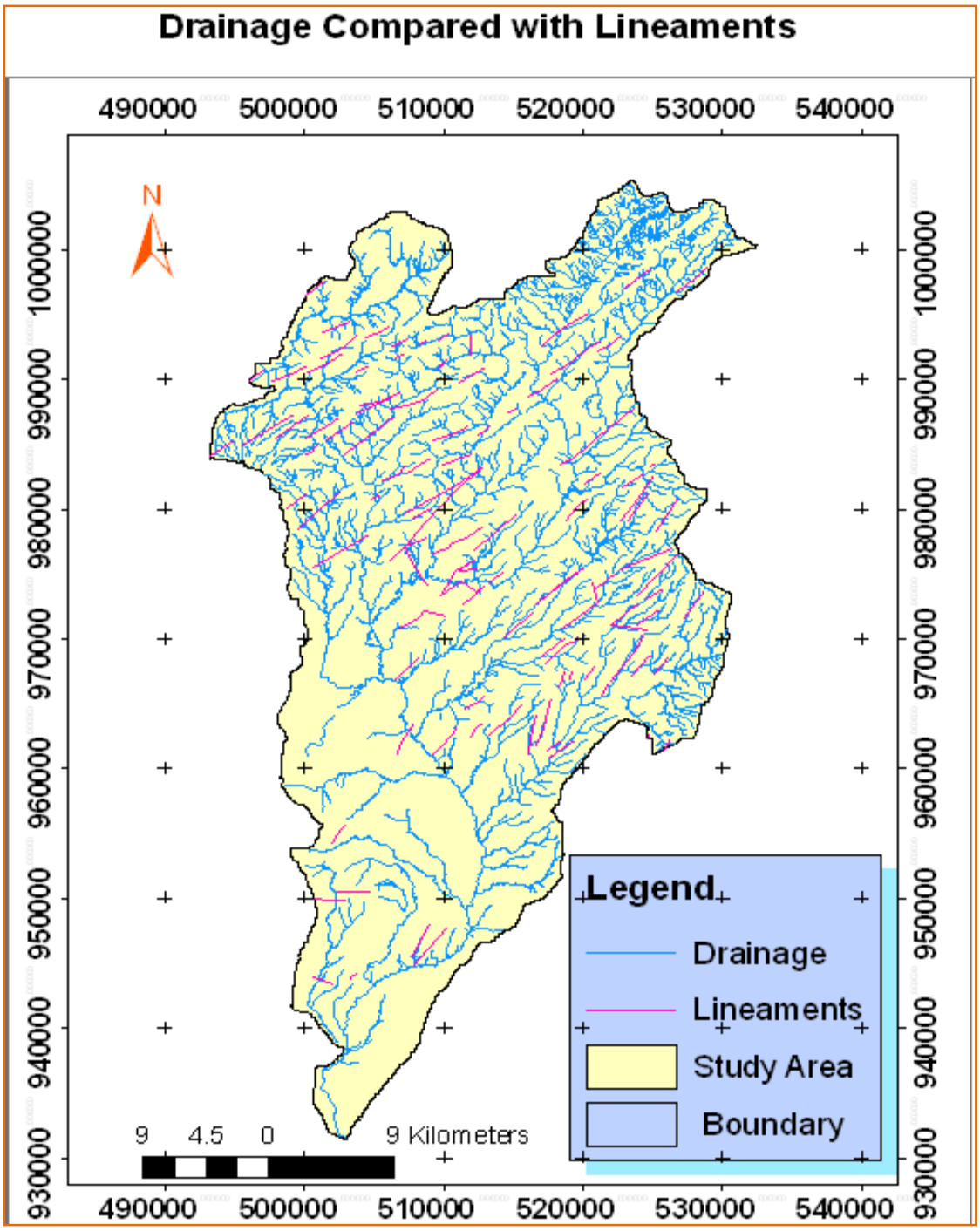


Figure2.3.2b Drainage and Lineaments

The drainage density has been calculated directly in Arc GIS 9.2 using spatial analyst extension. In the study area, mainly 4 drainage density categories have been identified and mapped as shown in (Figurer2.3.2c). Very high drainage density is found in the northern part of the study area whereas high drainage density is found in eastern, western and central parts. Moderate and low drainage densities concentrate in the southern and central part of the study area. Structurally controlled drainage is normally seen in northern part of the study area. Drainage texture and patterns are controlled by different litho-units, structure and morphology. In the northern part of the area drainage pattern is sub-dendritic to sub-parallel (Sisay 2007).

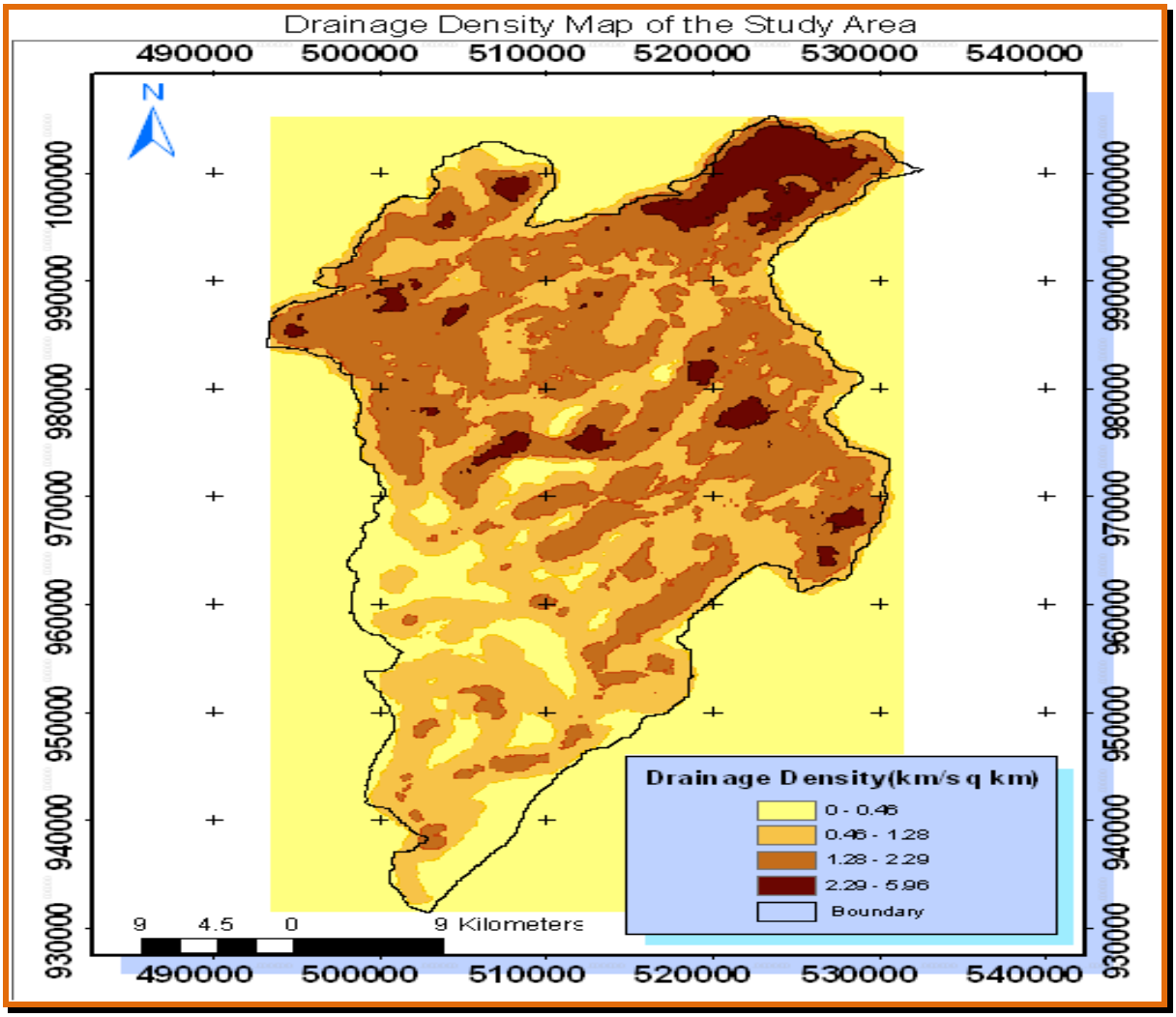


Figure 2.3.2c Drainage Density Map of Modjo River Catchment

With respect to contaminant transport, the higher drainage density is related to less chance of contaminant movement by advection to the ground owing to less recharge, which in turn leads to higher run off and vice versa.

2.2.3. Land use/Land cover

The land use land cover of the catchment has been considered for this research as it has great influence in the recharge calculation made in the hydrometeorology section (Chapter Four) of this thesis.

Land can be put to different uses based on the suitability of its different physical land resources, demand, climate, location, etc. The existing

land use patterns in the catchment have been broadly divided in to eight groups: Crop land with shrubs; crop land, grass land, forest, plantation, urban area with its associated different uses; bare land and water bodies.

The crop land covers a large part of the area that is in central, eastern, and western parts (Figure 2.3.2). Accordingly, the areal extent and proportions of each land use/land cover is given in table2.2.

It is evident from this table that the cropland takes largest share of the area (53.1%). It covers an area of 811.5sq km out of the total area of 1528sq km.

Table 2.2 Land use/Land cover of Modjo River Catchment

No.	Land Use Land Cover	Area(km^2)	Area (%)
1	Crop land with shrubs	374.9	24.5
2	Crop land	811.5	53.1
3	Grass land	222.4	14.6
4	Forest	55.5	3.6
5	Plantation	8.1	0.5
6	Towns	20.0	1.3
7	Bare land	24.3	1.6
8	Water body	11.3	0.7
	Total	1528.0	100

The land use/cover map of the area was readily interpreted from Land sat image by using visual interpretation, unsupervised classification, supervised classification and print outs of band 453,432 543 in RGB combination (Sisay, 2007)

For identification of vegetation cover band ration of band 4 to band 3 was done. After detailed analysis the result was compared and corrected by data collected from different locations of the area. Comparison of Landsat

image and topographic map of year 1975 has shown that there is remarkable expansion of settlements since 1974, which negatively affect the groundwater recharge of the area. The Yerer Mountain that is located west of the study area is covered by dense forest, it is protected by local administration, and the largest portion of the area located in the central part is agricultural land.

The original vegetation is more preserved in the elevated areas than the flat areas, especially in the stream valleys and foot of elevated areas where there is seepage of water or shallow groundwater. This is due to the fact that people had made the natural forest to disappear on the flat lands in order to grow Teff, one of the most important crops in central areas. Moreover, there are discouraging situations in which deforestation is still going on through improper utilization of the forest: clearing or cutting of the vegetation for trading and for new farmland, especially in the new resettlement areas. Flat and marshy areas are covered by elephant grasses and short trees, whereas big trees and mixed forest cover the riverbanks and stream valleys. The result of the various land use/land cover of the study area is given in (Figure 2.3.3).

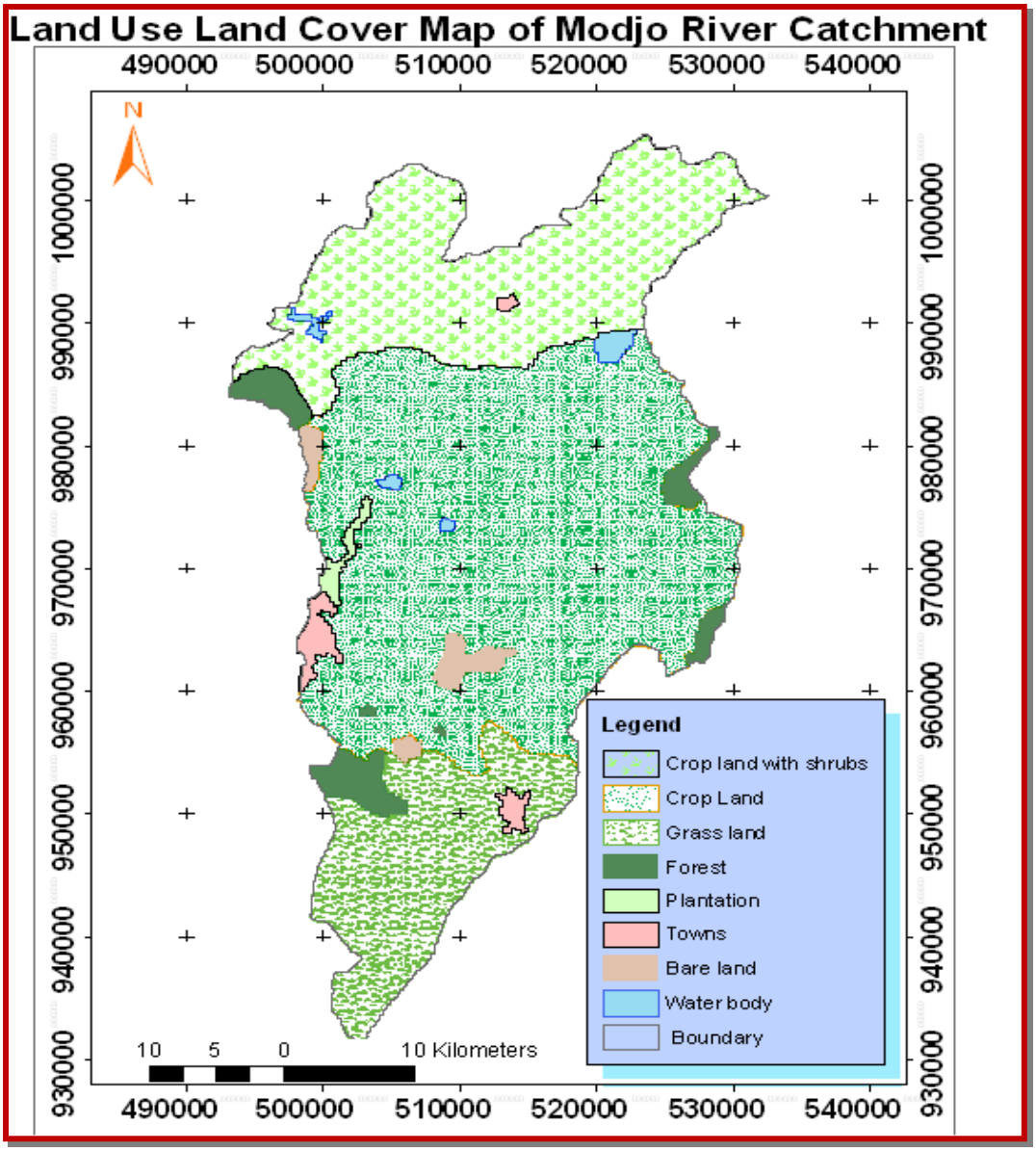


Figure 2.3.3 Land Use Land Cover Map of Modjo River Catchment (Adapted from Sisay, 2007)

2.3.4. Soil

The variation in the characteristics of soils resulted in variations and water holding capacity. Climate, topography, parent material, maturity and biological activities are the major controlling factors that control soil formations. The resulting porosity and permeability of soil, on the other hand, control the vertical as well as horizontal movements of

contaminants by surface- and sub-surface waters (Tamiru Alemayehu et al., 2005).

The thickness, permeability, porosity and shrink/swell characteristics of soils are crucial and control largely the infiltration of pollutants into subsurface

The soil development in the study area is mostly due to the physical disintegration and chemical decomposition of volcanic rocks. The weathering products either remain in places and form residual soils or are transported and deposited to form alluvial deposits in low-lying areas. Meanwhile, the difference observed in the type and development of soils in the catchment mostly depends on the topography, parent materials and the degree of weathering.

Although there is significant difference in the degree of weathering on the slopes, mostly the soils are highly eroded and result in thin soil cover along most parts of the divide lines of the catchment. In the localities where the topography is plain to gently sloping (central and southern parts) the area is covered by relatively thick soils (Figure2.3.4). The type of parent material and the length of time to which the parent material is subjected to weathering, control the variation in the thickness of soil.

In general, two types of soils dominate the study area Cambisols(46.4%), in the northern, northwestern, and eastern parts of the catchment and, vertisols(37.8%) in the central and eastern parts. The other soil types are Phaeozems,Leptosols,Luvisols,and Fluvisols. The areal extents of these soils are respectively 8.8%, 3.6%, and 3.0% and0.3% of the total catchment area (Figure2.3.4).

The soil Map of Modjo River Catchment has been adapted from the thesis work of (Sisay, 2007). Sisay in his thesis prepared the soil map of Ade'a Plain (Modjo Sub-catchment) from soil database of FAO, 1997 (The digital

Soil and Database of East Africa) in arcview shape file format. The study area soil map was clipped and six soil types were identified (Fig.2.3.4): vertic cambisols, euric vertisols, luvic phaeozems, chromic luvisols, lithic leptosols,and eutric fluvisols. Description of soils was made based on FAO/UNESCO "World reference base for soil resources 2006, A framework for international classification, correlation and communication".

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 (Ethiopin Road Authority , Drainage Design Manual ,2002). Classification of soil types in relation to groundwater was done based on data on texture of soils obtained from (FAO, THE DIGITAL SOIL AND TERRAIN DATABASE OF EAST AFRICA (SEA), 1997)
Soil types in the study area are described as follows:

2.3.4.1.Leptosols

Leptosols are very shallow soils over continuous rock and are extremely gravelly and/or stony with various kinds of continuous rock or of unconsolidated materials with less than 20 percent (by volume) fine earth. Leptosols have a resource potential for wet-season grazing and as forest land. Erosion is the greatest threat to Leptosol areas, particularly in mountain regions in the temperate zones where high population pressure (tourism), overexploitation and increasing environmental pollution lead to deterioration of forests and threaten large areas of vulnerable Leptosols. Steep slopes with shallow and stony soils can be transformed into cultivable land through terracing, the removal of stones by hand and their use as terrace fronts. The excessive internal drainage

and the shallowness of many Leptosols can cause drought even in a humid environment.

2.3.4.2.Phaeozems

Phaeozems accommodate soils of relatively wet grassland and forest regions in moderately continental climates. They have dark, humus rich surface horizon and are porous, fertile soils that make excellent farmland. Phaeozems are in use for the production of soybean and wheat and other small grains. Phaeozems in the temperate belt are planted with wheat, barley and vegetables alongside other crops. Vast areas of Phaeozems are used for cattle rearing and fattening on improved pastures. Wind and water erosion are serious hazards to these soil types.

2.3.4.3.Fluvisols

Fluvisols accommodate genetically young, azonal soils in alluvial deposits. They develop in alluvial plains, river fans, valleys and tidal marshes on all continents and in all climate zones; many Fluvisols under natural conditions are flooded periodically. A dry period also stimulates microbial activity and promotes mineralization of organic matter. Many dry land crops are grown on fluvisols as well, normally with some form of water control.

2.3.4.4.Luvisols

Luvisols are soils that have a higher clay content in the subsoil than in the topsoil as a result of processes (especially clay migration) leading to an argic subsoil horizon. Luvisols have high-activity clays throughout the argic horizon and a high base saturation at certain depths. Pedogenetic differentiation (especially clay migration) of clay content with a lower content in the topsoil and a higher content in the subsoil without marked leaching of base cations or advanced weathering of high-activity clays.

Most Luvisols are fertile soils and suitable for a wide range of agricultural uses.

2.3.4.5.Cambisols

Cambisols combine soils with at least an incipient subsurface soil formation. Transformation of parent material is evident from structure formation and mostly brownish discoloration, increasing clay percentage, and/or carbonate removal. They are soils with at least the beginnings of horizon differentiation in the subsoil evident from changes in structure, color, clay content or carbonate content. Cambisols are characterized by slight or moderate weathering of parent material and by the absence of appreciable quantities of illuviated clay, organic matter. Cambisols with groundwater influence in alluvial plains are highly productive paddy soils.

2.3.4.6.Vertisols

Vertisols are churning, heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out, which happens in most of the years. The name Vertisols (from Latin vertere, to turn) refers to sediments that contain a high proportion of swelling clays, or products of rock weathering that have the characteristics of swelling clays. Their physical soil characteristics and, notably, their difficult water management cause problems. Buildings and other structures on Vertisols are at risk. The vertical root system of cotton can resist damage by cracking of vertisol but tree crops cannot resist the cracking. The heavy soil texture and domination of expanding clay minerals result in a narrow soil moisture range between moisture stress and water excess. Excess water in the rainy season must be stored for post-rainy season (water harvesting) on Vertisols with very slow infiltration rates.

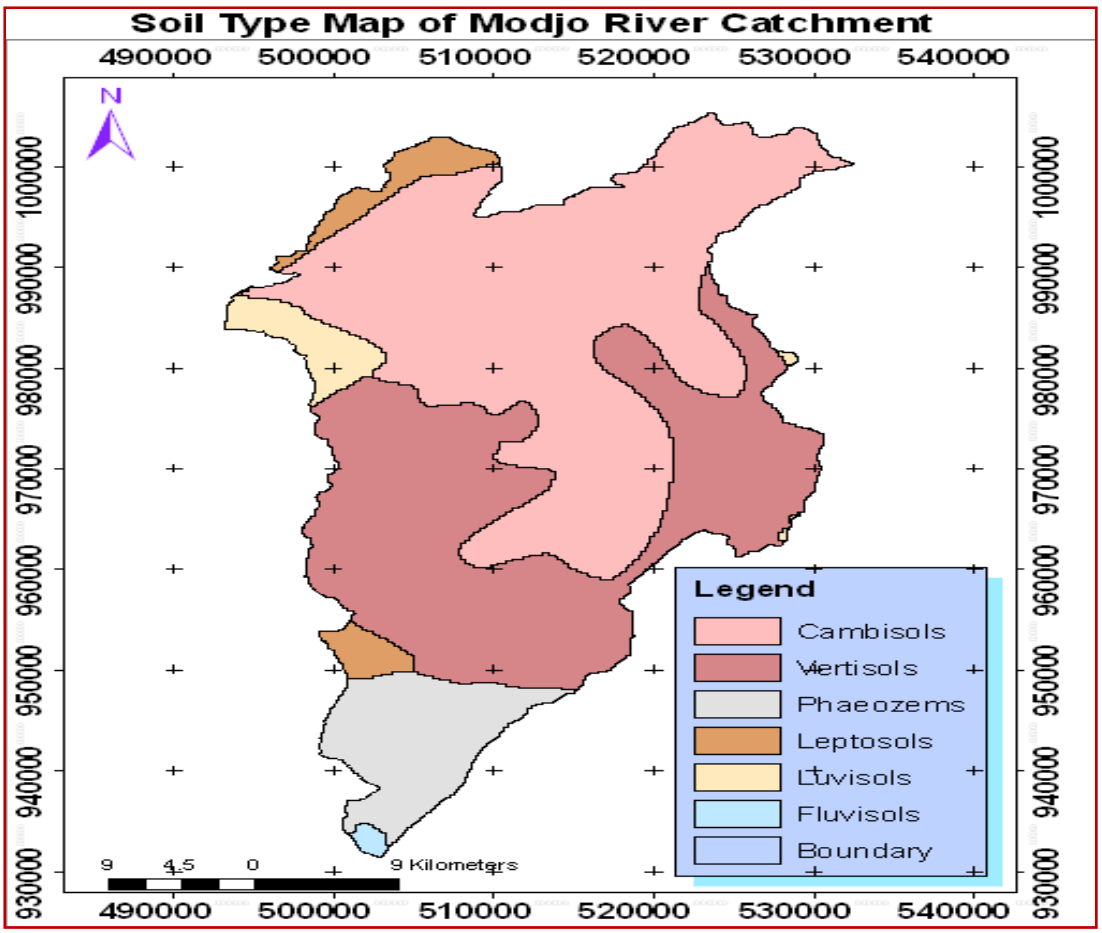


Figure 2.3.4 Soil Type Map of Modjo River Catchment

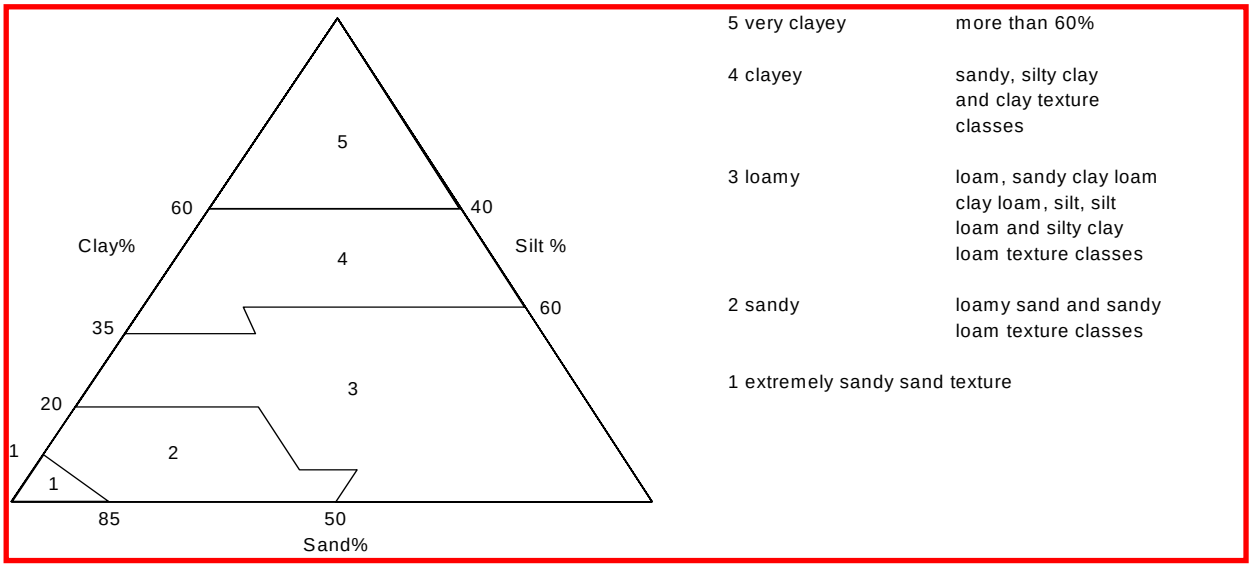


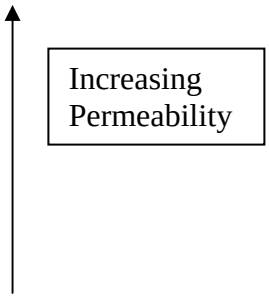
Figure 2.3.5 Texture class of soil based on sand, silt and clay content (THE DIGITAL SOIL AND TERRAIN DATABASE OF EAST AFRICA (SEA), 1997).

Table 2.3. Texture class of soils (THE DIGITAL SOIL AND TERRAIN DATABASE OF EASTAFRICA (SEA), 1997)

Code	Texture
1	Extremely sandy
2	sandy
3	loamy
4	Clayey
5	Very clayey

Table 2.4 Soil type in order of increasing permeability

No.	Soil Type	Code
1	Leptosols	3
2	Andosols	3
3	Phaeozems	4
4	Fluvisols	4
5	Luvisols	4
6	Cambisols	5
7	Vertisols	5



CHAPTER THREE
3. GEOLOGICAL SETTINGS

In the present study geological mapping was done using previous data from different studies as well as field verification. The study area is underlain by a variety of volcanic and sedimentary rocks that exhibit ages ranging from Miocene to present. The volcanic lithologies occupy the vast portion of the study area. Sedimentary rocks and deposits cover the remaining portion of the area.

The stratigraphic sequence of rocks in the study area, Modjo river catchments, established based on geological mapping that allow the recognition of nine volcanic units that were grouped into four volcanic complexes. These complexes define three main structural sectors: the

western rift margin, the main rift floor and intra-rift depression, respectively (F.Mazzarini et al., 1999). Stratigraphic relationships between the recognized units have been further constrained by isotopic and geochemical investigation conducted by various researchers (example Cherenet et al., 1999). This study also confirmed these stratigraphic sequence described by F.Mazzarini et al., (1999).

Volcanic rocks of the area include, central volcano, Nazret unit, Tulu Rie basalt unit, Chefe Donsa unit, Bishoftu volcanic unit and Bede Gababa Volcanic Unit. Lacustrin deposit and alluvial cover also exposed in the study area (fig. 3.2) These rock units are described in the following section and names used by Abebe et al., (1999) is adopted to describe the lithologies exposed in the study area.

3.1 Central volcano

Central volcano unit is represented by Yerer volcanic unit within the western rift margin complex and found in the northern part of the study area. It occurs occupying a series of NE-SW aligned ridges and domes within the largest Yerer volcanic edifies with relief of 1000m difference from the plain. This volcanic edifies is 14km wide along E-W direction. According to (Cherenet et al., 1999) in Sisay, 2007 rock samples taken from this unit were dated by K-Ar method and gave an age of 3.9 to 3.3Ma.

The Yerer volcanic unit mainly comprises lava flow with subordinate pyroclastic deposit in the central and eastern sectors. Porhritic trachyte is the main lava flow constituting this unit. It is composed of plagioclase, anorthoclase, oliven and clino-pyroxene phenocryst set in ground mass made up of alkali-feldspars, pyroxene and Fe- and Ti- oxides. The ground mass exhibits trachytic texture. To the top it consists recent spatter cones and associated basaltic lava. Due to their massive nature they have low permiabilty (Adane, 1999).

3.2 Nazret units

The Nazret unit is widely present in the north-eastern and eastern parts of the study area. The units are affected by the NE-SW trending lineaments, it consists sequence of welded rhyolitic ignimbrites, with four flow units that have thicknesses varying from 5 to 15 m. Also, the unit comprises numerous rhyolitic (Adadi, Ruketi, and Aminos) and trachytic domes (Gara Bokan, Dikub). The age of Nazret unit is between 9.5 and 3Ma (Kazmin and Berhe., 1978).

This unit is a basal unit grouped under the intra rift complex and may constitute the upper part of Nazret Group of (Kazmin and Berhe., 1978) with respect to age constraints. Fresh ignimbrite along the banks and floor of the Modjo River is interbedded with lacustrine deposit. Each ignimbrite layer has an average thickness of about 2 meters. This unit includes various welded and often jointed columnar ignimbrites. Basically, two types of ignimbrites have been identified: the slightly welded ignimbrite (top) and intermediately welded ignimbrite (bottom), separated by paleosoil and lacustrine deposits. Welded ignimbrite with well developed vertical joint and fracture provide high to moderate permeability (Adane, 1999).

3.3 Tulu Rie Basalt

Tulu Rie basalt is present in the eastern and northern section of the study area. It consists sub-horizontal to slightly tilted basalt that belongs to the intra rift complex. It covers the Nazeret unit and forms the upper part of NE trending escarpments. The maximum observed thickness is 20 m at Tulu Rie Basaltic ridge at the southeastern catchment. They are mainly olivine basalts with rare plagioclase phyric basaltic andesites. The

basalts show porphyritic to aphyric texture, and oliven is the main phenocryst mineral phase. The Tulu Rie Basalt was dated at 2.7-1.8Ma and for its stratigraphic position and composition was regarded as part of Bofa basalt of Kazmin and Berhe (1978). This unit when it is massive has low permeability where as with well-developed structural features they are good and productive aquifers (Adane, 1999).



Plate.2 An exposure at Tulu Rie basaltic ridge covered with shattered blocks of basaltic boulders. The unit is weathered and shows fracturing that line up with regional structures (Adapted from Alem, 2004)

3.4 Chefe Donsa Unit

This map unit is exposed in the south-eastern, eastern and north-eastern parts of the study area and belongs to the intra rift complex. It occurs mainly along the border of the central plain of the study area.

Chefe Donsa unit consists of fall deposits and poorly welded ignimbrites of rhyolitic composition. In the southwest, the lacustrin deposit in southeast overlies this unit, while in the eastern and northeastern parts, it overlies Nazret unit and Tulu Rie basalt. Fission track analysis applied to juvenile material (obsidian fragments) from the upper pumice falls in a section close to Chefe Donsa village yielded age of 2.2Ma (Abebe, 1999). Observed thickness of the unit varies from few meters up to 40m close to Chefe Donsa village, where the most complete section is exposed. It consists of four fall deposits each separated by paleosoils of up to one meter thick. In the eastern most section of the study area the Chefe Donsa unit is made up of pyroclastic fall with a thickness of about 12m. Generally this unit has low permeability due to its massive nature (Adane, 1999).

3.5 Bede Gababa Volcanic Unit

Bede Gababa Volcanic unit is found in the central part of the study area. It is a volcanic complex with a quasi-circular shape, slightly NNE elongated and with a maximum relief of 400m above the surrounding topography. The lacustrine deposit rests above BGV and its morphology is dominated by the occurrence of several coalescent calderic structures (Abebe, 1999).

The central part of Bede Gebaba volcanic unit comprises spatter cone and basaltic lava flow. The most recent products are represented by rhyolitic obsidians for which a radiometric age of 0.36 to 0.07Ma (Leeds University, Leeds) has been estimated. Pumices and lavas show a comparison ranging from rhyolites (Plate 4) to minor trachite. Subaphyric obsidian is common, sometimes are devitrified (Abebe, 1999).

The lavas contain microphenocrysts and the rare phenocrysts of sanadine and quartz as well as scattered plagioclase and clinopyroxene

set in glassy to micricrystalline groundmass (Gaspasron et al., 1999). The Bede Gababa unit, due to its composition of ryolites and trachytes, which have massive nature, has very low permeability (Adane, 1999).



Plate 3. Massive Ryolite composition of Bede Gebaba volcanic unit (Adapted from Sisay, 2007)

3.6 Bishoftu Volcanics

This unit is found extensively in the central part of the study area forming a NNE trending belt in the rift axis complex. Bishoftu volcanics represent the most recent basic lava flow of the Debrezeit area (Tsegaye Abebe. et al., 1999), which was also reported as the younger volcanics by Grasparon et al (1993).

In the BV there are two groups represented by spatter and cinder cones with associated tabular lavas and phreatomagmatic deposits, respectively. The latter, consisting mainly of pyroclastic surges and highly fragmented deposits associated with maars are chiefly

concentrated in the central part of the central section where the highest thickness of the lacustrine sediments frequently intercalated with the phreatomagmatic products. The composition of lavas and juvenile glass ranges from alkali basalts to olivine basalts and trachyandesites. (Abebe, 1999)



Plate 4 Pyroclastic deposit exposed in Erob Gebeya
(Adopted From Sisay, 2007).

Vesicular basalt is found associated with and/or sandwiched between pyroclastic (Plate 4) and lacustrine deposit and covering the volcanic tuff in some parts of the area. It is dark gray in color, vesicular, massive and sometimes scoracious and at places secondary minerals, dominantly zeolites and calcite fill the vesicles. According to (Adane, 1999), this unit has high porosity and permeability due to secondary structures and the interconnection of the pore spaces.

3.7 Lacustrine Deposits

The deposits are exposed in NE elongated depression in the central section of the area. Modjo town and the surrounding areas are supposed to have been covered by ancestral lake during the pluvial period of the Quaternary. Lacustrine environment started after the Bede Gebabe volcano unit and continued during the eruptive activity of Bishoftu (Abebe, 1999). The lacustrine sedimentations are the results of deposition in this large ancestral lake (Mohr, 1967 and Abebe, et al., 1999) and they are interbedded with Pliocene-Pleistocene ignimbrite in lakes region and on the rift shoulders in general, and within Modjo and the surrounding areas in particular (Mohr, 1966). These fine-grained deposits are generally brown-yellowish, thinly stratified and often contain abundant volcanic matrix. Their thickness ranges from less than 5 m up to 8 m. In these successions, volcanic layers are frequent and become predominant and coarse grained in the neighboring of the maars. Due to their fine-grained composition and compactness, these deposits have low porosity and permeability (Adane, 1999).

3.7 Alluvial Cover

This unit outcrops in NW west as well as around some of the Debrezeit Lakes that fall within the study area covering a small portion of the whole area. They consist regolith, red soils, talus and alluvium (Abebe, 1999). Due to their loose nature, alluvial sediments are porous and permeable. Moreover, their grain size constitution varies from coarse to silty and clayey, giving rise to the occurrence of highly yielded unconfined, confined and semi-confined aquifer together with local perched ones (Tamiru, 1992).

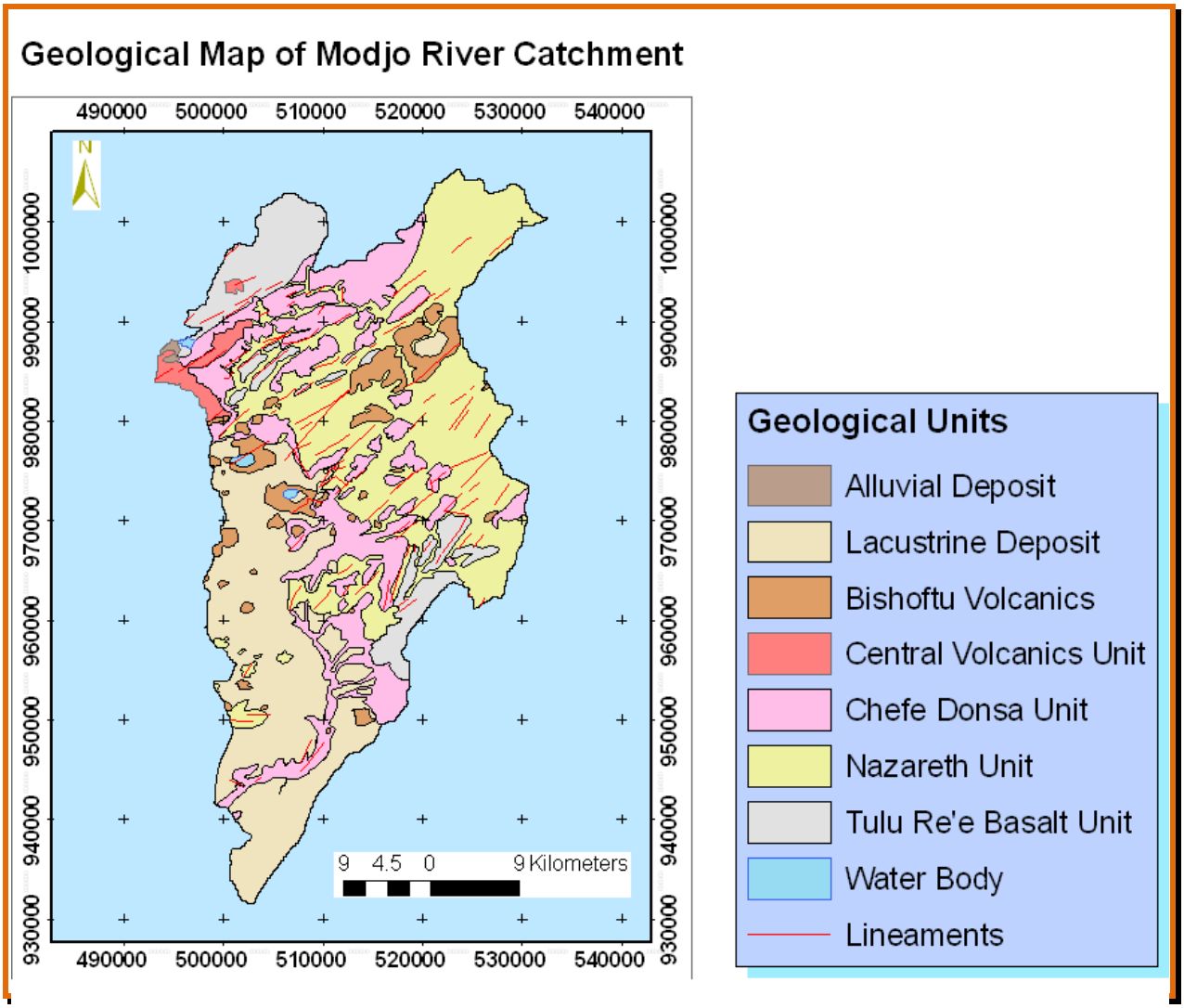


Figure 3.1 Geological Map of Modjo River Catchment (Adapted from Sisay, 2007)

3.8 Tectonic and Structures of the Study Area

Modjo, like the other Rift Valley areas was subjected to tectonic activities and intense volcanism. The Wonji fault belts are the prominent MER structures characterized by NNE-SSW system forming minor graben and horst structures as depicted in Modjo (Modjo graben) and Nazreth (Adama graben, Kimbibit and Delocha horest to the west and east of the town it self) areas (Tsegaye Abebe, et al., 1999).

Some faults have been observed in Modjo area (eastern, southern, southwestern parts) forming minor fault escarpment. The river channels, large gullies seem to outline and follow the hidden and an exposed fault line. In the MER, faults, joints, fractures, volcanic flows and layering and flow folding, which are associated with silicic lava flows, are main geologic structures. The presence of thick fluvo-lacustrine deposits and active erosional or denudational processes in the MER during pluvial period of the Quaternary mask the probable existence of fault/lineaments.

Brittle deformation consisting of fractures, joints and faults are dominant in the area. Structures are extensional and affect chiefly the rocks of the Intra Rift Complex and partially those of the Western Rift Margin Complex. These structures are grouped into four main fracture systems consisting mainly of joint sets and some faults. (Abebe et al., 1999). Those are the N-S/NNE-SSW fracture system which is analogous to Wonji Fault Belt, constitutes normal faults with steeply dipping joints dip angle of >85^{o}. The next one is NE-SW fracture system that parallels the regional trend of the MER, and has normal fault of about 1m thrown and dip angle >85^{o}. It is widespread especially in the Nazret unit where the most important physiographic features are NE trending ridges and escarpments.

The third one is E-W fracture system mainly concentrated in zones close to the Yerer Volcano or just east of Addis Ababa. It parallels the trend of the Yerer-Tullu Wellel Volcanic

Lineament (YTVL) structure. It consists of sub vertical to vertical joints with dip angle >85^0.

The last one is the NW-SE fracture system. Few high angle normal faults have been observed with high morphologic evidence (escarpments). This system affects mainly the oldest units of western Rift margin.

The geology of the area is strongly conditioned by the interaction between the left-lateral oblique rifting of the MER (Boccalitti et al., 1999) and right lateral transtensional Yerer-Tullu Wellel Volcanic Lineament structure (Tsegaye Abebe et al., 1998). Thus, the interference between the MER and YTVL structures would be the first order cause of features like gradual transition between the rift floor and the West Rift shoulder.

CHAPTER FOUR
4. HYDROMETEOROLOGY

4.1. General

Hydrometeorology is a science which links hydrology and meteorology. It studies the hydrological cycle which involve processes in the atmosphere and at the earth's surface (Shaw, 1985). Hydrometeorology data are required to determine the water balance of a certain basin for developing and managing its water resources. The most useful hydro meteorological elements are precipitation, evapotranspiration, sunshine hours, air temperature, and relative humidity, soil moisture and stream discharge (runoff), etc..

4.2. Meteorological parameters

There are eleven meteorological stations within and around the study area. There are four stations located within the catchment. These are

Debrzeit Airforce,Modjo,Chefe Donsa and Ejere Meteorological stations.The other adjacent stations; Alemtene,Koka,Ziquala,Dertu Liben,Aleltu and Arerti are located around Modjo River Catchment(Figure 4.1). The overall meteorological parameters available in the study area are; rainfall, temperature, relative humidity, wind speed, and sunshine duration. Accordingly, average of the eleven meteorological stations data has been used for the study area (Table 4.1). The meteorological data from the above mentioned staions and the hydrological data from Modjo River gauging near Koka Dam are the basis to determine the water balance of the catchment. The results of the climatological data analysis are presented in the following sections.

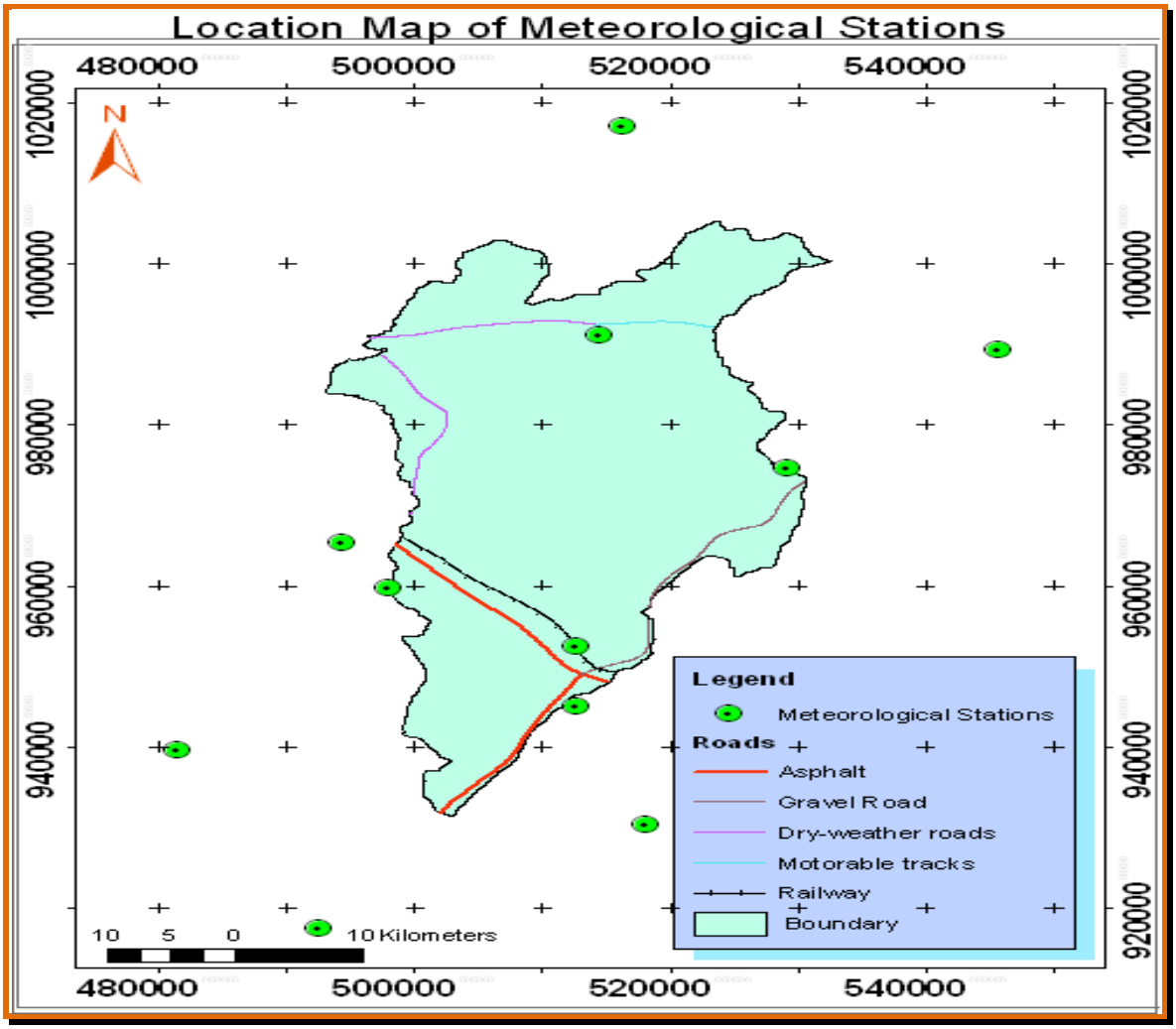


Figure 4.1. Location map of meteorological stations

Table 4.1 Meteorological Stations within and around Modjo River catchment

Meteorological Stations	UTM(m)		Annual Precipitation(mm)	Altitude(m amsl)
	UTME*	UTMN*		
Debrezeit Airforce	494500	965371	936.7	1900
Modjo	512837	952474	1015.6	1870
Nazareth	518347	930365	883.3	1622
Koka Dam	512839	945104	866.8	1595
Ejere	529325	974594	956.7	2100
Dertuliben	498167	959843	799.4	2025
Alemtena	492659	917464	773.0	1720
Ziquala	481657	939578	1144.3	3050
Aleltu	516478	1016967	1049	2550
Arerti	545804	989350	927.8	1850
Chefedonsa	514657	991170	790.3	2390

- UTME and UTMN stand for Universal Transverse Mercator Easting and Universal Transverse Mercator Northing respectively.

4.2.1. Seasonality of Rainfall

The areal pattern of the seasonality of rainfall in the study area determined by analyzing long term mean monthly rainfall data for eleven stations in and around the catchment.

Precipitation is the most commonly measured meteorological data. In this study, from 1996 to 2006 monthly total rainfall records of eleven

stations are used to analyze monthly mean rainfall, mean annual rainfall, rainfall coefficient and areal depth of precipitation. The mean monthly and annual mean rainfall as recorded by National Meteorological Services Agency (NMSA) at the stations Debrezeit Airforce,Modjo,Kaka,Ejere,Dertu Liben,Alemtena,Ziquala,Aleltu,Arerti,and Chefe Donsa are shown in Table4.2 and Figure4.2.

Table4.2 Mean Monthly Rainfall in eleven Stations (Pm) (mm)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
Debrezeit	15.0	44.9	59.8	60.3	44.8	120.3	228.9	211.4	95.0	42.7	5.7	7.6	936.2
Modjo	14.7	13.6	66.3	53.8	54.3	130.8	296.0	224.7	108.4	40.1	9.3	3.6	1015.6
Nazareth	22.6	19.1	77.0	44.1	52.5	67.9	208.8	220.0	96.0	58.4	13.1	9.8	883.3
Koka Dam	17.8	16.6	48.3	42.6	45.8	96.3	191.8	269.4	77.5	46.2	9.7	4.5	866.6
Ejere	26.5	22.0	53.9	38.0	42.4	91.8	249.2	272.0	93.2	41.6	12.1	14.0	956.7
Dertu Liben	11.6	18.0	36.7	57.1	44.1	86.9	219.9	188.2	89.4	43.8	5.1	1.6	799.4
Alem Tena	17.8	13.0	58.4	69.0	37.9	83.1	212.5	147.4	85.1	36.2	7.6	5.0	773.0
Ziquala	30.9	30.7	93.2	91.2	69.4	149.1	294.2	218.0	112.4	40.2	12.2	2.8	1144.3
Arerti	13.8	13.15	63.25	150	21.46	63.09	233	224.38	74.15	44.16	16.5	10.84	927.8
Aleltu	19.0	10.4	56.2	57.5	36.5	106.7	301.3	326.3	104.9	22.9	5.1	2.2	1049.0
Chefe Donsa	13.3	15.4	48.1	52.4	30.7	99.1	199.1	230.8	77.3	15.4	4.8	3.9	790.3
Modjo Catchment	18.45	19.7	60.1	65.1	43.6	99.6	239.5	230.2	92.1	39.2	9.2	6.0	922.75

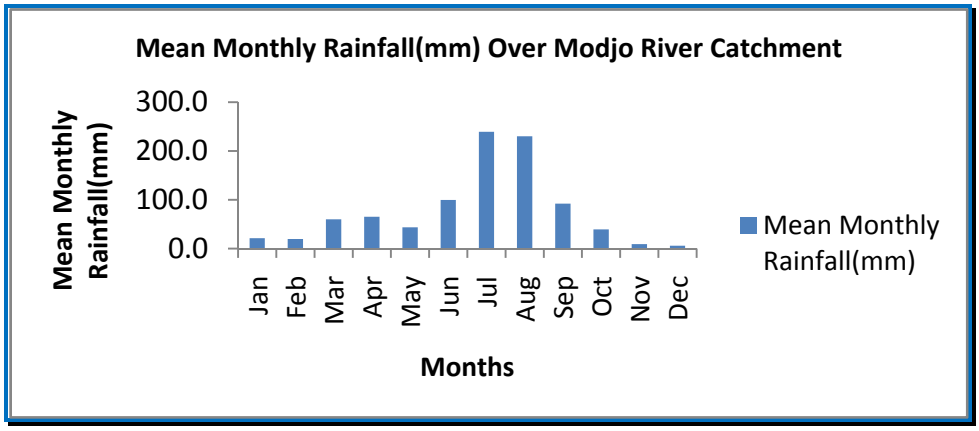


Figure 4.2 Mean Monthly Rainfall Pattern Over Modjo River Catchment

To compare the monthly distribution of rainfall at these stations, the method employed here was adapted from a study of precipitation for the Awash River basin (Daniel Gemechu, 1974 in Assaminew 2007). This involved the calculation of "Rainfall Coefficient" for each month of the study area, the coefficient being the ratio between the mean monthly rainfall and one-twelfth of the annual mean of the total rainfalls.

$RC = P_m / (Pa/12)$

Where, RC= Rainfall Coefficient

P_a= Mean Annual Rainfall of Eleven stations **922.75mm** (Table 4.2)

P_m= Mean monthly Rainfall of all the stations (Table 4.2)

In this study, a month was distinguished "rainy" if the rainfall coefficient is 0.6 or over. The term "a small rain is employed to refer to those months with a rainfall coefficient of 0.6 to 0.9; and the term "big" rainy months are further classified into three groups; those with "moderate concentration" of rainfall (coefficient of 2.0-2.9); and those with "very high concentration" of rainfall (coefficient of 3.0 and above). And if the rainfall coefficient is less than 0.6, the months are classified as dry seasons. This scheme of classification is presented in Table4.3.

Table 4.3 Rainfall Coefficient of Modjo river catchment.

Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
*** Pm(mm)**	**18.45**	**19.7**	**60.18**	**65.1**	**43.5**	**99.6**	**239.5**	**230.2**	**92.1**	**39.2**	**9.2**	**6.0**
RC	**0.24**	**0.26**	**0.78**	**0.85**	**0.57**	**1.30**	**3.11**	**2.99**	**1.20**	**0.51**	**0.12**	**0.08**
Season	**Dry**	**Dry**	**Rainy**	**Rainy**	**Dry**	**Rainy**	**Rainy**	**Rainy**	**Rainy**	**Dry**	**Dry**	**Dry**
Amount	**-**	**-**	**Small**	**Small**	**-**	**Big**	**Big**	**Big**	**Big**	**-**	**-**	**-**
Concentration	**-**	**-**	**-**	**-**	**-**	**-**	**V.high**	**High**	**-**	**-**	**-**	**-**

*P_m= Mean Monthly Rainfall of Modjo River Catchment taken as the average of the eleven stations (Table 4.2)

On the basis of the above classification, as depicted in table 4.3, the catchment is characterized by two rainy seasons and six dry months during the year. The two rainy seasons in total six months; March, April, June, July, August, and September. The first rainy season occurs during

the months of March and April. The rains are small, and account for 13.58% of the average annual rainfall of the catchment. The second big rainy season occurs from June to September, and accounts for 71.68% of the average annual rainfall of the area.

The rainfall occurs in very high and high concentrations during big rainy months of July and August respectively.

The catchment is characterized by six dry months. They occur during the months starts from October ends in February. The amount of rainfall that occurs during these six months of dry seasons in total accounts for **14.74**% of the average annual rainfall of the catchment.

4.2.2. Determination of Areal Depth of Precipitation

In water budget studies, it is necessary to know the average depth of precipitation over a study catchment. This may be determined for time periods ranging from the duration of part of a single storm to a year. The data are generally measurements of precipitation and/ or equivalent snow fall at a number of points through out the catchment (Fetter, 1994).

Because of the non-uniform distribution of the precipitation gauges and variation of topographic textures, the Thiessen polygon, and Arithmetic mean are selected for quantifying reliable and representative values of areal depth of precipitation.

4.2.2.1. Arithmetic mean method

Arithmetic mean method is the simplest one for evaluation of mean uniform distribution of rainfall of a basin. It is the mean of all the rain gauges that are located on relatively flat topography and closely and evenly spaced. Since only three stations (Debrezeit, Modjo and Koka Dam) are located closer to each other on relatively flat lands, the estimated average uniform precipitation (P_A) is computed as follows:

$PA = \sum_{i=1} P_i / n = \frac{936.2+1015.6+866.6}{3} =$ **939.47mm**

Where PA = average rain fall of the total area

Pi = Measured precipitation at a given station and time

n = Number of rain gauges.

Therefore, an annual areal precipitation depth computed from Arithmetic method is **939.47mm.**

4.2.2.2. Thiessen polygons

This method provides a good result for non-uniformly distributed rain gauges over the area for both flat and hilly terrain by determining a weighted factor for each gauge. Even though eleven stations are considered to construct Thiessen polygon, only five stations (Debrezeit Airforce, Modjo, Chefe Donsa,Ejere,and Nazareth) are used for computing weighted annual rainfall (Figure4.4).

Using the method, the computed annual rainfall of Modjo River Catchment is **901.64 mm** (Table4.4).

Table 4.4 Theissen polygon method to calculate the annual rainfall of Modjo River Catchment

Stations	Station Precipitation (mm)	Net area (Km^2)	Percent of Total Area (%)	Weighted Precipitation (mm)
	(A)	**(B)**	**(C)**	**(A*C)**
Debrezeit Airforce	936.2	216	14.14	132.38
Modjo	1015.6	403	26.38	267.92
Chefe Donsa	790.3	608	39.81	314.62
Ejere	956.7	270	17.68	169.14
Nazareth	883.3	30.4	1.99	17.58
Total		1527.4	100.0	**901.64**

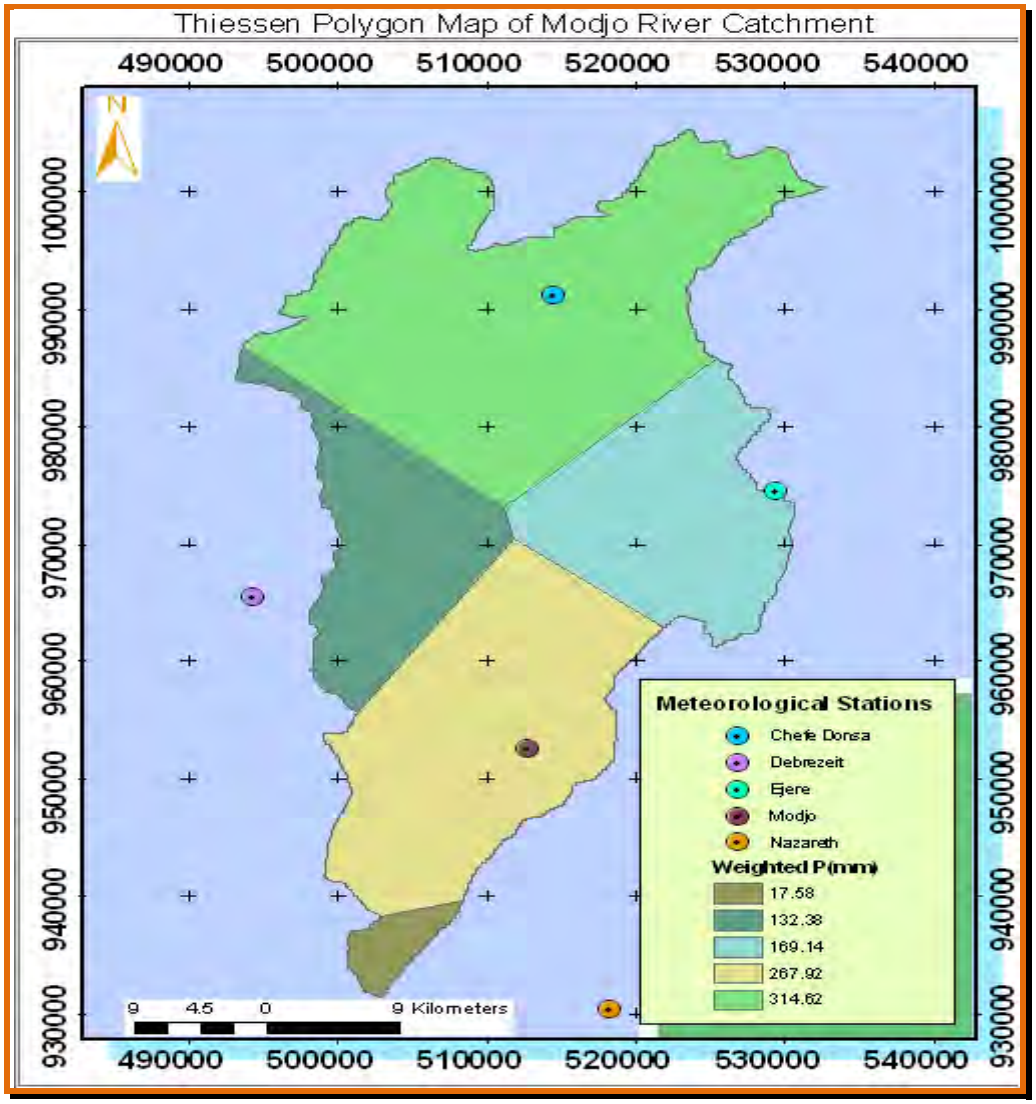


Figure 4.3 Theissen polygon map of Modjo River Catchment

There fore using different rain fall depth of different stations found in the target study and the adjacent area, the representative aerial depth of rain fall over the whole area is analyzed. Accordingly, Arithmetic mean, and Thiessen methods are selected, considering the non uniformity of the land and variation of topographic textures of the area and the average of them has been used for explanation purpose. An annual aerial precipitation computed from the average of these methods is **920.56 mm.**

4.2.3. Temperature

In the study area, as in all other places of Ethiopia, the altitude of the sun is always high, making solar radiation intense. Temperature is high during the day and is considerably reduced at night causing the daily range of temperature to be large. Temperature data are the major factor in computing potential evapotranspiration of the area.

From 1996 to 2006 monthly mean maximum and minimum temperature as recoded by the NMSA at the stations of Debrezeit Airforce and Modjo are used to calculate representative monthly and annual average temperature of the area. Accordingly the average monthly and annual maximum and minimum temperatures of the catchment are shown in Table4.5 and Figure4.4.

The mean annual minimum temperature of the study area is 12.23 ^{o}C and the mean annual maximum temperature is 27.6^{o}C. The mean annual air temperature of the area is 19.84^{o}C.

Table 4.5 Mean Monthly Temperature of Modjo River catchment

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annu. Av.
M.M.Max. Temp	27.6	29	27.9	29.7	30.3	28.1	25.4	25.1	26.6	27.4	27.1	26.9	27.6
M.M.Min. Temp	10.1	10.5	13.4	13.9	13.7	12.8	13.4	13.81	12.7	11.4	10	11	12.23
M.M.Temp	18.85	19.75	20.65	21.8	22	20.5	19.4	19.5	19.7	19.4	18.6	17.9	19.84

Where,M.M.Max. Temp. is mean monthly maximum temperature; M.M.min.Temp is mean monthly minimum temperature; M.M.Temp.is mean monthly air temperature.

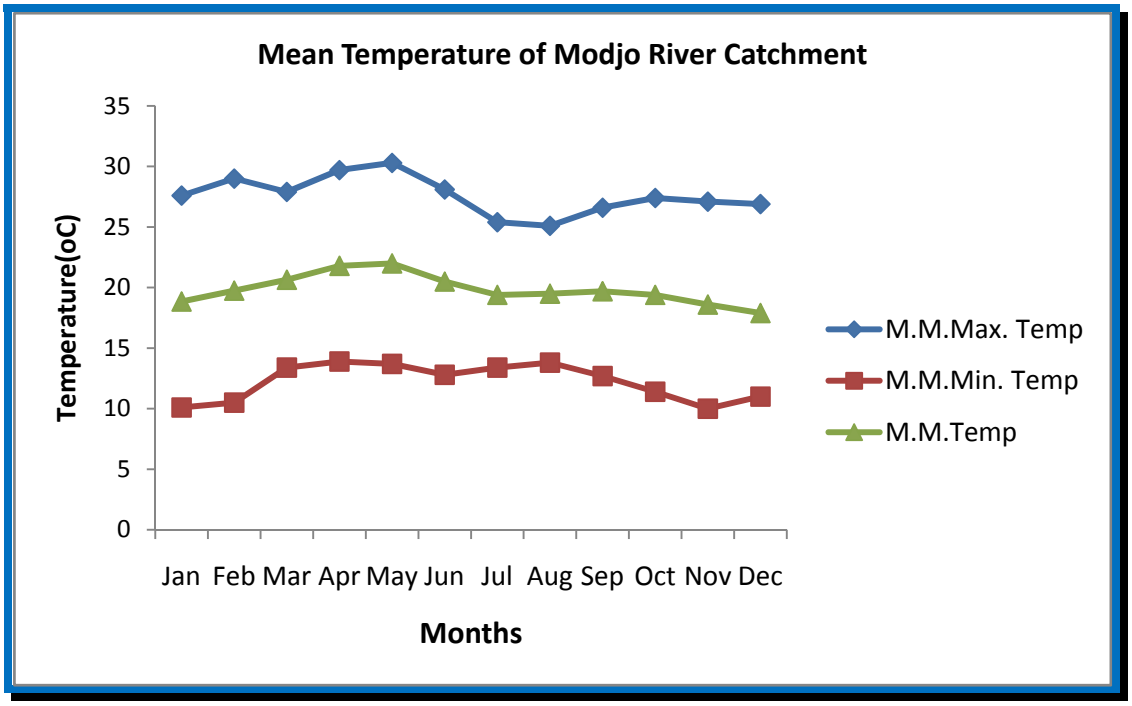


Figure 4.4 Mean air Temperature of Modjo River catchment

Figure4.5 shows long-term temperature and rainfall relation for the catchment. Even though the maximum air temperature occurs in May, high temperature values are observed during the rainy seasons. Months in the rainy seasons are warmer than months in dry seasons. The minimum temperatures as well as rainfall are also occurring almost in similar range of months.

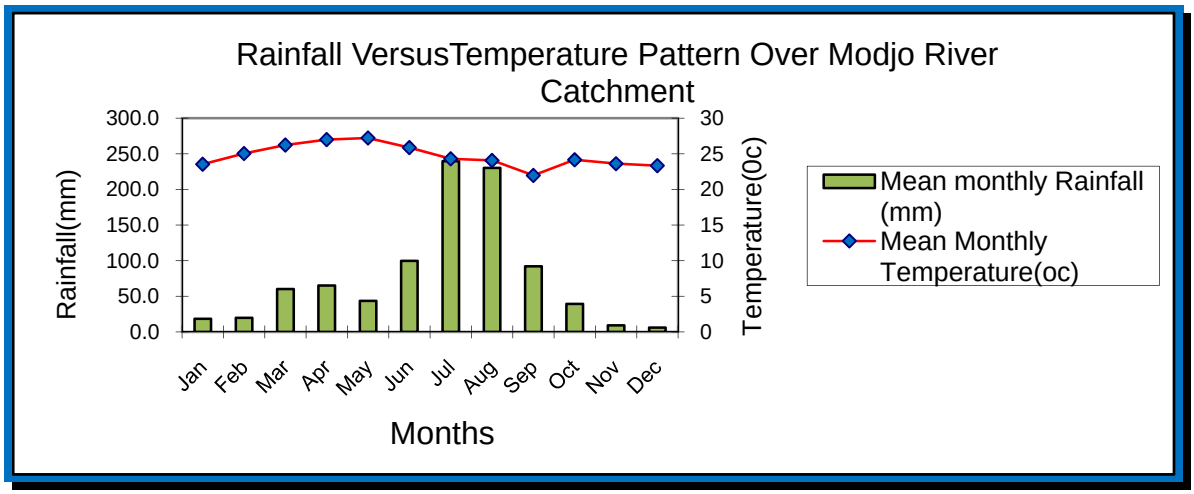


Figure 4.5 Temperature and Rainfall Relation Ship

4.2.4. Wind Speed

The movement of air and moisture transfer depends on wind speed and turbulence. Evaporation has a direct relation wind speed and turbulence (Shaw, 1988; Tamiru Alemayehu and Tenalem Ayenew, 2001). Wind speed and air temperature removes water vapor molecules from the air in contact with the water holding surface and enable evaporation to proceed at maximum rate governing with the existing main factors, temperature and humidity condition.

In this study, Wind speed data measured at height of 2m above the ground surface and recorded from 1994-2006 is analyzed from the Debrezeit station, located in the central part of the catchment. The mean monthly wind speed data is shown in Table4.6. The maximum wind speed is recorded in May (1.7m/s) and the minimum is recorded in August and September (1.0m/s). The magnitude varies from 1.0-1.7 m/sec. Wind speed is relatively low, especially in the rainy season (July-September).

4.2.5. Sunshine Duration

Monthly sunshine hours were collected from Debrezeit meteorological Station. The data were recorded from 1997 to 2006. The mean monthly sunshine hours of the area are given in the table4.6. The maximum sunshine hour is recorded in November and February (9.73 hours) whereas the minimum one is in August (5.72 hours). Generally, the maximum sunshine hours are found in dry months whereas the minimum are in very highly rainy months.

4.2.6. Relative Humidity

Relative humidity is the relative measure of the amount of the moisture in the air to the amount needed to saturate the air at the same temperature e_d/e_a represents as a percentage (Shaw, 1985).

$RH= (e_d/e_a)*100$

Where, RH is Relative humidity

e_d is actual vapor pressure at the dew point, T_d

e_a is saturated vapor pressure at air temperature, T_a

The relative humidity data (%) was taken from Debrezeit meteorological station. The data was recorded from 1996-2006. The mean monthly values were computed and are given in the table4.6 below. The maximum and minimum relative humidity is found in August (87%) and February (63%), respectively. This maximum and minimum value is also within very highly rainy month and dry month, respectively. In general the highest humidity values are found in the rainy months whereas the lowest values are in the dry months.

Table4.6 Mean Monthly wind speed, relative humidity, and sunshine hour.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annu.Av.
W.S(m/s)	1.39	1.6	1.6	1.6	1.7	1.6	1.2	1.0	1.0	1.5	1.5	1.5	1.43
S(Hrs)	8.86	9.73	8.23	8.42	8.64	7.19	8.47	5.72	7.79	8.99	9.73	9.67	8.45
R.H (%)	73	63	71	69	69	81	86	87	86	74	71	70	75

Where: S is Sunshine Hours; R.H. is relative humidity; and W.S is wind speed.

4.3. Runoff

Modjo River catchment is one of the sub-catchments of upper Awash River basin. Rivers, streams (both intermittent and perennial), small Crater Lakes and storage dams are the surface water bodies that are found in the study area.

Modjo River originates from the mountain at around 3050 m.a.s.l. in the northwestern and from the elevated lands in the northern, northeastern, and eastern parts of the study area.

The major rivers present in the study area as mentioned earlier in section 2.3.2 of chapter two are Wedecha, Tiliku Modjo and Modjo River. Both Wedecha and Tiliku Modjo are tributaries for Modjo River. The hydrological characteristic of the catchment is described by the Modjo River that discharges the run off from the catchment.

4.3.1. Mean monthly and annual flows.

Water that drains across the basin in to a stream channel as overland flow and ground water contribution to a stream as base flow is collectively known as runoff. The 10 years (1997-2006) daily river discharge (Time-Series data) of Modjo River gauged upstream of Koka Dam near Koka town is used in the total runoff analysis of the catchment (Table 4.7).

The mean annual discharge of Modjo River at the gauge station upstream of Koka Dam which is taken as outlet of the catchment with drainage area1527 km^2 is 2.44 m^3 / sec or total Annual flow of 77.55 Mm^3. This results in an average unit discharge of about 1.6 l/s /km^2.

Table 4.7:- Mean monthly flows of Modjo River upstream of Koka Dam close to Koka Town.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Monthly Flows(M^3/s)	0.48	0.46	0.79	0.68	0.79	2.19	7.46	10.09	3.91	1.25	0.59	0.54	29.22
Mm^3	1.29	1.11	2.12	1.76	2.12	5.68	19.98	27.03	10.13	3.35	1.53	1.45	77.55
mm	0.84	0.73	1.39	1.15	1.39	3.72	13.08	17.70	6.63	2.19	1	0.95	50.77

Figure4.6-Shows the monthly rainfall-runoff relationship. Runoff is concentrated from July to September. This runoff represents more than 80% of the annual runoff

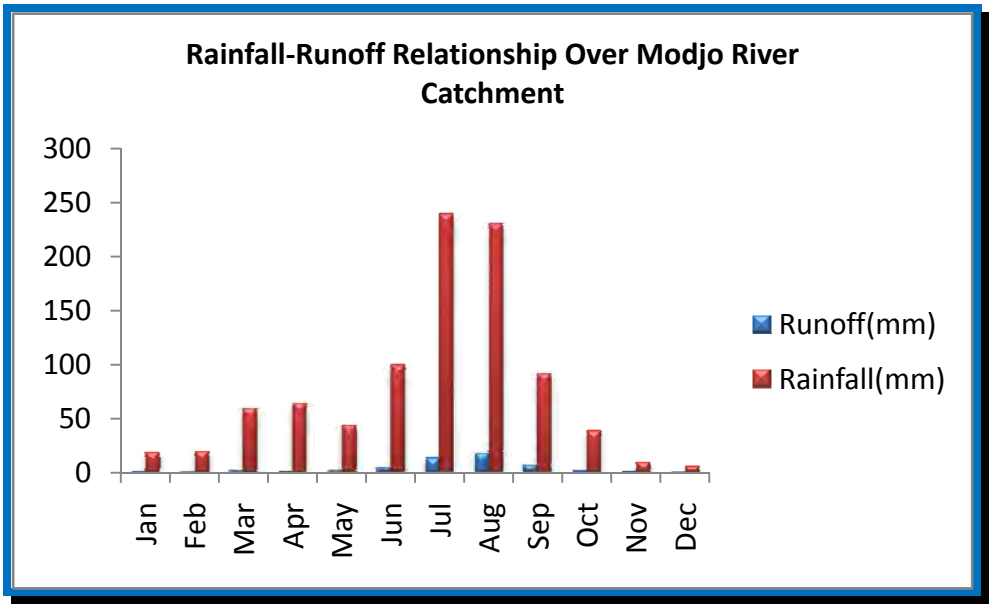


Figure 4.6 Rainfall-Runoff relationships at Modjo River catchment

4.4. Evapotranspiration

Evapotranspiration E_t is the process of water loss from a vegetated land surface by evaporation plus transpiration (Shaw, 1988). The evaporation from a vegetated surface is a function of available energy, net radiation, the temperature of the surface and air, the saturation deficit, the wind speed, and the available soil moisture. There fore, the assessment of

transpiration loss takes in to account the water available to the plant in the rooting zone of the soil.

Evapotranspiration has been computed using the recorded data of meteorological stations of the catchment employing the Penman, Thornthwaite and Mather empirical formulae.

4.4.1. Estimation of Potential Evapotranspiration (PET)

PET is defined as the evapotranspiration which would occur under unrestricted availability of water to a fully vegetated surface (Shaw, 1988) or it is the maximum possible evaporation under given meteorological conditions (Tenalem Ayenew and Tamiru Alemayehu, 2001). PET has a positive relation with temperature, sunshine, and wind speed but has a negative relation ship with air humidity.

4.4.1.1 Penman modified method

Penman modified method and adjusted Thorenthwaite are used based on the available data. Resulting from his experience, Penman produced a formula which was later modified by (MAFF, 1967 in Shaw) to allow the condition under which evaporation plus transpiration takes place forom a vegetated surface which is given by:

$$PET = \frac{(\Delta/\gamma)\, H_T + E_{at}}{(\Delta/\gamma) + 1} \quad \text{---------- 4.1}$$

Where the extra subscript‘t’ signifies inclusion of transpiration effects,

$$H_T = 0.75R_1 - R_o \quad \text{---------- 4.2}$$

Where; γ is the reflective coefficient for incident radiations or the Albedo of the basin that depends on the nature of the surface. For the specific study area, this is taken as 0.23 assuming majority of land cover of the study area as short grass surface. The term E_{at} is very similar to E_a

(Which is equal to 0.35[0.5 +u_2 /100] (e_a- e_d)) the coefficient 0.5 being replaced by 1 to allow for extra roughness.

$E_{at=}$ 0.35 (1+u_2/100) (e_a-e_d) ----------4.3

The empirical equations for the incoming and outgoing radiation in the energy term H_T are given by R_1 (1-r) = 0.75 R_a f_a (n/N) and f_a (n/N) for the study area within latitudes south of 541/2^{0}N, (Shaw. 1988) is equal to:

f_a(n/N) = (0.16 + 0.62 n/N)----------4.4

The empirical equation for the outgoing reduction takes the form:

$R_o=\sigma T^4$ (0.47-0.075$\sqrt{e_d}$) (0.17 + 0.83n/N)----------4.5

Albedo (short wave-reflection coefficient) of any basin can vary widely with time of day, season, latitude and cloud cover. In the absence of knowledge on crop the value of r (reflection coefficient), is recommended to be 0.23 (Maidment, 1993, in Shaw)

In the study area, the average and dominant crops, forests, soil and grass are cereal crops, clay soil, sandy loam,silly soil,, grass and pasture and bare soil with their Albedo 0.25, 0.13, 0.3 0.2, 0.25 and 0.22 respectively (Dunne and Leopold, 1978) and Maidment (1993). Therefore by averaging the above albedo the value of 'γ' is taken as 0.23. The calculated annual potential evapotranspiration of the study area according to penman is **1213.03 mm** (Table 4.8).

4.4.1.2 Thornthwaite method

Thornthwaite produced a formula for calculating PET based on temperature with an adjustment being made for the latitude location and number of daylight hours. This method uses air temperature as an index of energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of net radiation and other controls of evapotranspiration, and the available energy is shared in fixed

proportion between heating the atmosphere and evapotranspiration (Dunne and Leopold. 1978). The equation is given by (Shaw, 1988):

$PET_m = 16\ N_m\ (10T_m/I)^a$ mm---------- 4.6

Where m is the month 1, 2, 3..... 12, and N_m is the monthly adjustment factor related to hours of daylight, T_m is the monthly mean temperature ^0C (Table 4.7), I is the heat index for the year, given by:

$I = \sum i_m = \sum(T_m/5)^{1.5}$ for m=1... 12

And: $a=6.7x10^{-7}\ I^3 + 7.7\ x10^{-5}\ I^2 + 1.8x10^{-2}I+0.49$

The calculated annual PET of Modjo river catchment as of Thornthwaite is **904.42mm** (Table 4.9).

From the above two results, the PET obtained from Thornthwaite method seems to be representative. Penman modified method overestimates the value. Therefore, for further analyses the catchment's PET is assumed to be **904.42mm.**

Table 4.8:-Monthly potential evapotranspiration (PET in millimeter) of the study area from Penman Method

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T	18.9	19.7	20.6	21.8	22.0	20.5	19.4	19.3	19.7	19.4	18.6	19.0
K	292.0	292.9	293.8	295.0	295.2	293.6	292.6	292.4	292.8	292.5	291.7	292.1
N	8.86	9.73	8.23	8.42	8.64	7.19	8.47	5.72	7.79	8	8.5	8.3
N	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	8.99	9.73	9.67
n/N	0.76	0.82	0.69	0.68	0.69	0.57	0.67	0.46	0.64	0.89	0.87	0.86
H(100)	73.00	63.00	71.00	69.00	69.00	81.00	86.00	87.00	86.00	74.00	71.00	70.00
U1(m/s)	1.4	1.6	1.6	1.6	1.7	1.6	1.2	1.0	1.0	1.5	1.5	1.5
U2(mil/hr)	3.1	3.6	3.6	3.6	3.8	3.6	2.7	2.2	2.2	3.4	3.4	3.4
Ea (mmhg)	16.47	17.53	17.53	18.68	18.68	17.53	16.47	17.53	17.53	16.47	15.97	16.47
Ed(mmhg)	12.02	11.04	12.45	12.89	12.89	14.20	14.16	15.25	15.08	12.19	11.34	11.53
Ea-Ed	4.45	6.49	5.08	5.79	5.79	3.33	2.31	2.28	2.45	4.28	4.63	4.94
Δ/r	2.1	2.2	2.32	2.32	2.32	2.32	2.16	2.16	2.2	2.16	2.06	2.11
Ra(mm/day)	12.8	13.9	14.8	15.2	15	14.8	14.9	15	14.8	14.2	13.1	12.5
Eat	1.60	2.35	1.84	2.10	2.10	1.21	0.83	0.82	0.88	1.55	1.68	1.79
F(ed)	0.21	0.22	0.21	0.20	0.20	0.19	0.19	0.18	0.18	0.21	0.22	0.22
F(b)	0.80	0.85	0.74	0.74	0.74	0.64	0.73	0.55	0.70	0.91	0.90	0.88
Ri(1-r)	6.08	7.00	6.50	6.66	6.58	5.67	6.45	5.02	6.21	7.58	6.89	6.49
Ro	2.39	2.71	2.20	2.19	2.20	1.74	1.95	1.40	1.81	2.70	2.75	2.70

Fa(n/N)	0.63	0.67	0.59	0.58	0.59	0.51	0.58	0.45	0.56	0.71	0.70	0.69
∂Ta4	14.17	14.35	14.52	14.76	14.80	14.49	14.29	14.26	14.34	14.28	14.12	14.20
Ht	3.69	4.29	4.29	4.48	4.39	3.93	4.49	3.62	4.40	4.88	4.15	3.79
ET(mm/day)	3.02	3.69	3.55	3.76	3.70	3.11	3.33	2.73	3.30	3.83	3.34	3.15
PET(mm/mon)	93.53	103.18	110.16	109.04	114.68	93.39	96.66	84.73	99.01	110.94	100.15	97.55

1213.03mm/y

Table 4.9:-Monthly potential evapotranspiration (PET in millimeter) of the study area from Thoranthwaite Method

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Tm	18.9	19.7	20.6	21.8	22.0	20.5	19.4	19.3	19.7	19.4	18.6	19.0
N(posbl)	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
Nm	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.03	1.01	0.98	0.97	0.96
i(m)	7.32	7.82	8.36	9.10	9.23	8.30	7.64	7.58	7.82	7.64	7.17	7.40
I	95.38											
A	2.09											
Em	66.44	73.17	80.15	90.04	91.95	78.94	70.86	69.73	72.71	70.41	64.33	67.33
PET	64.23	71.95	80.15	92.29	96.55	83.54	74.41	72.05	73.31	69.23	62.18	64.53

904.42

4.4.2. Actual Evapotranspiration (AET)

AET is that amount of water lost through evapotranspiration under the existing field condition. A value of actual evapotranspiration (AET) over a basin is often obtained by first calculating the potential evaporation plus transpiration (PET), and then modifying the answer by accounting for the actual soil moisture content (Shaw, 1988). The term actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under the existing field conditions (Dunne and Leopold, 1978). The majority of the water loss due to evapotranspiration takes place during the winter months (dry hot seasons in Ethiopian case) while little loss is during the summer (wet cold season in Ethiopian case). Always actual evapotranspiration is less or equal to potential evapotranspiration. When the vegetation is unable to abstract water from the soil, then the actual evapotranspiration becomes less than potential.

Various approaches exist for the determination of Actual evapotranspiration. The methods employed in this paper are that developed by Thornthwaite and Mather (1957).

4.4.2.1. Thorenthwaite and Mather soil water balance model.

When the soil is saturated, it will hold on more water. In this condition, actual evapotranspiration is equal to potential evapotranspiration (Shaw, 1988). If there is no rain to replenish the water supply, the soil moisture gradually becomes depleted by the demand of vegetation to produce a soil moisture deficit (D). As soil moisture deficits increases, actual evapotranspiration becomes increasingly less than potential evapotranspiration. The values of soil moisture deficit and actual evapotranspiration vary with soil type and vegetation. When the moisture supply becomes limiting, the computed potential rate is modulated by a factor that depends up on the amount of water in the soil. The relationship can be expressed as (Dunne and Leopold, 1978);

AET=PETxf(AW/AWC)----------4.7

and PET are actual and potential rates of evapotranspiration respectively, f ( ) is some function of the term inside the parentheses, AW is the available soil moisture which is equal to soil moisture content minus permanent wilting point times the rooting depth of vegetation (cm), AWC is the available water capacity of soil which is equal to field capacity minus permanent wilting point times rooting depth of vegetation (cm).

Penman (1950), in Shaw introduced the concept of 'root constant' that defines the amount of soil moisture (mm depth) that can be extracted from a soil without difficulty by given vegetation. A soil moisture budget can be made on a monthly basis for various types of vegetation classified according to their root constants (Dunne and Leopold, 1978). Therefore,

to evaluate actual evapotranspiration over a basin area, the proportions of different types of vegetation covering the basin must be known.

Accordingly, the study area has been classified in to four major groups of soil type (Clay, clay loam, silt loam and sandy loam) respectively with available water capacity of root zone (mm) 75,100,125 and 150, and the types of rooting depth of vegetation cover are taken 1m on average, which are often cereal crops such as wheat, Barley, Maize, and Sorghum and Grass, Shrubs and Wood lands. The area is further divided into five polygons based on the Precipitation stations within the catchment. The dominant soil and vegetation types, rooting depth, available water capacity of the root zone and available meteorological data from the stations falling in each polygon are used to compute the actual Evapotranspiration (Table 4.10) using Thornthwaite and Mather (Ding man, 1994) standard soil water balance model. In puts to Thornthwaite model consists of monthly value of rain fall, Pm (Table 4.2), and potential evapotranspiration, PETm from Thornthwaite method (Table4.10b).

Alley (1984, in Dingman), found out that if in a given month $P_m > PET_m$, the value of soil moisture at the end of that month, S_m, is found as:

$s_m = \min \{[(p_m - PET_m) + S_m - 1] S_{mm}\}$ ----------4.8

If $P_m < PET_m$, a soil moisture deficit develops or increases. The soil moisture for this case is given as:

$$S_m = S_{m-1} \exp\left[\frac{PET_m - P_m}{S_{max}}\right] \quad \text{---------- 4.9}$$

The monthly actual evapotranspiration, AET_m is then found as:

$AET = PET$ if $P_m > PET$----------4.10 Otherwise,

$AET_m = P_m + S_{m-1} - S_m$ ----------4.11

Using this method and the potential evapotranspiration from Thornthwaite method, the actual evapotranspiration (AET) of each

Polygon area of Thiessen polygon map of the study area is calculated as shown in (Table 4.10).The actual evapotranspiration of the catchment is taken as the average of the values calculated for each of the subcatchments(polygons).Accordingly the average actual evapotranspiration of Modjo River catchment is estimated as **669.28mm/ year(Table4.11)**

Table 4.10(a-e) Estimation of Actual Evapotranspiration, AET of the areas within each Thiessen polygons by using Thornthwaite-Mather method.

a.

Precipitation from Debrezeit Statiopn Shallow-rooted crops For crop land,clay,W=75,Area=216sq km													
Months	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Yearly**
P	15.0	44.9	59.8	60.3	44.8	120.3	228.9	211.4	95.0	42.7	5.7	7.6	936.4
PET	64.2	72.0	80.2	92.3	96.6	83.5	74.4	72.1	73.3	69.2	62.9	64.5	905.1
P-PET	-49.2	-27.1	-20.4	-32.0	-51.8	36.8	154.5	139.4	21.7	-26.5	-57.2	-56.9	
APWL	-190	-217	-237	-269.3	-321	0	0	0	0	-26.5	-83.7	-140.6	
SM	5.9	4.2	3.2	2.1	1.0	75.0	75.0	75.0	75.0	52.7	24.6	11.5	
CSM	-5.6	-1.7	-1.0	-1.1	-1.1	74.0	0.0	0.0	0.0	-22.3	-28.1	-13.1	0.0
AET	20.6	46.6	60.8	61.4	45.9	83.5	74.4	72.1	73.3	65	33.8	20.7	658.1
SMD	43.6	25.4	19.4	30.9	50.7	0	0	0	0	4.2	29.1	43.8	247
SMS	0	0	0	0	0	0	154.5	139.4	21.7	0	0	0	315.6
Recharge													120.5

b.

Precipitation from Ejere Station Moderately deep-rooted crops For crop land,clay soil,W=150,Area=270sq km													
Months	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Yearly**
P	26.5	22	53.9	38	42.4	91.8	249.2	272	93.2	41.6	12.1	14	956.7
PET	64.2	72	80.2	92.3	96.6	83.5	74.4	72.1	73.3	69.2	62.9	64.5	905.1
P-PET	-37.7	-50	-26.3	-54.3	-54.2	8.3	174.8	200	19.9	-27.6	-50.8	-50.5	
APWL	-167	-217	-243	-297	-351	0	0	0	0	-27.6	-78	-129	
SM	49.4	35.4	29.7	20.7	14.4	150	150	150	150	124.8	88.9	63.5	
CSM	-14.1	-14	-5.7	-9	-6.3	135.6	0	0	0	-25.2	-35.9	-25.4	0
AET	40.6	36	59.6	47	48.7	83.5	74.4	72.1	73.3	66.8	48	39.4	689.4

SMD	**23.6**	**36**	**20.6**	**45.3**	**47.9**	**0**	**0**	**0**	**0**	**2.4**	**14.9**	**25.1**	**215.7**
SMS	**0**	**0**	**0**	**0**	**0**	**8.3**	**174.8**	**200**	**19.9**	**0**	**0**	**0**	**403**
Recharge													**65.8**

c.

Precipitation from Modjo Station Deep-rooted crops

For grass land,Sandy loam soil,W=150,Area=403sq km

P	**14.7**	**13.6**	**66.3**	**53.8**	**54.3**	**130.8**	**296.0**	**224.7**	**108.4**	**40.1**	**9.3**	**3.6**	**1015.6**
PET	**64.2**	**72.0**	**80.2**	**92.3**	**96.6**	**83.5**	**74.4**	**72.1**	**73.3**	**69.2**	**62.9**	**64.5**	**905.1**
P-PET	**-49.5**	**-58.4**	**-13.9**	**-38.5**	**-42.3**	**47.3**	**221.6**	**152.7**	**35.1**	**-29.1**	**-53.6**	**-60.9**	
APWL	**-187**	**-246**	**-259**	**-297.9**	**-340**	**0**	**0**	**0**	**0**	**-29.1**	**-82.7**	**-143.6**	
SM	**43.1**	**29.2**	**26.6**	**20.6**	**15.5**	**150.0**	**150.0**	**150.0**	**150.0**	**123.6**	**86.4**	**57.6**	
CSM	**-14.5**	**-13.9**	**-2.6**	**-6.0**	**-5.1**	**134.5**	**0.0**	**0.0**	**0.0**	**-26.4**	**-37.2**	**-28.8**	**0.0**
AET	**29.2**	**27.5**	**68.9**	**59.8**	**59.4**	**83.5**	**74.4**	**72.1**	**73.3**	**66.5**	**46.5**	**32.4**	**693.5**
SMD	**35.0**	**44.5**	**11.3**	**32.5**	**37.2**	**0.0**	**0.0**	**0.0**	**0.0**	**2.7**	**16.4**	**32.1**	**211.6**
SMS	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**47.3**	**221.6**	**152.7**	**35.1**	**0.0**	**0.0**	**0.0**	**456.7**
Recharge													**93.75**

d.

Precipitation from Chefe Donsa Station shallow-rooted crops

For Crop land with shyrubs,clay loam,W=100,Area=608sq km

Months	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Yearly**
P	**13.3**	**15.4**	**48.1**	**52.4**	**30.7**	**99.1**	**199.1**	**230.8**	**77.3**	**15.4**	**4.8**	**3.9**	**790.3**
PET	**64.2**	**72.0**	**80.2**	**92.3**	**96.6**	**83.5**	**74.4**	**72.1**	**73.3**	**69.2**	**62.9**	**64.5**	**905.1**
P-PET	**-50.9**	**-56.6**	**-32.1**	**-39.9**	**-65.9**	**15.6**	**124.7**	**158.8**	**4.0**	**-53.8**	**-58.1**	**-60.6**	
APWL	**-223**	**-280**	**-312**	**-352**	**-418**	**0**	**0**	**0**	**0**	**-53.8**	**-112**	**-172.5**	
SM	**10.7**	**6.1**	**4.4**	**3.0**	**1.5**	**100.0**	**100.0**	**100.0**	**100.0**	**58.4**	**32.7**	**17.8**	
CSM	**-7.1**	**-4.6**	**-1.7**	**-1.4**	**-1.5**	**98.5**	**0.0**	**0.0**	**0.0**	**-41.6**	**-25.7**	**-14.9**	**0.0**
AET	**20.4**	**20.0**	**55.4**	**53.8**	**32.2**	**83.5**	**74.4**	**72.1**	**73.3**	**57.0**	**30.5**	**18.8**	**591.4**
SMD	**43.8**	**52.0**	**24.8**	**38.5**	**64.4**	**0.0**	**0.0**	**0.0**	**0.0**	**12.2**	**32.4**	**45.7**	**313.7**
SMS	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**124.7**	**158.8**	**4.0**	**0.0**	**0.0**	**0.0**	**287.5**
Recharge													**55.15**

e.

Precipitation from Nazareth Station shallow-rooted crops

For grass land,Silt loam,W=125,Area=30.4sq km

Months	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Yearly**
P	**22.6**	**19.1**	**77.0**	**44.1**	**52.5**	**67.9**	**208.8**	**220.0**	**96.0**	**58.4**	**13.1**	**9.8**	**889.3**
PET	**64.2**	**72.0**	**80.2**	**92.3**	**96.6**	**83.5**	**74.4**	**72.1**	**73.3**	**69.2**	**62.9**	**64.5**	**905.1**
P-PET	**-41.6**	**-52.9**	**-3.2**	**-48.2**	**-44.1**	**-15.6**	**134.4**	**148.0**	**22.7**	**-10.8**	**-49.8**	**-54.7**	
APWL	**-157**	**-210**	**-213**	**-261**	**-305**	**-321**	**0**	**0**	**0**	**-10.8**	**-60.6**	**-115.3**	
SM	**35.6**	**23.3**	**22.7**	**15.5**	**10.9**	**9.6**	**125.0**	**125.0**	**125.0**	**114.5**	**76.7**	**49.8**	
CSM	**-14.2**	**-12.3**	**-0.6**	**-7.2**	**-4.6**	**-1.3**	**115.4**	**0.0**	**0.0**	**-10.5**	**-37.8**	**-26.9**	**0.0**

AET	36.8	31.4	77.6	51.3	57.1	83.5	74.4	72.1	73.3	68.9	50.9	36.7	714.0
SMD	27.4	40.6	2.6	41.0	39.5	0.0	0.0	0.0	0.0	0.3	12.0	27.8	191.1
SMS	0.0	0.0	0.0	0.0	0.0	0.0	134.4	148.0	22.7	0.0	0.0	0.0	305.1
Recharge													22.75

Where= Available water capacity of root zone, P= mean monthly precipitation, PET= potential Evapotranspiration' APWL= accumulated potential water loss,SM= Soil moisture, CSM= change in soil moisture, AET= Actual evapotranspiration, SMD=soil moisture deficit, and SMS=Soil moisture surplus.

Table 4.11 Estimated Actual Evapotranspiration and soil moisture surplus of Modjo River catchment computed as of Thornthwaite-Mather method.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	18.5	19.7	60.1	65.1	43.6	99.6	239.5	230.2	92.1	39.2	9.2	6.0	922.8
PET	64.2	72.0	80.2	92.3	96.6	83.5	74.4	72.1	73.3	69.2	62.9	64.5	905.1
AET	29.52	32.3	64.46	54.66	48.62	83.5	74.4	72.1	73.3	64.84	41.94	29.6	669.28
SMS	0.0	0.0	0.0	0.0	0.0	11.12	162	159.78	20.68	0	0.0	0.0	353.6

Where P=Mean monthly precipitation of Modjo River Catchment, PET=Potential Evapotranspiration,AET= Average Actual Evapotranspiration of Modjo River Catchment, SMS=Soil Moisture Surplus

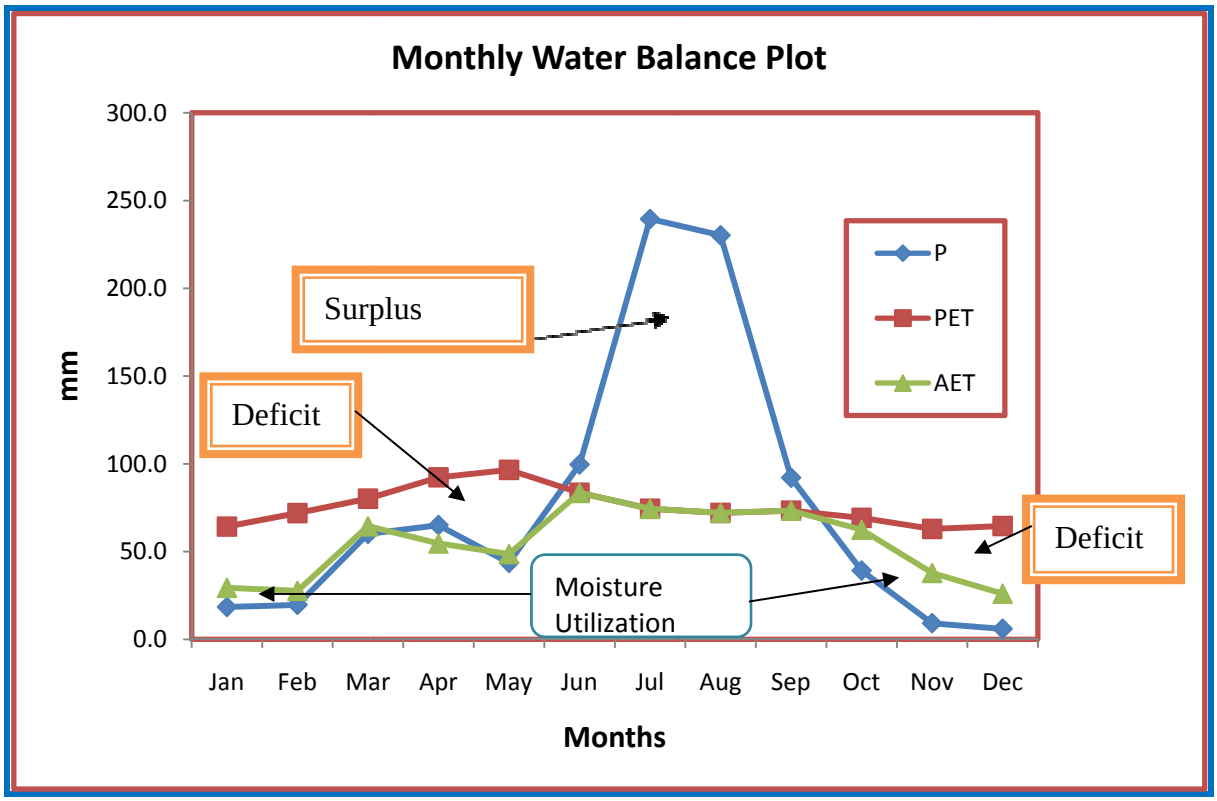


Figure 4.7 Monthly water balance plot for Modjo River catchment

4.5. Groundwater Recharge estimation

Ground water recharge can be defined as the entry of water in to the saturated zone of water made available at the water table surface together with the associated flow away from the water table with in the saturated zone (Freez and cheery 1979). Soil Water balance method has been used to estimate the annual groundwater recharge in the basin as follows:

Soil-Water balance method

The study area has been divided into five by the Thiessen polygon map (Figure 4.3) created using Analysis Tools extension of ArcMap 9.2 for Modjo River catchment. Based on the land use (figure 2.3.3), soil type Map (Figure 2.3.4) and the available meteorological data from the

stations (Table 4.4), the yearly areal depth of recharge to the groundwater of each polygon area is estimated as shown in Tables 4.10a-4.10e.as of Thornthwaite and Mather method. Here assumption is made that 50% of the total moisture surplus goes as runoff and the remaining 50% of the surplus is for detention in the soils of each polygon area. Accordingly, the yearly areal depth of recharge to the groundwater in Modgo River Catchment is taken as average of the yearly recharge rates for the polygon areas and is computed as shown below to be **71.59mm/year**.

Recharge=Average Recharge rates of the Thiessen polygon areas

$$=\frac{120.5+65.8+93.75+55.15+22.75}{5}$$ (Tables 4.10a-4.10e pp 59-61)

=71.59mm/year

CHAPTER FIVE

5. HYDROGEOLOGY

5.1 General

The groundwater circulation and the dispersion of pollutants depend on the hydrogeological characteristics of the material such as porosity, permeability, transmissivity, etc. The origin, flow and chemical constitute of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrostratigraphical units through which it moves. The stress from tectonism and weathering govern the hydrogeochemical characteristics of earth material (Tamiru Alemayehu et al., 2005).

5.2. Hydrostratigraphic units

From field hydro geological study of the area and the well log of several wells drilled in the catchment, the major hydrostratigraphic units can be categorized in to the following: Quaternary alluvial /lacustrine sediments, weathered and fractured Ignimbrites, Scoria, scoriaceous basalt and basalts.

5.2.1High to Moderate Productive Aquifers of Quaternary alluvial/Lacustrine sediments, Fractured and Scoriaceous Basalt

The alluvial cover mainly outcrops above the products of the western Rift margin complex and around some of the Debrezeit Lakes that fall within the study area and consist of regolith, and alluvium.

Lacustrine sediments cover most of the northwestern part of Modjo town. The thickness increases from northwest to southeast. These sediments are exposed in the study area with thin but extensive spatial distribution and consist of sands, silts, clays, tuffs, pumice, and ignimbrites. These sediments, in most places are mixed compositionally with quaternary volcanic products and form a specific mixed volcano-sedimentary rock type.

Laterally where the lacustrine deposits are exposed at the surface of the study area they appeared to be a loosely cemented material texturally ranging from fine grained to coarse-grained.

Tuff, diatomite and ignimbrite are partially interbedded in the lacustrine sediments and at some places form an extensive layer. Therefore, the permeability of this aquifer unit is some how reduced due to the intercalation of tuff layers which is visible around the gullies and banks of the Modjo River. Within

this formation the existence of different layers of Tuff, diatomite and ignimbrite make heterogeneity in the hydrogeological property of the lacustrine deposit. For instance the evolution of different volcanic products which is relatively abrupt in its origin and against the deposits of lacustrine (Diatomite) that is sluggish in its nature will have difference in hydraulic conductivity since the latter have a well cemented nature and compacted due to stress exerted by the overburden. This can make the volcanic products relatively a better media for the groundwater circulation than the lacustrine deposits. But, it has to be noted that the lacustrine deposit took place along with most of the quaternary volcanic activity, which made it to be deposited in alternating manner with the volcanic tuff and pumice (Alem, 2004).

The water supply wells found at the southwestern periphery of Modjo town at
an approximate UTM east 512500 and UTM north 950750 have depth varying
from 80 to 90 meters with static water levels varying from 32 to 35 meters. The
wells do not penetrate the main aquifer (vesicular basalt) and the full depth of
the wells is found in the lacustrine deposit (Figures 5.1and Figure 5.2). The yield of the wells
varies from 5 to 12 l/s with a drawdown of 19 to 25 meters and the specific
yield vary from 0.2 to 0.7 l/s/m.

Therefore, the aquifer materials found in this area are very fine-grained rocks of volcanic origin with some silty sand and pebble beds. Furthermore the rocks in the area are fractured and jointed with

concomitant secondary fine-grained the entire sequence may provide hydraulic connection between the individual aquifers. However, the fine-grained nature of the aquifer materials and the adverse effects of the filling materials contribute to the low yield of water- bearing formation.

The transmissivity of the municipal boreholes vary from 10-55 m2/d. Well number 2and 3 have comparatively high transmissivity values due to the thick layer of sand whereas lower transmissivity values (Alem, 2004).

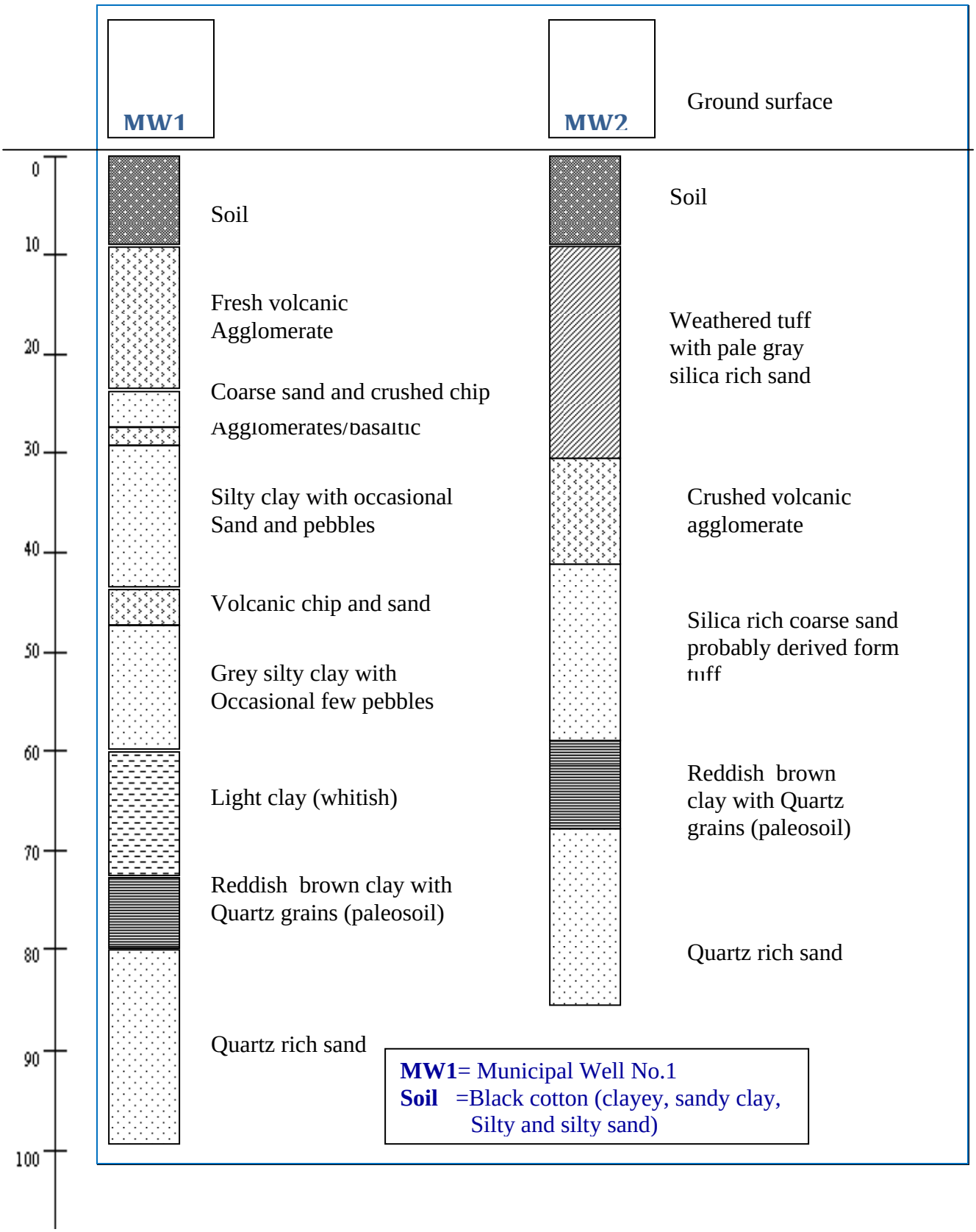

MW1
MW2
Ground surface
0
10
20
30
40
50
60
70
80
90
100
Soil
Fresh volcanic Agglomerate
Coarse sand and crushed chip
Agglomerates/basaltic
Silty clay with occasional Sand and pebbles
Volcanic chip and sand
Grey silty clay with Occasional few pebbles
Light clay (whitish)
Reddish brown clay with Quartz grains (paleosoil)
Quartz rich sand
Soil
Weathered tuff with pale gray silica rich sand
Crushed volcanic agglomerate
Silica rich coarse sand probably derived form tuff
Reddish brown clay with Quartz grains (paleosoil)
Quartz rich sand
MW1= Municipal Well No.1
Soil =Black cotton (clayey, sandy clay, Silty and silty sand)

Figure 5.1 Geological log of Modjo town municipal boreholes Well No.1 and No.2

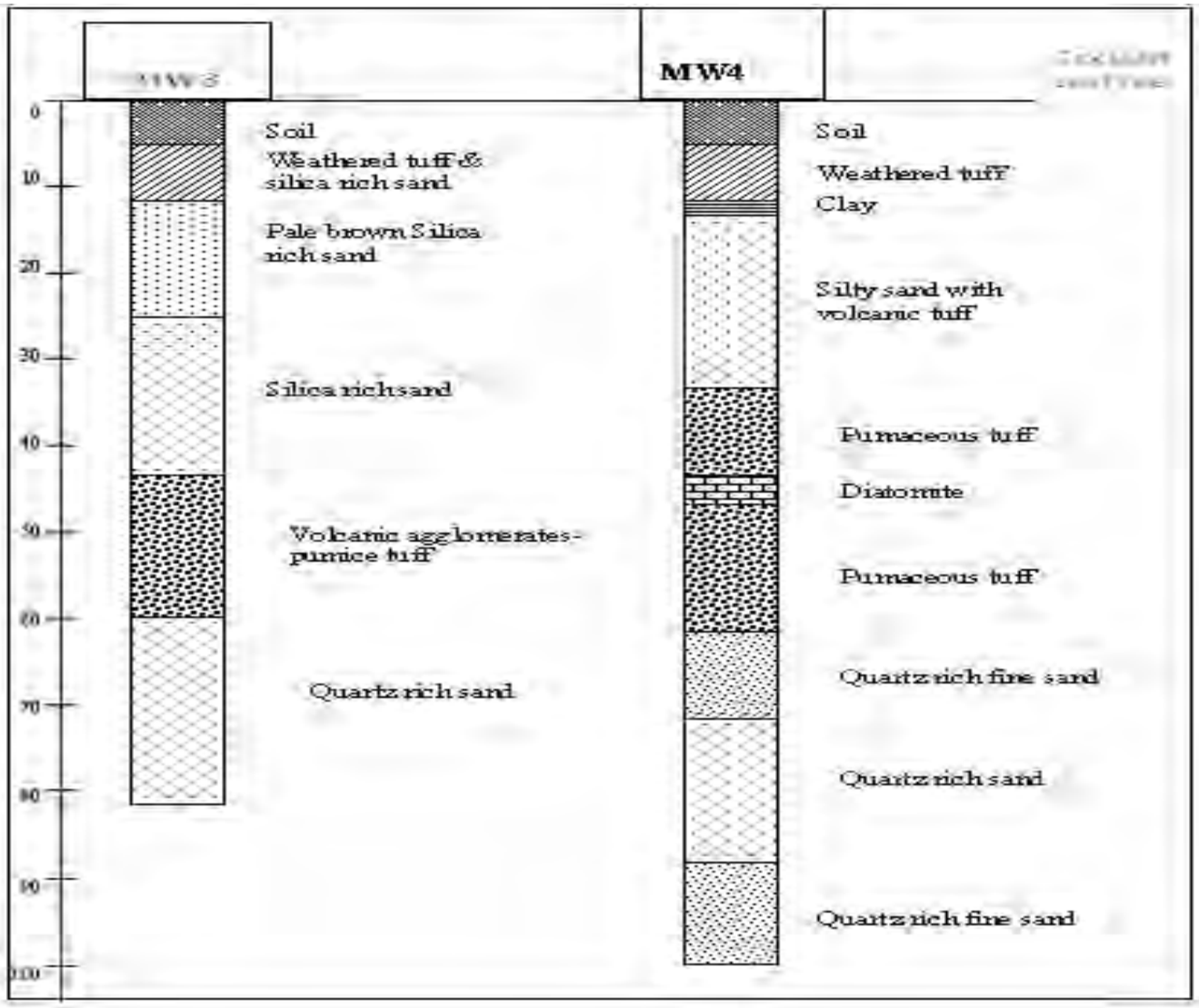


Figure 5.2. Geological log of Modjo town municipal boreholes Well No.3 and No.4

Alluvial and Lacustrine deposits occup large part (32%) of the study area. The alluvial deposit are sandy clay and silty clay with gravel at the lower bed. The lacustrine sediments are distributed around Debre Zeit lakes. This formation moderately favors groundwater storage and movement. Alluvial aquifer are found dominantly in Ada'a plain (Debre Zeit area), along the existing lakes as lacustrine sediment and alluvial.

The alluvial and lacustrine deposits at Adaa plain especially around the Debre Zeit lakes and Mojo area have thickness up to 80 meters and composed of coarse sediments. The static water level varies from 7 to 39 meters deep. The static water level is shallower at the Debre Zeit lake areas and becomes deeper to Mojo area. The specific capacity of bore holes varies from 950 to 90000 m3/day/m. The water quality is generally fresh and the electrical conductivity varies from 444 - 841 μS/cm and total dissolved solids from 220 to 750 mg/l. The high EC and TDS is in this formation has occurred mainly in the parts of the alluvial where it receives recharge from the lakes.

The alluvial sediments are recharged locally from rainfall and runoff and partly outflow of the lakes and discharged into the lakes and the Upper basaltic aquifer. The alluvial aquifers do not form an independent aquifer but it is interconnected with the upper basalt aquifer.

The well logs of Debre Zeit town water supply bore holes in Shimbira Meda show

that the lacustrine deposit has a thickness varying from 50 to 80 meters

underlain by vesicular basalt. The bore holes are shallow and partially penetrate

the regional aquifer of the area. The groundwater is semi confined with high

specific yield varying from 5 to 20 l/s/m and fresh water (TDS less than 400

mg/l). The wells data indicate that this part of the plain has a very high

groundwater potential if the aquifer is fully penetrated, with a potential of

encountering a number of aquifer within a well depth of 250 meters (Taken from

the report entitled Evaluation of Water Resources of the Ade'a and Becho Plains

Groundwater Basin for Irrigation Development Project prepared by the Water

Works Design and Supervision Enterprise, 2008). Generally, the permeability and productivity of the basaltic rocks is a function of both primary and secondary structures with in the rock matrix. The primary and secondary openings which make the rock porous and pervious are formed during and after the cooling process. Interconnected vesicles and fractures caused by buckling of the partly congealed lava and tectonics, voids between successive flows, are some of the features that may give high permeability to the rock body.

Very good aquifers are considered, Quaternary scoraceous and vesicular basalt distributed in the vicinity of Debre Zeit area (Berhane, 1982). The basalt in the project area is vertically and horizontally jointed, vesicular and has high permeability (Getahun Kebede, 1987). The basalts in the study area are highly fractured and in several places they are scoriaceous. Therefore, they have high permeability and productivity (Alem 2004).

5.2.2 Moderate to High Productive Aquifers of Bishoftu Spatter Cones and Lavaflows

Bishoftu volcanic units is composed of spatter cones and scoria which highly favors groundwater storage and movement**.**

This aquifer is distributed in the central, southern and in the north central parts of the study area (Figure 5.3).

5.2.3 Regional to Subregional Aquicludes of Nazareth Group,Welded Ignimbrite,Chefe Donsa Pyroclastics.

Chefe Donsa Pyroclastics, Nazaret unit (Welded ignimbrites) of low productive aquifers along the weathered and fractured zone. Acts as a regional aquiclude which separates the upper and lower volcanic aquifer.

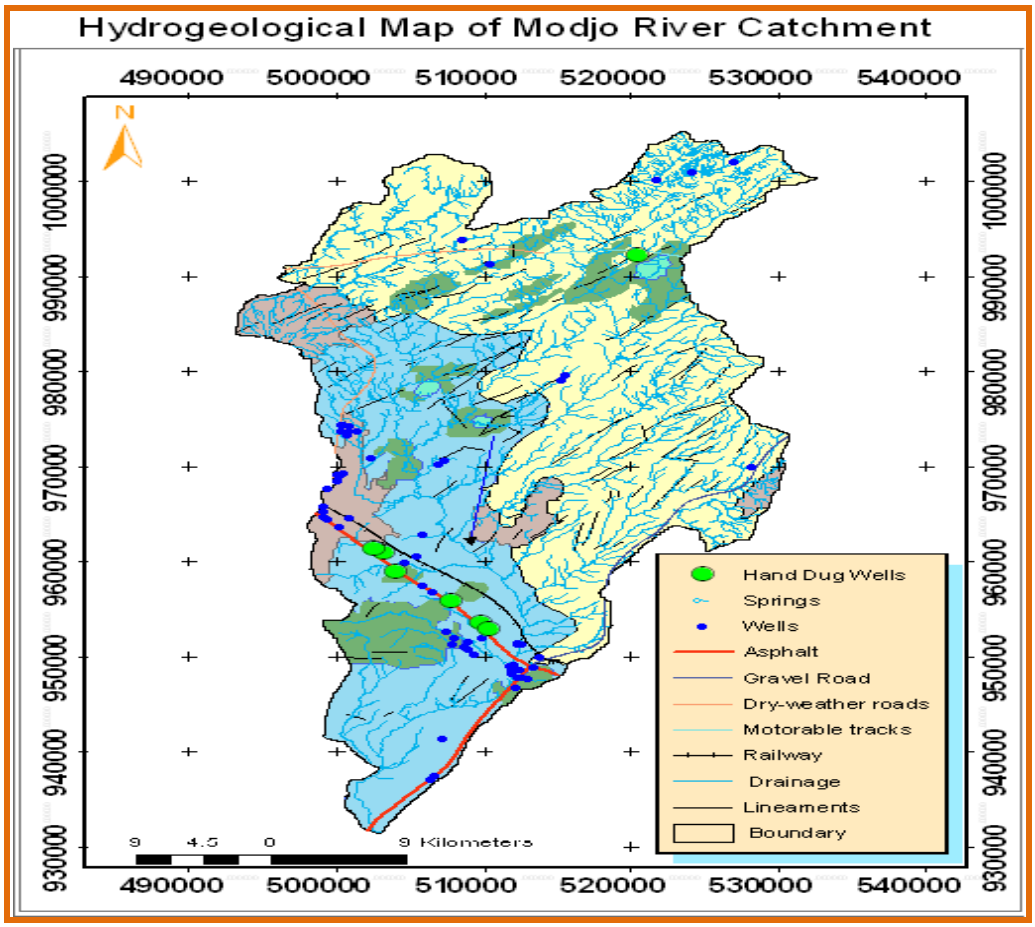
Chefa Donsa Pyroclastic , Nazaret group welded tuff, forms a wide distribution and occupies more than 50 % of the area the thickness of this formation varies from 150 to 300 meters. The formations have poor permeability except at the weathered and fractured zones.

The ignimbrite and rhyolitic ignimbrite cover most part of the study area. In most cases the ignimbrites are well jointed. Unfortunately there are no sufficient representative wells drilled in this unit. The litholog of the well drilled in Chefe Donsa Pyroclastics at the local place *Seftu* shows the aquifer material to be weathered ignimbrite with discharge of 4l/sec and shallower static water level (26.98m bgl). And the well data from Nazareth Unit at Tullu Dimtu local place shows the aquifer material to be slightly weathered ignimbrite, Trachyte and welded tuff and deep static water level (138.4m bgl).

5.2.4 Localized aquicludes of Tertiary and Quaternary Volcanic Ridges and Volcanic Centers of Beda Gebaba and Yerer

Huge mountains at the rift margin (eg. Yerer trachytic volcano in the study area) have poor hydraulic conductivity due to absence of primary porosity, massive nature of exposure. In addition, bare land steep nature of these highly elevated morphological features have poor groundwater storage and low infiltration property for the absence of vegetation which can delay the immediate rushing water that comes from precipitation.

Ryholites and Trachytes form Yerer and Bede Gebaba mountains. The formations have low permeability, except along weathered and fractured zones. These formations are less fractured and faulted**.**



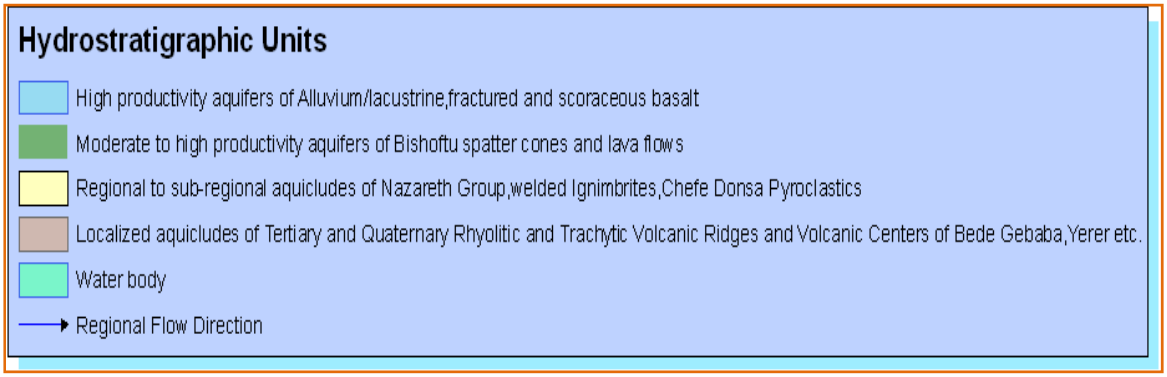


Figure 5.3 Hydrogeological Map of Modjo River Catchment

CHAPTER SIX

6. POSSIBLE SOURCES OF POLLUTANTS

Like in many sectors of the developing countries of the world, economic development usually does not take in to consideration the possible impact it has on the environment. On the other hand, absence of proper environmental management practice paralleling economic development may lead to an irrecoverable environmental degradation (Assaminew 2007).

There are numerous sources of pollutants that could deteriorate the quality of water resources. In most developing countries sources of pollution from domestic, agricultural and industrial activities are unregulated. Likewise, in Modjo River catchment, where there is as such no environmental protection practice there are a number of pollutant sources that could continuously deteriorate the quality of surface and groundwater. Based on observation made during field visits and analytical results, the following pollution sources have been considered as major categories of sources of pollutants in the study area. Among these are included agricultural activities and solid wastes. Meanwhile, in the catchment a number of cemetery (grave yard), health centers, and market areas contribute to the deterioration of the water environment. The potential sources of contaminants are summarized as follows:

The major sources of water pollution can be classified as municipal, industrial and agriculture sources. These include industrial establishment, agricultural activities, municipal wastes, and garages, fuel station and health centers.

6.1. Solid Waste Disposal

The solid waste (refuse) from both urban and rural areas includes wastes generated by domestic house holds, commercial centers, and local institutions. Wastes produced indirectly from agriculture and other

source is discussed under their respective sources. Addis Ababa Administration Region Health Regulation (Legal Notice no. 1/ 1986) defined solid waste as " anything discarded as public sweepings, food remains, ash, vegetables and grass remains, cigarette butts, papers of various sorts, discarded glass, metals, plastics, dead animals and the like that posses environmental health risks"(Assaminew,2007)

Open areas, quarries, streams and ditches within the study area are full of wastes coming from several sources. The problem becomes severe in the areas where there is a setting up of markets where people gather mostly. Consequently the areas become a breeding ground for viruses, bacteria and parasites. Outbreak and transmission of diseases as consequences of this poor sanitation remains to be a recurrent phenomenon in the catchment for a long period of time.

In urban areas (Debrezeit, Modjo, Ejere, Chefe Donsa and Koka), people dump their domestic and commercial wastes in undersigned excavated pit and open sites located in the outskirts of the towns by using carriage mostly. Whereas, in rural areas, domestic wastes are dumped in nearby streams, quarries, and open sites.

Open dumps are the oldest and located wherever land is available without regard to safety, health hazards and aesthetic degradation. Diseases such as, acute respiration, skin rushes, brocho-pneumonia and gonococcal infection are related to the improper waste management (Tamiru Alemayehu et al., 2005). It is known that leaching of the waste by percolating water is one of the most significant possible sources of surface and groundwater pollution. Leachate contains large number of inorganic, organic and toxic constituents. The amount of leachates becomes high when there is high amount of rainfall (June, July and August) and the groundwater level consequently rises.

6.2. Sewerage

The term sewerage refers to water whose quality is degraded as a consequence of human activities. The discharge of untreated sewerage into surface water can lead to organic pollution. In general, inefficient (or lack) of waste collection and disposal, lack of concern among responsible bodies to the available resources and the current illegal dumping practices threaten the sanitary situation of both urban and rural areas of the catchment more than ever. The problem will continue and will become severe in the coming years unless sound corrective and protective measures are taken.

6.3 Industries

The characteristics of industrial wastewater can differ considerably both with in and among industries. The impact of industrial discharges depends not only on their collective characteristics, such as biochemical oxygen demand and the amount of suspended solids, but also on their content of specific inorganic and organic substances. Three options are available in controlling industrial waste water control can take place at the point of generation in the plant; waste water can be pretreated for discharge to municipal treatment sources ; or waste water can be treated completely at the plant and either reused or discharged directly in to the receiving water bodies.

As indicated above industrial wasted are variable in natures. They may contain toxic heavy metal, oils, solvents and pesticides (herbicides). Effluent from textile processing are characteristically alkaline, high suspended solids and high BOD, industrial processing of the raw products of agriculture, i.e., food and fiber, produced potentially contaminating effluent generally high BOD and colloidal and dissolved organic substances odor and suspended solids, tannery waste water contain thigh concentrates of dissolved chlorides high BOD, total solids , hardness , sulfides and chromium . food and drink process wasted commonly give rise to taste and odor problem if allowed to contaminated

water supplies. In the study are there are a number of mostly small and medium scale industries.

waste water discharged from these industry and factories are often stored in basins, pits, ponds, or lagoons and /or directly discharged in to the nearby water bodies, different tanneries found in Modjo towns are the best example , which directly discharge their waste water in to Modjo River with out any prior treatment.

In the processes of impounding waste water for natural purification, if the site unlined, and the probability of the soil is high water seeps down water to contaminated ground water. This is a threat especially where the underlying rocks are permeable and shallow groundwater table.

The discharge of untreated tannery effluent in to receiving water bodies in the study areas has become a major causes (source) of water pollution , especially, in Mojo river.

Different industries use different chemicals, which in turn lead to the production of different effluents, which have different impact on the environment .The chemicals discharged from various industries in the area are tabulated as follows.

Table 6.1 Chemical discharge from different industries

No	Type of industries	Chemicals
1	Leather(Tannery industry)	Cr, Cacox, ca$(OH)_2$, S, H_2SO_4,NaHs, Nacl,$(NH_4)2SO_4$,
2	Textile industry	Na(OH),H_2O_2,HCOOH,Na_2,CO_3 , CH_3 COONa, Nacl NH_4 OH, AL_2 $(SO_3)_2$ Na_2 SO_4,Cr_2O_7
3	Meat industry	Na OH, HCl
4	Edible oil factory	CO2, chemicals for washing and heavy oil,
5	Plastic factory	Thernal and waste water

Source: Belema Gemechu, 2004

All industries produce and discharge west water from some stage in their process. Most of the effluents contain bacteriological pollutant, which could find their way in to a river or lake, either directly or though a treatment plant. Industry as sources of pollution can be divided in to three broad categories. These are gaseous waste, liquid waste, and solid waste. Table 6.2 gives an overview of various types wastes those industries generate in the study area and as whole. Many industrial wastes eliminate organic and inorganic substances, i.e., carbondioxide, and nitrous oxide, phosphorous compounds, chromium compounds and heavy metals. They can be very complex in their physical and chemical characteristics.

Table 6.2.Source characteristics and treatment of some industrial wastes

Waste producing industries and material	Origin	Characteristics	Treatment disposal methods.
Food bakeries	Washing and greasing of plant	High BOD , grease floor washing , sugars flour , detergent	Amenable to biological Oxidation
Meat and poultry	Stockyard, Slaughtering of animal , rendering of bones and fats, residues in condensates, grease and wash water, picking chickens	High in dissolved organic matter, blood other proteins ,and fact	Screening setting or Flotation tricking Filtration
Hospital	Washing , sterilization of facilities, used Solution spills	Bacteria, various chemical, Radioactive materials	Discharge to municipal sewers holding and Biological aeration in large facilities
Laundry	Washing of fabrics with soap or detergents.	High turbidity , alkalinity, an organic solids	Careening , chemical precipitation, flotation and adsorption

Leather	Un haring ,soaking, deliming, and bating of hides	High total solids, hardness, Salt , sulfides, chromium , PH precipitated lime and BOD	Equalization, sedimentation and biological treatment
Metal container	Cutting and lubrication metal , cleaning can surfaces	Metal fines, lubrication oil , variable PH, surfactants, Dissolved metal	Oil separation, chemical precipitations, collection and reuse lagoon storage, final carbon absorption
Metal plate product	Stripping of oxides Cleaning and plating of metal	Acid, metal, toxic, volume, Mainly mineral matter	Alkaline chlorination of cyanide, reduction and precipitation of chromium, lime precipitation other metals.
Plastic and resins	Unit operations from polymer preparation and use Spills and equipment wash downs.	Acids, caustic dissolved Organic phenols, formaldehyde, etc	Discharge to municipal Sewer, reuse, controlled discharge
Textiles	Cooking fibers, de sizing of fabric	Highly alkaline, colored, high BOD and temperature, high suspended solids	Neutralization, chemical perception, biological treatment, aeration or trickling filtration

Source:Belema Gemechu,2004

Parameters of Industrial pollution

Although there are many parameters of industrial pollution known to exist, only the following parameters are seen here due to lake of complete chemical analysis result.

Acidity, ALKALINITY AND PH .one of the most damaging characters of many industrial wastes, particularly from the inorganic industries, is their acid or alkali content. Either a high or a low pH may be damaging,

causing fish kills and general sterility in natural streams, and inactivating the essential micro-organisms in sewage treatment processes. Wastes of low pH are corrosive to steel and concrete structures in waterways or sewerage system.

Suspended solids the suspended solids test is a measure of the amount of undissolved and colloidal suspended matter (organic and inorganic) in the water bodies. This parameter is as important as the Biological oxygen demand (BOD) in stream pollution control since the degree of pollution also increases with the amount of suspended matters discharged in to the streams.

Chlorides:- Due to considerable amount of chlorides contained in both domestic and some industrial waste ,such as tannery the measure of chloride in receiving waters indicate the eves of salt pollution and thus the degree by which the beneficial use of water for agriculture can be affected.

Nitrate and Phosphate: - Nitrate and Phosphate are the principal constituents, which are responsible for the amount of plant growth in rivers and lakes. They are main causes for development of algae, some of which are poisonous to livestock. Decay of algae causes death of fish, high turbidity, color and taste in water. The discharge of phosphate and nitrate bearing wastes from both domestic and industrial sources, in to lakes and impounded reservoirs also induce the biological productivity in the water bodies and thus leads to their ageing.

6.4 Agricultural Pollution

In most part of the study area, crop production and animal husbandry are being carried out for a long of time and recently flower farming is being practiced widely. Agricultural activities in the catchment are

practiced on individual or cooperative basis. Within the catchment there are a lot of grazing animals and use fertilizer to plant 'Teff', and other cereals that have potential impact on the quality of the groundwater.

Uncontrolled addition of chemical fertilizers to the soil in order to increase the yield, in the study area, can be lost during the rainy season by rapid surface runoff where we can have a sloppy area and in relatively flat terrain they migrate in to the subsurface with the percolating water.
Of the three main nutrients in fertilizers, Urea ($CO(NH_2)$) is the one that most commonly causes contamination of groundwater beneath agricultural land (Freeze et al., 1979). Nitrate is generally much more mobile in subsurface flow system than any other fertilizer component. Cation exchanges cause potassium to have low mobility in most non-fractured geologic materials (Tamiru Alemayehu et al., 2005).

6.4.1.Flower (Rose) Farming

Among agricultural activities, flower (Rose) farming is most recently being practiced widely in the study area. Since it is confined in green houses, it is considered to be as a point source of pollutant. Green houses can affect the actual Evapotranspiration (AET) in it, i.e. they reduce the amount of AET by 50% of the total amount outside of it (Water watch, 2007) in (Assaminew, 2007). Therefore, this can facilitate the recharge rate in side the green house. Within the catchment, there are numerous green houses of Rose farming that can have adverse effect on the quality of groundwater due to uncontrolled discharge of chemical effluents. They are concentrated in central (Debrezeit and Modjo) and in the southern(Koka) part of the catchment .
These farms use various toxic and hazardous chemicals for fungicide, acarycide, and insecticide. Such as, Oscar, Previcur, Dynamic, Pegasus Mangister, Roviral, Cilitac, Mitag, and Mancozeb which composed of mostly copper sulphate and ethyldibromide. Most of them apply these chemicals on their product at least twice a weak on the basis of

environmental conditions, and they discharge the chemical effluents by mixing with water in to an excavated pit of about 2m depth unsafely, which is so dangerous that they can easily percolate and pollute the groundwater on the basis of hydrogeological settings (Assaminew 2007). Once they enter the groundwater system, they can easily migrate in the direction of flow path to southern part of the catchment.

CHAPTER SEVEN

7. GROUNDWATER VULNERABILTY MAPPING AND ASSESSMENT CONCEPT

7.1. General

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against human and natural impacts, especially with regard to contaminants entering the subsurface environment. That means the soil-rock-groundwater system may provide a degree of protection against contamination of groundwater by 'self-purification' or natural attenuation' (Zaporozec, 2001). Thus, the intrinsic (natural) groundwater vulnerability could be described as the 'relative inability' of the soil-rock-groundwater system to protect its water against contamination. As a result some land areas are more vulnerable to groundwater contamination than others this situation is due to the potential for contaminant attenuation possessed by earth materials (Dereje Nigussa, 2003).

Water pollutants do not always enter the groundwater system instead the pollutants tend to be removed or reduced in concentration with time and distance traveled. Rate of pollution attenuation depends on the type of pollutants and on the local hydrogeological situations. More over, mechanisms of pollution attenuation include filtration, sorption, chemical processes, microbiological decomposition and dilution (Tamiru

Alemayehu et al., 2005). Like wise, Civita and De Maio, (1998) considered the soil /overburden and the unsaturated zone as the first and the second defiance lines respectively. Thus, an important element in assessing groundwater resources is the investigation of aquifer exposure to contamination. The evaluation of the potential exposure of groundwater resources to contamination is termed as vulnerability. Thus, the preparation of aquifer vulnerability map is a key consideration and become a forecasting tool and via the planning processes a prevention tool and an identifier of action priority list (Civita and De Maio, 1998).

Le Grand (1964) developed an empirical point count system to evaluate the potential pollution from a given source. A new model (DRASTIC) was built up to assess aquifer vulnerability by United States Environmental protection Agency (Aller et al., 1987) directly derived from Le grand ideas. The intrinsic (natural) vulnerability map is based on the assessment of various natural factors or attributes, such as soil, unsaturated zone, aquifer properties, and recharge rate that enter into the determination of the vulnerability of groundwater. The application will be acquired when intrinsic vulnerability of a certain area is associated with danger sources. In this case one is considering integrated vulnerability, which is defined by the interaction of intrinsic vulnerability of hydrogeological system and danger sources. Specific vulnerability is the evaluation of groundwater for every type and class of contamination and for every mechanism of contamination. This type of evaluation needs a rather long time (Tamiru Alemayehu et al., 2005).

7.2. Ranges, Ratings and Weights analysis in DRASTIC Model

DRASTIC factors use a numerical ranking to assess groundwater pollution potential in hydrogeologic settings. The system consists of three parts, which are designated as: *ranges, ratings, and weights*. Each DRASTIC factor has been divided into either ranges or significant media

type, which have a significant impact on pollution potential. Ranges for each DRASTIC factor have been evaluated with respect to the other factors in order to determine the relative significance of each range with respect to pollution potential (Napolitano, 1995). The ranges for the model have been assigned a subjective rating, which varies between 1 and 10 (Table 7.1). For these factors; D, R, S, T, and C have been assigned one value per range, while the other two, A and I, have been assigned a "typical" rating and a "variable" rating. The variable rating permits the user to choose either a typical value or to adjust the value based on more specific knowledge (Aller et al., 1987). In this study, the typical rating is applied.

Two relative weight strings (varying from 1 to 5) have been assigned to each DRASTIC factor in order to determine the relative importance of each factor. The most significant factors assigned weights of 5 and a weight of 1 for the least significant factors. The two strings as shown in table 8.1 are weights for the "general or normal" DRASTIC and "Agricultural or Pesticide" DRASTIC. Agricultural DRASTIC was developed to reflect the effect of herbicides and pesticides. According to the authors Aller et al., (1987) weights are constant and cannot be changed. And the ratings assigned for each DRASTIC parameter are the same for both the Normal DRASTIC index and the pesticide DRASTIC index(Assaminew,2007).

According to Aller et al., (1987), once a DRASTIC index has been computed, it is possible to identify areas which are more likely to be susceptible to groundwater contamination relative to one another. The higher the DRASTIC index, the greater the groundwater pollution potential. The DRASTIC index provides only a relative evaluation tool and is not designed to provide absolute answers.

Table 7.1. Assigned ranges, ratings and weights for DRASTIC factors (Aller et al., 1987).

Factors	Weight		Range	Rating	Typical Rating
	General (Normal)	Agricultural (Pesticide)			
***Depth to Water(m)**	5	5	2.5-9.9 9.9-15.1 15.1-22.1 22.1-30.8 30.8-38.3 38.3+	8 5 4 3 2 1	
***Net Recharge(mm)**	4	4	170-350 350-400 400-600 600+	5 7 8 10	
Aquifer Media	3	3	Massive Shale Metamorphic/Igneous Weathered metamorphic/ Igneous Glacial Till Bedded sandstone, limestone, and shale sequence Massive sandstone Massive Limestone Sand and gravel Basalt Karsts limestone	1-3 2-5 3-5 4-6 5-9 4-9 4-9 4-9 2-10 9-10	2 3 4 5 6 6 6 8 9 10
Soil Media	2	5	Thin or Absent Gravel Sand Peat Shrinking and/or aggregated clay Sandy loam Loam Silty loam Clay loam	10 10 9 8 7 6 5 4 3 2	

			Muck Non-shrinking and non-aggregated clay	 1	
***Topography/ slope (%)**	1	3	0-2.8 2.8-8.5 8.5-14.8 14.8-21.9 21.9-29.7 29.7-38.2 38.2-48.8 48.8-96.2 96.2+	10 9 8 7 6 5 4 3 1	
Impact of the Vadose Zone Media	5	4	Confining layer Silty/clay Shale Limestone Sandstone Bedded limestone, sandstone, shale Sand and gravel with significant Silt and Clay Metamorphic/igneous Sand and gravel Basalt Karst limestone	1 2-6 2-5 2-7 4-8 4-8 4-8 2-8 6-9 2-10 8-10	1 3 3 6 6 6 6 4 8 9 10
***Hydraulic Conductivity (m/s)**	3	2	$4.72X10^{-7}$-$4.72X10^{-5}$ $4.72X10^{-5}$- $14.16X10^{-5}$ $14.16X10^{-5}$- $33.04X10^{-5}$ $33.04X10^{-5}$ -$4.72X10^{-4}$ $4.72X10^{-4}$- $4.72X10^{-3}$ $4.72X10^{-3}$+	1 2 4 6 9 10	

** Modified DRASTIC approach is followed to rate depth to water, net recharge, Topography, and Hydraulic conductivity.*

7.3. Definition and Significances of the DRASTIC parameters

In the following paragraphs definition of each DRASTIC layer will be discussed together with their significances in potential assessment.

7.3.1. Depth to Water (D)

Depth to Water represents the depth of the topographic surface and it gives an idea of the minimum distance that a pollutant has to travel to reach the saturated zone. In other words, it is the depth or thickness of the material through which a contaminant travels before reaching the aquifer. Depth to water table is important because it provides the maximum opportunity for oxidation of the contaminant by atmospheric oxygen. As the depth to water increases generally, there is a great chance for attenuation to occur because deeper water level implies longer times.

7.3.2. Net (effective) Recharge

Net recharge is the amount of water, which infiltrates from the ground surface to the aquifer on annual basis. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. The net recharge is the difference between total precipitation and the cumulative loss by direct runoff and effective Evapotranspiration. The vulnerability of an aquifer to groundwater contamination is in large part a function of the susceptibility of its recharge area to infiltration. Areas that are replenished at a high rate are generally more vulnerable to pollution than those replenished at a slower rate. In addition, it controls the volume of water available for dispersion and dilution of the contaminant in the vadose and saturated zones.

7.3.3. Aquifer media

An aquifer is defined as a subsurface rock unit that will yield sufficient quantities of water for use. Aquifer media is based on lithology and refers

to consolidated or unconsolidated rock, which serves as an aquifer (Aller et al., 1987). Aquifer media governs the rout and path length which a contaminant must follow within the aquifer. Textural and formation features of the saturated zone control the pollutant diffusion within the aquifer. That is the rout that the contaminant will take can be strongly influenced by fracturing, porosity, or by an interconnected series of openings which may provide preferential pathways for groundwater flow.

7.3.4. Soil Media

Soil is the portion of the unsaturated zone characterized by significant biological activity. It is an open three-phase accumulator and transformer of matter and energy sub-system, which is developed via the physical, chemical, and biological alterations of the bottom litho types and of the organic matter they made of. It is considered as the first defense-line of the hydrogeological system (Civita and De Mario, 2002). The characteristics of the soil influence the amount of potential dispersion, the purifying process of contaminants, and the ability of contaminants to move vertically into the vadose zone. The presence of fine-textured material such as silts and clays can decrease relative soil permeability and block contaminant migration.

7.3.5. Topographic Slope

Topographic slope is an important factor in vulnerability assessment as it governs the amount of surface runoff produced, the precipitation rate and displacement velocity of water (or a fluid and/or hydro-vectored contaminant) Civita and De Maio (2000).it refers to the slope variability of the land surface. Furthermore, the slope may be a genetic factor of the soil type and thickness that indirectly facilitate the attenuation potential of the hydrogeological system. It also determines the extent of runoff of the pollutant and the degree of settling sufficient for infiltration. Areas with steep slopes, having large amount of runoff and smaller amounts of

infiltration, are less vulnerable to groundwater contamination (Napolitano, 1995).Contrary to this; topography influences soil development and therefore have an effect on contaminant attenuation.

7.3.6. Impact of the Vadose Zone media

Vadose zone is defined as the unsaturated zone from the ground surface to the top of the aquifer (for unconfined aquifer); and for confined aquifer the vadose zone is defined all unsaturated and saturated zones between the ground surface and the top of the confined aquifer (Napolitano, 1995). The type of vadose zone media determines the attenuation characteristics of the material including the typical soil horizon and rock above the water table. The media also controls the path length and routing, thus affecting the time available for attenuation and the quantity of material. In short, it is defined as the zone above the water table that is unsaturated or discontinuously saturated (Lee, 2002). The type of vadose media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes that may occur within this media.

7.3.7. Hydraulic Conductivity of the Aquifer

This parameter refers to the ability of the aquifer materials to transmit water, which in turn, the rate at which the groundwater will flow under a given hydraulic gradient. It also controls the rate at which a contaminant moves away from the point at which it enters the aquifer (Aller et al., 1987). Hydraulic conductivity is controlled by the amount and interconnection of void space within the aquifer which may occur as a consequence of integranular porosity, fracturing and bedding planes. Hence, high hydraulic conductivity is associated with higher pollution potential (Adapted from Assaminew, 2007)

CHAPTER EIGHT

8. MODELING AND APPLICATION OF DRASTIC WITH GIS ON THE MODJO RIVER CATCHMENT

8.1. DRASTIC Approach and GIS

Geographic Information System (GIS) is used with DRASTIC model in this study. GIS is a tool for storing, manipulating, retrieving and presenting both spatial and non-spatial data in a quick, efficient and organized way.

When DRASTIC was proposed for the first time, its formulation did not take the advantage of advanced GIS technique (Napolitano, 1995). The method was primarily developed for manual overlay of semi-quantitative data layers (Vrba and Zaporozec, 1994). According to the earlier works in Napolitano (1995) many authors (Evans and Meyers, 1990; Cavallin and Giullano, 1992; Rundquist et al., 1991) used DRASTIC with raster-based GIS because the vulnerability index defined as an equation of linear combination of a linear combination equation (1.1) given in chapter one can be calculated with the overlay operation available in (ArcMap Version 9.2)

Many researchers agree why they use GIS for aquifer vulnerability assessment is recommended (Assaminew, 2007)

- Storage of a large amount of georeferenced data and of the attributes;
- Data processing with interpolation of spatial data, rating of variables with appropriate weighting and calculation of a final vulnerability index by digital overlaying of raster data layers;
- Out put of large data sets;

- Frequent update of time-dependent data sets in a flexible and comfortable way
- Use of several technique of parameter coding to apply and compare different scenarios or strategies.

8.2. Data Sources

Various data inputs pertaining to seven DRASTIC parameters must be available for data base construction. All pertinent secondary data were collected prior to the primary data collection. The main data both primary and secondary, used for this work are given in Table 8.1.

Table 8.1.The major data sources used

Data	Data Source	Data Format	Scale
Drainage, Contour lines	Topographic map (EMA)	Map Coverage/ Vector	1:50,000
DEM (Digital Elevation Model)	Contour of topographic Map (EMA)	Grid (Raster) map	1:50,000
Slope	Elevation Contours (generated from TIN image	Grid	1:50,000
Geology	Geological Surveys of Ethiopia	Map (Coverage)	1:100,000
Soil	Thesis work of Sisay Libasse,2007)	Maps and Report	1:50,000
Land use	Thesis work of Sisay Libasse,2007)	Map and report	1:50,000
Well data	Water Works Design and Supervision Enterprise and	Tables and reports	

	Drilling Companies		
Climatological data	National Meteorological Services agency	Tables	

8.3. Data Construction and Structure for Attribute Data

Attribute data were stored in a spreadsheet using Microsoft Excel while spatial data have been directly digitized and analyzed into a GIS using Arc Map Version 9.2.

The topographic maps of 1:50,000 scale produced by the Ethiopian mapping Agency (EMA) in1982 were used to digitize elevation contours, drainage and other related features. The base maps used for the production of topographic data and hydrographic network of the area are (Figure 8.1.): Addis Ababa NE, Addis Ababa SE, Ziquala, Sendafa, Chefe Donsa and Modjo.The topographic base maps with contour interval of 20m were used for the construction of the Digital Elevation Model (DEM). Tin and Slope were extracted from the DEM at the same resolution.



Figure 8.1 Index of topographic sheets used for the study

Lithological logs were used to classify aquifer media, type of vadose Zone and depth of Soil profiles. Based on the borehole database, the hydraulic conductivity of the aquifers was estimated using the ranges presented in Freeze and Cherry (1979)(Annex 3).

8.4 Sources of Errors

The vulnerability mapping process is highly subjected to errors that can vary
the results. Actually the output quality depends on the type of data, efficiency of interpretation etc. The main sources of errors in Groundwater vulnerability assessment expected to occur in the analysis are (Assaminew,2007)

1. Errors in Obtaining Data (Accuracy in locating sites collection and handling, interpretation results)
2. Errors due to spatial and temporal variability (Random sampling error, Rationalization, extrapolation, interpolation, etc.)
3. Errors in computerization (Digitizing) and storage of Data (data entry, data variability, change in format, etc.)
4. Inefficiency in data manipulation
5. Final classification of vulnerability classes

8.5 Model Output

The data incorporated in GIS resulted in polygons that are identified as shape files and grids. For the seven DRSASTIC parameters the resulting shape files and grids are presented in Figures 8.2-8.8.

8.5.1. Depth to water table

Depth to water table can be computed either by converting all water level observation data to water levels below land surface by using

topographical base maps and draw isobaths or lines of equal depth to groundwater. The water level map of the catchment is obtained by interpolating water level data of shallow (unconfined) aquifer (Figure 8.2)

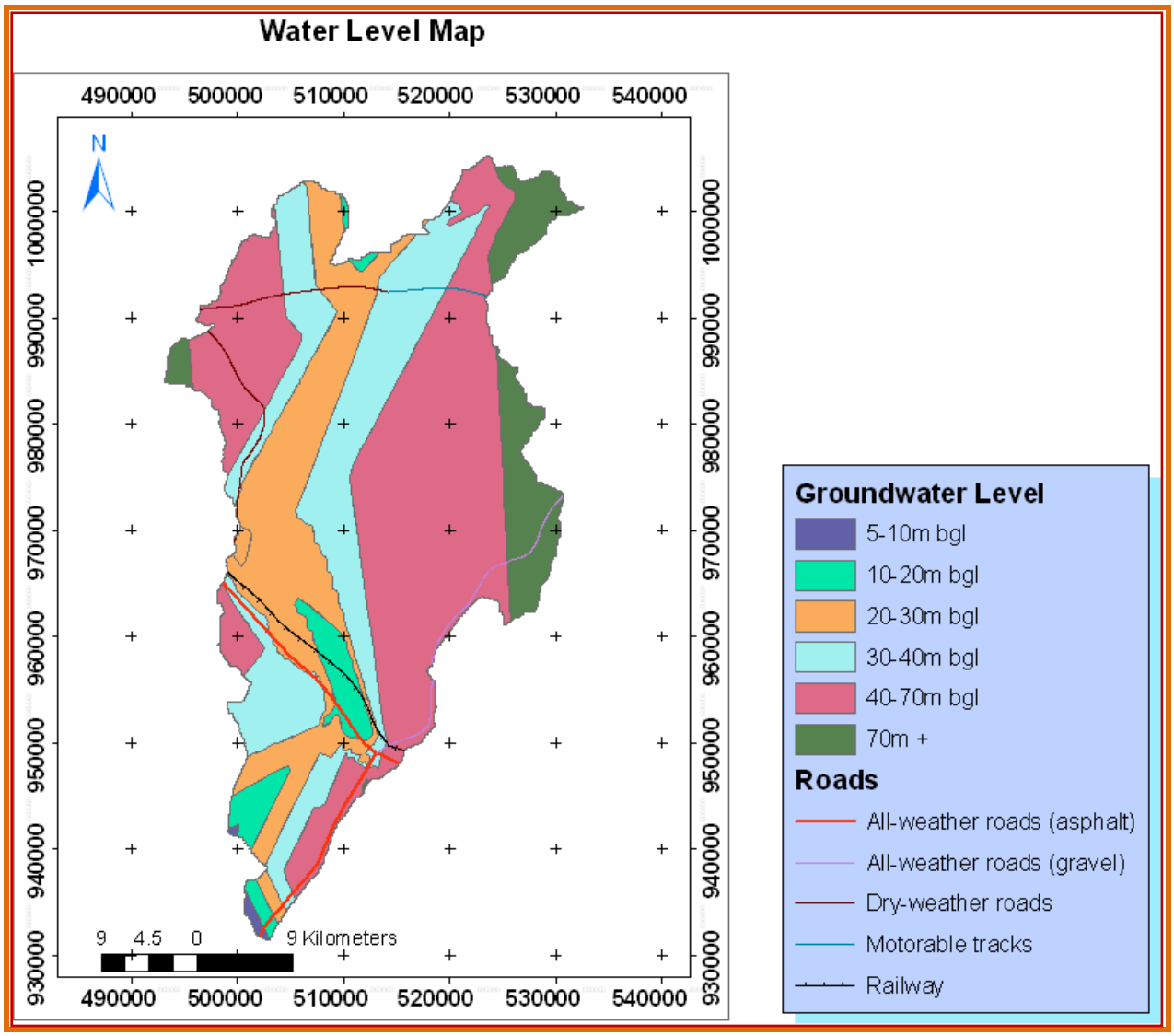


Figure 8.2. Water level Map

8.5.2. Net Recharge

The net recharge values for the study area are obtained by subtracting runoff value and actual Evapotranspiration values from precipitation values. As indicated in section 4.5.2, chapter four, the study area has been divided into five by the Thiessen polygon map (Figure 4.3) created

using Analysis Tools extension of Arc GIS 9.2 for Modjo River catchment. Based on the land use (figure 2.3.3), soil type Map (Figure 2.3.4) and the available meteorological data from the stations (Table 4.4), the yearly areal depth of recharge to the groundwater of each polygon area is estimated as shown in Tables 4.10a-4.10e.as of Thornthwaite and Mather method. Here assumption is made that 50% of the total moisture surplus goes as runoff and the remaining 50% of the surplus is for detention in the soils of each polygon area.

Accordingly, the vector map of net recharge is produced with the values obtained.

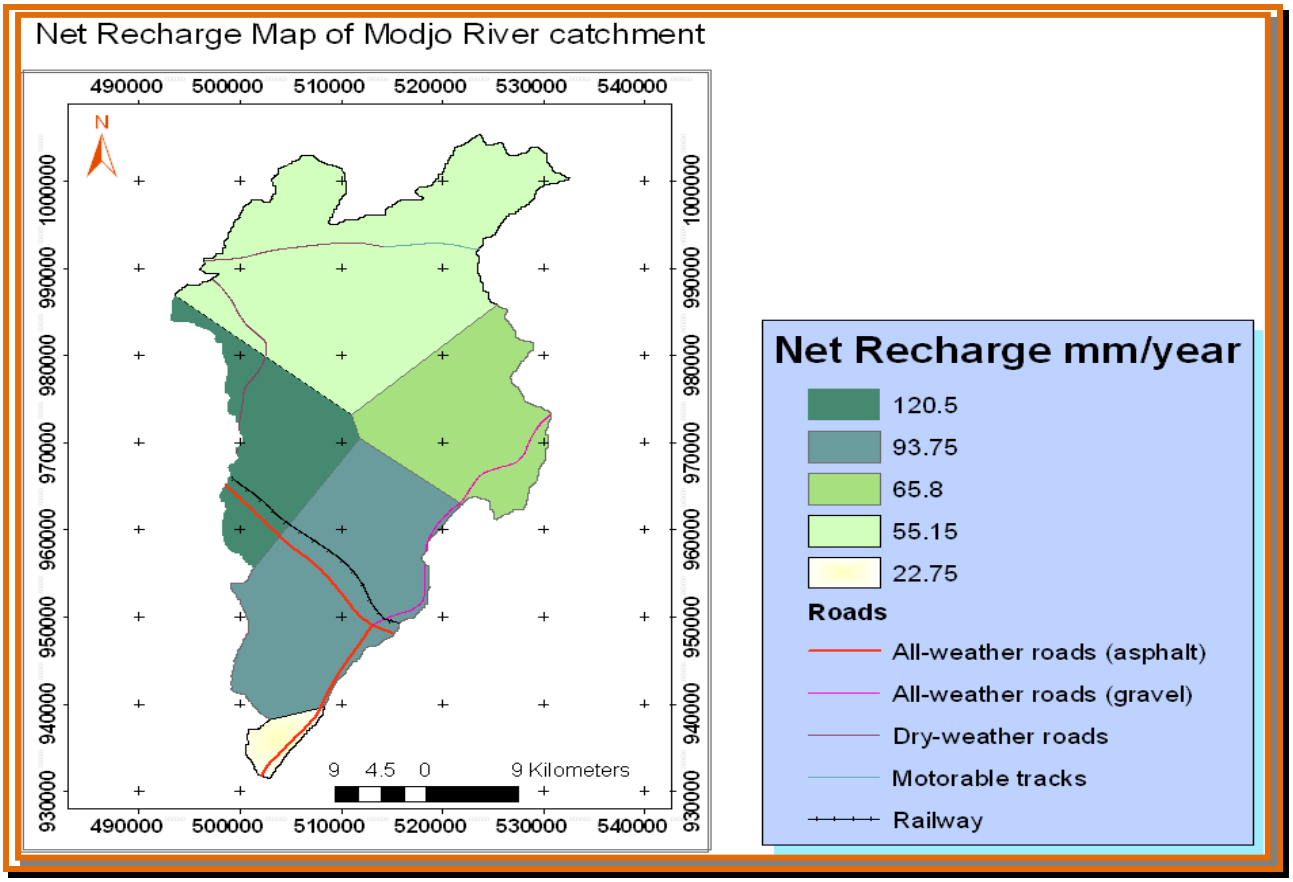


Figure 8.3. Net Recharge map

8.5.3. Aquifer Media

The general procedure is similar to that of vadose zone rating. The rating of the aquifer media assigned based on point (well) data was transformed

in to vector map of aquifer media. Thus the upper aquifer (unconfined aquifer) material was used in rating of aquifer media and hydraulic conductivity as well.

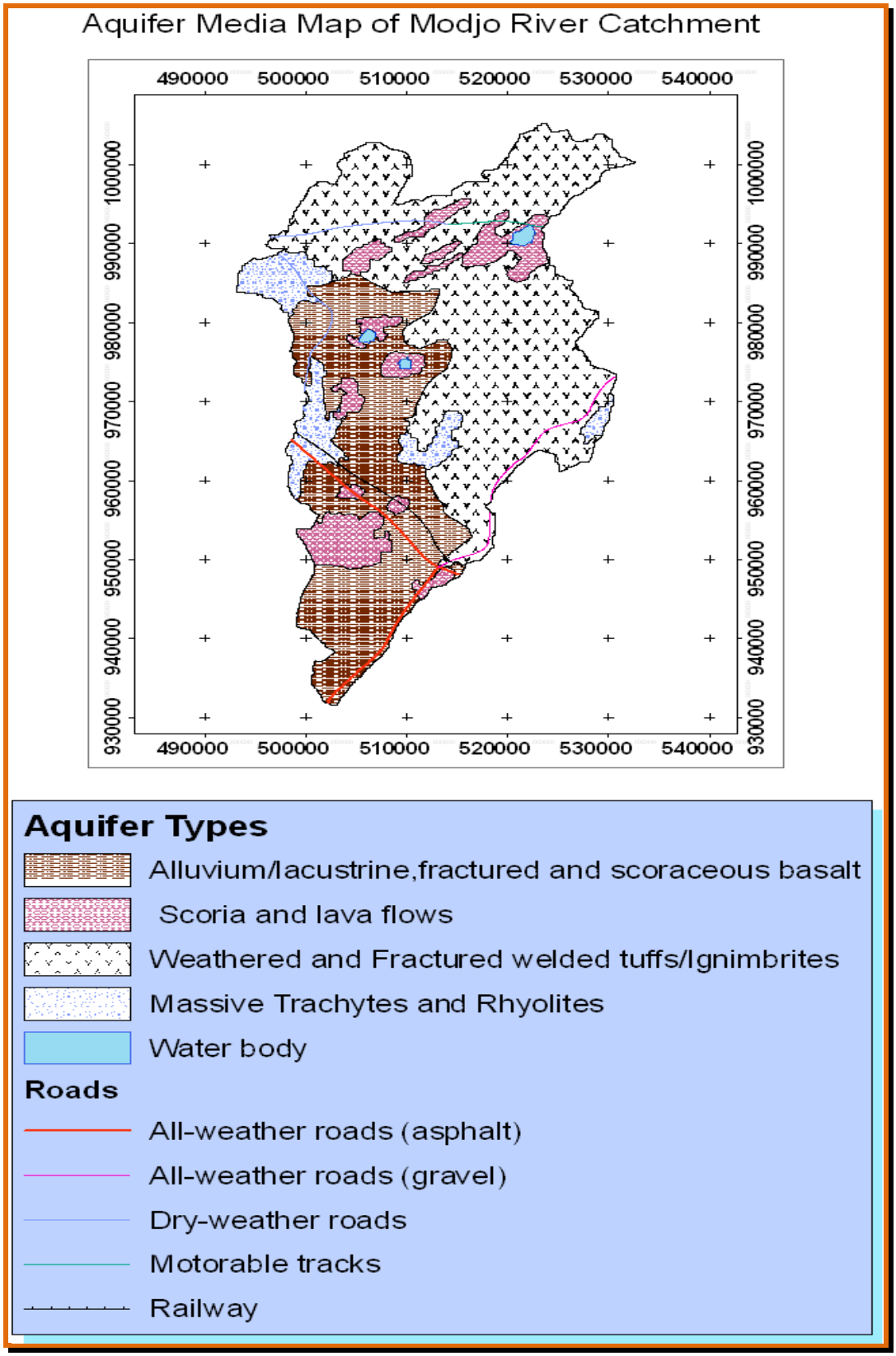


Figure 8.4 Aquifer type map

8.5.4. Soil Media

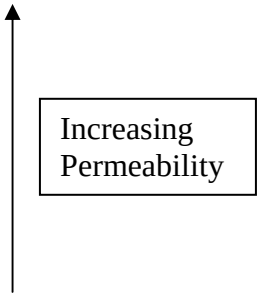
The soil Map of Modjo River Catchment has been adapted from the thesis work of (Sisay, 2007). Sisay in his thesis prepared the soil map of Ade'a Plain (Modjo Sub-catchment) from soil database of FAO, 1997 (The digital Soil and Database of East Africa) in arcview shape file format.

Table 8.2 Soil Code and Soil Texture

Code	Texture
1	Extremely sandy
2	Sandy
3	Loamy
4	Clayey
5	Very clayey

Table 8.3 Soil type in order of increasing permeability

No.	Soil Type	Code
1	Leptosols	3
2	Phaeozems	4
3	Fluvisols	4
4	Luvisols	4
5	Cambisols	5
6	Vertisols	5



Six soil types are mapped (Figure 2.3.4.) and the soil texture map of the catchment is as shown in (Figure 8.5). It is the soil texture map that is used for rating the soil media.

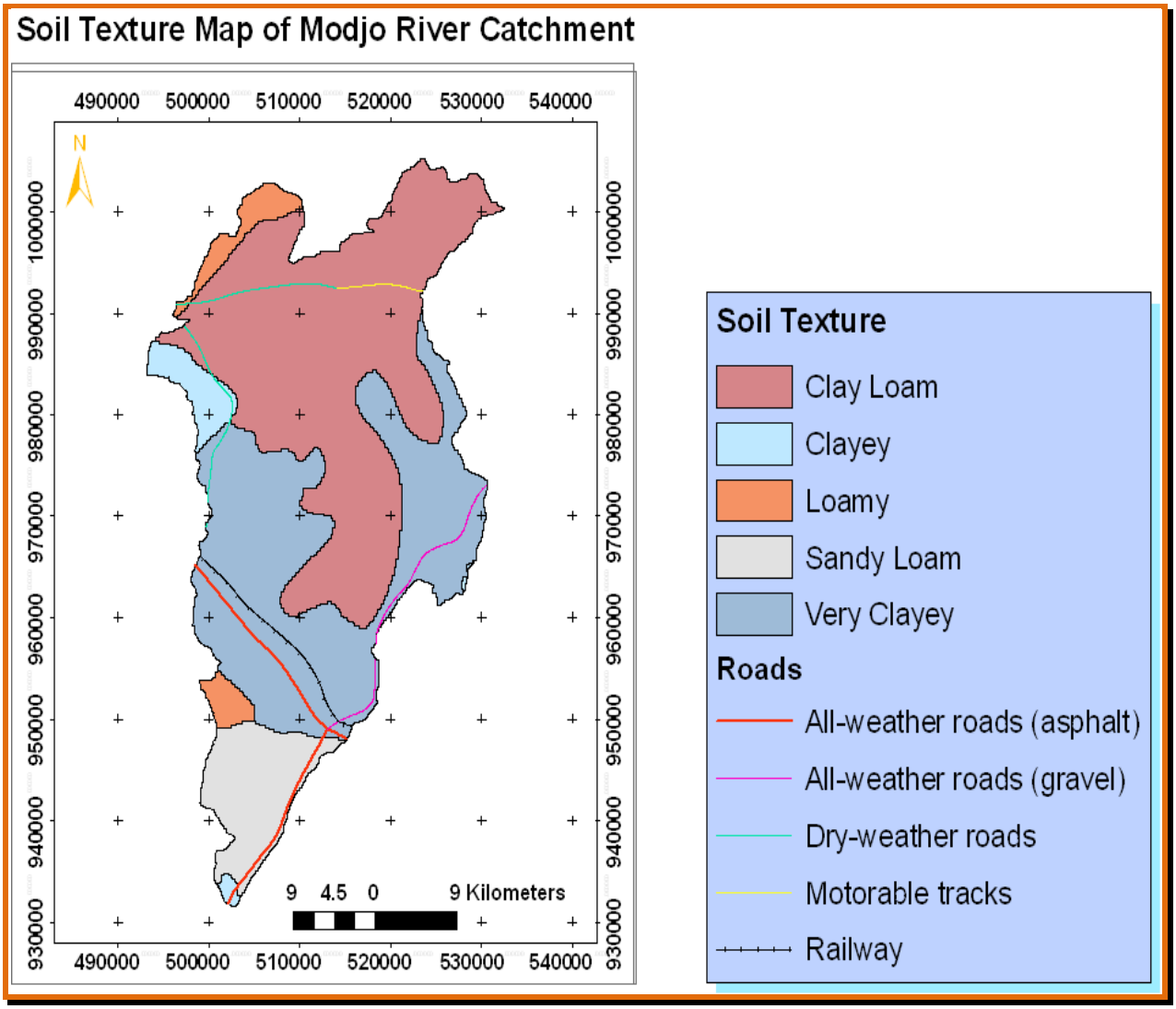


Figure 8.5. Soil texture map

8.5.5. Topographic Slope

Steps followed to prepare the slope amount of the study area are described below:

I. Generating digitized contours from the DEM of the area
II. Creation of Triangulated Irregular Network (TIN) model from the digitized contours
III. Derivation of Slope Amount from the TIN model using Arcmap Spatial Analysis.

The slope map shows very high variability ranging between 0° and 75.8° (Figure 8.6)

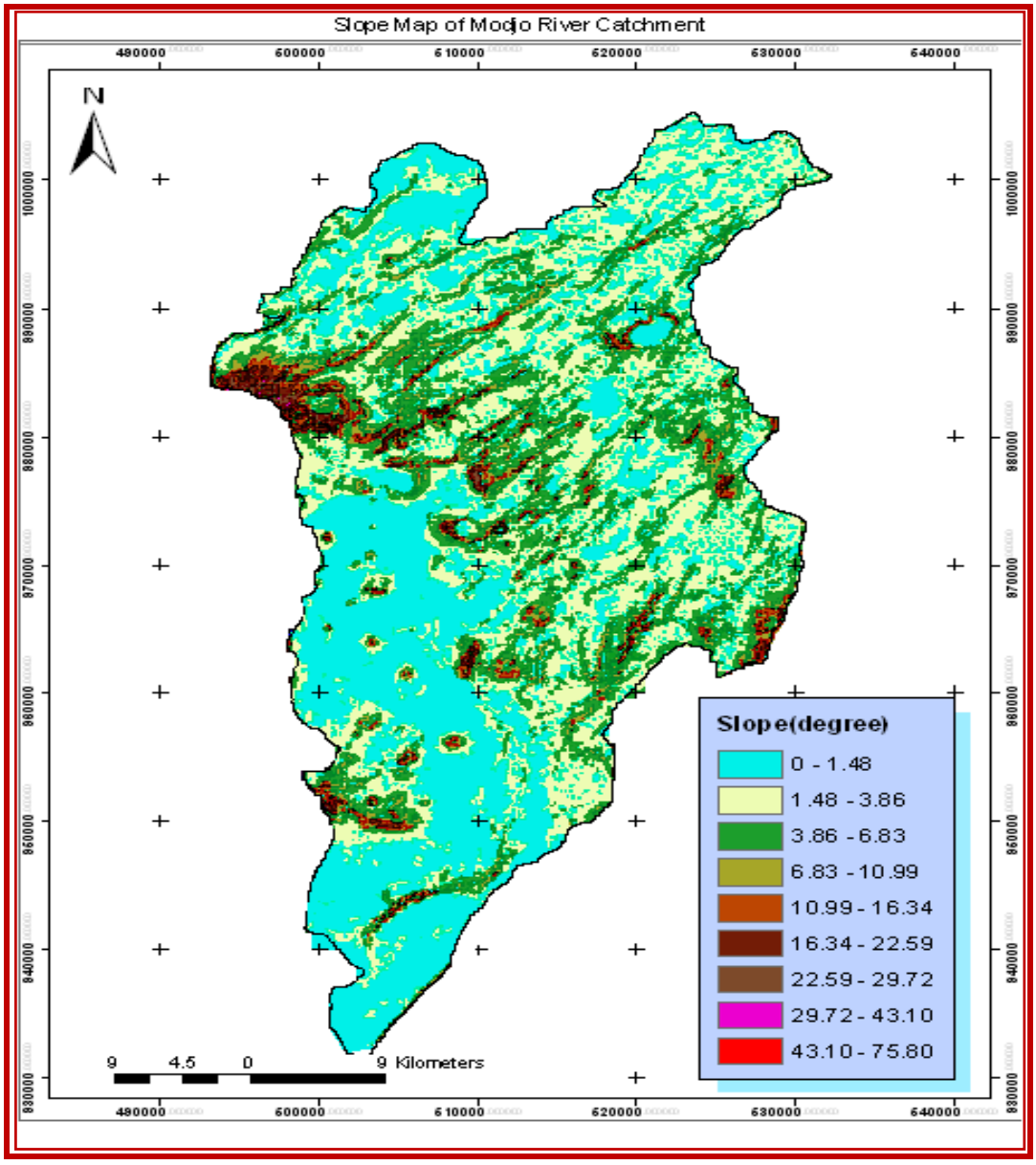


Figure 8.6. Topography and Slope map of the catchment

8.5.6. Impact of the vadose zone media

The vadose zone map (Figure 8.7) for the study area was developed by interpolating point data of the available well logs. The geological map of the area was also helpful while interpolating the point data.

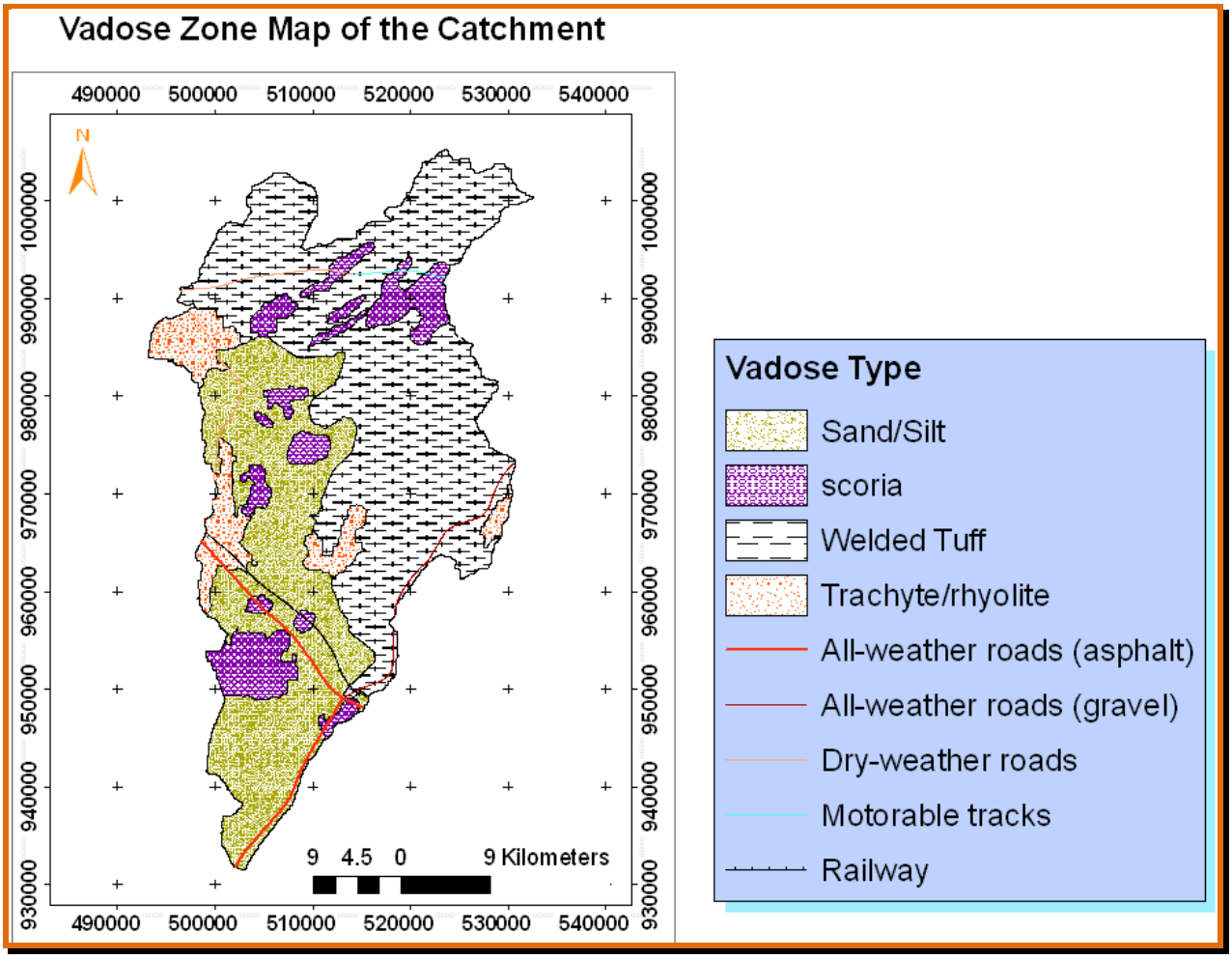


Figure 8.7 Vadose Zone Type Map

8.5.7. Hydraulic Conductivity

Hydraulic conductivity data estimated from pumping test analysis are not sufficient for mapping.

Thus, using the geologic database, hydraulic conductivity, which depends largely on the rock type and degree of weathering, was estimated according to the ranges given by Freeze and Cherry (1979) (Annex 3)

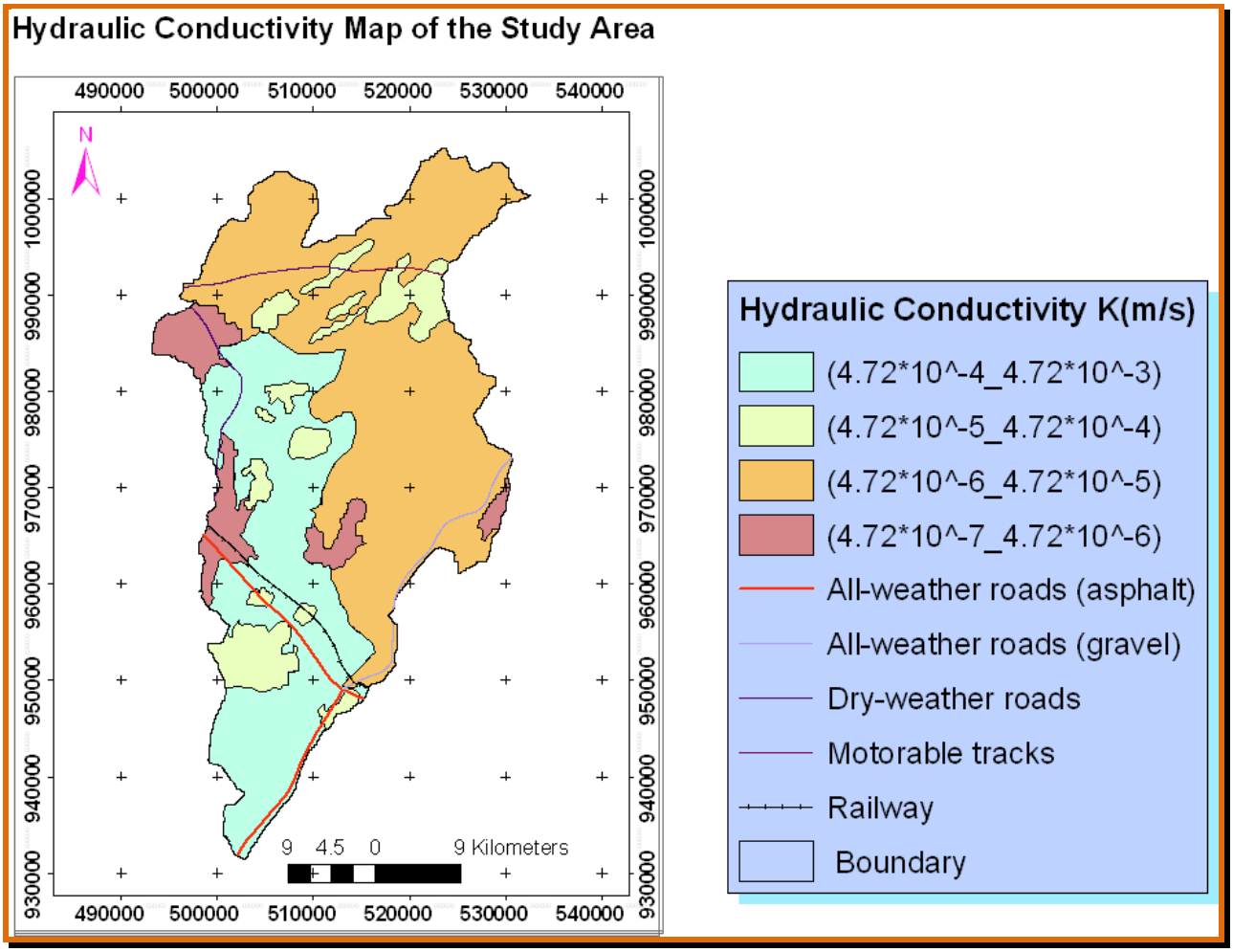


Figure 8.8. Hydraulic conductivity map

8.6. Results and Discussions

The shape files have been converted into grid (Raster) files where the cell size is 100X100. The results are given in figures 8.9 to 8.15.

8.6.1. Intrinsic Vulnerability Map

By overlaying the seven DRASTIC parameters the intrinsic vulnerability map (Figure 8.16) was generated using Arc map 9.2.

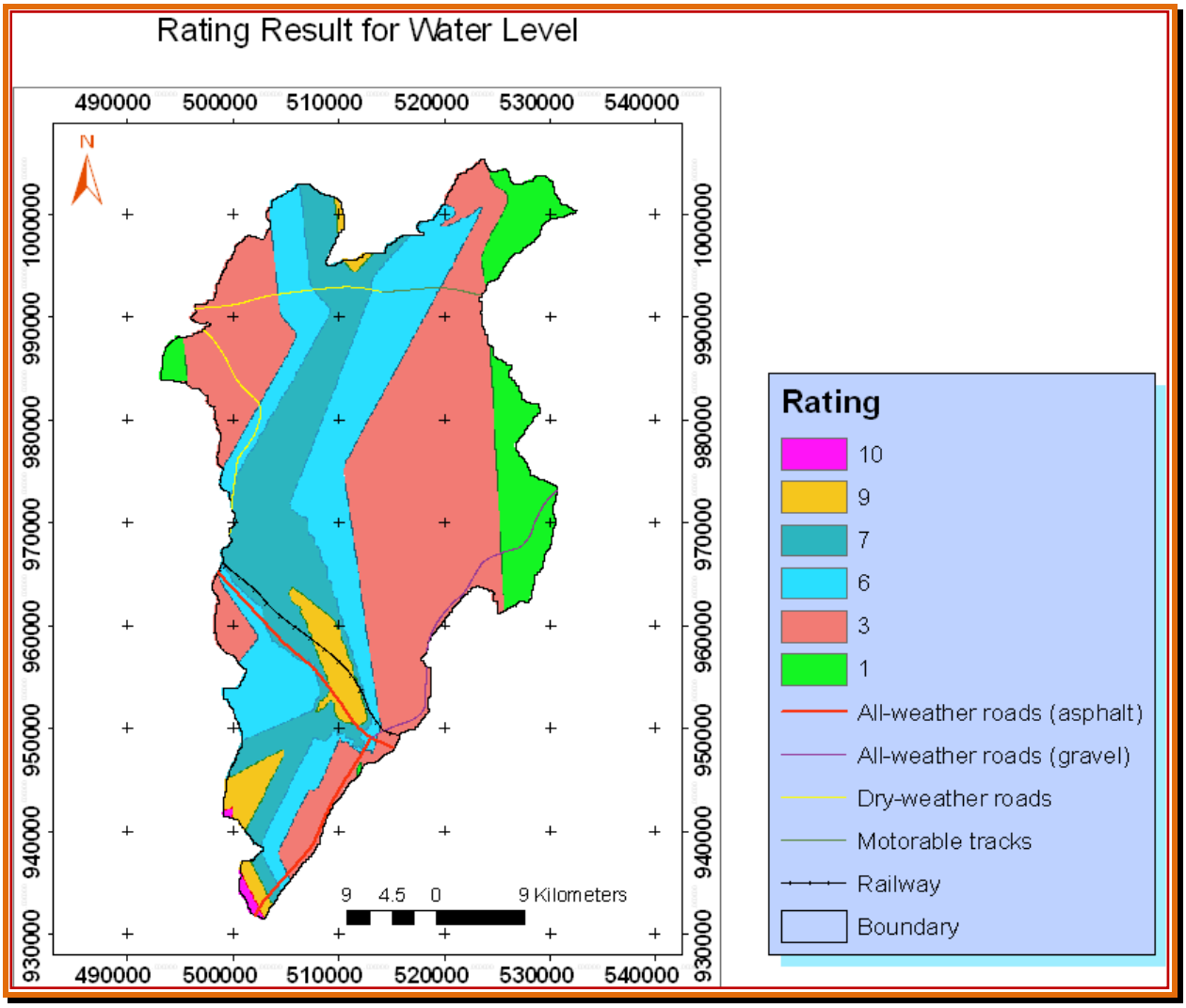


Figure 8.9 Rating result for Depth to water table (D)

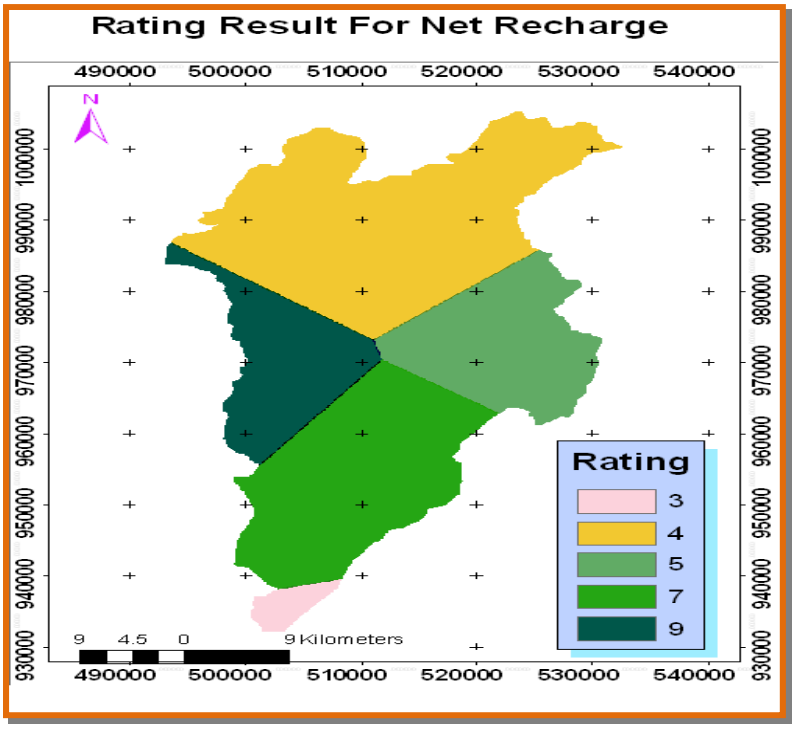


Figure 8.10 Rating Result for Net Recharge (R)

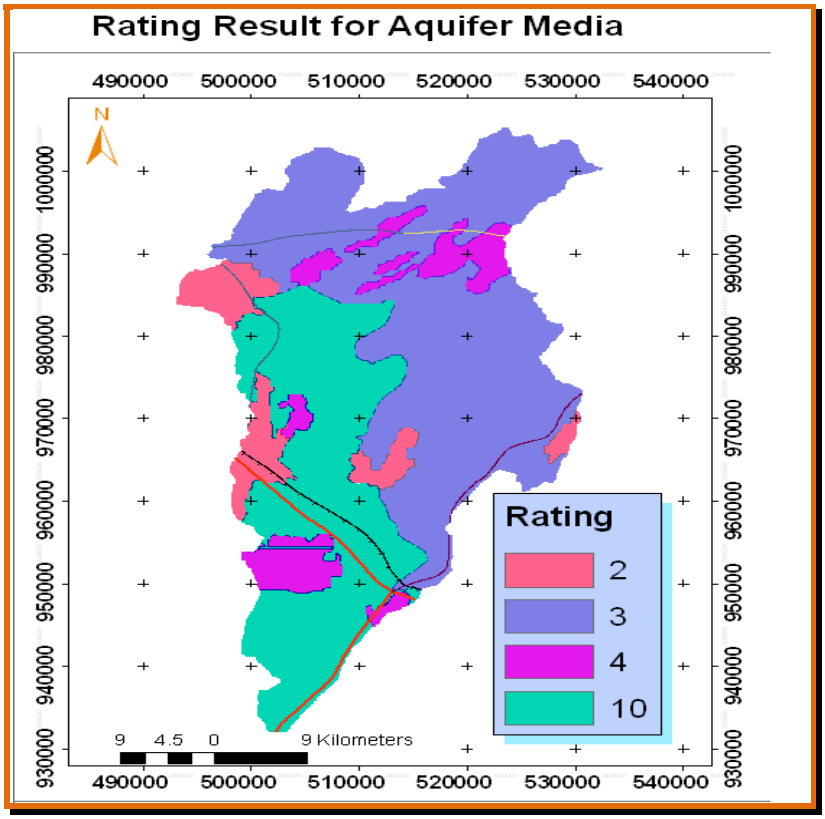


Figure 8.11 Rating result for Aquifer media (A)

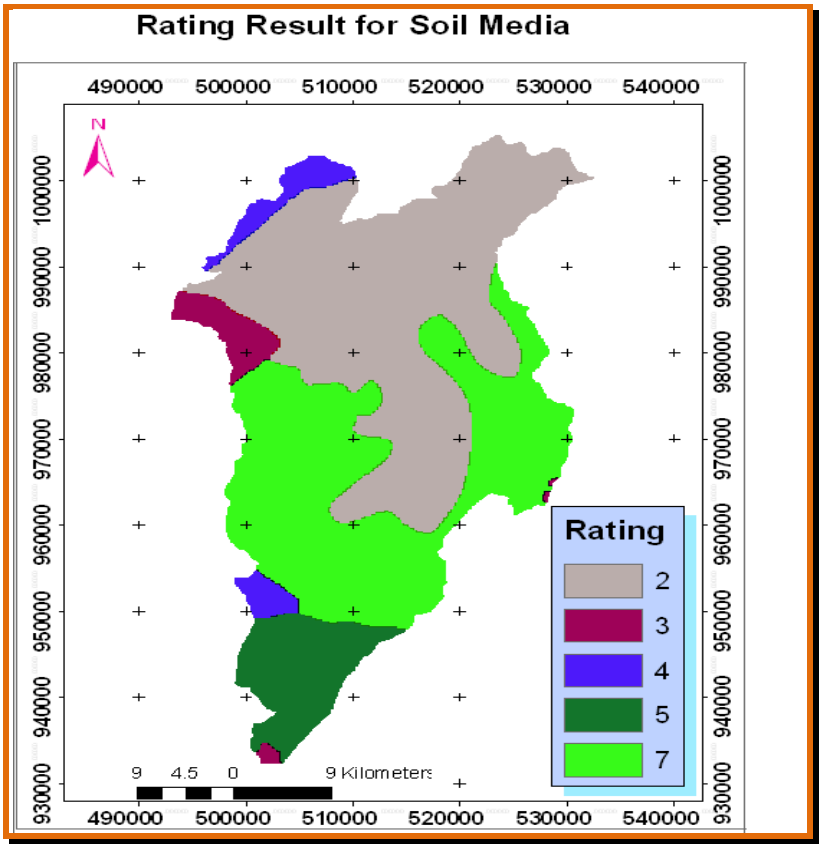


Figure 8.12 Rating result for soil media (S)

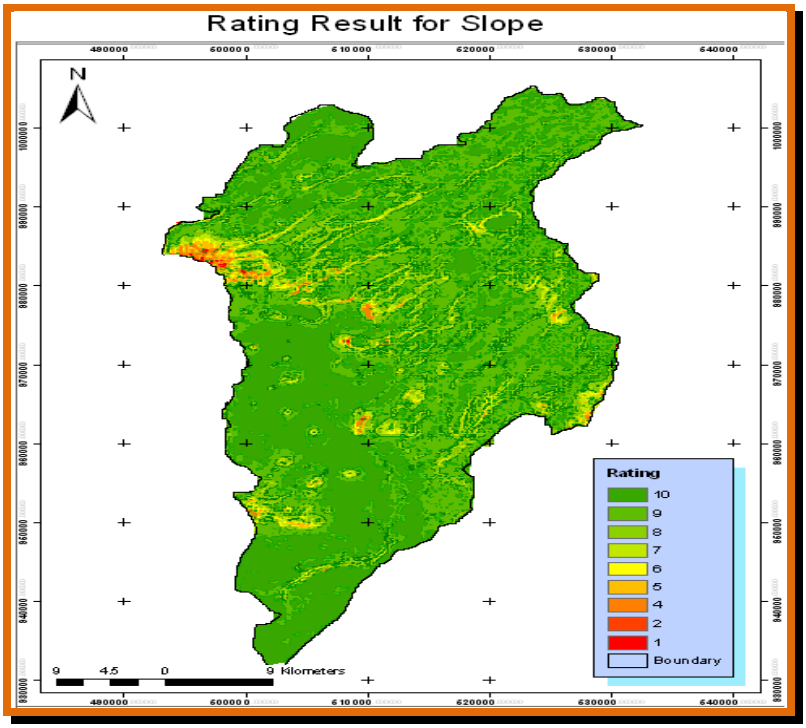


Figure 8.13 Rating result for slope (T)

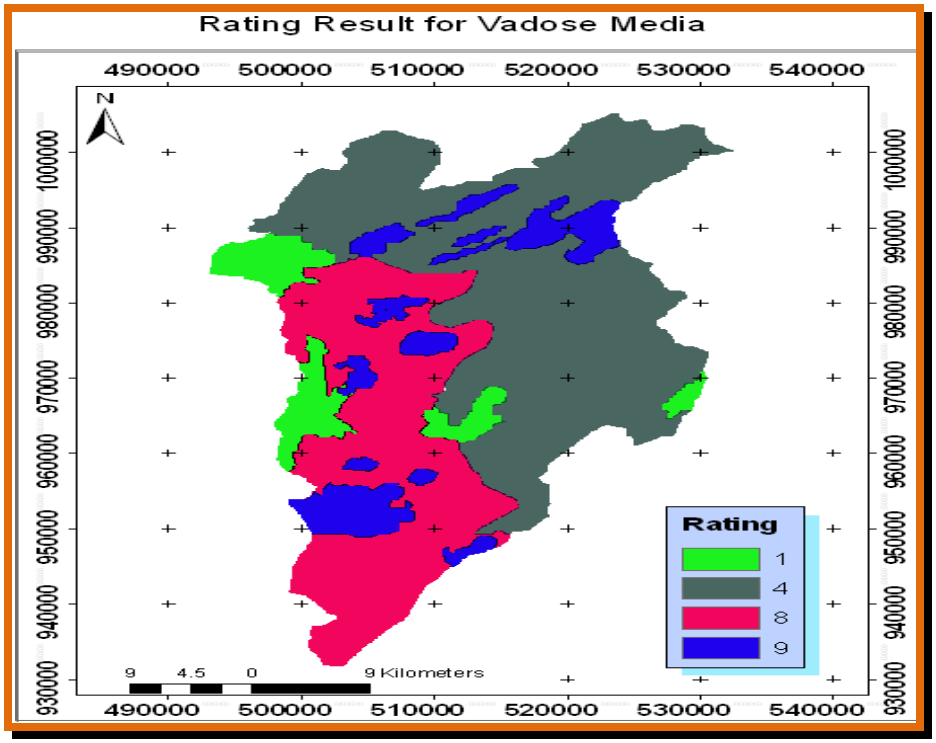


Figure 8. 14 Rating result for Impact of Vadose media (I)

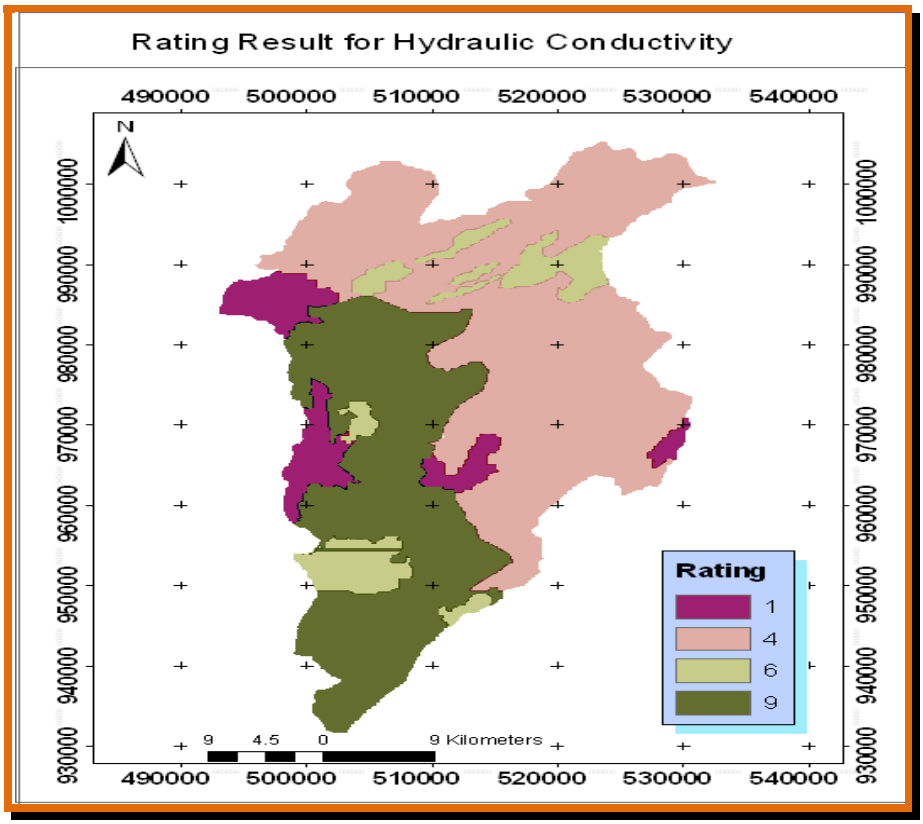


Figure 8.15 Rating result for Hydraulic Conductivity (C)

Hence, from the above data layers "General/Normal" and "Pesticide" DRASTIC maps are produced (Figure 8.16 and 8.17). The resultant DRASTIC index values from equation 1.1 by employing overlay analysis are as follows: the minimum normal/ general DRASTIC index is 35-85 and the maximum normal/ general DRASTIC index 166-210; where as, the minimum and maximum pesticide DRASTIC index is 33-88 and 171-238 respectively.

The final DRASTIC values have been grouped into very low, low, moderate, high, and very high pollution potential classes. These classes only represent the relative pollution potential within the study area. In terms of normal DRASTIC index extent, 35-85 is classified as indicating a very low pollution potential, 85-109 is classified as indicating a low pollution potential, 109-138 is classified as having a moderate pollution potential, 138-166 is classified as having a high pollution potential, and 166-210 as very high. The pesticide DRASTIC map is classified similar to that of normal DRASTIC map except for the range of the index values; 33-88, 88-110, 110-139, 139-171, and 171-238 classified as very low, low, moderate, high, and very high pollution potential respectively.

Generally, groundwater is highly vulnerable in central and southern part of the study area because of high rating values of depth to water, net recharge, aquifer media, hydraulic conductivity, soil and impact of vadose zone media, and slope. That means these areas with very high index values are characterized as relatively high pollution potential. The eastern, northeastern and northwestern parts of the catchment are classified as very low to pollution of the groundwater resources in general DRASTIC assessment. This is due to relatively deep groundwater, high slope amount, clay soil cover, low net recharge. Areas with high and moderate pollution potential to shallow groundwater cover significant parts of the central and southern catchment and also fall within high productive aquifer zones in part of Ade'a Plain.

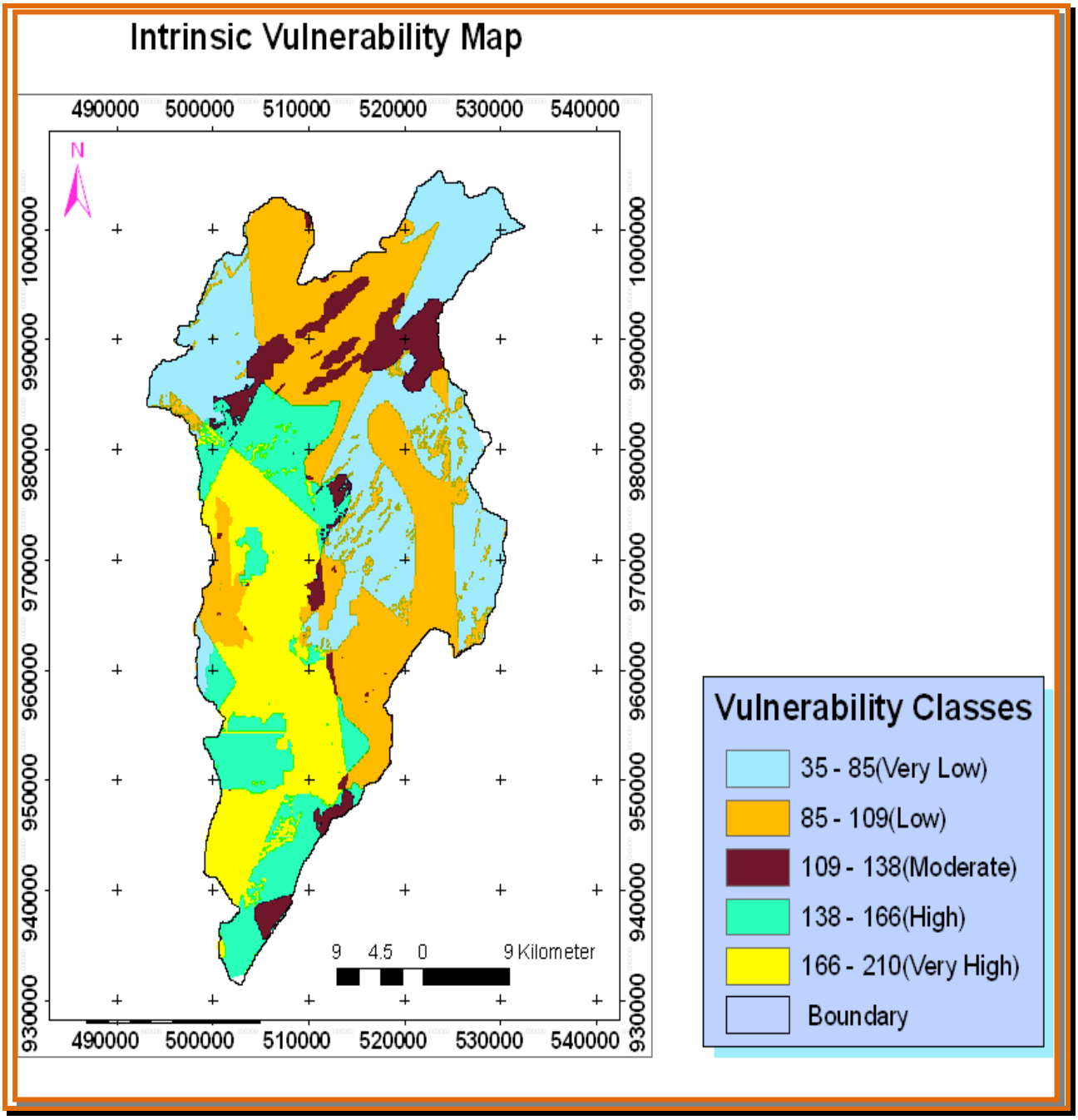


Figure 8.16 Intrinsic Vulnerability Map of Modjo River Catchment

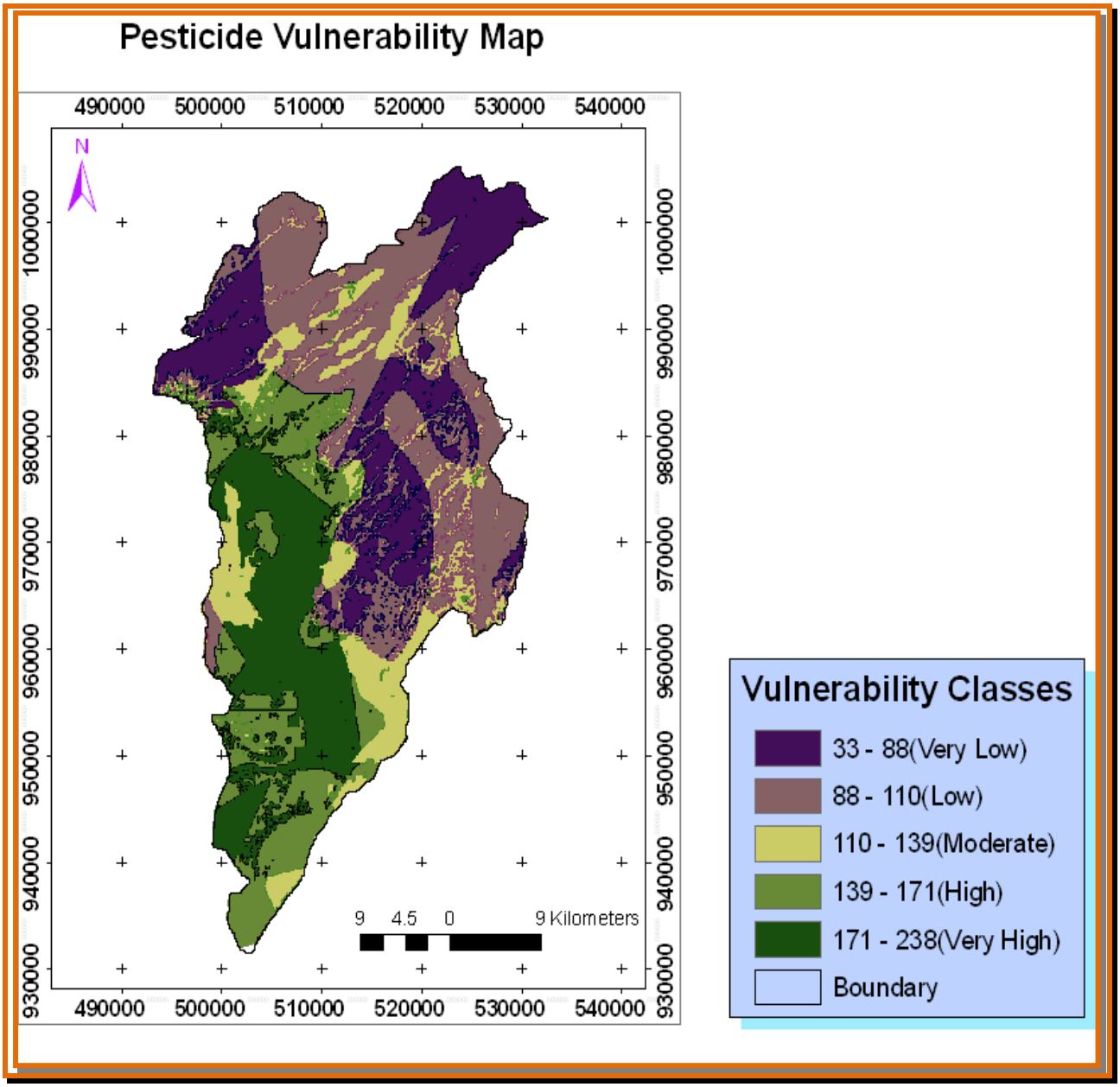


Figure 8.17 Pesticide Vulnerability Map of Modjo River Catchment

CHAPTER NINE

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Groundwater vulnerability mapping of Modjo River catchment is conceptualized that, the study area is characterized by high elevation ranges that can affect the runoff and even the infiltration rate of the pollutants. Therefore one of the parameters in the acronym DRASTIC, topography or slope of the catchment is obtained from elevation ranges. Groundwater system in sloppy areas will be less susceptible to pollution than plain lands.

One of the parameters in the acronym DRASTIC is soil. Soil is so crucial in determining and assessing the groundwater vulnerability by using various parameters. Accordingly, in this thesis soil texture map has been used to produce both the normal and pesticide DRASTIC maps.

The local geological settings of the area are important to understand the major Lithological and structural distribution within the catchment. And it also helps to recognize the major aquifer and vadose zone types of the area. Therefore, in order to determine the major aquifer type, which is one of the parameters of the DRASTIC model, it was identified and extrapolated from understanding of the local geological settings of the area with the help of well logs.

Hydro meteorological parameters are essential in determining the water balance of the catchment as well as, in this particular study; it helps to evaluate the major inputs of net recharge, such as precipitation, actual Evapotranspiration, and runoff of the study area. Once these parameters are obtained, it is possible to evaluate one of the DRASTIC parameters "effective recharge" of the catchment.

Hydrogeology determines the major hydrostratigraphic succession of the study area. The major aquifer (A) and vadose (I) or unsaturated zone types has been determined from the Lithological logs of various boreholes. Hydraulic conductivity (C) as well as depth to water table (D)

has also been evaluated from understanding of hydrogeology in combination with physiography of the catchment.

Water quality degradation is one of the major environmental problems in Modjo River catchment and its environs. Hence, determination of the degree of vulnerability to pollution based on hydrogeological factors is important for policy and decision makers. Therefore, the primary goal of this study was to perform an aquifer vulnerability assessment of the water supply aquifers of the study area using a DRASTIC approach assisted by GIS software. To apply the DRASTIC system; hydrometeorology, topography, drainage, borehole data, geology, soil. Land use/land cover database were constructed. Using the aforementioned database, hydrogeological factors such as depth to water, net recharge, aquifer media, soil media, slope, and hydraulic conductivity were extracted and the DRASTIC is applied.

The results suggest that this approach can assess the possible pollution potential of the study area and generate information that is readily usable by agencies and concerned bodies. The groundwater vulnerability map is ideal for use in future land-use planning studies and exclude areas, where potential contamination may occur. It also helps to avoid future contamination of the groundwater by considering the vulnerability of an area before high-risk activities are allowed to take place. The main potential sources of groundwater contaminants are municipal, industrial and agricultural activities including the flower farming which is a point-source.

The intrinsic vulnerability mapping of the water supply aquifers of Modjo river catchment revealed that major part of the eastern, northeastern, and northwestern catchment lie on very low risk area while the central (Debrezeit and Modjo Areas) and southern parts of the catchment lie on

high and very high vulnerable areas to pollution due to relatively high recharge rate, alluvial and fractured aquifer media, gentle and olw slope. Generally, vulnerability of groundwater increases from northeast, east and northwest to the central and southern parts of the catchment. Regarding pesticide vulnerability index, similar result is obtained in the central and southern part. However,the easternmost part of the catchment falls in low vulnerable zone as compared to very low vulnerability in the intrinsic Vulnerability case under natural hydrogeological settings.

9.2 Recommendations

- It is essential to give priority attention to the relatively vulnerable groundwater systems while planning future land use/ development/ activities
- The specific vulnerability mapping should be conducted using different pollution indicators.
- Seasonal water level monitoring, bacteriological and hydrochemical analysis of pollutant indicators, natural/artificial tracer test are recommend for further validation of the maps.
- Detail soil mapping, hydrogeological investigation, and recharge estimation are recommended for further validation of the vulnerability maps produced.
- Pumping test for multilayer aquifer systems is recommended to estimate the hydraulic parameters separately for shallow aquifers
- Comprehensive risk assessment is recommended to be done by analyzing the contamination scenario and toxicity including detailed analysis of the behavior and degree of toxicity of chemicals used by flower farming.
- Awareness creation on groundwater vulnerability to pollution among the decision/ policy makers and planners

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Annex-1 Climatological Data

Element: monthly total Rainfall in mm
Coordinate: Long. 38.57', Lat. 8.44
Station:Debrezeit Airforce
Elevation: 1900m.a.s.l.

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
1996	16.4	0.0	103.1	55.3	105.4	261.5	164.1	275.6	90.0	0.1	5.9	0.0	1077.5
1997	27.8	0.0	26.7	74.8	13.6	121.7	235.8	171.8	71.4	99.9	10.9	0.0	854.5
1998	32.0	51.4	13.9	77.2	41.8	77.7	206.3	293.5	97.6	93.3	0.0	0.0	984.9
1999	0.5	0.0	36.6	0.0	10.0	176.9	298.7	258.6	48.7	90.9	0.0	0.0	920.9
2000	0.0	0.0	8.6	50.4	65.4	77.4	244.3	181.4	139.4	40.0	23.4	3.4	833.7
2001	0.0	4.6	166.4	21.8	104.0	79.5	242.3	143.4	64.3	38.2	0.0	0.0	864.5
2002	8.6	0.0	48.0	34.6	11.0	109.1	179.3	178.0	58.4	0.0	0.0	21.3	648.3
2003	38.3	55.4	64.4	100.3	21.1	81.4	277.9	285.5	120.0	6.0	3.6	35.4	1089.3
2004	x	x	68.1	119.9	2.0	133.5	172.5	209.1	79.6	22.6	10.3	x	
2005	21.8	225.2	122.1	77.3	86.5	96.7	168.0	186.7	153.3	0.0	2.9	0.0	1140.5
2006	5	109	0	52.2	32.2	108.2	329	141.4	122.8	78.3	5.2	16	999.2
AV.	15.0	44.5	59.8	60.3	44.8	120.3	228.9	211.4	95.0	42.7	5.7	7.6	936.2

Element: monthly total Rainfall in mm
Coordinate: 39°07'(long.), 08°37'(lat.)
Station:Modjo
Elevation: 1870m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	x	0.0	97.5	72.2	127.0	214.9	221.3	220.9	79.8	0.0	3.0	0.0	
1997	30.4	0.0	37.6	16.8	16.1	130.6	216.1	158.6	77.8	55.3	21.0	0.0	760.3
1998	32.3	7.6	50.7	46.0	46.0	112.1	161.3	274.8	149.0	154.1	0.0	0.0	1033.9
1999	x	0.0	18.4	0.0	4.2	90.9	541.5	362.0	67.4	87.4	0.0	x	
2000	0.0	0.0	12.0	10.1	33.2	128.0	285.9	230.8	114.1	12.6	25.4	0.0	852.1
2001	0.0	28.5	79.4	22.5	111.0	131.5	184.7	175.6	54.9	0.0	0.0	0.0	788.1
2002	0.0	0.0	8.9	13.7	6.5	62.4	193.5	168.2	90.2	0.0	0.0	14.7	558.1

2003	40.6	55.9	74.9	84.3	23.2	129.0	393.2	148.6	96.1	0.0	0.0	14.3	1060.1
2004	12.5	0.0	99.3	114.6	9.8	x	393.8	211.2	123.7	99.1	32	x	
2005	x	19.1	160.5	149.6	201.4	200.6	320.6	296.1	143.4	7.3	10.9	0.0	
2006	1.6	38.5	90.5	61.6	19.2	108.1	344	x	x	24.9	x	x	
AV.	14.7	13.6	66.3	53.8	54.3	130.8	296.0	224.7	108.4	40.1	9.3	3.6	1015.6

Element: monthly total Rainfall in mm
Coordinate: 39°7'(long.), 08°33'(lat.)
Station:Nazareth
Elevation: 1622m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	27.2	0.0	111.3	65.1	115.2	120.2	220.2	250.0	93.9	0.0	7.9	0.0	1011.0
1997	14.4	0.0	75.3	28.5	6.9	94.0	193.1	240.9	75.5	116.5	31.5	0.0	876.6
1998	11.8	25.6	105.2	19.8	79.3	55.3	196.5	220.6	144.7	132.8	0.0	0.0	991.6
1999	8.7	0.0	22.6	1.2	18.6	68.0	283.2	194.4	66.3	164.7	3.1	0.0	830.8
2000	0.0	0.0	20.2	16.1	51.5	60.8	352.7	271.0	133.6	85.7	64.8	12.9	1069.3
2001	0.0	6.2	108.3	28.7	177.0	51.2	253.8	145.3	107.8	1.7	0.0	0.3	880.3
2002	20.9	11.1	21.4	51.3	22.5	50.2	129.9	205.7	65.3	1.1	0.0	34.5	613.9
2003	46.5	69.1	151.2	88.9	3.6	75.2	235.6	279.7	122.8	0.0	5.3	48.8	1126.7
2004	28.8	3.3	77.4	55.1	1.9	63.3	114.4	227.3	77.1	50	12.8	1.6	713.0
2005	72.5	6.3	89.1	41.3	73.1	50.2	143.8	165.0	73.4	0.0	5.3	0.0	720.0
2006	17.6	88.4	64.6	88.7	27.8	58.7	173.5			89.4			
Av.	22.6	19.1	77.0	44.1	52.5	67.9	208.8	220.0	96.0	58.4	13.1	9.8	883.3

Element: monthly total Rainfall in mm
Coordinate: 39°10'(long.), 08°25'(lat.)
Station:Koka Dam
Elevation: 1595m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	3.5	x	x	40.1	10.2	39.0	116.2	260.6	49.3	0.0	0.0	0.0	
1997	25.7	0.0	41.5	39.3	10.7	145.4	210.9	259.2	51.5	66.6	x	x	

1998	31.0	37.6	17.9	27.2	130.3	65.8	245.9	399.1	71.5	167.9	0.0	0.0	1194.2
1999	15.6	0.0	4.1	0.0	10.0	110.2	219.3	211.4	67.0	177.6	0.0	0.0	815.2
2000	0.0	0.0	1.6	57.9	122.7	90.6	337.0	264.3	212.1	0.0	67.8	0.0	1154.0
2001	0.0	x	141.2	40.9	154.7	178.3	50.1	436.0	119.0	13.3	5.9	21.7	
2002	19.8	32.3	13.1	58.3	8.9	13.0	217.0	175.6	63.1	0.6	0.0	13.9	615.6
2003	46.1	65.6	104.2	22.0	0.0	121.3	274.7	273.4	33.2	0.0	3.8	x	
2004	6.3	0.0	68.8	84.5	0.0	103.4	153.9	272.1	47.5	35.7	4.2	0.0	776.4
2005	47.9	0.0	34.8	30.4	10.6	x	92.8	142.6	61.2	0.0	5.8	0.0	
2006	0.3	14.0	56.0	68.3									
Av.	17.8	16.6	48.3	42.6	45.8	96.3	191.8	269.4	77.5	46.2	9.7	4.5	866.6

Element: monthly total Rainfall in mm
Coordinate: 39°16'(long.), 08°49'(lat.)
Station:Ejere
Elevation: 2100m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	104.7	0.0	94.6	30.2	151.7	170.7	191.6	151.1	121.4	0.0	17.5	0.0	1033.5
1997	23.4	0.0	29.0	39.9	x	x	x	x	26.3	132.8	62.4	0.0	
1998	2.2	128.3	4.1	32.8	47.6	63.6	251.8	270.4	107.3	153.2	0.0	0.0	1061.3
1999	x	x	56.0	0.0	25.6	57.5	319.0	305.2	60.8	95.6	0.0	0.0	919.7
2000	0.0	0.0	10.0	20.9	16.0	97.0	259.2	162.6	143.0	21.4	32.6	10.2	772.9
2001	0.0	12.8	99.3	14.7	75.3	131.3	306.5	224.4	42.3	0.0	0.0	14.5	921.1
2002	2.2	9.5	49.3	4.3	39.4	29.2	203.2	254.3	100.4	0.0	0.0	49.2	741.0
2003	29.4	50.8	5.7	101.0	0.0	112.5	318.9	359.5	124.9	0.0	0.0	66.4	1169.1
2004	47.2	2.9	76.4	64.9	0.0	74.0	165.6	392.7	100.1	28.0	0.0	0.0	951.8
2005	49.5	0.6	81.0	71.3	25.7	90.8	227.3	327.9	105.4	6.9	8.0	0.0	501.5

2006	6.4	14.8	87.3	x	x	x	x	x	x	20.1	x	x	
AV.	26.5	22.0	53.9	38.0	42.4	91.8	249.2	272.0	93.2	41.6	12.1	14.0	956.7

Element: monthly total Rainfall in mm
Coordinate: 38°59'(long.), 08°41'(lat.)
Station:Dertu Liben
Elevation: 2025m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1992	x	x		30.6	10.9	88.6	189.6	190.4	115.9	30.6	2.3	0.6	
1993	2.4	38.6	5.7	105.0	37.6	88.2	191.1	162.5	142.3	23.6	0.0	0.0	797.0
1994	0.0	0.0	34.8	x	x	x	186.9	129.0	127.7	0.0	23.1	0.0	x
1995	0.0	28.0	65.7	48.9	30.0	67.6	200.3	169.9	48.9	0.0	0.0	0.0	659.3
1996	x	x	x	x	x	x	x	x	x	z	z	z	z
1997	27.0	0.0	19.8	105.7	12.2	118.7	246.6	150.8	53.6	77.6	4.2	0.0	816.2
1998	22.4	61.6	1.6	48.0	96.5	56.8	265.1	280.5	118.9	102.8	0.0	0.0	1054.2
1999	0.0	0.0	7.0	6.1	29.6	109.9	208.6	273.8	71.7	150.8	0.0	0.0	1911.7
2000	0.0	0.0	22.6	46.2	22.0	67.4	250.3	189.4	84.5		20.9	1.7	705.0
2001	0.0	6.8	116.9	20.3	113.4	80.2	226.1	176.1	97.5	9.0	0.0	0.0	846.3
2002	38.8	0.0	26.7	11.6	39.0	105.0	144.3	159.3	33.0	0.0	0.0	13.7	571.4
2003	25.2	44.8	66.5	149.0	19.5	x	310.4	x	x	x	x	x	x
AV.	11.6	18.0	36.7	57.1	41.1	86.9	219.9	188.2	89.4	43.8	5.1	1.6	799.4

Element: monthly total Rainfall in mm
Coordinate: 38°56'(long.), 08°18'(lat.)
Station:Alem Tena
Elevation: 1720m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1994	0.0	0.0	8.6	25.3	17.2	117.1	206.1	126.5	X	X	16.0	13.2	
1995	0.0	44.8	87.8	47.5	31.5	29.9	159.8	135.6	89.0	5.2	0.0	0.0	631.1
1996	65.4	0.0	100.0	31.1	63.0	113.4	197.6	153.5	92.5	0.8	0.0	0.0	817.3

1997	10.7	0.0	32.3	92.0	9.3	158.4	194.6	151.2	70.7	48.0	6.0	0.0	773.2
1998	7.1	21.8	36.3	102.6	33.1	49.8	216.4	190.7	52.0	98.4	0.0	0.0	808.2
1999	2.4	0.0	19.7	6.8	19.2	81.1	227.5	165.6	72.1	119.9	0.0	x	
2000	0.0	0.0	0.0	127.1	89.0	51.7	207.8	142.0	155.8	52.7	54.0	x	
2001	0.0	24.6	157.7	15.7	113.8	104.2	200.2	155.5	73.1	0.0	0.0	0.0	844.8
2002	1.5	35.4	24.3	82.9	11.3	45.0	x	150.7	45.6	0.5	0.0	x	
2003	19.0	16.4	116.9	54.0	29.4	84.6	392.5	105.4	96.5	0.0	0.0	21.7	936.4
2004	89.4	0.0	58.4	174.3	0.0	78.8	122.9	145.0	103.6	x	x	x	
AV.	17.8	13.0	58.4	69.0	37.9	83.1	212.5	147.4	85.1	36.2	7.6	5.0	773.0

Element: monthly total Rainfall in mm
Coordinate: 38°5'(long.), 08°3'(lat.)
Station:Ziquala
Elevation: 3050m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1994	0.0	104.1	0.0	35.1	54.2	209.9	449.2	188.9	238.0	3.2	22.6	19.7	1324.9
1995	0.0	28.2	75.7	172.1	25.2	61.7	202.4	194.7	116.3	0.0	0.0	6.4	882.7
1996	56.4	0.0	120.1	108.6	156.9	283.0	403.7	215.9	76.7	1.2	5.1	0.0	1427.6
1997	61.5	0.0	29.9	126.2	13.4	119.3	183.6	155.9	126.1	66.6	19.2	0.0	901.7
1998	65.6	67.1	48.2	118.8	86.9	136.4	330.4	324.3	89.8	174.4	0.0	0.0	1441.9
1999	1.2	0.0	10.6	31.4	8.8	111.8	362.7	275.1	55.3	154.0	0.0	0.0	1010.9
2000	0.0	0.0	35.0	96.3	69.5	107.0	337.7	194.4	139.8	35.5	41.5	2.7	1059.4
2001	4.1	26.2	251.1	73.8	234.8	197.7	291.4	214.8	85.2	16.4	0.0	1.5	1397.0
2002	28.1	38.9	85.2	35.1	51.0	71.5	231.3	254.1	102.2	0.0	0.0	x	
2003	x	94.9	125.3	133.4	62.5	213.3	307.5	147.3	118.7	8.0	58.2	0.0	
2004	46.6	8.2	203.9	72.3	0.0	128.5	241.0	235.8	159.3	9.1	0.0	0.0	1104.7
2005	76.9	1.0	133.5	x	x	x	189.0	215.2	41.5	13.7	0.0	0.0	
Av..	30.9	30.7	93.2	91.2	69.4	149.1	294.2	218.0	112.4	40.2	12.2	2.8	1144.3

Element: monthly total Rainfall in mm
Coordinate: 39°09'(long.), 09°12'(lat.)
Station:Aleltu
Elevation: 2550m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1994	0.0	0.0	31.3	51.4	33.9	114.8	254.1	376.8	98.8	0.0	10.4	0.0	971.5
1995	0.0	52.9	64.5	110.5	12.3	39.6	299.5	326.0	123.7	0.0	0.0	0.8	1029.8
1996	66.4	0.0	99.1	37.6	x	158.9	312.9	x	42.5	0.0	2.8	0.0	
1997	52.8	0.0	55.7	68.9	46.0	130.4	297.6	248.1	57.3	98.2	33.1	0.0	1088.1
1998	24.9	20.0	15.0	20.5	45.6	117.0	363.4	379.5	300.1	59.6	0.0	0.0	1345.6
1999	4.6	0.0	48.8	2.2	13.0	98.2	365.1	443.4	96.1	50.3	0.0	2.0	1123.7
2000	0.0	0.0	11.1	17.5	53.8	68.2	276.3	482.2	123.6	x	10.5	4.3	
2001	0.0	10.8	154.9	4.3	63.7	194.7	305.9	227.2	42.4	3.0	0.0	0.6	1007.5
2002	32.4	12.8	111.4	8.3	35.8	73.2	200.4	341.4	109.4	2.2	0.0	5.0	932.3
2003	26.1	13.0	38.2	100.4	0.0	99.3	371.8	189.5	0.0	0.0	0.0	14.1	852.4
2004	10.2	2.9	16.1	193.5	4.3	108.4	309.8	265.0	98.9	32.5	4.0	0.0	1045.6
2005	10.2	12.0	28.4	75.0	92.6	77.4	258.5	310.4	165.4	6.4	0.0	0.0	1036.3
AV.	19.0	10.4	56.2	57.5	36.5	106.7	301.3	326.3	104.9	8.8	5.1	2.2	1043.3

Element: monthly total Rainfall in mm
Coordinate: 39°25'(long.), 08°57'(lat.)
Station:Arerti
Elevation: 1850m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1994	0	0	14.9	32.6	40.7	81.3	299	154	105	0.5	40	0	767.9
1995	0	33.5	35.9	88.8	3.4	30.7	135	215	78.8	0	0	3.1	623.9
1996	49.9	0	82.3	26.9	62.4	98	181	197	63	0	20	0	780.5
1997	19.6	0	70.7	65.5	12.8	104	200	217	38.9	108	56	0	893.3
1998	24.2	56.2	73	21.6	23.2	55.6	249	242	99.7	169	0	0	1012.8
1999	1.8	0	129	1.1	4.1	143	256	273	79.4	113	4	0	1003.7
200	0	0	21.	36.	41.	54.	242	189	80.	50	45	8.1	767.4

0 2001	0.0	24.3	4 125.4	1 15.6	6 40.2	9 40.2	248.7	167.0	4 29.2	0.4	0.0	5.6	696.6
2002	2.8	0.0	51.1	31.5	0.0	8.1	164.9	199.8	112.4	0.8	0.0	44.1	615.5
2003	29.5	25.7	10.0	61.2	7.5	63.3	327.1	348.6	74.7	0.0	0.0	47.5	995.1
2004	24.0	4.9	81.9	129.9	0.2	15.4	262.0	266.1	53.7	x	x	x	
AV.	13.8	13.2	63.3	150	21.5	63.1	233	224	74.2	44	17	10.84	927.8

Element: monthly total Rainfall in mm
Coordinate: 39°08'(long.), 08°58'(lat.)
Station:Chefe Donsa
Elevation: 2390m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1997	x	0.0	x	61.6	12.1	84.0	154.6	152.6	66.5	59.9	18.3	0.0	609.6
1998	17.2	46.4	48.7	39.0	27.3	87.0	217.5	262.6	96.5	36.6	0.0	0.0	878.8
1999	0.0	0.0	22.8	0.0	14.4	X	232.9	264.0	48.9	26.9	0.0	0.2	
2000	0.0	0.0	23.8	40.0	18.9	96.2	182.9	226.8	X	X	19.1	0.0	
2001	0.0	23.8	109.7	17.4	69.1	89.0	202.6	111.2	46.6	0.0	0.0	6.3	675.7
2002	0.0	0.0	41.7	20.0	17.0	59.6	156.0	265.8	53.4	0.0	0.0	12.0	625.5
2003	12.1	43.4	54.3	78.0	0.0	73.7	228.3	353.0	113.8	0.0	0.0	15.5	972.1
2004	14.2	1.3	36.0	73.1	4.3	122.3	230.1	184.3	108.8	0.0	5.6	0.8	780.8
2005	62.8	24.0	47.6	142.7	113.2	181.0	186.9	256.9	83.6	0.0	0.0	0.0	
2006													
AV.	13.3	15.4	48.1	52.4	30.7	99.1	199.1	230.8	77.3	15.4	4.8	3.9	790.2

Element: monthly Maximum Temperature(°c)
Coordinate: 39°07'(long.), 08°37'(lat.)
Station:Modjo
Elevation: 1870m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	x	x	32	31.8	33	28.3	24.8	23.9	25.2	27.2	27	26
1995	27.9	29.2	29.1	29.1	30.7	30	24.5	24.8	26	27.9	28	28
1996	x	28.7	29.1	29.9	29.9	29.3	26.6	24.9	26.9	27.5	28	27

1997	28	28.5	30.9	29.1	30.7	28.6	25.2	26.3	28.1	28.5	28	29
1998	29.2	30.4	31.1	32	31.9	32.3	26.9	24.5	25.7	27	27	27
1999	x	30.8	30.5	31	30.9	30	29.4	28.9	28.8	28.6	29	
2000	28.5	29.7	30.9	30.6	30.6	20.3	24.3	23.7	26.4	27.5	28	28
2001	28.1	29.6	29.5	30.9	30.1	28.3	26.3	26	27.8	29.7	30	30
2002	29.2	30	29.4	29.9	30.5	29.4	28.1	27.5	28.8	28.4	29	28
2003	28.6	29.3	29.9	29.6	32.1	30	25.5	26.8	29.4	30.3	29	28
2004	29.2	29.4	30.2	31.1	33	x	27.4	29.1	30.3	29.4	31	x
AV.	28.6	29.6	30.2	30.5	31.2	28.7	26.3	26	27.6	28.4	28	28

Element: monthly Minimum Temperature(°c)
Coordinate: 39°07'(long.), 08°37'(lat.)
Station:Modjo
Elevation: 1870m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	**Jun**	**Jul**	Aug	Sep	Oct	Nov	Dec
1994	x	x	13.7	14.5	15.1	13	15.2	14.7	14	11	9.7	9.3
1995	8.4	12.6	14.2	15.2	14.8	14	14.5	14.8	14	13.6	10	11
1996	x	11	13.3	13.3	13.5	13.2	15	14.4	13	10.2	10	8.1
1997	11.5	9.7	14.6	13.3	13.4	15.1	14.6	14.6	12.6	11.7	13	9
1998	11.5	11.1	12.6	13.8	13.1	13	14	15.4	14.5	13	8.4	6.8
1999	x	11.9	14.2	13.1	12.5	12.7	12.9	12.7	12.9	12.7	13	x
2000	9.4	10.1	13.3	14.7	14.7	13.6	14.4	13.9	13.4	11.7	9.5	7.7
2001	7.7	10.3	12.6	13.1	13.9	13.6	13.5	14	12.4	10.7	10	7
2002	9	8.7	12.3	12.6	12.4	12.9	14	14.5	12.3	10.6	9.2	9.4
2003	9.7	10.7	10.8	13.7	13.4	12.4	8.7	8.5	10	8	9.6	6.1
2004	9	9.3	10.2	11.1	12.9	x	6.9	7.6	9.2	8.6	6.9	x
AV.	9.52	10.5	12.9	13.5	13.6	12.2	13.1	13.2	12.6	11.11	10	12

Element: monthly Mean Maximum Temperature(°c)
Coordinate: 38°57'(long.), 08°44'(lat.)
Station:Debrezeit
Elevation: 1900m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	x	27.8	28.4	28.9	29.6	26.9	23.8	23.1	24.4	26	25	25.5
1995	26.4	28.7	28.5	27.8	29.9	29.2	24.4	23.7	25	26.2	26.1	26.4
1996	26	28.7	28	27.8	27.2	24.2	24	24.2	25.5	26.5	25.7	25.7
1997	26.1	27.4	29	27.2	29.7	27.7	24.9	25.2	26.9	25.9	25.3	25.9
1998	26.6	27.8	28.6	30.1	29.6	28.9	24.6	23.6	25.3	25.8	25.7	25.4
1999	26.9	28.8	27.8	29.7	30	28	23.7	24.3	x	x	25.1	25.4
2000	26.7	28.2	29.7	29.4	29.1	27.5	24.8	23.7	24.9	25.1	25.5	25.8
2001	26.5	29.2	27.7	29.1	28.4	26.7	24.6	24.1	26.9	27.6	26.9	27.6
2002	27	29.9	29.3	30.4	31.4	29.1	26.8	25.3	26.4	27.9	27.3	26.2
Av.	26.5	28.5	25.6	28.9	29.43	27.57	24.62	24.13	25.66	26.37	25.84	26

Element: monthly Mean Minimum Temperature(°c)
Coordinate: 38°57'(long.), 08°44'(lat.)
Station:Debrezeit
Elevation: 1900m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	x	10.8	13.5	14.5	13.9	13.2	13.7	13.3	12.4	10.4	9.8	9.1
1995	9.2	12.2	13.9	14.7	14	12.6	13.6	13.9	12.1	11.6	9.8	11.5
1996	11.8	11.4	14.3	13.7	13.7	13.9	13.3	13.7	12.6	10.7	9.8	9
1997	11.9	10.3	13.9	13.9	13.8	14.1	13.8	13.8	13.3	13.3	12.6	9.8
1998	12.8	14.2	14.7	15.2	14.5	13.8	14.5	14.3	13.5	12.2	8.4	7.6
1999	9.8	10.2	13.5	14.3	13.7	13.2	13.4	13.5	x	x	8.1	8.5
2000	9	10.3	12.5	14.3	13.3	12.9	13.6	13.2	13.3	11.5	10.5	9.9
2001	10.2	11.1	13.7	13.8	14.1	13.3	13.9	14.5	12.6	11.8	9.8	11.1
2002	11.4	11.8	14.3	14.4	13.7	14.2	14.3	14.1	13.3	12.2	10.8	12.6
Av.	10.8	10.4	13.8	14.3	13.85	13.46	13.78	13.81	12.88	11.71	9.95	9.9

Element: Sunshine Duration(Hours)
Coordinate: 38°57'(long.), 08°44'(lat.)
Station:Debrezeit
Elevation: 1900m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	7.5	11	8.9	7.2	9.9	8.1	5.8	6.3	8.9	7.8	7.6	9.8
1998	8	7.9	7.8	8.9	8.2	7.8	5.5	4.6	6.3	7.6	10.4	10
1999	9.5	11	7.4	10	8.9	8	4.5	6.4	x	x	10.1	11
2000	10.1	X	X	X	8.4	6.9	6.2	5.2	5.5	8.1	9.1	9.5
2001	9.1	10.0	6.6	9.9	7.9	6.5	6.1	4.7	8.7	9.8	10.2	10.0
2002	8.2	10.1	8.1	9.2	8.5	7.7	7.0	6.4	8.2	9.9	10.4	7.1
2003	8.8	8.9	9.8	7.3	9.5	7.1	5.0	4.9	10.4	10.4	9.9	9.3
2004	X	X	8.4	7.6	9.3	6.6	5.8	5.9	7.4	8.4	10.2	9.5
2005	8.5	10.1	9.0	8.1	7.0	6.5	4.8	7.1	6.9	9.9	9.7	10.8
2006	10.1	9.7	8.1	7.6	8.8	6.7						
Average	8.86	9.73	8.23	8.42	8.64	7.19	8.47	5.72	7.79	8.99	9.73	9.67

Element: Monthly Mean Relative Humidity at 0600 L.S.T.
Coordinate: 38°57'(long.), 08°44'(lat.)
Station:Debrezeit
Elevation: 1900m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	69	52	70	67	69	82	87	87	83	55	61	60
1997	71	52	62	67	56	73	83	84	73	68	72	63
1998	72	72	66	62	66	71	85	89	82	71	54	49
1999	57	43	64	46	60	73	85	81	X	X	74	76
2000	68	54	57	70	79	84	87	88	91	87	81	78
2001	74	69	81	71	84	86	87	87	90	80	73	71
2002	78	64	75	73	76	84	89	90	88	66	65	78

2003	74	69	72	75	59	78	86	88	91	72	74	74
2004	x	x	x	x	68	85	84	88	88	83	79	79
2005	83	73	83	77	70	89	91	91	92	86	78	76
2006	81	83	80	85	76	x	x	x	x	x	x	x
AV.	73	63	71	69	69	81	86	87	86	74	71	70

Element: Monthly Wind speed at 2mts in (m/s).
Coordinate: 38°57'(long.), 08°44'(lat.)
Station:Debrezeit
Elevation: 1900m.a.s.l.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	x	1.6	1.6	1.9	2.0	1.4	1.3	1.0	1.1	2.0	1.6	1.6
1995	1.4	1.5	1.8	1.5	2.4	1.4	1.1	1.0	0.9	1.7	1.4	1.5
1996	1.4	1.6	1.5	1.6	1.4	1.0	1.0	1.0	0.9	1.5	1.5	1.4
1997	1.3	1.9	1.7	1.5	2.0	1.5	1.1	0.9	1.1	1.5	1.5	1.5
1998	1.5	1.3	1.7	1.6	1.4	1.2	1.2	1.0	0.8	0.9	1.3	1.4
1999	1.4	1.7	1.5	2.0	1.7	1.3	1.1	1.0	x	x	1.6	1.4
2000	1.5	1.7	1.8	1.8	1.4	1.3	1.1	1.0	0.8	1.2	1.3	1.3
2001	1.1	1.3	1.0	1.3	1.0	1.1	1.0	0.9	0.9	1.2	1.4	1.3
2002	1.2	1.3	1.2	1.6	1.3	1.2	1.1	1.0	1.0	x	x	x
2003	1.3	1.3	1.6	1.3	2.0	1.5	1.3	1.0	0.9	1.4	1.5	1.4
2004	x	x	x	x	1.7	1.6	1.3	1.1	1.2	1.6	1.9	1.7
2005	1.5	1.9	1.9	1.9	1.7	1.3	1.2	1.1	1.0	1.6	1.9	1.7
2006	1.7	1.7	1.4	1.4	1.7	x	x	x	x	x	x	x
AV.	1.39	1.6	1.6	1.6	1.7	1.6	1.2	1.0	1.0	1.5	1.5	1.5

Annex-2 Lithologic Logs of Water Points

Local Name	UTME	UTMN	Elv	T.Depth	SWL, m	Formation	Q(l/s)	S	SP.Y	T	Thiess
D/Z-Green Star	494598	967157	1896	80	66.78	Basalt	6.7	0.2			
D/Z-Veternary College BH2	500078	968505	1880	56	14.5		15.4	0.5	30.8	3193.34	18
D/Z-Sahilu	494829	967088	1917	80	64.1		3.37	0.3	11.23	1164.67	12
D/Z-Almaz Ayele poultry Farm	499320	970175	1890	68	18.9		6	0.39	15.38	1595.08	24
D/Z-New well	492803	969204	1906	116.3	64.3	Basalt	4.5	7.25			
D/Z-Blue Nile Plastics	495765	966397	1910	94	46.6		4.5	0.33	13.64	141.82	
D/Z-Hora Tannery	498633	970028	1890	74	34.1		10	2.5	4	414.72	
D/Z-Assembly Church	496646	967481	1905	60	20.4						
Mekaneyesus orphanage Debrezeit (Dug Well)	499445	967905	1900	20							
D/Z-Health College	497100	968198	1901	92	36.4	Basalt	10	1.54			
D/Z-Sunshine Con	488408	973431	1984	150	42.52	Basalt	5	2.31			

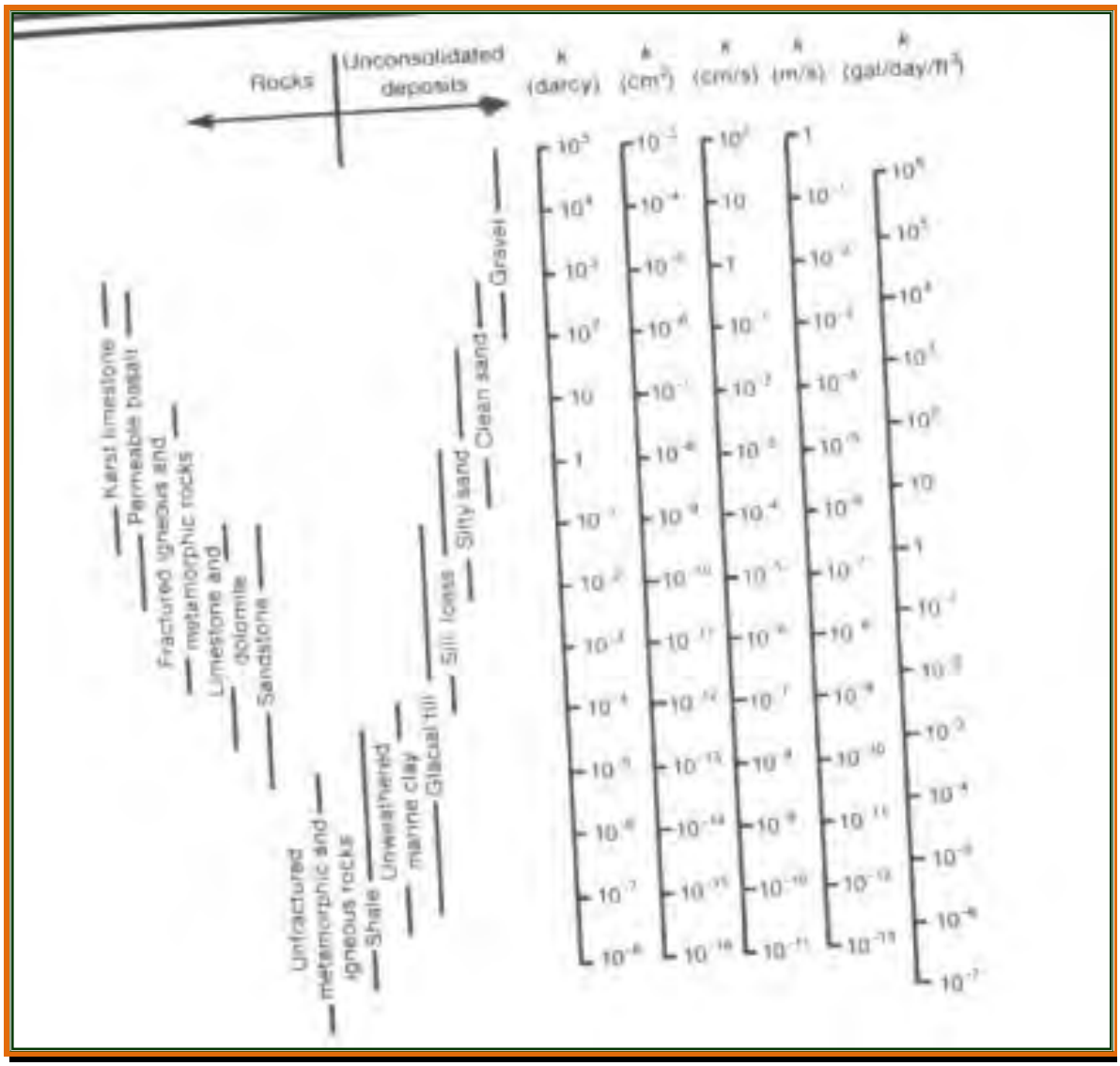
D/Z-Girma Gebre Kidan	495561	968574	1906	60	49.9		2.43	0.22	11.05	1145.19	12
D/Z-Dugda PLC	502364	970907	1893	74	23.78	Basalt	24.4	4.5			
D/Z-Dombosco	496479	965700	1930	104	56.56	Basalt					
D/Z-Air force	500909	964676	1903	36	24.13	Alluvium	5.6	0			
D/Z-Airforce Next to main gate	499228	964796	1910	80	43.07	Scoraceous basalt	8	0.18			
D/Z-Airforce,main gate well	499131	965767	1909	38	27.8						
D/Z-Airforce	500204	963672	1900	47	31.5						
Shimbira meda	500424	974376	1914	81.7	30.6	Alluvium	6.55	1.1			
D/Z-Airforce,Head office	499148	965330	1911	62	34.25						
Shimbira Meda	500766	973335	1905	80	22.64	Alluvium	7.1	1.42			
D/Z-Sunshin Pharmat	493545	968537	1924	105	66.68	Scoraceous basalt					
D/Z-Genesis Farm#1	495447	968068	1902	70	49.68		16.6				18
Shimbira Meda	500494	974376	1914	80.5	24.87	Alluvium	16.7	0.68			
D/Z-Airforce No.2	499500	964500	1890	72	30.5		4.5	0.75	6	622.08	
D/Z-Hospital	492987	967055	1928	108	42.45		5.1	44.54			

D/Z-Flour and Pasta factory BH1	496147	967674	1900.3		40.3		4	0.8	5	518.4		
D/Z-steel rolling mill BH-2	496159	966870	1900	74	40.5		20					
Shimbra Meda	501422	973727	1910	80	24.1	Alluvium	12.46	0.7				
Wajitu	488463	965890	1912	115	93.5							
D/Z-Dragados	494054	968452	1932	130	66.11	Basalt						
D/Z-Genesis farm	495447	968060	1963	92	48.3	Scoraceous basalt						
Tulu Dimtu 1	515693	979646	2116		121.1	Ignimbrite						
Tulu Dimtu 2	515449	979174	2108		138.4	Ignimbrite						
Borora Gudda 1	507431	970664	1900		33							
Borora Gudda 3	506964	970295	1894		27							
Dhenkaka Delo	505950	962920	1865		19							
Hand Dug Well(Tewabech)	503247	960974	1873		25							
Bore Hole Near Arose Hotel	505900	957500	1852		28							
Arose Hotel	506506	956871	1862		28.8							
Koka Ejersa	506460	937165	1656		53.27							
Legese HDW	502609	961393	1887		32							
Abera HDW	504074	958924	1887		25							
Aychilu HDW	509725	953604	1817		16							
Tefera	510	9529	182		16							

HDW	332	39	4									
Modjo-Biyo Beseka hand dug	507714	955875	1855	33	31.6							
Modjo Lume#3	512957	947774	1783	134	36.7	Alluvium	8.5	8.79				
modjo kolba Tannery	512602	947821	1770	116.5	39.1	Alluvium						
Modjo-Biyo Beseka	507722	955887	1855	50	32			12.5				
Ude Village	503886	958637	1879	37	30							
Modjo#4	511927	948292	1770	113.5	8.3	Alluvium	4.5	10.6				
Gafat#8	509020	950736	1795	150	28.9	Basalt	4	28.7				
Gafat#9	508684	951058	1806	146.2	23.91	Tuff	4	9.38				
Gafat#10	507950	951364	1819	150	25.55	Tuff	4	6.11				
Modjo Hand pump	509969	952000	1800	16	15.1	Ash						
Koka	503210	930527	1610	100	7.8		22	6.58				
Gafat#1	507491	952694	1862	102	40.1	Basalt	5.6	32.9				
Gafat#7	509385	950325	1994	150	26.08	Basalt	4	9.6				
Koka	506728	937459	1669	129.66	53.27	Trachyte	4	2.71	1.48	158.11		
Modjo Abudabstab	512159	946729	1792	141	72.52	Ignimbrite	8.3	11.77				
Modjo Ethio Japan Nylon	513773	949998	1795	148	39.52	Basalt	4.7	24.06				
Modjo Bekele Mola	513423	948940	1784	100	37.2	Basalt	6.2	51.8				
Modjo#2	511	9486	178	80	35.3	Alluviu	12	19				

	976	71	6		4	m	.8	.08				
Gafat#2	508079	952013	1822	114.5	7.9	Ash	4.5	29.49				
Gafat#4	508995	951614	1810	150	31.26		5	15.91				
Koka Ethi-Cutting	502329	929321	1606	130	5.4	Ignimbrite	25	0.95				
Modjo Lume#2(New TWS)	512355	951516	1777	124.83	9.25	Alluvium	8.3	56.6				
Modjo#3	512408	948682	1782	80	34.14	Alluvium	5	16.1				
Modjo Export Slaghter	511848	948993	1765	90		Basalt						
SUN Tannery	512356	947895	1752	113.5	25.7	Alluvium						
Modjo#1	512011	949196	1785	90	31.77	Pumice	4.5	23.61				
Modjo lume#1(town WS)	512282	951356	1762	123	7.34	Alluvium	8.3	32.04				
Modjo Dairy Development	512282	951356	1762	150	7.1	Basalt						
Godino	501798	978894	1998									
Gimbichu Fentale	518068	992824	2317									
Areda Weyra	527049	1002033	2485		78.22	Ignimbrite						
Koka Dayi	521842	1000254	2447		45	Ignimbrite						
Foche Shallow Well	524220	1000990	2452		40	Ignimbrite						
Kersa Hamus Gebeya	513646	999111	2458		8	Ignimbrite						
Seftu	510393	991274	2390	120	26.98	Ignimbrite						

Annex-3 Hydraulic Conductivity and Permeability ranges of Common geological materials (Freeze & Cherry, 1979)



Annex-4 Modjo River Average Daily Flow Data

	Daily Average Flows of Modjo River @ Koka Dam (CMS)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.482	0.398	0.33	1.049	0.337	0.629	2.566	9.295	7.768	1.297	0.613	0.526
2	0.482	0.406	0.327	0.6	0.951	0.634	5.579	9.181	8.266	1.309	0.619	0.533
3	0.487	0.429	0.351	0.603	1.236	0.621	2.578	9.343	6.464	3.918	0.631	0.524
4	0.484	0.392	0.365	0.393	1.422	0.636	4.818	9.53	6.807	1.149	0.599	0.522
5	0.465	0.377	0.846	0.812	1.43	0.786	3.413	8.719	4.85	1.365	0.599	0.516
6	0.455	0.373	0.396	0.447	2.866	1.086	4.395	9.64	6.443	1.864	0.602	0.532
7	0.448	0.377	0.427	0.455	0.681	0.857	5.019	10.045	5.334	2.652	0.591	0.532
8	0.449	0.363	0.812	0.366	1.589	1.753	4.988	8.794	5.462	1.51	0.591	0.533
9	0.449	0.359	0.43	0.872	0.566	2.311	8.115	9.224	4.998	1.071	0.602	0.524
10	0.438	0.351	0.432	0.412	0.417	1.02	4.666	12.587	3.849	4.223	0.594	0.524
11	0.427	0.347	0.432	1.244	1.422	1.357	4.733	12.381	4.402	3.372	0.582	0.514
12	0.629	0.34	0.679	0.526	0.797	2.768	7.107	12.65	4.803	3.413	0.593	0.519
13	0.498	0.343	533	0.546	0.79	1.214	5.247	9.634	3.539	2.096	0.601	0.505
14	0.487	0.348	0.534	0.424	0.706	0.909	5.799	14.711	2.831	1.144	0.581	0.511
15	0.492	0.343	0.397	0.398	0.901	2.114	7.366	11.101	3.622	0.869	0.576	0.507
16	0.492	0.341	0.641	0.363	1.024	1.487	6.323	10.752	3.933	0.805	0.558	0.508
17	0.473	0.34	0.453	0.372	0.778	1.292	6.831	8.047	2.784	0.764	0.556	0.503
18	0.462	0.362	1.15	0.345	0.845	2.47	9.44	10.174	2.537	0.752	0.556	0.506
19	0.459	0.401	0.616	0.842	1.174	2.658	12.51	8.3	2.191	0.895	0.569	0.51
20	0.458	1.66	1.603	0.566	0.659	1.902	12.297	10.502	1.879	1.572	0.57	0.502
21	0.458	0.543	0.663	0.47	0.514	1.723	9.896	9.416	1.595	0.985	0.557	0.507
22	0.452	0.388	0.483	0.412	0.527	4.099	9.45	8.396	3.25	0.762	0.562	0.548
23	0.522	0.36	0.395	0.441	0.446	2.736	9.726	9.22	2.072	0.699	0.565	0.513
24	0.485	0.333	0.398	0.656	0.391	2.063	11.058	7.851	1.552	0.704	0.573	0.541
25	0.452	0.324	1.631	0.791	0.399	5.63	11.005	10.1	1.259	0.672	0.576	0.552
26	0.472	0.324	1.558	0.473	0.38	4.035	7.771	8.446	1.166	0.653	0.558	0.55
27	0.634	0.334	2.063	0.392	0.376	2.916	8.252	8.53	1.437	0.631	0.545	0.562
28	0.908	0.316	0.575	0.329	0.367	4.422	7.749	8.307	1.109	0.631	0.51	0.565
29	0.619	0.499	1.055	0.304	0.42	5.799	10.286	7.441	1.128	0.614	0.533	0.542
30	0.511		0.594	0.309	0.5	4.404	11.737	7.2	1.017	0.626	0.537	0.536
31	0.495		1.947		0.524		10.384	6.891		0.62		0.535

D E C L A R A T I O N

I here by declare that the thesis entitled "Aquifer Vulnerability Assessment in Modjo River Catchment (Central Main Ethiopian Rift)" has been carried out by me under the supervision of Dr. Seifu Kebede, Department of Earth Sciences, Addis Ababa University, Addis Ababa during the year 2007/2008 as a part of Master of Science programme in Hydrogeology. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Ewnetu Bedane(Candidate)

Signature_____

Place and date of submission: School of Graduate Studies, Addis Ababa University, November 2008

Dr. Seifu Kebede(Advisor)

Signature _____