

**HYDROGEOCHEMISTRY AND NEW WATER RESOURCE
IDENTIFICATION OF AXUM AREA**

**A Thesis Submitted to the School of Graduate Studies
Addis Ababa University**

**In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Geology (Hydrogeology)**

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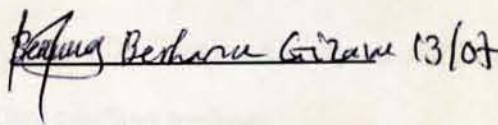
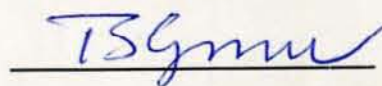
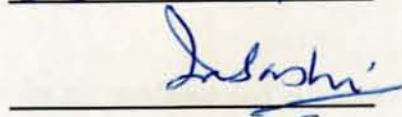
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ABSTRACT

The investigation of groundwater in Axum area that emphasize on geochemical Variations on the study are is conducted using hydrometerological, geological, hydoro-geolgical, hydochemical, and geophysical techniques.

The study area is found in Tigray region, central zone, which is situated about 1025 km north of Addis Ababa. It is located on UTM coordinates between 154760-156700N and 458000-480,000E, including Axum town and its surrounding areas with a total areal coverage of 425.7 sq.km. The area is covered by basement complex, Mesozoic formations, basalt and phonolite & trachyte plugs.

The area has a mean annual rainfall of 672mm and mean annual temperature of 19.4⁰c. Based on qualitative borehole data, borehole logs and field observation four types of hydrostratigraphic units are found in the study area. These are metamorphic rocks, Siltstone and Sandstone, Basalt and Adwa formation.

The geochemical study indicates that there is a difference in chemical composition of waters from different lithologies, especially boreholes that penetrate the basalt and mudstone have high chemical ions resulting a deteriorate water quality on TH, TDS, EC.

Based on the available geophysical data high values of total transverse unit resistance (T) is obtained from VES 12, VES 9, VES1 and VES5 suggesting that a thick with high resistivity material is located in the area where these VES are taken.

High values of total longitudinal unit conductance (S) is obtained from VES5, VES1, VES3, VES7 and VES 13 indicating a deeper basement where as the rest show low values of S suggesting the presence of shallow basement.

LIST OF TABLES	IX
LIST OF FIGURES	X
LIST OF MAPS	XI
LIST OF ABBREVIATIONS	IX
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Objectives	2
1.3 Significance	2
1.4 Scope	3
CHAPTER 2 GENERAL OVERVIEW OF THE STUDY AREA	4
2.1 Location and map sheet	4
2.2 Topography	4
2.3 Climate	6
CHAPTER 3 GEOLOGY	7
3.1 Regional Geology	7
3.1.1 Proterozoic Terranes	7
3.1.2 Palaeozoic Terranes	8
3.1.3 Mesozoic Tertiary Age	8

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	I
ABSTRACT.....	III
LIST OF TABLES.....	X
LIST OF FIGURES.....	X
LIST OF MAPS.....	XII
LIST OF ANNEXTURES.....	IX
 CHAPTER 1 INTRODUCTION.....	 1
1.1 Background.....	1
1.2 Objectives.....	2
1.3 Methodology.....	2
1.4 Work Plan.....	3
 CHAPTER 2 GENERAL OVERVIEW OF THE STUDY AREA.....	 4
2.1 Location and areal extent.....	4
2.2 Topography.....	6
2.3 Climate	6
 CHAPTER 3 GEOLOGY	 7
3.1 Regional Geology.....	7
3.1.1 Precambrian Formations.	7
3.1.2 Paleozoic Formations.....	8
3.1.3 Mesozoic Formations.	8

3.1.3.1 The Adigrat Formation	9
3.1.3.2 The Antalo Formation	9
3.1.3.3 The Agula Formation	10
3.1.3.4 Amba Aradom.	10
3.1.4 Cenozoic Volcanic and Sedimentary Rocks.	11
3.1.4.1 Ashangi Formation.	11
3.1.4.2 The Aiba Basalts	12
3.1.4.3 The Alajae Formation	12
3.1.4.4 Tarmaber Formation	12
3.1.5 Quaternary sediments.	14
3.2 Local Geology.....	15
3.2.1 Basement Complex	19
3.2.2 Mesozoic Sedimentary Rocks	19
3.2.3 Basalt Rocks.	21
3.2.4 Trachyte & Phonolite.....	22
3.2.4.1 Trachyte Plugs	23
3.2.4.2 Phonolite Plugs	23
3.3 Structures	24
CHAPTER 4 HYDROMETEOROLOGY.....	26
4.1 General	26
4.2 Precipitation.....	26
4.2.1 Availability of data.....	27
4.2.2 Seasonability of Rainfall	28

4.2.3 Availability of Rainfall.....	29
4.3 Air Temperature.	30
4.4 Evapotranspiration	31
CHAPTER 5 HYDROGEOLOGY	32
5.1 Introdoction	32
5.2 Hydrostratigraphic units.	32
5.2.1 Metamorphic Rocks	33
5.2.2 Adigrat Formation	34
5.2.2.1 Siltstone (Mudstone)	34
5.2.2.2 Sandstone intercalated with siltstone	35
5.2.3 Basalt	37
5.2.4 Adwa Formation	38
5.3 Structural effect	39
5.4 Aquifer Hydraulic Characteristics.....	40
5.4.1 Hydraulic Characteristics of the Precambrian Rocks	41
5.4.2 Hydraulic Characteristics of the Adigrat Formation.....	42
5.4.2.1 Siltstone (Mudstone).....	42
5.4.2.2 Sandstone intercalated with Siltstone	42
5.4.3 Hydraulic Characteristics of the basalt aquifer	42
5.4.4 Hydraulic Characteristics of the Adwa Formation.....	52
5.5 Behavior of Groundwater	54
5.5.1 Grid Deviation Water table Map.	55
CHAPTER 6 HYDROGEOCHEMISTRY.	59

6.1 Introduction	59
6.2 Water Sampling Methods.	62
6.3 Water Analysis Results.	62
6.3.1 Physico-Chemical Analysis Results.	62
6.4 Data Interpretation.	67
6.4.1 Hydrogen Ion Activity (PH)	68
6.4.2 Total Dissolved Solids (TDS)	69
6.4.3 Total Hardness	71
6.4.4 Electrical Conductivity (Ec)	72
6.4.5 Major Cations	74
6.4.6 Major Anions.	77
6.5 Metasomatism of Groundwater.	79
6.5.1 Index of Base Exchange	79
6.5.2 Groundwater Types (Schoeller).....	81
6.5.3 Stuyfzand's Classification of Water.....	83
6.5.3.1 Stuyfzand's Main Water Type.	83
6.5.3.2 Stuyfzand's Sub Water Type	85
6.6 Water Quality	86
6.6.1 Water Quality Criteria.....	87
6.6.1.1 Drinking Water Quality.....	87
6.6.1.2 Agricultural Water Quality.....	87
6.7 Water supply to different consumers.....	91

6.7.1 Corrossivity Index.....	91
6.7.2 Langlier Index.....	92
6.8 Groundwater Quality Index (GWQI).....	93
6.9 Microbiological Analysis.....	93
CHAPTER –7 GROUNDWATER GEOPHYSICS.....	95
7.1 Introduction.....	95
7.2 Geo-electrical parameters.....	96
CHAPTER- 8 WATER RESOURCE IDENTIFICATION.....	102
8.1 Introduction.....	102
CHAPTER –9 CONCLUSION AND RECOMMENDATION	105
9.1 Conclusion.....	105
9.2 Recommendations.....	109
REFERENCES.....	108
ANNEXTURE -1.....	112
ANNEXTURE –2.....	115
ANNEXTURE –3.....	122
ANNEXTURE – 4.....	123

LIST OF FIGURES

Fig 4.1 Long term mean monthly rainfall variation.....27

Fig 4.2 Temporal variation of annual sum of rainfall on Axum station.....30

Fig 5.2 Semi logarithmic plot of Draw down versus time of Ew-1.....44

Fig 5.3 Semi losaritumic plot of drawdown versus time of EW-2.....45

Fig 5.4 Semi logarithmic plot of residual draw down versus ration t/t' of EW-2..... 45

Fig 5.5 Semi logarithmic plot of drawdown versus time of EW-3.....46

Fig 5.6 Semi logarithmic plot of residual drawdown versus ratio t/t' of EW-3..... 47

Fig 5.7 Semi logarithmic plot of drawdown versus time, EW-4 48

Fig 5.8 Semi logarithmic plot of drawdown versus time, EW-6..... 49

Fig 5.9 Semi logarithmic plot of residual drawdown versus ratio t/t' of EW-6.....50

Fig 6.1 Average values of major ions in different lithologies and streams..... 67

LIST OF TABLES

Table 4.1	mean monthly contributions of the mean annual rainfall.....	28
Table 4.2	Mean monthly Rainfall coefficient.....	29
Table 5.1	Summarized puming test results of analysis for 11reholes.....	51
Table 5.2		
Table 6.1	Average values and range of major ions from Basement complex	63
Table 6.2	Average values and range of major ions from basalt.....	64
Table 6.3	Average values and range of major ions from basalt and mudstone	64
Table 6.4	Average values and range of major ions from surface water.....	65
Table 6.5	Range of Total dissolved solids (TDS mg/l) in different lithologies and streams	69
Table 6.6	Range and Average Values of Total Hardness.....	71
Table 6.7	Range of EC in microS/cm in different lithologies and streams.....	73
Table 6.8	Wicox's classification for groundwater.....	73
Table 6.9	Average values of major cations (mg/l).....	75

Table 6.10	Average values of major anions (mg/l).....	77
Table 6.11	CAI ₁ and CAI ₂ Groundwater in the study area	80
Table 6.12	Schoeller's Groundwater Type of the study area	82
Table 6.13	Stuifand's Groundwater Main Type.....	83
Table 6.14	Groundwater types based on Alkalinity (After Stuyfzand).....	85
Table 6.15	Classification of water based on % Na.....	88
Table 6.16	Residual Sodium Carbonate Values of Groundwater	89
Table 6.17	Permeability Index classification of groundwater.....	90
Table 6.18	Table of Incrustation and Corrosion.....	92
Table 6.19	Table of Groundwater Quality Index.....	93

LIST OF MAPS

Map 1.1	Location map of Axum Area.....	5
Map 3.1	Geological Map of the study area	17
Map 3.2	Geological Cross section along AB & CD.....	18
Map 5.1	Hydrogeological Map of Axum area.....	36
Map 5.10	Map of Grid Deviation of water table (GDWT).....	56

Map	5.11	Contour Map of water level Above Mean Sea Level.....	57
Map	5.12	Contour Map of water Level Below Ground Level (WL BGL).....	58
Map	6.2	Contour map of TDS in the study area.	70
Map	6.3	Contour map of Ec in the study area.....	74
Map	6.4	Contour Map of IBE in the study area.....	80
Map	6.5	Map of Scoeller's Groundwater type.....	82
Map	6.6	Map of Stuyftand's Mainwater Type	84
Map	6.7	Map of Stuyftand's Subwater type	86
Map	6.8	Map of permeability Index class.....	91
Map	7.1	Geoelectrical T of the study area.	100
Map	7.2	Longitudinal conductance in the study area.....	101
Map	8.1	Location map of new proposed site.....	104

CHAPTER 1

INTRODUCTION

1.1 Back ground

For water supply of Axum town a number of studies had been conducted on Axum area. Preliminary hydrogeological reports were given by German water Engineering GmbH (1973), Devecon Engineers and Architects (1995), water supply and sanitation of the city of Axum by Denver people (2002), and others. A detail regional geology of Axum sheet (ND 37-6) at a scale of 1:250,000 was given by Ethiopian Geological Survey.

The first drilled borehole in Axum started in 1961 with the installation of three shallow wells and one deeper well belonging to the hospital. But these boreholes have no documents about their depth and lithological logs.

In 1973 based on the study of German water Engineering GmbH, six wells were drilled on a southeastern drainage stream that is on the reaches of the Gebru creek with a distance of about 1 to 8 km from the town. Due to poor water quality and quantity they were abandoned. Additional wells were drilled and installed in well field No1 that is 2 to 5 km south west of the town in 1992. But the demand of the municipality could not be satisfied by the 1992-drilled wells. So, additional boreholes sponsored by Tigray State government were drilled and completed between 1998 and 2000 at a cost of over 50 million Birr. But these bore holes except APW-2 all are nonfunctional due to very poor water quality. (Note, APW- 2 also has poor water quality but it has good yield and hence mixed with the other boreholes and distributed to the municipality). Surrounding the town there are also shallow wells drilled in deferent lithologies intended for rural water supply.

1.2 Objective

The general and specific objectives of this work are listed below

1.General

- To study and prepare a geological map of the area at a scale of 1:50,000
- Preparation of various types of water quality maps.
- Sample collection from different types of wells drilled in different lithologies.
- Chemical, bacteriological analysis of waters and discussion.

2. Specific

Since no detailed investigations have been done so far from the above said general objectives, the specific objections can be reached with out difficulty.

1.Ground water table maps (BGL, G DWT, A MSL); 2. D etermination o f major c hemical i ons, bacterial assemblies and preparation of thematic maps; 3 .Utility o f ground water; 4 . From the chemistry, preparation of: TDS: 2. Ec; 3. pH; 4. IBE (Index of Base Exchange); 5. Water type (Schoeller, Stuyfazand); 6. RSC (Residual Sodium Carbonate); 7. SAR (Sodium Adsorption Ratio); 8. PI (Permeability Index and Classes); 9. Ground water hardness; 10. Ground water salinity – sodium hazard; 11. Ground water facies (Stuyfazand); 12. Ground water quality index

1.3 Methodology:

To achieve the above objectives the following materials were used.

- Two topographic maps at a scale of 1:50,000
- Aerial photographs of three strips 15 in number, published in 1994.
- GPS (Garmin- X12) for locating water sampling points, to locate specific lithologies likes geological contacts, faults, etc

- Existing meteorological, geophysical, well log, pumping test data, water quality analysis data.
- Deep meter- for measuring static water levels in hand dug wells and shallow wells.

1.4 Work plan

For the fulfillment of the objectives listed above a schedule is arranged as follows

- July 20-29, 2003 literature review and collection of previous geological hydrogeological and water quality data is done.
- July 30 - August 15 2003 interpretation of aerial photos, existing geological and hydrogeological map is done.
- August 20 -September 10, 2003: First fieldwork is conducted. During this field work a geological map at a scale of 1:50,000 is produced, wells reservoirs are also located in a 1:50,000 scale map.
- February 20 up to March 28, 2004 second field work is done
During this fieldwork hydrogeological map at a scale of 1:50,000 is Produced,
- 13 samples for total chemical analysis and 12 samples for bacteriological/microbiological analysis are collected.
- Ground water level of hand dug wells and shallow wells were measured.

CHAPTER –2

GENERAL OVERVIEW OF THE STUDY AREA

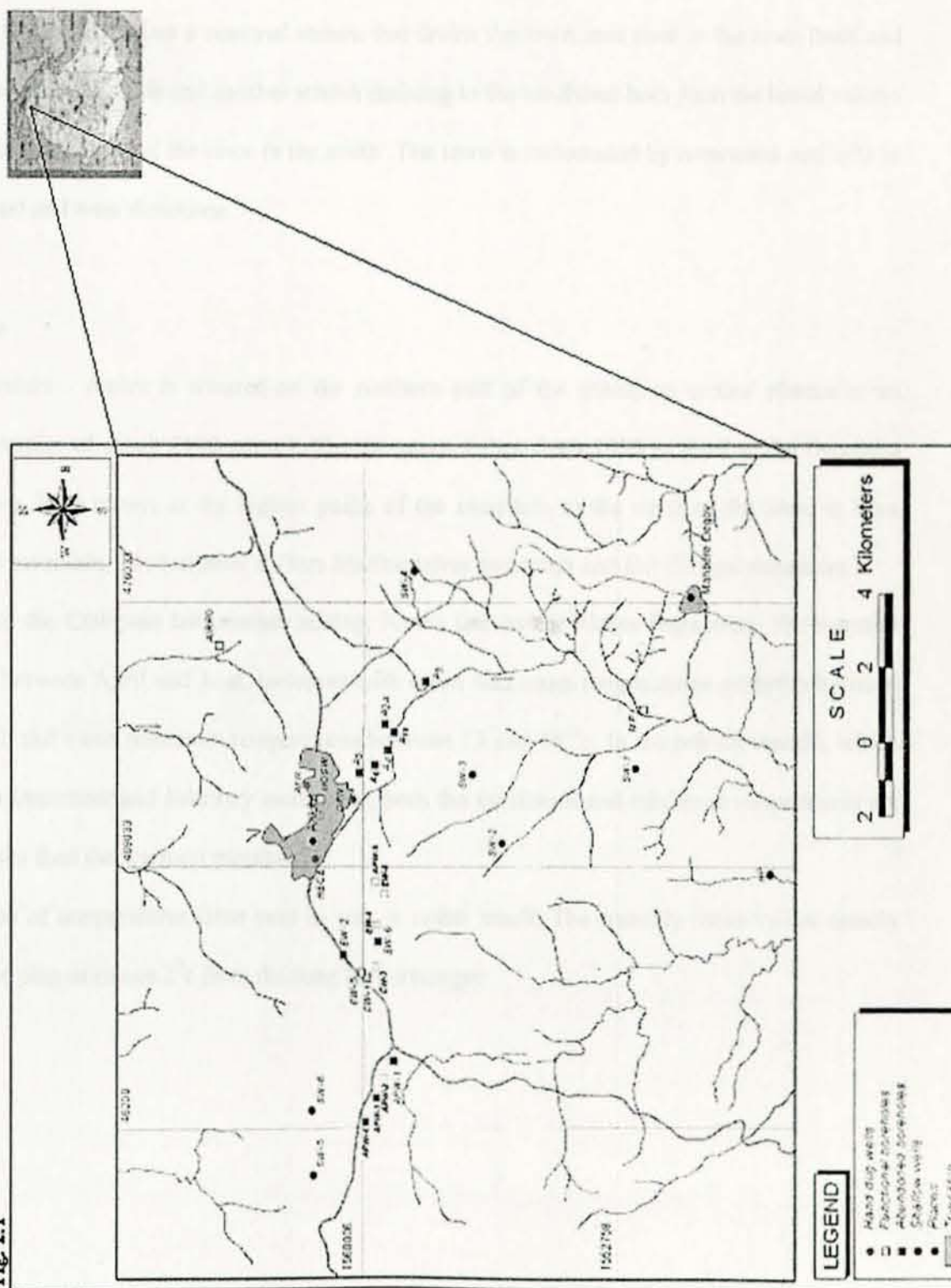
2.1 Location and Areal extent

The study area is found in Tigray region, central zone, which is situated about 1025 km north of Addis Ababa. It is located on UTM coordinates between 1547650-156700 N and 458000-480000E, Including Axum town and its surrounding areas with a total area of 425. 7 sq km.

Axum town is located on the narrow ridge that forms the divide between two major drainage systems, i.e. Tekeze River south of Axum town and Mereb River north of the Axum town.

LOCATION MAP OF AXUM AREA

Fig 2.1



2.2 Topography

The town is situated very near a divide between the watersheds draining to the north and those draining to the south. In fact a seasonal stream that drains the town area rises in the town itself and flows to the southeast. This and another stream draining to the southeast both form the broad valleys and plains in the fringes of the town to the south. The town is surrounded by mountains and hills in the north, east and west directions.

2.3 Climate

Air temperature - Axum is situated on the northern part of the Ethiopian central plateau at an average elevation of about 2100 a.m.s.l. The elevation varies from 1980 m amsl at the Dembeba gorge to over 2640 meters at the highest peaks of the mountain to the north of the town in Dura Mekdelawit mountain, 2440 m amsl at Dura Medhanialem mountain and Bet Giorgis mountains.

According to the Ethiopian temperature zoning, Axum lies on the Woina Dega zone. The warmest months are between April and June, inclusive with mean maximum temperatures generally between 28 and 30 °c and mean minimum temperatures between 13 and 15 °c. In the coldest months, which are between December and February inclusively, both the maximum and minimum temperatures are 3 to 5 °c lower than the warmest months.

The variation of temperatures from year to year is rather small. The monthly mean values usually range with in plus or minus 2°c from the long term averages

CHAPTER - 3

GEOLOGY

3.1 Regional Geology

The Tigray region comprises of wide range of geological formations. The underlying rocks of this region are of basement complex. These rocks are weakly metamorphosed (Mohr, 1962) and extremely folded and foliated. Little evidence remains of any succeeding Lower Paleozoic formations because erosion rather than deposition dominated at this time. During this era the surface of the Precambrian rocks of the shield were reduced to an extensive peneplain. After this period of erosion, detrital rocks, Permo Triassic in age, as well as limestones and marls, Mesozoic in age were deposited overlies the basement in clear unconformity. This series was later overlapped by Tertiary basalt flows. In the south and extreme north there are extensive outcrops of Tertiary basalts. Quaternary sediments are abundantly found in the western and southern parts of the region overlying mostly basement rocks and Tertiary volcanics, respectively.

3.1.1 Precambrian formations

The rocks are volcano-sedimentary successions associated with minor ultramafic bodies and intrusives ranging from mafic to granitic in composition. Though in many cases strongly folded and foliated, they have generally undergone only weak metamorphism being of green-schist facies, but locally reaching amphibolite facies. The most conspicuous foliation trend is N-S with deviations to NE and SW.

The Precambrian intrusive rocks are pre to syn-orogenic intrusive masses of diorite, tonalite, granodiorite and granites. These intrusions ranging from small stocks to batholiths do occur intruding into the low-grade volcano-sedimentary terrain of the region. In addition to these, meta-

ultramafic rocks, late-tectonic granites and post-tectonic granites are also found intruding the basement rocks.

The basement rocks outcrop dominantly in the western, central and in some parts of eastern Tigray.

3.1.2 Paleozoic formations

The Paleozoic rocks of Tigray region were described to be of two types (Dow et. al., 1971): the Enticho sandstone and the Edaga Arbi glacials.

The Enticho sandstone unconformably overlies the folded basement rocks. It is composed of white fine-grained sandstone cemented by calcareous materials. It is well bedded, cross bedded with slump structures. At places the sandstone becomes friable medium grained and well sorted. Polymictic conglomerate beds containing well- rounded pebbles, cobbles and boulders are encountered. The sandstones are usually rich in scattered erratic of granites and gneisses.

The Paleozoic formations, in general, outcrop dominantly in the central, central southern and eastern part of Tigray.

3.1.3 Mesozoic Formations

The majority of rocks represented by this era are calcareous and stratigraphically form the bottom to top the four main geological divisions Adigrat Formation, Antalo Formation, Agula Formation, and Amba Aradom formation. These formations are extensively found in the central, eastern and southern parts of the region. The Mesozoic Formations comprising mostly calcareous rocks are described as the " Mekelle outlier ".

3.1.3.1 The Adigrat Formation

The Adigrat formation, which varies in thickness from a few meters to 800 meter was originally named as Adigrat sandstone after Adigrat town in the eastern Tigray (Blanford, 1870),

unconformably on the Precambrian basement and overlain unconformably by the Antalo formation (Dow et. al., 1971; Garland, 1980). In some parts of the region this formation rests with slight disconformity on the late Paleozoic to early Mesozoic sedimentary rocks of Enticho sandstone and Edaga Arbi Glacials and is overlain by Antalo formation.

The Adigrat formation lies at the base of the Mesozoic sequence. It outcrops around the margins of the Mekelle outlier where it has been faulted up or where river incision has exposed it below the limestone complex. It also outcrops below the Tertiary basalts in the extreme north of the region.

3.1.3.2. The Antalo Formation

The Antalo formation was first named by Blanford (1873) at the type locality as Antalo limestone in the region, and later described in detail by Mohr (1963), Beyth (1971), Kazmin (1972 & 1978), Merla et. al., (1973) and Marla (1979).

The Adigrat Formation conformably passes to Antalo sequence of Jurassic age, which in turn is overlain by Agula group. The contact between Adigrat sandstone and Antalo sequence is transitional. These beds are of 20-30 m of shale with some calcarenites and sandstones intercalation (Basellini et. al. 1997)

The Antalo Formation is a 750 m thick sequence, which consists predominantly of fossiliferous yellow limestone containing thin beds of marl and calcareous shale, and occasionally arenaceous bands near the top.

In Mekelle area, it conformably overlies the Adigrat Formation and grades upward into Agula Formation (Garland, 1980). The marginal parts of the Mekelle outlier consists of sandy oolitic facies suggesting a near shore environment. While in the escarpment black limestone and shale indicated deeper water conditions of deposition.

3.1.3.3. Agula Formation

In Tigray region, in the Mekelle outlier and around the escarpment gray green and black shale, marl and claystone interlaminated with finely crystalline black limestone containing disseminated pyrite with some gastropods and brachiopods, previously named as Agula shale after Agula village, overlies the Antalo Formation (Arkin et al., 1971, Kasmin, 1975). The sequence, which is 60 to 250 m thick, contains some thin beds of gypsum and dolomite and a few beds of yellow coquina. Near Antalo village a 200 m thick unit of a correlatable red and greenish silty marl occurs. The Agula Formation is of late Jurassic age, and is of probably of lagoonal origin representing a regression phase of the Jurassic sea.

The Agula Formation occurs extensively in the central part of the Mekelle outlier. The unit as a whole is highly intruded and displaced by sills of the Mekele dolerite.

3.1.3.4. Amba Aradom formation

Amba Aradom Formation, formerly known as the upper sandstone (Mahadi, 1968; Beyth, 1971; Arkin et al., 1971; Kazmen, 1972 & 1975) consists of clay, silt, white to pink cross bedded sometimes lateritized sandstones and conglomerates accumulated in a fluvio-lacustrine depositional environment. It is cliff forming and the thickness reaches almost 150 m. In the region it lies unconformably on the Jurassic sediments (Mahadi, 1968; Greitzer, 1970; Kazmin, 1975)

In northern part of the Mekelle outlier, the formation consists of claystone and siltstone with interblended massive, sometimes cross-bedded, white to pink sandstone (Arkin et. al., 1971; Beyth, 1971). The rocks become progressively coarser in grain size southwards. Further south, on the southern rim of the outlier, the conglomerates and sandstones give way to fine grained sediments as the formation gain thickness. In most of the area, the formation is lateritized.

The Amba Aradom Formation is probably of late cretaceous age and represents a regressive facies of the cretaceous sea (Kazmin, 1975).

3.1.4. Cenozoic volcanic and sedimentary Rocks

The Tertiary volcanics are composed chiefly of deeply weathered alkaline and transitional basalt flows of Ashangi Formation, Aiba basalts, Alajae Formation and Tarmaber Gussa formation. They are well presented in the region and cover nearly 16 % of the total area of the Tigray region (Bureau of planning and economic Development, 1998, Atlas of Tigray). They are outcropping predominantly in the western, northern, central and southern parts of Tigray. They form elevated and main mountainous areas with very rugged topography where many higher peaks occur.

3.1.4.1. Ashangi Formation

The Ashangi Formation represents the earliest fissural flood basalt volcanism on the northwestern plateau. The basalt flows are several hundreds of meters to a kilometer thick of strongly weathered, crushed, tilted basalts, which lie below the major pre-Oligocene unconformity (Zanettin et al., 1980). The Ashangi Formation consists of predominantly mildly alkaline basalts with interbedded pyroclastics and rare rhyolites. The formation is commonly injected by dolerite sills, acidic dykes and gabbro-diabase intrusions.

The upper part of the Ashangi Formation is more tuffaceous, contains locustrine deposits including lignite seams, and acid volcanics, and locally overlies the older part of the group with angular unconformity. This formation probably has a Paleocene to Miocene age range (Kazmin, 1975).

3.1.4.2. The Aiba Basalts

The Aiba basalts represent the second major pulse of fissural basalt volcanism on the northwestern plateau.

They are typical transitional basalts, and uncomfortably overlie the Ashangi Formation and attain a thickness of 200 to 600m. The absolute age of the Aiba Basalt range from 34 to 28 Ma placing them in Oligocene (Zanettin et al., 1980; Kazmin, 1979).

3.1.4.3. Alajae Formation

The Aiba Basalts are generally followed by the Alajae Formation, represented by interlay red silicic rocks and transitional basalts, but sometimes only by silicic rocks, mostly slightly peralkaline rhyolites. This formation ranges in age between 36-13 Ma (kazmin, 1979; Zanettin et al., 1980). In the region, the Alajae Formation rests conformably on the Aiba Basalts.

3.1.4.4 Tarmaber Formation

In the northwestern plateau, the fissural Alajae volcanism was followed by Tarmaber central volcanism that built up large shield volcanoes decreasing in age from North to south. The change in volcanic regime is matched by a change in lava composition; no longer transitional basalts, but alkali basalts and basanites (Zanettin, 1993).

In the region Tarmaber central volcanism or Tarmaber Formation is represented by Tarmaber Gussa Formation. The name Tarmaber Gussa Formaation was given for the shield volcanoes of the northern Ethiopia plateaus with an absolute age range of 26 to 16 Ma (Kazmin, 1979)

In addition to the above mentioned volcanics, stratigraphically above them, trachytic and phonolitic plugs and associated lavas occur in the areas around Adwa and Axum. Tilting and up doming of the surrounding rocks is thought to have preceded the viscous emplacement of vertical-sided plugs.

As a consequence of extensive erosion during Cretaceous times, the Tertiary basalts, in general, overlie un-conformably the Jurassic Adigrat Formation. Even in some places they rest directly up on the Precambrian basement. The thickness varies from about 100m, west of Adigrat, to up to 3000 m in the south of the region (around Maychew).

In several areas the upper part of the basalt is weathered and near Axum this alteration that must have occurred during periods when tropical climatic conditions prevailed resulted in thick laterite soils of more than 10m. However the most common (recent) alteration of the top layer produced the black cotton soils (vertisols).

The oldest sediments found in the region are represented by the Danakil group. The name Danakil group (Red Series) was given to the oldest detrital formation that occur within the Danakil depression (Garland, 1972). The formation consists of several hundred meters of conglomerate, sand, sandstone and red, green or multicolored clays, with interbedded basaltic lavas and acidic intrusions with some marine beds locally present.

Sediments of the Danakil Group are outcropping only in the northeastern part of the region along the escarpments bordering to Afar. The Danakil Group lies unconformably on the Mesozoic limestone and sandstone or directly on the epi-metamorphic basement that constitute the foot of the Ethiopian escarpment and the Danakil Alps.

3.1.5 Quaternary sediments.

The youngest sediments are of Quaternary age. These sediments are outcropping in different parts of the region occupying flat lying areas forming lowlands.

Undifferentiated alluvial and lacustrine deposits.

These consist of sand, silt, clay, diatomite, limestone and beach sand. These continental deposits spread out in alluvial plains and are abundantly found in the western and southern lowlands overlying mostly the low-grade metamorphic rocks and Tertiary volcanic, respectively.

Holocene sediments are undifferentiated alluvial, lacustrine and beach sediments. These sediments are found in the southern parts of the region occupying lowlands along the Raya valley. The total thickness of these sediments is between 60 and 160m at different places.

Pleistocene. These are Quaternary undifferentiated alluvial, lacustrine and marine sediments. They are found in the northern part of the region bordering to Eritrea. These sediments are consists of conglomerate sand clay reef, limestone, marl land gypsum.

3.2 Local geology

The study area that has a total area extent of 426.8 sq. km covers the Axum town area and its surroundings. It is covered by four major lithologies. The majority part of the study area is covered by Tertiary basaltic flows that account 61% and a total area of 260.3sq km. The basement complex occupies most part of the southern part and covers 13% and 35.5sq.km areas of the study area. The Mesozoic sedimentary formation mostly covered by tertiary basaltic flows and black cotton soil

developed from weathered basalts. The clearly exposed out crop covers 11% of the study area with 46.9 sq km areas coverage. The trachyte and phonolite plugs cover the minor portion of the study area restricted to north central and northwestern part occupying 9% and 7% respectively

A long the streams and small creeks a thin (mostly less than 3m thickness) alluvial sediments that are silty clay to sand are developed. Due to insitu weathering and alteration of top part of basaltic flows a black cotton soil that crack during dry season covers most of plateau of the study area above the basalt. It is rich in clay and the thickness ranges between 3 to 9 meters. Due to weathering of the basement complex, thin cover of soil (regolith) developed above the out crop but in most part of the study area the rocks are exposed with no soil cover due to extensive erosion of the soil by running water. Due to their shallow thickness and limited area extent of the unconsolidated sediments of the study area, they are not mappable on the scale provided.

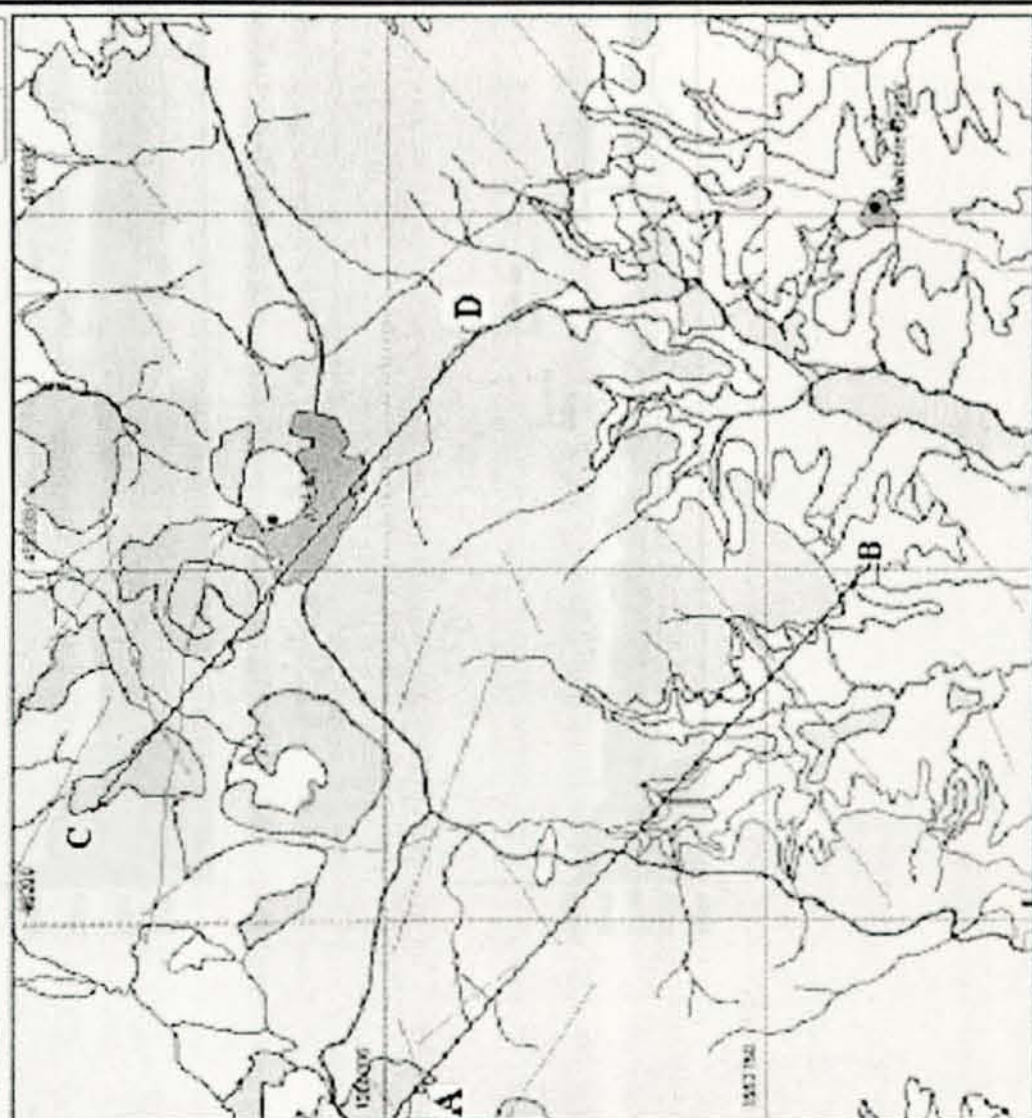
Generally the study area is covered by four major lithologies namely from older to the younger formations

1. Basement complex
2. Mesozoic sedimentary rocks
3. Basaltic rocks
4. Trachyte and Phonolite plugs

Their lithology, their distribution with in the study area is given below.

GEOLOGICAL MAP OF THE AXUM AREA

Fig. 3.1



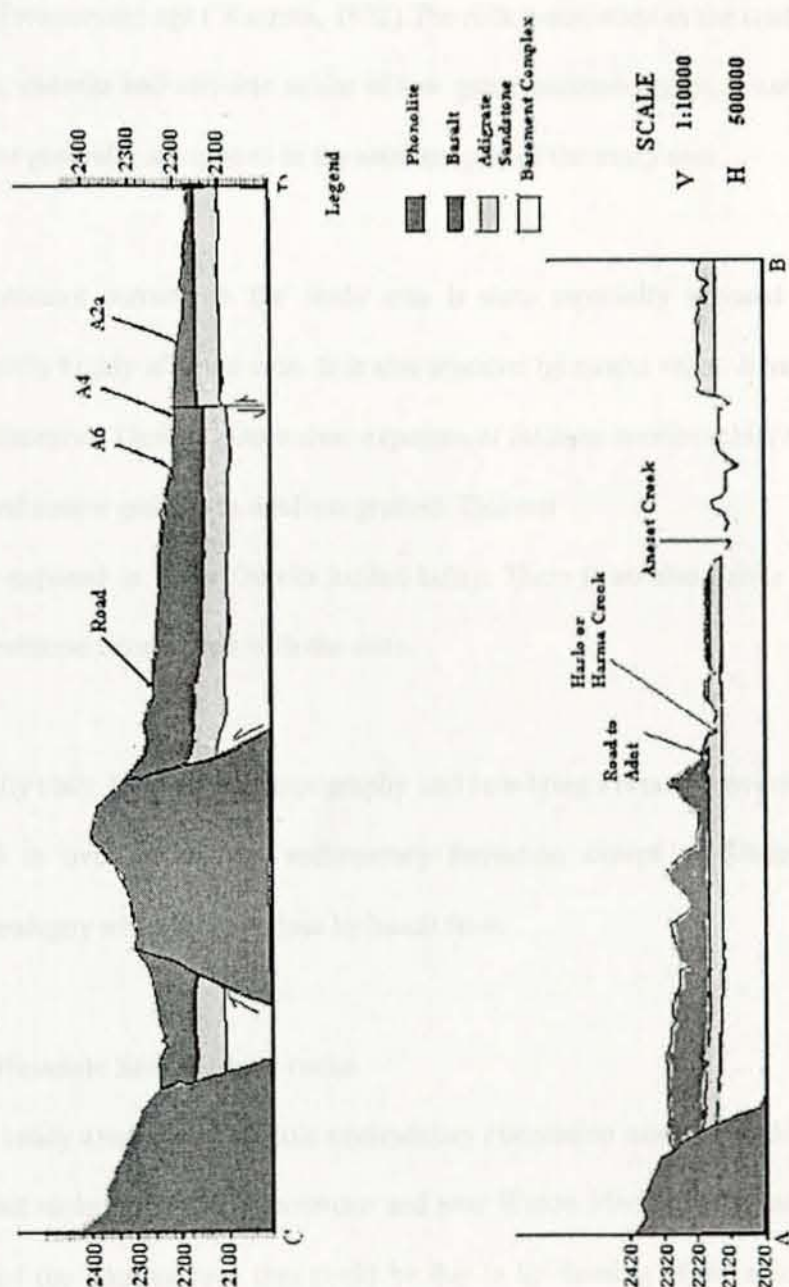
LEGEND

- Places
- ▨ Township
- Dry weather road
- All Weather Roads
- ~ Major Streams
- Geology
- Lineaments
- ▨ Basament Complex
- ▨ Adigrare Sandstone
- ▨ Basalt
- ▨ Phonolite
- ▨ Trachyt

SCALE

2 0 2 4 Kiloms

FIG. 3.2 Geological Cross section along CD & AB



3.2.1 Basement complex

The metamorphic rocks of northern Ethiopia including the Axum area belong to the Precambrian (upper Proterozoic) age (Kazmin, 1972). The rock association in the study area is composed of slate, phyllite, chlorite and sericitic schist of low grade metamorphism. It covers 13% of the study area. This unit generally is exposed in the southern part of the study area.

The dominant outcrop in the study area is slate especially exposed on Tabia Zehay and it is tectonically highly affected area. It is also smeared by quartz veins. It has a general trend of NE-SW strike direction. There is also a clear exposure of feldspar sericite schist that has a light gray to white color and coarse grained-to medium grained. This outcrop is exposed in Tabia Dereka kushet kuhiy. There is an also minor outcrop of metapyroclastic, metasandstone intercalated with the slate.

Generally they form rugged topography and low-lying areas. In most part of the study area this outcrop is overlain by the sedimentary formation except in Sinke river i.e. North west of Mahberedegoy where's is overlain by basalt flow.

3.2.2. Mesozoic Sedimentary rocks

In the study area, the Mesozoic sedimentary succession unconformably overlies the Precambrian basement rocks but in Dura mountain and near Wukro Mary this formation occurs at the top of and flanks of the alkaline lava that could be due to up doming of the acidic viscous lava. They have variable thickness and rock types but are the eastern extension of the Adigrat sandstone.

This unit occupies 11% of the study area in the south central, southeastern and minor exposure in the northern parts and forms a plain topography.

The major part of the Mesozoic sedimentary rocks is covered by overlying Tertiary volcanics. So exposure is limited to southcentral and southeastern part of the study area. At places river cut also expose it.

The distinct features of the sedimentary rocks in the study area are lateral and vertical variations both in thickness and sediment type. From borehole logs and field observation the thickest section in the study area is exposed in the southeastern around Mahbere degoy village that attains an average thickness greater than 80 m and decreases westward in the Haselo creek (Tributary of Harma creek) and attain a thickness below 60m.

Based on the thickness and dominant sediment type two types of sedimentary formation occurs in the study area though they are mapped and named altogether Adigrat sandstone

1. Siltstone (mudstone?) dominated and intercalated with sandstone
2. Sandstone dominated and intercalated with siltstone.

The siltstone (mudstone?) dominated outcrop is exposed south central and southwestern part of the study area and the thickness of the whole section is below 60 m. The siltstone (mudstone?) beds are soft, friable, thinly laminated reddish brown or whitish color and form gently slopping topography where as the sandstone is a cliff forming.

To the southwest of the study area in Harma creeks this formation is interbedded with thin (50cm) limestone bed.

The sandstone-dominated outcrop is exposed in the southeastern part of the study area covers most part of Mahbere Degoy area. It has an average thickness of 80 m and the sandstone is thickly bedded reddish brown at lower parts, upwards it is cross bedded, well sorted and rounded and it is quartzitic sandstone. It is interbedded with thin layers of laminated siltstone.

Generally at the base of the sedimentary formation there is a thin layers of (less than 4m) polymictic conglomerate. But at the northern part of the study area the conglomerate occur above the sandstone-siltstone intercalation.

3.2.3. Basalt rocks

According to the geological map of Ethiopia and Somalia (Marla et. al, 1973), the Northern Tigray basaltic rocks belong to Amba Aiba basalts of Oligocene to Miocene age. Thin basaltic flows cover most part of the study area and thick succession of stratified basaltic unit is developed along the ridges that generally run north-south direction west of Adet road. The maximum thickness of the basaltic pile in the study area is 400 m in Ferasit ridge south west of the study area. There are also isolated hills, eg Dereka ridge, Hankera ridge; that form parts of the stratified volcanic succession of the study area. It occupies 61% of the study area.

The stratified basaltic rock is characterized by textural and compositional variation along with the presence of horizons of thin red paleo-soils with in the succession. This suggests that there has been successive lava flows separated by considerably time gap.

The basaltic rocks rest unconformable over the Mesozoic sedimentary strata. But at some places; example 3 km west of Mahberedegoy village along the Sinke River the basaltic rock rests over angular unconformity on the Precambrian basement rocks.

In most part of the study area the basalt flow is massive, aphanitic to phyric basalt but highly jointed and it is enveloped by amygdaloidal and vesicular basalt. The amygdaloidal basalt is filled with calcite, silica and some (minor) zeolites. In some localities example on the road to Shire the basalt is scoraceous with layers of massive fractured basalt. In the upper succession of the layer the massive basalt is affected by vertical and columnar joints. Spheroidal weathering is common in the basalts of the study area.

Generally the basaltic rock in the study area is highly fractured and extensively weathered though the degree and depth of weathering varies from place to place.

In between layers of the basaltic flow there are thin red palieo-soils that indicate there had been a time lag between successive layers of the basaltic flows.

3.2.4. Trachyte and phonolite plugs

In the study area, stratigraphic positions and crosscutting relationships show that they are the youngest volcanic rocks in the area overlying the Amba Aiba basalts.

They **form** an independently standing **irregular** to sub-circular highly elevated bodies. Their evolution **is** related to tilting and **up doming** of the surrounding rocks is thought to have preceded the viscous **emplacement** of vertical sided **plugs** (Kazmin, 1975).

3.2.4.1 Trachyte plugs

They **occupy** the northwestern part, **9% of the** study area, and occur as independent irregular dome shaped **bodies** forming a highly elevated **area**.

The **fresh** outcrop of the rock is **relatively hard**, compact and massive. It is medium to fine grained light **gray** color irregular, jointing **horizontal** exfoliation is common, up on weathering it tends to be soft, **white** that is changed to kaolin.

Generally the outcrop in the study **area is slightly** weathered, hard and compact with irregular joints.

3.2.4.2 Phonolite plugs

In the study area they appear as **independent**, sub circular dome shaped bodies risen above the plateau. **Occupies** 7% in the North **central and** Northwestern part of the study area. In Dura and Bet Georgis **mountains** basalt and sandstone **the doming** of the phonolite to a higher elevation pushes up beds. **Wide-open** vertical joints and **extensive** spheroidal weathering (changed to white to light-red colored **soil**) are the characteristic of **the rock**. They occur as big blocks floated above the basalt flow **due to** wide-open joints and **spheroidal** weathering departed from the main mass of cliff forming **plugs**.

The rock is coarse grained; pale gray to pale green color with unevenly distributed dark rounded shining mafic minerals and light pinkish to white felsic minerals.

Generally the rock in the study area is highly dissected by joints and extensively weathered. It is highly susceptible to weathering and fracturing when it is exposed to water as it is seen in the field that where the course of water passing through, it is highly distorted and etched out crop.

3.3 Structure

The next discussion on the structure of the study area is mainly based on aerial photo interpretation and field investigation in the study area.

The basement complex of the study area has undergone only slight metamorphism being of greenschist facies. The most prominent foliation trend in the slate, phyllite and schistose rocks is NE-SW direction. This coincides with foliation trend of the regional structure. From aerial photo interpretation fault lines and lineaments in the basement complex have also a North Eastern-South Western trend. In the Sinke River, northwest of Mahberedegoy the basaltic flow that rests on angular unconformity of over the basement complex follow a trend that runs North east - South west direction. This may be due to the regional structure that allow for the basalt to fill the weak zone of the basement complex.

The dominant fault lines and lineaments in the study area have north west - south east orientation and are located along and on the periphery of the trachyte and phonolite plugs. Most probably this may be related with the updoming of the viscous lava. Sandstone and basaltic beds are up trusted to

a higher elevation due to the up doming of the plugs. There are also some faults and lineaments trending in the East-West, North east - South west and North-South direction.

The trachyte and phonolite plugs show flow structures, wide and deep linear joints and concentric exfoliations.

The Mesozoic sedimentary rocks occurring to the south central and southeaster show fracturing and jointing besides their primary sedimentary structures like bedding, cross bedding etc.

The volcanic rocks (the basaltic rock) especially which outcrop south west of Axum town are highly fractured and extensively weathered and columnar jointing is common in the upper succession of the basalt flow. But most of the fractures are filled with secondary minerals.

CHAPTER -4

HYDROMETEOROLOGY

4.1 General.

In the study area the available hydrometeorological data are only air temperature and rainfall obtained from National meteorological service agency (NMSA). Due to absence of the other hydrometeorological variables and the main target of the study is hydrogeochemistry of the study area; only a brief explanation is given below based on the available data

4.2 Precipitation.

It is defined as the total amount of water falling from the atmosphere in the form of rain snow, mist etc on the earth. It is measured in form of depth of water occurred on horizontal land surface due to precipitation in a particular day, month or year (R. Suresh, 1997)

From the viewpoint of rainfall climatology, the study area lies between the tropical zone and the sub-tropical high-pressure belt. Thus the area is affected at least part of the year by the latitudinal oscillation of the inter-tropical convergence zone (ITCZ)

In the period between October and January, the northeastern continental air streams have dominant influence on climate. They are controlled by the extensive North African high-pressure zone. This cool air stream of desert origin produces the dry season.

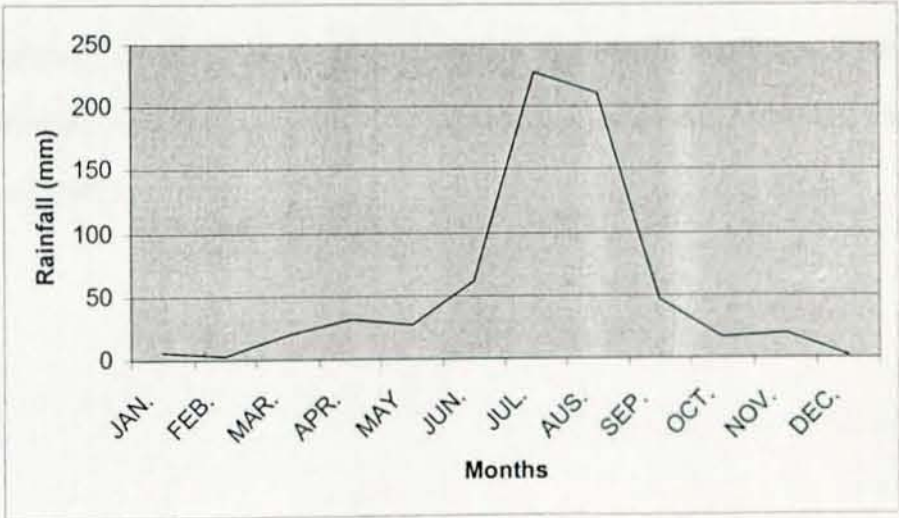
In the period between March and May, the ITCZ returns to the northern hemisphere, and rainfall accompanies the fronts entering with equatorial air. From May on wards the North African high-pressure consolidates and control the northward movement of the ITCZ. This produces a small

decrease in precipitation. At the beginning of the main rainy season in June the ITCZ again begins to move to the north and becomes active. The southwestern air streams extend over the area and often produce heavy rains. This weather type lasts until the northeastern continental air stream is re-established.

4.2.1 Availability of Data.

Within the study area one meteorological station is found in Axum town. The rainfall data from this station is not continuous and it is short period data. About 15 years of precipitation records are available from this station. The data are collected on monthly basis used to see the pattern and variability of rainfall in the study area. The long term mean monthly rainfall variation at the study area can be seen by plotting Rainfall verses Months of the year.

Fig.4.1 Long-term mean monthly rainfall variation



July and August with mean precipitation amounts of 228 mm and 211 mm respectively. Their combined share of the mean annual precipitation is as high as 65 percent. The mean monthly

contribution of the mean annual rainfall is given below (Table 4.1). When missing monthly values are substituted by the monthly means the annual precipitation in Axum averages to 672 mm.

Table 4.1 Mean Monthly contribution of the mean annual rainfall

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean rainfall in mm	6.5	3.3	19.7	31.3	26.7	61.3	227.5	211.	47.4	16.5	19.2	1.3
% contribution	0.97	0.5	2.93	4.66	3.97	9.12	33.86	31.4	7.05	2.46	2.86	0.19

4.2.2 Seasonality of Rainfall

The areal pattern of the seasonality of rainfall in the study area is determined by analyzing mean monthly rainfall data for the station. To compare the monthly distribution and to identify dry and rainy seasons, "rainfall coefficient was employed. The rainfall coefficient is computed by dividing mean monthly rainfall to one twelve of the annual mean rainfall (UNFAO, 1985 cited in Daniel Gemechu, 1977).

Table 4.2 Mean monthly designation (* D-Dry, R- Rainy)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean rainfall in mm	6.5	3.3	19.7	31.3	26.7	61.3	227.5	211.2	47.4	16.5	19.2	1.3
Coefficient	0.12	0.06	0.35	0.56	0.48	1.09	4.06	3.77	0.85	0.29	0.34	0.02
Designation*	D	D	D	R	D	R	R	R	R	D	D	D

From the above table (Table 4.2), 86.13% of the mean annual rainfall occurs during the five months of rainy period and the remaining 13.87% occurs during the seven months of dry period.

The small rains are in April and September at the beginning and the end of the rainy season. These account for 11.71% of the annual rainfall and 13.6% of the rains that occur in the rainy period. The big rains with moderate and very high concentration occurs from June to August that account 74.41% of the mean annual rainfall and 86.4% of the big rains occur in June and 87.74% occurs in July and August with high concentration. The big rains in these two months accounts 65.29% of the mean annual rainfall.

4.2.3 Variability of Rainfall.

From the fig below the precipitation record show annual variation on the study area

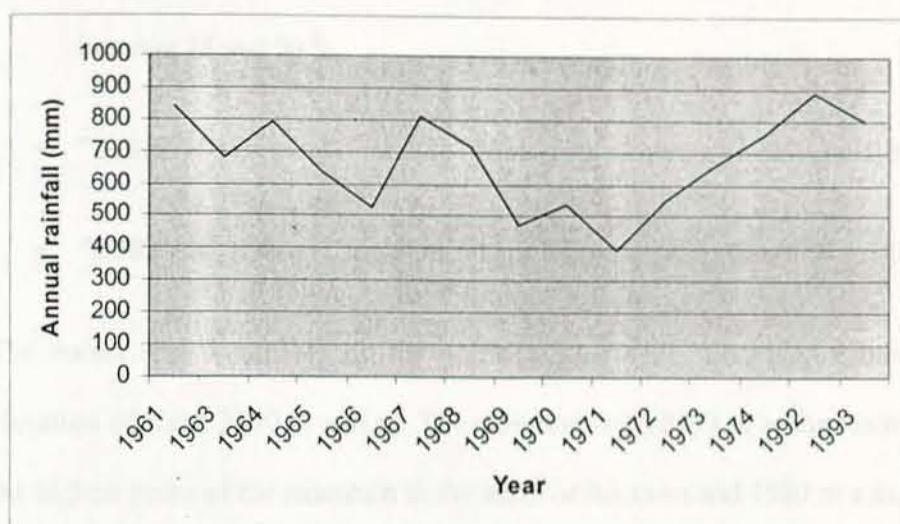


Fig.4.2 Temporal variation of annual sum rainfall on Axum station

4.3 Air temperature.

It has been observed that in general in Ethiopia the average annual temperature decreases with an increase in altitude (Tesfaye Chernet, 1989). On basis of this, five traditional temperature or climatic zones are differentiated in a description presented by the Ethiopian Mapping Agency (1981), in the National Atlas of Ethiopian, p 14 . The description taken from the atlas is given below and next to each traditional name for the temperature zone, the English equivalent is written in brackets as suggested in another source by Daniel Gamechu (1977).

- " KuR" (Alpine), 3300m and above. The mean anural temperature is 10 ⁰c or less.
- " Dega" (Temperate), 2300m to about 3300m. The mean annual temperature is between 10 and 15⁰c

- "WEINA DEGA" (subtropical), 1 500m, to about 2300m. The mean annual temperature is between 15 and 20 °c
- " KOLLA" (Tropical), 500m to about 1500. Hot temperature about 30 °c
- "BEREHA" (Desert), less than 500 m. Very hot temperature 30 to 40°c

The Axum area is situated on the northern part of the Ethiopian central plateau at an average elevation of about 2100 m a.m.s.l. The elevation from 2100 m at the town center to over 2400m at the highest peaks of the mountain to the north of the town and 1980 m a.m.s.l. at Harma creek, west of Dembaba Mikael church.

According to the Ethiopian temperature zoning, Axum lies in the woina Dega Zone. At Axum station, the mean annual temperature is 19.4°c, and the yearly average maximum and minimum temperature is 27.0 and 11.7°c respectively. The annual range of temperature is 3.4°c. The warmest months are between December and February inclusively.

The variation of temperature from year to year is rather small; the monthly mean value usually ranges within plus or minus 2°c from the longterm averages.

4.4 Evapotranspiration

In the available data solar radiation and the no. of hrs of bright sunshine in a day are missing or not measured. With the available scanty meteorological data, an attempt could be made to assess approximately the evapotranspiration using Thornthwaite, Turc and Langbein formulae.

CHAPTER-5

HYDROGEOLOGY

5.1 Introduction

Hydrogeology in general encompasses the link between various geological materials with water. In its intent, it deals with the movement, chemistry, origin, storage and aquifer hydraulic characteristics of the subsurface material. The groundwater body receives rainwater or snowmelt that has percolated through the unsaturated zone. The total storage potential is governed by the thickness and extent of the aquifers and by its porosity (Fetter, 1994).

A formation, part of formation or group of formations that contains sufficient saturated permeability material to yield significant quantity of water to wells or springs is called an aquifer. An aquifer can be made up of a single formation or group of formations. Some aquifers may only consist of units of varying lithologies and ages. Generally an aquifer is characterized in a given geological stratum on its volume in relation to the amount of water that are being extracted, its porosity intern which depends on the nature of the geological material, the dominant grain size, degree of sorting and packing, degree of weathering, fracturing and faulting and its readiness to easy movement of water to wards a well.

5.2 Hydrostratigraphic units

A hydrostratigraphic unit is a body of rock or sediment that has hydrogeologic characteristics that make it distinct from surrounding bodies or sediment. One critical characteristic of hydrostratigraphic units is that their boundaries are not necessary the same as formation boundaries. The primary characteristic that defines a hydrostratigraphic unit is hydraulic conductivity. The

boundary of a hydrostratigraphic unit separates a unit with high hydraulic conductivity from a unit with low hydraulic conductivity. Based on qualitative borehole data that are scarce and mainly concentrated on the basalt, geological log of boreholes and field observation; four types of hydrostratigraphic units are found in the study area.

1. Metamorphic Rock; 2. Adigrat Formation; 3. Basalt; 4. Adwa Formation

5.2.1 Metamorphic Rock

Solid pieces of fresh metamorphic rock have porosity of less than 3 percent and most commonly less than 1 percent. The few pores that are present are small and generally are not interconnected. As a result permeability is so small that they can be regarded as zero in almost all practical problems. Appreciable porosity and permeability however, are developed through fracturing and weathering of the rock. Fractures that are not associated with pronounced faults produce only a small increase in the overall porosity of the rocks (Davis and Dewiest, 1991).

The weathered layer (regolith) and fractures are the main source of ground water in the study area. The weathered layer developed on the metamorphic rocks is an important source of groundwater, especially for rural water supply in the study area. But the weathered zone is largely clayey material resulting in a low productivity aquifer that is indicated by low yield hand dug and shallow wells. It is also seen that most of the weathered materials is removed by runoff and the rock is exposed barely in most part of the study area. The main controlling factor in the study area is fracturing of the metamorphic rock. This results in a secondary porosity and permeability of the rocks that make the rock good for water supply purpose especially for rural water supply. Fractures occur more frequently near the ground surface but become rare with depth as revealed from boreholes. Fractures tend to close at depth because of vertical and lateral stresses imposed by overburden load. Therefore,

the yield of wells in the fractured rock reservoir decreases with increasing depth. Differences in well yields tend to reflect differences in degree of weathering or fracturing rather than inherent differences of mineralogy of fabric within the rocks.

5.2.2 Adigrat Formation

This unit occupies 11% of the study area in the south central, south eastern and minor exposure in the northern part, and forms a plain topography.

The distinct features of the Adigrat formation in the study area are lateral and vertical variations both in thickness and sediment type. Based on the thickness, dominant sediment type, hydraulic property and water quality; two types of sub formations occur in the study area that are Siltstone (mudstone?) intercalated with sandstone and Sandstone intercalated with siltstone (mudstone?).

5.2.2.1 Siltstone (mudstone?) intercalated with sandstone.

This out crop is exposed west of Sinke River, and these beds are soft, friable, thinly laminated reddish brown or whitish color and form gently slopping topography and it is intercalated with sandstone that is cliff forming.

Most fine-grained detrital rocks have relatively high porosities but very low permeability. Most commonly the fine-grained rocks will be barriers to the movement of water and the rock serve as widespread confining bed, but significant amount of movement may take place. Fracturing and faulting of these rocks may yield a few gallons of water per minute to wells (Davis and Dewiest, 1991).

In the study area most of the boreholes (mainly penetrate this formation) have a very low yield that is below 2 l/s yield.

Boreholes A₃, A_{2a} and A_{1a} are drilled mainly in this formation and have a safe yield of 1.25, 2 and 1.9 l/s respectively. These boreholes are also known for their exceptional water quality that is not potable and useful for domestic purposes.

5.2.2.2 Sandstone Intercalated with Siltstone

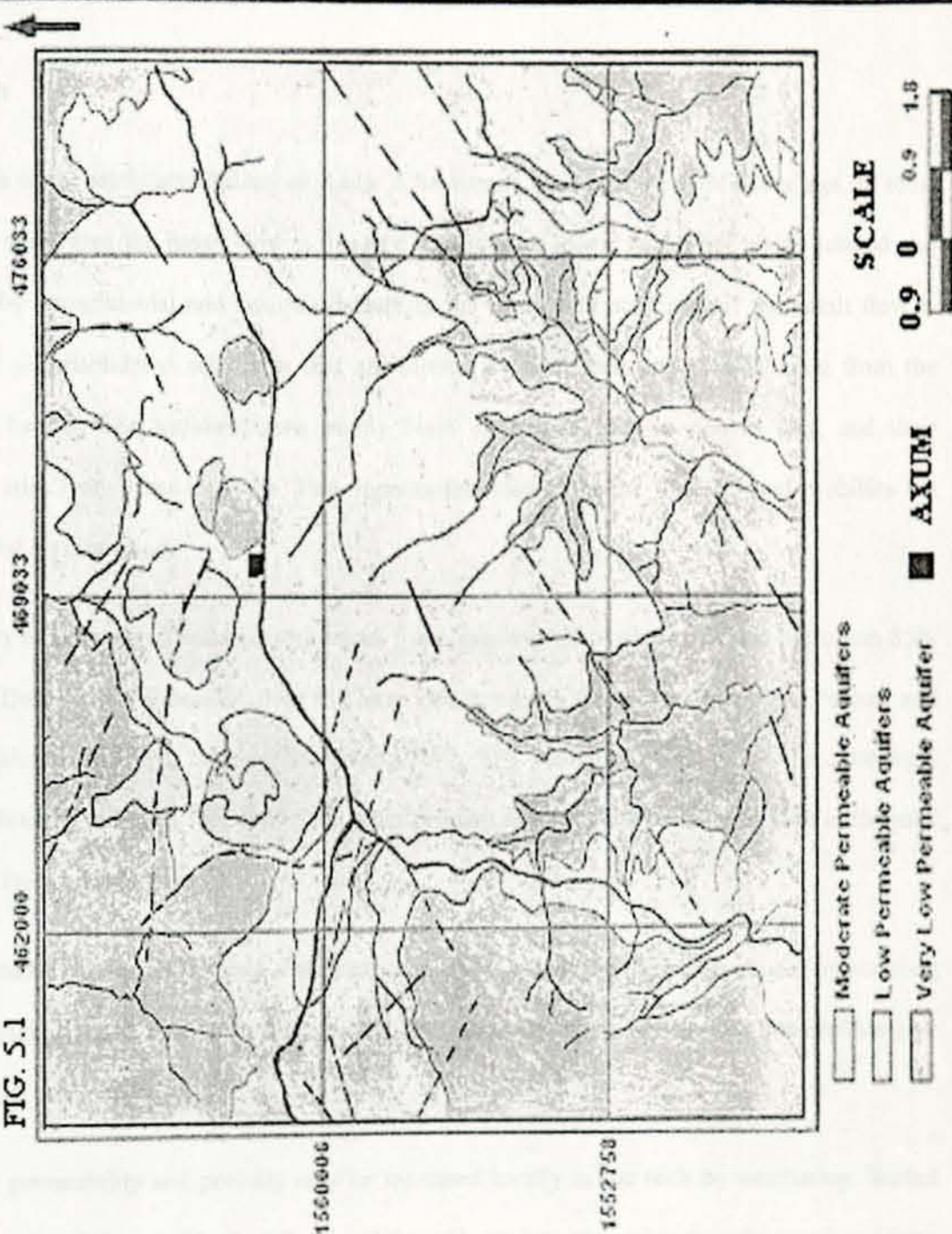
This is a common type of Adigrat formation that is exposed also out of the study area. In the study area it is exposed in the southeastern part and covers most part of Mahbere Degoy area. This formation comprises sandstone with minor lens of siltstone and basal conglomerates. It is fine to medium grained, rounded, well sorted and cross-bedded. At places it also shows deep vertical joints.

The assessment of permeability and productivity of this formation is based on previous studies out of the study area and field observation due to unavailability of both lithological logs and pumping test data in the study area.

Accordingly, this formation has a moderate permeability and productivity and this is the result of the limited intercalation, bedding planes and the deep vertical jointing. Its lack of high degree of permeability and productivity is a result of the grain size and degree of cementation.

HYDROGEOLOGICAL MAP OF AXUM AREA

FIG. 5.1



5.2.3 Basalt

The basalts of the study area belong to Amba Aiba basalts of Oligocene to Miocene age. In most part of the study area the basalt flow is massive, aphanitic to phyrlic basalt but highly jointed and enveloped by amygdaloidal and vesicular basalt. In the study area most part of the basalt flow is covered by unconsolidated sediments that are formed by the processes of weathering from the underlying basalts. The sediments are mainly black cotton soil that is rich in clay, and their thickness varies from place to place. This impermeable clay clogs the fractures and prohibits the infiltration of surface water.

The porosity of unfractured volcanic rock varies from less than 1% in dense basalt to more than 85% in pumice. Dense massive basaltic flow will have values ranging from 1 to 10 percent. Porous, and vesicular volcanic rock will have values ranging 10 to 50%. Although Porosity may be quite high, the permeability is largely a function of the other primary and secondary structures with in the rock (Davis and Dewiest, 1991).

Joints caused by cooling, lava tubes, vesicles that intersect, tree molds, fractures caused by buckling of partly congealed lava, and voids left between successive flows are some of the features that give basalt its high permeability.

In addition permeability and porosity may be increased locally in the rock by weathering. Buried soils are common features of layered flows and the soils are less permeable than the basalt and form perched water. Sediments interbedded with basalt flows will act as a confining bed and storage space for water that will greatly increase the average porosity of the whole rock

The basalts of the study area have developed good permeability due to primary porosity and secondary porosity created by weathering and fracturing. High productive boreholes in the study area are located in this formation though low yield also encountered where the degree of weathering and fracturing is less and the basalt is massive.

In the study area the productivity of the basaltic aquifers is limited by the fact that they form a morphologically elevated area and mostly water divides or recharge areas.

5.2.4 Adwa Formation

The Adwa formation comprises of the alkaline phonolitic and trachytic composition. They form an independently standing irregular to sub circular highly elevated plugs.

The trachyte is relatively hard, compact and massive with irregular jointing creating a zone of runoff rather than infiltration. In the study area it has also low permeability and porosity based on field observation. Whereas the phonolite is highly dissected by joints extensively weathered and coarse grained. It is highly susceptible to weathering and fracturing when it is exposed to the chemical action of water as it is seen in the field that the streams are deeply cut and they are rare. The phonolite plugs form a zone of infiltration and are recharge area of the well fields in the study area. Due to the extensive weathering and fracturing the phonolite has a high water transmission capacity but with negligible storage capacity.

In general the Adwa formation has negligible ground water potential due to the land it forms, steep slopes, small recharge area, lack of significant porosity and very low permeability of massive trachytes.

5.3 Structural effect

Fracturing of any rock increases the volume of voids in the parent rock. The voids due to fractures give rise to secondary porosity. Fractures (unless filled with cementing material) facilitate the flow of the water through the rock. Furthermore, compared with a porous medium, a fractured medium offers relatively less resistance to water movement because the water molecules are not subject to barriers within the fracture. (Sen, 1995).

In the study area the water bearing capacity of the crystalline rocks depends almost entirely on the secondary porosity and permeability that develops as a result of fracturing.

The basement complex of the study area has undergone only slight metamorphism. From aerial photo interpretation fault lines and lineaments in the basement complex have North easterly-Southwesterly trend that coincides with regional foliation trend. The weak zone planes created by foliation will make water to circulate easily and transmissivity is higher than massive basement rock. Besides, weathering also increases the storativity of the foliated rock.

In the Mesozoic sedimentary rock terrains of the study area the fractures, joints and karstic features impart an enhanced capability for ground water occurrence and flow.

In the study area the basaltic rock possess fractures creating a secondary porosity and permeability that facilitate storage and movement of ground water through them.

The alkaline plugs of the Adwa Formation show flow structures, jointing and due to the doming of these plugs numerous fault lines and lineaments are created. These discontinuities facilitate the flow of water through this formation.

5.4 Aquifer Hydraulic characteristics

In evaluating the ground water potential of an area or a basin it is important to know the hydraulic parameters of the aquifer of the basin. Hydraulic Parameters are physical characteristics of an aquifer that control ground water flow and storage.

The transmissivity and storage coefficients are especially important because they define the hydraulic characteristics of a water-bearing formation. The coefficient of transmissivity indicates how much will move through the formation and the coefficient of storage indicates how much water can be removed by pumping or draining. Knowing these parameters of an aquifer will help to determine drawdown on the aquifer at various distances from pumping wells, drawdown in a well at any time after pumping starts, interference of wells within the aquifer, to know the long term yield capability of the aquifer, to know the effect of the proposed pumping scheme on regional water level etc.

To determine the hydraulic characteristics of an aquifer two common methods can be applied. These are laboratory testing and field-testing. The field method that is conducted using pumping test, is the most commonly used and can predict the actual behavior of an aquifer.

The principle of pumping test is that if we pump water from a well and measure the discharge of the well and the drawdown in the well and in the piezometers at known distances from the well, we can substitute these measurements into an appropriate well-flow equation and can calculate the hydraulic characteristics of the aquifer (kruseman & De Ridder, 1983).

METHODS: To determine the aquifer hydraulic characteristics of the study area pumping test data are used. A total of 11 borehole data are collected and analyzed (annex). Seven boreholes with constant discharge data are analyzed using Cooper and Jacob method and their recovery data is analyzed using Theis & Jacob method. One borehole (EW1) has only constant discharge data. The

remaining three boreholes have a variable discharge data and are analyzed using stepwise pumping Cooper & Jacob method.

All of the 11 analyzed data are mainly from the basalt aquifer. In order to characterize the hydraulic characteristics of the other lithologies in the study area pumping test results are taken from boreholes drilled in Adwa town nearly 22 Km from Axum, which have similar geological setting as the study area.

In the study area due to the unavailability of the piezometer data, the pumping and recovery analysis have been performed with the pumping borehole data.

Results and discussions are given below for the different lithologies in the study area.

5.4.1 Hydraulic characteristics of the Precambrian rocks.

The Precambrian rocks are outcropping in the south central part of the study area. Extent of weathering and fracturing characterize their hydraulic properties. There is no a pumping test data in this lithology in the study area. But out of the study area, around Adwa town (which have similar geological setting as the study area and it is 22 km from Axum) there are 3 boreholes drilled in Precambrian rocks. The pumping test data of these wells were analyzed by water well Drilling Agency (1993) who conducted the drilling and pumping test operations of the wells.

Based on water well drilling Agency analysis results are summarized below:

Name of the well	Discharge l/s	SWL (m)	Draw- down (m)	Permeability (m/day)	Transmissivity (m ² /day)	Specific Capacity (m ³ /day/m)
Adwa well No. 1	2.4	10.55	14.51	0.47	7.58	14.29
Adwa well No. 2	0.83	7.83	21.76	0.33	3.33	3.19
Adwa well No. 4	2.5	5.37	16.43	0.26	7.32	11.15

Source: - water well Drilling Agency (1993).

Based on the above results the metamorphic rocks are characterized by very low transmissivity that ranges between 3.33 and 14.29 m²/day and low specific capacity. Also due to structures and weathering local aquifers may be created, example well No 3 that has transmissivity of 56.47 m²/day.

5.4.2. Hydraulic characteristics of the Adigrat Formation.

The assessment of permeability and productivity of this formation was carried out based on field observation due to unavailability of both lithological logs and boreholes pumping test data in the study area and near by out of the study area.

Based on the thickness, dominant sediment type, hydraulic characteristic two types of sub formations occurs in the study area

1. Siltstone (mudstone?) intercalated with sandstone
2. Sandstone intercalated with siltstone (mudstone?)

5.4.2.1 Siltstone (mudstone?) sub-formation

The siltstone (mudstone?) are fine grained and have relatively high porosity but very low permeability, and act as a barrier for ground water movement. They also act as a confining bed sandwiching the sandstone. It is also characterized by a low yield wells mostly less than 2 l/s that drilled in this formation.

5.4.2.2 Sandstone intercalated with siltstone

According to previous studies and the author field observation, this formation has a moderate permeability and productivity due to the limited siltstone intercalation, bedding planes and the deep vertical jointing .Its lack of high degree of permeability and productivity is as a result of the grain size and degree of cementation.

5.4.2 Hydraulic characteristics of the basalt aquifer

This rock covers most part of the study area. A number of boreholes are drilled in this rock and 11 boreholes with pumping test data are collected and analyzed. Nine boreholes with constant discharge data are analyzed using Cooper and Jacob method and their recovery data is analyzed using Theis & Jacob method. The remaining three boreholes have only a variable discharge data and are analyzed using a stepwise pumping Cooper & Jacob method.

Six of the pumping test data are collected from Nata Tadesse's PhD thesis, 1998 and the remaining five are obtained from Water Well Drilling Agency (1993 & 1998). The next discussion gives the hydraulic characteristics of the basalt aquifer and the analysis results are given for representative boreholes.

EW-1

A continuous pumping test was conducted for 42 hrs with a constant discharge of 2 l/s. After the continuous pumping test a maximum draw down of 7.77m was measured. Using Cooper & Jacob method the transmissivity value is $2.36 \times 10^{-2} \text{ m}^2/\text{min}$.

In this borehole there is no appreciable draw down, (Fig. 5.2). But between 60 min -120 min pumping duration the rate of draw down is increased this may be the cone of depression intercept relatively lower hydraulic formation. Between 120 min and 2520 min, the rate of drawdown is decreased this recharge boundary may be the extent of the aquifer thickness. Remark: the pumping duration is only 42 hrs and the actual potential of the well is not determined from this data.

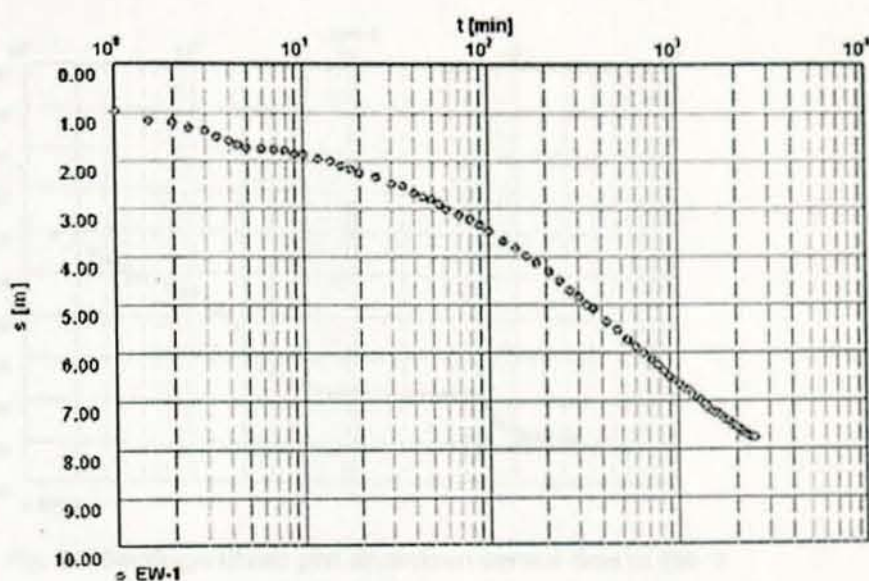


Fig. 5.2 Semi logarithmic plot drawdown versus time of EW-1

EW-2

Pumping test was conducted for 41 hrs of duration with a constant discharge of 2 l/s and a recovery was measured after the continuous test for about 52 hrs. After continuous pumping test a maximum drawdown of 28.35 m is measured. Using Cooper and Jacob method a transmissivity value of $1.86 \times 10^{-2} \text{ m}^2/\text{min}$ is obtained (Fig. 5.3). From the recovery data using the Theis and Jacob recovery method the transmissivity value is $1.85 \times 10^{-2} \text{ m}^2/\text{min}$. Using Hantush's method (for leaky aquifers, with no aquitard storage) a transmissivity value of $1.94 \times 10^{-2} \text{ m}^2/\text{min}$ is obtained.

In this borehole there is no appreciable drawdown measured. Only between 15 min and 45 min and between 660 min and 840 there is a slight increase in the drawdown rate that may be attributed to the cone of depression intercepts relatively a lower hydraulic conductivity layer as compared with the main aquifer. The recharge boundary is may be from the near by non-functional small dam.

The recovery of this borehole is very slow only 85% of the total drawdown is recovered with in 52 hrs.

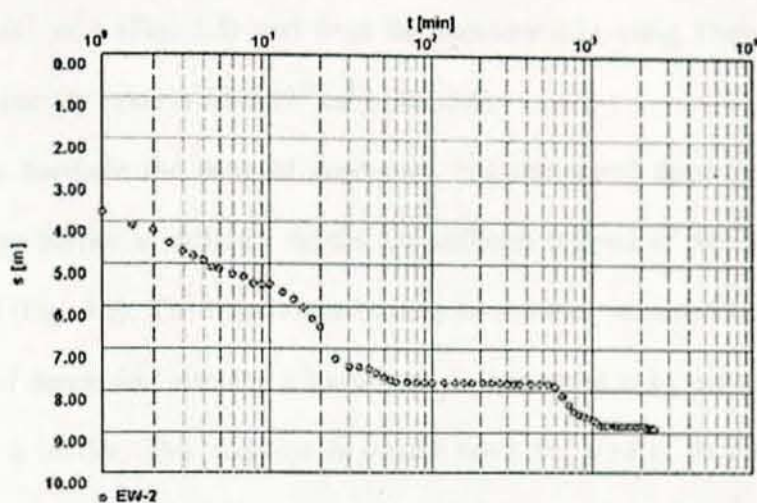


Fig. 5.3 Semilogarithmic plot drowdown versus time of EW-2

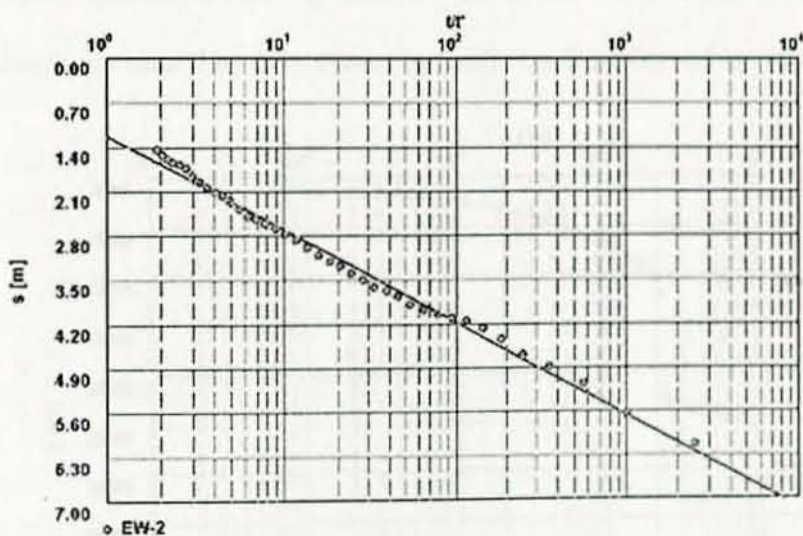


Fig. 5.4 Semi logarithmic plot of residual drawdown versus ratio t/t' at the pumping borehole.

EW-3

A continuous pumping test was conducted for 72 hours and recovery was measured for additional 14 hrs with a constant discharge of 2.5 l/s (Annexure 2A). After continuous pumping a maximum drawdown of 42.69 m was measured. Using Cooper-Jacob method the transmissivity value is

8.66x10⁻⁵ m²/s (Fig. 5.5) and from the recovery data using Theis- Jacob recovery method the transmissivity value is 5.92x10⁻⁵ m²/s (Fig. 5.6).

In this borehole the cone of depression had intercepted three impervious boundaries and two recharge barrier at different depths and different interval of time within the 72 hrs of pumping period (Fig. 5.5). The impervious boundaries show an increased rate of drawdown caused by the cone of depression reaching a barrier which is assumed to be unfractured formation or a fault that act as a barrier. This situation is created when the cone of depression reached a low hydraulic conductivity formation as compared with the aquifer. The recharge boundaries are characterized by a decreased drawdown rate. As there are no surface water bodies near this borehole, the reduced drawdowns are caused by in increased hydraulic conductivity and /or aquifer thickness.

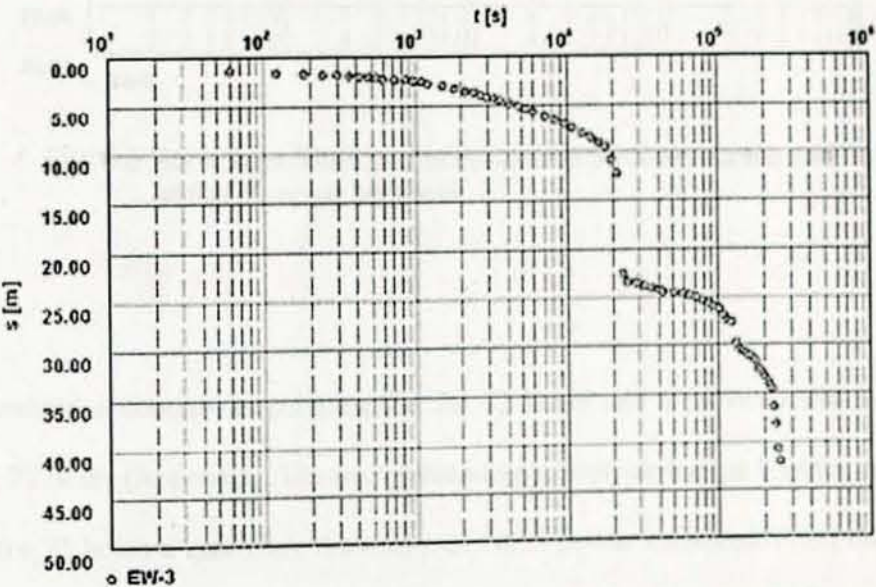


Fig. 5.5 Semi logarithmic plot of drowdown versus time of EW-3

The recovery of this borehole is very fast. The borehole recovered 99.85 % of the total drawdown within 14 hrs.

As seen from the residual draw down versus time graph (fig. 5.6) t/t' intercept is greater than 2, suggesting that there is a source of recharge resulting in a full recovery in shorter time than the corresponding time of draw down.

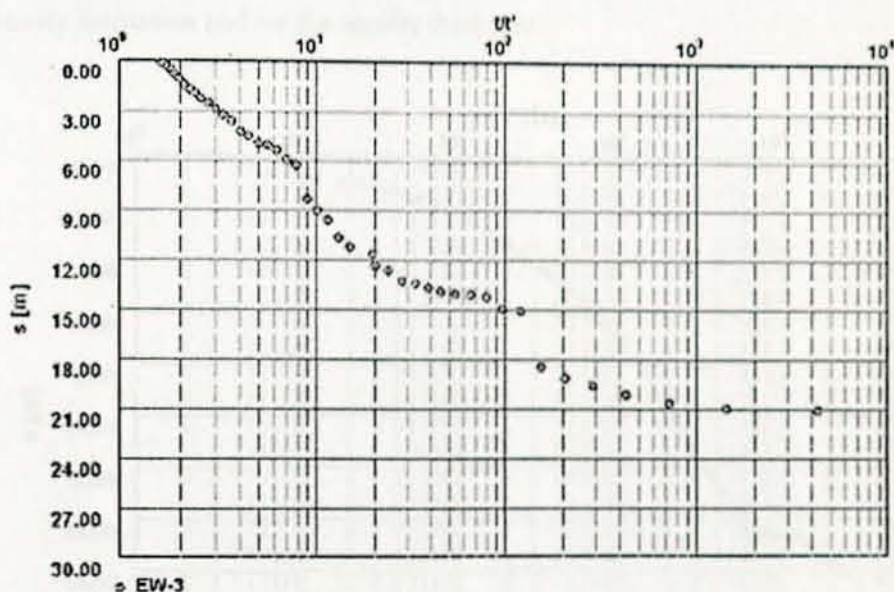


Fig. 5.6 Semi logarithmic plot of residual drawdown versus ratio t/t' at the pumping borehole

EW 4

In this borehole a continuous pumping test for 72 hours and a recovery test was conducted for additional 72 hours (Appendix). The rate of discharge is kept constant at 9.14 l/s. After a continuous pumping for 72 hours a maximum drawdown of 16.15 m was measured. From the drawdown time plot using Cooper and Jacob method the transmissivity value is $2.98 \times 10^{-4} \text{ m}^2/\text{s}$ (Fig. 5.7). From the recovery data using Theis and Jacob recovery method a transmissivity value of $2.2 \times 10^{-3} \text{ m}^2/\text{s}$ is obtained (Fig 5.8).

As shown in fig 5.7, the Cooper and Jacob analysis shows that from 120 to 1080 min the rate of drawdown is increased. This is caused by the cone of depression reach a barrier boundary that may

be caused by a low hydraulic conductivity formation. The rate of drawdown decreased significantly from 1080 to 2280 min of test, suggesting that a recharge barrier had been intercepted. As there is no surface water near the borehole the decreased drawdown rate may be due to a high hydraulic conductivity formation and /or the aquifer thickness.

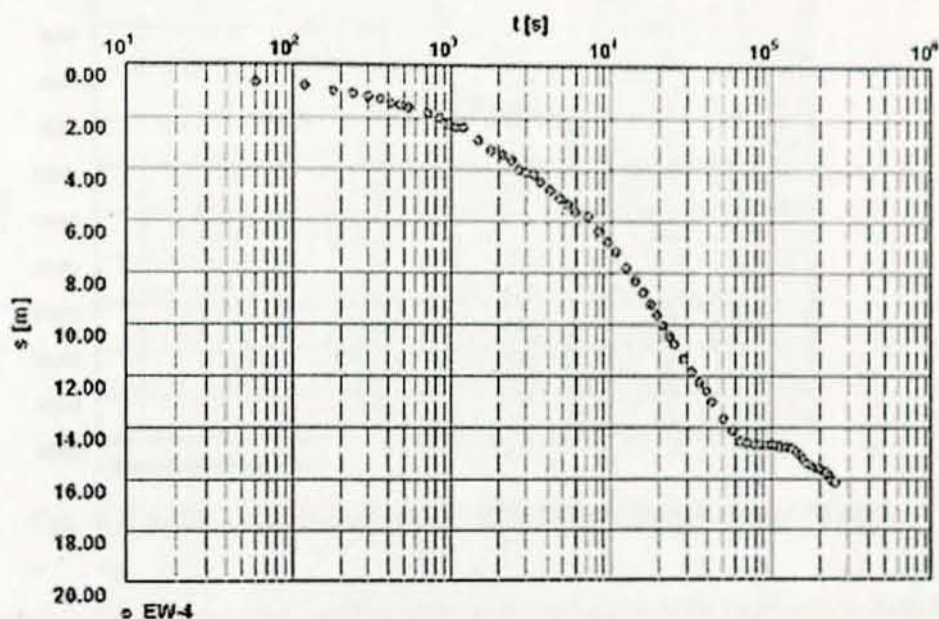


Fig. 5.7 Semi logarithmic plot of drawdown versus time,EW-4

In this borehole the recovery is slow and incomplete .The borehole recovered only 85.94% of the total drawdown in the 72 hrs of the recovery time. This is due to limited potentiality of the aquifer.

EW-6

A continuous pumping test was conducted for 72 hrs and a recovery was measured for additional 24 hrs. The discharge is kept constant at 3.40 l/s, (Annexture 2A). Using the Cooper and Jacob method a transmissivity value of $1.12 \times 10^{-4} \text{ m}^2/\text{s}$ is calculated. Based on the recovery data using Theis-Jacob Recovery method, the transmissivity value is $1.85 \times 10^{-4} \text{ m}^2/\text{s}$.

In this borehole the cone of depression had intercepted two impervious boundaries. The first boundary is slope between 360 to 2280 min of the test. The 2nd boundary (impermeable) is between 2280 to 4320 min of the test. These boundaries may be due to a fault, which act as a barrier.

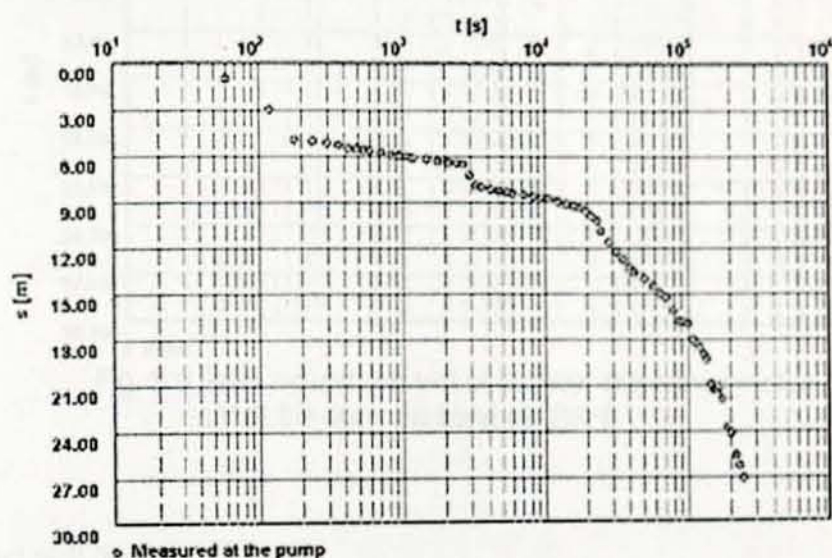


Fig. 5.8 Semi logarithmic plot of drawdown versus time of EW-6

The recovery is fast. It recovered 98.03% of the total drawdown with in 24 hours. Also the t/t' intercept is greater than 1

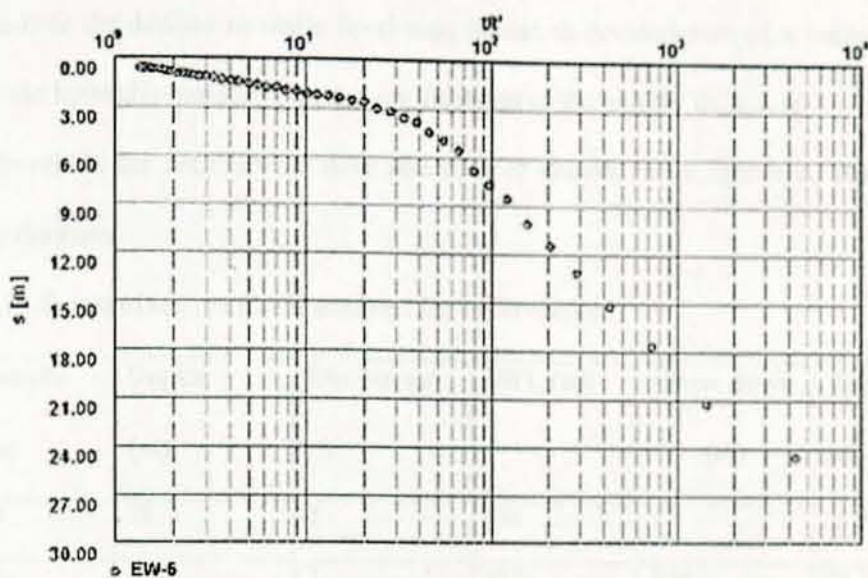


Fig. 5.9 Semi logarithmic plot of residual drawdown versus ratio t/t' at the pumping borehole EW-6

Airport well No 2

In this borehole a continuous pumping test was conducted for 42 hours with a constant discharge of 3 l/s. Recovery data is also measured after the constant discharge test for 41 hours. A maximum drawdown of 71.95 m was attained from the continuous pumping test. Using Cooper and Jacob method the transmissivity value is $1.57 \times 10^{-3} \text{ m}^2/\text{min}$ from the continuous pumping test and from the recovery data using Theis and Jacob recovery method the transmissivity value is $1.4 \times 10^{-3} \text{ m}^2/\text{min}$.

During the continuous pumping duration the cone of depression intercepts two impermeable boundaries and two recharge boundaries. The time between 70 minutes up to 180 min and in between 360 minute up to 540 the rate of draw down is increased that is when the cone of depression intercept an impermeable boundaries that may be non-fractured basalt and /or impermeable fault that has a low hydraulic conductivity. The pumping duration between 180 minute up to 360 minute and in between 540 minutes up to 2460 the rate of drawdown is reduced that happen when the cone of depression intercept recharge boundary. As there is no surface water near

this bore-hole the decline in water level may be due to development of a secondary porosity that increase the hydraulic conductivity and /or the extent of the aquifer thickness.

In this borehole the recovery is slow and 85% of drawdown is recovered during the 41 hours recovery duration.

Table 5.1 Summarized results of analyses for 11 boreholes

Borehole name	Depth (m)	Discharge l/s	SWL (m)	Draw down (m)	Transmissivity m ² /day
EW-1	73	2	6.09	7.7	33.98
EW-2	100	2	19.29	9.06	26.78
EW-3	66	2.5	2.42	42.12	7.48
EW-4	74	9.14	3.65	16.15	25.74
EW-6	102	3.4	1.75	31.55	9.67
EW-8	151	4.96	9.26	81.47	5,616
EW-9	88	11.03	3.82	27.76	59.70
Airport w2	110	3	10.6	71.95	2.26
Apw -2	68	8	4.54	19.06	103.54
Apw-3	56	21	7.91	21.71	109.44
Apw-5	92	3.8	8.05	48.91	24.34

Based on the above summarized results and field observations the basalt of the study area also characterized by moderate permeability and high potential aquifers of the area due to primary and secondary porosity, very low permeability and low potential aquifers also encountered in the area due to lack of secondary structures massive nature of the basalt.

The transitivity values range between 2.26 and 109.44 m²/d with an average value of 37 m²/day and many high yield boreholes are located in this formation .The variation in the yield of the boreholes

in this formation is mainly due to secondary structures, the size of the catchment area and in lesser extent in the variation of the basaltic composition.

The productivity of the basaltic aquifers is limited by the fact that they form highly elevated topography that makes them water divides and recharge areas

5.4.4 Hydraulic characteristics of the Adwa formation.

The next discussions based only on field observation as there are no pumping test data. The Adwa formation comprises of the alkaline phonolites and trachyte composition.

The trachyte is relatively hard, compact and massive with irregular jointing creating a zone of run off rather than infiltration. In addition they are water divides as they form irregularly shaped mountains.

Due to the nature of this formation and its morphological appearance it is characterized as a very low permeability and a very low aquifer potential of the study area.

The phonolite is highly dissected by joints, extensively weathered fractured and unstable when exposed to water. This formation also appears as subcircular plugs forming a zone of infiltration and recharge area for the well fields 1 and 2. Due to the extensive weathering and fracturing the phonolite has a high permeability but due to the morphological appearance they have negligible storage capacity.

Based on the above discussions on hydraulic characteristics of the aquifers & borehole log data the different lithologies of the study area are categorized in to three main groups.

1. Moderate Permeable aquifers

- Highly weathered and fractured vesicular basalt
- Phonolite

2. Low permeable aquifers

- Slightly to moderately weathered and fractured aphanitic to phyric basalt
- Sandstone

3. Very Low permeable aquifers

- The metamorphic rocks
- Siltstone (mudstone)
- Massive, Poorly weathered aphanitic basalt
- Trachyte

1. Moderate permeable aquifers

Highly weathered and fractured vesicular basalt, which is characterized by relatively high potential aquifer for groundwater development. It is also highly affected by lineaments that produce good secondary porosity and permeability. Boreholes drilled in this group of aquifer may have a safe yield greater than 4 l/s.

Phonolite that is highly dissected by joints and extensively weathered, due to the morphological appearance groundwater development is very limited. It is a zone of infiltration and recharge area for the underlying aquifers.

2. Low permeable aquifers

This group includes slightly to moderately weathered and fractured aphanitic to phyric basalt and sandstone intercalated with siltstone.

The sandstone has moderate permeability but due to lack of large catchment areas in the study area and it also forms a plain topography development of ground water limited. Boreholes drilled in this group of aquifer have a safe yields between 2 and 4 l/s.

3. Very Low Permeable Aquifers.

This group includes the metamorphic rock, siltstone (mudstone), massive and poorly weathered aphanitic basalt and trachyte.

They are characterized by very low yield boreholes commonly below 2 l/s. At localities the metamorphic rock due to fracturing may give yields greater than 2 l/s but it is localized in small area.

The massive poorly weathered aphanitic basalt is peculiar as it forms a chain ridges and isolated elevated highs in the study area.

The siltstone (mudstone?) due to local fractures secondary porosity and permeability may be developed but generally the yield is below 2 l/s

The trachyte is the least permeable formation in the study area in addition the land it forms.

The hydrogeological map is produced based on the above discussion and it is mainly dependent on field observation and hydraulic characteristics of the different lithologies occurred in the study area.

5.5 Behavior of groundwater

Water levels systematically measured in large diameter dug wells are conveniently by means of groundwater contour maps. Most frequently used are water table contour maps with reference to below ground level (BGL) map 5.12, above mean sea level (AMSL) map 5.11 or water level change maps. Davis and De Wiest (1996) mentioned that the water level contour maps can be precisely classified as piezometric or potentiometric maps if the details of the aquifer geometry are known.

These maps can summarize (i) the state, saturated thickness of aquifer, gradient, direction of movement and the behavior of groundwater and (ii) the nature of inflow into and outflow from the groundwater system.

Representation of water table by the conventional maps (water table contours), showing the elevation of water level above MSL or below ground level, is more generalized in nature, not capable of projecting out the prominent natures of the dynamics of groundwater flow and liable to subjective errors (Biswas and Chatterjee, 1967).

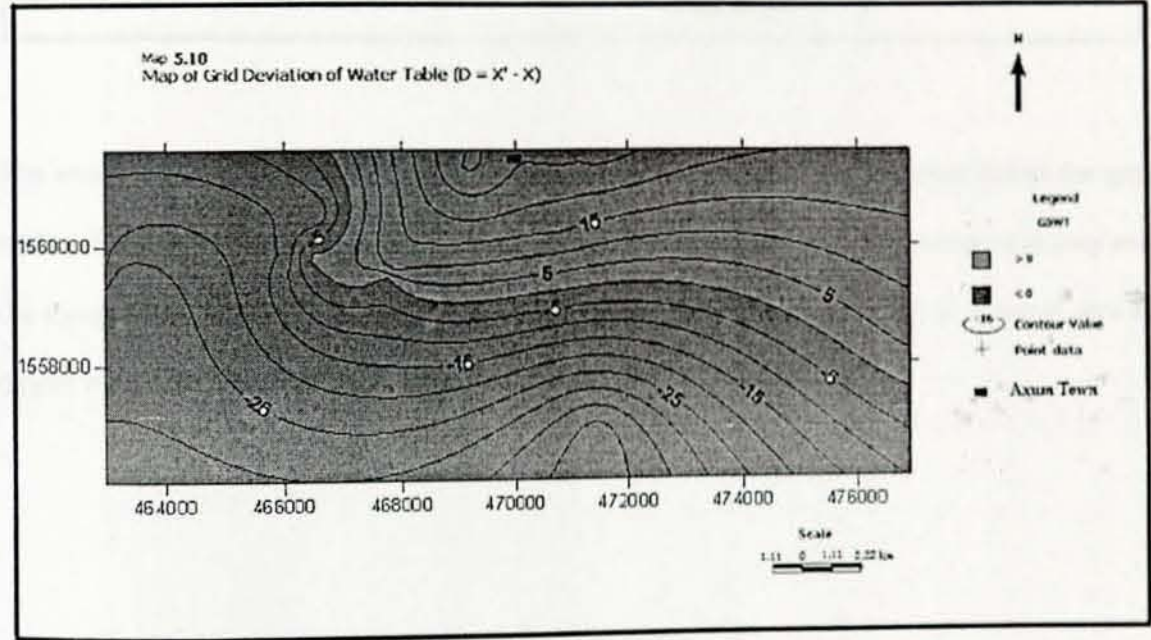
Saha and Chakravorthy (1963) opined that the grid deviation method of representing geological data to be more convenient, objective, informative and projects out more sharply the regional trend by eliminating the local interference (Biswas and Chatterjee, op cit.). Due to this advantage, the grid deviation water table map has been prepared and used in this study.

5.5.1 GRID DEVIATION WATER TABLE MAP:

The preparation of the Grid Deviation Water Table Map, as given by Biswas and Chatterjee (1967) is as follows:

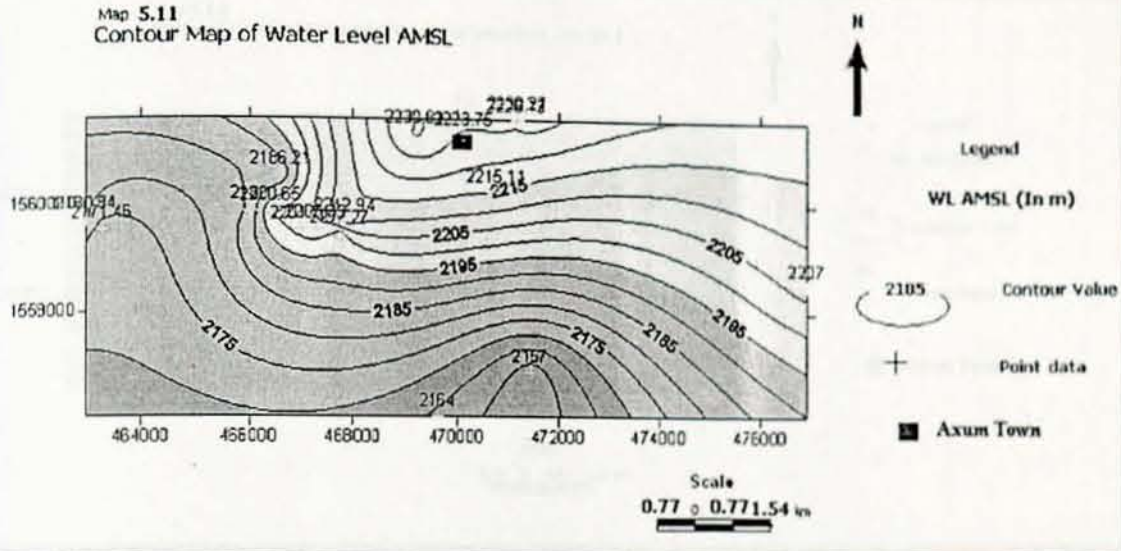
- i) Monthly water levels measured below the measuring points (BGL) have been recalculated to water level altitudes above MSL.
- ii) An average elevation of water table (X_1) for each observation well has been computed after calculating the monthly averages of water levels.
- iii) An average value (X) of all the average elevations of water tables computed in step (ii) has been determined for the basin. This is called the basin average.
- iv) The deviation $D_i = (X_i - X)$ from the basin average water level altitude and the average elevation of water levels of individual observation wells have been determined.
- v) The desired deviation map results from an objective contouring of the deviations of each of the observation wells of the basin.

Annex 2B gives the grid deviation water levels and Map5.10, depicts the grid deviation water table map. It could be observed that the entire watershed is characterized by a positive and a negative horizon separated by a zero level of grid deviation water level. The positive zone, forming the area of recharge lies in the upstream area of the catchments, where as the negative zone forming the discharge area, is located in the lower reaches of the catchment. The wide spacing of the contours and their disposition are suggestive of a flat and gentle gradient of the water table and comparatively high permeability of the lithology when compared to the areas where closely spaced contours occur.



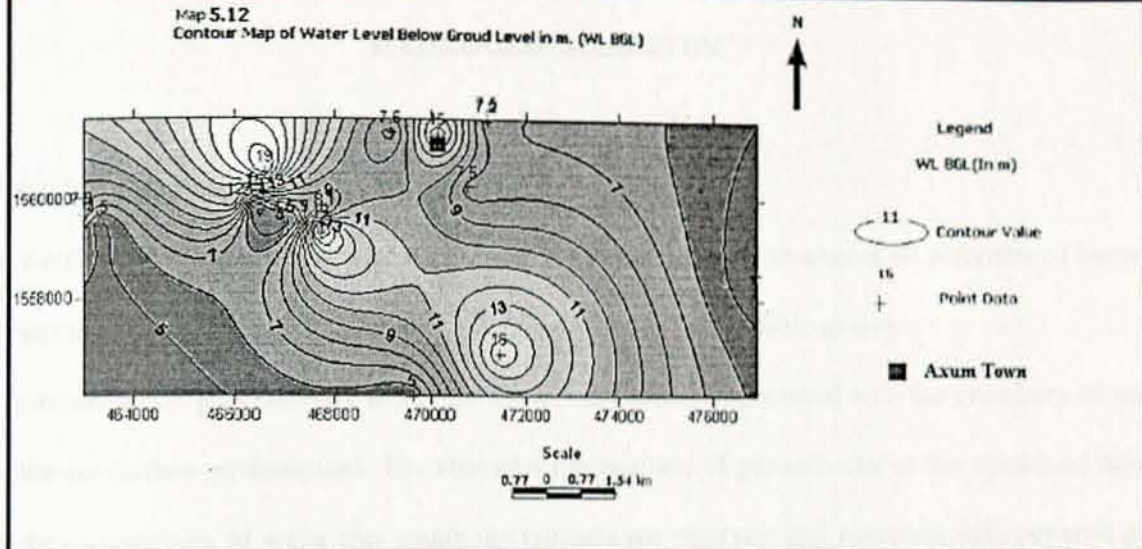
The water level above mean sea level is obtained by subtracting water level below ground level from topographic height of the well. As shown in Map 5.11 it shows similar trend as grid deviation water level.

Map 5.11
Contour Map of Water Level AMSL



The water level below ground level (WL BGL) simply shows the level of water below the ground surface irrespective of topographic height. As it is shown in map 5.12 the contour map only reflect the topographic difference where the well are located. That is wells located at elevated area have dipper water level below the ground surface than wells located at lower area.

Map 5.12
Contour Map of Water Level Below Groud Level in m. (WL BGL)



CHAPTER-6

HYDROGEOCHEMISTRY

6.1 Introduction

Water is vital for the existence of life and is essential directly to almost all activities of human and animals' kind. The quality of water is as importance as its available quality.

Ground water geochemistry is an interdisciplinary science concerned with the chemistry of water in the subsurface environment. The chemical composition of groundwater is the combined results of the composition of water that enters the groundwater reservoir and reactions with minerals present in the rock that may modify the water composition. A part from natural processes as controlling factors on ground water quality, human activity also influences the groundwater chemistry (Appelo & Pastma, 1994).

Groundwater geochemistry has a potential use for tracing the origins and the history of water. Water a compositions change through reactions with the environment and water quality may yield information about the environments through which the water has circulated (Aprelo & Postma, 1994).

Dissolved constituents in the water provides clues on its geologic history, its influence on soil or rock masses through which is has passed, the presence of hidden ore deposits, and its mode of origin within the hydrologic cycle (Freeze and Cherry, 1979).

The Physical, chemical, biological, and hygienic properties of groundwater determine its usefulness for human purposes, namely agriculture, industry and domestic use. Furthermore, groundwater

properties give important indications of the nature of aquifers, and supply valuable information about the origin, flow velocity, and direction of groundwater flow. Modern geochemical prospecting techniques in which substances are carried by ground water are used for detecting concealed mineral ores and deposits of oil and natural gas (George Mathhess, 1982).

Solutes contained in natural water represent the effect of a series of antecedent chemical reactions that have dissolved material from another phase, have altered previously dissolved components, or have eliminated them from solution by precipitation or to her processes. The chemical processes are influenced strongly by biologic activity in some environments and by a great many processes of a physical nature (Hem, 1985).

Once precipitation reaches the ground, it reacts with soil, rock, and organic debris, dissolving still more chemicals naturally aside from any pollution generated by human activities. The type and concentration of salts in water depend on the processes that have affected the water since it has fall as a rain or snow.

Among the factors determining the level of trace and major elements are the content of solute in the initial rain, the extent of reaction with role and soil, loss of constituents by precipitation absorption, gain of constituents by dissolution on exchange, and loss of water because of evaporation, transpiration or reaction with minerals.

Groundwater is not pure water because it usually contains dissolved mineral ions. The type and concentration of these dissolved minerals can affect the usefulness of groundwater for various

purposes. The main purpose of water quality analysis is to determine the usefulness of the water for intended purpose.

In the hydrochemical investigation of the study area a total no of 13 water samples for physico-chemical analysis and 12 water samples for bacteriological analysis are taken from town hand dug wells, shallow wells fitted with hand pump and motorized boreholes. In addition to the above water quality analysis results, previous data are obtained from Water Well Drilling Agency, German Water Engineering (GMBH) and Devecon Engineers and Architects.

The main objective of the hydrochemical study is to demonstrate the relationship of geology with water chemistry. In addition water chemistry and quality data evaluated with regard to the suitability of the groundwater for drinking and irrigation purpose. For this purpose the different water analysis result are categorized in to four groups, based on from where the water samples are taken. These are:

1. Water analysis results from boreholes that penetrate mainly on the basement complex that are MP, HP and SW1.
2. Water analysis results from boreholes that penetrate mainly the basalt. Those are EW1, EW5, EW4, APW5, SW2, SW3, SW4, SW5, SW6, A6, A5, A4, Hospital well and May Edaga well.
3. Water analysis results from boreholes that penetrate the basalt and mudstone (Siltstone?). This group includes APW1, APW2, APW3, A2a, A1a, and EW2
4. Water analysis results from streams and a spring. This group includes Gebru Creek, Harma Creek, Hatela Creek and May Shum spring.

Because of the geomorphology they from in the study area the phonolite and trachyte plugs, they have no any well development and the physico- chemical analysis result is impossible to obtain.

6.2. Water Sampling Methods.

A total of 25 water samples were collected for physico-chemical analysis and for bacteriological analysis from domestic water wells within the study area.

For physio-chemical analysis the samples were analyzed in the Water Laboratory of Water Works Design & Supervision Enterprise and for bacteriological analysis in the Central Laboratory Service of Addis Ababa Water and Sewerage Authority.

The chemical analysis result for major ions is checked for the accuracy of the laboratory results by using the equation of Electro Neutrality (E.N) conditions since the sum of positive and negative charges in the water must balance:

$$\text{Electro Neutrality (E.N., \%)} = (\text{Sum cations} + \text{Sum anions}) / (\text{Sum cation} - \text{Sum anions})$$

Where cations and unions are expressed as meq/l.

Differences in E.N. up to 5% are acceptable (Appelo & Postma, 1994) and all of the chemical analyses are below the acceptable limit.

6.3 Water analysis results.

6.3.1 Physico -chemical analysis results.

The resulting physical and chemical properties of groundwater is mostly related to its relationship with the media through which the water passed and its residence time. In addition to the natural factors a major change in the constituents of groundwater is resulted from the activity of human beings. Analyses of groundwater samples are used to correlate the geology and water composition and to infer the relationship or interaction existing between surface and ground water bodies.

The major chemistry of groundwater from different lithologies and for comparison purpose from surface water is summarized in table 6.1, 6.2, 6.3 and 6.4.

Table 6.1 Average values and range of concentration of major ions in mg/l from basement complex

Ellement	Range	Average
pH	7.01-7.41	7.16
Na ⁺	16 - 46	31.66
K ⁺	0.4 - 3.7	1.60
Ca ²⁺	64.7 - 105	81.5
Mg ²⁺	16.3 - 20.9	81.5
HCO ₃ ⁻	291.0 - 360	19.2
NO ₃ ⁻	5.3 - 34.3	333.8
Cl ⁻	12.5 -25.1	17.9
SO ₄ ⁻²	8.96 - 36.90	19.93

Table 6.2 Average values and range of concentration in mg/l of major ions from basalt.

Element	Range	Average
pH	6.9 - 7.44	7.19
Na ⁺	28 - 86	53
K ⁺	0.4 - 5.8	3.5
Ca ⁺²	24 - 542.8	78.11
Mg ⁺²	5.1 - 42.8	22.06
HCO ₃ ⁻	323 - 488	393.81
NO ₃ ⁻	2.6 - 11.3	30.59
Cl ⁻	9.7 - 88	34.89
SO ₄ ²⁻	0.26 - 45	14.65
SiO ₂	45 - 9.5	67.43

Table 6.3 Average values and range of concentration of major ions from Basalt and mudstone

Element	Range	Average
PH	6.5 - 7.59	7.058
Na ⁺	28.4 - 250	179.96
K ⁺	2.84 - 42.1	19.15
Ca ²⁺	149-677.4	308.73
Mg ²⁺	14.6-264.6	126.92
HCO ₃ ⁻	869-3465.2	1769.72
NO ₃ ⁻	0.066-5.3	1.1
Cl ⁻	5-120	64.12
SO ₄ ²⁻	5.3-100.75	44.27
SiO ₂	48.2-148	77.04

Table 6.4 Average values and range of concentration of major ions in mg/l from surface water.

	Range	Average
pH	7.8 - 8.4	8.0
Na ⁺	61 - 119	84.87
K ⁺	4 - 4.3	4.1
Ca ²⁺	32 - 35	33.57
Mg ²⁺	20 - 49	32.4
HCO ₃ ⁻	258.6 - 537	362.87
NO ₃ ⁻	0.5 - 3.0	1.83
Cl ⁻	20.6 - 62	38.87
SO ₄ ²⁻	18 - 22	20.33
SiO ₂	16 - 65.5	34.83

Most of water samples taken in the study are tasteless, odorless and colorless. The only excretions are water samples taken from the basalts and mudstone penetrated boreholes. APW1 and APW3 have objectionable odor and taste. EW2 have salty taste but odorless and tasteless. The taste of water is mostly controlled by concentration of ions in the water. The objectionable taste of these boreholes is most probably associated with their high amount of concentration of ions. The objectionable odor also associated with high amount of gas in those boreholes.

The pH of most ground water results from the balance between dissolved carbon dioxide gas, carbonate and bicarbonate in the water (Driscoll, 1991)

The hydrogen-ion activity in an aqueous solution is controlled by interrelated chemical reactions that produce or consume hydrogen ions (Hem, 1985).

Certain properties of water, especially pH, are so closely related to the environment of water they are likely be altered by sampling and storage, and a meaningful value can be obtained only in the field. Most of the water analysis results in the study area give pH values measured in laboratory that may not give an actual value of the pH of the ground water. But they may give general information how the pH value may range in the study area.

In the water analysis results the pH value of water samples from the basement complex range between 7.01 and 7.41, while from the basalt and basalt + mudstone the pH ranges from 6.9 up to 7.44 and 6.5 up to 7.59 respectively. Water sample results from the surface water have pH value between 7.8-8.4. According to David et.al., (1966) this range can be categorized under moderately high pH values, that commonly associated with water high in bicarbonate.

In the analysis results the dominant cations and anions are the same from the boreholes penetrating different lithologies though they vary in amount. The dominant cations in the boreholes are Ca - Na - Mg - K in decreasing order. Analysis results from the streams have different dominant cation than the boreholes but have similarity in anions. The dominant cations are Na - Ca - Mg - K in decreasing order.

Analysis results from boreholes that penetrate the basalt and mudstone have an exceptional high value of all cations and anions except nitrate with an average value of 1.1 mg/l. The analysis results

from other lithologies and even from streams have more or less similar values of cations and anions (Fig 6.1).

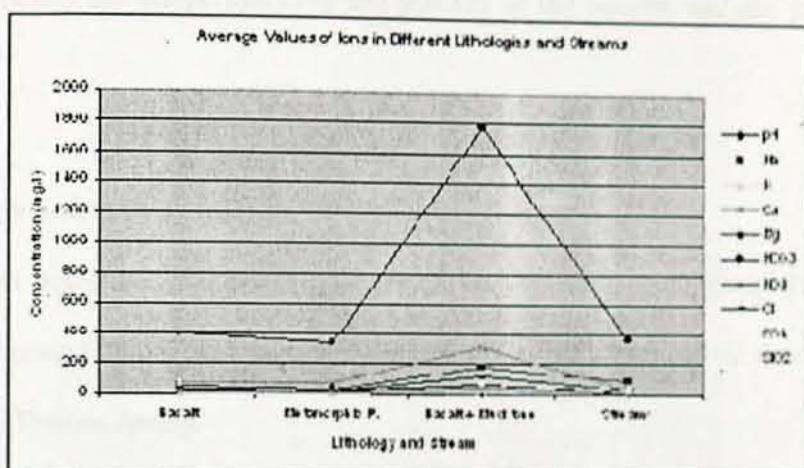


Fig. 6.1 Average values of major ions in different lithologies and streams.

6.4 Data Interpretation

The physical, chemical and biological properties of groundwater determine its usefulness for human purposes, namely agriculture, industry, and domestic use. Furthermore, groundwater properties give important indications of the nature of aquifers, and supply valuable information about the origin, flow velocity: and direction of groundwater flow (Matthess, 1982).

In the study area the chemical properties of groundwater is dominantly influenced by geology through which the water has passed and in lesser extend by the activity of man. Though there is no difference in dominant cations and anions, the main difference in the chemical data obtained from different lithologies is the amount of cations and anions.

When water passes through different aquifers the chemical property of the initial water change depending on the chemical composition of the aquifers, predominant geochemical reactions taking place between the water and the aquifer, the residence time of the water in the different aquifers, that is governed mainly on the permeability and porosity of the aquifer, and the pressure created by overburden.

6.4.1 Hydrogen ion activity (pH)

The pH of an aqueous system is a measure of the acid-base equilibrium achieved by various dissolved compound and in most natural water it is controlled by the carbon dioxide - bicarbonate - carbonate equilibrium system.

The hydrogen - ion activity in an aqueous solution is controlled by interrelated chemical reactions that produce or consume hydrogen ion. The dissociation equilibrium for water is always applicable to any aqueous solution, but many other equilibria and many non-equilibrium reactions that occur in natural water among solute, solid and gaseous, or other liquid species also involve hydrogen ions. The pH of natural water is a useful index of the status of equilibrium reactions in which the water participates (Hem, 1971).

In the study area the pH values of the chemical analysis results are obtained from laboratory pH measurement that may not represent the actual values. The average pH values in different lithologies and the streams have more or less similar values that range between 7 and 8. The ranges of pH values are mostly associated with the high bicarbonate contents of the water. The pH of water from the basalt + mudstone would have pH values higher than the measured values as they have high bicarbonate concentration. This could be associated either with the incorrect laboratory pH

measurement as they are not field measurements or there are other sources that produce hydrogen ion other than the CO_2 - HCO_3 - CO_3 equilibrium.

6.4.2. Total dissolved solids (TDS).

Due to rock water interaction and the residence time of groundwater in the aquifer, increase in TDS and major ions normally occur. Freeze and Cherry (1979) noticed that shallow groundwater in recharge areas is lower in TDS than the water in the discharge areas. The total concentration of dissolved minerals in a water is a general indication of its suitability for the intended use. The principal ions contributing to total dissolved solids (TDS) are carbonate, bicarbonate, chloride, sulfate, nitrate, sodium, calcium, and magnesium. In the study area the main contributing anion for TDS is bicarbonate.

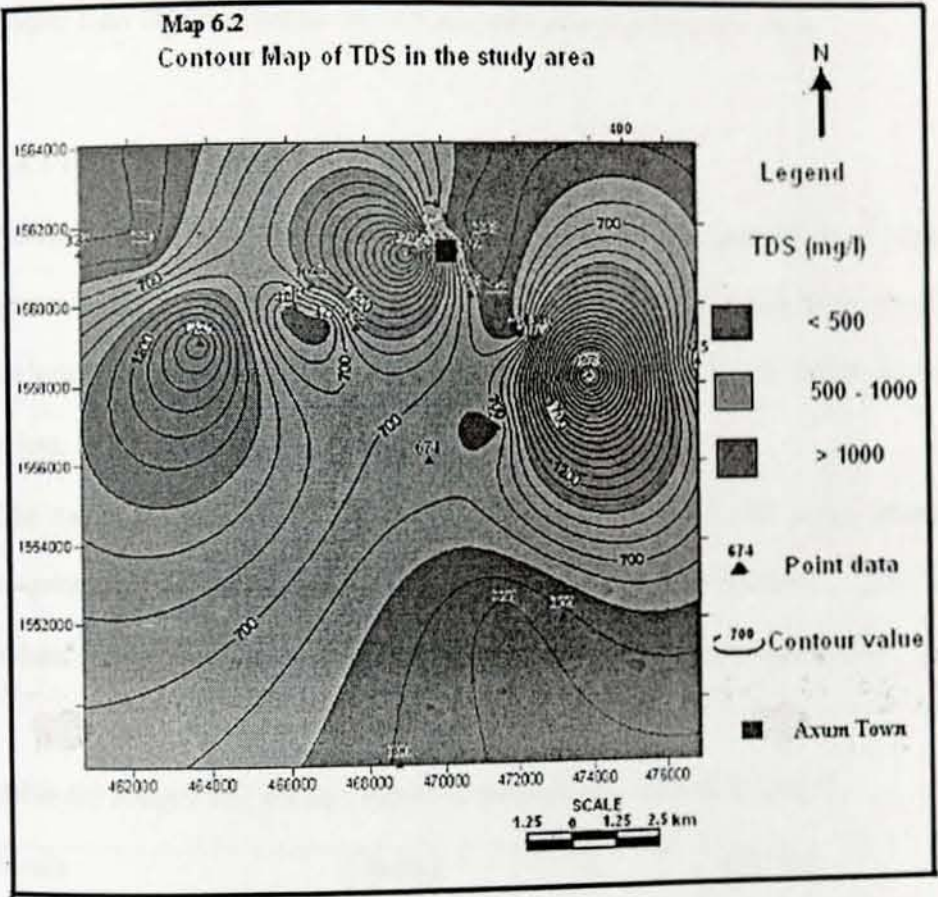
The water sample analysis results show that there is similarity in the amount of TDS from the basalt, Basement complex and streams but high amount of TDS is measured from water samples collected from the boreholes that penetrate the basalt and mudstone formation.

The average values and range of TDS from different lithologies and streams is given below

Table 6.5 Range of Total dissolved solids (mg/l) in different lithologies and streams

Media	Range	Average
Basalt	493 - 854.7	631
Metamorphic Rock	428 - 615	541
Basalt + Mudstones	1250.3 - 4747.2	2514.6
Streams.	470 - 824	588.4

Spatial distribution of TDS in the study area is shown in Map 6.2



The high TDS values from the analysis results from the boreholes that penetrate the basalt and mudstone is due to rock - water interaction when the water enter different formations and in the mudstone due to low permeability the residence time of the water is very long that allow the water to interact with the mudstone resulting in high TDS values.

According to their total dissolved solids concentration the water in the study area can be categorized in to fresh water (TDS less 1000mg/l) and brackish water (TDS values b/n 1000 and 10,000 mg/l). In the study area the water from the basalt, metamorphic and streams have TDS values less than 1000 mg/l, so categorized under fresh water the water from basalt - mudstone have TDS values greater than 1000 but below 10, 000, categorized under brackish water.

6.4.3 Total Hardness.

Because most of the effect observed with soap results from the presence of calcium and magnesium, hardness is generally defined in term of these constituents. The other ions that might precipitate soap include H^+ and all polyvalent metal cations, but they are present mostly in insignificant amounts (Hem, 1971).

The major sources of cations in the study area are attributable to the presence of calcium and magnesium bearings minerals in volcanic, metamorphic and mudstone. The range and average values of total hardness in different lithologies and streams are given below.

Table 6.6 Ranges and average values of total hardness (as $CaCO_3$, mg/l)

Media	Range	Average
Basalt	157.5-453.6	309
Metamorphic Rock	245.7-329.7	365
Basalt + Mudstones	700-2350	1195
Streams	32-200	135

In general the streams have lower average total hardness values than the groundwater. This is due to rapid movement of the water in the stream that causes short time contact with the geology than the groundwater.

The average total hardness values from the basalt and metamorphic rocks show similarity with average values of 309 and 365 respectively, but high amount of total hardness is obtained from water samples collected from the boreholes that penetrate the basalt and mudstone.

This may be attributed to long residence time of the water in the mudstone that allow to have enough time to interact with the mudstone.

Durfer and Becker (1964) defined range of hardness concentration in milligram per liter and proposed the following classification.

Hardness range, CaCO ₃	Description
0-60	Soft
61-120	Moderately Hard
121-180	Hard
Greater than 180	Very hard

In the study area, the hardness values of the groundwater from the different lidholgies are greater than 180 ml/l accordingly they are categorizing under very hard water and hence no thematic map could be made.

6.4.4 Electrical Conductivity (E.c)

Specific electrical conductivity is the index of the degree of mineralization, which is temperature dependent.

The presence of charged ionic species in solution makes the solution conductive. As ion concentrations increase, conductance of the solution increase; therefore, the conductance measurement provides an identification of ion concentration (Hem, 1971).

There is a strong correlation between total dissolved solids and specific conductance.

The range and average values of Ec in defferent lithologies and streams are shown below.

Table 6.7 Ranges and average of Ec in $\mu\text{S}/\text{cm}$

Media	Range	Average
Basalt	577-1023	804
Metamorphic Rocks	490-692	614
Basalt + Mudstone	2325-5972	3379
Streams	516-913	675

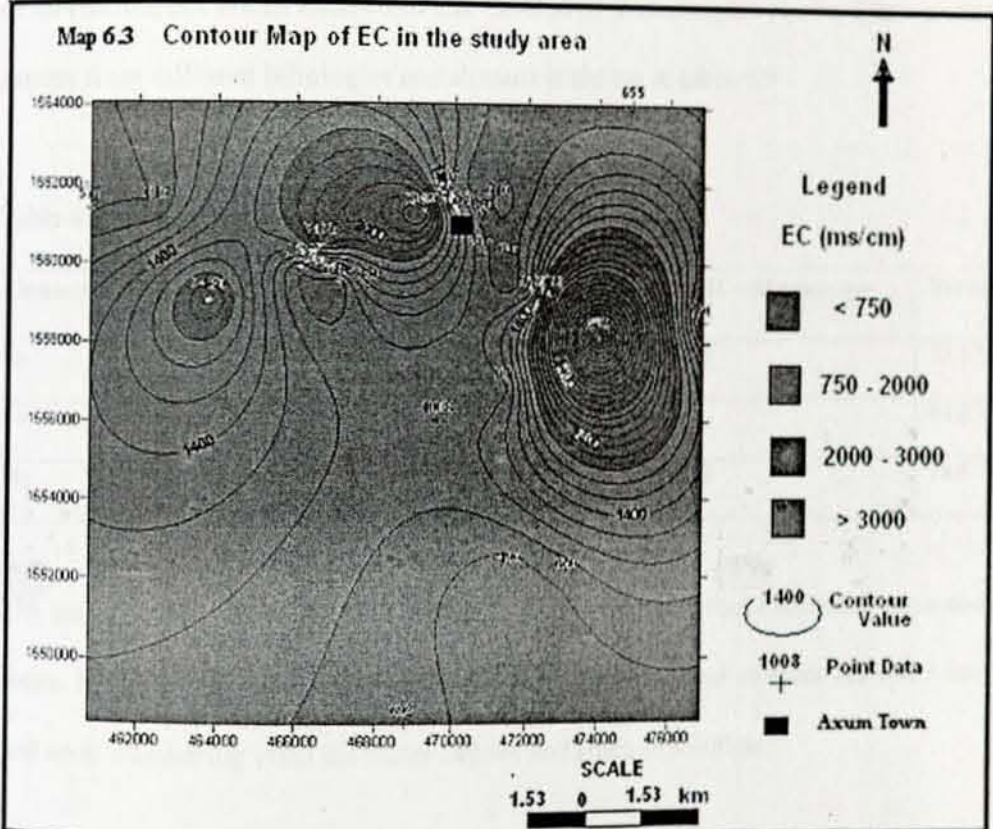
As can be seen from table 6.7, the average electrical conductivity values from the basalt, metamorphic and streams show similar results, where a high values of electrical conductivity is measured from water samples collected from boreholes that penetrate the basalt and mudstone formations.

Wilcox (1955) proposed the following classification of water based on electrical conductivity.

Table 6.8 Wilcox's classification for groundwater.

Ec Range ($\mu\text{S}/\text{cm}$)	Quality
< 250	Excellent
250 - 750	Good
750 - 2000	Permissible
2000 - 3000	Doubtful
> 3000	Unsuitable

Accordingly majority of samples from the basalt, Metamorphic and streams belong to 750-2000 $\mu\text{S}/\text{cm}$ and cover the majority of the study area. The samples from the boreholes that penetrate the basalt and mudstone belong to 2000-3000 $\mu\text{S}/\text{cm}$ but A₃ has Ec value of 5972 $\mu\text{S}/\text{cm}$. The distribution of electrical conductivity within the study area is shown in map 6.3, and show similar trend as TDS map of the study area.



6.4.5 Major Cations

Chemical analysis of water samples collected from the different lithologies and streams revealed that calcium, sodium and magnesium are the dominant cations.

In the analysis results the dominant cations are the same from boreholes that penetrate different lithologies. Analysis results from boreholes that penetrate the basalt and mudstone have high values of all the major cations than from the basalt and metamorphic rocks. The variation of the major cations from different lithologies and streams is shown in table 6.9

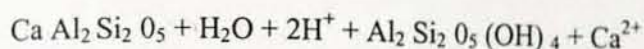
Table 6.9 Average values of major cations

Element	Basalt	Metamorphic	Basalt +Mudstone	Streams
Ca	78.11	81.5	308.78	33.57
Na	53	31.67	180	84.87
Mg	22.06	19.2	126.92	32.4

The major sources of calcium and sodium are the minerals that constitute basic and acidic volcanic rocks. Hem (1971) stated that species containing sodium and calcium are more are less susceptible and upon weathering yield the metal cations and silica in solution.

Calcium is an essential constituent of many igneous rock minerals, especially of the chain silicates pyroxene and amphibole and the feldspars. The plagioclase feldspar group of minerals represents mixture in various proportions of the end members albite, $Na\ Al\ Si_3\ O_8$ and anorthite, $Ca\ Al_2\ Si_2\ O_5$. Calcium also occurs in other silicate minerals that are produced in metamorphism. Some calcium is, therefore, to be expected in water that has been in contact with igneous and metamorphic rock.

The concentration generally is low, however, mainly because the rate of decomposition of most igneous-rock minerals is slow (Hem, 1971). The decomposition of anorthite can be represented as



Ground water in silicate terrain often contains less than 100 mg/l of calcium (Matthess, 1981). In the study area most of the water sample results show values less than 100 mg/l

Water Sample analysis results from the basalt and mudstone show a higher value with an average value of 308.79 mg/l of calcium. This indicates that there is a source of calcium other than the weathering of silicates. The mudstone is deposited under salt water and don't transmit water easily, some of the solutes may remain in the pore space for long periods creating a higher concentration of dissolved solids. This may contribute to the high amount of calcium in the boreholes that penetrate the basalt and mudstone.

Sodium is a major constituent of igneous rocks in which mainly occurs in plagioclase, the soda-lime feldspar with the sodium-rich end member as albite.

The decomposition of plagioclase feldspar results increases of sodium in natural water.

The water analysis results from the basalt and metamorphic rock show lower amount of sodium than from the boreholes that penetrate the basalt and mudstone. This may be due to low permeability of the mudstone that enriches sodium in the mudstone and partly because of the sorptive bonding of sodium to clay minerals. Besides sodium can enter groundwater as a result of ion exchange with Ca.

In igneous rock, magnesium is typically a major constituent of the dark-colored ferromagnesian minerals. In altered rocks, magnesian mineral species Such as chlorite and serpentine occurs

The alteration of magnesian olivine (Forsterite) to serpentinite can be written as $5\text{Mg}_2\text{SiO}_4 + 8\text{H}^+ + 2\text{H}_2\text{O} + \text{Mg}_6(\text{OH})_5\text{Si}_4\text{O}_{10} + 4\text{Mg}^{2+} + \text{H}_4\text{SiO}_4$.

The concentration of Mg^{2+} in natural water is generally less than 50 mg/l (Todd, 1980). In the study area high concentration of magnesium is obtained from the boreholes that penetrate the basalt and mudstone. This may be attributed to the low permeability of the mudstone enriching in Mg as the other major cations.

Davis and De Wiest (1966) attribute the low concentration of Mg^{2+} to slow dissolution of magnesium bearing minerals and greater abundance and solubility of calcium.

In the study area due to slow dissolution of magnesium bearing minerals, the amount of Mg^{2+} in the water analysis results are low as compared to the corresponding amounts of calcium and sodium

6.4.6 Major Anions

Chemical analysis of water samples collected from the different lithologies and streams revealed that bicarbonate is the dominant anion followed by chloride, sulphate and nitrate.

The variation of the dominant anions from different lithologies and streams is shown in table 6.10

Table 6.10 Average values of major anions (mg/l)

Element	Basalt	Metamorphic	Basalt +mudstone	Stream
HCO_3^-	393.81	33.8	1769.72	362.87
Cl^-	34.89	19.93	64.12	38.87
SO_4^{2-}	14.65	18.35	44.27	20.33
NO_3^-	30.59	17.9	1.1	1.83

The average bicarbonate ions are highest from the boreholes that penetrate the basalt and mudstone. The analysis results from basalt metamorphic and streams show similar average bicarbonate values.

The origin of carbonate CO_3^{2-} ions, undissolved H_2CO_3 , dissolved carbon dioxide (CO_2) and bicarbonate (HCO_3) ions in ground water and from the carbon dioxide in the atmosphere, carbon dioxide in the soil, and solution of carbonates rocks (Davis and De Wiest, 1966).

Higher HCO_3 values from the boreholes that penetrate the basalt and mudstone indicate that there is additional source of carbon dioxide source other than the atmospheric and soil carbon dioxide. The additional source of carbon dioxide can be associated with mainly the presence of organic matter incorporated within the mudstone

The presence of sulfate in natural water can be attributed to the oxidation of sulfide minerals and may occur in certain igneous rock minerals of the feldspathoid group. In the study area the concentration of sulphate is low though it shows relatively higher value from the boreholes that penetrate the basalt and mudstone.

Chloride in natural water comes from feldspathoid sodalite and apatite as minor sources in igneous rocks and the main source in sedimentary rocks are evaporates (Hem, 1972). In the study area the amount of chloride from different lithologies is low though it shows relatively higher values from the boreholes that penetrate the basalt and mudstone.

Nitrate in the study area is found in low concentration as compared to the other anions. Nitrate is the end product of oxidation of nitrogen in the environment and its higher level of concentration in

ground water often an indication of pollution from either sewage or agricultural fertilizer. But it doesn't have any connection with the type of lithology. Relatively higher values of nitrate and measured from the basalt is mainly attributed to agricultural activity in the area.

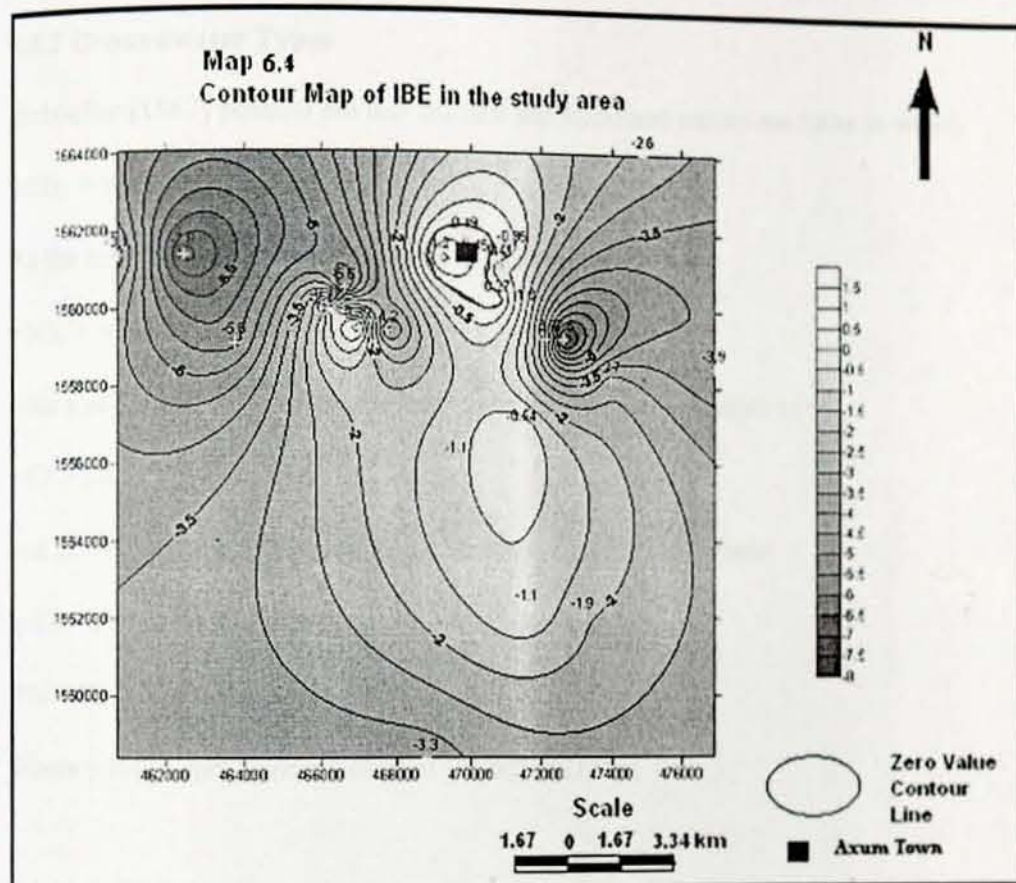
From the chemical analysis result of the different sources in the study area shows variable values. The chemical compositions of the analyzed samples from the boreholes that penetrate the basalt mudstone are above the WHO standard in TDS. Due to this reason most of the wells are abandoned. The analyzed results from basalt and metamorphic rocks are in the acceptable limit with the exception of nitrate in hand dug wells located in Axum town and May Edega well.

6.5. Metasomatism of Groundwater

Ground water quality changes from the point of its entry to the point exit in the water bearing formation chloro-alkaline indices (Index of Base exchange IBE, Schoeller, 1967) throw more light on this phenomenon.

6.5.1 Index of Base exchange

Two indices were proposed by Schoeller (1965a). They are CAI_1 and CAI_2 (Chloro alkaline Index 1 and 2). $CAI_1 = Cl - (Na + K) / Cl$ and $CAI_2 = Cl - (Na + K) / (SO_4 + HCO_3 + NO_3)$ where all ionic values are expressed as epm. When there is exchange between $(Na+K)$ in water with $(Ca+Mg)$ of rocks both CAI_1 and CAI_2 are negative. If the exchange is between $(Ca + Mg)$ of rocks both CAI_1 and CAI_2 are negative. If the exchange is between $(Ca + Mg)$ of water with $(Na + K)$ of the rock both CAI_1 and CAI_2 are positive.



These indices depend on the residence time of water in the formation and hence the negative or positive symbol. In typically weathered geological situations the recharge area is characterized by positive CAI_1 and CAI_2

Table 6.11 CAI_1 and CAI_2 of Groundwater in the study area

CAI_1 & CAI_2	No. Of Samples	%	Area Sq.km
Negative	21	80.77	277.8
Positive	5	19.23	3.7

16.67 Percent of the groundwater have positive and 83.33 percent of the ground waters have negative values as evidenced by table 6.11. Map 6.5 clearly shows that a majority of the study area has negative CAI_1 , or CAI_2 indicating a comparatively long residence time of water in the rocks.

6.5.2 Groundwater Types

Schoeller (1967) pointed out that the first and fore-most waters are those in which

$$\gamma \text{CO}_3 > \gamma \text{SO}_4 \quad \text{Type I}$$

As the residence time increases there is a change to

$$\gamma \text{SO}_4 > \gamma \text{Cl} \quad \text{Type II}$$

with a still more increase in residence time the chemistry changes to

$$\gamma \text{Cl} > \gamma \text{SO}_4 > \gamma \text{CO}_3 \quad \text{Type III}$$

and in the final stage the ionic concentrations reach a stage where

$$\gamma \text{Cl} > \gamma \text{SO}_4 > \gamma \text{CO}_3 \text{ and}$$

$$(\text{Na} + \text{K}) > \text{Mg} > \text{Ca} \quad \text{Type IV}$$

Where γ is the eqm concentration of the different ions.

Map 6.5
Schoeller's water type in the study area

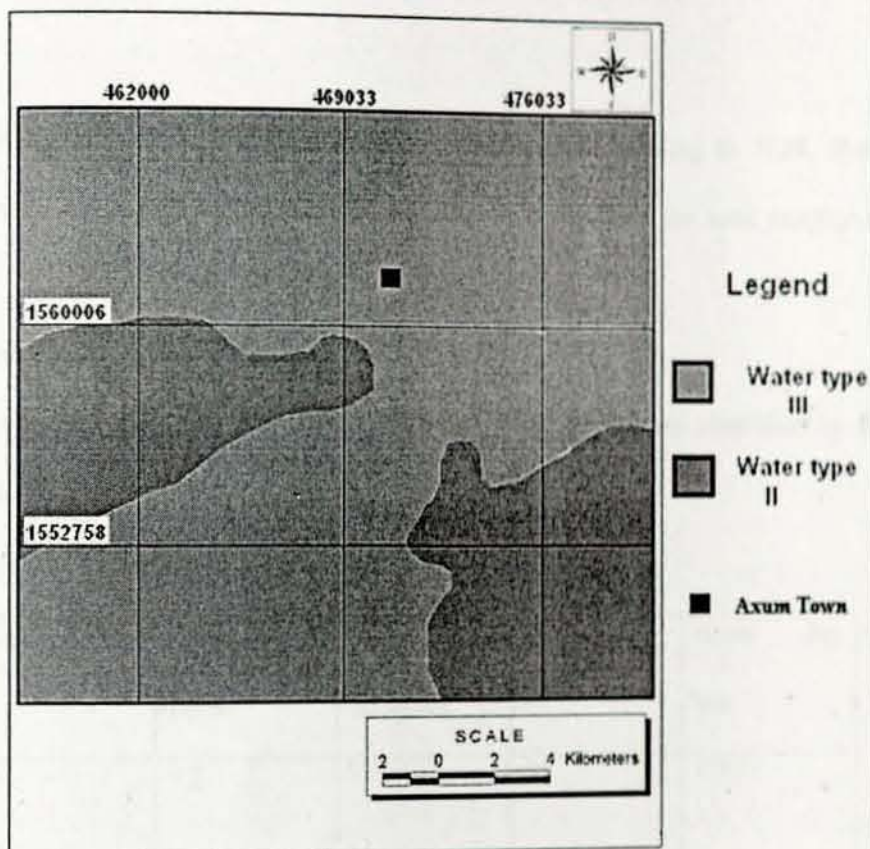


Table 6.12 Schoeller's Groundwater types of the study area.

Groundwater	No of Samples	%	Area sq. Km.
II	3	11.54	180
III	23	88.46	238

From Table 6.11 and Map 6.5 it is clear that type III predominate (88.46%) 23 samples out of 26 confirming a comparatively long residence time of water in the rocks.

6.5.3. Stuyfzand's classification of water

Stuyfzand (1989) in her classification formulated 8 main types, 11 types, 27 sub-types and 3 classes (Annexure 3)

Theoretically she formulated a maximum number of water types totaling to 7128. She further, explained that many water types do not exist in nature, which reduce the total number to a few hundreds.

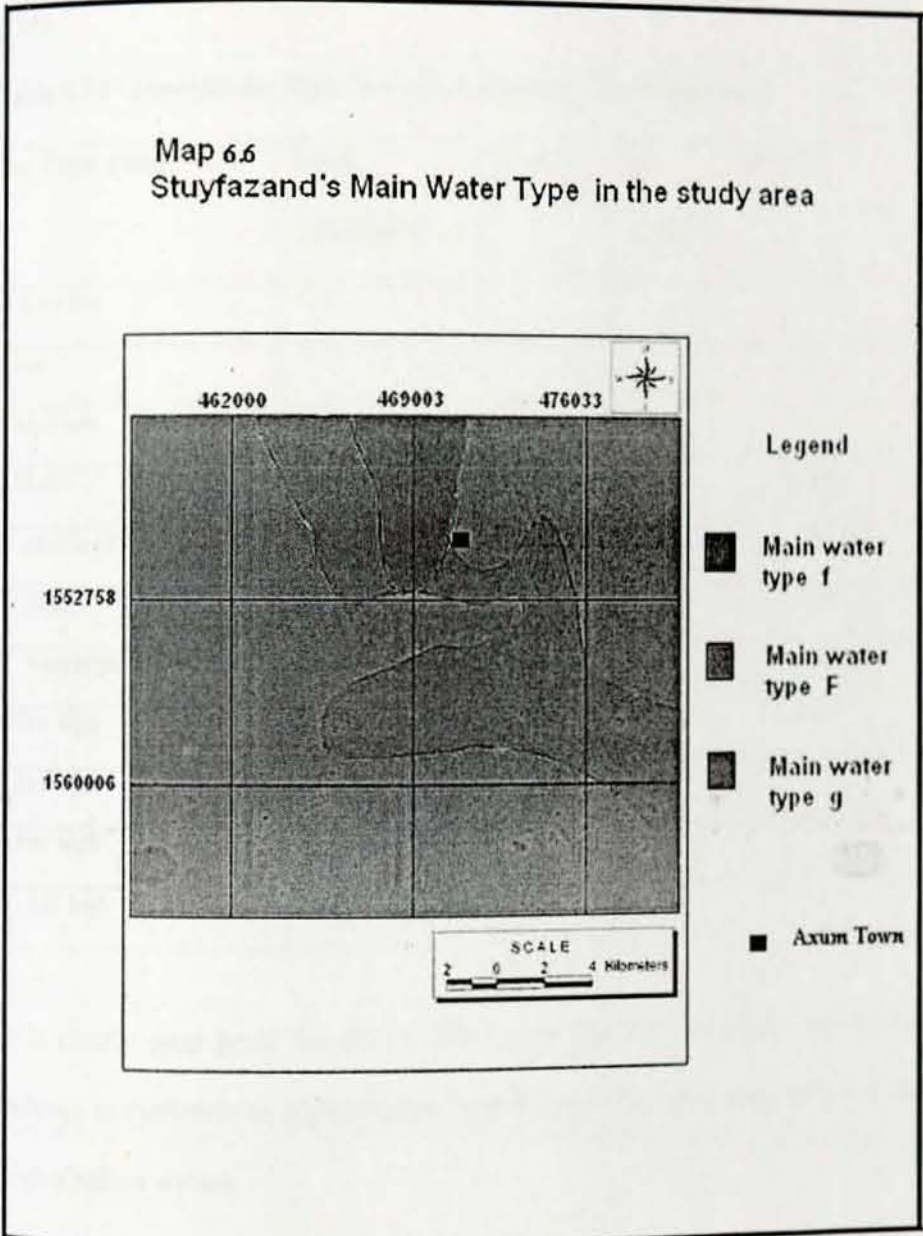
6.5.3.1 Stuyfzand's Main water type

Based on epm chlorine concentration 8 main types of water have been identified by stuyfzand (Op.Cit) (Table 6.13)

Table 6.13 Groundwater main type of the study area.

Main type	Code	Chlorine ppm	No of Samples	%	Area Sq. km
Very oligohaline	G	< 5	13	50	119.17
Oligohaline	g	5-30	12	46.15	282.94
Fresh	F	30-150	1	3.85	27.88
Fresh-brackish	f	150-300			
Bracksish	B	300-103			
Salt	S	104 -2x104			
Hyperhaline	H	>2x104			

It could be seen from the above Table 6.13 that fresh water types predominate followed by oligohaline and fresh brackish.



Map 6.6 shows the different main water types and their areal distribution in the study area.

6.5.3.2 Water Types

Stuyfzand (OP.Cit,) based on epm alkalinity classified the waters in to eleven sub-types (Table 6.14).

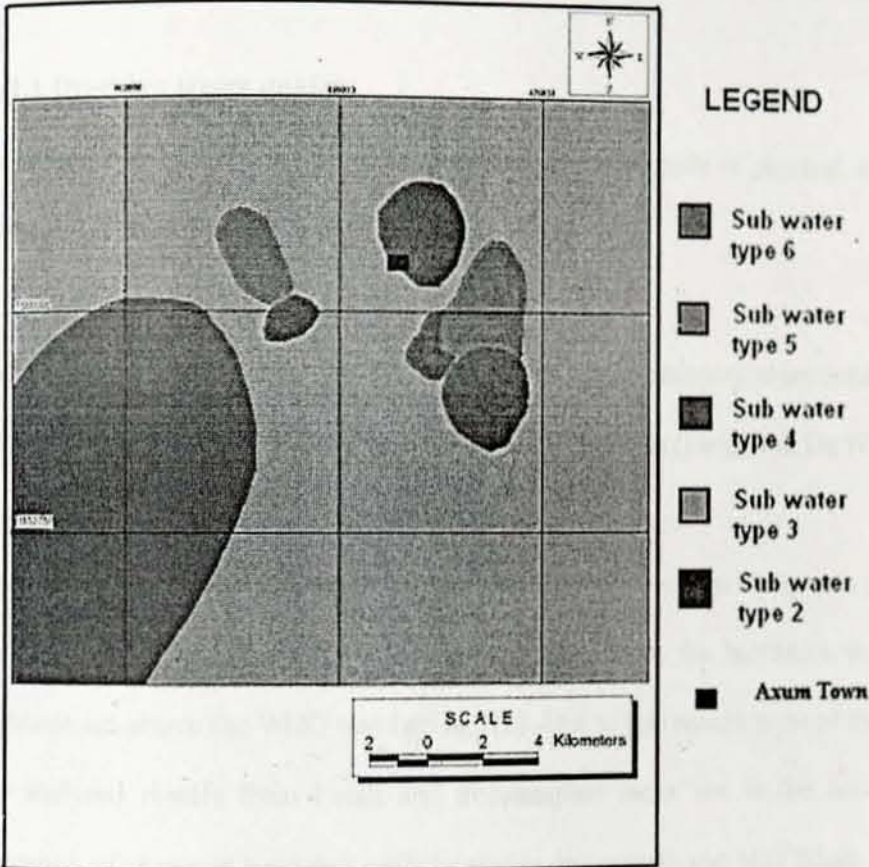
Table 6.14 Groundwater types based on alkalinity (after Stuyfzand)

No. Type name	Epm Alkalinity	Code	No of samples	%
-1 Very low	< ½	-		
0 low	½ - 1	0		
1 Mod-low	1-2	1		
2 Mod	2-4	2	2	7.69
3 Mod-high	4-8	3	19	70.07
4 High	8-16	4	2	7.69
5 Very high	16-32	5	2	7.69
6 Ext. high	32-64	6	1	3.85
7 Ext. high	64-128	7		
8 Ext. high	128-256	8		
9 Ext. high	>256	9		

It is clearly seen from the above Table 6.14 that 70.07% of the groundwater of the study area belongs to moderate to high alkaline type followed by equal proportion of moderate, high and very high alkaline waters.

Map 6.7

Stuyfzand's Sub water Type of the study area



Map 6.7 concentrates on Stuyfzand's water type based on alkalinity. The map is subdivided into 6 types and the quality of water is with reference to alkalinity in the upstream area is moderately high where as at the confluence downstream it is of extensively high.

6.6 Water Quality

In specifying the quality characteristic of water chemical, physical and biological analyses are normally required.

6.6.1 Water quality criteria

The quality required of a ground water supply depends on its purpose thus, needs for drinking water, industrial water and irrigation water vary widely (Todd)

6.6.1.1 Drinking water quality

Water that is to be used for drinking must have high standards of physical, chemical and biological purity.

Drinking water standards are based on two criteria; the presence of objectionable taste, odor or color and the presence of substances with adverse physical effects (Davis and De Wiest, 1966).

From the chemical analysis result of the different sources in the study area shows variable values. The chemical composition of the analyzed samples from the boreholes that penetrate the basalt mudstone are above the WHO standard in TDS. Due to this reason most of the wells are abandoned. The analyzed results from basalt and metamorphic rocks are in the acceptable limit with the exception of nitrate in hand dug wells located in Axum town and May Edega well.

6.6.1.2 Agricultural water quality

Water for agricultural needs demands salinity and sodium hazard to be low so that crop yields are good. % Na, R.S.C., SAR and PI are the same of the chemical parameters, which were coined for different uses. They are as follows.

Sodium Adsorption Ratio (SAR): Water quality problems in irrigation include salinity and toxicity. When sodium-rich water is applied to soil, some of the sodium is taken up by clay: the clay gives up

calcium and magnesium in exchange. This exchange alters the physical characteristics of soil and can lead to growth retardation (Tenalem & Tamiru,, 2001).

The effect of Sodium could be calculates by the sodium Adsorption Ratio (SAR) using the following relation.

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)}}$$

The three ions are expressed in milliequivalents.

Development of excessive sodium in soil will result from irrigation water that has high SAR Values (18 or above). Values below 10 indicate little danger of sodium hazard. In the study area all of the chemical analysis results show SAR values below 10. So Sodium hazard is minimum in the study area.

Considering the sodium hazard it is also possible to classify water for irrigation according to the following formula and EC values of water.

$$\% Na = \frac{(Na + K) 100}{(Ca + Mg + Na)}$$

Table 6.15 Classification of water based on % Na

Water class	Ec in µS/cm	% Na
Excellent	Less than 250	< 20
Good	250-750	20-40
Permissible	750-2250	40-60
Doubtful	2210-4000	60-80
Unsuitable	Greater than 4000	> 80

Based on the percentage sodium water class a contour map is produced. From the Map it is clearly seen that the chemical analysis results of % Na in the study area is below 20 and belongs to good water class for irrigation.

Residual sodium carbonate (RSC)

Eaton (1950) indicated that if waters which are used for irrigation contain excess $\text{CO}_3 + \text{HCO}_3$ than the equivalent $\text{Ca} + \text{Mg}$, then there will be a residue of NaHCO_3 when evaporation takes place and there will be an increase of soil pH.

$$\text{RSC} = \text{CO}_3 + \text{HCO}_3 - 2 (\text{Ca} + \text{Mg}), \text{ all ions expressed in epm.}$$

Table 6.16, Residual Sodium Carbonate values of Ground water.

RSC	Quality
< 1.25	Safe
1.25 - 2.5	Marginal
> 2.5	Not suitable

The study area is occupied by groundwater having $\text{RSC} < 1.25$ (100%), so it is safe quality for all irrigational utilities.

Permeability Index (PI)

Permeability Index was given by Doneen (1947) as

$\text{PI} = 100 (\text{Na} + \text{HCO}_3) / (\text{Ca} + \text{Mg} + \text{Na})$, using epm ionic values. Using permeability Index and total epm concentration the irrigation water quality could be determined as class I, II or III

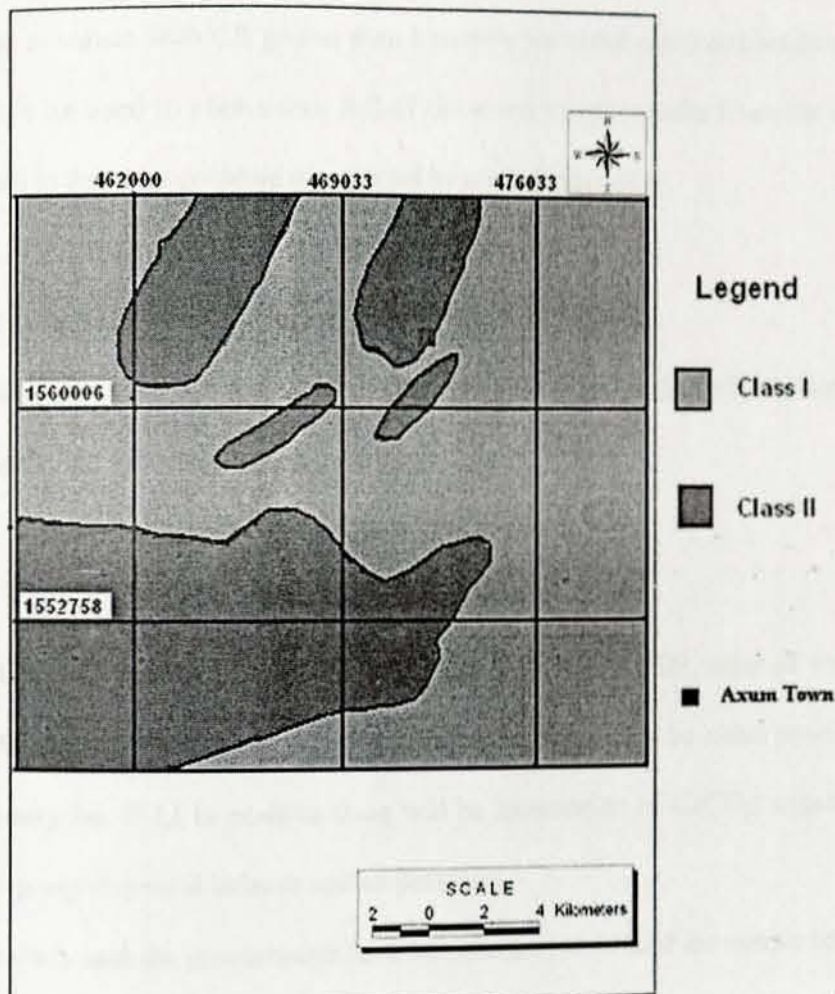
respectively (Annexture 3). Higher the PI lower will be the permeability of the soils and hence greater drainage problems i.e. unfit for irrigation.

Table 6.17, Permeability Index Classification of Groundwater.

Doneen's class	Quality	No. Of samples	%	Area sq. km
I	Good	20	76.92	
II	Moderate	6	23.07	
III	Unfit			

From the above Table 6.16 and Map 6.8, it could be seen that Doneen's permeability index class I predominate (76.92%) indicating high permeable horizons when used for irrigation.

Map 6.8
Pemeability Index Class of the study area



6.7 Water supply to different consumers

6.7.1 Corrosivity Ratio (CR)

A ratio for evaluating the corrosive tendency of waters towards metallic pipes was proposed by Ryzner (1944) and was used by Badrinath et. al., (1984) in India to evaluate the subaramathi river water to be transported by metal pipes.

Corrosivity Ratio = $(0.028 \text{ Cl} + 0.021 \text{ SO}_4) / 0.02 (\text{HCO}_3 + \text{CO}_3)$. All ionic values are expressed in ppm concentration. Water with less than 1 corrosivity ratio could be transported by metallic pipes, whereas waters with CR greater than 1 corrode the metal pipes and hence non-corrosive PVC pipes have to be used in such areas. All of the water sample results from the study area have CR <1. Waters in this area could be transported by metal pipes safely.

6.7.2 Langlier index

This is an index computed from the chemical analysis data (TDS, temperature of water, total hardness and total alkalinity).

$$pH_s = 9.3 + (A + B) - (C + D)$$

$$LI = pH - pH_s$$

A, B, C and D are values based on the concentration of TDS, temp of water, 2/3 (Total hardness) and total alkalinity and LI is the Langlier index.. The LI can be either positive or negative or zero as case may be. If LI is positive there will be incrustation of CaCO₃; negative means corrosion and zero means chemical balance and no problems.

The study area the groundwater have incrustation (61.54% of the sample tested).

Table 6.18 , Table of incrustation and corrosion of the study area

LI	No of Samples	%	Remarks
Positive	16	61.54	Incrustation
Zero	1	3.85	No problems
Negative	8	30.76	Corrosion
Not determined	1	3.85	
	26	100.00	

6.8 Groundwater Quality index (GWQI):

This may be defined as a rating reflecting the composite influence of overall quality of a number of individual quality characteristics. The procedural details are given in annexures of this thesis.

Table 6.19 Groundwater Quality Index

	Pollution Status	No. of Samples	%
<50	Severe	1	3.85
50-80	Moderate	5	19.23
80-95	Slight	5	19.23
>95	Permissible	19	73.08
	Total	26	100

The above table clearly points out the pollution status of the groundwater of Axum. chemically there is still life in these waters.

6.9 Microbiological analysis:

Since the tourist town of Axum has no underground drainage an detending on line financial status of the owners the septic tank utility or pit utility is practiced to release the sewage waste. Since the property is limited in areal extent the drinking water wells are adjacent to the sewage waste tanks and there is quite a sure chance of seepage to the deeper water sources. Groundwater samples have been collected and subjected to the Microbial Analysis to assess the coliforms and E. coli in the samples. (Annexures)

Except the hand pump well in the extreme south of the study area all the wells tapping the shallow, deep water table and the surface lakes are highly polluted by sewage waste.

The water has to be thoroughly boiled, cooled and filtered through microporous filters before drinking.

CHAPTER - 7

GROUNDWATER GEOPHYSICS

7.1 INTRODUCTION

Geophysics refers to the study of the earth with special reference to its physical properties, structure and composition. The geophysical prospecting techniques are based on various fundamental principles of physics like law of gravitational attraction, magnetics, optics, refraction and reflection, those elements of electricity and theory of electromagnetism. Geophysical methodologies have been in wide practice for the determination of lithology, depth of water bearing horizons and quality of groundwater etc. As time passed on using sophisticated instrumentation, intensive geophysical studies for gaining knowledge about the geometry of the water bearing horizons came in to existence.

Any groundwater investigation is considered to be incomplete without the application of geophysical methods for the assessment of water resources potential.

Taking advantage of the contrast in the physical property between dry, non-water bearing formation and water saturated formation, electrical resistivity surveys have become indispensable tools for hydrogeologists. A dry formation in comparison to the water bearing formation has a substantially high electrical resistivity. Thus, resistivity method helps in furnishing information regarding the depth to water table, thickness of water bearing horizon, depth to bedrock, existence of fissures, fractures and fault zones, existence of aquifers in sedimentary regions, structural and stratigraphic conditions, salt water-freshwater interfaces and permeability of the aquifer.

The resistivity method is used in the study of horizontal and vertical variations in the electrical properties of the ground, and in the detection of three-dimensional bodies of anomalous electrical conductivity.

Best results are obtained generally from a combination of horizontal profiling and electrical sounding data. Electrical sounding is the process by which depth investigations are made and horizontal profiling is the method by which lateral variation in resistivity are detected.

7.2 Geo-electrical parameters

A geoelectric layer is described by two fundamental parameters- its resistivity ρ_i and its thickness h_i where the subscript i indicates the position of the layer in the section ($i = 1$ for the uppermost layer).

Other geoelectric parameters are derived from its resistivity and thickness. These are

1. Longitudinal unit conductance, $S = h_i / \rho_i$, m/ Ω m i.e mhos

2. Transverse unit resistance, $T_i = h_i \rho_i$, Ω m²

3. Longitudinal resistivity, $\rho_L = h_i / S_i$, m/mhos i.e., Ω .m

4. Transverse resistivity, $\rho_t = T_i / h_i$, Ω m²/m i.e., Ω .m

5. Anisotropy, $\lambda = \sqrt{(\rho_t / \rho_L)}$, dimensionless.

For an isotropic layer $\rho_t = \rho_L$ and $\lambda = 1$. These secondary geo-electric parameters are particularly important when they are used to describe geo-electric sections consisting of several layers.

I) For n layers, the total longitudinal unit conductance is

$$S = \sum (h_i / \rho_i) = h_1 / \rho_1 + h_2 / \rho_2 + \dots + h_n / \rho_n$$

II) The total transverse unit resistance is

$$T = \sum (h_i \rho_i)$$

III) The average longitudinal resistivity is

$$\rho L = H / S$$

IV) The average transverse resistivity is

$$\rho t = T/H$$

V) and the anisotropy is

$$\lambda = \rho t / \rho L = \sqrt{T i / h i}$$

The parameters $S, T, \rho L, \rho t$, and λ are derived from consideration of a column of unit square cross-sectional area (1x1 meter) cut out of a group of layers of infinite lateral extent. If current flows vertically only through the column, then the layers in the column will behave as resistors connected in series, and the total resistance of the column of unit cross-sectional area will be:

$$R = R_1 + R_2 + R_3 + \dots + R_n,$$

$$= \Sigma(\rho_i h_i) = T$$

The symbol T is used instead of R to indicate that the resistance is measured in a direction transverse to the bedding and also because the dimensions of this "unit resistance" are usually expressed in ohm-m² instead of ohms.

If the current flows parallel to the bedding, the layers in the column will behave as resistors connected in parallel and the conductance will be

$$S = 1/R = 1/R_1 + 1/R_2 + \dots + 1/R_n$$

The dimensions of the longitudinal unit conductance are m/ohm- m/ohm-m = 1/ohm = mho. It is interesting to note that the quantity $S_i = h_i / \sigma_i = \sigma_i h_i$ where σ_i is the conductivity (inverse of

resistivity), is analogous to transmissibility $T_i = k_i b_i$ used in ground-water hydrology, where k_i is the hydraulic conductivity of the i th layer and b_i is its thickness.

The parameters T and S were named the "Dar Zarrouk" parameters by Maillet (1947).

Variations in ' S ' from the VES to the other have been used in a qualitative sense to indicate changes in the total thickness of low resistivity materials (Zohdy, 1969; Henrit, 1975; Worthington, 1977; Galin, 1979). Large ' S ' values are indicative of deeper basement and small ' S ' values are indicative of shallow basement. It has also been reported (Henriet, 1975; Galin, 1979) that high ' S ' values are indicative of low aquifer transmissibility.

This has been interpreted by either a qualitative or a quantitative manner. Quantitative interpretation attempts to develop a correlation between T and aquifer transmissibility (Scarascia, 1976).

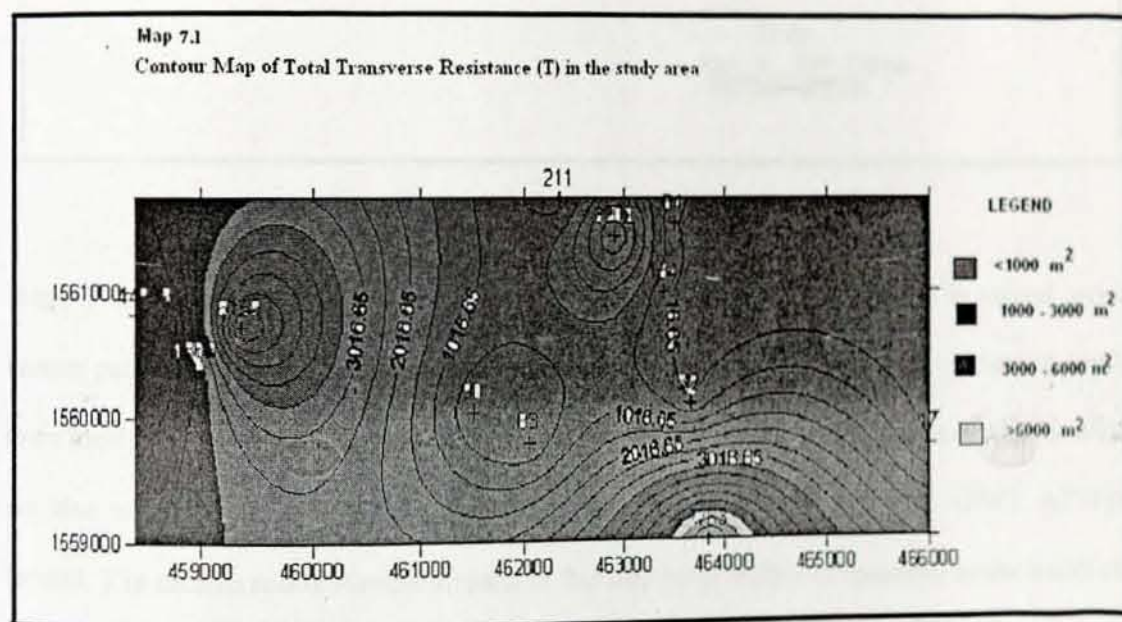
This property has been used to indicate the varying thickness of high resistivity materials and/ or variations in their transverse resistance (Zohdy et al. 1974). Increasing T values are indicative of an increase in the thickness of the high resistivity materials. It has been noticed (Matzner, 1983) that increasing Ts have coincided with high transmissibility's of aquifers.

The coefficient of anisotropy is usually greater than 1.00 but does not often exceed 2.00 (Zohdy et al., 1974). It can be used as a measure of finding out the extent of anisotropism prevailing in an area of interest. It accounts 1.02-1.10 for alluvium, 1.05-1.15 for sandstones and shales, 1.40-2.25 for slates and 2.0-2-8 for graphitic slates. As the hardness and compaction of rocks increase the coefficient of anisotropy also increase *(Keller and Frischknecht 1996).

Results:

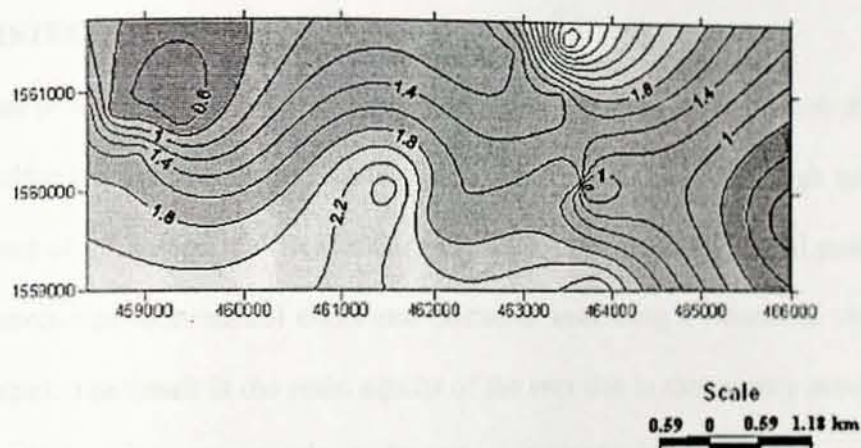
Geoelectrical T (* M2): Sharma (1982) pointed out that in sedimentary terrain of India (Haryana state) area with $T > 2000$ proved to be potential zones. Matzer (1983) observed that increasing values of T coincides with high hydrogeological transmissibility.

T values of the present study area varies between 8.63-7763.1. Both locations not covered in the map due to quite a lot of area is not studied geophysically. The consultants Devecon Engineers and Architects chose the sites at random adjacent to the Axum-Gondar road and the results are shown below.



As Map 7.2 clearly show high T value are located in the south east of this map and increases from north to south indicating that the resistive layer increases towards south where the basalt thickness increases and become more fresher than the basalt in the center of map area.

Map 7.2
Longitudinal Conductance (mhos) in the study area



Map 7.2 also show that high values of longitudinal conductance (S) is located in central and north eastern part of the map indicating that the basement (aquiclude) is located at a deeper depth. At these localities the basalt is highly fractured and weathered overlying the mudstone. These localities are also where high yield but deteriorated water quality boreholes (APW1, APW2, APW3) are located. The eastern and northwestern parts of this map have shallower basement as the basalt of this area is less weathered and aphanatic ridge forming basalt.

CHAPTER -8

WATER RESOURCE IDENTIFICATION

8.1 INTRODUCTION

Axum is situated in a water divide between the Tekeze River and Mereb River. This area is also characterized low amount of annual precipitation (672 mm/year), high amount of run off, low amount of infiltration and lack of large catchment area resulting limited groundwater development. However, due to structural effect and extensive weathering a substantial amount of water may be obtained. The basalt is the main aquifer of the area due to the primary structures of the basalt and secondary structures created due to fracturing and weathering of the basalt.

In the study area apart from lack of good potential area for groundwater development there is also a water quality problem. As it is said in the hydrogeochemistry part boreholes that penetrate the basalt and the mudstone (siltstone) area known for their deteriorated water quality though they may have relatively good quantity of water. In most of the boreholes drilled for water supply of Axum, good yield wells are known for their deteriorated water quality and low yields that penetrate mainly the basalt have excellent water quality but this may not be always true.

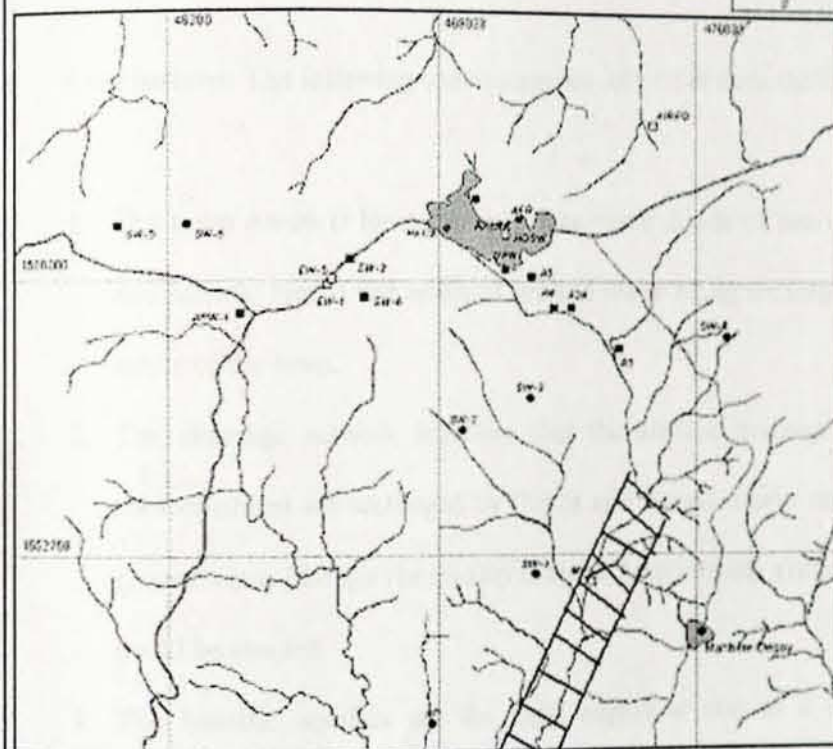
As can be seen from geological cross section in page 18 the mudstone (siltstone) appears below the basalt and covers the almost all party of the study area except where the phonolites and trachyte plugs appears. But surface exposure of this rock is very limited as it is covered by basaltic flows. The main problem in development of groundwater in the study area is the extensive coverage of the mudstone (siltstone) almost in all part of the study area that is responsible for deteriorated water quality though it may give a good yield during drilling.

In the study area, northwest of MahbereDegoy in Sinke River there is an angular discomformity that is the basalt lies immediately above the basement complex. In this area (map 8.1) the basalt is highly

fractured and weathered and the basaltic flow follow an en echelon type of structure and as it lies immediately above the basement that may suggest that the basalt may be recent and appear following the weak zone. In this area the water quality will be portable for drinking water as there is no mudstone below the basalt. In addition to locate potential areas and to detect the structures in detail a systematic geophysical survey should be conducted before any development is undertaken.

As it can be seen from the hydrogeochemistry part the water samples from the streams have good water quality and they have a lower amount of ions as compared to the ground water. Surface water development is recommended if the groundwater potential is limited in the proposed area.

Map 8.1
Location Map of New proposed site



LEGEND

- Hand dug wells
- Functional boreholes
- Abandoned boreholes
- Shallow wells
- ▲ Flocks
- ▨ Township
- Dry weather road
- - - All weather Road
- ~ Major Streams



Proposed area

CHAPTER- 9

CONCLUSION AND RECOMMENDATIONS

9.1 Conclusions: The following conclusions are arrived at from the foregoing discussions.

1. The town Axum is located at a surface water divide of two major rivers, that are Tekeze and Mereb. Hence not much of ground water being recharged and available within the limits of the town.
2. The drainage network indicates that the surface drainage density is low hence the subformations are recharged by Gebru and Harma creeks resulting a potential areas for groundwater (though the quality may be deteriorated) and artificial recharge structures could be erected.
3. The basaltic aquifers are the most exploited due to a better quality and quantity groundwater when compared with the other lithologies. The transmissivity values range between $2.26 - 109.44 \text{ m}^2/\text{d}$ with an average transmissivity value of $37 \text{ m}^2/\text{d}$
4. The trachytes plugs in the area are zone of run off rather than infiltration where as the phonolites are highly fractured and weathered creating a zone of recharge for groundwater. The mudstone & Basement complex are regional aquicludes with very limited potential for groundwater development.
5. Boreholes that penetrate the basalt and sedimentary formation are characterized by deteriorated water quality than the other boreholes may be due to metasomatism of ground water in the low permeable mudstone and may be the presence of a source of hydrocarbon with in this formation.

There are also floats of lacustrine deposits mainly calcium carbonate and the presence of a thin limestone bed above the mudstone may suggest that there was a paleo lake before the basalt flow cover the area. Thus dissolution may result mineralized water.

6. Water quality is excellent for agricultural use due to the low values of SAR and RSC.
7. Donneen PI class I predominates suggesting that soils have a good drainage and there will be no water logging problems when used for irrigation.
8. A large number of samples of groundwater have had long residence time and becomes chemically enriched due to Type III water of Schoeller that is $Na > Mg > Ca$.
9. Stuyfzand's scheme also suggests that groundwater of the area is moderately good.
10. A large majority of waters belong to Temporary hardness, which could be removed by strong boiling, cooling and filtration through microporous filters.
11. Salinity – Sodium hazard is moderate- but could be used for salt tolerant crop cultivation.
12. Majority of the ground water samples belong to $Ca-HCO_3$ facies.
13. Based on Langlier Index groundwaters of this area capable of incrustation of salts and not corrosive. And hence any material pipe can be used for transportation of water to consumer points.
14. Based on GWQI chemically the groundwater still has usable life by consumers not highly deteriorated.
15. Microbially the area is highly polluted by *E. coli* indicating human sewage pollution.

9.2 Recommendation

1. Meteorological data collecting observatory network not enough and has to be upgraded
2. Geomorphological analysis of the terrain has to be thoroughly done to locate places of recharge of groundwater.
3. Location of geophysical sites randomly has to be replaced by systematic survey in areas where small drainage density is low and are marked for future groundwater exploitation
4. Underground drainage, proper arrangement of discharge of human waste has to be arranged in the town.
5. For detail study of the hydrochemical variation of chemical ions isotopic data should be collected especially from the boreholes that penetrate the basalt and mudstone.
6. Public utility facility should be located where necessary.
7. Public systems like community shower, houses and toilets do not cover the most needy parts of the town as explained by some members of Axum town to Denver group.
8. New boreholes should be placed where the basalt is thick, the sedimentary formation may be the main reason for the deteriorated water quality.

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ANNEXTURE 1A

Monthly Precipitation (mm) at Axum

Year	J	F	M	A	M	J	J	A	S	O	N	D	Sum	Sum'
1961	-*	-	-	15	7	58	291	246	172	5	-	-	794	843
1963	0	0	7	46	49	58	249	203	11	26	31	0	680	680
1964	-	0	17	0	21	70	438	200	21	17	0	2	786	792
1965	5	0	22	14	0	15	183	309	36	19	27	10	641	641
1966	27	0	22	0	2	60	176	110	90	30	6	0	524	524
1967	0	0	95	42	17	92	249	-	-	21	35	0	552	811
1968	6	0	10	9	71	74	319	109	-	6	65	0	670	717
1969	23	25	32	72	22	28	171	99	0	3	2	0	476	476
1970	0	9	2	25	0	72	169	241	14	4	0	0	536	536
1971	1	0	0	19	57	52	134	124	0	10	0	0	396	396
1972	-	-	1	59	0	98	266	80	10	0	26	-	540	551
1973	0	0	6	63	61	50	223	156	64	42	0	0	665	665
1974	4	0	0	7	31	60	141	442	73	0	0	0	758	758
1992	-	-	-	15	20	57	176	427	78	24	57	4	858	887
1993	5	5	42	83	43	75	-	-	-	40	-	-	293	800
Mean	6	3	20	31	27	61	228	211	47	16	19	1		672

-* Missing data

ANNEXCTURE 1B

Mean Monthly Air Temperature ($^{\circ}\text{C}$) at Axum Station

Latitude: $14^{\circ}07'$

Longitude: $38^{\circ}44'$, altitude: 2239 m amsl

Year	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Annual Temp.
1992	19.45	19.45	22.15	21.80	21.95	22.10	18.65	17.60	17.70	17.75	17.15	17.25	19.42
1993	17.35	17.35	19.65	19.80	20.75	20.40	18.50	18.75	18.90	18.75	18.50	18.05	18.90
1994	18.25	19.25	20.55	21.45	22.20	20.45	18.10	18.00	17.50	18.30	18.80	18.40	19.27
1995	19.05	20.05	21.00	22.35	21.85	22.40	20.40	19.80	19.25	18.05	18.60	18.80	20.13
1996	18.40	19.35	20.90	19.25	19.80	19.40	18.60	18.95	19.90	19.30	19.05	16.90	19.15
Mean	18.50	19.09	20.85	20.93	21.31	20.95	18.86	18.62	18.65	18.43	18.42	17.88	19.37

Absolute Maximum Air Temperature ($^{\circ}\text{C}$) at Axum Station

Year	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	27.10	27.10	32.40	30.00	29.50	30.10	24.80	21.50	24.00	24.90	24.80	25.50	26.81
1993	26.50	25.80	28.20	26.80	28.50	28.20	23.90	26.00	25.30	26.60	27.30	27.60	26.73
1994	28.00	28.60	30.40	30.70	31.00	28.20	23.10	23.30	23.40	25.70	27.40	28.00	27.32
1995	29.10	29.50	30.00	30.60	29.70	29.80	27.10	25.30	26.20	26.20	27.60	28.10	28.26
1996	28.10	28.70	29.70	25.20	26.10	25.30	24.50	24.40	24.40	26.30	28.00	25.70	26.37
1997	25.80	26.50	27.90	27.80	27.80	27.00	25.20	26.10	25.20	27.40	27.10	26.40	26.68
Mean	27.43	27.70	29.77	28.52	28.77	28.10	24.77	24.43	24.75	26.18	27.03	26.88	27.03

Absolute Minimum Air Temperature ($^{\circ}\text{C}$) at Axum Station

Year	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	11.80	11.80	11.90	13.60	14.40	14.10	12.50	13.70	11.40	10.60	9.50	9.00	12.03
1993	8.20	8.90	11.10	12.80	13.00	12.60	13.10	11.50	12.50	10.90	9.70	8.50	11.07
1994	8.50	9.90	10.70	12.20	13.40	12.70	13.10	12.70	11.60	10.90	10.20	8.80	11.23
1995	9.00	10.60	12.00	14.10	14.00	15.00	13.70	14.30	12.30	9.90	9.60	9.50	12.00
1996	8.70	10.00	12.10	13.30	13.50	13.50	12.80	13.50	15.40	12.30	10.10	8.10	11.94
Mean	9.24	10.24	11.56	13.20	13.66	13.58	13.04	13.14	12.64	10.92	9.82	8.78	11.65

ANNEXTURE 1A: PUBLIC PARTICIPATION

Name of Beneficiary: _____
Address: _____
City: _____

Phone: _____
Fax: _____
E-mail: _____

ANNEXTURE 2: HYDROGEOLOGICAL DATA

ANNEXTURE 2A: PUMPING TEST DATA

Name of borehole EW-1

Discharge 5.00 l/s, Depth 73 m

SWL: 6.090 m

Duration (Min)	Water Level (m)	Drow Down (m)			
1.00	7.06	0.97	330	11.10	5.01
1.50	7.26	1.17	360	11.18	5.09
2.00	7.30	1.21	420	11.44	5.35
2.50	7.41	1.32	480	11.61	5.52
3.00	7.46	1.37	540	11.82	5.73
3.50	7.58	1.49	600	11.96	5.87
4.00	7.68	1.59	660	12.09	6.00
4.50	7.76	1.67	720	12.23	6.14
5.00	7.81	1.72	780	12.35	6.26
6.00	7.83	1.74	840	12.46	6.37
7.00	7.86	1.77	900	12.60	6.51
8.00	7.88	1.79	960	12.66	6.57
9.00	7.94	1.85	1020	12.75	6.66
10.00	7.97	1.88	1080	12.83	6.74
12.00	8.04	1.95	1140	12.89	6.80
14.00	8.10	2.01	1200	12.96	6.87
16.00	8.20	2.11	1260	13.03	6.94
18.00	8.26	2.17	1320	13.10	7.01
20.00	8.33	2.24	1380	13.18	7.09
25.00	8.42	2.33	1440	13.23	7.14
30.00	8.56	2.47	1500	13.29	7.20
35.00	8.62	2.53	1560	13.34	7.25
40.00	8.75	2.66	1620	13.35	7.26
45.00	8.84	2.75	1680	13.41	7.32
50.00	8.89	2.80	1740	13.46	7.37
55.00	8.98	2.89	1800	13.49	7.40
60	9.09	3.00	1860	13.53	7.44
70	9.21	3.12	1920	13.58	7.49
80	9.30	3.21	1980	13.61	7.52
90	9.43	3.34	2040	13.65	7.56
100	9.54	3.45	2100	13.68	7.59
120	9.75	3.66	2160	13.71	7.62
140	9.90	3.81	2220	13.75	7.66
160	10.06	3.97	2280	13.78	7.69
180	10.21	4.12	2340	13.81	7.72
210	10.41	4.32	2400	13.83	7.74
240	10.60	4.51	2460	13.85	7.76
270	10.80	4.71	2520	13.86	7.77
300	10.92	7.83			

Name of borehole EW-2
 Discharge: 2.50 l/s, depth 100 m
 SWL: 19.29 m

Continuous Pumping Test						Recovery Test		
Duration (min)	Water Level (m)	Drow Down (m)				Time from end of pumping	Water Level (m)	Residual drowdown
1.00	23.05	3.76	330	27.12	7.83	1	25.41	6.112
1.50	23.37	4.08	360	27.12	7.83	2.5	24.93	5.64
2.00	23.50	4.21	420	27.12	7.83	4.5	24.45	5.16
2.50	23.78	4.49	480	27.12	7.83	7	24.17	4.88
3.00	23.99	4.70	540	27.12	7.83	10.00	23.99	4.70
3.50	24.10	4.81	600	27.18	7.89	13.50	23.74	4.45
4.00	24.21	4.92	660	27.41	8.12	17.50	23.57	4.28
4.50	24.37	5.08	720	27.63	8.34	22.00	23.45	4.16
5.00	24.41	5.12	780	27.79	8.50	27.00	23.40	4.11
6.00	24.53	5.24	840	27.85	8.56	33	23.34	4.05
7.00	24.61	5.32	900	27.90	8.61	40	23.27	3.98
8.00	24.75	5.46	960	27.95	8.66	48	23.19	3.90
9.00	24.76	5.47	1020	28.00	8.71	57	23.05	3.76
10.00	24.77	5.48	1080	28.07	8.78	67	22.97	3.68
12.00	24.95	5.66	1140	28.13	8.84	79	22.90	3.61
14.00	25.13	5.84	1200	28.13	8.84	93	22.79	3.50
16.00	25.34	6.05	1260	28.13	8.84	109	22.69	3.40
18.00	25.58	6.29	1320	28.13	8.84	127	22.57	3.28
20.00	25.76	6.47	1380	28.13	8.84	147	22.50	3.21
25.00	26.55	7.26	1440	28.13	8.84	172	22.39	3.10
30.00	26.73	7.44	1500	28.15	8.84	202	22.28	2.99
35.00	26.73	7.44	1560	28.15	8.86	237	22.17	2.88
40.00	26.77	7.48	1620	28.15	8.86	277	22.06	2.77
45.00	26.88	7.59	1680	28.15	8.86	322	21.98	2.69
50.00	26.97	7.68	1740	28.15	8.86	372	21.90	2.61
55.00	27.05	7.76	1800	28.15	8.86	427	21.83	2.54
60	27.08	7.79	1860	28.15	8.86	487	21.78	2.49
70	27.09	7.80	1920	28.15	8.86	557	21.67	2.38
80	27.10	7.81	1980	28.15	8.86	637	21.55	2.26
90	27.11	7.82	2040	28.15	8.86	727	21.47	2.18
100	27.11	7.82	2100	28.15	8.86	827	21.40	2.11
120	27.11	7.82	2160	28.15	8.86	947	21.33	2.04
140	27.11	7.82	2220	28.20	8.91	1087	21.25	1.96
160	27.11	7.82	2280	28.20	8.91	1247	21.15	1.86
180	27.11	7.82	2340	28.20	8.91	1427	21.03	1.74
210	27.11	7.82	2400	28.20	8.91	1637	20.97	1.68
240	27.11	7.82	2460	28.20	8.91	1877	20.94	1.65
270	27.11	7.82				2147	20.88	1.59
300	27.12	7.83				2447	20.80	1.51
						2777	20.74	1.45

Name of borehole EW-3

Discharge: 2.5 l/s, borehole depth 60 m

Static Water Level: 2.42 m below datum. Continuous and Recovery tests

Pumping Duration (s)	Water Level(m)	Drawdown (m)				Time from End of Pumping	Water Level (m)	R. Drow-down			
60	3.9	1.48	21600	14.67	12.25	60	23.50	21.08	25200	3.84	1.42
120	4.1	1.68	23400	24.98	22.56	120	23.35	20.93	28800	3.48	1.06
180	4.15	1.73	25200	25.83	23.41	180	23.02	20.60	32400	3.15	0.73
240	4.25	1.83	28800	25.92	23.50	240	22.53	20.11	36000	2.85	0.43
300	4.33	1.91	32400	26.30	23.88	300	21.98	19.56	39600	2.66	0.24
360	4.40	1.98	36000	26.45	24.03	360	21.56	19.14	43200	2.55	0.13
420	4.48	2.06	39600	26.66	24.24	420	20.86	18.44	50400	2.48	0.06
480	4.55	2.13	43200	26.95	24.53	480	17.49	15.07			
540	4.60	2.18	50400	27.01	24.59	540	17.35	14.93			
600	4.70	2.28	57600	27.06	24.64	600	16.61	14.19			
720	4.80	2.38	64800	27.30	24.88	720	16.51	14.09			
840	4.84	2.42	72000	27.56	25.14	840	16.40	13.98			
960	4.88	2.46	79200	27.83	25.41	960	16.29	13.87			
1080	5.01	2.59	86400	28.12	25.70	1080	16.07	13.65			
1200	5.23	2.81	93600	28.41	25.99	1200	15.78	13.36			
1500	5.48	3.06	100800	28.63	26.21	1500	15.65	13.23			
1800	5.75	3.33	108000	29.45	27.03	1800	15.04	12.62			
2100	6.03	3.61	115200	29.87	27.45	2100	14.75	12.33			
2400	6.20	3.78	122400	30.17	27.75	2400	14.06	11.64			
2700	6.52	4.10	129600	32.25	29.83	2700	13.60	11.18			
3000	6.68	4.26	136800	32.89	30.47	3000	13.03	10.61			
3300	6.83	4.41	144000	33.18	30.76	3300	12.00	9.58			
3600	7.03	4.61	151200	33.34	30.92	3600	11.42	9.00			
4200	7.32	4.90	158400	33.56	31.14	4200	10.75	8.33			
4800	7.65	5.23	165600	33.75	31.33	4800	8.70	6.28			
5400	7.96	5.54	172800	34.06	31.64	5400	8.37	5.95			
6000	8.22	5.80	180000	34.96	32.54	6000	7.79	5.37			
7200	8.74	6.32	187200	35.14	32.72	7200	7.48	5.06			
8400	9.19	6.77	194400	35.45	33.03	8400	7.35	4.93			
9600	9.60	7.18	201600	35.83	33.41	9600	6.93	4.51			
10800	9.93	7.51	208800	36.21	33.79	10800	6.64	4.22			
12600	10.54	8.12	216000	36.74	34.32	12600	6.07	3.65			
14400	10.98	8.56	223200	37.07	34.65	14400	5.68	3.26			
16200	11.53	9.11	230400	38.85	36.43	16200	5.28	2.86			
18000	11.94	9.52	237600	40.68	38.26	18000	4.92	2.50			
19800	13.21	10.79	244800	43.29	40.87	19800	4.65	2.23			
			252000	44.54	42.12	21600	4.32	1.90			
			259200	45.11	42.69	23400	4.08	1.66			

Name of borehole EW-4

Discharge: 9.14 l/s, SWL: 3.65 m, depth 70 m

Continuous Pumping Test						Recovery Test					
Duration (s)	Water Level	Drow- Down (m)				Time From end Of pumping	Water Level (m)	Resid- ual Drow- down			
60	4.33	0.68	23400	14.10	10.45	60	19.51	15.86	25200	16.45	12.80
120	4.46	0.81	25200	14.38	10.73	120	19.49	15.84	28800	16.12	12.47
180	4.65	1.00	28800	14.97	11.32	180	19.48	15.83	32400	15.76	12.11
240	4.75	1.10	32400	15.50	11.85	240	19.47	15.82	36000	15.56	11.91
300	4.87	1.22	36000	15.88	12.23	300	19.45	15.80	39600	15.24	11.59
360	4.96	1.31	39600	16.25	12.60	360	19.43	15.78	43200	14.98	11.33
420	5.10	1.45	43200	16.63	12.98	420	19.41	15.76	50400	14.72	11.07
480	5.18	1.53	50400	17.30	13.65	480	19.39	15.74	57600	14.54	10.89
540	5.26	1.61	57600	17.77	14.12	540	19.38	15.73	64800	13.84	10.19
720	5.48	1.83	64800	18.20	14.55	600	19.37	15.72	72000	13.15	9.50
840	5.67	2.02	72000	18.28	14.63	720	19.35	15.70	79200	12.73	9.08
960	5.92	2.27	79200	18.30	14.65	840	19.33	15.68	86400	12.35	8.70
1080	6.01	2.36	86400	18.33	14.68	960	19.31	15.66	93600	11.95	8.30
1200	6.02	2.37	93600	18.37	14.72	1080	19.30	15.65	100800	11.50	7.85
1500	6.54	2.89	100800	18.32	14.67	1200	19.28	15.63	108000	11.14	7.49
1800	6.88	3.23	108000	18.35	14.70	1500	19.20	15.55	115200	10.68	7.03
2100	7.05	3.40	115200	18.40	14.75	1800	19.14	15.49	122400	10.33	6.68
2400	7.27	3.62	122400	18.40	14.75	2100	19.12	15.47	129600	10.20	6.55
2700	7.63	3.98	129600	18.45	14.80	2400	19.08	15.43	136800	9.80	6.15
3000	7.75	4.10	136800	18.49	14.84	2700	19.06	15.41	144000	9.39	5.74
3300	7.80	4.15	144000	18.60	14.95	3000	19.01	15.36	151200	9.05	5.40
3600	8.10	4.45	151200	18.75	15.10	3300	18.98	15.33	158400	8.75	5.10
4200	8.45	4.80	158400	18.90	15.25	3600	18.93	15.28	165600	8.50	4.85
4800	8.74	5.09	165600	19.05	15.40	4800	18.81	15.16	172800	7.95	4.30
5400	9.00	5.35	180000	19.20	15.55	5400	18.73	15.08	180000	7.90	4.25
6000	9.28	5.63	187200	19.22	15.57	6000	18.68	15.03	187200	7.63	3.98
7200	9.45	5.80	194400	19.23	15.58	7200	18.55	14.90	194400	7.48	3.83
8400	10.03	6.38	201600	19.26	15.61	8400	18.37	14.72	201600	7.20	3.55
9600	10.45	6.80	208800	19.30	15.65	9600	18.20	14.55	208800	7.07	3.42
10800	10.83	7.18	216000	19.40	15.75	10800	18.07	14.42	216000	6.85	3.20
12600	11.45	7.80	223200	19.41	15.76	12600	17.81	14.16	223200	6.62	2.97
14400	11.95	8.30	230400	19.57	15.92	14400	17.58	13.93	230400	6.40	2.75
16200	12.42	8.77	237600	19.68	16.03	16200	17.31	13.66	237600	6.28	2.63
18000	12.87	9.22	244800	19.78	16.13	18000	17.18	13.53	244800	6.15	2.50
19800	13.28	9.63	252000	19.78	16.13	19800	17.01	13.36	259200	5.92	2.27
21600	13.68	10.03	259200	19.80	16.15	21600	16.84	13.19	252000	6.05	2.40
						23400	16.60	12.95	259200	5.92	2.27

Name of borehole EW-6
 Discharge: 3.40 l/s, depth 102 m
 SWL: 1.75 m

Continuous pumping test						Recovery test					
Duration (s)	Water Level (m)	Drow down				Time From end Of pump(m)	Water Level	Resi. Drow Down			
60	2.75	1	25200	12.66	10.91	60	2.31	24.56	210900	2.70	0.95
120	4.76	3.01	28800	13.45	11.70	180	22.98	21.23	236100	2.67	0.92
180	6.76	5.01	32400	14.06	12.31	360	19.40	17.65	264900	2.60	0.85
240	6.84	5.09	36000	14.57	12.82	600	16.92	15.17	297300	2.56	0.81
300	6.93	5.18	39600	15.05	13.30	900	14.89	13.14	333300	2.47	0.72
360	7.08	5.33	43200	15.38	13.63	1260	13.19	11.44	372900	2.45	0.70
420	7.26	5.51	50400	15.83	14.08	1680	11.79	10.04	416100	2.43	0.68
480	7.32	5.57	57600	16.29	14.54	2160	10.28	8.53	466500	2.41	0.66
540	7.38	5.63	64800	16.75	15.00	2700	9.38	7.63	524100	2.40	0.65
600	7.46	5.71	72000	17.08	15.33	3300	8.56	6.81	588900	2.39	0.64
720	7.57	5.82	79200	17.92	16.17	4020	7.34	5.59	660900	2.38	0.63
840	7.67	5.92	86400	18.60	16.85	4860	6.70	4.95	740100	2.38	0.63
960	7.75	6.00	93600	18.69	16.94	5820	6.17	4.42			
1080	7.82	6.07	100800	18.78	17.03	6900	5.57	3.82			
1200	7.91	6.16	108000	19.80	18.05	8100	5.31	3.56			
1500	8.00	6.25	115200	20.10	18.35	9600	4.91	3.16			
1800	8.10	6.35	122400	20.39	18.64	11400	4.72	2.97			
2100	8.20	6.45	129600	20.82	19.07	13500	4.38	2.63			
2400	8.23	6.48	136800	21.10	19.35	15900	4.24	2.49			
2700	8.29	6.54	144000	22.78	21.03	18600	4.13	2.38			
3000	9.08	7.33	151200	23.12	21.37	21600	4.02	2.27			
3300	9.67	7.92	158400	23.12	21.37	24900	3.92	2.17			
3600	9.83	8.08	165600	22.95	21.20	28500	3.87	2.12			
4200	9.94	8.19	172800	23.69	21.94	32700	3.76	2.01			
4800	10.05	8.30	187200	25.62	23.87	37500	3.68	1.93			
5400	10.14	8.39	201600	25.92	24.17	42900	3.51	1.76			
6000	10.24	8.49	216000	27.40	25.65	48900	3.50	1.75			
7200	10.32	8.57	230400	28.08	26.33	56100	3.39	1.64			
8400	10.42	8.67	244800	28.90	27.15	64500	3.30	1.55			
9600	10.50	8.75				74100	3.20	1.45			
10800	10.59	8.84				84900	3.15	1.40			
12600	10.78	9.03				97500	3.07	1.32			
14400	10.93	9.18				111900	2.94	1.19			
16200	11.07	9.32				128100	2.87	1.12			
18000	11.21	9.46				146100	2.85	1.10			
19800	11.37	9.62				165900	2.80	1.05			
21600	11.68	9.93				187500	2.78	1.03			

Name of borehole EW-8
 Discharge:4.96 l/s, depth
 SWL: 9.26 m

Continuous test						Recovery test					
Duration (s)	Water Level(m)	Drow Down (m)				Time From End of p	Water Level (m)	Resi - dual D.D			
60	37.08	27.82	23400	76.46	67.20	60	79.08	69.82	210900	29.11	19.85
180	37.53	28.27	25200	76.73	67.47	180	71.83	62.57	236100	28.93	19.67
240	39.58	30.32	28800	77.03	67.77	360	66.13	56.87	264900	28.68	19.42
300	41.93	32.67	32400	77.40	68.14	600	61.13	51.87	297300	28.23	18.97
360	44.95	35.69	36000	77.45	68.19	900	57.23	47.97	333300	27.78	18.52
420	46.88	37.62	39600	78.23	68.97	1260	53.63	44.37	372900	27.35	18.09
480	48.76	39.50	43200	79.08	69.82	1680	51.03	41.77	416100	27.05	17.79
540	52.06	42.80	50400	79.63	70.37	2160	48.63	39.37	466500	26.77	17.51
600	52.88	43.62	57600	80.38	71.12	2700	46.93	37.67	524100	26.18	16.92
720	54.90	45.64	64800	80.74	71.48	3300	44.88	35.62	588900	25.72	16.46
840	56.73	47.47	72000	81.10	71.84	4020	42.98	33.72	660900	25.26	16.00
960	58.39	49.13	79200	81.63	72.37	4860	41.28	32.02	740100	24.93	15.67
1080	59.06	49.80	86400	81.13	71.87	5820	40.02	30.76	826500	24.5	15.24
1200	59.88	50.62	93600	81.73	72.47	6900	39.09	29.83	920100	24.23	14.97
1500	61.75	52.49	100800	82.01	72.75	8100	38.08	28.82	1020900	24.08	14.82
1800	63.38	54.12	108000	81.83	72.57	9600	37.03	27.77	1078900	23.76	14.50
2100	64.30	55.04	115200	81.73	72.47	11400	36.13	26.87	1244100	23.44	14.18
2400	65.18	55.92	122400	82.63	73.37	13500	35.63	26.37	1366500	23.16	13.90
2700	65.74	56.48	129600	82.98	73.72	15900	35.13	25.87	1496100	22.91	13.65
3000	66.29	57.03	136800	83.17	73.91	18600	34.83	25.57			
3300	66.83	57.57	144000	82.83	73.57	21600	34.48	25.22			
3600	67.01	57.75	151200	83.65	74.39	24900	34.16	24.90			
4200	67.71	58.45	158400	83.65	74.39	28500	33.93	24.67			
4800	68.23	58.97	165600	83.70	74.44	32700	33.63	24.37			
5400	70.15	60.89	172800	84.18	74.92	37500	33.33	24.07			
6000	70.93	61.67	180000	84.58	75.32	42900	32.98	23.72			
7200	71.80	62.54	187200	87.73	78.47	48900	32.75	23.49			
8400	72.26	63.00	194400	87.43	78.17	64500	32.53	23.27			
9600	73.93	64.67	201600	87.68	78.42	74100	31.93	22.67			
10800	74.63	65.37	208800	88.03	78.77	84900	31.63	22.37			
12600	74.73	65.47	216000	88.58	79.32	97500	31.35	22.09			
14400	75.23	65.97	223200	88.58	79.32	111900	30.88	21.62			
16200	75.26	66.00	230400	88.36	79.10	128100	30.47	21.21			
18000	75.68	66.42	237600	88.63	79.37	146100	30.11	20.85			
19800	75.96	66.70	244800	88.79	79.53	165900	29.75	20.49			
21600	76.21	66.95	252000	88.73	79.47	187500	29.48	20.22			

ANNEXTURE 2B

Water Level Measurements in Hand dug wells and Shallow wells

Name	Easting	Northing m	Topographic		WL AMSL (X')	GDWT (D=X'-X)
			WL BGL	Height AMSL		
HP	471180	1561600	7.5	2237.77	2230.27	30.57
GPN	470767	1560230	7.55	2222.66	2215.11	15.41
AFH	471168	1561562	7.2	2233.33	2226.13	26.43
HCW	469176	1561319	7.45	2238.26	2230.81	31.11
KALH	470133	1561286	15.25	2239	2223.75	24.05
EW-1	466025	1559856	12	2198	2186	-13.7
EW-2	466609	1560520	19.29	2205.5	2186.21	-13.49
EW-3	466413	1559832	3.35	2204	2200.65	0.95
EW4	467284	1559517	5.91	2209.66	2203.75	4.05
EW6	466989	1559509	4.5	2206.21	2201.71	2.01
EW8	467739	1559428	18.89	2216.16	2197.27	-2.43
APW2	463266	1559519	4.54	2176	2171.46	-28.24
APW3	462970	1559686	7.91	2188.75	2180.84	-18.86
APW5	467841	1559658	8.06	2221	2212.94	13.24
SW-3	471444	1556889	16	2173	2157	-42.7
SW-4	476915	1558519	4	2211	2207	7.3
SW-2	469617	1556049	5	2169	2164	-35.7
Average					X= 2199.7	

ANNEXTURE 3: HYDROCHEMISTRY

NATIONAL RESEARCH INSTITUTE OF HEALTH: WELL N^o 1 (TR 30032) (AXUM), 5/08/92

I
 Temperature at the time of collection: 21.30 °C
 Appearance: Colourless
 Odour: Odourless
 Taste: Tasteless
 Settling Solids: Absent
 Floating Solids: Absent
 Suspended Solids: Colourless
 Colour, true: Clear
 Turbidity: 476.0
 Filterable Residue dried at 105 °C: -
 Filterable Residue dried at °C: -
 Total Solids dried at °C: -
 Electrical Conductivity/Resistivity at 25°C: 7.1
 pH at 20°C: Nil
 Carbonate Alkalinity as CaCO₃: 320.0
 Bicarbonate Alkalinity as CaCO₃: -
 Hydroxyl Alkalinity as CaCO₃: -
 Acidity as CaCO₃: -
 Total Hardness as CaCO₃: 260.0 ✓
 Organic Nitrogen (N): -
 Phenolic Compounds as Phenol: -
 Carbondioxide (CO₂): -
 Oxygen (O₂): -
 Chlorine, residual (Cl₂): -
 Chlorine, total (Cl₂): -
 Sulphide as Hydrogen Sulphide: -
 Silica, total (SiO₂): 65.0
 Oxygen absorbed from Permanganate at for: -

VI
 Miscellaneous

II
 Cations: mg/L (mmoles)
 H⁺: -
 NH₄⁺: Nil
 Na⁺: Nil
 K⁺: 4.0
 Li⁺: -
 Ag⁺: -
 Ba⁺⁺: -
 Ca⁺⁺: 52.9
 Mg⁺⁺: 33.0
 Fe⁺⁺: -
 Fe⁺⁺⁺: -
 Fe, total: 0.06
 Mn⁺⁺: -
 Zn⁺⁺: -
 Cu⁺⁺: -
 Al⁺⁺⁺: -
 Sn⁺⁺⁺⁺: -
 Anions:
 OH⁻: -
 Cl⁻: 28.4
 NO₂⁻: Nil
 NO₃⁻: 15.0
 I⁻: -
 Br⁻: -
 P⁻: 0.32
 HCO₃⁻: 320.4
 CO₃⁻: Nil
 SO₄⁻: 10.8
 PO₄⁻ Ortho: Nil
 PO₄⁻ meta/poly: -

III
 Arsenic: - Lead: -
 Cadmium: - Mercury: -
 Chromium, hexavalent: - Nickel: -
 Cobalt: - Selenium: -
 Cyanide: - Strontium: -

IV
 Boron: -
 Sodium%: Na x 100 : -
 Na+K+Mg+Ca

V
 Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH: WELL N° 2 (TR 30038) (AXUM), 15/9/92

I
 Temperature at the time of collection: _____
 Appearance: _____ Colourless
 Odour: _____ Odourless
 Taste: _____ Salty
 Settleable Solids: _____ Present
 Floating Solids: _____ Absent
 Suspended Solids: _____ Present
 Colour, true: _____ Colourless
 Turbidity: _____ Clear
 Filterable Residue dried at 105 °C: 1257.0
 Filterable Residue dried at °C: _____
 Total Solids dried at °C: _____
 Electrical Conductivity/Resistivity at 25°C: _____
 pH at 20°C: 7.3
 Carbonate Alkalinity as CaCO₃: Nil
 Bicarbonate Alkalinity as CaCO₃: 1010.0
 Hydroxyl Alkalinity as CaCO₃: _____
 Acidity as CaCO₃: _____
 Total Hardness as CaCO₃: 700.0 ✓
 Organic Nitrogen (N): _____
 Phenolic Compounds as Phenol: _____
 Carbondioxide (CO₂): _____
 Oxygen (O₂): _____
 Chlorine, residual (Cl₂): _____
 Chlorine, total (Cl₂): _____
 Sulphide as Hydrogen Sulphide: _____
 Silica, total (SiO₂): 70.0
 _____ absorbed from Permanganate at
 for _____

II
 Cations
 H⁺: _____
 NH₄⁺: 0.18
 Na⁺: 204.0
 K⁺: 14.5
 Li⁺: _____
 Ag⁺: _____
 Ba⁺⁺: _____
 Ca⁺⁺: 256.5
 Mg⁺⁺: 14.6
 Fe⁺⁺: _____
 Fe⁺⁺⁺: _____
 Fe, total: 1.92
 Mn⁺⁺: _____
 Zn⁺⁺: _____
 Cu⁺⁺: _____
 Al⁺⁺⁺: _____
 Sn⁺⁺⁺⁺: _____

Anions
 OH⁻: _____
 Cl⁻: 49.6
 NO₃⁻: 0.04
 NO₂⁻: 5.3
 I⁻: _____
 Br⁻: _____
 F⁻: Negligible
 HCO₃⁻: 1268.8
 CO₃²⁻: Nil
 SO₄²⁻: 45.3
 PO₄³⁻ Ortho: Nil
 PO₄³⁻ meta/poly: _____

III
 Arsenic: _____ Lead: _____
 Cadmium: _____ Mercury: _____
 Chromium, hexavalent: _____ Nickel: _____
 Cobalt: _____ Selenium: _____
 Cyanide: _____ Strontium: _____

IV
 Boron: _____
 Sodium%: $\frac{\text{Na}}{\text{Na} + \text{K} + \text{Mg} + \text{Ca}} \times 100$: _____

V
 Radiological Examination _____

VI
 Miscellaneous

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH MAI DAGA N^o8 (AXUM), 4/02/94

I	
Temperature at the time of collection: _____	
Appearance:	Colourless
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	Colourless
Turbidity:	Clear
Filterable Residue dried at 105 °C:	707.0
Filterable Residue dried at _____ °C:	_____
Total Solids dried at _____ °C:	_____
Electrical Conductivity/Resistivity at 25°C:	904.0 $\mu\text{mhos/cm}$
pH at 20°C:	6.9
Carbonate Alkalinity as CaCO_3 :	Nil
Bicarbonate Alkalinity as CaCO_3 :	262.0
Hydroxyl Alkalinity as CaCO_3 :	_____
Acidity as CaCO_3 :	_____
Total Hardness as CaCO_3 :	408.0
Organic Nitrogen (N):	_____
Phenolic Compounds as Phenol:	_____
Carbondioxide (CO_2):	_____
Oxygen (O_2):	_____
Chlorine, residual (Cl_2):	_____
Chlorine, total (Cl_2):	_____
Sulphide as Hydrogen Sulphide:	_____
Silica, total (SiO_2):	56.0
Oxygen absorbed from _____	Permanganate at _____
for _____	_____

VI
Miscellaneous

II	
Cations	Anions
H^+ : _____	OH^- : _____
NH_4^+ : 0.08	Cl^- : 78.0
Na^+ : 39.0	NO_2^- : 0.01
K^+ : 3.0	NO_3^- : 113.0
Li^+ : _____	I^- : _____
Ag^+ : _____	Br^- : _____
Ba^{++} : _____	F^- : Nil
Ca^{++} : 115.4	HCO_3^- : 319.6
Mg^{++} : 29.2	CO_3^{--} : Nil
Fe^{++} : _____	SO_4^{--} : 35.8
Fe^{+++} : _____	PO_4^{--} Ortho : 0.06
Fe, total : Nil	PO_4^{--} meta/poly : _____
Mn^{++} : Nil	
Zn^{++} : _____	
Cu^{++} : _____	
Al^{+++} : _____	
Sn^{++++} : _____	

III	
Arsenic : _____	Lead : _____
Cadmium : _____	Mercury : _____
Chromium, hexavalent : _____	Nickel : _____
Cobalt : _____	Selenium : _____
Cyanide : _____	Strontium : _____

IV	
Boron : _____	
Sodium% : _____	Na x 100 : _____
Na+K+Mg+Ca	

V
Radiological Examination

Note: Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH : WELL A4 (AXUM), 21/1/94

I	
Temperature at the time of collection: _____	
Appearance:	Colourless
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	Colourless
Turbidity:	Clear
Filterable Residue dried at 105 °C:	571.0
Filterable Residue dried at _____ °C:	_____
Total Solids dried at _____ °C:	_____
Electrical Conductivity/Resistivity at 25°C:	823 μ hos/cm
pH at 20°C:	6.8
Carbonate Alkalinity as CaCO ₃ :	Nil
Bicarbonate Alkalinity as CaCO ₃ :	420.0
Hydroxyl Alkalinity as CaCO ₃ :	_____
Acidity as CaCO ₃ :	_____
Total Hardness as CaCO ₃ :	336.0
Organic Nitrogen (N):	_____
Phenolic Compounds as Phenol:	_____
Carbondioxide (CO ₂):	_____
Oxygen (O ₂):	_____
Chlorine, residual (Cl ₂):	_____
Chlorine, total (Cl ₂):	_____
Sulphide as Hydrogen Sulphide:	_____
Silica, total (SiO ₂):	72.0
Oxygen absorbed from _____	Permanganate at _____
for _____	_____

VI
Miscellaneous

II	
Cations	Anions
H ⁺ : _____	OH ⁻ : _____
NH ₄ ⁺ : Nil	Cl ⁻ : 23.0
Na ⁺ : 71.0	NO ₂ ⁻ : 0.03
K ⁺ : 3.0	NO ₃ ⁻ : 2.0
Li ⁺ : _____	I ⁻ : _____
Ag ⁺ : _____	Br ⁻ : _____
Ba ⁺⁺ : _____	F ⁻ : 0.20
Ca ⁺⁺ : 74.0	HCO ₃ ⁻ : 512.0
Mg ⁺⁺ : 37.0	CO ₃ ⁻ : Nil
Fe ⁺⁺ : _____	SO ₄ ⁻ : 17.0
Fe ⁺⁺⁺ : _____	PO ₄ ⁻ Ortho : Negligible
Fe, total : Nil	PO ₄ ⁻ meta/poly : _____
Mn ⁺⁺ : Negligible	
Zn ⁺⁺ : _____	
Cu ⁺⁺ : _____	
Al ⁺⁺⁺ : _____	
Sn ⁺⁺⁺⁺ : _____	

III	
Arsenic : _____	Lead : _____
Cadmium : _____	Mercury : _____
Chromium, hexavalent : _____	Nickel : _____
Cobalt : _____	Selenium : _____
Cyanide : _____	Strontium : _____

IV	
Boron : _____	
Sodium% : _____	Na x 100 : _____
	Na+K+Mg+Ca

V
Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH OF HEALTH : WELL N^o A7h (AXUM), 5/02/94

I	
Temperature at the time of collection:	-
Appearance:	Colourless
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	Colourless
Turbidity:	Clear
Filterable Residue dried at 105 °C:	567.0
Filterable Residue dried at °C:	-
Total Solids dried at °C:	-
Electrical Conductivity/Resistivity at 25°C:	759.0 //mhos/cm
pH at 20°C:	7.2
Carbonate Alkalinity as CaCO ₃ :	Nil
Bicarbonate Alkalinity as CaCO ₃ :	300.0
Hydroxyl Alkalinity as CaCO ₃ :	-
Acidity as CaCO ₃ :	-
Total Hardness as CaCO ₃ :	296.0
Organic Nitrogen (N):	-
Phenolic Compounds as Phenol:	-
Carbondioxide (CO ₂):	-
Oxygen (O ₂):	-
Chlorine, residual (Cl ₂):	-
Chlorine, total (Cl ₂):	-
Sulphide as Hydrogen Sulphide:	-
Silica, total (SiO ₂):	75.5
Oxygen absorbed from	Permanganate at
for	

VI
Miscellaneous

II	
Cations	Anions
H ⁺ :	OH ⁻ :
NH ₄ ⁺ :	Cl ⁻ :
Na ⁺ :	NO ₂ ⁻ :
K ⁺ :	NO ₃ ⁻ :
Li ⁺ :	I ⁻ :
Ag ⁺ :	Br ⁻ :
Ba ⁺⁺ :	F ⁻ :
Ca ⁺⁺ :	HCO ₃ ⁻ :
Mg ⁺⁺ :	CO ₃ ⁻ :
Fe ⁺⁺ :	SO ₄ ⁻ :
Fe ⁺⁺⁺ :	PO ₄ ⁻ Ortho :
Fe, total :	PO ₄ ⁻ meta/poly :
Mn ⁺⁺ :	
Zn ⁺⁺ :	
Cu ⁺⁺ :	
Al ⁺⁺⁺ :	
Sn ⁺⁺⁺⁺ :	

III	
Arsenic :	Lead :
Cadmium :	Mercury :
Chromium, hexavalent :	Nickel :
Cobalt :	Selenium :
Cyanide :	Strontium :

IV	
Boron :	
Sodium% :	Na x 100 : Na+K+Mg+Ca

V
Radiological examination

Note:- Unit is mg/L unless otherwise stated.

I

Temperature at the time of collection:	---
Appearance:	Colourless
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	Colourless
Turbidity:	Clear
Filterable Residue dried at 105 °C:	459.0
Filterable Residue dried at °C:	-
Total Solids dried at °C:	-
Electrical Conductivity/Resistivity at 25°C:	620.0 μ mhos/cm
pH at 20°C:	8.0
Carbonate Alkalinity as CaCO ₃ :	Nil
Bicarbonate Alkalinity as CaCO ₃ :	300.0
Hydroxyl Alkalinity as CaCO ₃ :	-
Acidity as CaCO ₃ :	-
Total Hardness as CaCO ₃ :	240.0
Organic Nitrogen (N):	-
Phenolic Compounds as Phenol:	-
Carbondioxide (CO ₂):	-
Oxygen (O ₂):	-
Chlorine, residual (Cl ₂):	-
Chlorine, total (Cl ₂):	-
Sulphide as Hydrogen Sulphide:	-
Silica, total (SiO ₂):	69.0
Oxygen absorbed from Permanganate at for :	

VI

Miscellaneous

II

Cations	Anions
H ⁺ :	OH ⁻ :
NH ₄ ⁺ :	Cl ⁻ :
Na ⁺ :	NO ₂ ⁻ :
K ⁺ :	NO ₃ ⁻ :
Li ⁺ :	I ⁻ :
Ag ⁺ :	Br ⁻ :
Ba ⁺⁺ :	F ⁻ :
Ca ⁺⁺ :	HCO ₃ ⁻ :
Mg ⁺⁺ :	CO ₃ ⁻ :
Fe ⁺⁺ :	SO ₄ ⁻ :
Fe ⁺⁺⁺ :	PO ₄ ⁻ :
Fe, total :	Ortho :
Mn ⁺⁺ :	meta/poly :
Zn ⁺⁺ :	
Cu ⁺⁺ :	
Al ⁺⁺⁺ :	
Sn ⁺⁺⁺⁺ :	

III

Arsenic : _____ Lead : _____
 Cadmium : _____ Mercury : _____
 Chromium, hexavalent : _____ Nickel : _____
 Cobalt : _____ Selenium : _____
 Cyanide : _____ Strontium : _____

IV

Sodium% : $\frac{\text{Na}}{\text{Na} + \text{K} + \text{Mg} + \text{Ca}} \times 100$: _____

V

Radiological Examination

Note:- Unit is mg/L unless otherwise stated

I

Temperature at the time of collection: _____

Appearance: _____ Colourless

Odour: _____ Odourless

Taste: _____ Tasteless

Settleable Solids: _____ Present

Floating Solids: _____ Absent

Suspended Solids: _____ Present

Colour, true: _____ Colourless

Turbidity: _____ Clear

Filterable Residue dried at 105 °C: 648.0

Filterable Residue dried at _____ °C: _____

Total Solids dried at _____ °C: _____

Electrical Conductivity/Resistivity at 25°C: 780 μ mhos/cm

pH at 20°C: 7.4

Carbonate Alkalinity as CaCO₃: Nil

Bicarbonate Alkalinity as CaCO₃: 320.0

Hydroxyl Alkalinity as CaCO₃: _____

Acidity as CaCO₃: _____

Total Hardness as CaCO₃: 364.0

Organic Nitrogen (N): _____

Phenolic Compounds as Phenol: _____

Carbondioxide (CO₂): _____

Oxygen (O₂): _____

Chlorine, residual (Cl₂): _____

Chlorine, total (Cl₂): _____

Sulphide as Hydrogen Sulphide: _____

Silica, total (SiO₂): 65.0

Oxygen absorbed from _____ Permanganate at _____
for _____

VI
Miscellaneous

II

Cations	Anions
H ⁺ : _____	OH ⁻ : _____
NH ₄ ⁺ : 0.06	Cl ⁻ : 88.0
Na ⁺ : 65.0	NO ₂ ⁻ : 0.05
K ⁺ : 3.0	NO ₃ ⁻ : 19.0
Li ⁺ : _____	I ⁻ : _____
Ag ⁺ : _____	Br ⁻ : _____
Ba ⁺⁺ : _____	F ⁻ : 0.40
Ca ⁺⁺ : 102.0	HCO ₃ ⁻ : 390.0
Mg ⁺⁺ : 26.0	CO ₃ ⁼⁼ : Nil
Fe ⁺⁺ : _____	SO ₄ ⁼⁼ : 45.0
Fe ⁺⁺⁺ : _____	PO ₄ ⁼⁼ Ortho : 0.09
Fe, total : Nil	PO ₄ ⁼⁼ meta/poly : _____
Mn ⁺⁺ : Negligible	
Zn ⁺⁺ : _____	
Cu ⁺⁺ : _____	
Al ⁺⁺⁺ : _____	
Sn ⁺⁺⁺⁺ : _____	

III

Arsenic : _____	Lead : _____
Cadmium : _____	Mercury : _____
Chromium, hexavalent : _____	Nickel : _____
Cobalt : _____	Selenium : _____
Cyanide : _____	Strontium : _____

IV

Boron: _____

Sodium% : $\frac{\text{Na}}{\text{Na}+\text{K}+\text{Mg}+\text{Ca}} \times 100$: _____

V

Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH: MAISHUM SPRING (AXUM), 18/01/94

I	
Temperature at the time of collection:	-
Appearance:	Light yellow
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	175 units of chloroplatinate
Turbidity:	46 FTU
Filterable Residue dried at 105 °C:	87.0
Filterable Residue dried at °C:	-
Total Solids dried at °C:	-
Electrical Conductivity/Resistivity at 25°C:	122 μ mhos/cm
pH at 20°C:	6.5
Carbonate Alkalinity as CaCO ₃ :	Nil
Bicarbonate Alkalinity as CaCO ₃ :	20.0
Hydroxyl Alkalinity as CaCO ₃ :	-
Acidity as CaCO ₃ :	-
Total Hardness as CaCO ₃ :	7.0
Organic Nitrogen (N):	-
Phenolic Compounds as Phenol:	-
Carbondioxide (CO ₂):	-
Oxygen (O ₂):	-
Chlorine, residual (Cl ₂):	-
Chlorine, total (Cl ₂):	-
Sulphide as Hydrogen Sulphide:	-
Silica, total (SiO ₂):	14.0
Oxygen absorbed from	Permanganate at
for	

VI
Miscellaneous

II	
Cations	Anions
H ⁺ :	OH ⁻ :
NH ₄ ⁺ :	Cl ⁻ :
Na ⁺ :	NO ₂ ⁻ :
K ⁺ :	NO ₃ ⁻ :
Li ⁺ :	I ⁻ :
Ag ⁺ :	Br ⁻ :
Ba ⁺⁺ :	F ⁻ :
Ca ⁺⁺ :	HCO ₃ ⁻ :
Mg ⁺⁺ :	CO ₃ ⁻ :
Fe ⁺⁺ :	SO ₄ ⁻ :
Fe ⁺⁺⁺ :	PO ₄ ⁻ Ortho :
Fe, total :	PO ₄ ⁻ meta/poly :
Mn ⁺⁺ :	
Zn ⁺⁺ :	
Cu ⁺⁺ :	
Al ⁺⁺⁺ :	
Sn ⁺⁺⁺⁺ :	

1.06
2.75%

III	
Arsenic :	Lead :
Cadmium :	Mercury :
Chromium, hexavalent :	Nickel :
Cobalt :	Selenium :
Cyanide :	Strontium :

IV	
Boron :	
Sodium% :	Na x 100 : Na+K+Mg+Ca

V
Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH; MAI GODAE (HATELA CREEK) (AXUM), 11/02/94

I

Temperature at the time of collection: _____

Appearance: _____ Colourless

Odour: _____ Odourless

Taste: _____ Tasteless

Settleable Solids: _____ Present

Floating Solids: _____ Absent

Suspended Solids: _____ Present

Colour, true: _____ Colourless

Turbidity: _____ Clear

Filterable Residue dried at 105 °C: _____ 358.0

Filterable Residue dried at _____ °C: _____

Total Solids dried at _____ °C: _____

Electrical Conductivity/Resistivity at 25°C: _____ 516.0 μ mhos/cm

pH at 20°C: _____ 8.4

Carbonate Alkalinity as CaCO_3 : _____ 24.0

Bicarbonate Alkalinity as CaCO_3 : _____ 212.0

Hydroxyl Alkalinity as CaCO_3 : _____

Acidity as CaCO_3 : _____

Total Hardness as CaCO_3 : _____ 200.0

Organic Nitrogen (N): _____

Phenolic Compounds as Phenol: _____

Carbondioxide (CO_2): _____

Oxygen (O_2): _____

Chlorine, residual (Cl_2): _____

Chlorine, total (Cl_2): _____

Sulphide as Hydrogen Sulphide: _____

Silica, total (SiO_2): _____ 65.5

Oxygen absorbed from _____ Permanganate at _____
for _____

VI
Miscellaneous

II

Cations	Anions
H^+ : _____	OH^- : _____
NH_4^+ : _____ 0.16 0.01	Cl^- : _____ 20.8 0.58
Na^+ : _____ 47.6 2.07	NO_3^- : _____ 0.02
K^+ : _____ 4.3 0.11	NO_2^- : _____ 0.5 0.01
Li^+ : _____	I^- : _____
Ag^+ : _____	Br^- : _____
Ba^{++} : _____	F^- : _____ 0.7 0.04
Ca^{++} : _____ 33.7 1.68	HCO_3^- : _____ 258.6 4.24
Mg^{++} : _____ 28.2 2.32	CO_3^{--} : _____ 28.8 0.96
Fe^{++} : _____	SO_4^{--} : _____ 21.0 0.44
Fe^{+++} : _____	PO_4^{--} Ortho: _____ 0.04
Fe , total: _____ 0.03	PO_4^{--} meta/poly: _____
Mn^{++} : _____ Nil	
Zn^{++} : _____	
Cu^{++} : _____	
Al^{+++} : _____	
Sn^{++++} : _____	

0.64%
1.27 ✓

III

Arsenic: _____	Lead: _____
Cadmium: _____	Mercury: _____
Chromium, hexavalent: _____	Nickel: _____
Cobalt: _____	Selenium: _____
Cyanide: _____	Strontium: _____

IV

Boron: _____

Sodium%: _____ Na x 100: _____
Na+K+Mg+Ca

V
Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH: MAIGONA (HARMA CREEK) (AXUM), 18/01/94

I	
Temperature at the time of collection:	—
Appearance:	Colourless
Odour:	Odourless
Taste:	Tasteless
Settleable Solids:	Present
Floating Solids:	Absent
Suspended Solids:	Present
Colour, true:	Colourless
Turbidity:	Clear
Filterable Residue dried at 105 °C:	352.0
Filterable Residue dried at °C:	—
Total Solids dried at °C:	—
Electrical Conductivity/Resistivity at 25°C:	597 μ mhos/cm
pH at 20°C:	7.8
Carbonate Alkalinity as CaCO ₃ :	Nil
Bicarbonate Alkalinity as CaCO ₃ :	240.0
Hydroxyl Alkalinity as CaCO ₃ :	—
Acidity as CaCO ₃ :	—
Total Hardness as CaCO ₃ :	—
Organic Nitrogen (N):	172.0
Phenolic Compounds as Phenol:	—
Carbondioxide (CO ₂):	—
Oxygen (O ₂):	—
Chlorine, residual (Cl ₂):	—
Chlorine, total (Cl ₂):	—
Sulphide as Hydrogen Sulphide:	—
Silica, total (SiO ₂):	16.0
Oxygen absorbed from Permanganate at for :	—

VI
Miscellaneous

II	
Cations	Anions
H ⁺ :	OH ⁻ :
NH ₄ ⁺ :	Cl ⁻ :
Na ⁺ :	NO ₂ ⁻ :
K ⁺ :	NO ₃ ⁻ :
Li ⁺ :	I ⁻ :
Ag ⁺ :	Br ⁻ :
Ba ⁺⁺ :	F ⁻ :
Ca ⁺⁺ :	HCO ₃ ⁻ :
Mg ⁺⁺ :	CO ₃ ⁻ :
Fe ⁺⁺ :	SO ₄ ⁻ :
Fe ⁺⁺⁺ :	PO ₄ ⁻ Ortho :
Fe, total :	PO ₄ ⁻ meta/poly :
Mn ⁺⁺ :	
Zn ⁺⁺ :	
Cu ⁺⁺ :	
Al ⁺⁺⁺ :	
Sn ⁺⁺⁺⁺ :	

1.05%

6.27

III	
Arsenic :	Lead :
Cadmium :	Mercury :
Chromium, hexavalent :	Nickel :
Cobalt :	Selenium :
Cyanide :	Strontium :

IV	
Boron :	
Sodium% :	Na x 100 : Na+K+Mg+Ca

V
Radiological Examination

Note:- Unit is mg/L unless otherwise stated

NATIONAL RESEARCH INSTITUTE OF HEALTH: MAI ZERO (GEBRU CREEK) (AXUM), 18/01/94

I

Temperature at the time of collection: _____

Appearance: _____ Colourless

Odour: _____ Odourless

Taste: _____ Tasteless

Settleable Solids: _____ Present

Floating Solids: _____ Absent

Suspended Solids: _____ Present

Colour, true: _____ Colourless

Turbidity: _____ Clear

Filterable Residue dried at 105 °C: _____ 612.0

Filterable Residue dried at _____ °C: _____

Total Solids dried at _____ °C: _____

Electrical Conductivity/Resistivity at 25°C: _____ 913.0 *μmhos/cm*

pH at 20°C: _____ 7.8

Carbonate Alkalinity as CaCO₃: _____ Nil

Bicarbonate Alkalinity as CaCO₃: _____ 440.0

Hydroxyl Alkalinity as CaCO₃: _____

Acidity as CaCO₃: _____

Total Hardness as CaCO₃: _____ 32.0

Organic Nitrogen (N): _____

Phenolic Compounds as Phenol: _____

Carbondioxide (CO₂): _____

Oxygen (O₂): _____

Chlorine, residual (Cl₂): _____

Chlorine, total (Cl₂): _____

Sulphide as Hydrogen Sulphide: _____

Silica, total (SiO₂): _____ 23.0

Oxygen absorbed from _____ Permanganate at _____
for _____

VI
Miscellaneous

II

Cations	Anions
H ⁺ : _____	OH ⁻ : _____
NH ₄ ⁺ : _____ 0.04	Cl ⁻ : _____ 62.0 1.75
Na ⁺ : _____ 119.0 5.17	NO ₂ ⁻ : _____ 0.03
K ⁺ : _____ 4.0 0.10	NO ₃ ⁻ : _____ 3.0 0.05
Li ⁺ : _____	I ⁻ : _____
Ag ⁺ : _____	Br ⁻ : _____
Ba ⁺⁺ : _____	F ⁻ : _____ 0.30 0.02
Ca ⁺⁺ : _____ 32.0 1.60	HCO ₃ ⁻ : _____ 537.0 9.80
Mg ⁺⁺ : _____ 49.0 4.03	CO ₃ ⁼⁼ : _____ Nil
Fe ⁺⁺ : _____	SO ₄ ⁼⁼ : _____ 18.0 0.37
Fe ⁺⁺⁺ : _____	PO ₄ ⁼⁼ Ortho : 0.1
Fe, total : _____ Nil	PO ₄ ⁼⁼ meta/poly : _____
Mn ⁺⁺ : _____ Nil 10.90	
Zn ⁺⁺ : _____	
Cu ⁺⁺ : _____	
Al ⁺⁺⁺ : _____	
Sn ⁺⁺⁺⁺ : _____	

0.41%

III

Arsenic : _____	Lead : _____
Cadmium : _____	Mercury : _____
Chromium, hexavalent : _____	Nickel : _____
Cobalt : _____	Selenium : _____
Cyanide : _____	Strontium : _____

IV

Boron : _____

Sodium% : _____ Na x 100 : _____
Na+K+Mg+Ca

V
Radiological Examination

Note:- Unit is mg/L unless otherwise stated

ANNEXURE 3B

Table 2. Microbiology Results from March 26, 2002.

Location	Volume analyzed	Multiply Result by	Total Coliform Count per plate	Total Coliform per 100 ml
Control	100 ml	1	0	0
Control	100 ml	1	0	0
St. Mary Hospital	1 ml	100	0	<100
St. Mary Hospital	10 ml	10	11	110
St. Mary Hospital	100 ml	1	5	5
Africa Hotel Well	1 ml	100	5	500
Africa Hotel Well	10 ml	10	33	330
			0	
Mai Shum Well	10 ml	10	4	40
Mai Edaga	10 ml	10	5	50
Queen of Sheba's Bath	1 ml	100	12	1200
Zorat/Mishlam	10 ml	10	TNTC	TNTC

TNTC = Too numerous to count.

< = Less than

Table 3. Microbiology Results from April 2, 2002.

Location	Volume analyzed	Multiply answer by	Total <i>E. coli</i> Per plate	<i>E. coli</i> per 100 ml	Total Coliform Count/plate	Total Coliform Per 100 ml
Yeha Res. #1	10 ml	10	0	<10	5	50
Yeha Cistern	10 ml	10	TNTC	TNTC	TNTC	TNTC
Still Reservoir	10 ml	10	0	<10	11	110
Sheba Tank Inlet	10 ml	10	0	<10	2	20
Sheba Tank Outlet	10 ml	10	0	<10	4	40
Axum Health Center	10 ml	10	0	<10	6	60
Abraha we Atsbaha Primary School	10 ml	10	0	<10	5	50
Axum High School	10 ml	10	0	<10		
Hand pump well behind Amhay Hotel	10 ml	10	0	<10	4	40
Hand pump well behind Amhay Hotel	10 ml	10	4	40	27	270
Hadera Kidane well	10 ml	10	13	130	60	600

TNTC = Too numerous to count.

Plant near

ANNEXURE 3C
Water Works Design & supervision Enterprise
Water Laboratory

SELECTED PHYSICAL AND CHEMICAL WATER ANALYSIS RESULTS

CLIENT : A.A.U Department of Geology and Geophysics Science Faculty

NATURE OF SAMPLE	Ground water	Ground water	Ground water	Ground water	Ground water	Ground water
DATE OF COLLECTION	31/04/04	31/04/04	31/04/04	31/04/04	31/04/04	31/04/04
DATE RECEIVED	2/4/04	2/4/04	2/4/04	2/4/04	2/4/04	2/4/04
CLIENTS ID NO.	SW-4	Govt Plant Nursery	SW-1	SW-2	Hand pump	Motrized well
LAB ID NO.	319/96	320/96	321/96	322/96	323/96	324/96
Colour (app)	—	—	—	—	—	—
Turbidity (NTU)	2.0	1.0	1.0	2.0	1.0	2.0
Total Solids 105 °C (mg/l)	392.0	582.0	280.0	692.0	422.0	392
T Dissolved Solid 105 °C (mg/l)	378.0	578.0	266.0	674.0	390.0	366.0
Electrical Conductivity (µS/cm)	596.0	887.0	490.0	1008.0	692.0	660.0
pH	7.35	7.59	7.08	7.44	7.01	7.41
Ammonia (mg/l NH ₃)	0.310	0.414	0.418	0.439	0.387	0.353
Sodium (mg/l Na)	30.0	40.0	16.0	55.0	33.0	46.0
Potassium (mg/l K)	1.3	2.7	0.7	1.4	0.4	3.7
Total Hardness (mg/l Ca CO ₃)	277.2	390.8	245.7	453.6	329.7	273.0
Calcium (mg/l Ca)	102.5	138.6	64.7	142.8	105.0	74.8
Magnesium (mg/l Mg)	5.1	10.7	20.4	23.5	15.3	20.9
Total Iron (mg/l Fe)	0.018	0.02	0.039	0.035	0.015	0.012
Manganese (mg/l Mn)	0.1	0.1	0.1	0.1	0.1	0.1
Fluoride (mg/l F)	0.3	0.39	0.22	0.06	0.36	0.54
Chloride (mg/l Cl)	9.70	87.8	12.5	40.5	22.2	25.1
Nitrite (mg/l NO ₂)	—	—	—	—	—	—
Nitrate (mg/l NO ₃)	19.6	35.2	14.1	91.96	34.3	5.3
Alkalinity (mg/l CaCO ₃)	283.2	264.0	237.6	396.0	295.2	288
Carbonate (mg/l CO ₃)	Trace	Trace	Trace	Trace	Trace	Trace
Bicarbonate (mg/l HCO ₃)	345.50	322.1	289.9	483.1	360.1	351.4
Sulphate (mg/l SO ₄)	0.26	44.80	9.20	16.40	8.96	36.90
Phosphate (mg/l PO ₄)	0.511	0.813	0.105	0.213	0.246	0.293

REMARK:-

Checked by [Signature]
 Date 6/04/2004



Approved
 Date 05/04/04

Water Works Design & supervision Enterprise
Water Laboratory

SELECTED PHYSICAL AND CHEMICAL WATER ANALYSIS RESULTS

CLIENT : A.A.U Department of Geology and Geophysics Science Faculty

NATURE OF SAMPLE	Ground water	Ground water	Ground water	Ground water	Ground water	Ground water
DATE OF COLLECTION	31/04/04	31/04/04	31/04/04	31/04/04	31/04/04	31/04/04
DATE RECEIVED	2/4/04	2/4/04	2/4/04	2/4/04	2/4/04	2/4/04
CLIENTS ID.NO.	SW-5	Health center well	Africa Hotel	SW-6	Hotel Kaleb	SW-3
LAB.ID NO.	325/96	326/96	327/96	328/96	329/96	330/96
Colour (app)	—	—	—	—	—	—
Turbidity (NTU)	3.0	1.0	Trace	2.0	6.0	1.0
Total Solids 105 °C (mg/l)	348.0	2236.0	330.0	366.0	924	626
Total Dissolved Solids 105 °C (mg/l)	328.0	2205.0	328.0	334.0	886.0	580.0
Electrical Conductivity (µS/cm)	577.0	3090.0	510.0	615.0	1266.0	950.0
pH	7.13	7.17	6.74	7.21	6.87	7.15
Ammonia (mg/l NH ₃)	0.338	2.81	0.308	0.271	0.488	0.491
Sodium (mg/l Na)	28.0	140.0	25.0	86.0	50	38
Potassium (mg/l K)	0.4	19.0	1.1	1.2	3.3	1.1
Total Hardness (mg/l Ca CO ₃)	275.1	1369.2	212.1	157.5	525	405.3
Calcium (mg/l Ca)	83.2	403.2	65.5	53.8	176.4	110.88
Magnesium (mg/l Mg)	16.3	87.7	11.7	5.61	20.4	31.11
Total Iron (mg/l Fe)	0.016	0.023	0.019	0.019	0.024	0.028
Manganese (mg/l Mn)	0.1	0.1	0.1	0.1	0.1	Trace
Fluoride (mg/l F)	0.42	0.62	0.06	3.5	0.24	0.21
Chloride (mg/l Cl)	10.60	294.3	28.95	15.4	145.7	38.6
Nitrite (mg/l NO ₂)	—	—	—	—	—	—
Nitrate (mg/l NO ₃)	17.2	1078.0	66.9	9.7	303.6	77.4
Alkalinity (mg/l CaCO ₃)	276.0	292.8	153.6	288.0	206.4	391.2
Carbonate (mg/l CO ₃)	Trace	Trace	Trace	Trace	Trace	Trace
Bicarbonate (mg/l HCO ₃)	336.70	357.2	187.4	351.4	251.8	477.3
Sulphate (mg/l SO ₄)	1.60	10.60	8.40	18.90	15.60	18.50
Phosphate (mg/l PO ₄)	0.474	0.449	0.489	0.176	0.512	0.294

REMARK:-

Checked by Tadesse
Date 6/04/2004



Approved by [Signature]
Date 06/04/04

Water Works Design & supervision Enterprise
Water Laboratory

SELECTED PHYSICAL AND CHEMICAL WATER ANALYSIS RESULTS

CLIENT : A.A.U Department of Geology and Geophysics Science Faculty

NATURE OF SAMPLE	Ground water				
DATE OF COLLECTION	31/04/04				
DATE RECEIVED	2/4/04				
CLIENTS ID.NO.	Axum Air port well				
LAB.ID NO.	331/96				
Colour (app)	—				
Turbidity (NTU)	Trace				
Total Solids 105 °C (mg/l)	412.0				
T. Dissolved Solid 105 °C (mg/l)	400.0				
Electrical Conductivity (µS/cm)	655.0				
pH	7.61				
Ammonia (mg/l NH ₃)	0.294				
Sodium (mg/l Na)	43.0				
Potassium (mg/l K)	3.1				
Total Hardness (mg/l Ca CO ₃)	315.0				
Calcium (mg/l Ca)	92.4				
Magnesium (mg/l Mg)	20.4				
Total Iron (mg/l Fe)	0.015				
Manganese (mg/l Mn)	Trace				
Fluoride (mg/l F)	0.17				
Chloride (mg/l Cl)	19.30				
Nitrite (mg/l NO ₂)	—				
Nitrate (mg/l NO ₃)	18.9				
Alkalinity (mg/l CaCO ₃)	321.6				
Carbonate (mg/l CO ₃)	Trace				
Bicarbonate (mg/l HCO ₃)	392.30				
Sulphate (mg/l SO ₄)	9.00				
Phosphate (mg/l PO ₄)	0.222				

REMARK -

76

Checked by *[Signature]*
Date 6/04/2004

Approved by *[Signature]*
Date 06/04/04

ANNEXURE 3D

ADDIS ABABA WATER AND SEWERAGE AUTHORITY CENTRAL LABRTORY SERVICE P.O.BOX 1505, Tel. 112594, ADDIS ABABA

LABORATORY REPORT ON BACTERIOLOGICAL WATER QUALITY

Examination Requested by:- Tigray Water Bureau (MEKELE)

Sampled by:- SAMSON TEFERA

Lab. N°.	Date of sampling	Code of sample	Nature of disinfecting	Free Residual Chlorine mg/l	Date of Examination	Time of Examination	Total coliforms MPN/100 ml	E.Coli. MPN/10ml
RE/2038	20/03/004	Municipality Health Center	Not-chlorinated	Nil	30/03/004	10:00	16,000	16,000
RE/2039	"	Hand Pump	"	"	"	"	<1	<1
RE/2040	"	Africa Hotel	"	"	"	"	490	490
RE/2041	"	Kaleb Hotel Well	"	"	"	"	110	110
RE/2042	"	Govt. Plant Nursery	"	"	"	"	20	20
RE/2043	"	Motorized	"	"	"	"	<1	<1
RE/2044	"	SW ₁	"	"	"	"	<1	<1

Remark:- Samples taken from Municipality Health Center, Africa Hotel, Kaleb Hotel Well and Government Plant Nursery are not suitable for human consumption since coliforms and E.Coli have been detected (Fecally polluted). There fore these water sources should be disinfected with high strength of calcium or Sodium Hypochlorite to prevent contamination of the well water.

Examined by:- SA
Microbiologist

Date of Report :- 04/04/004

Approved by: SA
Head Laboratory Service



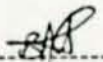
ADDIS ABABA WATER AND SEWERAGE AUTHORITY
CENTRAL LABRTORY SERVICE
P.O.BOX 1505,Tel. 112594,ADDIS ABABA
LABORATORY REPORT ON BACTERIOLOGICAL WATER QUALITY

Examination Requested by:- Tigray Water Bureau (MEKELE)

Sampled by:- SAMSON TEFERA

Lab. N°.	Date of sampling	Code of sample	Nature of disinfecting	Free Residual Chlorine mg/l	Date of Examination	Time of Examination	Total coliforms MPN/100 ml	E.Coli. MPN/10ml
RE/2045	20/03/004	SW ₂	Not-chlorinated	Nil	30/03/004	10:00	<1	<1
RE/2046	"	Shallow Well N° 4	"	"	"	"	<1	<1
RE/2047	"	Shallow Well N° 5	"	"	"	"	70	70
RE/2048	"	Shallow Well N° 6	"	"	"	"	2790	2790
RE/2049	"	No number	"	"	"	"	<1	<1
/		/	/		/		/	

Remark:- Samples taken from Shallow Well N° 5 and Shallow Well N° 6 are not suitable for human consumption since coliforms and E.Coli have been detected (Fecally polluted). There fore these water sources should be disinfected with high strength of calcium or Sodium Hypochlorite to prevent contamination of the well water.

Examined by:- 
Microbiologist

Date of Report :- 04/04/004



Approved by:- 
Head, Laboratory Service

While individual chemical parameters can not give an overall picture of its suitability for drinking, a criterion called groundwater quality index (GQI) is recommended in the study of quality of groundwater (Subba Rao, 1998). In this method, to calculate the GQI, the chemical parameters determined are multiplied by appropriate weights (W) based on their importance in the overall water quality (Table 1), following the guidelines of Tiwari and Mishra (1985). A weight of 4 has been assigned to the parameters like pH, TDS, NO_3 and F, 3 to Na, SO_4 and Cl and 2 to TH, Ca and Mg. In terms of unit-weights (W_i), the weightages of 4, 3 and 2 are equated to 0.16, 0.12 and 0.08, respectively. The GQI is finally calculated, using the following formula

$$\text{GQI} = \sum q_i W_i$$

Where q_i is the degree of groundwater quality (pollution) rating, assigned one of the values of 100, 80, 50 or 0 based on the values of the parameters measured as explained in Table 2 and W_i is the unit-weight.

The computed value of GQI is worked out to be 84.4, suggesting that the samples in the area are subjected to slight rating of pollution.

Table 1: Chemical composition of groundwaters and its weight (W) and unit weight (W_i)

Parameter s	Min	Ma x	Mean	ISI Standards	Weights (W)	Unit weight (W_i)
pH	7.1	8.2	7.8	6.5 to 8.5	4	0.16 ✓
TDS	768	420 0	1825	500-1500	4	0.16 ✓
TA	245	639	387	-		
TH	193	158 4	545	300- 600	2	0.08 ✓
Ca	30	270	87	75-200	2	0.08 ✓
Mg	25	310	87	30-100	2	0.08 ✓
Na	120	900	354	200	3	0.12 ✓
K	6	25	14	-		
HCO_3	300	780	469	-		
Cl	100	200 0	723	250-1000	3	0.12 ✓
SO_4	5	64	28	150-400	3	0.12 ✓
NO_3	13	74	36	45	4	0.16 ✓
F	0.7	2.5	1.1	0.6-1.2	4	0.16 ✓

Table: 2. Scale rating (qi) for groundwater quality parameter

Parameter s	Degree of groundwater quality (pollution) rating (qi)			
	Permissible	Slight	Moderate	Severe
	100	80	50	0
pH	7 - 8.5	8.6-8.8	8.9-9.2	>9.2
	>7	6.8-7	6.5-6.7	<6.5
TDS	500	501-1000	1001-1500	>1500
TH	300	301-450	451-600	>600
Ca	75	76-137	138-200	>200
Mg	30	31-65	66-100	>100
Na	200	201-400	401-600	>600
Cl	250	251-625	626-1000	>1000
SO ₄	150	151-275	276-400	> 400
NO ₃	<14	15-29	30-44	>45
F	0.6	0.7-0.9	1-1.2	>1.2

Table 3 Calculation of GQI based on the mean values, as shown in Table 1

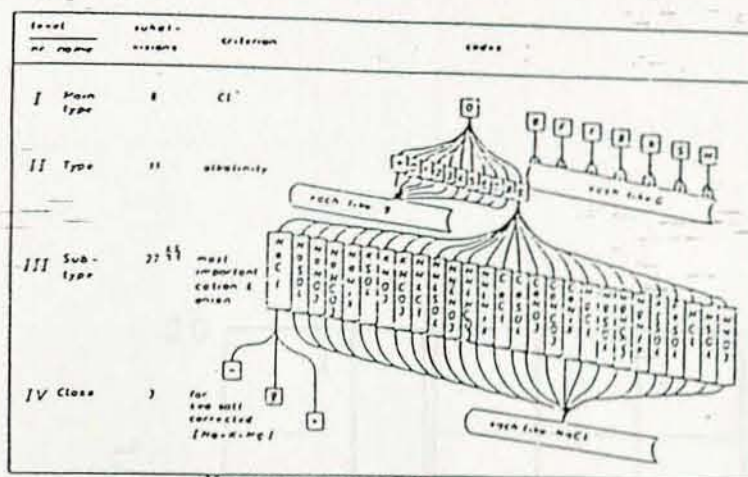
Parameter s	qi	Wi	GQI (qiWi)
pH	100	0.16 ✓	16.0
TDS	50	0.16 ✓	8.0
TH	80	0.08 ✓	6.4
Ca	80	0.08 ✓	6.4
Mg	50	0.08 ✓	4.0
Na	80	0.12 ✓	9.6
Cl	50	0.12 ✓	6.0
SO ₄	100	0.12 ✓	12.0
NO ₃	50	0.16 ✓	8.0
F	50	0.16 ✓	8.0
Total GQI			84.4

Subba Rao, N (1998). Groundwater quality in crystalline terrain of Guntur district, Andhra Pradesh. Visakha Science Journal, v. 2, No. 1, pp. 51-54

Tiwari, T.N. and Mishra, M.A. (1985). A preliminary assignment of water quality index of major Indian rivers. Indian Journal of Environmental Processes, v. 5, pp. 276-279.

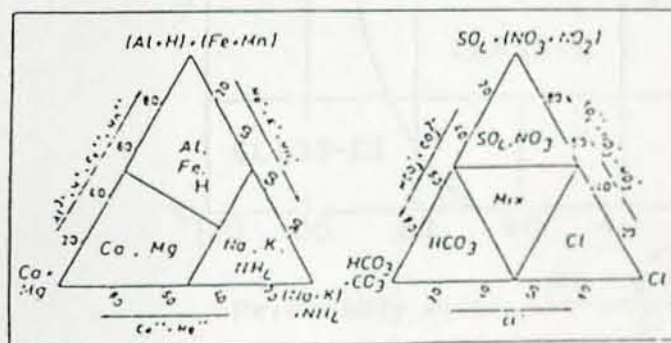
Fig.

The hierarchical structure of the classification system, with four levels of subdivision.



Main type	code	Cl ⁻ mg/L	Main type	code	Cl ⁻ mg/L
very oligohaline	G	<5	brackish	Z	300-10 ³
oligohaline	g	5-30	brackish-salt	b	10 ³ -10 ⁴
fresh	F	30-150	salt	S	10 ⁴ -10 ⁵
fresh-brackish	f	150-300	hyperhaline	H	>10 ⁵

type	alkalinity	code	type	alkalinity	code
no. name	(meq/L)		no. name	(meq/L)	
1 very low	< 1	1	5 very high	15 - 32	5
0 low	1 - 1	0	4 extremely high	32 - 54	4
1 moderately low	1 - 2	1	3 extremely high	54 - 128	3
2 moderate	2 - 4	2	2 extremely high	128 - 256	2
3 moderately high	4 - 8	3	1 extremely high	256 - 512	1
4 high	8 - 16	4			



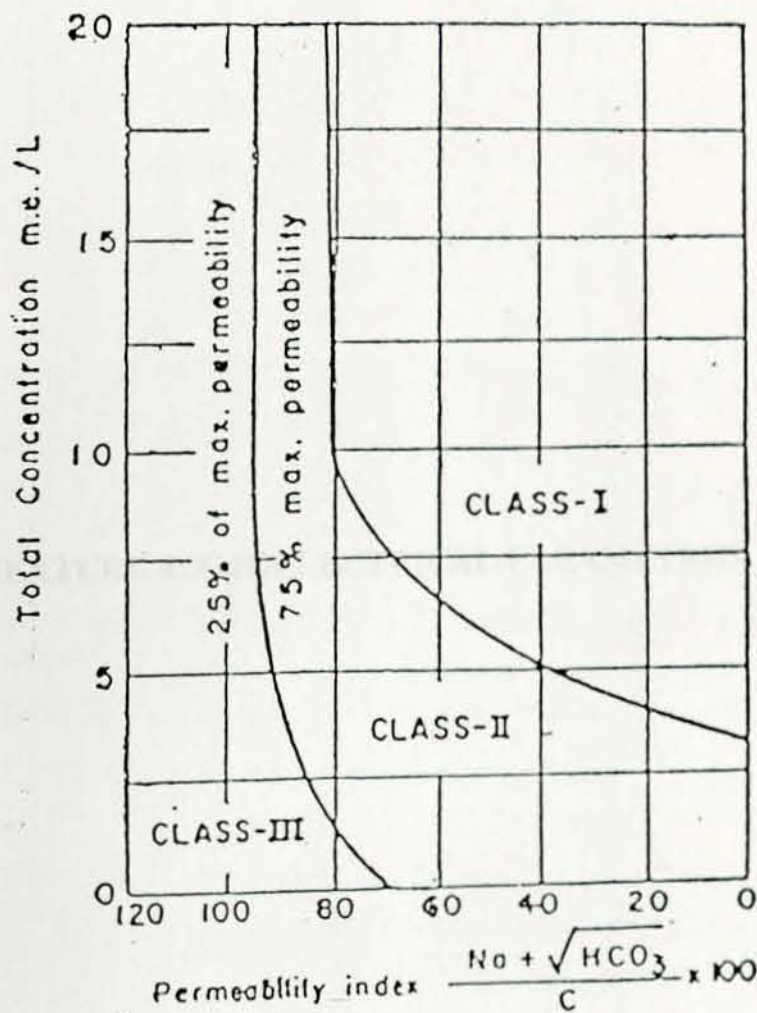
Subdivision of types into subtypes on the basis of the proportional share of main constituents in the sum of the cations (left) and anions (right), both in meq/L.

Class	Code	Conditions for the + & - mg corrected (meq/L)
1a = & - mg deficit	1	1 - 2/Cl and 1.5/1a - 1a
1b = & - mg equilibrium	2	2 - 2/Cl and 1.5/1a - 1a
1c = & - mg surplus	3	3 - 2/Cl and 1.5/1a - 1a

- 1 = often indicative of a salt water intrusion (anytime, any time)
- 2 = often indicative of adequate flushing with water of constant composition
- 3 = often indicative of a fresh water intrusion (anytime, any time)

$$1a = \left[\frac{(1a + b + \text{Mg} + \text{Ca})}{(1a + b)} \right] \cdot \left[\frac{(1a + b)}{(1a + b)} \right] \cdot \left[\frac{(1a + b)}{(1a + b)} \right]$$

ANNEXTURE 3G



Classification of irrigation waters for soils of medium permeability (Doncen, 1946)

Parameters of Geoelectrical Survey

Station No.	ρ ₁	ρ ₂	h ₁ (m)	h ₂ (m)	ρ ₃ (m)	ρ ₄ (m)	Depth (m)	Theoretical ρ ₀	Obs. ρ ₀	ρ ₀ (%)
1	42.542	0.0024	7.15	1.50	10.00	7.4	7.4	1.2	1.2	0.0024
			1.50	2.20	7.90	7.90	7.9	10.0	10.0	
2	1.342	0.0004	0.30	0.30	1.30	1.30	1.3	1.3	1.3	0.0004
			0.30	0.45	2.00	4.20	2.4	1.2	1.2	
3	4.444	0.2750	0.00	1.50	10.00	10.0	10.0	1.2	1.2	0.2750
			1.50	1.20	10.00	10.0	10.0	1.2	1.2	
4	1.200	0.00005	0.00	1.50	1.20	1.20	1.2	1.2	1.2	0.00005
			1.50	1.20	1.20	1.20	1.2	1.2	1.2	
5	42.542	0.0024	0.00	0.30	10.00	10.00	10.0	1.2	1.2	0.0024
			0.30	1.50	10.00	10.00	10.0	1.2	1.2	

ANNEXTURE 4: GEOELECTRICAL PARAMETRES

Summary of Geoelectrical Survey

VES No	ρL	ρt	h_i/ρ_i	S	$\rho_i \cdot h_i$	T	Specific Resist (ohm-m)	Thickness (m)	Σh_i	λ
1	44.542	0.0224	0.10 0.92 1.38	2.40	16.9 6.24 7740	7763.14	13 2.6 75 33.2	1.3 2.4 103.2	106.9	0.0224
2	7.582	0.1319	0.08 0.03 0.56	0.67	12.00 7.20 23.04	42.24	12 15 6.4 288	1 0.48 3.6	5.08	0.1318
3	4.444	0.2250	0.10 1.70	1.90	10.00 28.80	38.8	10 4.12 196	1 7	8	0.2250
4	21.429	0.04667	0.03 1.30	1.33	78 56.2	134.2	52 20.8 120	1.5 27	28.5	0.1476
5	42.521	0.0235	0.01 0.67 0.51	1.19	121 181.5 2899.05	3201.55	110 16.5 75.3 2000	1.1 11 38.5	50.6	0.0235
6	7.674	0.1303	0.009 1.02	1.029	135.3 75.63	210.98	123 8.6	1.1 8.8	9.9	0.1303
7	16.945	0.0590	0.023 1.09 2.298	3.411	28 53.2 2.3	83.5	35 7 21.5 128.1	0.8 7.6 49.4	57.8	0.0590
8	7.009	0.1427	0.048 1.55	1.598	13.44 69.68	83.12	16.8 6.7 79	0.8 10.4	11.20	0.1427
9	64.486	0.0155	0.044 0.88 0.681	1.605	51 40.8 13627.8	13627.8	34 6.8 141 16.6	1.5 6 96	103.5	0.0155
10	16.719	0.0598	0.026 1.55	1.576	28.05 420.75	448.80	33 16.5 185	0.85 25.5	26.35	0.0598
11	28.973	0.0345	0.021 0.22 0.422	0.633	19.2 30.68 540.58	590.46	30 11.8 38.8 435	0.64 2.6 15.1	18.34	0.0345
12	32.211	0.0311	0.057 0.343		6.3 3.52		10.5 3.2	0.6 1.1		

			0.052 0.023	0.475	55.93 6092.8	58.55	32.9 512 60	1.7 11.9	15.3	0.0311
13	5.112	0.1956	0.012 2.531	2.543	2.94 60.76	90.16	49 4.9 264	0.6 12.4	13	0.1956
14	9.857	0.1015	0.008 0.444 0.048	3.50	32 9 336	377	64 4.5 10.5 35	0.5 2 32	34.5	0.1015
15	31.027	0.0322	0.008 0.277 0.611	0.896	64.4 92.31 792	948.71	92 18.4 36 26	0.7 5.1 22	27.8	0.0322
16	6.635	0.1507	0.041 0.167	0.21	14.4 2.16	16.56	18 3.6 37	0.8 0.6	1.4	0.1507
17	8.141	0.1228	0.218 2.073	2.948	6.60 250.8	257.40	5.5 11 49	1.2 22.8	24	0.1228
18	3.411	0.2932	0.333 0.40	0.733	3.00 5.625	8.625	3 3.75 70	1 1.5	2.5	0.2932
19	22.72	0.0440	0.061 0.929 0.012 0.226	1.228	27.3 65.52 5527.2 87843	16498.45	21 8.4 392 62.3 2240	1.3 7.8 4.7 14.1	27.9	0.0440
20	38.265	0.0261	0.035 0.035 0.026 0.316	0.392	55.3 13.86 1239 323.2	1631.36	39.5 19.8 442.5 32 90	1.4 0.7 2.8 10.1	15.0	0.0261
21	9.579	0.1044	0.126 0.657	0.783	790 64.35	72.25	7.9 9.9 392	1 6.5	7.5	0.1044

Source: DEVECON Engineers and Architects, 1995. Water Supply and Sanitation Study of Axum

Declaration

The thesis is my original work and has not been presented for a degree in other university.

Name: Samson Tefera

Signature: 

Date of Submission: 19/07/04