ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES

HYDROGEOLOGY OF ADIGRAT AND SURROUNDING AREAS EASTERN TIGRAY, NORTHERN ETHIOPIA

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

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JUNE 2006
ADDIS ABABA

ACKNOWLEDGEMENTS

I am highly indebted to the Tigray Water Works Consrtuction Enterprise for sponsoring me to attend my postgraduate study and its logistic and financial support during my fieldwork periods.

My great credit goes to my advisor Dr. Tenalem Ayenew, for his comments in my research works.

I duly acknowledge Dr. Asfawossen Asrat, staff of the department of Earth Science AAU, Ato Tesfamichael, staff of the department of Applied geology, Mekelle University, for their readiness in providing me the material they could.

Many institutes that helped me in providing me data and materials deserve especial thanks. Among them, Tigray Water Resource Bureau, Tigray office of mine, National Metrological Service Agency (NMSA), Ezana Mining Development PLC, Ganta Afeshum woreda Health Department, Adigrat town water and sewage authority and Tigray eastern zone water resources department.

I am great full to my friend Asmelash Meressa, for his continuous morale and encouragement during my postgraduate study. His unlimited support in allowing me to use his personal computer is greatly acknowledged. Especial thanks go to my friend Mussie Araya for his valuable help in developing my maps using GIS techniques. Among others, my thanks goes to Esayas T/Birhan,Samuel yehdego, Shewaye Beyene, G/Medhin Birhane, Solomon G/Michael, Fethanegest W/Mariam, H/Mariam Hailu and other who helped me in various ways.

Last but not least, my deepest heart felt thanks go to my family for their morale and encouragement that brought me to this level. God bless them.

ABSTRACT

The study area has a total surface area of $152km^2$ with a wide difference in altitude ranging from 2000 m.a.s.l to 3000 m.a.s.l (meters above sea level). The high altitude topography mainly occupies the western scarp of the study area. The central and eastern parts in turn have rugged topography with flat to gentle slopes.

The paleozoic-mesozoic sedimentary rocks cover larger part of the study area. The dominant lithological units in the area are the alluvial sediments unit, the tertiary basalt unit, the Adigrat sandstone unit, the Edagaarbi glacial unit, the Enticho sandstone unit and the metamorphic rocks unit.The main structures of the area are sedimentary beds, cross bedding, fracture/joint sets and foliation.

From long term mean monthly rainfall data, the area receives 694mm mean annual rainfall. The potential evapotranspiration of the area calculated using the Penman combined method is 1261mm.The actual evapotranspiration computed by the Thorthwaite-Mathes soil balance model is 583mm. The mean annual surface run off that leaves the catchment is 62mm of water. The amount of groundwater recharge is 46.4mm.

Based on pumping test data analysis results and additional qualitative field descriptions such as degree of weathering, extent and frequency of fractures, the rocks in the study area are classified in to four hydrogeological units These are rocks with high permeability ($K>1.45m/d$), rocks with high to medium permeability ($K=1.45m/d$ to $0.15m/d$), rocks with medium to low permeability ($K= 0.15m/d$ to $0.09m/d$) and rocks with very low permeability ($K<0.09m/d$). The highly permeable lithology corresponds to the alluvial sediments and fractured Enticho sandstone. The Edagaarbi glacial and the Adigrat sandstone rock units that occupy high topography area with steep slope are under the very low permeability group.

Hydrochemical study indicated the presence of two major water types in the study area. These are $Ca-Mg-HCO_3$ and $Ca-Na-HCO_3$. One borehole water sample shows Ca and NO_3 as dominant cation and anions respectively. The high nitrate concentration in the borehole is attributed to

contamination by domestic wastes. Bacteriological analysis result conducted in the years 2000 and 2005 indicated the presence of E.coli and coliform bacteria, above permissible limit for drinking, in a borehole that supply water to the residences of Adigrat town. With exception of the above, the groundwater quality with respect to drinking, agricultural and industrial water quality standards is within the permissible limits set by different organizations. However, it has some limitations for textile and paper manufacturing plants.

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CHAPTER ONE

INTRODUCTION

1.1 Back ground

The study area i.e. Adigrat and its surrounding, is part of the Danakil drainage basin. The area has got little attention both in geological and hydrogeological investigations.

Early works focusing in geological mapping and search for mineral deposits, as that of Ferret and Garlienier, two staffs of the French army in their regional work of 1844 and 1847 had subdivided the rocks of the area into gneissic, phyllitic, mafic, oalitic, sedimentary and intrusives. W.T Blandford (1870), Merla and Minucci (1938), Mohr of Addis Ababa university (1963) and worked on the regional geology i.e. stratigraphy, lithology and structure of the area. Since the formation of the geological survey of Ethiopia in 1968, under the directorship of D.B Dow and the provisional supervision of M.Beyth and later V.Kazmin some geologists have visited the area.

A regional geological mapping at a scale of 1:50,000 by C.R Garland (1980) had established the stratigraphy of the lithologies in the area from youngest to oldest as follows.

1. Tertiary intrusive (dolerites and syenites)
2. Holecene (evaporates, alluvium and recent volcanic)
3. Cainzoic volcanics
4. Cainzoic sediments
5. Tertiary volcanics (Trap series, Adwa trachyte & phonolites)
6. Mesozoic sedimentary rocks
7. Precambrian intrusive rocks (granites, granodiorites & diorite)
8. Precambrian

From hydrogeological perspective, Tesfaye Chernet's (1973) work at regional scale addressed the preliminary hydrogeology of the area. Besides to this, water resource assessment for Adigrat town by TAHAL consultancy engineers group Ltd. with Metaferia consulting group PLC (2000) entitled " water resource assessment for Adigrat town" draft version has enlightened the possible ground water resource area for Adigrat town only. Mekelle University (2003) carried out GIS and Remote sensing supported water resource identification for Adigrat town and surrounding. (T/Michael, et al. 2003)

The previous regional investigations were carried out with out sufficient bore hole and metrological data that are relevant to the present hydrogeological condition. Besides, to this the possibility of utilizing the groundwater resource for agriculture was treated. The present research work therefore focuses on detail groundwater assessment and carrying out hydrochemical studies.

1.2 Objectives

1.2.1 General objectives

The main objective of the project area is qualitative and quantitative evaluation of the groundwater aimed to be supplied for different purposes and understanding of ground water system.

1.2.2 Specific objectives

The main objective of this research work is

- To produce hydrogeological map of the area at a scale of 1:50,000
- To perform water balance evaluation of the area based on available **m**etrological data
- To produce geological and other supportive maps of the area at a scale of 1:50.000
- To evaluate aquifer parameters
- To determine water type using appropriate software package.
- To evaluate chemical, physical and biological properties of ground water, determine its suitability for municipal, industrial, agricultural purpose& tracing pollution if any and forward recommendation.

1.3 Methodology

A standard and scientific hydrogeological investigation procedure is carried out and is given as follows

- Literature review and collection of data including published and unpublished data, geological and hydrogeological maps, topographic maps, aerial photographs, well log completion, spring, bore wells and hand dug wells inventory data, pump test data, chemical analysis data, geophysical data especially electrical resistivity from regional and federal organizations and institutions.
- Aerial photo interpretation to have preliminary picture on lithology, structure (lineaments), soil development and type, geomorphology, drainage systems, land use and land cover etc.
- Collection of hydrometrelogical and geomorphological data from respective institutions to determine the different input parameters of the water balance.
- Verification and upgrading geological map of the area developed from aerial photo and satellite image interpretation and collected from previous works.
- Identification of elevation and geographic position of boreholes, hand dug wells and springs which is helpful in spatial analysis of data using Geographic Information System (GIS).
- Collecting field test parameters such as temperature, Total Dissolved Solutes (TDS) and Electrical Conductivity (EC)
- Collecting water samples for laboratory analysis

1.4 Materials Used

To achieve the objectives of the of this research work, the following materials were used.

- 1:50,000 scale aerial photos of four strips sixteen in number published in 1994
- 1:50,000 scale topographic maps (Adigrat, Nebelet, Asimba and Freweini sheets) published in 1998.
- GPS (Magellan model) for locating water sampling points, geological contacts, dykes, water points etc.
- Water quality kit (Hanna meter) for measuring insitu Ec, Eh, temperature and P^h)
- Geological field kits such as compass, hammer, lense, camera etc.
- Existing metrological, hydrometric, well log and pump test data collected from different organizations.

1.5 Application of the results

In general, the result from this research will be useful and can be referenced in groundwater exploration and development.

CHAPTER TWO

GENERAL OVER VIEW OF THE AREA

2.1 Location and accessibility

The study area which include the town of Adigrat and its surrounding areas is located in Tigray regional state, northern Ethiopia. It is 900km north of Addis Ababa and 120km north of Mekelle city, the capital of Tigray, in zone 37 UTM grid of 1570000mN to 1580000mN and 543000mE to 562000mE. The extent of the study area is 152km^2

It is accessible though all whether asphalt road which runs from Addis Ababa to Woldia and the newly constructed asphalt road from Woldia to Alamata. Currently the possible route from Alamata to Mekelle city is the all whether gravel and partly asphalt road that passes through Mekoni town. The study area is connected with Mekelle city through asphalt road. The study area is accessible by seasonal, all whether gravel roads and trails.

2.2 Topography

The study area which includes Adigrat town and its surroundings is characterized by continuous rugged mountains topography that is dissected by many minor tributaries of the surrounding river, flat lands in the center and some small plateau towards the eastern boundary. Its altitude ranges from 2000m in the valleys of eastern portion to above 3000m above sea level in the steep western boundary and mountains in southeast and south like Andel ridge.

Steep slope characterizes the western and eastern boundaries of the study area. The Adigrat ridge which is the western boundary of the study area divides the plateau to the northern (Eritrea) part and the southern (Tigrean part).

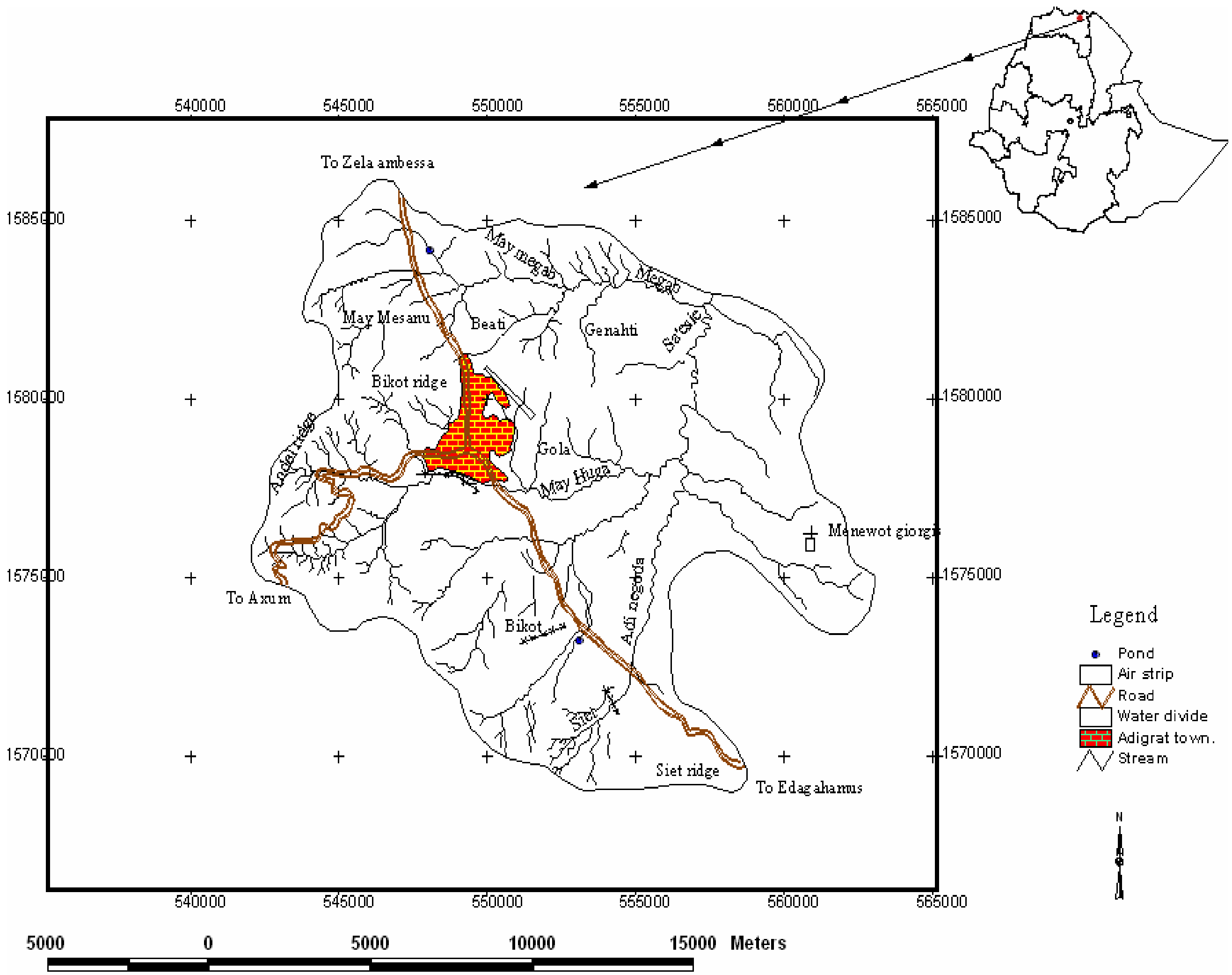


Fig 2.1 Location map of the area

The ridge is a triple water shade between the Tekeze (south), Mereb-Gasha (north) river basin and the escarpment in the east (Danakil river basin). The study area lies in the upper catchment of Danakil river basin.

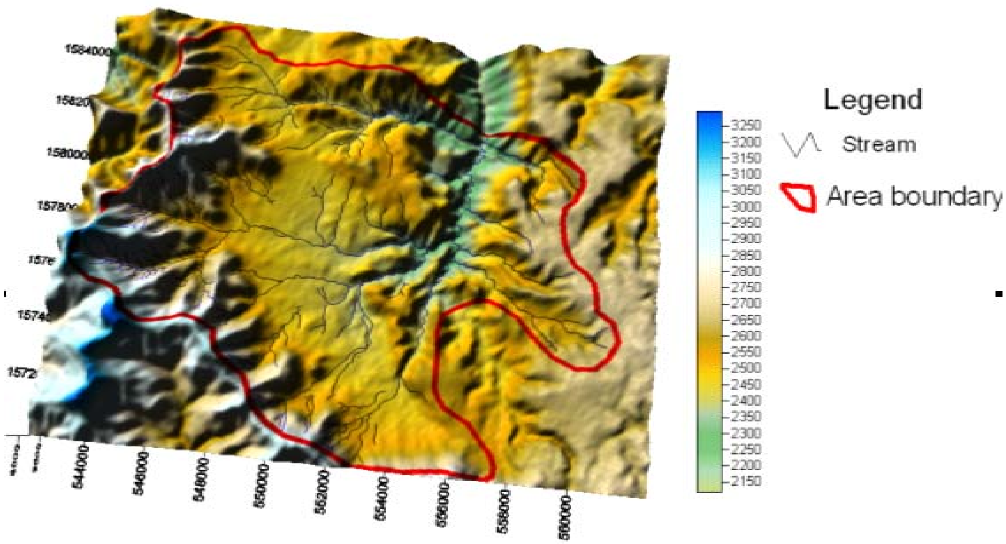


Fig 2.2 Topographic map of the study area

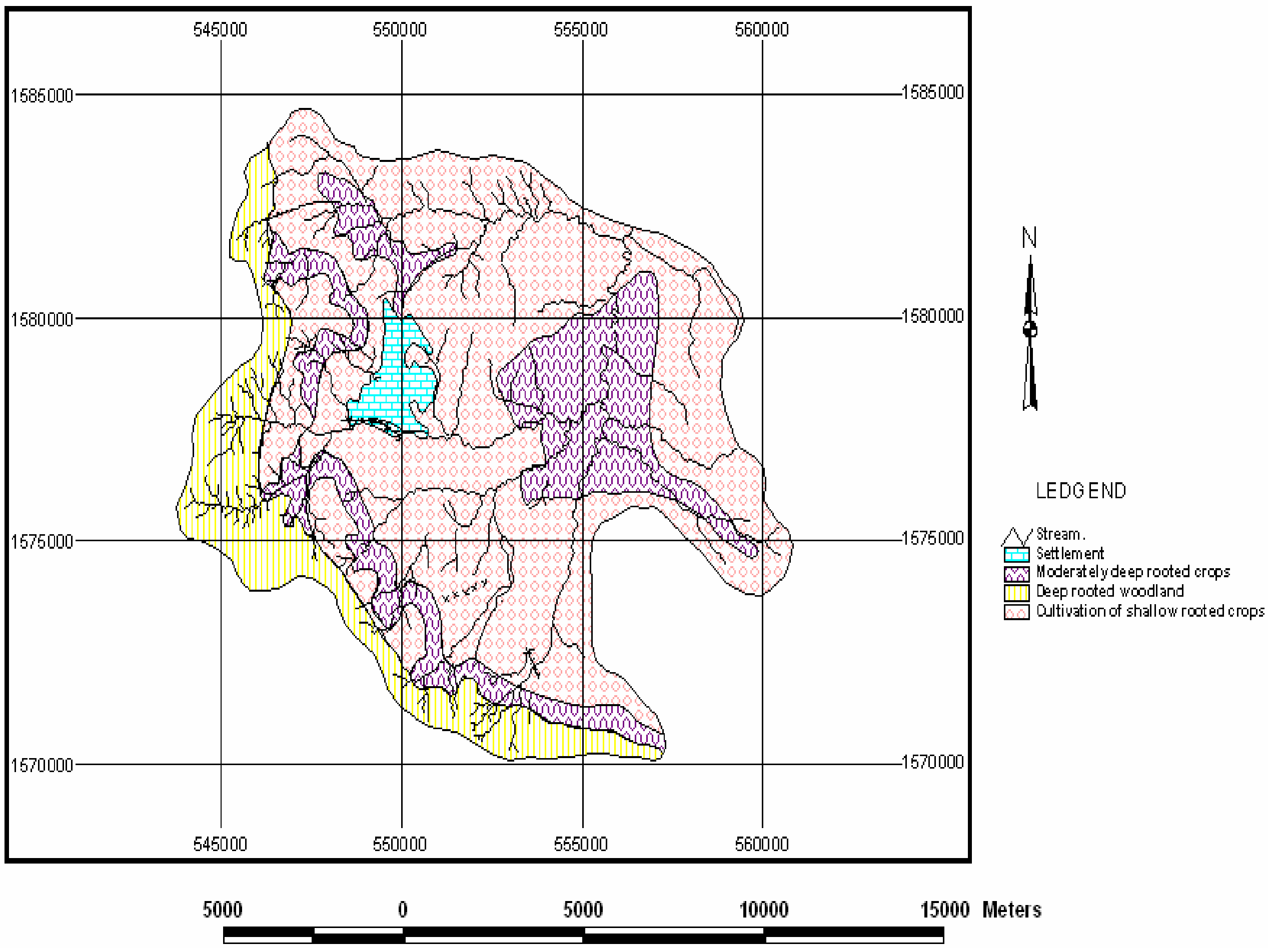
The study area lies in the upper catchment of Danakil river basin.
The area is drained by many small and medium scale intermittent rivers that originate from western highlands towards the Danakil depression. The main source of recharge for the rivers is precipitation during the rainy season.

2.3 Land use, land cover and soils

The study area constitutes four land cover classes namely the grassland, thorn bushes& shrubs; sparse vegetation of eucalyptus tree and juniper; the cultivated land and settlement.
The cultivated land constitutes the larger part of the study area and is mainly located in the central part and eastern plateau. It generally rests on the Enticho sandstone. The grasslands are small lenses type fields confined to the major rivers. The sparse vegetation of juniper and eucalyptus trees is located on the western scarps of the study area. Scattered settlement within the

cultivated land and dense settlement in the town of Adigrat are also part of the land cover and land use. The major crops in the area are barley, teff, wheat, sorghum.

Fig 2.3 Land use-land cover of the study area



Three soil classes are mapped in the study area. These are clay which occupy the relatively steep part of the study area is thin in thickness. The second soil class is loam clay. It is generally confined to the major rivers and gentle slopes of the basaltic formation. The third one is the loam sand, which lies on the central and eastern plateau of the study area.

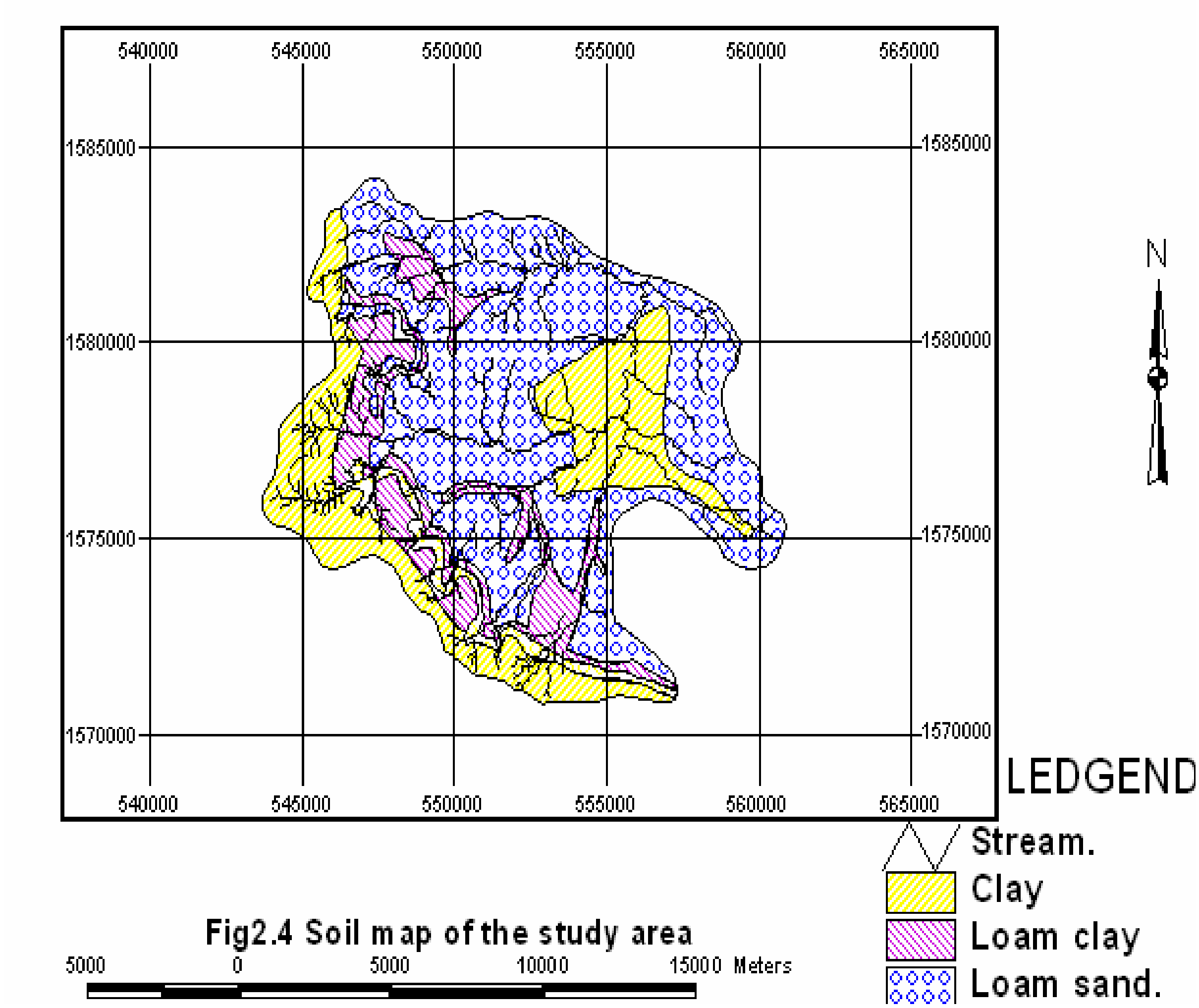


Fig2.4 Soil map of the study area

2.4 Climate

According to the Ethiopian temperature zoning, the study area is located in the Woina Dega climate zone where the mean annual temperature is between 15 and 20^{0}C. In the study area the hottest month is June with a mean maximum temperature of 15.7^{0}C; a mean minimum of 10.4^{0}C.

The coldest month, December, is about 10.4^{0}C cooler, the corresponding maximum and minimum values being $23.^{0}$C and 6.6^{0}C. The variation of the temperature cycle from year to year is small.

As far as precipitation is concerned, from the long-term rainfall record, the highest average value of rainfall is recorded in the month of August with value 195mm and the minimum in the month of January with average rainfall value of 8mm.

CHAPTER THREE

GEOLOGY

3.1 Regional Geology

Blandford regional work (1867-1868) that include the watersheds from Adikeyh to wards south up to wollo was able to divide the geology and assign age to the formations. The latest regional geological work including the Adigrat area was carried out by the staffs of geological Survey of Ethiopia since its establishment in 1968.

C.R Garland, 1980 has described the regional geology of the area and the description is adopted for this work.

3.1.1 Precambrian Rocks

The Precambrian rocks of Ethiopia are considered [Kazmin 1971, 1975 cited C.R Garland] to be direct continuation of two folded belts, the Mozambique belt which mainly include the oldest crystalline rocks of southern Ethiopia and one referred as “lower complex”. Above this gneissic and amphobilitic basement and apparently filling the north- northwesterly trough in it, lie the strongly folded but weakly metamorphosed (green schist facies) rocks of “upper complex” which are phyllite, slates, some limestone and volcanic rocks. The upper complex forms the basement in the study area.

3.1.1.1 Lower Complex: - Rocks of this complex are hardly observable on ground but can be detected on air and space photographs by their dark photo tone in the northern part of the escarpment area (C.R. Garland, 1980). They form a block 8 to 10 km wide and about 50 km long striking northwesterly concordant with general trend of basement structures in the study area.

3.1.1.2 Upper Complex: - The upper complex rocks are tightly folded but subjected to lowest grade of metamorphism, mainly greenschist facies, with typomorphic minerals quartz, sericite, chlorite and talc. Original depositional structured such as ripple marks, graded bedding and slump structures are clearly making estimation of depositional environment relatively easy (C.R. Garland,1980).

The upper complex is divided in to Tambien group and Didkama formation, which are metasediments , Tsaliet group that is mainly of metavolcanics and Matheos formation (Beyth, 1971).

The Tsaliet group- The greater part of the basement is formed by heterogeneous series of rocks with obvious volcanic associations. They are breccias agglomerate bedded tuff and lavas all interbedded with marine clastics, rare limestone tuffaceous slates redeposit ash and greywacke composed partly of volcanic fragments. Due to considerable lateral variation in lithology, they have been mapped throughout northern Ethiopia as single unit, Tsaliet group.

The Tamien Group- includes three lower members first recognized by Beyth and Doro later renamed by Tsegay Hailu as Werii slate, Assem limestone Tsedia slate. He also recognized the Arequa formation the lowest formation of the Tambien group. The formation above that, the May Kinetal limestone has not been found in the present area.
The rocks in the Arequa formation are slate, but in the North West the thick dividing Assem limestone allow them to be subdivided in to three members. (Beyth, 1971)

Matheos formation- The formation that is known in "Negash syncline" is thought the youngest Precambrian formation in Ethiopia. It is less than 30m in maximum thickness, folded in to a gentle syncline and has almost angular unconformity relationship with underlying dolomite and slates. It is grey to black, well laminated and undisturbed limestone, partly detrital, veined with calcite (C.R. Garland,1980).

The Didikama formation- The Didikama formation consists of yellowish color medium grained dolomite interbedded with gray,black or colored slate. It is 300m thick at its western most out crop and over 1500m thick at its central part around Gunda Gundi.

3.1. 2 Precambrian Intrusive rocks

Syntectonic granite – The rather weathered, medium grained epidotized granite intrusion in the Werii river basin show a slight foliation and are elongated along the strike , for this reason they are marked as syntectonic granite. The same outcrop though small and few in dimension are found in the Enticho area below the metavolcanic.

Post tectonic granites, granodiorites and & diorites

These are granite to diorite stocks, which were named “Mereb granite”, and “Forstage diorite” by Beyth (1971) .Granite forms the prominent mountain of Asimba. Granodiorite seems to form rather lower areas with distinctive radial drainage and clear jointing. The post tectonic granites are generally coarse grained with characteristics mineral of microcline perthite, sodic plagioclase (zoned), biotitic and green pleochronic hornblende with sphene and apatite as accessory minerals (C.R. Garland,1980).

3.1.3 Upper Paleozoic – Mesozoic Rocks

Recent workers (Dow et al 1971) spitted the upper Paleozoic- Mesozoic clastic rocks (Adigrat group) in to Enticho sandstone, Edagaarbi glacial and the Adigrat sandstone.
There is very close spatial and lithological relationship between all the three formations, although the upper most i.e. Adigrat sandstone is apparently transgressive and covers wide area. The unconformity as the base of Adigrat sandstone, although it undoubtedly exists, it is not strong and is rather poorly expressed & in many instance no subdivision is possible (C.R. Garland,1980).

3.1.4 Mesozoic Rocks

Between the Adigrat sandstone and the upper sandstone in Tigray, there lies the Antalo succession. The Antalo succession comprises the Agulae shale and Antalo limestone. The Agulae shale (type section at Agulae village) consists of variegated shale, marl and clay interlaminated with finely crystalline black limestone and some thin beds of gypsum and dolomite. It has a maximum thickness of 250m (Beyth, 1971, Garland, 1980, Bosellini et al 1997), unconformably overlies Antalo limestone and forms wide terraced slopes. The Antalo limestone consist of white (and rarely black) limestone, finely crystalline to lithographic well- bedded, fossiliferrous, typically well indurated and interbedded with yellow marl and sandy limestone (Asrat,2001)
The Antalo limestone never been observed lying directly on the basement complex in northern or central Ethiopia, always being underlain by the Adigrat sandstone. The Antalo limestone formation varies in thickness from zero to 800m. (P.A Mohr, 1971)

3.1.5 Tertiary Rocks

The tertiary rocks include the plateau volcanics (trap series) and the Adwa trachytes and phonolites (Adwa plugs). The dark stratoid basaltic flows that lie on the laterized surface of the Mesozoic sediments named the trappean (or trap) series by Blanford (1869). He was able to divide them in two distinct groups at Lake Ashange. (12^o, 45'N, 39^o35'E) the groups being separated by a clear angular unconformity & each with different lithogical characteristics. The lower group, the Ashange was found to be composed of almost entirely of basalt, while the upper Magdala group contained many silicic intercalations.Stratigraphically above the trap volcanics are pale colored, fine-grained lavas and plugs composed of alkaline trachytic rocks (C.R. Garland,1980).

3.1.6 Cenozoic Sediments, Holecene and Tertiary intrusive rocks

The Cenozoic sediments, which are observed in the Danakil depression consists of four formations, the Danakil formation (red series), the Enkafala formation (white series) and the Afdera formation. The central graben of the Danakil depression is a north-northwesterly trending trough filled with evaporites, alluvial and recent volcanics in part younger than the Enkafala beds. Many basaltic dykes occur in the escarpment, some of them being feeders for eruption of the trap series. Most of them strike northwest or North-north west and are parallel to the red sea Afar escarpment (C.R. Garland,1980).

3.2 Regional Structures

The dominant structures in the region are the faults of different age and system,Beyth (1970). These are faults of the basement complexes, which are the oldest and were active in the Precambrian. They are steeply dipping and strike north- east parallel to the strike of the metasediment and metavolcanics of the area. Most of them are reverse faults.

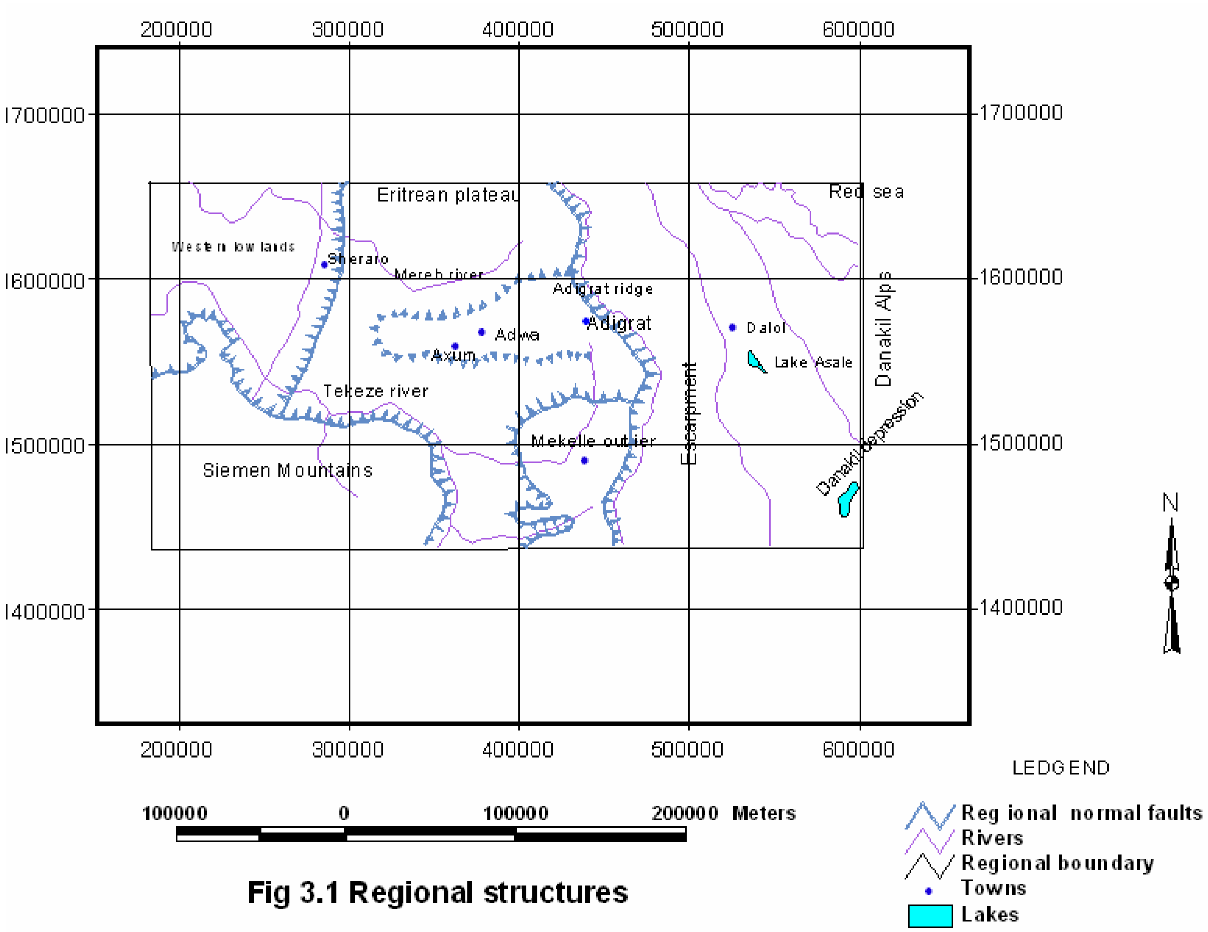


Fig 3.1 Regional structures

The other next prominent structure in the region is the parallel faults that displace the Mesozoic sediments. They are oriented west-north-west direction this includes the Wukro, Mekelle, chelokot and Fusia mariam located from north to south of Mekelle and they are parallel to each other. They are characterized by normal faults, dip at moderate to steep slope angle and the presence of dolerite dykes along the fault zone.

The third and by far the largest fault system belong to the African rift, a system of predominantly normal steep faults. It forms the escarpment and the Danakil depression. The faults of this system have been active from the tertiary to recent and strike north-south to north-east. These normal faults generally dips to the east with a total throw of more than 3000m over a horizontal distance of less than 50km. The system in general is formed of numerous normal faults with steep planes, forming grabens and tilted blocks.

3.3 LOCAL GEOLOGY

3.3.1 Alluvial sediments (Unconsolidated Sediments)

The Alluvial sediments are extensively observed In the southern part of the study area, along flood plains, river banks and depressions such as Bikot, Abunearegawi, Huga, Agoro, Ifla, Adimeskel valleys and May mesanu in the north.

They are composed of sand, gravel, silt and clay. In addition to these pebble and cobble size, sediments are observed at river banks of Betemichael church, Abunearegawi church, Dibla, May mesanu(Dikue')and Adinegoda.

The thickness of the alluvial sediments ranges from 0.5m in the southern margin of Adigrat town overlying the basement rocks up to 10m in river banks that drain from Dibla ridge and tributary of the May megab in the northern part of the study area, which is marshy. They are grouped as recent fluvial- eluvia deposits and hence are the youngest of all the rock units exposed in the study area. Geomorphologically they form the flat and low lying valleys.

3.3.2 Aiba Basalt

This unit unconformably overlies the Adigrat sandstone. It out crops in the western part of the study area forming high steep cliffs and gentle slopes.

Its thickness varies from place to place. It is thicker to wards north and thins southwards. The highest thickness lies in the Adigrat-Adwa road, which is around 1000m. Thin layers of paleosol around 10cm thick along Adigrat-Adwa road indicating time gap probably show different episodes of magmatic eruption for the crystallization basaltic unit.

The Aiba basalt forms the Andel ridge, Bikot ridge Dibla ridge and chechat ridge in the study area. It is dark in color fine grained (aphanitic) and at places vesicular filled by amygdales. In most areas, it is moderately weathered to pinkish and brownish color. The contact between the Aiba basalt and Adigrat sandstone is clearly seen throughout the study area.

This Aiba basalt at the top of the ridges is affected by vertical to sub vertical joints in the direction of E-W and at places show spheroidal weathering.

The Aiba basalt represents the second major pulse of fissural basalt volcanism on the north-western plateau of Ethiopia. They are generally aphanitic compact. The absolute age of the Aiba basalt arranges from 34 to 28ma, placing them in Oligocene (Zanathin, et al, 1980, Kazmin 1979 in Mengesha Teferra).

3.3.3 Adigrat sandstone

This unit is the uppermost clastic sequence that overlies unconformably on the Edagaarbi glacial. In the study area, its lower contact with the Edagaarbi glacial is clearly seen. This unit is overlain and underlain by basalt and Edagaarbi glacial respectively. It shows gradational contact with Edagaarbi glacial whereas, the contact between the upper Aiba basalt and the Adigrat sandstone is sharp.

Unlike the Aiba basalt, it is thicker in the southern part of the study area and pinches out towards north. It is observed to disappear 4km north of Adigrat along Adigrat- Zalambessa road. The Adigrat sandstone forms high cliffs of approximately 100m thick as it is observed west of Edagahamus -Adigrat road.

The Adigrat sandstone is yellowish to pinkish in color owing to Iron as cementing material. This unit is fine to medium grained, non-calcareous quartz sandstone.
It is well sorted, rounded grain and cross-bedded. At surfaces, it is weathered to red color, with deep vertical jointing. (Garland 1980) Most of the joints are oriented at $N030^0$ with vertical to sub vertical dip. The joint spacing ranges from 1to 5m.

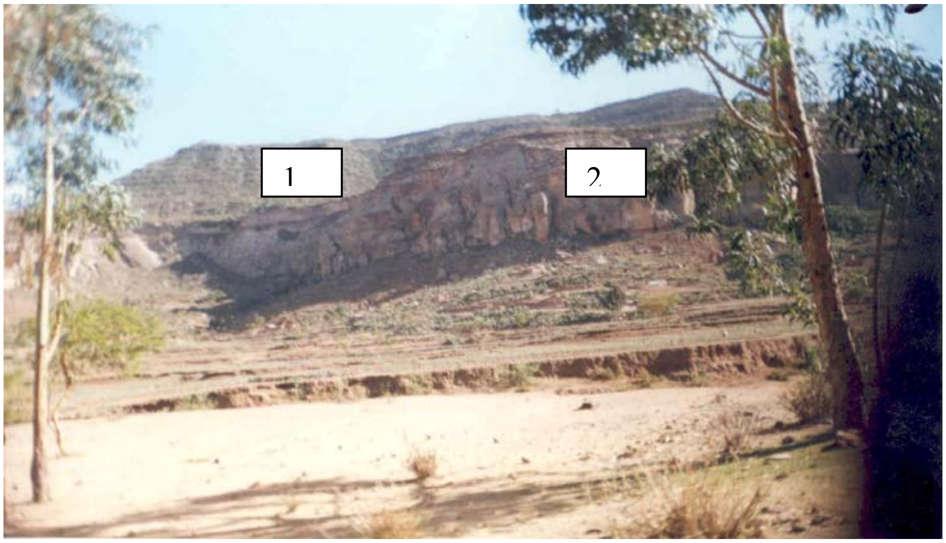


Fig.3.2 An exposure of thick alluvial deposit (bottom) along Adigrat-Adwa road & Edagaarbi glacial above it. 1 is Aiba basalt 2 is Adigrat sandstone

3.3.4 Edaga-Arbi glacial

As described in Leveti (1970) and C.R Garland (1980) the Edagaarbi glacial interfinger with the Enticho sandstone. However, in the study area, the two units are clearly exposed and the Enticho sandstone falls below the glacial tillite.

This unit is exposed in the study area underlying the Adigrat sandstone and overlying the Enticho sandstone forming gently sloping morphology. It forms conical hills and weathered irregular escarpments surface.

At places where the Edagaarbi overlies the Enticho sandstone like west of Edaghamus- Adigrat road, it has variegated color (purple to pinkish, dark gray to black), friable silty shale, small angular quartz fragments supporting triangular pebble 1 to 5cm long metavolcanic and rounded granite in the matrix of clay. It forms conical hills and weathered irregular escarpments at surface. The friable shale makes up the greatest thickness of the glacial (C.R Garland 1980).

In general, the unit is composed of silt and shale material that vary in color, lamination and content of eratics such as pebble and boulders. The upper part of the unit immediately below the Adigrat sandstone is observed as finely laminated thick layer of red and greenish shale and greenish gray shale inter bedded with thin beds of silty limestone that varies in thickness between few meters to 100m thick.

The lowest part of the unit is of massive dark greenish –gray shale and dark gray tilite at the base that consist of pebble and boulders of metamorphic and granite respectively.

3.3.5 Enticho sandstone: - This unit comprises more than 50% of the study area and occupies the area east of Edagahamus- Adigrat main asphalt road and partly west of the road. The Enticho sandstone is exposed unconformably underlying the Edagaarbi glacial and unconformably overlying the basement rocks, as it is observed west of the Edagahamus-Adigrat road east of Nihbi Michael church, the white plateau of endahawariat and Gola' Betemaria.

The Enticho sandstone is whitish in color, medium to coarse grained, friable sandstone cemented by calcite. It is mainly horizontally bedded, composed of quartz, feldspar and mica.

At places like west of Beati Michael the surfacial exposure of the Enticho sandstone shows conglomerate, pebble to cobble size rock fragments that are rounded to surrounded in shape and is surfacially ferrugenized. It is less cemented with calcareous and kaoline type of cementing material and relatively coarse grained with angular poorly sorted grains of quartz. It is dominantly yellowish to unit color and is coarsely cross bedded.

The Enticho sandstone in most part of the study area is affected by vertical to sub vertical fractures with general strike ranging from N10^{o}E to N20^{o}W. The dominant fracture systems are oriented in the direction E-W, NW-SE and NE-SW and N-S.

The Enticho sandstone and the Edagaarbi glacial observed to interfinger at Gilamo Gabriel church, 2.5km south west of Adigrat town and along Adigrat –Zalambessa road, 4km north of Adigrat town, where the Adigrat sandstone disappears west of the road.

Geomorphologically it forms both gentle and steep slopes. Its thickness reaches 50 to 100m in the gentle and steep slopes respectively. Its thickness decreases to wards south of the study area. One of the distinctive features of this unit is it shows primary sedimentary structures, such as cross bedding. The cross beddings are very closely spaced almost every 2m and show paleo-current direction.

Bore hole logging around Abune Aregawi church indicated that the basement complex is not encountered up to a depth of 110m b.g.l, whereas from field observation 3km south of Adigrat town, in some local ponds dug for water harvesting, the basement complex mainly slate is encountered at a depth of 1m bgl over lied by alluvial sediment indicating thinning of the overlying sediments and sedimentary rocks mainly Enticho sandstone.

The position of the two beds i.e. the Edagaarbi glacial overlying the Enticho sandstone vary from place to place and some units are seen to interfinger thus not stratigraphic horizons but facies of the same age. (C.R Garland 1980)

The EdagArbi glacial and the Enticho sandstones are quite characteristics of glacial deposits, even though the tillite form less than 10% of the whole thickness. (Du Toit 1953)

From aerial photo interpretation and intensive field observation the dominant fractures which are vertical to sub vertical that affect the Enticho sandstone are oriented in the of N330^0, N010^{0}E, N080^{0}E indicated by basaltic feeder dykes like the basaltic dykes across the siet stream, which is southern margin of the study area, oriented in the direction of N330^0 and at Dibla Gabriel in the direction of N080^{0}E.

The spacing of the fractures ranges from 0.5m to 10m. In northwestern part of the study area around May Mesanu the fractures are closely spaced with average fracture spacing of 0.5m.

Fig 3.3 an out crop of Enticho sandstone with orthogonal fractures

3.3.6 Metamorphic and intrusive rocks

The metamorphic rocks of the study area are represented by "upper complex" which are inhomogeneous phyllite, slate volcanic rocks and graywacky deposited in a geosynclinal basin overlaid by sedimentary slate, limestone and sandy greywacke. (Garland 1980)

The metamorphic rocks in the study area have both volcanic and sedimentary origins. The metamorphic rock complex, which dominantly comprises slate/phyllite with white and dark banding indicate their sedimentary origin. The slate /phyllite intercalated with metagrewacky as observed around Betermaria, eastern Gola' and Nihibi Michael is thinly foliated striking N010^{o}E dipping 20^{0} towards North-east.

The slate is very fine gained in texture, dark gray in color and has perfect slaty cleavage. The phyllite on the other hand is pinkish to whitish in color, fine to medium grained, shiny and has soapy appearance. The slate/phyllite is slightly weathered and exhibits pyrite mineralization, quartz vein lets and micro fractures discordant to the strike of the foliation. The slate in contact with the granite is silicified, fresh and forms ridges.

The metavolcanoclast/ metavolcanic rock are massive to slightly foliate. These rocks are surfacially exposed in the central part of the study area around Adinegoda and sasun depressions and gorges. It is light greenish in color, probably derived from intermediate magma and bears quartz veins and vein-lets.

The degree of metamorphism is expected to be low because relicts of pyroxene and plagioclase feldspars are megascopically seen. The foliation plane strikes in the range of $000^0/45^oSE$ to $N50^0W/30^oNE$ as observed around Endahawariat and Adinegoda areas. Moreover, they are affected by east- west running vertical to cub vertical joints.

Fig 3.4 An out crop of metasediment, on top is the Enticho sandstone

The granites & granodiorites are the major intrusive in the study area. They are medium to coarse grained in texture, composed of quartz, feldspar and chlorite. Generally they are massive and silicfied but, at places surfacially fractured. The fractures are oriented in the directions of N-S and NW-SE.

Fig3.5 An out crop granite

3.3.7 Dolerite dykes

Although not map- able, it is described as separate due to its significance in the hydrogeology of the study area.

Dyke formation as an effect of compressional stress and like sub axial splitting o tension (or pressure relief perpendicular to the maximum stress direction, show open up fractures in the crust, deep enough to reach region with molten rock. It is evident that dike formation means tension acting perpendicular to the direction of crust.

As explained in the regional structure regional tensional forces affect the area. Therefore, the dykes of the study area are results of the regional structural effect.

These dykes are found cross cutting the whole sequence of the lithologic succession of the study area. As interpreted from aerial photo and field observation most of the dykes run across the direction of streams as that of Siet stream. They are generally tabular and basaltic in composition. They are less weathered and in general vary in width from less than 2m to about 6m. They extend along strike for a distance of less than kilometer to greater than tens of kilometers. The general trend of the dikes is N 70^{0} W and 50 ^{0} SW.

Fig 3.6 An outcrop of basaltic dyke

3.4 Structure

The dominant structures observed in the area include joints/fractures, bedding planes, foliations and faults.

3.4.1 Fractures: are defined as structures on rocks or minerals in which their surfaces are broken or lost cohesion. Some fractures as faults show displacement of the one block with respect to the other in different directions. Fractures that do not show or show little displacement is called Joints. Coming to our study area, many fractures with different orientations and spacing have been identified by aerial photo interpretation and field excursions.

As stated above joints and fractures are most abundant structural features in the study area. The density, orientation, spacing, aperture and continuity in the different lithologies available are considered. The result of systematic measurements of these structures in different lithologies is adopted from WAPCOS (2000) and is verified by field measurements and observations.

Table 3.1 structural features in Enticho sandstone

joint set	Strike	Dip	spacing	Aperture	Continuity
1	N-S	vertical	50cm to 1m	10-20mm	Long
2	E-W	vertical	2-4cm	20mm	Long
3	NE-SW	60^0 to SE	50cm-80cm	Filled open up to 10mm	Long
4	NW-SE	vertical	1m in general	10mm	Long

Source: WAPCO (2000)

Table 3.2 structural features in Adigrat sandstone

joint set	Strike	Dip	spacing	Aperture	Continuity
1	N-S	60^0 to east	30-60cm	15mm	Long
2	E-W	vertical	1-2cm	20-50mm	Fair
3	NW-SE	80^0 to SW	50-80cm	10mm	Fair

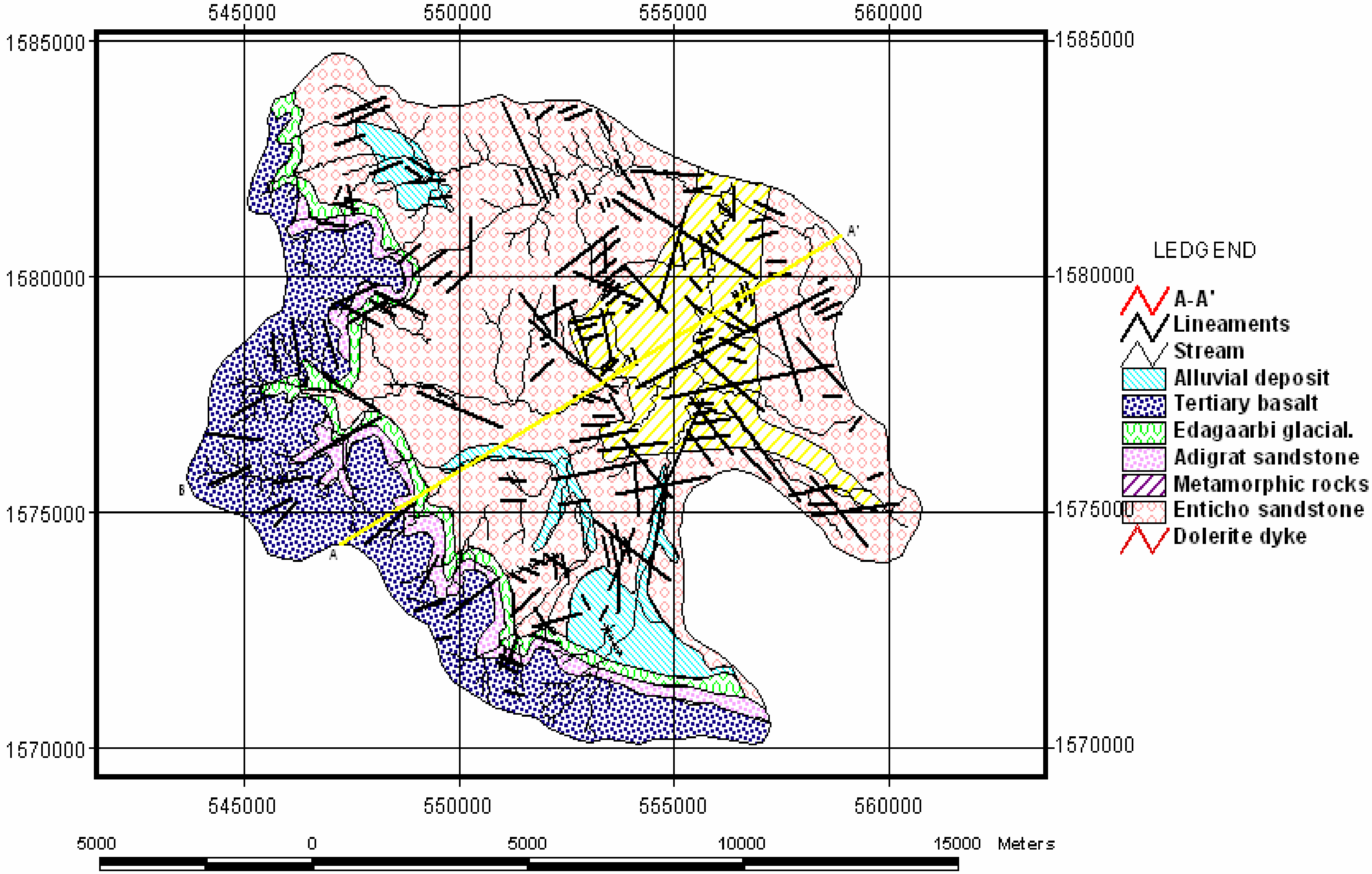
Source: WAPCO (2000)

Table 3.3 structural features in the metavolcanics

joint set	Strike	Dip	spacing	Aperture	Continuity
1	E-W	50^0 to S or N Vertical	30-50cm	10mm or tight	Long
2	NW-SE	45^0 to NE	50-80cm	20mm	_
3	N-S	vertical	10-20cm	20-30mm	Long
4	NE-SW	50^0 to SE	30-50cm	5-10mm	_

Source: WAPCO (2000)

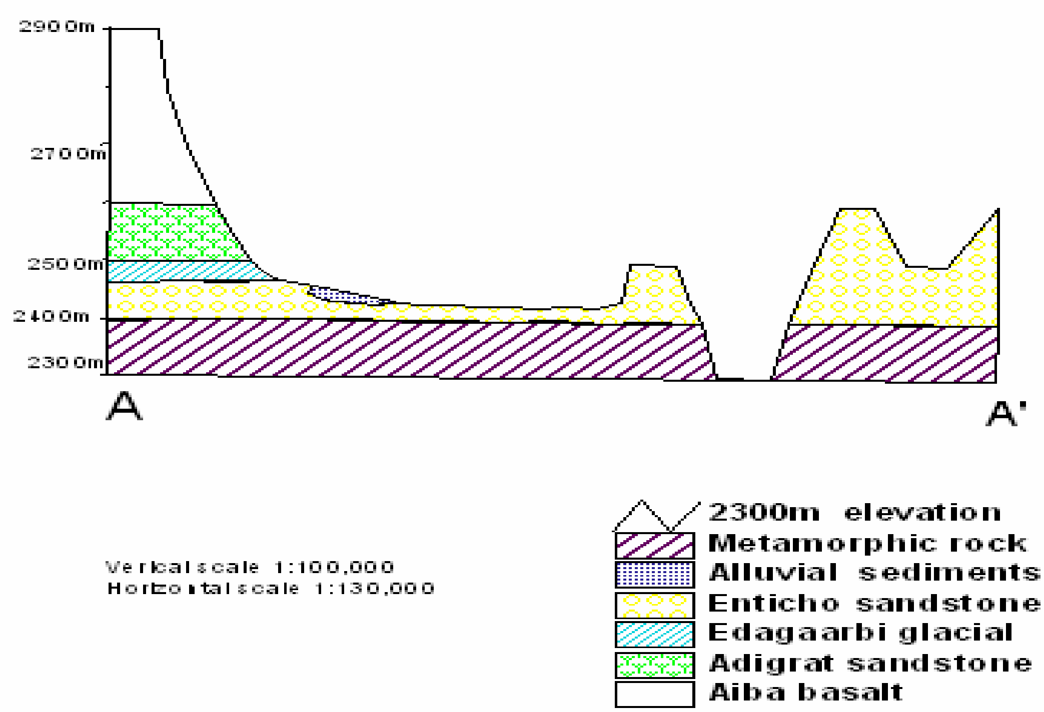
Fig 3.7 Geological map of the study area



3.4.2 Bedding and Foliation: Bedding planes are primary structures and weak planes where one bed is separated from the other below or above. These weak surfaces are frequently seen in the Enticho sandstone and Adigrat sandstone. In addition, are generally horizontal. However, some bedding planes in both units are dipping as observed in UTM location 0548310E, 1582503N, towards north. The other important bedding features are the interflow beddings and paleosoils observed in the Aiba basalt.

Foliation is another structure observed in the met-sediment and meta-volcanic rocks of the study area. In the slate/phyllite-metagraywacke, it strikes in the direction of NE and moderately dips towards NW direction; where as in the meta-volcanics the strike of the foliation ranges from NS to NW and gently dips towards NE direction.

Fig 3.8 Geological cross section



CHAPTER FOUR

HYDROMETREOLOGY

4.1 General

The process by which water enters the atmosphere through either evaporation or transpiration and returns to the earth through condensation and precipitation is called hydrologic cycle.

The most useful hydrometrological variables are precipitation, evaporation, evapotranspiration, solar radiation, air temperature, relative humidity, soil moisture, and stream discharge. (Shaw 1994)

The available data in the study area includes metrological data of precipitation, air temperature and relative humidity. Wind speed, sunshine hours and stream run off data are considered from adjacent areas for the climatological analysis and to estimate the water balance of the catchment. In addition to the above, data about soil land use/land cover are used in conjunction with the above mentioned metrological data to estimate the water balance of the catchment

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4.2 Precipitation

Precipitation is general form of atmospheric moisture, which may occur in any number of forms and may change from one form to another during its descent. In other words, the precipitation can be defined as the total amount of water falling from the atmosphere in the form of rain, snow, mist etc., on the earth (Shaw, 1994).

4.2.1 Average Depth of Precipitation

The precipitation measured by a rain gauge gives depth and intensity of rainfall only at a particular geographic point where it is set up, not the aerial rainfall. For determining average depth of rainfall of an area, there are many ways of deriving the aerial rainfall over a watershed from rain gauge measurements. Selection of suitable method among arithmetic mean method, Theissen polygon method and isoheytal method for computing the mean aerial precipitation depends on the following main factors; rain gauge network of the catchments, size of the watershed and topographic feature of the catchments.

The generally preferred method for averaging precipitation over an area is the isohyetal method. The method has several advantages over the other two methods; because it doesn't take only precipitation at the neighboring stations, but also the result s yielded by this method remains practically unaffected whether any new station s are added to or missing from the net work over the area under study. Further this method also takes in to account the physiographic feature of the region.

To compute the average depth of rainfall of the study area, isohyetal technique has been employed. The formula used is

$$\bar{P} = \frac{\sum_{r=1}^{n} \Pr Ar}{\sum_{r=1}^{n} Ar} \tag{4.1}$$

Where P = Average precipitation over the catchment

A_1, A_2, A_3--------A_n = Areas between successive isohytes

P_1, P_2, P_3----------P_n = Average rainfall i.e. the mean of the two successive isohyets over the areas $A_1A_2A_3$-------An

The metrological stations from where the data was made for analysis is shown in table 4.1

The general rainfall pattern of the study area is that the rainfall increases towards north east and south east as one move from the centre of the study are. The central part of the area receives 694mm of rainfall. The average depth of precipitation of the study area by this method is 694 mm

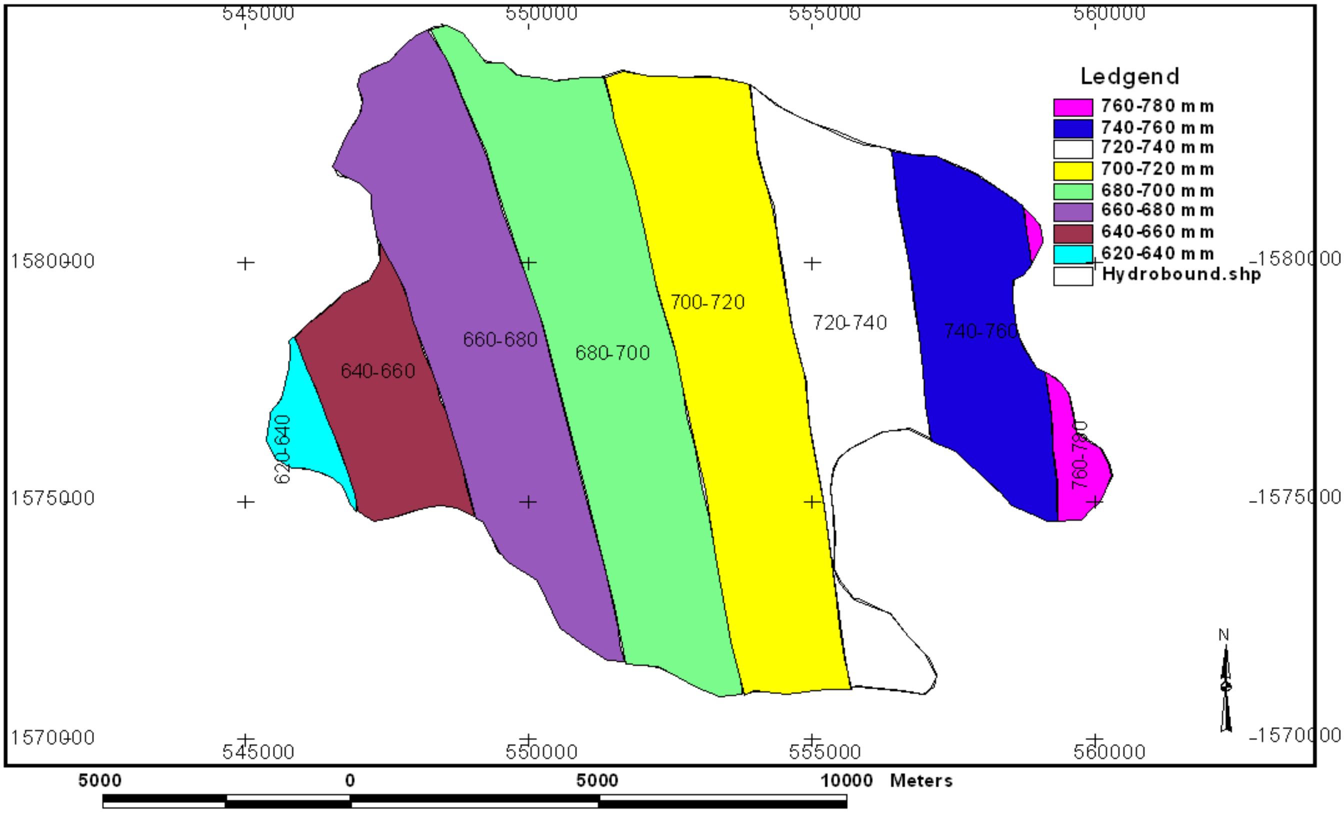


Fig 4.1 Isohyetal map of the study area.

Table 4.1 Location, elevation and average annual rainfall of the rainfall stations

S. No	Name	Z.dex no.	Latitude.	longitude	height of station(m)	Annual rainfall(mm)
1	Adigrat	39140023	1578583	538830	2457	597.29
2	Edagahamus	39140064	1568672	560427	2690	762.6
3	Hawzien	39140114	1545419	546441	2280	571.2

4.2.2 Monthly Distribution of Rainfall

In the study area a total of 31 years from (1970-1988) and 91992-2003) for Adigrat; 23 years from (1971-1981) and (1992-2003) for Hawzien and 28 years from (1973-1988) and (1992-2003) for Edagahamus stations (Annex1) monthly sum precipitations are collected and used to see the pattern and variability of rainfall in the catchment. The mean monthly rainfall ranges between 8mm and 195mm.

The annual rainfall of the area is 694mm with the maximum amount recorded during July and August.

Table 4.2 Monthly percentage contribution of rainfall

Month	Jan	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov	Dec.
Mean Rain	8	10	55	67	54	50	168	195	28	26	20	13
%	1.18	1.49	7.96	9.7	7.83	7.18	24.15	28.1	3.95	3.7	2.95	1.82

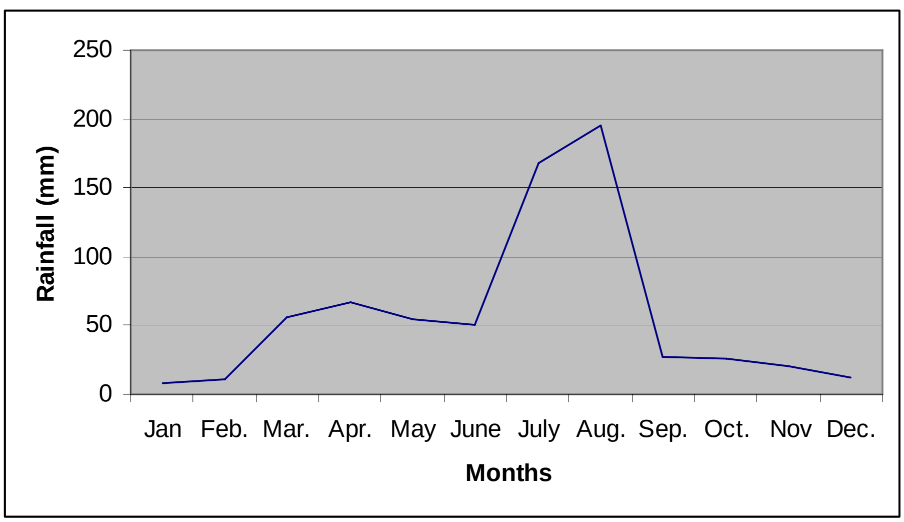


Fig. 4.2 Long term mean monthly rainfall variation at the catchment

To compare the monthly distribution and to identify dry and rainy seasons, ‘‘rainfall coefficient’’ was employed. The rainfall coefficient is being obtained by dividing mean monthly rainfall to one twelve of the annual mean rainfall (UNFAO, 1965 cited in Daniel Gemechu, 1977) .A month is distinguished as rainy when the corresponding month rainfall coefficient reaches 0.6, where as dry month has less than 0.6 rain fall coefficient. Driest months are October, November, December, January and February. In most years the effective rainy season is limited to the two rainy months. Daniel (1977) also classified the rainy months of Ethiopia in to small rain (0.6 to 0.9), and big rains (1.0 & above).

Table 4.3 Mean monthly designation (D: Dry,SR: Small Rainy,BR: Big Rain)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Rainfall(mm)	8	10	55	67	54	50	168	195	28	26	20	13
Coefficient	0.14	0.18	0.95	1.16	0.94	0.86	2.9	3.37	0.47	0.44	0.35	0.22
Designation	D	D	SR	BR	SR	SR	BR	BR	D	D	D	D

According to rainfall regime classification given by Daniel Gemechu (1977), the area is characterized by Type II rainfall with one rainy season lasting from March to August.

4.2.3 Rainfall variability

As it is shown below, the 30 years mean value of annual sum precipitation records of the three stations (1970-2003) show annual variability over the catchment. (Fig 4.2)

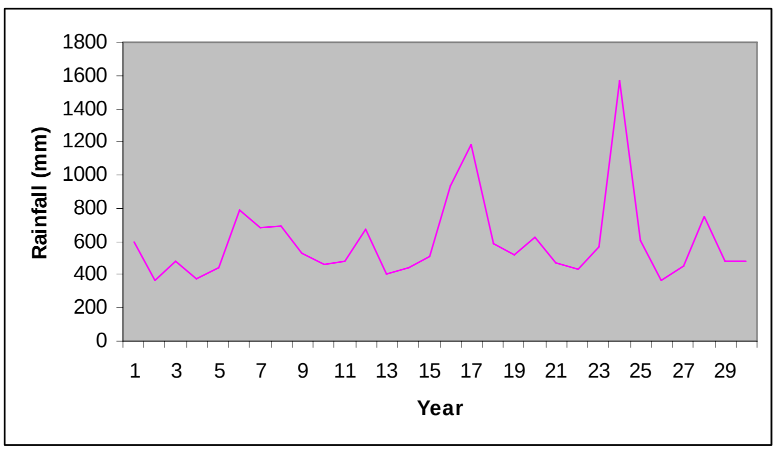


Fig 4.3 Temporal variation of the average annual sum rainfall for the study *area.*

Corresponding to the wettest and dry periods prevailing throughout the region; five maximum and three minimum mean annual sum rainfall in 1975, 1977, 1985, 1987, 2001 and 1971, 1973, 1999 has occurred respectively. The highest deviation below annual mean is shown in 1971.

4.3 Temperature

A temperature data of 32 years (1972-2000) for monthly maximum temperature; 8 years (1996-2003) for monthly minimum temperature of Adigrat station are available.

The monthly minimum temperature varies from the lowest value of 7.7^{o}C in December with gradual increment up to April, to a maximum of 13.1 ^{o}C in May. From August to December there is a decrease in the monthly minimum temperature.

The highest maximum monthly temperature was recorded in the months of March, April, May and June, (24.5^{o}C to 24.8^{o}C) and the minimum, in the month of July (22.02^{o}C) and August (22.27^{o}C). There is a general increase from January to June.The mean annual temperature for the area is 13 ^{o}C.

4.4 Relative humidity

Data for relative humidity is available from Adigrat station of only six years. The monthly mean value is computed by averaging the relative humidity values recorded at 0600 LST, 1200 LST and 1800 LST and is used for the catchment in the evapotranspiration calculation and in the evaluation of the water balance of the catchment.

The highest relative humidity value corresponds to the rainy season s of July and August with values 74.6% and 78.5% respectively. The minimum values 45.4% and 65.4% are recorded in the dry seasons of February and March respectively.

4.5 Wind speed

Mean monthly wind speed recorded data at Aynalem station for 5-years (1992-2000 G.C) and from Ellala station for 15-years (1982-1988& 1995-2002 G.C) (Annex 1) of Mekelle area are used in evapotranspiration computation by averaging the values for the whole catchment

4.6 Sunshine hours

Data for sunshine hours are obtained from both Aynalem and Ellala stations of Mekelle area, for 10-years (1992-2001 G.C) and 14-years (1980-1988& 1995-2002 G.C) respectively (Annex 1). The mean monthly data is used for computation of evapotranspiration for the whole catchment

Table 4.4 Summary of monthly average value of metrological elements in the study area

Months	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Rainfall	8	10	55	67	54	50	168	195	28	26	20	13
Temperature	11.6	12.7	13.9	14.1	14.3	15.7	14.5	13.5	12.6	11.9	11.4	10.4
Sun shine hours	9.6	9.6	8.8	9.0	9.0	7.5	5.4	5.2	7.8	8.4	9.7	9.7
Wind speed	8.0	8.6	9.2	9.0	6.9	4.3	3.4	2.8	3.8	7.1	8.1	
Relative humidity	55	45.4	54.4	59.4	55	60.8	74.6	78.3	62.9	65.1	73.3	65.5

Rainfall (mm), Temperature (^oC), Sun shine hours in (hours/day),

Wind speed (miles/day) & Relative humidity (%).

4.7 Evapotranspiration

Evapotranspiration is a collective term for all the processes by which water in the liquid or solid phase at or near the earths land surface becomes atmospheric vapor. The term thus includes evaporation of liquid water from rivers and lakes, bare soil and vegetative surface, evaporation from within the leaves of plants (transpiration) and sublimation from ice and snow surface. It is the additive value of both evaporation and transpiration. It is affected by air and soil temperature, vapor pressure of air (air humidity), sun radiation, wind speed, soil moisture and physiological characteristics of vegetation (Dingman, 1994).

4.7.1 Potential evapotranspiration

Potential evapotranspiration is defined as the amount of water that would be removed from the land surface by evaporation and transpiration processes if unlimited water is available in the soil to meet the demand (Dunne & Leopold, 1978).

The value of the actual evapotranspiration (AET) over a catchment is more often obtained by first calculating the potential evapotranspiration by assuming unrestricted availability of water, and then modifying the result of PET by accounting for the actual soil moisture content. In this work the modified penman, Thornthwaite and Malstrom methods are employed to compute potential evapotranspiration.

The modified penman formula is given by:

$$PE = \frac{\left(\Delta / \gamma \right) H_T + E_{at}}{\left(\Delta / \gamma \right) + 1} \qquad (4.2)$$

Where H_T - available heat (W/m-2)

E_{at} – saturation vapour pressure at air temperature, Ta

Δ - slope of the curve of saturation vapor pressure plotted against temperature

γ – Hydrometric constant (0.27 mmHg / C)

Table 4.5 Computation of Potential Evapotranspiration using Penman Combination (Penman 2) method.

Months	T0c	ea	ed	U2	T(k)	n	N	Ra	n/N	fa(n/N)	RI(1-r)	R0	HT	Eat	PETm
Jan.	11.6	10.29	5.66	119.3	284.6	9.5	11.375	11.95	0.84	0.68	6.40	3.33	3.07	3.55	98.20
Feb.	12.7	11.06	5.02	128.30	285.70	9.80	11.63	13.26	0.84	0.68	7.15	3.53	3.62	4.83	115.23
Mar.	13.9	11.97	6.51	137.30	286.90	9.20	12.00	14.16	0.77	0.64	7.11	3.07	4.04	4.53	131.08
Apr.	14.1	12.12	7.20	134.20	287.10	9.40	12.47	15.20	0.75	0.63	7.53	2.93	4.60	4.03	131.57
May	14.3	12.28	6.75	102.90	287.30	9.60	13.28	15.30	0.72	0.61	7.35	2.91	4.44	3.92	131.50
June	15.7	13.44	8.17	64.10	288.70	7.40	12.96	15.22	0.57	0.51	6.18	2.30	3.88	3.03	107.16
July	14.5	12.44	9.28	50.70	287.50	5.40	12.86	15.28	0.42	0.42	5.08	1.73	3.35	1.67	84.09
Aug.	13.5	11.66	9.13	41.80	286.50	5.30	12.57	15.17	0.42	0.42	5.05	1.72	3.33	1.26	78.09
Sep.	12.6	10.99	6.91	56.80	285.60	7.80	12.19	14.97	0.64	0.56	6.59	2.57	4.02	2.24	98.99
Oct.	11.9	10.49	6.83	105.90	284.90	9.30	11.80	13.65	0.79	0.65	6.99	3.00	4.00	2.64	106.45
Nov.	11.4	10.15	7.44	120.80	284.40	9.70	11.43	12.33	0.85	0.69	6.68	3.05	3.63	2.09	89.48
Dec.	10.4	9.50	6.22	123.80	283.40	9.90	11.25	11.61	0.88	0.71	6.47	3.30	3.17	2.57	90.13
														Total	**1261.98**

The Thorthwaite method is given by a formula

$$PEm^* = 1.6[10t/J]^{a} \qquad (4.3)$$

Where a is $675 \times 10^{-9}J^3 - 771 \times 10^{-7}J^2 + 178 \times 10^{-5}J + 0.49239$

t is mean annual temperature(^oC)

J is the sum of the 12 months heat index, j given by

$$j = (t_n/t)^{1.514}$$

tn is average temperature in oC.

t is mean annual temperature(^oC)

$$\text{then } PEm = PEm^* [(STz/30 \times 12)]$$

PEm = potential evapotranspiration in cm of a standard month of 30 days and 12 hours between sun rise and sunset .

where PEm* = total potential evapotranspiration of the month under consideration

S is number of the days of the month in question

Tz is average number of hours in day between sunrise andsunset in the the month.

The third method used in the computation of evapotranspiration is the Malstrom (1969) method. It is given by

PETm = 0.409[esat(Ta)] (4.4)

Where PETm is evapotranspiration in cm/month

esat is saturation vapor pressure in mb

Ta is mean monthly average temperature in oC

The results obtained using the three methods is summarized below

Table 4.6 Summary of PETm obtained by different methods

Month	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Total
Penman	98	115	131	131	131	107	84	78	99	106	89	90	1259
Thornthwaite	45.5	44	45.5	45	47	35	27	26	37	46	46	49	494
Malstrom	56	60	65	65	67	73	68	63	60	60	57	55	740

The values obtained from Malstrom amd Thornthwaite methods are underestimated thus; the result obtained from combined penman method is used in the computation of AET.

4.7.2 Actual evapotranspiration

Actual evapotranspiration is smaller or equal to potential and is affected by the availability of water in the soil. Thus the relation between the potential evapotranspiration and the actual evapotranspiration depends on the soil moisture contents (Shaw, 1994).

The actual evapotranspiration of Adigrat and its surrounding area is computed by considering the monthly potential evapotranspiration direct run off and the major soil type of the study area.

The computation is adopted from the monthly water balance model proposed by Thornthwaite and Mather (1955), which is a simple 'book keeping' model that uses monthly values of precipitation, direct run off and potential evapotranspiration to estimate monthly actual evapotranspiration.

In this monthly water balance model, the soil-water storage of the region is represented by a single value , Smax and an initial value of soil moisture, So, is specified.

Following Alley (1984), if for a given month Pm> PET, the value of soil moisture at the end of that month , Sm is found as:

$$S_m = \{\min [(P_m\text{-PE}\}T)+ S_{m-1}], S_{max} \} \quad (4.5)$$

If Pm< PET, a soil moisture deficit develops or increases. The soil moisture for this case is given by:

$$S_m = S_m\text{-}1 \exp [- (PET\text{-}P_m)/S_{max}] \quad (4.6)$$

The monthly actual evapotranspiration, AETm is then found as:

$$AETm = PETm \qquad \text{if } Pm > PET \quad (4.7)$$

$$AETm = Pm + S_{m-1} – Sm \qquad \text{other wise} \quad (4.8)$$

Table 4.7 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is sand loam with an available water capacity of 75mm. Vegetations are shallow rooted crops (cereals, like barley, wheat etc

Months	P_m	DRo	Pm-DRom	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	0	-1	9	89	0
Feb.	10	0	10	115	-105	-429	0	0	10	105	0
Mar.	55	7	48	131	-83	-575	0	0	48	83	0
Apr.	67	5	62	131	-69	-644	0	0	62	69	0
May	54	0	54	131	-77	-721	0	0	54	77	0
June	50	0	50	107	-57	-778	0	0	50	57	0
July	168	29	139	84	55		55	55	84	0	0
Aug.	195	32	163	78	85		75	20	78	0	65
Sept.	28	0	28	99	-71	-71	29	-46	74	25	0
Oct.	26	0	26	106	-80	-151	10	-10	45	61	0
Nov.	20	0	20	89	-69	-220	4	-6	26	63	0
Dec.	13	0	13	90	-77	-297	1	-3	16	74	0
Total	694	73	621	1261	-638				556	703	65

Where P_m: Mean monthly precipitation (mm)

PET_m: Monthly potential evapotranspiration (mm)

AWL: Accumulated potential water loss (mm)

S_m: Soil moisture (mm)

ΔS_m: Change in soil moisture

AET_m: Monthly actual evapotranspiration (mm)

D: Soil moisture deficit (mm)

S: Soil moisture surplus (mm)

DRo_m: Direct run off (mm)

Table 4.8 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is clay loam with an available water capacity of 200mm. Vegetations are moderately-deep rooted crops such as grasses, shrubs etc

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	29	-16	24	74	0
Feb.	10	0	10	115	-105	-429	17	-12	22	93	0
Mar.	55	7	48	131	-83	-575	11	-6	54	77	0
Apr.	67	5	62	131	-69	-644	8	-3	65	66	0
May	54	0	54	131	-77	-721	5	-3	57	74	0
June	50	0	50	107	-57	-778	4	-1	51	56	0
July	168	29	139	84	55		59	55	84	0	0
Aug.	195	32	163	78	85		144	85	78	0	0
Sept.	28	0	28	99	-71	-71	140	-4	32	67	0
Oct.	26	0	26	106	-80	-151	94	-46	72	34	0
Nov.	20	0	20	89	-69	-220	67	-27	47	42	0
Dec.	13	0	13	90	-77	-297	45	-22	35	55	0
Total	694	73	621	1261	-638				621	638	0

Table 4.9 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is clay loam with an available water capacity of 100mm. Vegetations are shallow rooted crops (cereals, like barley, wheat etc)

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	2	-3	11	87	0
Feb.	10	0	10	115	-105	-429	1	-1	11	104	0
Mar.	55	7	48	131	-83	-575	0	-1	49	82	0
Apr.	67	5	62	131	-69	-644	0	0	62	69	0
May	54	0	54	131	-77	-721	0	0	54	77	0
June	50	0	50	107	-57	-778	0	0	50	57	0
July	168	29	139	84	55		55	55	84	0	0
Aug.	195	32	163	78	85		100	45	78	0	40
Sept.	28	0	28	99	-71	-71	49	-51	79	20	0
Oct.	26	0	26	106	-80	-151	22	-27	53	53	0
Nov.	20	0	20	89	-69	-220	11	-11	31	58	0
Dec.	13	0	13	90	-77	-297	5	-6	19	71	0
Total	694	73	621	1261	-638				581	678	40

Table 4.10 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is sand loam with an available water capacity of 150mm. Vegetations are deep rooted wood land of eucalyptus tree, Indigeous trees of Juniper etc.

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	11	-10	18	80	0
Feb.	10	0	10	115	-105	-429	6	-5	15	100	0
Mar.	55	7	48	131	-83	-575	3	-3	51	80	0
Apr.	67	5	62	131	-69	-644	2	-1	63	68	0
May	54	0	54	131	-77	-721	1	-1	55	76	0
June	50	0	50	107	-57	-778	1	0	50	57	0
July	168	29	139	84	55		56	55	84	0	0
Aug.	195	32	163	78	85		141	85	78	0	0

Sept.	28	0	28	99	-71	-71	93	-48	76	23	0
Oct.	26	0	26	106	-80	-151	55	-38	64	42	0
Nov.	20	0	20	89	-69	-220	35	-20	40	49	0
Dec.	13	0	13	90	-77	-297	21	-14	27	63	0
Total	694	73	621	1261	-638				621	638	0

Table 4.11 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is sand loam with an available water capacity of 150mm. Vegetations are moderately-deep rooted crops such as grasses, shrubs etc

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	11	-10	18	80	0
Feb.	10	0	10	115	-105	-429	6	-5	15	100	0
Mar.	55	7	48	131	-83	-575	3	-3	51	80	0
Apr.	67	5	62	131	-69	-644	2	-1	63	68	0
May	54	0	54	131	-77	-721	1	-1	55	76	0
June	50	0	50	107	-57	-778	1	0	50	57	0
July	168	29	139	84	55		56	55	84	0	0
Aug.	195	32	163	78	85		141	85	78	0	0
Sept.	28	0	28	99	-71	-71	93	-48	76	23	0
Oct.	26	0	26	106	-80	-151	55	-38	64	42	0
Nov.	20	0	20	89	-69	-220	35	-20	40	49	0
Dec.	13	0	13	90	-77	-297	21	-14	27	63	0
Total	694	73	621	1261	-638				621	638	0

Table 4.12 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is clay with an available water capacity of 150mm. Vegetations are moderately-deep rooted crops such as grasses, shrubs etc

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	11	-10	18	80	0
Feb.	10	0	10	115	-105	-429	6	-5	15	100	0
Mar.	55	7	48	131	-83	-575	3	-3	51	80	0
Apr.	67	5	62	131	-69	-644	2	-1	63	68	0
May	54	0	54	131	-77	-721	1	-1	55	76	0
June	50	0	50	107	-57	-778	1	0	50	57	0
July	168	29	139	84	55		56	55	84	0	0
Aug.	195	32	163	78	85		141	85	78	0	0
Sept.	28	0	28	99	-71	-71	93	-48	76	23	0
Oct.	26	0	26	106	-80	-151	55	-38	64	42	0
Nov.	20	0	20	89	-69	-220	35	-20	40	49	0
Dec.	13	0	13	90	-77	-297	21	-14	27	63	0
Total	694	73	621	1261	-638				621	638	0

Table 4.13 Computation of AET using Thornthwaite and Mather soil water balance method. Soil type is clay with an available water capacity of 200mm. Vegetations are deep rooted wood land of eucalyptus tree, Indigeous trees of Juniper etc

Months	P_m	DRo	Pm-DRo_m	PET_m	P_m-PET_m	AWL	S_m	ΔS_m	AET	D	S
Jan.	8	0	8	98	-90	-387	29	-16	24	74	0
Feb.	10	0	10	115	-105	-429	17	-12	22	93	0
Mar.	55	7	48	131	-83	-575	11	-6	54	77	0
Apr.	67	5	62	131	-69	-644	8	-3	65	66	0
May	54	0	54	131	-77	-721	5	-3	57	74	0
June	50	0	50	107	-57	-778	4	-1	51	56	0
July	168	29	139	84	55		59	55	84	0	0
Aug.	195	32	163	78	85		144	85	78	0	0
Sept.	28	0	28	99	-71	-71	140	-4	32	67	0
Oct.	26	0	26	106	-80	-151	94	-46	72	34	0

Nov.	20	0	20	89	-69	-220	67	-27	47	42	0
Dec.	13	0	13	90	-77	-297	45	-22	35	55	0
Total	694	73	621	1261	-638				621	638	0

Table 4.14 The relation ship between soil type, vegetation, AET, soil moisture surplus and deficit is tabulated below.

Land use-land cover	Soil type	Area proportion	AET(mm)	Surplus(mm)	Deficit(mm)
Shallow rooted roorrootecrops	loam sand	0.54	556	65	703
	loam clay	0.09	581	40	678
Moderately deep rooted	loam clay	0.05	621	0	638
	loam sand	0.05	621	0	638
	clay	0.11	621	0	638
Deep rooted wood land	clay	0.13	621	0	638
	loam sand	0.03	621	0	638
	Weighted average		583	39	675

The actual evapo-transpiration obtained for the study area as a weighted sum of aerial proportion of each soil type is 583mm, which is 84% of the mean annual rainfall of the area, with surplus of 39mm that occur in the rainy month of August. The average surplus accounts 5.7 % of the total precipitation. The rest of the months are under soil moisture deficit with weighted average value of 675mm. As observed from the results of the computation, values of AET vary with soil and vegetation type.

4.8 Run off

General

Run off is defined as the portion of the precipitation that makes its way towards channels, streams, rivers, lakes oceans etc., as surface or subsurface flow. The path by which water reaches a stream depends upon such controls as climate, geology, topography, soil vegetation and land use (Freeze and Cherry, 1979).

4.8.1 Run off Computation

In the study area there is no functional gauging station for measuring and recording of monthly stream discharge, thus the monthly run off record (1960-2000) of Suluh river observation site is utilized to simulate the mean monthly run off of the study area.

The Suluh valley, which is a sub basin of the Tekeze river basin, shares the same surface water divide with the study area, which is a sub basin of the Danakil depression drainage system. Both sub basins have the same lithological coverage. These are Aiba Basalt, Adigrat Sandstone, EdagaArbi Glacial, Metamorphic rocks and alluvial soil. They are also characterized by the similar phsiographical , soil, rain fall distribution & intensity and land use/cover.

Considering the topography, surface area & rainfall amount at Suluh and the study area a run off coefficient of 0.39 is considered to calculate the mean monthly run off of the study area from Suluh valley run off records..

Table 4.15 Comparison of Average elevation, catchment area, and mean annual rainfall of Suluh river stream gauging station and the study area

	Average elevation (m.a.s.l)	Area (km^2)	Mean annual rain fall (mm)
Suluh gauging station	2350	350	717
Ungaged Site(May Megab)	2500	152	695
	K1 = 0.94	K2 = 0.43	K3= 0.97

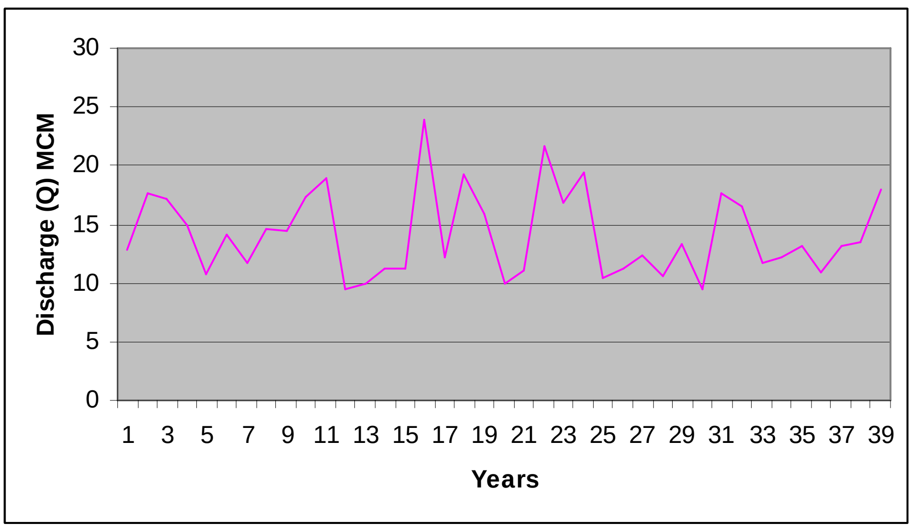
Based on the result obtained from the above mentioned transformation procedure the simulated river run off of the study area is tabulated below.

Table 4.16 Simulated mean monthly stream run off of the study area Q = MmC

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Suluh	0.58	0.47	2.6	1.91	1.7	0.97	11.26	12.3	1.88	1.78	0.47	0.24	36
Study area	0.23	0.18	1.01	0.74	0.66	0.38	4.39	4.8	0.73	0.7	0.18	0.09	14

From the simulated monthly average hydrometric records it can be observed the volume of river discharge vary monthly.

Figure 4.4 Simulated long term hydrograph of the study area.



The simulated annual run off of the study area is 92.1mm. It shows that the maximum run off takes place in the rainy seasons of July and August.

4.8.2 Base flow separation

The total discharge of a river consists of surface runoff and the base flow. The portion of rainfall which enters the streams, channels etc., immediately after rainfall or in other words the process may be described as when all losses are satisfied and if rain is still continued with the rate greater than infiltration rate, then excess water makes a head over the soil surface, which tends to move to land slope, known as surface runoff. The water which percolates into the soil and starts flowing laterally without joining the water table to the stream, rivers etc., called as sub-surface flow and is considered as part of surface runoff due to the fact that, it takes very little time to reach the rivers. On the other hand the water that percolates to the ground table and later after long times joins the river stream is known as groundwater flow. The runoff, thus actually consists of three portions; surface runoff, groundwater flow and direct precipitation over the river. The second factor is important for the minimum flow while the first factor is important for the maximum flow of a river, and the third factor being negligible and is generally ignored.

Table 4.17The hydrograph components of simulated run off the study area.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Q (mm)	1.6	1.2	6.6	4.9	4.3	2.5	28.9	31.6	4.8	4.5	1.2	0.6	92.5
BF(mm)	1.5	1	5.3	3.3	3.7	2.5	3.2	1.3	2.4	4.5	1.2	0.6	30.5
RO(mm)	0	0	1.3	1.6	0.6	0	25.7	30.3	2.4	0	0	0	62
P(mm)	8	10	55	67	54	50	168	195	28	26	20	13	694
RC(mm)													0.133

Q: Discharge of river (mm) RO: Surface runoff component

P: Precipitation

BF: Base flow component (mm) Rc: Runoff coefficient

From base-flow separation using graphic method, it is found the proportion of surface run off to base flow is 67% to 33%. This attributes to the fact that the catchment is characterized by flash flood during the rainy seasons. They are formed as a result of intense rainfall showers. The surface run off during the rainy season contributes 67% of the total run off. Almost all streams in the study area are seasonal and indicate much of the runoff record in the area is in the rainy season. A total of 92mm of water leaves the catchment annually.

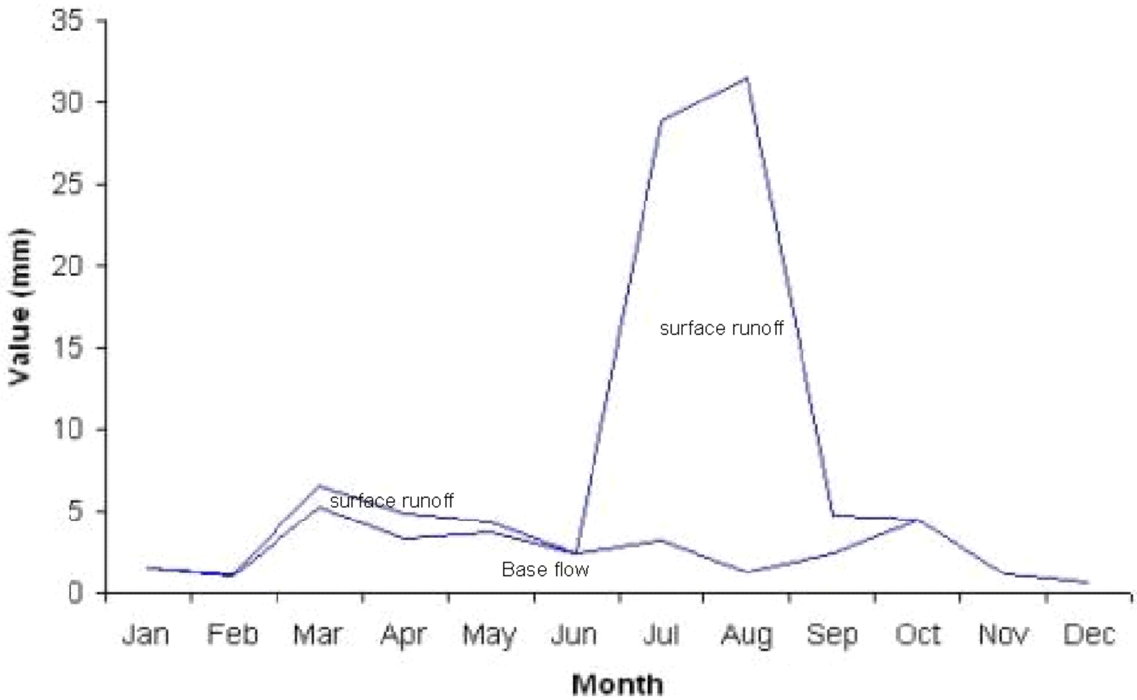


Fig 4.5 Base flow and surface runoff components of stream hydrograph

4.8.3 Rainfall-runoff relationship

For short duration (hours) the complex interrelationship between rainfall and runoff is not easily defined, but as the time period lengthens the connection becomes simpler until on an annual basis, a straight-line correlation may be obtained. The size of the area being considered also affects the relationship. For very small areas of a homogenous nature- the derivation of the relationship could be fairly simple; for very large drainage basins and for long time periods, difference in catchment effects are smoothed out giving relatively simple rainfall-runoff relationship (Shaw, 1994).

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	8	10	55	67	54	50	168	195	28	26	20	13
Runoff	1.5	1.2	6.6	4.9	4.3	2.5	28.9	31.6	4.8	4.6	1.2	0.6
Loss	6.5	8.8	48.4	62.1	49.7	47.5	139	163	23.2	21.4	18.8	12.4
PE	71	75	85	85	87	75	63	61	70	77	71	70

Table 4.18 Relationship between rainfall and runoff of the catchment on monthly basis.

Where PE: Evapotranspiration Loss= Rainfall- Runoff

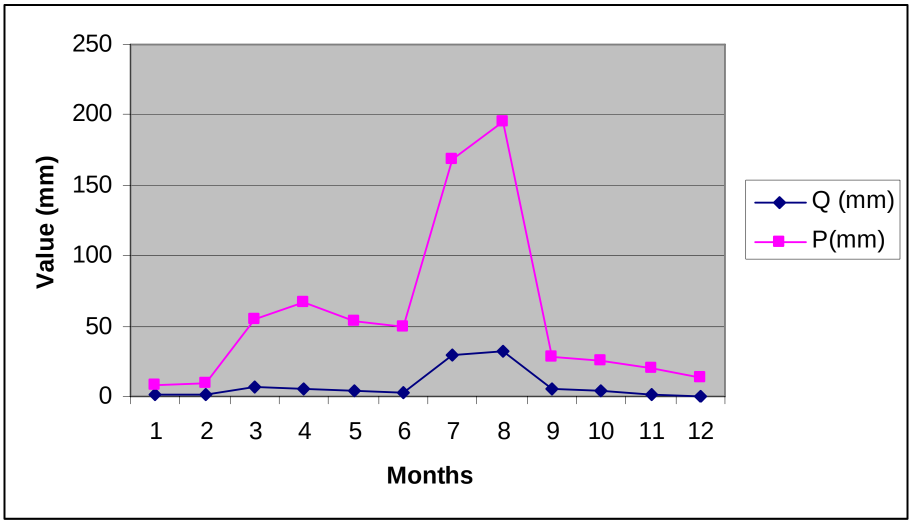


Fig 4.6 Relation ship between rainfall and run off

4.9 Water Balance

The water balance represents the hydrological gain and losses of a given system (reservior, column of soil, aquifer, river basin etc) over a specific period. (Tenalem Ayenew & Tamiru Alemayehu, 2001).

For a natural catchment measurement of the precipitation and rive discharge may be made satisfactorily with some degree of precision. But the measurement of ground water movement in to or out of the drainage area can not be made easily.

In groundwater studies one of the most important objectives is to make a quantitative assessment of groundwater resources. This can be considered in two ways; the total volume of water stored in aquifer and the long-term average recharge to the aquifer. The more significant figure in terms of groundwater resource is the long-term average recharge, and it is usual for this value to be regarded as the available resources (Brassington, 1988).

Water balance refers that the water entering an area is equal to the water leaving an area plus or minus any change in storage. The water balance equation for the study area considers no ground water inflow and out flow to and from the aquifer, change in storage is assumed zero and all quantities are long tem average values.

From field observation and aerial photograph interpretation and field observation the absence of prominent structure like fault, extending out of the catchment area for groundwater out low and inflow; the stratigraphic condition; topography controlled surface water divide and groundwater divide (generally west to east flow) enabled to draw the water balance equation of the catchment as follows.

$$P = AET + SRo + W \qquad (4.6)$$

Where P= Mean annual precipitation (694mm)

AET= Actual evapotranspiration (583mm)

W = Withdrawal (2.62mm)

SRo= Surface run off (62.2mm)

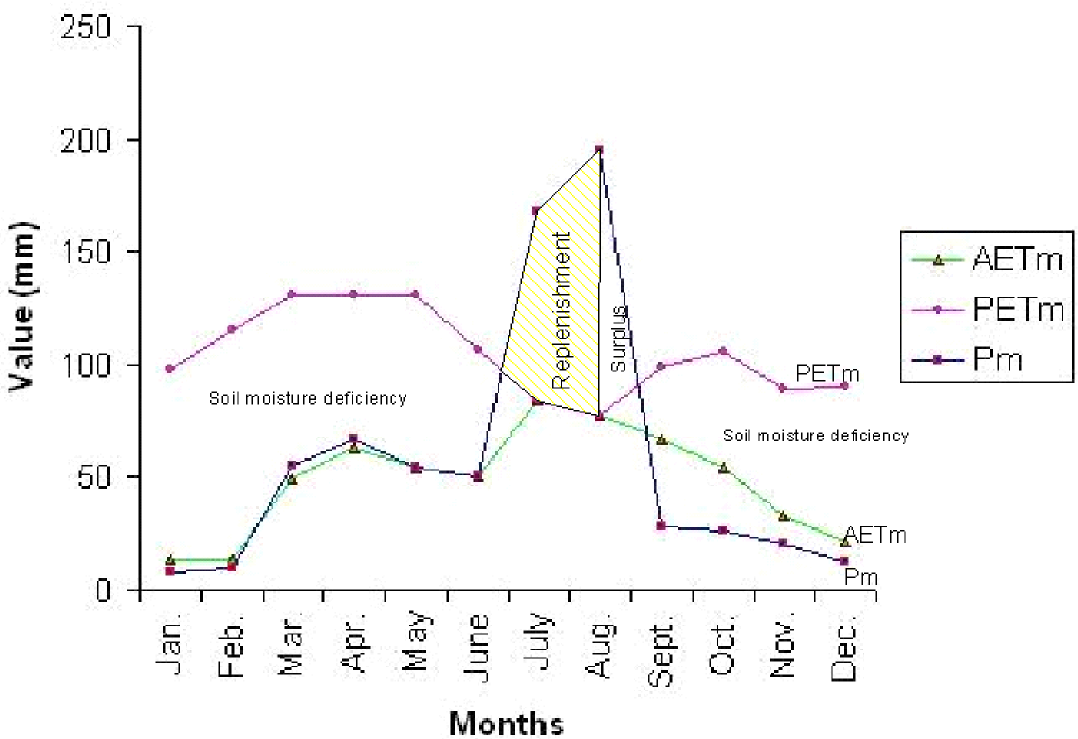


Fig 4.7 Monthly water balance plot

From the above equation the mean annual groundwater recharge of the catchment is calculated 46.4mm. The water balance result indicate the annual groundwater recharge, the actual evapotranspiration and surface runoff over the catchment are 6.7%, 84% and 8.9% of the total annual rainfall respectively.Fig 4.6 plot of monthly water balance

CHAPTER FIVE

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 aquifer and by its porosity (Fetter, 1994).

The water bearing unit in the groundwater reservoir that provide good supply of water to wells and spring is called aquifer. Geological features such as lithology, petrology and structure, control the ease with which water will flow through the ground. Hence, by looking at these features, it is possible to identify the various flow mechanisms that exist in an aquifer. These be assessed in general terms by considering the over all geological thickness and extent of the aquifer, topographic position, its porosity and the secondary openings occur because of tectonic joints, cooling fractures, bedding planes, fault zones and degree of weathering and also karistification.

5.2 Hydrolithostratigraphy

The hydrogeologicl characteristic of the different lithologies in the study area and their classification in to different permeability groups is based on quantitative borehole data and qualitative field descriptions. The quantitative bore hole data which are few in number are unevenly distributed in space and poorly distributed in the different lithologies of the study area. Some bore hole data like pumping test data result from adjacent area with similar hydrogeological set up and references of standard books are also utilized.

In areas where quantitative bore hole data are absent, qualitative field description, which gives the basic understanding for the hydro-geological characteristics of the rocks, is used to characterize and classify the different lithologes in to in the study area. This includes the magnitude and distribution of spring discharge, the degree of fracturing of the rock units, thickness of formations, topographic positions, the grain size, rounding & sorting, the clay proportion, the type and degree of cementation, the extent of weathering etc. These two approaches provide evidence as to whether a rock unit is likely to be an aquifer of low, moderate or high potential and productivity.

Ground slope, drainage density, land use, land cover and lineament density influence run off intensity and infiltration of water to the subsurface reservoir. Their hydrogeological significance in respect to the study area is addressed below.

I. Land use/ cover: - ground water is highly controlled by the type of land use /land cover of certain area. Keeping all factors /parameters constant, cultivated, vegetated land, grass land and areas close to water bodies such as lakes and big perennial rivers are of high ground water potential zones. This is because these land use classes are favorable for water infiltration and ground water recharge. In contrast to this areas covered by urban settlement, bare land and other impermeable infrastructures like paved or asphalted roads favor surface run off due to their low porosity and permeability. Thus, these land cover and land use classes are expected to be of low ground water potential zones.

In line of the above discussion, in the area under investigation the cultivated land that constitutes larger part is located in the central and eastern plateaus. It generally rests on the Enticho sand stone. The grasslands are confined to the major rivers. The sparse vegetations of eucalyptus tree and Juniper are located along the western scarp of the study area and mainly lie on the basaltic and Edagaarbi glacials. The eastern portion of the study area which is occupied by the basement rocks develops very thin layer of soil because of its steep slope. Accordingly the Enticho sand stone is potential zone for groundwater storage and movement relative to other formations.

II. Slope: - The study area is classified in to five slope classes, namely 0^o-10^o (flat land), 10^o-25^o (gentle), 25^o-50^o (intermediate), 50^o-65^o (Slightly steep) and 65^o-90^o (steep). (T/ Michael et al, 2003)

The central part of the study area is characterized by flat and gentle slope which is suitable for infiltration and percolation of water to the sub surface reservoir and recharge groundwater. In addition to this, the rate of groundwater flow is slow thus the residence time of percolated water in the sub surface reservoir is high This slope class almost lies on the Enticho sand stone thus the Enticho sandstone is expected to be of high groundwater potential lithology. The western and eastern parts of the study area are dominated by steep slope. It is known that steep slope suppress infiltration and percolation of water to the sub surface reservoir and enhances surface run off. The areas characterized by this slope class are covered by the Adigrat sandstone, basalt and the Edagaarbi glacials. Therefore based on their slope these lithologic units are expected to be of very low ground water potential zones.

III Drainage Density: - Depending on the length of drainage per square kilometer, the study area is divided in to three drainage density classes. These are low, medium and high drainage density. (Tesfa Michael et al 2003)

Table 5.1 Categories of drainage density range (after Deju, 1977)

Drainage density	Low	Medium	High
Range in km^2	<0.5	0.5-1.5	>1.5

The central, northern and south western parts of the study area, which are lithologically dominated by the tertiary basalt and Enticho sandstone have medium drainage density. Most eastern, northeastern and southeastern parts of the area, covered by the basement rocks and partially by Enticho sandstone and some portion in the west by the tertiary basalt, are areas with low drainage density. The western, southern and some portion of the central part of the area have high drainage density.

From hydrogeological point of view drainage density is used to measure the fineness of basin topography. High drainage density is related to steep slope and higher average relief. Thus drainage density is higher in mountainous area. In such areas run off is high following precipitation. Generally higher drainage density is characteristics of regions with weak or impermeable sub surface materials, sparse vegetation and mountainous relief. The type of rock also affects the drainage density; low drainage density is favored in regions of highly fractured or highly permeable sub soil material under dense vegetation cover and where relief is low. There fore with this perspective the areas with low drainage density have high groundwater potential than areas with high drainage density.

IV Lineament Density: - Based on the frequency of lineaments, the area is classified in to three lineament density classes. These are low, medium and high lineament density. Most part of the central and northern portion of the study area fall in the medium lineament density class with pockets of high density classes. Lithologically it is occcupied by Enticho sandstone and the tertiary basalt sequences. The high lineament density zones are observed to be very small in area coverage and are found to lie on the basement rocks.

Based on the aforementioned approaches and parameters, four hydrogeological units are recognized in the study area. The description of the units is as follows.

5.2.1 Aquifers permeability: High

This hydrogeologic unit occupies the central and southern part of the study area. The general characteristics of this unit are it occupies with flat slope areas, has porous lithology and suitable land use for ground water infiltration and storage. Relatively higher permeability and transmissivity characterize the unit. The alluvial sediments and the Enticho sand stone with the aforementioned criteria are classified under this hydrogeological unit.

5.2.1.1 Alluvial sediments

The alluvial sediments are mostly unconsolidated and the grain boundaries between the sediments are not held each other by a cementing material. It is composed of clay, sand, gravel and conglomerate, characterized by intergranular primary porosity underlain by different rock units.

These sediments are exposed along flood plains, river banks and depressions with thickness ranging from 0.5m to 10m.   In a vertical section the deposit have coarse material (gravel & conglomerate) at the bottom of river channel and fine material (silt & clay) at the top.

The primary porosity and permeability of the alluvial sediments result from voids between the grains. The magnitude in turn depends on the size, shape, sorting and packing of grains. The alluvial sediments under favorable condition may store appreciable amount of water & are characterized by high water infiltration capacity. Thus being shallow with limited aerial extent the alluvial sediments in the study area can be considered as perched aquifer with high permeability. The hydraulic conductivities of some deposits of unconsolidated sand and gravel are among the highest of any earth materials (C.W Fetter, 2001). Depression springs like that of Sasun school and abundant hand-dug wells with yield ranging between 0.05l/s and 0.17l/s are inventoried in the alluvial sediments.

5.2.1.2 Enticho sandstone.

The Enticho sandstone with high groundwater potential is located mainly in the central part of the study area.. It is generally coarse in grain size; at places with conglomeratic layers intercalated with it, less to moderately cemented, moderately weathered and fractured.

The high ground water potential of this hydrogeologic unit is dependent on both primary and secondary porosities and permeability of the rock unit. The main permeability of the Enticho sandstone unit categorized under this hydrogeological unit mainly depends on the secondary porosity which results from deep rooted vertical joints and fractures. The fractures have different orientations, spacing and apertures. The differently oriented and dominantly open fractures facilitate direct infiltration of rain water. The high ground water potential in the Golgol-Natsa Well Field at Abune Aregawi church can be related to the presence of a major structure crossing the area and thick alluvial deposit adjacent to a river crossing the well field.

In areas where the EdagaArbi glacial, Adigrat sandstone and the Aiba basalts are eroded, the Enticho sandstone is exposed on flat to gentle slopes &undulating streams. In such areas the Enticho sandstone is underlain by acquiclude metamorphic rocks. This enhances the storage of infiltrated water as observed in the Abunearegawi well field of Adigrat town. In flat slope plains it is the main water bearing formation for the extraction of ground water as evidenced from the distribution of many productive wells with different yields in the area. Wells sunk in this formation have yields that vary from 0.8l/s to >7l/s.

As discussed earlier, at places the Enticho sandstone is intruded by dolerite dykes with different orientations that run long distance. These dykes act as a natural dam and increase the storage of the unit. The presence high yield springs that emerge from fractures & bedding planes, as that of Yohannese church in Adigrat town, and the presence of bedding staining support the high ground water potential of the Enticho sand stone unit. The closely cross bedded Enticho sandstone is highly recharging compared to the massive one, for its big open fissure.

Analysis of bore-hole pumping test data indicated this hydrogeological group has relatively higher permeability value averaged to 1.45m/d with corresponding transmissivity value that varies between $45m^2/d$ and $114m^2/d$. The highest transmissivity value is attributed to medium& high degree of fracturing in the formation & its coarser grain size with conglomeratic layer intercalation.

5.2.2 Aquifer permeability: high to moderate

The hydrogeological unit with high to moderate permeability occupies larger part of the area & is located in almost all part of the study area except the western scarp. This hydrogeological unit occupies 55.8% of the study area.. It generally rests on flat to gentle slope areas that are dominantly cultivated lands. This hydrogeological unit comprises the Enticho sandstone. The Enticho sandstone under this category is medium to coarse grained, moderately cemented and sub angular in grain shape.

The ground water potential of this hydrogeological unit is mainly dependent on the secondary porosity and permeability resulting from fractures and joints. The fractures are moderately spaced and have different orientations.

Abundant springs of moderate discharge that emerge from contacts of bedding planes and fractures and bore holes with moderate yield that vary between 1.5l/s and 7l/s are inventoried in this formation. Pumping test analysis result indicated that the permeability value ranges between 0.15m/d to 1.45m/d with corresponding transmissivity value that ranges in between $6m^2/d$ and $45m^2/d$.

5.2.3 Aquifers permeability: moderate to low

This hydrogeological unit comprises part of the tertiary basalt in the western scarp of the area and the densely fractured metamorphic rocks.

5.2.3.1 Aiba Basalt: - The Aiba basalt with moderate to low permeabilty has intermediate slope (25^0-50^0). The water bearing capacity of this rock unit depends on secondary porosity and permeability resulting from deep weathering and fracturing of the formation. Lithological log of hand dug wells dug in this formation indicate the major aquifer is highly weathered basalt.

Low to moderate yield springs emerge at the contact between the fractured basalt and underlying Adigrat sandstone. Besides to this as observed at Andel ridge springs emerge from successive beds of basaltic flows and topographic breaks. Most springs at various levels in the Aiba basalt are intermittent. The presence of paleosols that are mainly silt & clay, between successive flows forces the water infiltrated through joints and weathering zones, to discharge at foot of hills and topographic breaks. This is manifested by intermittent, low to moderate yield springs.

There is no bore hole pumping test data in this hydrogeological unit for quantitative evaluation of aquifer hydraulic parameters. But, the lithological log of hand dug wells sunk in this formation, indicate the yield of the hand dug wells vary in between 0.03l/s and 0.63l/s.

The trap series in the highlands is dominantly basaltic with interbedded rhyolite. These rocks are highly weathered and slightly fractured. The different hydrostratigraphic units are separated by different paleosols (mainly clay and silt). The density of faults in the highlands is quite low. Much of the water bearing zones in the highlands are within the upper few ten meters in the weathered volcanic sequence and locally in interbedded river gravel and alluvial deposit. (Tenalem, 2004)

5.2.3.2 Metamorphic Rocks

The primary porosity in this basement rocks is practically zero, but the prospect of ground water in these rocks is attributed to the pattern of the fracture system and intensity of weathering.

As field observation, locally there are high density joints, fracture zones and weathered top layers that can provide productive zones. In addition to this at places their lower topographic position increases their potential for ground water storage. Thus, the metamorphic rocks that are fractured and weathered under favorable topographic position are classified as aquifers with low to moderate productivity.

There is no borehole pumping test data for quantitative evaluation of the aquifer hydraulic parameter. But, borehole pumping test result from adjoining Basin of Suluh River showed that the fractured and weathered metamorphic rocks at lower topographic position have a permeability value of 0.09m/day

5.2.4 Aquifer Permeability: very low

5.2.4.1 Aiba Basalt

The Aiba basalt which is exposed at the western extreme of the study area is located at higher topography with steep slope and thin clay soil development. Due to its topography and slope high run off and low infiltration characterize this basalt. In addition to the unfavorable slope and topographic position, amygdale in the vesicular basalt reduces the primary porosity of the formation. Thus, it is categorized under aquifer with very low permeability and productivity.

5.1.4.2 Adigrat Sandstone unit

This unit is fine to medium grained in texture and forms steep cliffs. As it indicated earlier in the local geology and structure, this unit is affected by vertical to sub vertical fractures with different orientations. The spacing of joints and fractures ranges from 10cm to 80cm with 10 to 50mm aperture.

The water bearing capacity of the Adigrat sandstone is dependent on its secondary porosity and permeability, resulting from weathering and fractures. In general there are three set s of joints that strikes in N-S, E-W and NW-SE directions with dip angle that vary from 60^0 to vertical with dominancy of the vertical ones.

The Adigrat sandstone could be have aquifer wit h high storage capacity and productivity resulting from secondary porosity and permeability, if the basaltic layer and its lateritic cap don't underlie it and if it is exposed to surface The above conditions are important factors for rain water infiltration and percolation through the joints/fractures and recharge the groundwater.

There is no borehole pump test result in the study area to quantify the permeability of the Adigrat sandstone aquifer.

The hydraulic conductivity of fracture systems vary considerably and are dependent on aperture, frequency or density (density), length, orientation (randomness or preferred) wall roughness (asperities, including skin factor), presence of filling materials fracture connectivity, channeling (preferred path), porosity and permeability of the rock.

The empirical formula of Serfim (1968) is used to calculate the permeability of the formation. The formula is expressed as:

$K = e^3 \gamma_m / 12 d\mu$ (5.1)

Where e is joint opening (aperture)

d jointing

μ= Viscosity of water at 20°C from field measurement

γ_m Unit weight of water

Source: Bell (1990) Engineering geology, South Africa.

Taking an average value of opening 0.5m and 5m of spacing the permeability results in an average value of 2. 08 m/d. This could classify the Adigrat sandstone as good aquifer when it is exposed to surface and is found in favorable topography.

However, from field observation the Adigrat sandstone in the study area is exposed at higher elevation topography and is affected by stratigraphy for its recharge. It is overlain by basaltic layer and underlain by Edagaarbi glacial, which is considered as aquifuge in the study area. In most part of the study area an impermeable lateritic cap underlies the basalt. This impermeable lateritic cap of the basalt doesn't allow recharge the underlying Adigrat sandstone. A number of springs at the contact between the Adigrat sandstone and the weathered basalt evidence the impermeability of the laterilitic cap beneath the basaltic unit. The absence of springs between Adigrat sandstone and Edagaarbi glacial strengthen the fact that the Adigrat sandstone is not recharging unit.Thus, considering its higher topographic position and stratigraphic position of the formation i.e. the formation being overlain by impermeable lateritic cap of the basaltic layer, the Adigrat sandstone is under very low potential for ground water storage and movement.

Edagaarbi Glacial unit, Metamorpic and intrusive rocks

In the study area this unit is exposed underlying the Adigrat sandstone and at places overlying the the Enticho sandstone. It form conical hills,weathered irregular escarpment and at places, it forms steep slopes.

This unit is composed of variegated color, friable silty shale, small quartz fragments, rounded granite in a clay matrix. The shale and clay that are dominant in the Edagaarbi glacial have high porosity and very low permeability. Thus, considering its topographic position, hydrogeological characteristics of overlying Adigrat sandstone and the very low permeability of the dominant components of the formation (shale and clay); this unit is categorized under very low groundwater potential zone and acts as aquiclude.

Solid unfractured plutonic and metamorphic rocks have porosities that are rarely larger than 2%. The intercrystalline voids that make up the porosity are minute and many are not interconnected. Because of small size of the pores and lack of interconnection, the primary permeability of these rocks is small (10^{-11} -10^{-13} m/s) and are classified as aquifuge. The primary porosity in this basement rocks is practically zero. In the study area the metamorphic rock that are exposed in the eastern part forming rugged topography with thin to no soil development are categorized under this hydrogeological unit.

5.3 Aquifer hydraulic parameters

5.3.1 Pump test analysis

The characteristics, which control groundwater flow and storage, are usually referred as the hydraulic properties.

The aquifer system in the study area is leaky type. Data collected from different organizations, well lithological log (Annex 2) indicate the aquifer system is leaky type.

Table 5.2 Summary of static water level and water strike relation ship

No.	Well location	Well type	Depth (m)	Water strike (m)	SWL (m)	Source
1	Kendaero	Bore well	60	48	16	REST
2	Dibla (Gena')	Bore well	61	54	27	REST
3	Gelamo	Bore well	51	25	6	REST
4	May weyni	Bore well	51	20	20	REST
5	Adigrat town	Bore well	84	27	4	REST
6	Bokete	Bore well	110	10	5.3	TWWCE
7	Gula' Genahti (Bet maria)	Bore well	40	18	15	TWWCE
8	Gira meka	Bore well	51	25	6	REST

9	Adi mesanu	Bore well	61	3.6	12	TWWCE

Based on the above fact, the Hantush –Jacob solution is used with the following Major conditions.

- the aquifer has infinite aerial extent
- aquifer is homogeneous, isotropic and uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully or partially penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating.
- aquifer is leaky
- flow is unsteady
- water is released instantaneously from storage when decline of hydraulic head
- confining bed has infinite aerial extent, uniform thickness, uniform hydraulic conductivity and uniform thickness
- confining bed is overlain or underlain by an infinite constant-head plane source
- flow in aquitard is vertical

Then the analytical solution for predicting water level response to pumping in a leaky confined aquifer assuming steady flow (no storage) in the aquitard(s):

$$S = \frac{Q}{4\Pi T} \int_{u}^{\infty} \frac{e^{-y-r2/4B2}}{y} dy \qquad (5.2)$$

Where Q is pumping rate (L^2/T)

S is draw down in the confined aquifer (L)

T is transmissivity of the confined aquifer (L^2/T)

$$U = \frac{r^2 S}{4 \Pi t} \qquad B = \sqrt{\frac{Tb'}{K'}}$$

S is storativity of the confined aquifer (dimension less)

t is time since pumping began (T)

r is the distance from the pumping well to the observation well (L) b’ is the thickness of the aquitard (L)

k’ is hydraulic conductivity of the aquitard (L^2/T)

Table 5.3 Results from pumping test

No.	Well name	Main aquifer	T (m^2/day)	K (m/day)	S (m^3/day/m)	Data Source
1	BGA-1	conglomeratic sandstone with oxidation mark	113.93	7.1	117.6	ADCS
2	BGA-2	conglomeratic sandstone	7.41	0.6	12.2	ADCS
3	BGA-3	fractured Enticho sandstone	0.92	0.31	3.2	ADCS
4	WN-1	fractured Enticho sandstone	6.18	0.17	9.57	WWDA
5	WN-2	coarse grained Enticho sandstone	0.79	0.026	1.54	WWDA
6	WN-3	fractured Enticho sandstone	7.01	0.05	21.53	WWDA

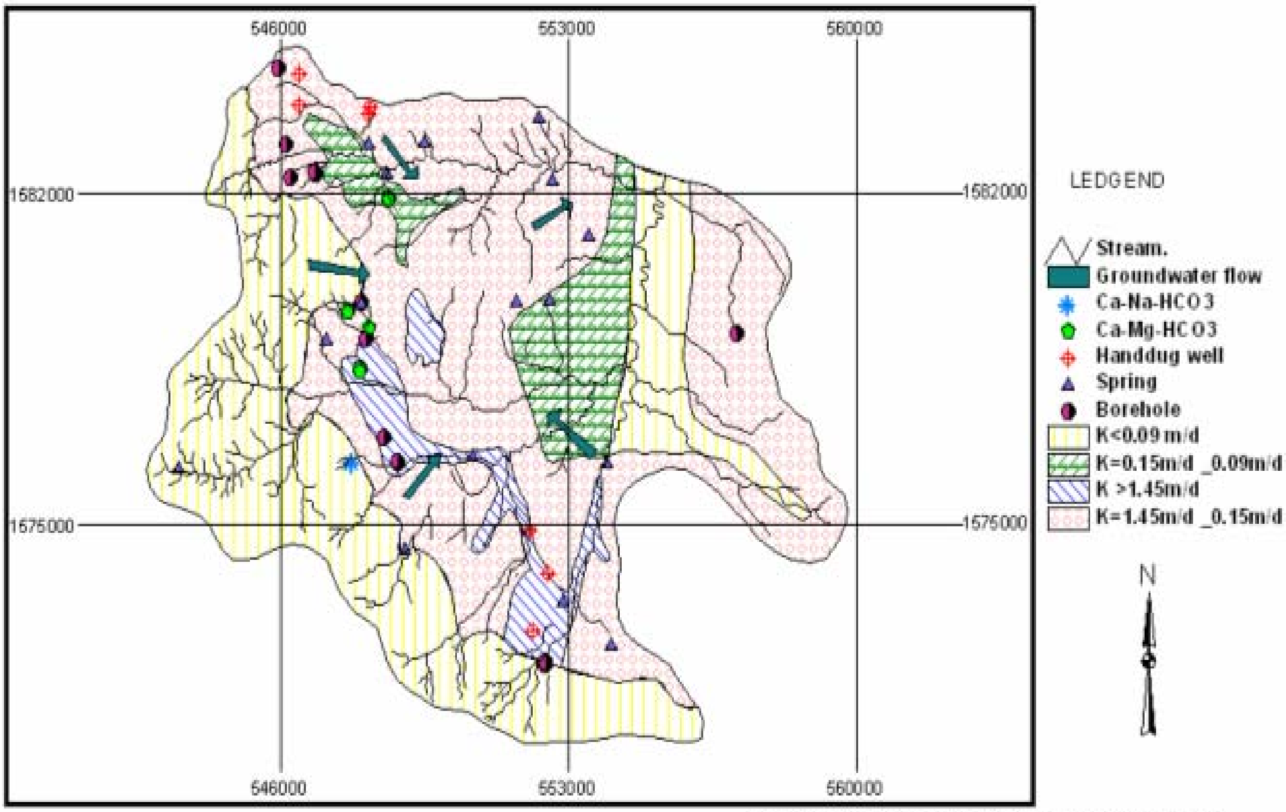


Fig 5.1 Hydrogeological map of the area

7	WN-4	weathered, medium grained sandstone	43.56	1.45	54.6	WWDA
8	BH-3	friable, medium to coarse grained Enticho sandstone	143.4	5.7	24	TWWCE
9	BH-2	fractured medium grained Enticho sandstone	26.2	1.1	35.6	

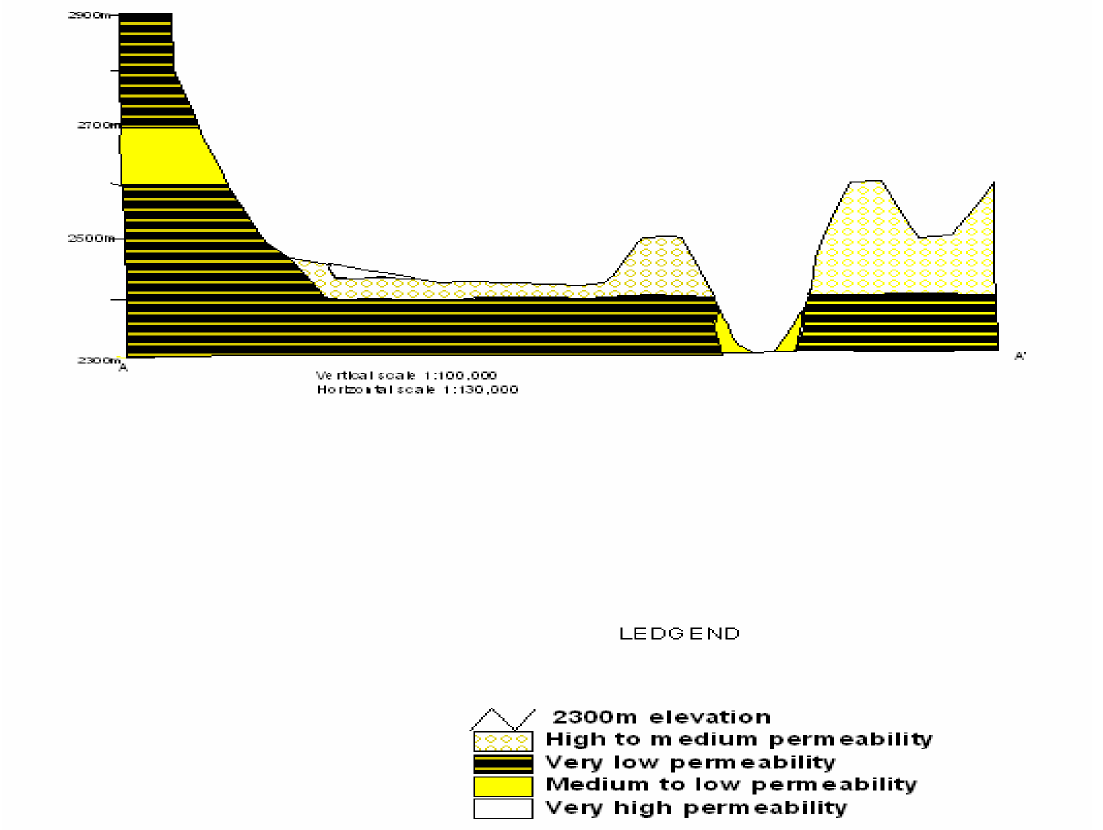


Fig 5.2 Hydrogeological cross section along A-A''

From the result the transmissivity value ranges from< 0.8 m^2/day to113.93 m^2/day. As it is indicated in the table all the wells are drilled on the major aquifer of the area, Enticho sandstone. The variation in the value of T is attributed to the variation in degree of fracturing, the presence or absence of fine material intercalation in between the Enticho sandstone beds.

The highest Transmissivity value (BGA-2) is related to conglomeratic sandstone with high degree of weathering.

5.4 Ground water movement, Recharge and Discharge

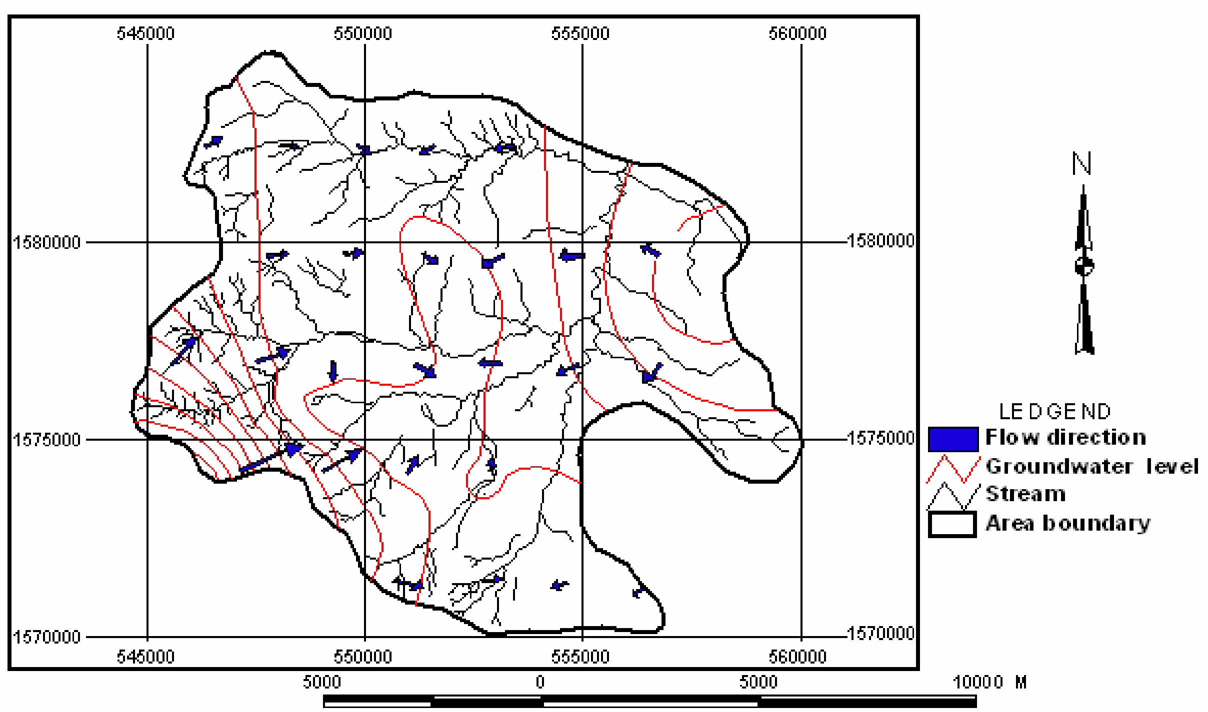
5.4.1 Ground water movement

From the static water level data (Table 5.2) and lithological logs, the catchment area is characterized as a semi confined. The ground water in the overlying aquitard is under a water table condition because the water level in this layer is free to rise and fall. The water in the bore hole that penetrate the permeable layer stands above the top of this layer or even above the land surface depending on the pressure extent by the aquitard.

In order to understand the ground water flow direction within the catchment area, ground water level contour map is constructed with the help of SURFER8 computer program.

The ground water flow follows topography. The general flow is from highlands of western scarp and the elevated eastern part of the study area to wards the middle of the catchment. The ground water flow is in the same direction with that of surface water flow.

Fig 5.2 Groundwater flow direction



5.4.2 Ground water recharge and discharge

Groundwater recharge can be defined as the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone. Groundwater discharge can be defined as the removal of water from the saturated zone across the water table within the saturated zone (Freeze & Cherry, 1979).

To discriminate the recharge and discharge zones of the study area, a water level measurement data of hand dug wells and bore holes are used. The method used to discriminate the recharge and discharge zones is the ***grid deviation.*** This is the difference between the water level of the wells below the ground level and the elevation of the surface and the result is deduced by mean ground water level elevation from sea level.

The result of the grid elevation is either negative, zero or positive .The result of the grid deviation indicated the western elevated scarp of the area is a recharge zone. The main source of recharge is rain fall.

The longest segment of the hydrologic cycle is completed when groundwater is discharge at the surface or into bodies of surface water. The discharge may take place in a variety of ways of which spring, artificial (hand dug wells, boreholes) and evapo-transpiration from soils, vegetations and seepage (Davies, 1966)

a) Spring

Springs have been important in the social, cultural and economic history of man kind. They have been an important source of water for people.

Most springs in the study area are seasonal and intermittent, with discharge of less than 0.03liter per second to about 3l/sec. They are gravity springs caused by different permeabilities i.e. at geological contacts (mainly manifested at the contact between the Aiba basalt and Adigrat sandstone and interbedding contact of the Enticho sandstone (Endabalibanos spring) and at the contact between successive basaltic flows, (like that of

Andel rigde Kidist mariam springs.) The basaltic dykes in the Enticho sandstone act as an aquiclude and cause springs (Dibla yohannes spring). Many springs are fracture controlled, as is at Beati Michael spring. Depression spring around Sasun school is also observed in the study area. With respect to temperature the springs in the study area are cold springs.

b) Wells

The geographic distribution of water points in the study area is uneven mainly determined by the hydrogeological characteristics of the geological units. With respect to this more than 90% the water points lies in the Enticho sandstone and alluvial sediments. Few water points are inventoried at the Aiba basalt with favorable hydrogeological parameters.

Most hand dug wells are constructed in shallow depth by excavation in 200cm to 320cm diameter. The depth of the handdug wells ranges from 2.65m to 12m. They are mainly located in the shallow overburden or alluvial sediments intervening rock formation. As per the data from ADCS/COOPI report the yield of the handdug wells is in the range of 0.03l/sec to 0.63l/sec.

The bore wells constructed by The Down Hole Hammer (DTH) rigs are dominantly concentrated at the Enticho sandstone. The depth of the bore wells range from 40m to 124m. The depth water strikes also ranges from 10m to 54m and the yield of the wells is in between 0.8l/sec to >10l/sec.

CHAPTER SIX

HYDROCHEMISTRY

6.1 Introduction

The chemical composition of natural waters is derived from many different sources of solutes , including gases and aerosols from the atmosphere , weathering and erosion of rocks and soils, solution and precipitation reaction occurring below the land surface and cultural effects resulting from human activities. The way solutes are taken up or precipitated and the amount present in solution are influenced by many environmental factors especially climate, structure and position of rock strata and biochemical effects associated with life cycle of plants and animals, both microscopic and macroscopic. (Hem, 1989)

The chemical composition of groundwater is the combined result of the composition of water that enters the groundwater reservoir and the reactions with mineral present in the rock that may modify the water composition (Appelo & Postma, 1992).

The main objective of hydrochemical study in this paper is to discriminate the different water types and their origin, to know the water quality of the different waters for different purposes and uses.

6.2 Water sampling and analysis

The interpretation of chemical analysis result starts with checking the accuracy of the laboratory results, when all the major anions and cations have been determined, the sum of the anions expressed in milliequivalents per liter should be equal the sum of the anions expressed in the units (Hem, 1992). The analytical error of all the analyzed samples is with in the acceptable range i.e. 5%

Before a field work the available chemical data of the study area were collected and checked for electrical neutrality errors.

The collected data includes data from WWDA (Water Well Drilling Agency) (1993) and TAHAL (2000). For all chemical data the result of electrical neutrality error is with in the acceptable range. In addition to the above, additional three water samples from bore well, hand-dug well and spring are collected in the current year, February 2006. The chemical analysis has been carried out at Water works Design and Supervision laboratory.

In situ measurements of some important parameters, such as PH, temperature, EC and Eh is carried out in the field using HANNA METER, which is a standard digital instrument for field measurement.

Table 6.1 Field measured parameters TDS (mg/l is computed value)

Units TDS (mg/l), EC (µs/cm)

Code	Water source	PH	Easting	Northing	EC	TDS	Remark
NAGT-1	Handdug	7.5	535495	1560934	697	453	
Sasun	Spring	7.1			202	131.3	
Dibla	Handdug	7	553201	1572447	158	103	
EELPA	Handdug	7			189	123	
Siet Dibla	Bore well	7	551102	1572342	533	346	
NAGT-4	Bore well	7.2	549689	1581598	243	158	
NAGT-5	Spring	7.4	549224	1582765	160	104	
Cheat	Bore well	7			588	382	
Laekay	Bore well	7.1	547910	1582103	599	389	
Medicine Factory	Handdug	7			292	190	
BH-Gorno	Bore well	7.2	548696	1578863	511	332	
Chiqualu	Handdug	7.1			248	161	
May Abea	Handdug	7.7	529682	1564573	471	306	
Gelamo	Handdug	7.4			465	302	

Code	Water Source	Easting	Northing	TDS	EC	PH	Na	Ca	Mg	Cl	So_4	HCO_3	NO_3	Source
WN1	BH	549204	1578863	335	670	7	24	71	24	14	0	366	7.1	WWDA
WN2	BH	549385	1579483	414	826	6.9	52	83	29	28	0	488	2	WWDA
WN3	BH	548696	1579214	545	1090	7.9	46	96	46	35	83	464	8	WWDA
WN4	BH	548989	1577986	426	852	7	33	88	31	28	22	415	12	WWDA
EELPA	BH			280	500	7.2	3.5	144	19	25	60	366	0	TAHAL
GORNO	BH	548696	1579214	390	778	7.3	129	137	17	20	300	415	66	TAHAL
ERA	BH	549204	1578863	260	530	7	7.4	88	19	20	8	345	0	TAHAL
AGAZI	BH			200	490	7.2	52	84	17	10	8	360	0	TAHAL
BH2	BH	548790	1576000	310	620	7.3	61	120	17	20	150	391	3	TAHAL
BH1	BH	548989	1577956	430	870	7.1	34	160	38	25	100	610	4	TAHAL
NAGT1	HDW	535495	1560934	790	1209	7.5	61.8	132	53	118	71	438	20	
NAGT4	BH	549689	1581598	188	286	7.2	7.3	38	15	6	26	145	0.2	
NAGT5	SP	549224	1582765	132	225	7	6.3	28	6	17	25	58	1.5	

BH borehole HDW handdug well SP spring

Table 6.2 results of chemical analysis of water samples

Units TDS(mg/l), EC (μs/cm), cations and anions in (mg/l)

Gelamo	Bore well	7.1	549590	1576522	396	257	
May aba'	Bore well	7.3			570	370	
BH-1	Bore well	7.1	548989	1577986	572	372	
BH-3	Bore well	7.2	529249	1565396	571	372	
BH-4	Bore well	7.2			596	387	
BH-Agazi	Bore well	7.2			491	320	
BH-ERA	Bore well	7.3	549204	1578863	440	286	
Yohannes church	Spring	7.6	552808	1579413	95	62	
Lekay	Bore well	7.3	547910	1582103	607	377	
Bado	Bore well	7.2	547293	1582025	330	204	
Momona	Bore well	7.1	547070	1584340	438	272	
Adi Meskel	Bore well	7.5	547885	1582121	433	699	
Kendaero	Bore well	7.7	549015	1579381	131	86.15	
Siet	Bore well		553511	1571776	699	454.35	
Ziban Tafat	Bore well	8.7	550612	1584236	120	78	
Chahat	Handdug	7.3	547934	1582897	395	257	
Zelalita	Handdug	7.7	553535	1573661	142	92	
Kashahat	Handdug	8.2	544421	1573529	195	127	
May Deban	Handdug	7.3	550184	1580797	534	334	
Adi Meskel	Handdug	8	553019	1572542	342	222.3	
Goho mayele	Spring	8.3	552036	1583824	123	80	
Sasun school	Spring	8.3	553986	1571465	106	69	
Adigedia	Spring	8	555124	1572176	117	76	
May Kaga	Spring	7.1	549654	1582133	211	130	

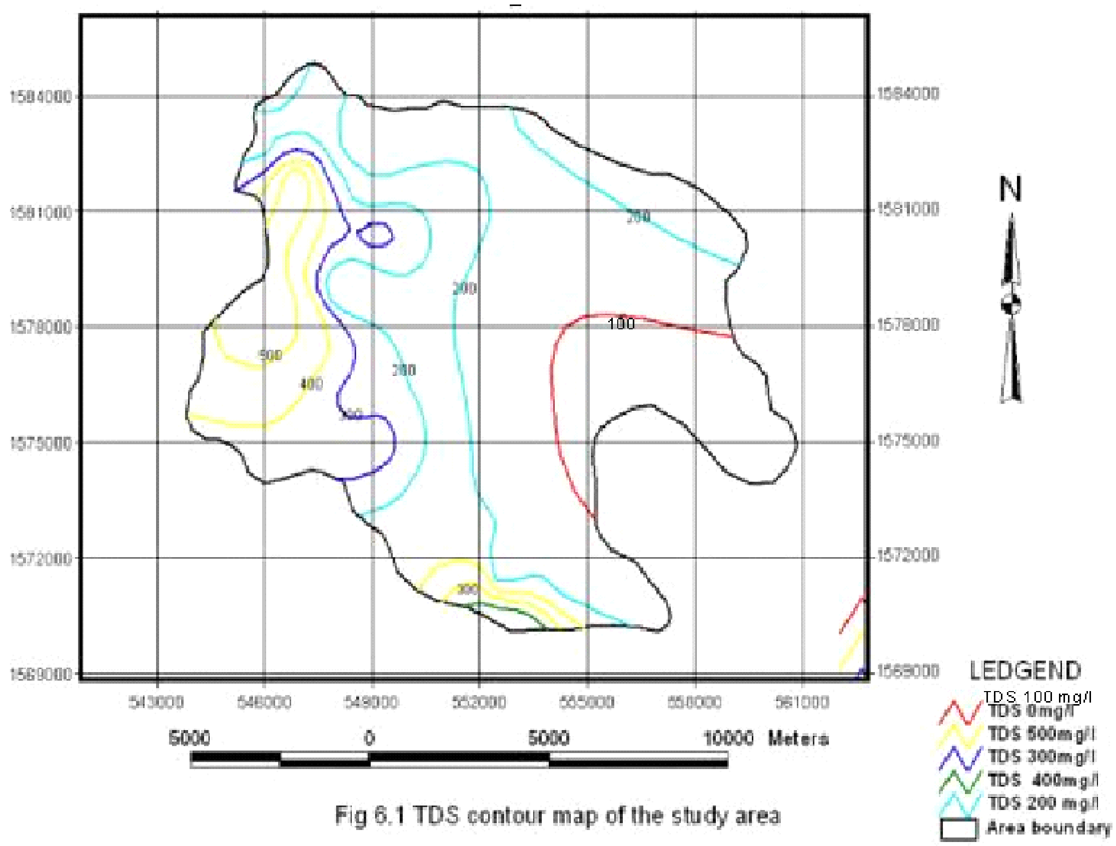


Fig 6.1 TDS contour map of the study area

6.3 Water analysis result In addition to the natural factors, a major change in the constituents of groundwater is resulted from the activities of human beings. Analysis of groundwater samples is used to infer the relationship or interaction existing between surface and groundwater bodies.

The major chemistry borehole water is summarized below. TDS (mg/l), EC (µs/cm) and hardness (mg/l $CaCO_3$)

Element	Range
PH	6.9-7.9
Na^+	3.45-128.8
K^+	2-4.6
Ca^{2+}	37-160
Mg^{2+}	14.58-45.7
HCO_3^-	145-610
NO_3^-	0-66.3
Cl^-	5.64-35.5
SO_4^{2-}	0-300
EC	286-1090
TDS	200-545
Hardness	154-560

Table 6.3 major chemistry of borehole waters

TDS (mg/l), EC (µs/cm) and hardness (mg/l $CaCO_3$) Ions in mg/l

The groundwater samples collected from boreholes, hand-dug wells and springs are mostly colorless and odorless.

The pH of most groundwater results from the balance between dissolved carbon dioxide gas, carbonate and bicarbonate in the water (Driscoll, 1995). In the collected samples the pH values of the groundwater (boreholes, springs and hand-dug wells) range between 6.9 to 7.9 which according to Davis et al., (1966), can be categorized under moderately high pH values, that commonly associated with water high in bicarbonate.

6.4 Data Interpretation

In this work the result of chemical analysis, obtained from different organizations and additional chemical analysis data obtained from current year water sampling of bore hole, spring and hand-dug well, is used to assess the various constituents in ground water.

6.4.1 Major cations

The chemical analysis data of bore wells, hand dug well and spring revealed that Ca is the most dominant cation followed by magnesium sodium and potassium.

The range of concentration and average value of calcium in bore holes are 1.89 meq/l to 7.98meq/l and 5.03meq/l respectively. The variation in the concentration of calcium in the bore holes is mainly attributed to the presence or absence of clay and shale material and the variation in thickness of the clay and shale material overlying the aquifer and proportion of clay matrix in the aquifer.

From hydrochemical data, which is analyzed in the year, 1993 (WWDA) the highest calcium concentration is that is 4.8meq/l is observed at WN-3 (Gorno). The lithological log of the bore hole indicates that the aquifer has high proportion of, 24m thick clay soil.

The high amount of calcium in ground water is related with the presence of the clay and shale material of the sedimentary rocks, which release calcium from the dissolution of calcium containing material such as calcite, anhydrite, and gypsum.

The lowest calcium concentration that is observed at WN-1 is attributed to the absence of clay and shale material overlying or intercalating the Enticho sandstone aquifer.

Three boreholes were resampled in the year 2000, by TAHAL. These are WN-1, WN-3, and WN-4; and are named as BH-ERA, BH-GORNO and BH-1 respectively. The chemical analysis result data revealed that, there is an increase in concentration of calcium in the bore holes with time indicating a parallel increase in concentration of the cations and rock-water interaction relative to the average recharge.There is no significant variation in the concentration of magnesium and potassium among bore hole water samples both in space and time.

The second dominant cation in bore holes is sodium. The range of concentration of sodium in boreholes is between 3.45mg/l to 128.8mg/l. The temporal variation in the concentration of cations especially sodium in WN-3, shows that the increment in the concentration of sodium in the bore hole with time is almost twice to the change in concentration of calcium. The possible reason for the higher increase in concentration of

sodium relative to calcium could be cation exchange process i.e. the aquifer penetrated by the well has high clay proportion with high cation exchange capacity.

There is no significant variation in the concentration of magnesium and potassium among bore hole water samples both in space and time.

The range of concentration for magnesium and potassium in the bore well water samples is 1.2 to 3.76meq/l and 0.56 to 2.19meq/l respectively. For the hand dug wells , the concentration of calcium, magnesium and sodium+ potassium is 6.59meq/l, 4.35meq/l and 2.67meq/l respectively, where as for spring water the value are 1.41meq/l, 0.49meq/l and 0.25meq/l respectively.

6.4.2 Major anions

The major anions in water samples of the study area in their decreasing order are bicarbonate, sulphate, chloride and nitrate. The origin of carbonateCO_3^{2-} ions, undissolved H_2CO_3, dissolved carbondioxide (CO_2) and bicarbonate (HCO_3^-) ions in ground water are from the carbondioxide in the atmosphere, carbondioxide in the soil and dissolution of carbonate rocks (Davis and DeWiest, 1966).

The higher amount of bicarbonate anion in the groundwater of the study area is also attributed to the clay cementing material in the major aquifer of Enticho sandstone and the glacial deposit, which is composed of clay, thin layers of carbonate, and boulders of granite and pebbles of metamorphic rocks.

The concentration of sulphate in natural water is commonly less than 300mg/l (Todd, 1980). In the study area the range of concentration of sulphate in bore holes is 7.6mg/l to300mg/l, with an average value of 68.85mg/l.

The natural concentration of nitrate in groundwater ranges from 0.1mg/l to 10mg/l (Davis and DeWiest, 1966). Unlike most other elements in ground water, nitrate is not derived primarily from the minerals in the rocks that make up the ground water reservoir (Driscoll, 1995).

One bore hole sample, WN-3 (TAHAL), showed a nitrate value of 66.3mg/l which is above the permissible limit. The most probable source of the nitrate anion in this bore hole is contamination from domestic waste, which is noticed during field work in the study area. This is confirmed by correlation coefficient value of 0.49 for Cl vs NO_3. A correlation coefficient value above 0.35 for Cl vs NO3 indicate that the ground water probably has been affected by domestic waste (Pacheo and Cabrera, 1997).

6.4.3 Electrical Conductivity

Electrical conductance or conductivity is the ability of water to conduct an electric current. The unit is in microSiemens per centimeter.

From the figure above, the mentioned direct proportional relation ship between TDS and EC is valid. According to Hem, (1979) as cited in Freeze (1979) TDS and EC have linear relationship i.e. TDS= AC where A is factor that varies between 0.55 to 0.75 depending on the ionic composition of the groundwater and C is the ionic conductance.

The electrical conductivity of bore- hole samples varies from 119µs/cm to 1090µs/cm.The variation in EC is dependent on the variation in lithology. The lower EC values are observed on the Enticho sandstone where as the highest value on the alluvial deposits dominated by clay material, derived from the Edagaarbi glacial unit. The highest ECvalue for WN-3 i.e. 1090µs/cm is attributed to the thick clay soil horizon of 24m thick overlying and intercalating the aquifer. The lowest value, which is 119µs/cm, is observed on a well located on the Enticho sandstone where no clay material is present.

The range of EC values for springs and handdug wells is 95µs/cm to 374µs/cm and 20µs/cm to 1209µs/cm respectively. Like the bore holes, the variation in the EC values of the hand dug wells is mainly controlled by litholog the highest value lies on the Edagaarbi glacial unit where clay is the dominant proportion and the lowest value corresponds to the tertiary basalt. The same factor controls the variation in the EC values in springs

6.5 Water Type Classification

In order to trace the origin of the various water bodies and to study the interconnection of groundwater and surface water different ground water classifications methods are used.

6.5.1 Classification based on dominant cations and anions

An important task in hydrogeochemical investigation is the compilation and presentation of the chemical data in convenient manner for visual interpretation. Among the different methods of water classification, it is believed that methods based on major ions are the best for practical purpose and are widely used. This type of classification uses a percentage of milliequivalents per liter (meq/l) of the anions and cations. In this work the chemical analysis results of the water samples from the study area are plotted on the piper tri-linear diagram using Aquachem computer program. The plot shows two types of major water groups.

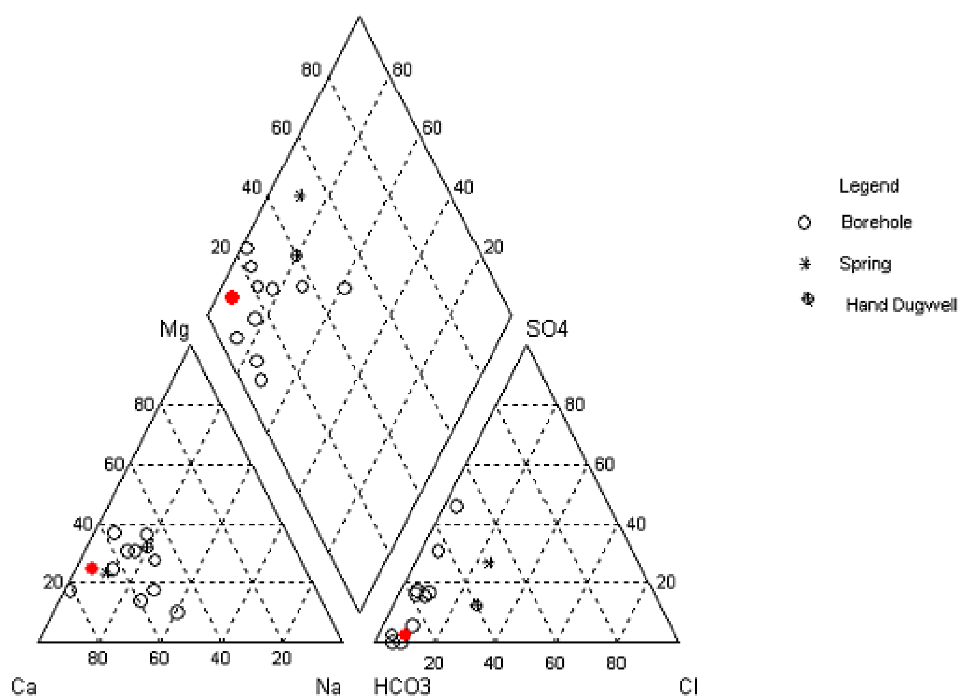


Fig 6.2 Piper Trilinear diagram for water sources of the study area.

The plot in the cation triangle shows calcium is the dominant cations followed by magnesium and sodium. On the other hand the anion triangle contains bicarbonate as dominant anion. There fore Ca-HCO_3 and Ca-Mg –HCO_3 are the major water types in the study area. The higher amount of sodium at places can be explained by the presence of plagioclase feldspar in the basaltic dykes of the study area and cation exchange process as discussed earlier.

6.5.2 Classification based on TDS value

In this work in addition to the laboratory TDS values, field EC values are used to calculate TDS values according to the formula

$$TDS= AC \qquad (6.1)$$

where A is factor that varies between 0.55 and 0.75 and C is the ionic conductance.
Based on the total concentration of dissolved constituents Davis and DeWiest (1966) have proposed the following classification.

Water source	Minimum	Maximum
Bore well	77	699
Hand-dug well	13	790
Spring	62	237

Table 6.4 TDS variation for different water sources in the area. TDS in mg/l

All waters in the area lie in the fresh water category.

6.5.3 Classification based on hardness

The total hardness as $CaCO_3$ can be computed from the concentration of calcium and magnesium by the following formula (Todd, 1980).

Where concentrations are in mg/l.

$$\text{Total hardness (mg/l)} = 2.5[Ca^{2+}] + 4.1[Mg^{2+}] \qquad (6.2)$$

The total hardness as CaCO3 and MgCO3 of the different water sources lies under moderately hard to very hard categories. For bore- holes the range of values for total harness is between 154mg/l to 560mg/l.

6.6 Water Quality

In specifying the quality characteristic of water, chemical, physical and biological analyses are normally required. A complete chemical analysis of water sample includes the determination of the concentration of the inorganic and organic constituents (Todd, 1980).

In this study, the quality of the water in the study area will be assessed based on the chemical and biological analysis result.

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In this study, the quality of the water in the study area will be assessed based on the chemical and biological analysis result.

6.6.1 Water quality criteria

The quality required of a groundwater supply depends on its purpose; thus needs for drinking water, industrial water and irrigation water vary widely (Todd, 1980).

Water analysis interpretation often includes some consideration of standards and tolerance that have been established for water that is to be used for various purposes

6.6.1.1 Drinking water quality

Water that is to be used for drinking must have high standard 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 DeWiest, 1966).

	Water sources average value (mg/l)			
Parameter	Hand dug	Spring	Borehole	Ethiopian standard maximum permissible (mg/l)
				(mg/l)
calcium	132	28.2	100.8	200
Chloride	118.4	16.92	21.1	600
Sulphate	70.6	24.75	68.85	400
Nitrate	20.24	1.15	12.21	45
PH	7.48	7.6	7.4	6.5-7.2
TDS	232.3	115.4	301.5	1500
Total hardness	545.6	94.6	347.8	500

Table 6.5 Comparison of the chemistry of different water sources with Ethiopian standard

The chemical analysis result of the different sources in the study area shows variable values. The analyzed chemical composition of the water sources in the study area lie in within the permissible limit set by the Ethiopian standard, but one bore hole BH-GORNO shows high concentration of nitrate above the maximum permissible limit.

Biological analysis conducted in the year 2000 and 2005 show the presence of coliforn and E.coli counts in some bore- holes attributed to human excreta.

6.6.1.2 Agricultural water quality

Water required for non domestic purpose on farms and ranches include that consumed by livestock and that used for irrigation (Hem, 1992).

The quality requirement of irrigation water varies based on the soil type and its structure, the local topography, the amount of irrigation water applied and the local climate. Thus, rigorous universal standards for irrigation water cannot be formulated.

The ratio of Na^+ ions to the total cations content, stated in meq/l %, in conjunction with the total dissolved solids expressed as the sum of total dissolved solids or as electrical conductance, can be used for the assessment of the suitability of particular water for irrigation. (Todd, 1980).

Sodium content is usually expressed in terms of percent sodium defined by:

$$\%Na = [(Na+K)/ (Ca+Mg+Na+K)]*100 \qquad (6.3)$$

All ionic concentration expressed in milliequivalent per liter

Water class	% Na	EC (µs/cm)
Excellent	<20	<250
GoodGoodGGood	20-40	250-750
Permissible	40-60	750-2250
Doubtfull	60-80	2250-4000
Unsuitable	>80	>4000

Table 6.6 Qualitative classification of watershed on the EC and alkali hazard for irrigation (US regional laboratory, 1954)

The ability of water to expel calcium and magnesium by sodium can be estimated with the aid of the sodium adsorption ratio (SAR) expressed as:

$$SAR= Na/ (Ca+Mg)\ ½ \qquad (6.4)$$

The concentration of the ions present is given in meq/l. High SAR values indicates the risks of a displacement of the alkaline metal.

Water classes	Alkali Hazard (SAR)
No hazard	<2
Little hazard	2-10
Medium hazard	10-18
High hazard	18-26
Very high hazard	>26

From the results in -Table 6.7 the SAR value for all water sources is below 2 categorizing them in the no hazard category. With regard to sodium percent all the water sources are excellent for irrigation. Based on the EC of the water samples, spring water and 50% of the bore hole samples are good for the purpose of irrigation. Water from hand dug well and almost 50% of the bore hole waters lie in the permissible range of salinity.

No.	Code	Water source	SAR	%Na	EC(µs/cm)
1	WN-1	Bore hole	0.38	14.8	670
2	WN-2	Bore hole	0.81	25.04	826
3	WN-3	Bore hole	0.60	18.11	1090
4	WN-4	Bore hole	0.50	16.57	852
5	BH-EELPA	Bore hole	0.018	0.635	500
6	BH-GORNO	Bore hole	0.72	20.12	778
7	BH-ERA	Bore hole	0.05	1.97	530
8	BH-AGAZI	Bore hole	0.35	12.96	490
9	BH-2	Bore hole	0.36	11.55	620
10	BH-1	Bore hole	0.16	4.704	870
11	NAGT-1	Hand-dug	0.80	19.65	1209
12	NAGT-4	Bore hole	0.12	8.118	286
13	NAGT-5	Spring	0.17	11.91	225

Table 6.7 %Na, SAR and EC values of different water sources in the study area.

6.6.1.3 Industrial Water Quality

Salinity, hardness, silica, sulfate, chloride, pH and iron are some of the parameters that usually are considered for industrial purpose (Todd, 1980). A water quality requirement for selected industrial and processes is summarized in Annex 3.

Parameter		Na+K	Ca	Mg	HCO_3	SO_4	NO_3	Cl	Fe	PH	TDS	Total hardness ($CaCO_3$)
Food processing			80	40	300							
Textile		100	-	-	-	0-5	-	100	0-0.3	25	0.3-5	0-50
Fruits& vegetable		-	100	-	-	250	10	250	0.2	6.5-8.5	500	250
Paper		-	-	-	-	10-100	-	0-200	0.1-1	20-100	-	100-200
Water source	Bore hole	40.7	101	24.9	397	68.8	3.54	21.1	0.03	7.2	434	353
	Hand-dug well	61.8	132	52.9	438	70.6	20.2	118.4	0.22	7.54	790	546
	Spring	6.3	28.2	5.9	57.6	24.7	1.15	16.9	0.02	7	132	95
Average		36.3	87	27.9	297.5	54.7	8.3	52.1	0.09	7.2	452	331

Table 6.8 Comparison of quality requirement for selected industrial plants and ground water quality of the study area. (Numbers indicate mg/l)

From the result with exception of calcium, the average value of the analyzed water sources have values of magnesium and bicarbonate lower than the upper limiting valuese; 40mg/l and 300mg/l respectively. With regard to fruits and vegetables processing plant quality requirement, the water sources in the study area fit the requirement, but the magnesium, bicarbonate, and sodium- potassium values are above the upper limiting values. The waters in the study area are unsuitable for textile plant. Only the Fe, Cl, PH and Na-K values are within the requirement. The same is true for paper manufacturing plant except for the Fe, Cl, PH and

SO_4 values.In general, the average TDS, NO_3, Ca, Mg and HCO_3 values of water samples in the study area are higher than the limit set for textile and paper manufacturing plants.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study an attempt is made to analyze and recommend appropriate recommendations concerning ground water resources potential zones of Adigrat and its surroundings based on geological, metrological, hydrogeological and hydrochemical data. Primary field data measurements, primary chemical analysis results of different water sources and secondary hydrogeological and hydrochemical data from different organizations are inputs in the evaluation of different hydrogeological and hydro-chemical parameters.

The study area has a total surface area of $152km^2$ with a wide difference in altitude ranging from 2000 m.a.s.l to 3000 m.a.s.l. The high altitude topography mainly occupies the western scarp of the study area. The central and eastern part in turn has rugged topography with flat to gentle slopes.

Geological map at a scale of 1:50,000 shows the paleozoic-mesozoic sedimentary rocks are dominant rock units. The main lithological units in the area are the alluvial sediments unit, the tertiary basalt unit, the Adigrat sandstone unit, the Edagaarbi glacial unit, the Enticho sandstone unit and the metamorphic rocks unit.

Geological structures which are the most important and influencing parameters in controlling the ground water occurrence and movement in the study area has been studied. The main structures of the area are sedimentary beds, cross bedding, fracture/joint sets and foliation. Fractures with EW and NE-SW trending are the dominant trending. The drainage system in the area follows the trend of the dominant fracture sets.

7.1.1 Results from analysis of water balance components:

Rainfall: - precipitation in the area shows variation both in space and time. The high lands in southeastern part of the area receive more precipitation that ranges in between 700mm and 750mm, than the north western part of the study area. According to the data records, the precipitation in the catchment area is bimodal with first from March to May, which is with small peak, & the second is from July to August with highest peak. Due to high topographic difference in the catchment, isohyetal method is deployed to determine the average annual depth of precipitation; accordingly the result of the computation is 694mm.

The value of Evapotranspiration, which combines evaporation and transpiration processes, is computed using Penman's combined method, Thornthwaite and Malstrom methods. The computed values from Thornthwaite and Malstrom are underestimated. Thus the value obtained from Penman's combined method which is 1259mm, is considered in the computation of AET for the study area. The actual evapotranspiration, which is the actual amount of water that evaporates and transpired depending on the available water and climatic condition, is computed using the Thorthwait and Mathes Soil-water balance model. The result of computation of the model yields a value of 583mm for the actual evaportanspiration. The value of actual evapotranspiration accounts 84% of the mean annual precipitation of the area under investigation.

River discharge:- Due to lack of stream gauging station to measure and record the monthly stream discharge of the study area, a long term mean monthly stream discharge data of Suluh river basin are used to simulate the run off of the study area. The Suluh river basin and the study area are characterized by the same geological and similar physiographical, soil, rainfall distribution & intensity and land use. Based on the above fact, the simulated mean annual depth of run off for the area is computed to 92.1mm. To separate the surface run off and base flow components of the total run off, graphical method is used. From the result of the graphic separation, it is found that the proportion of surface run off and base flow components is 67% and 33% of the total run off respectively.

7.1.2 Results from the analysis of water balance

The evaluation of water balance is done based on the metrological and hydrogeological data analysis. The amount of water entered in to the catchment is break down in to other components as, surface run off, recharge, evapotranspiration, and change in storage.

The water balance equation for the study area considers **no ground water in flow and out flow from and to the aquifers** in the, catchment, due to the absence of prominent structures extending out of the catchment for ground water in flow and out flow to and from the catchment area. Using the water balance equation the mean annual ground water recharge is computed to 46.4mm, which is about 6.7% of the mean annual rainfall of the study area.

7.1.3 Result from the analysis of hydrogeology

Quantitative borehole data and qualitative field descriptions are used to classify the rock units of the study area in to hydro-geological units. Accordingly, four hydrogeological units are recognized. These are rocks with high permeability, rocks with high to medium permeability, aquifers with medium to low permeability and rocks with very low permeability.

The high ground water potential aquifers that comprise the Enticho sandstone and alluvial sediments are characterized by high porosity and permeability. The permeability value is greater than 1.45m/d with corresponding transmissivity value that varies between $45m^2/d$ and $114m^2/d$. The lithologic units under this category are moderately to highly fractured and are located in flat slope area that facilitates infiltration& percolation of rainwater. In contrast to this the very low ground water potential aquifers are topographically placed at higher elevation areas with steep slopes > 50^o and have very permeability. The Edaga Arbi glacials, the Adigrat sandstone unit, the metamorphic rocks and tertiary basalts placed at higher elevation forming rugged topography and steep slopes, are under this hydrogeological group.

7.1.4 Results from analysis of hydrochemistry

Laboratory analysis supplemented by field measurements provides the information to characterize the different water sources, according to their chemistry. According to their TDS value, most of the water samples are fresh and have TDS value less than 1000mg/l. Based on hardness classification the different water sources are moderately hard to very hard. The PH value of most water samples range between 6.9 and 7.9, which is common for ground water.

In addition to this, the hydrochemical study indicated the presence of two major types. These are Ca-HCO_3 and Ca-Na-HCO_3. In general, terms the ground water in the study area fulfills the standard limits set for domestic and agricultural purposes but the standards for industrial purposes of textile and paper manufacturing are partially satisfied. One bore hole water sample WN-3 showed high concentration of NO_3 above the recommended limit for drinking purpose. The source of the high nitrate value is attributed to domestic wastes dump near the bore hole site.

7.2 Recommendations

- In ground water exploration scheme, areas covered by the Enticho sandstone unit with high degree of fracturing should get better attention.
- Pumping test data are unevenly distributed in space, so additional pumping test is recommended at selected bore holes for a better quantitative evaluation of aquifer hydraulic parameters and understanding of the ground water potential of the area.
- In the study area there is no stream gauging station to measure and record the monthly stream discharge. So, it is recommended to set a stream gauging station around May Megab river which is close to Adigrat town.
- Secondary geological, hydrogeological and hydrochemical data that are important for ground water study are not accessible. So, systematic and proper collection and handling of data is inquired from concerned bodies so that easy access to the data is possible.
- Policy makers should give emphasis on environmental policy that takes in to consideration the contamination risk hazard of the Golgol-Natsa well field and other ground water potential areas, by domestic waste disposal and agricultursl activities. Well field protection of the Golgol-Natsa well field in particular is highly recommended.
- To determine the depth and thickness of the water bearing formation and to quantify the ground water resource of the area, geophysical investigation especially Vertical Electrical Sounding (VES) is recommended at selected sites.

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ANNEX 1 HYDROMETROLOGY

Element Monthly Total rainfall in mm

Region: Tigray X missed data

Station: Adigrat

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
1970	0	12.1	35.7	51.2	0	15.3	179.2	249.3	13.5	25.8	0	13	***594.9***
1971	2.5	0	35.4	16.5	42	34	98.5	91.4	0	14.2	0	0	***334.5***
1972	46	7.5	26.6	37.6	58	34.9	61.8	26.8	6	43.8	88	2	***438.9***
1973	0	0	1.5	90.4	27.6	10.3	146.8	103.5	10	14	0	0	***404.1***
1974	14	1.5	44	32.5	21.4	20.3	121.6	139.6	8.3	0	0	0	***403.2***
1975	3	2.1	50	74.2	34	114	182.2	319.8	79.6	0	12	24	***894.8***
1976	0	10	43.8	63.4	41.5	23.5	89.3	68.3	14.6	0.6	151	2.6	***508.6***
1977	0	0	24.9	22.5	64.6	56.6	182.2	192	0.5	103	0	48	***694.5***
1978	2.5	0	100	22	6.8	59.4	140.2	96.4	10.9	0	24	40	***502***
1979	42.8	0	2	0	79.1	100	66.8	131.9	19.6	80	0	7	***529.5***
1980	0	8.6	88.4	150.4	17.3	48.5	12.4	X	31.3	0	16	0	***372.8***
1981	9.5	9.7	4.8	48.7	32.5	7.8	260.1	302	17.8	38.7	23	X	***754.2***
1982	19.2	22.9	56.1	130.4	102.2	6.6	67.7	X	X	X	X	X	***405.1***
1983	X	X	X	X	X	X	63.8	200.6	15	35.4	22	0	***336.6***
1984	0	11.8	43.3	16.5	46.9	12.3	159.3	104	12	0	14	34	***454.2***
1985	24.8	27	51.8	115.5	70.8	25.9	192.2	120.4	18.2	X	16	5	***667.2***
1987	X	X	23.2	11.5	48.2	4.2	33.5	143.2	7.5	171	3.2	11	
1988	0	33.8	0	17	X	X	118	149.8	6.2	X	X	X	
1992	0	X	X	74.1	71.1	8	99.6	146.4	3.2	20.8	86	25	***534.7***
1993	8.3	25.6	78.4	214.4	100.8	9.9	165.4	112.6	37.4	8.1	0	0	***760.9***
1994	0.2	31	9.9	87	43.8	76.8	235.7	279.5	23.9	1.4	3	2.1	***794.3***
1995	0	6.2	32.7	153.3	77.4	13.8	184.9	112.3	11.3	1.9	0	43	***636.7***
1996	28.9	20.6	82.8	98.9	59.5	14.2	220.7	160.7	0	0	50	8.5	***745***
1997	6.6	0.1	85.4	11.8	148	48.2	170.6	112.4	0.6	210	79	1.4	***874.4***
1998	3.6	0.4	73.4	52.1	86.1	9.6	202.7	221.3	X	X	X	X	***649.2***
1999	32.9	1.8	12	15.3	0	9.5	97.2	124.3	8	0	0	X	***301***
2000	0	0	10	10	18.6	36.7	X	X	X	X	X	X	***75.3***
2001	X	X	X	X	45.7	51.4	237.9	171.5	8.6	41.4	X	X	***556.5***
2002	10.6	0	90	16.7	31.6	43.6	172.5	98.4	8.8	14.2	7.7	70	***564.5***
2003	6.1	43.8	62.1	42.5	0.6	48.2	201.6	105.4	22.2	13.3	0.7	1.7	***548.2***
Average	***9.7***	***10.6***	***43.3***	***59.871***	***49.15***	***34***	***143.6***	***151.3***	***14.6***	***33.5***	***24***	***15***	***597.19***

Source: National Metrological Service Agency (NMSA)

Element: Monthly Total rainfall in mm

Region: Tigray **X missed data**

Station: Edaga Hamus

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	*Sum*
1973	X	X	X	X	X	X	X	123.1	4.4	11.7	0	1.8	***141***
1974	15.3	0.3	89.1	51.6	88.5	13.2	169.6	134	8.1	0	0	0	***569.7***
1975	0.4	17.7	59.6	56.1	17.8	53.9	252.2	229.5	52.9	0	0	28.2	***768.3***
1976	0	11.2	24.8	75	34.8	4.1	177.9	61	10.8	1.7	100	0	***501.3***
1977		0	117.8	5.7	56.7	73.1	169.3	214.4	9.5	68.8	15.3	0	***730.6***
1978	1.1	0	40	26.5	12.1	42.1	130.2	307.4	0	0	48.4	36.2	***644***
1979	25.9	1.2	0.4	24.9	71.7	17.9	100.2	123.3	35.1	43.1	0	0	***443.7***
1980	12.5	10.1	85	83.6	13.6	37.2	125.7	76.7	2.7	0	108	0	***555.1***
1981	8.7	8.5	22.6	33	25	7.3	153	271.2	15.2	24.6	6.4	20.5	***596***
1982	10	24.3	73.9	184	75.7	34.8	2	X	X	X	X	X	***404.8***
1983	X	0	8.6	48.7	119.9	80.5	71.2	92.1	111.2	18	0	0	***550.2***
1984	0	0	42.8	5.3	202.6	60.6	117.2	119.9	15.7	0	0	0	***564.1***
1985	3.4	72.3	171.6	198	37.5	116.5	143.1	279.7	94.7	52.1	8.8	13.7	***1191.2***
1986	0	59.4	73.4	398	136.2	341.9	346.1	710.5	253.1	108	109.9	0	***2536.5***
1987	7.1	16.5	113.1	399	394.1	192	9.4	730.3	50.6	X	X	X	***1912.2***
1988	34.6	9.2	317.4	395	94.6	X	X	X	X	X	X	X	***851.1***
1992	X	X	X	72.4	18.1	5.8	196.3	125.5	21.7	36.1	98.7	18.5	
1993	22.1	19.2	21.1	188	48.5	5.9	115.2	71.9	19.3	41.9	0	7.7	
1994	0	3.6	56.9	50.2	X	X	X	X	X	X	X	X	***110.7***
1995	0	21.5	9.3	97	22.5	7.9	X	X	0	0	X	X	***158.2***
1996	21	18	104.8	53.7	29.1	213.5	X	X	X	0	0	8.4	***448.5***
1997	X	15.3	42.4	6.3	9.6	47.7	97.7	45.7	1.6	91.9	0	X	***358.2***
1998	0	0	21.1	6.5	77.3	0	234.3	228.6	21.6	0	0	0	***589.4***
1999	31	0	1.1	0	X	6.6	X	159.5	4.5	10	0	3.9	***216.6***
2000	0	0	1.3	X	43.6	5.7	194.8	205.1	5.3	11.7	27.3	17.9	***512.7***
2001	0	0	84.9	20.9	70.3	96.8	239.2	292.7	7.4	5.4	0	1.5	***819.1***
2002	0	15	28.4	0	58.2	42.6	112.8	117.7	21.2	2.5	3.9	X	***402.3***
2003	10.2	49.3	8.3	82.5	6.9	37.8	139.7	152	4.6	3.3	0	3.4	***498***
Average	***8.8***	***14.3***	***62.3***	***99***	***70.6***	***61.8***	***149.9***	***211.8***	***32.1***	***22***	***22.9***	***7.7***	***762.6***

Source: National Metroloical Service Agency (NMSA)

Element: Monthly Total rainfall in mm

Region: Tigray X missed data

Station: Hawzien

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1971	X	X	X	X	57.7	37.6	140	145.6	10.1	1.1	0	0
1972	0	5.1	8.3	52.8	20.1	63.9	172	155.1	17.7	3.6	25.2	6.3
1973	0.4	0	0	22.1	52.8	24	192	254.8	12.3	34.9	0	0
1974	1.9	0	23.7	30.4	28.7	24.3	128	88.4	34.8	0	0	0
1975	4.5	2.3	28.5	16.7	17.5	65.3	284	200.2	77.5	0	0	9.8
1976	0	12.7	52.6	30.2	42	34	170	158.5	21.5	0	38.9	2.4
1977	4.2	0	23.3	10.1	54.7	44.7	209	245.3	21.8	37.4	1.2	3.9
1978	0	0	18.5	0	18.8	35	163	127.7	27.6	17	41	0
1979	26.7	0	2.6	0	38.6	39.5	55.5	154.2	59.2	36	0	0
1980	0	20.2	6.4	64.4	0	48.8	196	164.5	2.1	0	0	0
1981	0	0	59.3	9.9	29.5	10.4	315	150.5	17.5	74.5	4.3	0
1989	X	X	X	X	X	X	X	X	X	X	X	X
1990	X	X	X	X	X	X	X	X	X	X	X	X
1991	X	X	X	X	X	X	X	X	X	X	X	X
1992	X	X	X	0.3	44.8	37.8	54	146.7	24.1	31	81.5	3.3
1993	0	8.9	23	113.2	29.2	34.7	136	137.1	45.2	18	0	0
1994	0	0	1.2	17.5	27.8	62.8	161	204.9	42.7	2.3	0	0.6
1995	0	0	30.1	48.2	51.8	5.4	140	177.7	19.9	0	0	22.6
1996	18.7	4.4	78.9	22.6	38.9	66.9	122	118.6	18	0	12	3
1997	0	0	60.9	35.8	26.9	42	149	80.5	0	66	26.8	0
1998	X	0	1	3.3	59.6	17	276	199.5	32.5	2.5	0	0
1999	29	0	4.3	3.1	19	20.1	235	240.3	24	2.3	0	3.7
2000	0	0	0	24.5	27.9	71.7	244	341.1	27.1	20.9	6	0

Element- Monthly maximum temperature in ^{o}C X missed data

Region Tigray

Satation Hawzien

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1976	X	X	X	X	X	X	X	X	X	24.2	22.9	23.3
1977	24.5	26.3	25.8	27.6	27.1	26.6	22.8	22	24.2	24.3	23.6	23.8
1978	24.3	26.2	27.5	26.9	28.1	28.6	22.9	22.7	24.8	24.8	23.4	23.7
1979	23.4	25.5	26.7	26.7	25.7	25.9	24.9	23.4	24.9	24.1	24.4	25.3
1980	25.7	26.5	27.5	26..4	28	27.6	23.2	22.8	25.1	24.7	23.6	25
1981	25.7	26.1	26	26.6	27	28.1	24	23.5	24.8	23.4	23.6	24
1992	X	X	X	27.6	27.1	27.9	23.9	21.4	23.7	24	22.9	23.8
1993	23.6	24.6	26.5	24.7	25.9	25.9	22.9	23.3	25	25.4	25.4	25
1994	26.1	26.5	27.6	27.8	27.9	26.1	21.7	22.8	23.5	24.9	25.1	25.1
1995	25.7	27	27	26.2	27.4	28	24	23.6	25	26.1	26.7	26.2
1996	25.7	28	27.4	27.1	27.2	26	23.7	22.9	27	26.2	25.8	25.3
1997	26.2	26.7	27.3	27.6	27.4	27.4	23.6	24.5	27.9	25.8	25.5	26.9
1998	26.4	27.7	29.2	30.3	28.9	28.7	23.6	22.4	25.7	26.6	25.9	26.1
1999	26.1	28.2	28	28.8	29.5	29.6	22.9	22.7	26.5	26.6	26	26.3
2000	26.6	27.4	28.5	27	29.3	28.5	22.8	22	25	25.5	25.4	25.5
2001	24.5	25	26.5	25.5	28.4	27	24.8	25	24.9	26.7	27	26.7
2002	26.9	28.3	28.4	28	29.4	29	26.7	23.6	24.7	26.5	26.6	25.9
2003	25.7	27.7	28.4	28.9	29.3	27.6	24	24.1	25.8	26.4	25.4	25.3

Element- Monthly minimum temperature in ^{o}C

Region Tigray

Satation Hawzien

X Missed data

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1976	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*9.2*	*7.9*
1978	*7.8*	*9.8*	*11.5*	*13.1*	*13.7*	*13.6*	*12.7*	*12.2*	*8.9*	*10*	*8.4*	*8.4*

1979	*9.5*	*9.9*	*12.1*	*12.6*	*14.2*	*14.4*	*13.8*	*12.6*	*13*	*11*	*8.9*	*8.8*
1980	*8.9*	*11.1*	*12.1*	*13.4*	*14.4*	*13.4*	*13.1*	*12.9*	*12.4*	*12.4*	*15.3*	*12.9*
1981	*9.9*	*9.2*	*13.1*	*13.4*	*13.7*	*13.6*	*13.7*	*12.9*	*12.3*	*10.4*	*9.1*	*7.7*
1992	*X*	*X*	*X*	*12.3*	*13*	*12.6*	*12.2*	*13.1*	*10.1*	*9.7*	*9.7*	*8.8*
1993	*8*	*8.7*	*10.3*	*12.4*	*12.2*	*11.9*	*12.6*	*12.1*	*10.5*	*8.6*	*7*	*6.5*
1994	*7.1*	*9*	*10.7*	*12.5*	*13.3*	*12.2*	*12.8*	*13.2*	*9.9*	*8.3*	*8*	*6.1*
1995	*6.8*	*9.8*	*11.1*	*12.8*	*13*	*11.6*	*12.5*	*13.1*	*9.9*	*10.9*	*7.2*	*7.9*
1996	*8.2*	*8.9*	*10.9*	*12.3*	*12.4*	*12.4*	*13.1*	*13.1*	*10.9*	*8.6*	*7.8*	*7.5*
1997	*8.3*	*8.5*	*11.7*	*12.6*	*12.9*	*13.7*	*13.3*	*12.5*	*10.9*	*11.8*	*11.4*	*8.5*
1998	*9.6*	*9.5*	*12.1*	*13.9*	*14.1*	*13.4*	*14.4*	*14.6*	*12*	*9.8*	*6.7*	*5.2*
1999	*7.5*	*7.4*	*9.3*	*11.2*	*12.5*	*13.1*	*12.7*	*12.9*	*10.6*	*9.8*	*6.6*	*7.2*
2000	*6.6*	*7.2*	*10.2*	*12.7*	*13.1*	*12.5*	*12.7*	*12.6*	*10.8*	*9.3*	*8.3*	*7.4*
2001	*8*	*8.5*	*11.6*	*12.5*	*13*	*12.2*	*12.8*	*12.5*	*13.2*	*12.8*	*7.9*	*6.5*
2002	*7.9*	*7.5*	*10.9*	*11.2*	*12.2*	*12.3*	*12.3*	*11.7*	*9.8*	*8.1*	*8.1*	*8.5*
2003	*6.8*	*8.8*	*11.5*	*11.6*	*12.8*	*11.8*	*12.6*	*12.8*	*10.3*	*8.4*	*7.5*	*6*

Element- Monthly maximum temperature in ^{o}C

Region Tigray

Satation Adigrat X missed data

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1992	**X**	**X**	**X**	**25.8**	**24**	**25.1**	**23.1**	**21.5**	**21.8**	**21.9**	**21.3**	**21.4**
1993	**22.6**	**23.2**	**24.1**	**22.2**	**21.8**	**23**	**22.7**	**22.4**	**23.1**	**22.7**	**22.6**	**23.7**
1994	**22.9**	**23.2**	**24.7**	**25.2**	**25.3**	**24.5**	**20.9**	**21.3**	**23.1**	**22.7**	**23.2**	**23.5**
1995	**23.7**	**24.3**	**25**	**25**	**24.1**	**26.1**	**22.6**	**22.3**	**23.6**	**23.6**	**24.1**	**23.6**
1996	**22.4**	**24.3**	**24.3**	**24.3**	**23.2**	**23.8**	**22.9**	**22.1**	**24.5**	**23.2**	**22.1**	**23.2**
1997	**24**	**25**	**24.7**	**24.7**	**23.9**	**24.8**	**21.6**	**22.4**	**24.7**	**22.9**	**21.5**	**23.1**
1998	**23**	**24.1**	**24.9**	**24.9**	**25.1**	**25.6**	**21.9**	**21.7**	**X**	**X**	**X**	**X**
1999	**21.6**	**24.5**	**24.6**	**24.6**	**26.1**	**26.5**	**21.2**	**21.1**	**22.6**	**22.3**	**22.7**	**X**
2000	**X**	**X**	**X**	**X**	**X**	**25.6**	**X**	**X**	**X**	**X**	**X**	**X**

2001	**X**	**X**	**X**	**X**	**25.9**	**23.4**	**21.2**	**21.5**	**22.4**	**23.1**	**X**	**X**
2002	**23.1**	**24.7**	**24.6**	**24.6**	**26.5**	**24.9**	**24**	**23.9**	**23.9**	**23.5**	**23**	**22.1**
2003	**23.4**	**25.3**	**25**	**25**	**26.4**	**25**	**21.2**	**24**	**24**	**23**	**23.2**	**23.4**

Element- Monthly minimum temperature in ^oC X missed data

Region Tigray

Satation Adigrat

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1996	**6.3**	**6.1**	**8.6**	**10.4**	**9.9**	**11.5**	**11.7**	**11.6**	**8.3**	**5.9**	**5.8**	**4.6**
1997	**4.5**	**5.3**	**8.6**	**8.8**	**8.8**	**10.9**	**11.2**	**9.8**	**9.1**	**9.8**	**9.2**	**7.8**
1998	**7.4**	**6.6**	**8.5**	**10.7**	**10.7**	**11.3**	**11.6**	**11.9**	**X**	**X**	**X**	**X**
1999	**4.9**	**6.4**	**8.6**	**11.2**	**11.2**	**12.2**	**10.1**	**X**	**X**	**X**	**X**	**X**
2000	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
2001	**X**	**X**	**X**	**11.4**	**11.4**	**11.8**	**11.3**	**11**	**7.3**	**8.6**		**X**
2002	**7.5**	**7.8**	**10.1**	**10.8**	**10.8**	**12.4**	**11.6**	**9.2**	**7.1**	**6.5**	**7.9**	**7.5**
2003	**6.6**	**9.4**	**10.1**	**13.1**	**13.1**	**13.4**	**13.5**	**12.3**	**12.3**	**8.1**	**7.7**	**6.4**

Element- Sun shine hours (hours/day)

Region Tigray X missed data

Satation Mekelle

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1991	X	X	X	X	X	X	5.4	X	X	X	X	
1992	X	X	x	9.4	9.8	8.1	5	4.3	6.9	7.9	6.9	9
1993	9.7	8.5	9.6	8.4		6.5	5.4	5.3	7.1	8.6	10.4	10.2
1994	10.3	9.9	9	9.5	10.1	6.4	4.4	58.1	7.9	10.5	9.8	10.2
1995	10.3	8.9	9.3	8.8	9.3	9.2	5.4	5.1	8.7	9.8	10	9.4
1996	8.9	9.6	8.2	9.1	8.4	5.9	6.1	5.8	7.7	9.8	9	9.9
1997	9.4	9.8	8.5	9.1	8.4	5.9	6.1	5.8	7.7	9.8	9	9.9
1998	8.4	8.7	9.1	9.4	9.4	7.3	4.9	4.1	7.1	9.2	10.2	10.3
1999	9.4	10.5		10.3	10	7.2	4.1	5.5	8	9.2	10.3	9.9
2000	10.1	10	10	7.8	9.6	7.2			7	9	9	9.4

2001	9.6	9.7	6.4	9.6					8.6	9.3	10.2	10.1

Element- Sun shine hours (hours/day)

Region Tigray

Satation Illala(Mekelle)   X missed data

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1996	9.3	10	8.8	9.8	8.9	6.2	6.2	5.7	7.6	10.3	9.3	10
1997	9.4	10.5	9	9.5	9.8	8.4	6.3	6.8	8.8	8.6	9.3	10
1998	9	9.2	9.5	9.9	10	7.9	5.1	4.2	7.4	9.6	10.6	10.3
1999	9.6	10.7	10	10.7	10.5	7.7	4.5	5.5	8.2	8.8	10.5	9.8
2000	10.3	10.6	10.6	8.2	10.2	8.4	6.4	5.4	7.5	9.6	9.6	9.4

Element- wind speed (m/s)

Region Tigray

Satation Mekelle

X missed data

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1995									1.9	3.4	3.4	3.7
1996	3.6	4	3.7	4.1	3	1.9	2	1.6	2	3.3	3.6	3.7
1997	3.3	4.9	3.9	3.2	3.6	2.3	2.3	1.5	2.3	3.5	3.7	3.8
1998	3.5	3.2	4.4	4.7	3.4	2.4	2.3	1.7	1.6	2.7	3.3	3.5
1999	3.5	4.4	3.7	4.2	2.9	2.1	1.9	1.6	1.5	2.7	3.4	3.6
2000	3.7	4.4	4.7	1.1	3	2.3	2.1	1.9	1.7	2.8	3.1	

Element- wind speed (m/s)

Region Tigray

Satation Illala (Mekelle)

X missed data

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec

1996	3.4	3.6	3.5	3.9	2.6	1.3	1.4	1.2	1.6	3	3.3	3.4
1997	2.7	4.3	3.3	3.5	2.9	1.7	1.1	0.9	1.7	3	4.5	3.1
1998	2.8	2.5	3.5	3.7	2.6	1.6	1.3	0.9	1.5	2.2	2.7	2.9
1999	2.9	3.5	3.2	3.8	2.5	1.6	1	0.9	1.1	2.1	2.7	3.1
2000	2.9	3.5	3.9	2.8	2.3	1.4	1.1	0.9	1.2	2.5	2.9	2.8

Element Relative humidity at LT 1800

Region Tigray

Station Adigrat

X missed data

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1996	X	X	X	X	X	X	X	X	X	X	X	X
1997	X	X	X	X	54	48	78	67	48	60	85	65
1998	59	45	42		46	32	72	73	X	X	X	X
1999	73	43	52		51	68	91	93	91	93	91	X
2000	X	X	X	X	X	82	X	X	X	X	X	X
2001	X	X	X	X	45	53	69	74	48	42	X	
2002	57	60	63		55	47	60	67	49	53	56	68

Element Relative humidity at LT 6000

Region Tigray

Station Adigrat

X missed data

Year	January	February	March	April	August	Sep	Oct	Nov	Dec	Jan	Feb	March
1996	X	X	X	X								
1997	X	X	X	X	75	75	86	X	X	X	X	X
1998	X	X	X	X	X	X	X	X	X	X	X	X
1999	X	X	X	X	X	X	90	90	85	89	90	

2000	X	X	X	X	X	86	X	X	X	X	X	X
2001	X	X	X	X	X	X	X	X	X	X	X	X
2002	X	X	68	76	72	57	78	87	72	73	74	81

Element Relative humidity at LT 1200

Region Tigray

Station Adigrat X missed data

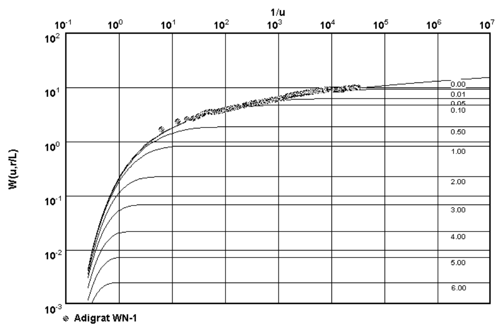
Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1997	X	X	X	X	45	47	65	X	X	X	X	X
1998	X	X	X	X	X	X	X	X	X	X	X	X
1999	58	42	41	43	45	66	88	91	83	85	88	X
2000	X	X	X	X	X	81	X	X	X	X	X	X
2001	X	X	X	X	24	41	59	66	39	37	X	x
2002	36	41	45	51	51	39	50	58	32	35	33	49

ANNEX 2 HYDROGEOLOGY

Generated Runoff Series of Suluh River (at Observation Site)

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
1960	0.10	0.67	1.26	1.72	1.07	0.00	12.91	14.79	0.00	0.23	0.15	0.16
1961	0.24	0.65	2.74	2.82	0.78	0.19	16.51	18.65	2.05	0.41	0.21	0.09
1962	0.22	0.42	4.18	2.64	2.37	1.07	13.04	17.44	1.54	0.42	0.70	0.12
1963	0.91	0.43	1.72	2.41	3.12	0.69	15.00	13.13	0.14	0.44	0.24	0.21
1964	0.57	0.07	2.57	1.65	1.68	1.63	9.87	8.94	0.00	0.29	0.15	0.23
1965	0.48	0.90	2.93	2.34	0.93	0.37	11.57	13.67	1.91	0.84	0.18	0.10
1966	0.03	0.54	2.13	1.49	0.66	0.55	9.71	10.45	2.79	1.37	0.16	0.10
1967	0.23	0.07	1.18	1.98	1.92	0.09	12.72	16.84	0.00	2.02	0.25	0.09
1968	0.01	1.03	1.86	2.07	0.97	2.68	11.38	13.65	1.01	1.36	0.21	0.73
1969	0.56	0.45	5.03	2.53	4.58	1.16	14.04	13.32	2.49	0.08	0.16	0.12
1970	0.03	1.15	2.21	1.64	2.37	0.96	9.07	29.00	1.16	0.75	0.19	0.17
1971	0.07	0.13	3.50	0.90	1.46	0.44	10.78	6.45	0.00	0.29	0.19	0.09
1972	0.01	0.54	2.90	1.88	1.56	3.53	8.69	1.70	2.98	1.16	0.62	0.11
1973	0.15	0.08	1.13	1.88	1.30	0.03	11.37	11.80	0.35	0.29	0.15	0.18
1974	0.18	0.07	3.01	0.35	1.30	0.00	11.03	12.45	0.00	0.00	0.15	0.09
1975	0.04	0.89	1.84	1.47	0.45	1.78	11.42	36.47	6.30	0.03	0.15	0.41
1976	0.01	0.30	1.69	1.66	1.78	0.00	12.01	8.66	1.87	1.05	1.42	0.78
1977	0.04	0.07	3.17	0.85	1.23	1.04	20.8	11.61	3.64	5.96	0.18	0.83

							1					
1978	0.10	0.36	2.94	1.50	0.76	1.95	13.51	17.33	0.00	0.85	0.71	0.71
1979	3.94	0.86	1.20	1.66	3.64	1.08	4.51	5.36	2.27	1.33	0.16	0.13
1980	0.55	0.11	2.91	3.32	0.86	1.36	6.46	9.91	1.34	0.82	0.59	0.09
1981	0.60	0.21	4.25	1.76	1.56	0.16	16.59	18.48	1.34	6.62	3.55	0.41
1982	1.59	1.28	4.14	3.00	3.76	2.22	7.30	6.16	11.83	1.62	0.18	0.19
1983	1.58	0.07	1.00	1.19	2.97	0.87	11.72	15.30	9.48	5.13	0.23	0.10
1984	0.01	0.13	3.21	1.41	2.33	1.14	8.61	7.03	1.13	0.93	0.58	0.24
1985	0.39	0.24	3.05	1.69	2.26	0.40	9.53	7.73	1.05	0.77	1.05	0.87
1986	0.21	1.81	2.06	0.93	1.62	0.24	16.20	8.39	0.00	0.24	0.14	0.07
1987	0.03	0.58	1.90	1.86	4.03	1.49	6.70	9.50	0.48	0.42	0.18	0.00
1988	5.16	0.04	0.00	1.00	1.45	1.48	10.43	13.25	0.00	1.15	0.20	0.10
1989	0.03	0.12	4.10	2.46	0.90	0.28	8.50	7.13	0.00	0.26	0.18	0.30
1990	0.07	0.19	4.79	1.68	1.37	1.87	16.49	12.46	2.15	3.29	0.39	0.44
1991	0.42	0.26	4.63	2.47	1.80	1.72	9.09	12.07	3.31	5.74	1.05	0.11
1992	0.08	1.49	2.50	1.74	1.18	0.00	9.36	11.32	0.28	0.46	1.37	0.23
1993	1.43	0.13	1.86	4.60	1.98	0.25	3.97	7.79	4.92	4.34	0.03	0.01
1994	0.01	0.32	1.52	3.62	0.18	0.16	9.17	15.03	3.28	0.00	0.15	0.25
1995	0.01	0.48	1.38	4.05	1.12	0.00	14.41	5.71	0.00	0.50	0.15	0.24
1996	1.45	0.44	4.24	2.07	1.16	2.34	12.54	8.78	0.00	0.03	0.30	0.15
1997	0.65	0.44	4.25	1.63	1.03	1.34	9.26	5.29	0.00	9.00	1.29	0.09
1998	0.32	0.34	0.37	1.84	0.90	1.34	12.98	16.63	2.35	8.80	0.18	0.09
Average	**0.58**	**0.47**	**2.60**	**1.99**	**1.70**	**0.97**	**11.26**	**12.30**	**1.88**	**1.78**	**0.47**	**0.24**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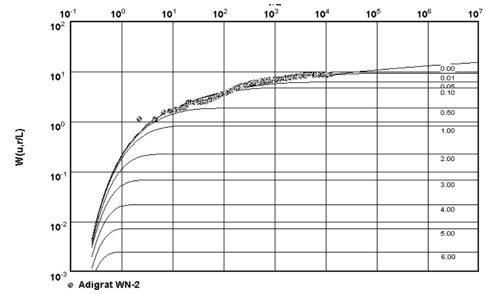
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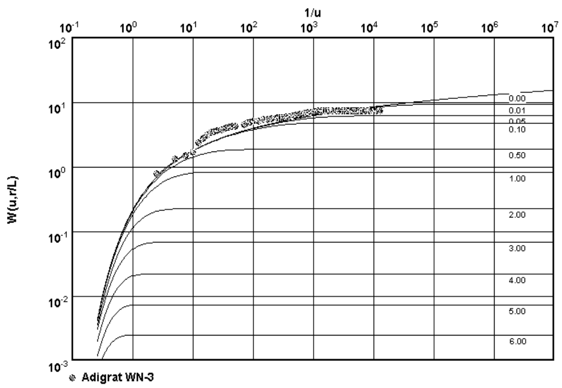
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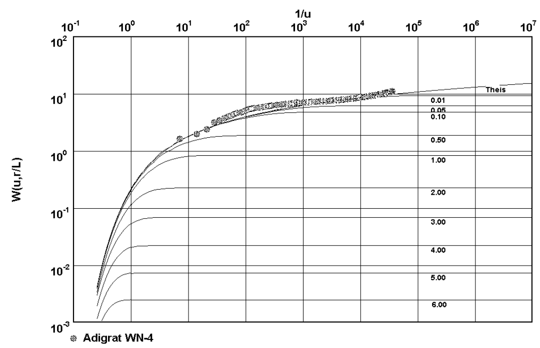
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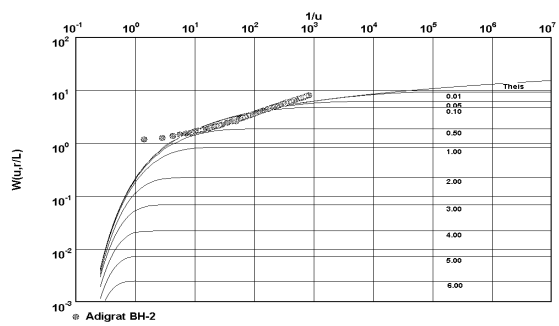
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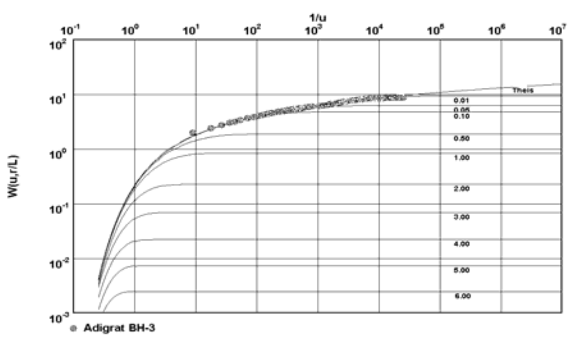
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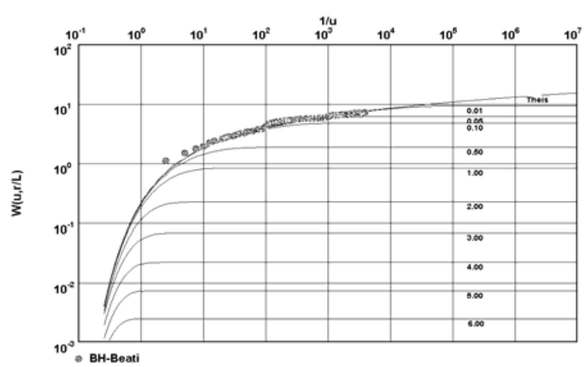
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Well name: WN-1

Drilling started 17/7/93 G.C

Drilling Completed 19/7/93 G.C

Major aquifer: Fractured sandstone

Aquifer thickness: 36.7m

Well yield: 2.5l/s

T= 6.18m^2/day

K= 0.176m/day

Depth	Geology	
(m)	Classification	Description
0-3	Silty sand	Red color silty sand
3-15	Sandstone	Slightly weathered and fractured sandstone
15-42	Sandstone	Fresh and fractured sandstone. There is light colored clay intercalation in the depth interval 21-27m
42-108	Sandstone	Fresh, light colored sandstone
108-124	Sandy shale	Fresh, dark color shale with fragments of metamorphic rock at bottom

Source: Water Well Drilling Agency

Source: Water Well Drilling Agency

Well name: WN-2

Drilling started: 1/8/93 G.C

Drilling Completed: 5/8/93 G.C

Major aquifer: coarse grained sandstone

Aquifer thickness: 30m

Well yield: 1l/s

T= 0.79m^2/day

K= 0.026m/day

* Open well

Depth	Geology	
(m)	Classification	Description
0-3	Silty sand	Pale brown color, silty sand
3-36	Sandstone	Fresh, whitish color, fine grained with intercalation of silt.
36-54	Sandstone	Fresh, whitish color,poorly sorted, fine grained sandstone.
54-66	Sandstone	Fresh, coarse grained sandstone.
66-81	Sandstone	Fresh, whitish color, poorly sorted, fine grained sandstone.
81-106	Sandstone	Fresh, whitish color, fine grained sandstone.

Source: Water Well Drilling Agency

Well name: WN-3

Drilling started: 8/8/93 G.C

Drilling Completed: 18/8/93 G.C

Major aquifer: coarse grained and fractured sandstone

Aquifer thickness: 44.4m

Well yield: 6.12l/s

T= 7.019m^2/day

K= 0.15m/day

Depth	Geology

(m)	Classification	Description
0-3	Silty sand	Reddish color silty sand
3-6	Clay	Black color clay
6-10	Clay	Reddish color clay
10-18	Clayey sand	Brown colored clayey sand
18-27	Sandy clay	Grey color, sandy clay
27-40	Sandstone	Gray color, fractured, slightly weathered sandstone
40-48	Sandstone	Whitish-gray, fine to coarse grained sandstone
48-70	Sandstone	Fresh, whitish-yellowish color, poorly sorted , fine to coarse grained sandstone.
70-80	Sandstone	Fresh, whitish color, fine to medium grained sandstone.
80-90	Sandstone	Fresh, yellowish color, fine to coarse grained sandstone.
90-98	Sandstone	Fresh fractured sandstone
98-108	Sandstone	Fresh sandstone

Source: Water Well Drilling Agency

Well name: WN-4

Drilling started: 25/8/93 G.C

Drilling Completed: 27/8/93 G.C

Major aquifer: Medium to coarse-grained sandstone

Aquifer thickness: 30m

Total depth: 114m

Well yield: 6.12l/s

T= 43.50m^2/day

K= 1.45m/day

Depth	Geology	
(m)	Classification	Description
0-3	Silty sand	Reddish color silty sand
3-6	sandstone	Weathered sandstone
6-10	sandstone	Fine grained slightly weathered sandstone
10-31	sandstone	Fresh, fine to medium grained, poorly sorted , whitish color sandstone
31-50	sandstone	Fresh, whitish to pale brown color sandstone
50-54	sandstone	Fresh, fine to coarse grained sandstone
54-102	sandstone	Fresh, poorly sorted, whitish color sandstone
102-114	sandstone	Fresh, fine grained sandstone

Source: Water Well Drilling Agency

Bore Name BH-BGA1 (Near Adigrat Hospital)

Bore- hole depth 74m

Major aquifer: weathered sandstone and conglomerate

Aquifer thickness 16m

Well yield 2.45 l/sec

Permeability 7.1m/day

Transmissivity 311.93 m^2/day

Specific capacity

Depth (m)	Classification	Description	Remark
0-2	Sandy soil	Brown color gravely sandy soil	
2-12	Sandstone	Yellowish color sandstone	
12-15	Sandstone	White color sandstone	
15-16	Marl	Grey whitish marl	
16-25	Sandstone	Dark yellow sandstone	
25-27	Sandstone	Pale brownish sandstone with oxidation marks	
27-34	Sandstone	Dark yellow color sandstone	
34-43	Conglomerate	Yellow colored conglomerate	
43-48	Sandstone	Grey color sandstone	
48-74	Sandstone	White color sandstone	

Source: ACDS (Adigrat Catholic Diocese Secretariat)

Bore Name BH-BGA2

Borehole depth 86.15m

Major aquifer: conglomerate

Aquifer thickness 13m

Well yield 2.32 l/sec

Permeability 0.57 m/day

Transmissivity 7.41 m^2/day

Specific capacity

Depth (m)	Classification	Description	Remark
0-1.3	Sandy silt	Brown color sandy silt	
1.3-34	Sandstone	White color sandstone	
34-48	Marl	Grey whitish marl	
48-53	Conglomerate	Conglomerate	
53-59	Sandstone	Mostly whitish and yellowish color sandstone	
59-67	Conglomerate	Conglomerate	
67-82	Sandstone	White color sandstone	
82-86.15	Metamorphic	Dark gray color weathered slate	

Source: ACDS (Adigrat Catholic Diocese Secretariat)

Bore Name BH-BGA3

Borehole depth 55.62m

Major aquifer: Sandstone

Aquifer thickness

Well yield 1.42l/sec

Permeability m/day

Transmissivity 0.92m^2/day

Specific capacity

Depth (m)	Classification	Description	Remark
0-2.4	Sand sit	Reddish color sandy silt	
2.4-6	Sandstone	Reddish color silty sandstone	
6-9	Siltstone	Dark red siltstone	
9-12	Sandstone	Reddish color sandstone	
12-21	Siltstone	Reddish and greenish color siltstone with white marks	
21-41	Shale	Dark color shale	
41-45	Sandstone	Dark red color sandstone	
45-48	Sandstone	Brown color sandstone with thin shale intercalation	
48-51	Shale	Pale gray colored shale	
51-55.62	Edagaarbi glacial	Boulders of granite, conglomerate and pebble size rock fragments in shale/clay matrix. (Glacial deposit)	

Source: ACDS (Adigrat Catholic Diocese Secretariat)

ANNEX 3 HYDROCHEMISTRY

Drinking water guideline and standards (After Tebbutt, 1998). The guideline values for the EC is for the abstraction of surface water for simple physical treatment and disinfections

Substance or property	Unit	WHO Guideline	EC Guideline	UK Standard
Aluminum	Mg/l	0.2	-	0.2
Antimony	"	0.005	-	0.01
Ammonium	"	1.5	0.05	0.5
Arsenic	"	0.01	0.05	0.05
Barium	"	0.7	-	1
Boron	"	0.3	1	2
Cadmium	"	0.003	0.001	0.005
Calcium	"	-	-	250
Chloride	"	250	200	400
Chromium	"	0.05	-	0.05
Color		15 TCU[χ]	10 TCU	20 mg/l[ε]
Conductivity	µS/cm	-	1000	1500
Copper	Mg/l	2	0.02	3
Cyanide	"	0.07	-	0.05
Fluoride	"	1.5*	0.7-1	1.5
Hydrogen sulfide	"	0.05	-	-
Iron	"	0.3	0.1	0.2
Lead	"	0.01	-	0.05
Magnesium	"	-	-	50
Manganese	"	0.1	0.05	0.05
Mercury	"	0.001	0.0005	0.001
Nitrate	"	50	25	50
Nitrite	"	3	-	0.1
PH	PH unit	6.5-8.5	6.5-8.5	55-9.5
Selenium	Mg/l	0.01	0.01	0.01
Sodium	"	200	-	150
Suphate	"	250	150	250

Temperature	^0C	-	22	25
TDS	Mg/l	1000	-	1500
Turbidity		5NTU$^\delta$	-	4 FTU$^\phi$
Total coliforms/100ml	No.	0	50	0
Zinc	Mg/l	3	0.5	5

Where,

χ - True color units

ε - Pt/Co unit

δ - Nephelometric turbidity unit

ϕ - Formazin turbidity unit