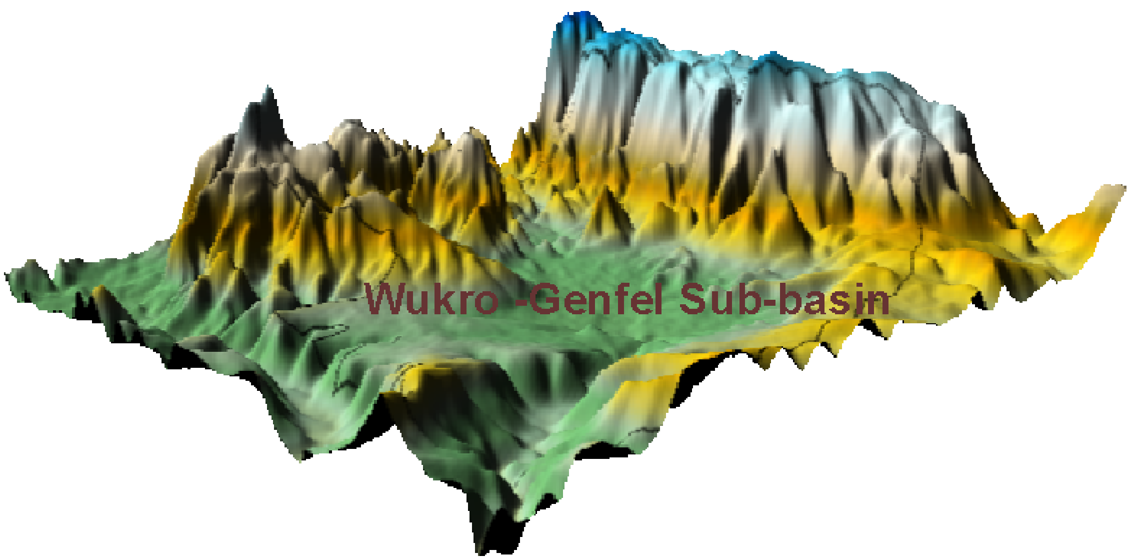
ADDIS ABEBA UNIVERSITY SCHOOL OF GRADUATE STUDIES DEPARTMENT OF EARTH SCIENCE

GROUNDWATER EVALUATION
OF
THE WUKRO-GENFEL SUB-BASIN
TIGRAY, NORTHERN ETHIOPIA



A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS IN HYDROGEOLOGY

BY

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Addis Ababa
Ethiopia

Acknowledgement

I would like to express my sincere gratitude to my advisor Dr. Tamiru Alemayehu for his critical comments on the over all thesis work. And also may thanks goes to Dr. Shimeles Fisiha for his humble approach and helping me in interpreting the vertical electrical sounding results.

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Abstract

The Wukro-genfel-sub-basin is found in Tigray Region at distance of 829 Km from Addis Ababa. Geographically, it is located in 13^0 55'' 00'N_13^0 42'' 50'N and 39^0 31'' 00'E _39^0 40'' 34' E. The climate is classified as temperate (weinadega) with an altitude of 1900-2700m m.a.s.l. and annual mean weighted rain fall and temperature of 584mm and 18.8 c^0 respectively. The annual Actual and potential evapotranspiration are also 546 mm and 1392mm respectively. The average annual recharge of the area is estimated 33.25 mm.

The area is dominated by Mekelle outlier sediments in the central and south and low grade metamorphic rock in the north and east which are highly affected by faults and lineaments. The characteristic aquifer of the area is fractured confined aquifer and multilayered semi-confined aquifers. The hydraulic conductivity are variable with in very short distances that indicates there is very weak hydraulic relation among the formations laterally. The hydraulic conductivity of the area is higher in the central and southern part that ranges from 3.14 m/d and 11.87m/d respectively.

The hydrochemical analysis showed that the dominant water type are both Mg-Ca- HCO_3 and Ca-Mg-HCO_3 that varies from site to site that indicates the formation is dominated by Ca and Mg-carbonate rich minerals or rocks /such as limestone and dolomite rich slates .But far to the southern part of the area where shale is dominating and also in Deep well in the limestone areas Ca-Mg-SO_4-Cl type water is observed. Therefore, the hydrochemical is controlled more by geological formation than groundwater flow interaction with rocks.

The water from wells in the limestone is very hard to bad class (2214 mg/l) TDS and also the salinity ranges from medium to very hazardous range for plant growth .

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DECLARATION

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

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July 2007

The thesis has been submitted for examination with my approval as university advisor.

Tamiru Alemayehu, Dr. ________________________________

CHAPTER 1

1 . Introduction

Ethiopia is a country with a huge amount of groundwater resource. But the problem of wise use of this resource has caused the country's socio economy to decline in the previous years. Therefore, it is very important to urge policy makers to plan accordingly so as to get out the people from famine.

In order to achieve food security in the country, understanding and studying available groundwater resource is helpful for water supply of big towns and rural areas. Moreover, irrigation activities will be improved and the dependency on only rain fed agriculture will be transformed. Therefore, the evaluation of groundwater is important at country level and even at specific localities. According to Vernier et al., 1987, mentioned in Vernier, 1993, Hydro geological research programs are especially useful in nations which are periodically affected by sever drought and famine, such as Ethiopia.

Studying the availability of groundwater also helps in identifying groundwater scarce areas, so that to take measure for future planning and management.

In general groundwater resource is a fundamental science that has to be given a due attention in evaluating, exploitation, management and recharge to be used efficiently for a longer time.

In this sprite, it is planned to work on evaluation of groundwater resource of wukro area in Tigray regional state of Ethiopia, thesis for the fulfillment of the master's degree in hydrogeology in Addis Ababa University.

1.1 Location and Accessibility

The study area, Wukro-Genfel sub-basin, is found in Tigray Regional state at a geographically location of 13^0 55'' 00'N_13^0 42'' 50'N and 39^0 31'' 00'E _39^0 40'' 34' E having a perimeter of 78.8 km and an enclosed area of 230.44 sq km. The project area is 829 km far from Addis Ababa to the north. (See figure 1-1)

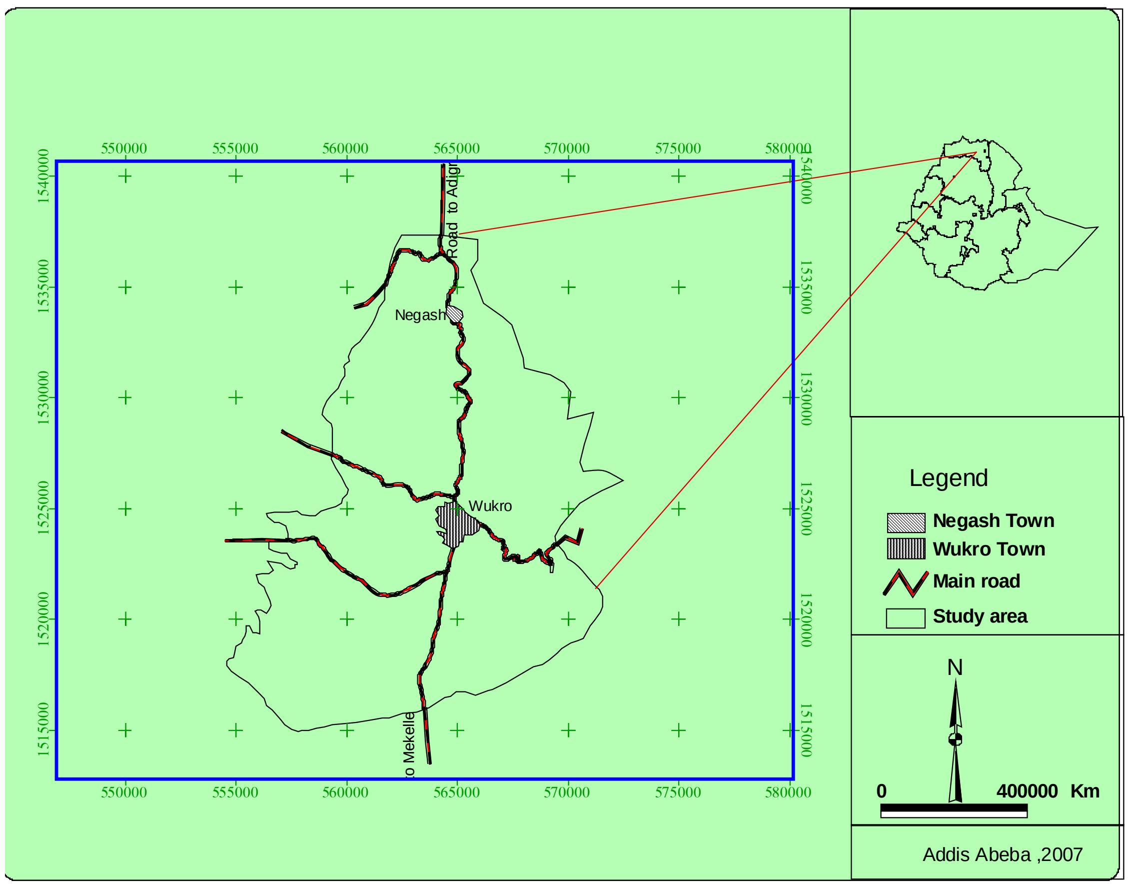

Figure 1-1 Location Map of the Study Area

The project area is accessed through asphalt road 46 km North of Mekelle. There are also all weathered road and trails that takes to the near by villages of the study area.

1.2 Climate

The climatic condition of the area is generally classified as Temperate (wayna dega) with an altitude that ranges 1900_2700m from m.a.s.l, and a mean annual temperature that varies from 11.28_26.49 °C .There is an erratic three month rainy season (June August) with an annual rain fall that varies from 238.7-868.7 mm. 67% of the total annual rain fail is contributed from these months while the remaining rainfall is from April, May, June and September,

The annual actual evapotranspiration rate of the study area is 546 mm/annum and potential evapotranspiration of 1392 mm/annum.

1.3 Geomorphology and Land use

Geomorphologically, the area is surrounded by chained escarpment in the east and the trough of Negash syncline in the north and by low lying limestone ridges in the west. The plane to gentle sloping part of the area is covered by crops and grasses .The chained escarpment ridges are covered with Shrubs and bushes, there are also bare land and exposed rocks in the area. The river and streams of the area are of dendritic and leafy in pattern .The dendritic and leafy streams come together to form the big river called genfel which passes through the center of the town wukro that finally join to other tributaries reach to the Giba basin. One of the tributary of Tekeze River. (See figure 1-2)

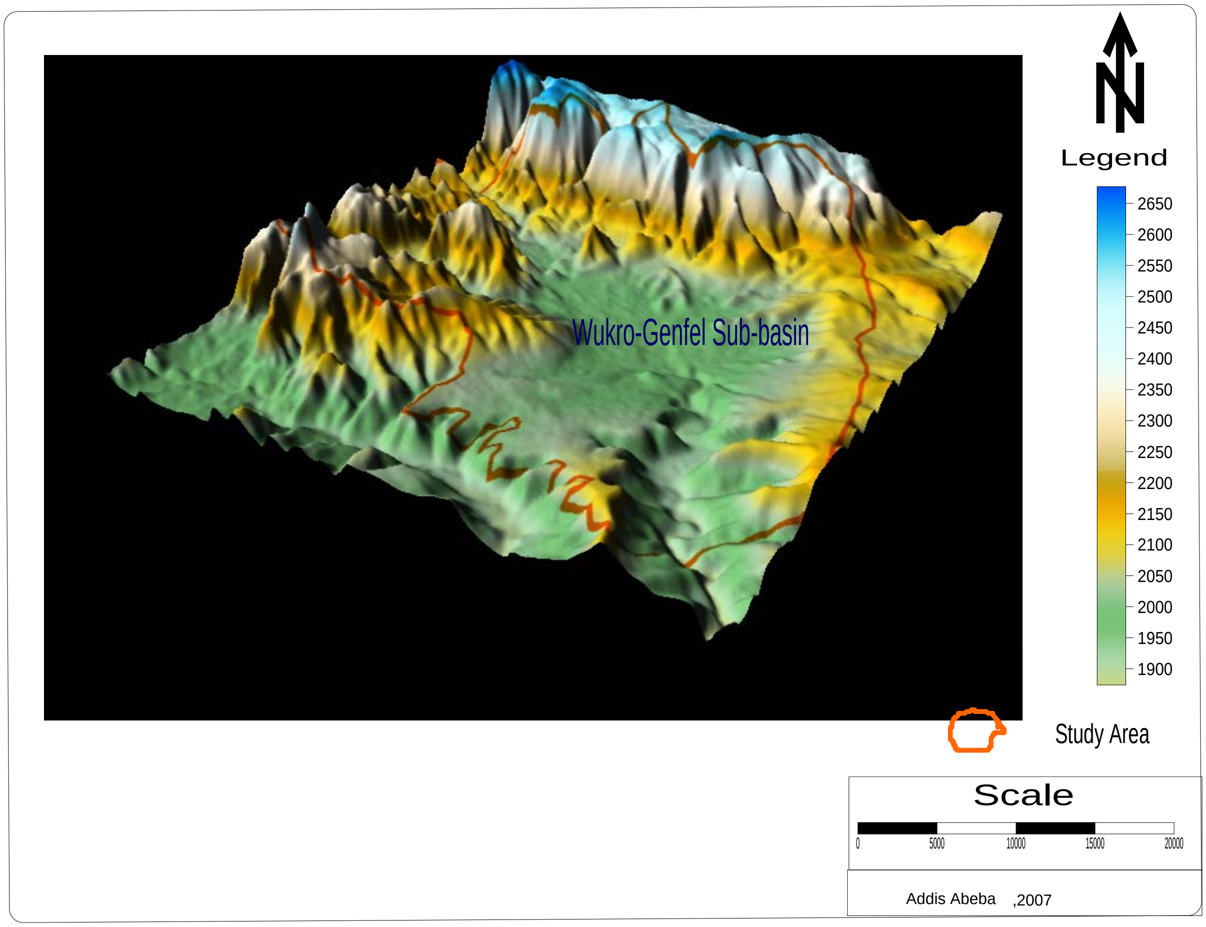

Figure 1-2 Digital Elevation model of the area

The major land use of the wukro is cultivated land, homesteads, bare land and rocky areas, very limited irrigated land are found in areas. The soil type of the area is clay loam, sandy silt and clay of which the clay loam comprises by far the largest proportion of all the soils. Where there are near by Semi_perinal rivers and earth dams. Regenerated indigenous shrubs, bushes and some other types of trees, cover most of the mountains areas. Crops such as wheat, barely, lentil, sorghum, maize, finger millet, beans, and chickpeas cover the arable land. (See Figure 1-3)

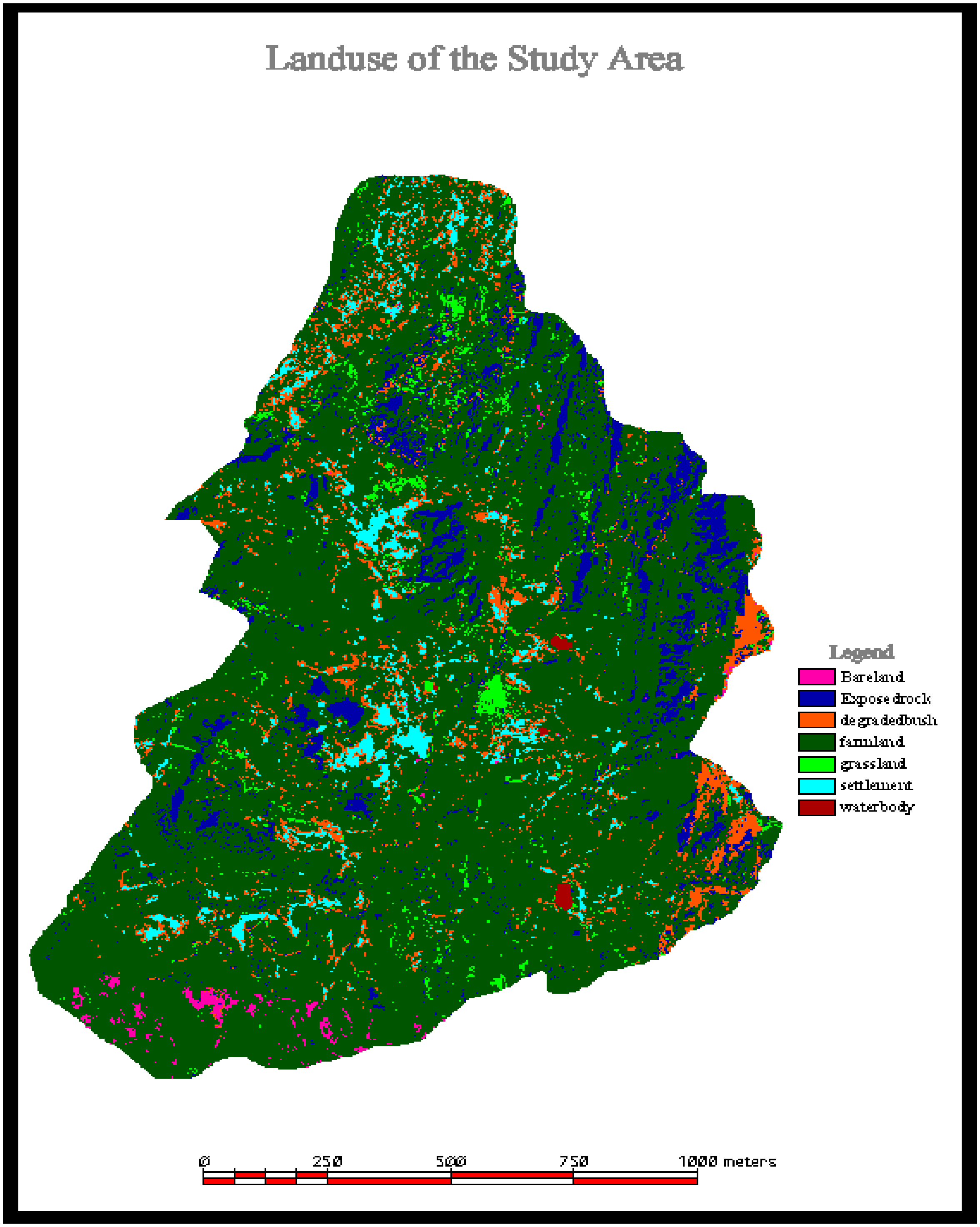

Figure 1-3 Land Cover Map of the study Area

The population of Wukro is 133,578(2006) among which 24% are living in town while the remaining 76% are living in rural areas. The population is growing from time to time and the demand for the quantity of potable water is growing equally. So the need for evaluating the available groundwater resource is crucial and important to give possible solution for the future development and management.

1.4 Previous Work

The previous study of the area is carried out on geology. Garland(1980) on the Geology of Adigrat Area , Levittee(1970) on the Geology of the Mekelle on the central part of the sheet ND 37-11 and Bosellini et al (1997) on Mesozoic Succession of the Mekelle Outlier.

Hydrogeological studies in the area are conducted by Beyth and E.Shachnai (1970) on the hydrogeology of the Mekelle area; Ethiopian Institute of Geological Survey (1978) on Hydrogeology of Mekelle with 1:250,000 scale Hydrogeological map. Studies specific to the study area are carried out, in by Ezana mining Development Plc (1999) on Hydrogeology and Water Resources Development of Agulae and Genfel catchments .The study comprises four woreda including the present study area at a scale of 1:100,000 mostly focusing on the rural water demand and supply conditions. In 1992-1993 the Water Well Drilling Enterprise the then Water well Drilling Agency has conducted a survey for town water supply in the upper part of the study area. Moreover, very small surveys for rural water supply are being done by different NGOs.

1.5 Objective of the Study

The main objective of the study is to quantify the groundwater potential of the Wukro-Genfel sub-basin.

Specific Objectives

The following specific objectives will be achieved at this work.

- Mapping of the geology of the area
- Determine Water balance of the area based on the Hydrometerological data.
- Quantifying the major hydrological components.
- Characterizing the aquifers and establish hydrogeological map
- Determine the recharge and discharge conditions in relation to tectonic structures.
- Determine the hydrochemical evolution during groundwater flow (rock and groundwater interactions of the study area).
- Evaluate the water quality of the area.

1.6 Methodology

The methodology carried out during the over all work of this thesis comprises material collection, office work and field work.

- **Desk Work**

  Office work comprises the collection of published and unpublished documents and literature review and preparation of the necessary materials which help for the achievement of the objectives of thesis work such as top map, aerial photos, Gps, Compass and plastic bottle for water sample collection)

- **Field Work**

The aim of the field work is to prepare a geological map, and measure in situ electrical conductivity, temperature of the water source and collect water sample and other valuable information at field level from woreda bureau In addition to this, to locate the position of the water points with geographic coordinates. Moreover, conduct vertical electrical Sounding in selected areas and observation of land use and land cover of the area

- **Materials and Data input used**

- ✓ Topographic map with scale of 1:50,000 of Wukro, Aguale,1997
- ✓ Aerial photo with scale of 1:50,000 , five strips comprising of each 5 , 1994
- ✓ Geological map and Hydrogeological map of Mekelle at a scale of 1:250,000
- ✓ Hydrometerological data
- ✓ Chemicals from the analysis water
- ✓ Pump test and borehole logs of the study area
- ✓ compass , GPS and geological hammer
- ✓ Electrical meter ,PH meter , thermometer and plastic bottle for water sampling

- **Compilation and Analysis**

After collecting the necessary data input for the thesis work, compilation of the data is carried out so as to make ease for analysis. The following analysis is undertaken during this thesis work.

- ✓ Characterization of the lithologic units with hydrogeology of the study area
- ✓ Characterization of Hydrometerological components for potential evapotranspiration calculation and groundwater recharge calculation.
- ✓ The application of different software such as Waterloo hydrogeologic inc software Aquachem4.0, Aquifer test for windows 2.01, Surfer, Arc view and Rezix –IP, for the analysis of vertical electrical sounding and Global mapper 7.

CHAPTER 2

2 Geology

2.1 Regional Geology

The first geological report of interest on Ethiopia was written by Ruppel (1834) .But Blanford (1870) was the first to establish a well –known division of basement, Adigrat sandstone, Antalo Limestone, upper sandstone and Trap series. Then after a lot of works has been done by Merla and Minucci (1938) focusing on geology of Tigray .Levitte, (1970), the work of these two scholars is taken as a standard reference for Tigray region geology, Garland (1980). Till now a lot of researches are working on geology of Ethiopia in general and specifically in areas of geologically important and interesting areas for academic and exploration of oil and minerals purpose.

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2.1.1 Precambrian Basement complex

The Precambrian basement exposures are found in areas not intensively affected by Cenozoic volcanism and rifting and where the phanerozoic cover rocks have been eroded away. (Mengesha Tefera etal., 1996).

The volcano-sedimentary succession typically ranges from green schist to lower amphibolites facies .The most conspicuous foliation trend is north-south with deviations to northeast and northwest. These trends are characteristics of both the low grade volcano-sedimentary succession and the high grade rocks. (Mengesha et al,1996)

The Precambrian contains a wide variety of sedimentary, volcanic and intrusive rocks which have been metamorphosed to varying degrees. The intrusive marked the end of tectonic activity in late Proterozoic to Early Paleozoic and are widely known as post or late tectonic intrusions. Following the Proterozoic to early Paleozoic tectonic and magmatic activity, peneplanation of the basement took place until carboniferous and Permian (Kazmin 1972)

The upper proterozoic contains a very thick succession of north-south trending volcano-sedimentary successions of Pan- African age enclosed by high grade genisses(Kazmin,1972 &1978;Kazmin et al .,1987;Davidson,1983;Mengesha 1990;Teklewold and Moore,1989;Kozyrev et al.,1985;Garland,1980 cited in Mengesha etal.,1996)).The upper proterozoic rocks are well developed in northern Ethiopia where they form a very thick succession of geosynclinals formations, that is rocks which originally accumulated in subsiding marine basin. They have a characteristic structural style. They are less mobile than the more strongly metamorphosed basement rocks and have been folded and sometimes refolded in more regular manner. Folding is locally of isoclinals intensive and recumbent folding, sometimes accompanied by thrust faulting, is evident in certain zones. (Kazmin,1975) .The Precambrian basement units from the oldest to the youngest; Tsaliet Group,Tembien Group, Didkama Formation,Matheos Formation (Levitte,1970; Garland,1980)and Shirato Formation(Kazmin,1975,).

2.1.1.1 Tsaliet Group

The greater part of the basement is formed by a heterogeneous series of rocks with obvious volcanic associations. They are breccias ,agglomerates, bedded tuffs and lavas, all interbedded with marine clastics, rare limestones, tuffaceous slates,redeposited ash, and greywacke composed partly of volcanic fragments. .The maximum thickness is about 2000m.(Kazmin,1975). The rocks have been faulted and tightly folded to build anticlinoriums and anticlines but subjected to only low grade metamorphism. The dips are N40-55W; ranging 30-55 .The formation comprises acid metavolcanics, semi-green schist, shales and black quartzite. Only few exposures of acidic metavolcanics and some basic metavolcanics appear in the eastern part of Tigray (Levitte, 1975)

2.1.1.2 Tembien Group

The youngest Precambrian units that underline northern Ethiopia are dominantly clastics with subordinate carbonates. The tembien group consists of thousands of meters thick mainly slate and limestone with interbedded phylites (Beyth, 1971).The upper unit of the Tembien group, consists of about 800 meters thick of black,massive,fine grained limestone, partly algal and oolitic commonly weathering into karstic topography and has thin interbeds of dolomite and thinly bedded limestone.

2.1.1.3 Didkama Formation

This formation is typically developed in Tigray region. It overlies conformably the Tembien group in central and eastern Tigray.However in the west, where the Tambien group is not fully developed; it rests uncomfortably on older formations. The Didkama formation consists of creamish to white dolomite alternating with grey, black or variegated slates. (Garland, 1980).The formation consists of yellowish, medium grained dolomite interbedded with grey, black or coloured slate. It is 300 meters thick at its westernmost outcrop and over 1,500 meters thick at its central part around GundaGundi (Garland,1980) the most eastern part of Tigray region .In the Sheraro area , at Negash syncline, it is unconformable overlapped by Matheos Formation, of youngest limestone(Kazmin 1975;Garland,1980) .

2.1.1.4 Matheos Formation

This formation is known only in the Negash syncline (Garland,1980)and the limestone with algal fragments and stromatolites, solomitic limestone and dolomite which make up the formation form small outcrops in the shiraro area of Tigray (Kazmine,1975) is thought to be the youngest Precambrian formation in Ethiopia(Kazmine,1975,Garland,1980;).The Matheos Formation overlies the older rocks uncomfortably and in places rests directly on the Tsaliet metavolcanics.It is less than 30 meters in maximum thickness, folded into a gentle syncline(Kazmin,1975).

2.1.2 Basement Intrusive

The most prominent basement intrusive of the Mekelle sheet (ND 37-11) is granite stocks, batholiths and other acidic dykes mostly of aplitic characters. The granite rocks are porphyritic with large crystals of microcline and orthoclase in addition to quartize and albite. (Levitte, 1970).

There are numerous in the north, becoming abundant in the folded upper proterozoic rocks of Tigray,the granite vary in composition and texture, and have been dated as from 690-450 million years, older diorite and granodiorite is locally associated with the granite.(Kazmin.1975)

2.1.3 Sills, Dykes and Plugs (other intrusion)

Both isolated and swarms of narrow dykes and sills of basalt dolerites, trachyte, diabase and granite are common. In the northern part of the country cluster of dolerite dykes and sills occur within the Mesozoic sediments (Arkin et al 1971) were named as Mekelle dolerites and are black andesite dolerite with ophitic texture. They usually occur as sills and dykes intruding the adigrat Formation, Antalo Formation, and Agulae Formation in the Mekelle outlier and as small stocks intruding crystalline basement and Sedimentary rocks in the escarpment (Mengesha et al, 1996).

2.1.4 Palaeozoic rocks

Two rock units assigned tentatively to the Paleozoic in the Mekelle area in the North of Ethiopia are the Enticho sandstone and the Edaga Arbi shales, silts and tilites. A glacial origin has been proposed for the latter. The Adigrat sandstone closely resembles these underlying formations, which it covers without the development of a significant unconformity. (Kazmin, 1975).

2.1.4.1 Enticho Sandstone

The Enticho sandstone is widespread, and takes its name from the town of Enticho on the Axum –Adigrat road. (Garland,1980).The Enticho sandstone is about 160m thick and composed of white, calcareous coarse grained ,cross bedded sandstone containing lenses of siltstone, grit and polymict conglomerate with subrounded to well rounded pebbles, cobbles and boulders, scattered erratically ,mainly granite and gneiss are common in places.(Mengesha et al ,1996). The position of the beds and completeness of the sequence vary from place to place, and some units are seen to interfinger, thus being not stratigraphic horizons but facies of the same age. It is seen resting on the basement in many places is a white medium grained quartize with very angular grains, in a few places cemented by kaolin. (Garland, 1980 and there cited in)

2.1.4.2 Edaga Arbi Glacials

The Edaga Arbi glacial takes their name from the town where their type section was described. The glacial unit, shows features of a glacial-fluvial deposit, angular, poorly sorted grains of quartz(indicating immaturity) and lenses of conglomerate which mark channels made by braided steams .The bedded calcareous silt, is a transitional facies between the glacio-fluvial sandstone and the tillite.The thickness of the Edaga Arbi glacial is in the range of 150-180 meters(Mengesha et al ,1996)

2.1.5 Mesozoic Sediments

2.1.5.1 Adigrat Sandstone

This is name given by Blandford (1870) to the basal clastics in Tigray.It has a maximum thickness of 700 meters. It is gray or red, fine-grained, well sorted and very mature (practically quartize arenite), cross bedding is quite common and bioturbation of the silt-shale occurs frequently in the upper part of the section, where several red, ferruginous laterite beds occur. (Bosellini et al, 1997). It rests uncomfortably on the Edaga Arbi glacial ,on the Enticho sandstone and basement (Kazmin,1975; Garland,1980).The adigrat sandstone is sub-horizontal with the dip usually only 2^0-3^0 but higher in places where it has been tilted with block faulting of the rift escarpment, dips reaching up to 30^0.(Levitte ,1970).

2.1.5.2 Antalo Limestone

The Antalo Formation was first named by Blandford (1870) at the type locality as Antalo Limestone in Tigray region. The Antalo Formation is a 750m thick sequence consists predominantly of fossiliferous yellow limestone containing thin beds of marl and calcareous shale, and occasionally arenaceous bands near the top. (Mengesha et al, 1996).The marginal parts of the Mekelle outlier consists of sandy oolitic facies, suggesting a near shore environment, while in the escarpment black limestone and shale indicate deeper water conditions.

The beds are almost horizontal with very small easterly dips. Normally the angle is 2^0-5^0 but in certain cases it dips 7^0-10^0. The inclination is due to tilting of large blocks hinged on very long northwesterly trending faults (Levitte, 1970).

2.1.5.3 Agulae shale

In Tigray region, in the Mekelle outlier and around the escarpment a gray, green and black shale, marl and claystone interlaminated with finely crystalline black limestone containing disseminated pyrite with some gastropods, previously named as agulae shale after agulae village, overlies the Antalo formation. (Arkin et al., 1971; Kazmin, 1975) cited in Mengesha et al., 1996.

The sequence which is 60 to 250 meters thick contains some thin beds of gypsum and dolomite and a few beds of yellow coquina. The agulae formation is of late Jurassic(Kimmeridgian)age, and is of probable lagoonal origin representing a regression phase of the Jurassic sea.(Mengesha et al., 1996).In Agula,Dessa,Wukro ,the agulae group is largely represented by shale and marly limestone.(Bosellini et al., 1997)

2.1.5.4 Amba Aradom Formation

The upper Jurassic sedimentary succession of Tigray is abruptly overlain in angular unconformity by siliciclastic sediments, the so called “upper Sandstone” or Amba Aradom Formation (Shumguro, 1968) cited in Bosellini et al., 1997.

In Tigray, the Amba Aradom Formation, 100-200 meters thick and overlain by trap basalts, mainly consists fluviatile sandstone and shale, purple, violet or yellow, with numerous laterite soils rich in vadose pisoids. The laterite at the base of the formation is quite thick. (Bosellini et al., 1997)The rock is hard and contains many pebbles of quartz up to 4cm diameter.

2.1.6 Tertiary Volcanic

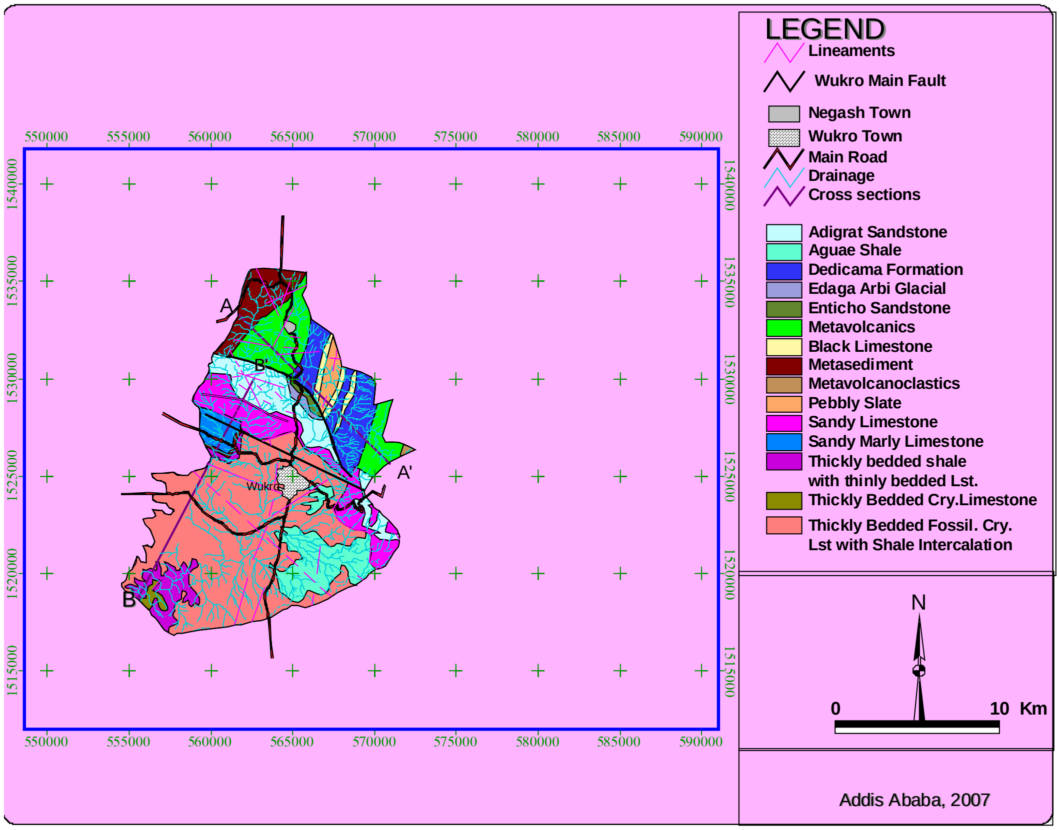
The dark station basaltic flows that lie on the satirized surface of the Mesozoic sediments were named the trapping series by Blanford (1869). And Kazmin 1975 has described the trap series as the earliest and most extensive group of volcanic rocks, erupted from fissures during the early and middle Tertiary. Blandford (1869) divided into two groups which have separated by angular unconformity, and different litho logical characterstics.The lower group, the ashangi was composed almost entirely of basalts while the upper Magdala group contains many silicic intercalations. Later studies by Italian geologist the rocks above the ashangi group were sub divided into the Aiba Basalt, Alaje basalt and rhyolites and Termaber basalt. (Garland, 1980).The total thickness is from 200-1200 meters. (Kazmin, 1970).

2.2 Local Geology

The study area consists of different types of rocks of sedimentary and metamorphic origin .The sedimentary rocks that are classified as Mekelle outlier are found in this area. Metamorphic rocks of the low grade also cover the northern part of the area.

Table 2-1 the area coverage of each rock types are presented below

Formations	Type	Area Coverage by percent (%)
Antalo Limestone	Sedimentary	58
Adigrat SST		8
Agulea shale		8
Enticho sandstone		0.40
Edaga Arbi glacial		0.50
Metasediment	Metamorphic	5
Matheos Formation		2
Pebbly slate		2
Metavolcanoclastics		0.10
Massive metavolcanic rocks		9
Dedicama Formation		7



Source: Ezana Mining Development Plc (1999) and modified

Figure 2-1 Geological Map of the study area

2.2.1 Basement

The basement rock are distributed around Negash syncline .The majority of the rocks being in the area around 4 km south, 3 km north ,2 km East and 3 km West of the town of Negash and also North east of Wukro town. (See Figure2-2)

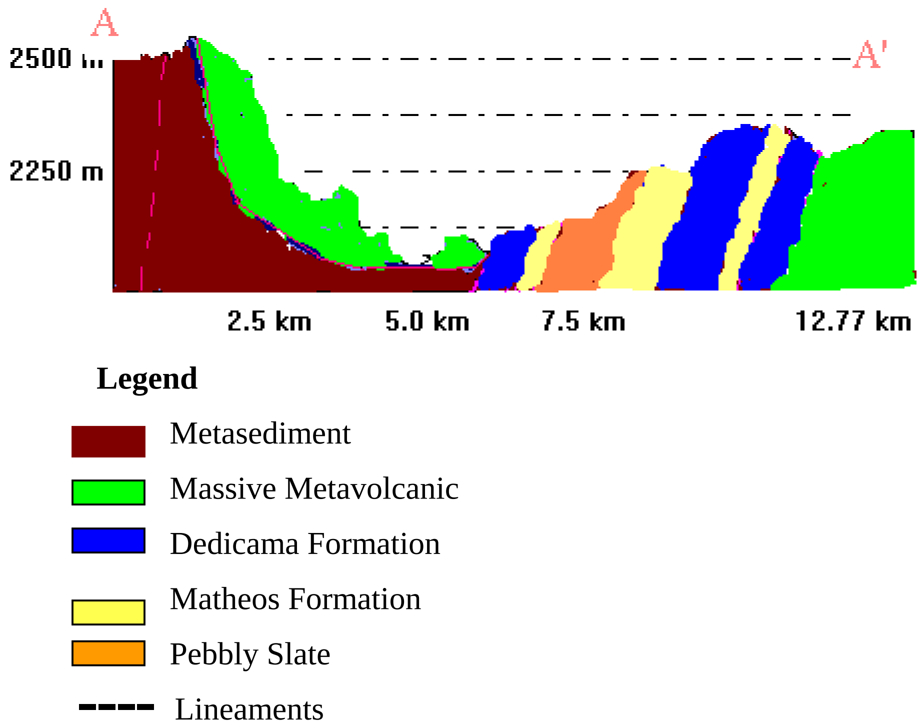


Figure 2-2 Geological Map Cross Section AA’

2.2.1.1 Metavolcanics

The metavolcanic of the study area is found around the Negash town bounding the Negash syncline on the western and eastern side. The color of the rocks varies from gray to yellow depending on the degree of weathering. The rock is highly foliated and jointed striking N20W and N50W respectively. The joints dip 50W while the foliation dips in sub-vertical.

There are metavolcanics having clasts of deformed pebble to coble size phenocrysts of different colours with light green dominant color. The ground mass is greenish in colour of probably basalt protelite and also an alteration due to epidotazation processes. The unit is strongly affected by three sets of fracturing N 20 E, N 100 E and N 30 W.

These types of rocks are observed west of the highly foliated metavolcanics (slate) specifically around the Negash town.

At the west side of the metavolcanoclasts dark green to greenish in color jointed metavolcanic having less or almost non- foliated and moderately weathered rocks are exposed. But the fracturing is highly interconnected. As it is seen from the excavation of shallow dug wells in the area, the vertical extent of jointing goes to depths of 12 meters and may be far deep.(See Figure 2-2).

2.2.1.2 Metasediment

a) Phylite and schist

This type of rocks is found in the NNW part of the study area. Small grains in very fine groundmass gray to yellow in color phylite that has less developed foliation are the rocks that cover this part of the area. At some distance intervals basaltic dykes intruding this formation at a strike of N 70 W is common. The thickness of the dikes varies from 1-5m parallel to the foliation of the phylite.

In the most North part of the area, light gray in color schist rocks that have a well developed schistose plane dipping 20 W, intersected by two sets of joints N 10 E and N 30 W are observed.

b) Pebbly Slate

These are metasediments which are located in the center of the Negash syncline bounded by black limestone and the Wukro fault belt on the south. The dominant rock type of this group is the pebbly slates. The pebbly slate that contains pebbles of light dark in color is changed to black powder leaving the original shape on the surface of the fine groundmass of the foliated slate. Quartz veins are observed to intrude slates in

Northwest of the study area. The slates are highly foliated trending in a strike of N-S and sub vertical dip. It is also cut by an E-W crossing main fault that crosses the whole syncline.

2.2.1.3 Metamorphosed Black Limestone

The Weakly metamorphosed limestone is found bounding the pebbly slate in the East and West sides of the syncline. It forms “n” shape when it is seen on top view from south. Similar to the pebbly slate it is bounded by the wukro fault belt (Figure 2-3) in the south .There are weathering results of limestone (travertine) in areas where there are wider lineaments through which water flows. Moreover, there are thickly foliated and crossed with widely spacing fracturing and karts caves solution holes developed along the joints in the Northeast of the study area. The eastern part is highly foliated near to slate with some calcite veins 20-30 cm in spaces. This formation forms ridges of 20 to 30 meters thick with an average bedding thickness that ranges from 10-20cm.

The measurement of fractures in the metamorphosed black limestone indicates the beds striking N 10 E and dip 60W.

2.2.1.4 Metamorphosed dolomite dominated Slates.

The metadolomite slates are observed in the most east boundary of the black limestone and about 3.5 km South of Negash town. In these areas dolomite dominated slate with calcite /quartz vein lets and stringers are typical characteristic of the rock. The foliation of the slate is not well developed but it comprises of highly interconnected fractures. The dolomite is 10-30cm thick and is affected by an E-W trending joints while the strike of the slate is N 40 E and dipping sub vertically toward west.

2.2.2 Palaeozoic Sediments

The Edaga Arbi glacial and Entichosanstone are the two rocks that included in these sediments. These two Paleozoic sediments area found south of the wukro fault belt that is 2-3km north of the town Wukro along the Wukro- Negash road.

2.2.2.1 Enticho Sandstone

Enticho Sandstone is exposed south of the wukro fault, East and West of the road 3-4km Wukro to Negash towns.

The Enticho sandstone is white calcareous medium to coarse grained moderately compacted, the grains are well sorted and strongly cemented with light in color most probably calcite minerals. There are conglomerate beds that range from 2-3cm observed in the central part of the formation that strike N-S dipping toward south. In some part of the area thinly bedded sandstones are also observed (see Figure 2-4). The joints are filled with reddish materials, which could be laterite.The Enticho sandstone that interfinger with the glacial forms low laying hills and gently sloping land forms.

The Sedimentary structures, cross beds are observed on the top part of the Enticho sandstone.

The Entichosanstone rests uncomfortably on the basement rocks. On the northern part it is separated by a fault that brought in contact with metamorphosed black limestone. Two sets of fracture system are observed on this unit .The first set strikes N 70 W and the second set strikes N 15 E.

Figure 2-4 thinly bedded and jointed Enticho sandstone

2.2.2.2 Edaga Arbi Glacial

The Edaga Arbi Glacial is found in the northern Wukro town interfinger or underlying the Enticho sandstone .The Edaga Arbi glacial is concentrated on the road side to the west and East 2-3km north of Wukro.But the majority of the formation is exposed in northern part of the plain called Metseko plain. It consists of dark, gray, reddish in color friable shale and tilites or striated sub rounded, well rounded pebbles, cobles and boulders of granite are observed. The Edaga Arbi Glacial is conformably underlain the Adigrat sandstone. It forms gently sloping landforms in the study area.

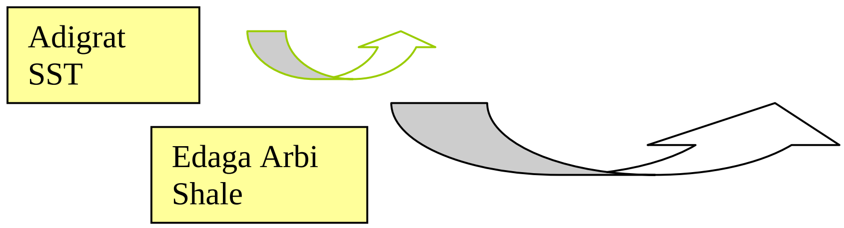


Figure 2-5 Edaga Arbi glacial (red shale) overlain by Adigrat sandstone 4km north of Wukro Town.

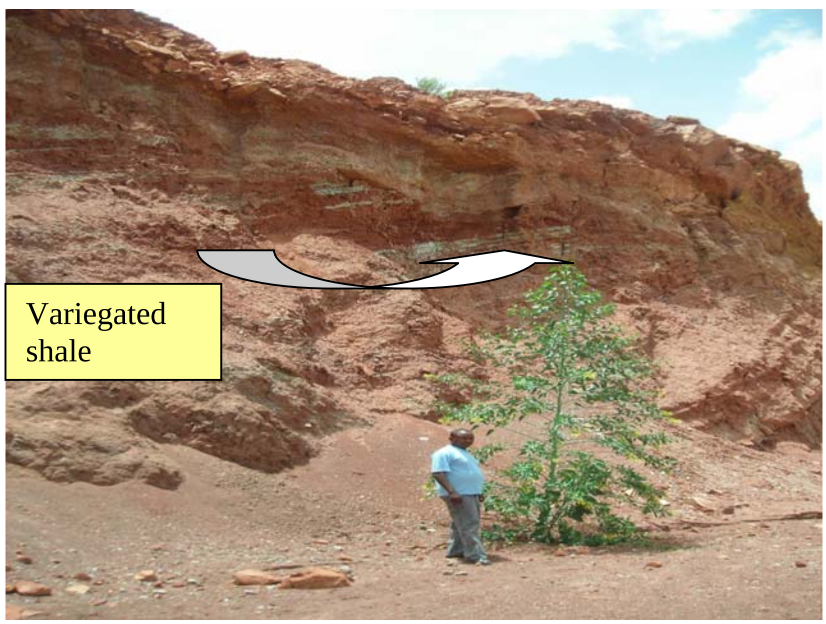


Figure 2-6 Variegated shale 4 km north of Wukro town

2.2.3 Mesozoic Sediments

Most of the Mesozoic sediments are outcropped in the Central, Eastern and Southern part of the study area.

2.2.3.1 Adigrat Sandstone

The Adigrat sandstone is exposed in the area that surrounded the metseko plain and in the high lands west of the road of Wukro- Atsbi at about 3-4 km distance.

The Adigrat sandstone is generally pink to reddish and yellowish interbeds with some dark weathered surfaces. The grain of the sandstone is fine to medium cemented with ferruginous minerals that give reddish color to the sandstone. In area where the fault that brought limestone in contact to the adigrat sandstone ,there are solution effects observed on the surface of the sandstone that could be the effect of calcareous cementing material dissolution(see Figure 2-7 below).

It is cliff forming, moderately weathered and jointed with strikes of N 60W and dip 20 to ward west. Some of the joints have spacing of 5-10 cm. There are also 20-50cm thick lateritic beds, the grain is well sorted. Moreover, there are thickly bedded sandstone with clear separation plane among the beds is also observed on the road side around wukro town (see Figure 2-8 below)

The sedimentary structure, cross bedding, which is typical characteristic of Adigrat sand stone, is observed on the beds

Figure 2-7 Adigrat Sandstone with solution holes and Fault plane that brought in contact the Antalo limestone and Adigrat sandstone

Figure 2-8 thickly bedded Adigrat Sandstone with planes of separation among them

2.2.3.2 Antalo Limestone

Antalo limestone is also outcropped in the Western and southern part of the study area. The south western part of the study area is covered with thinly bedded light yellow in colour limestone intercalated with yellow marl; below some depth fissile gray marl are also observed down a small creek.

While SSW part of the area is covered by thinly bedded and thickly bedded limestone with thickness of 2-5cm and 50-60cm respectively. While the steam cut are intercalations of thinly bedded limestone with thinly layered gray marl. Travertine development is also observed at the middle of the stream. In this limestone three sets of joints striking N-S, N 70 E and N 10 E with a dip of 15 W, 5 W and 55W respectively are measured. In the tabia (Kebele) called aynalem there are exposures of thinly bedded limestone which has joints trending in NW-SE and SW-NE. (See Figure 2-9).

2.2.3.3 Agulae Shale

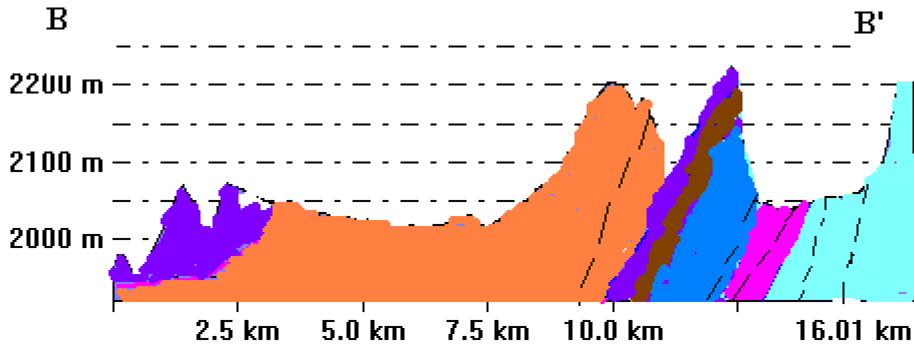
This unit is outcropped in a road that links Wukro –Agula towns at a distance of about 4-8 Km south of Wukro, on the east and west side of the road. The color of Agulae shale is whitish grey, yellowish, and green and black that varies from place to place. Moreover, variegated colors are also observed in some places. They are fissile with very thinly bedded limestone intercalated with thickness of 2-5cm. Most of the time, they form a gently sloping and flat plain.

2.2.4 Mekelle Dolerite

This unit is exposed in the genfel river beds and in some places intruding the thickly bedded limestone south west of the tannery at a distance of about 2 km. It is fine to medium grained dark in colour hypabasalts which have affected by spheriodal weathering.

2.2.5 Quaternary Alluvial and Colluvial deposits

Quaternary deposits are exposed in the area called Aynalem where the Wukro Tannery is located. And also it is exposed northeast of the tannery nearby to the Genfel river areas. In addition to this, there is a thick deposit of alluvials in the plain called Metseko, North of wukro at a distance of 2-3Km.



Legend

Agulae Shale

Antalo Limestone

Metasediment

Marl Limestone

Sandy Limestone

Adigrat Sandstone

Lineaments

Figure 2-9 Geological Cross Section BB'

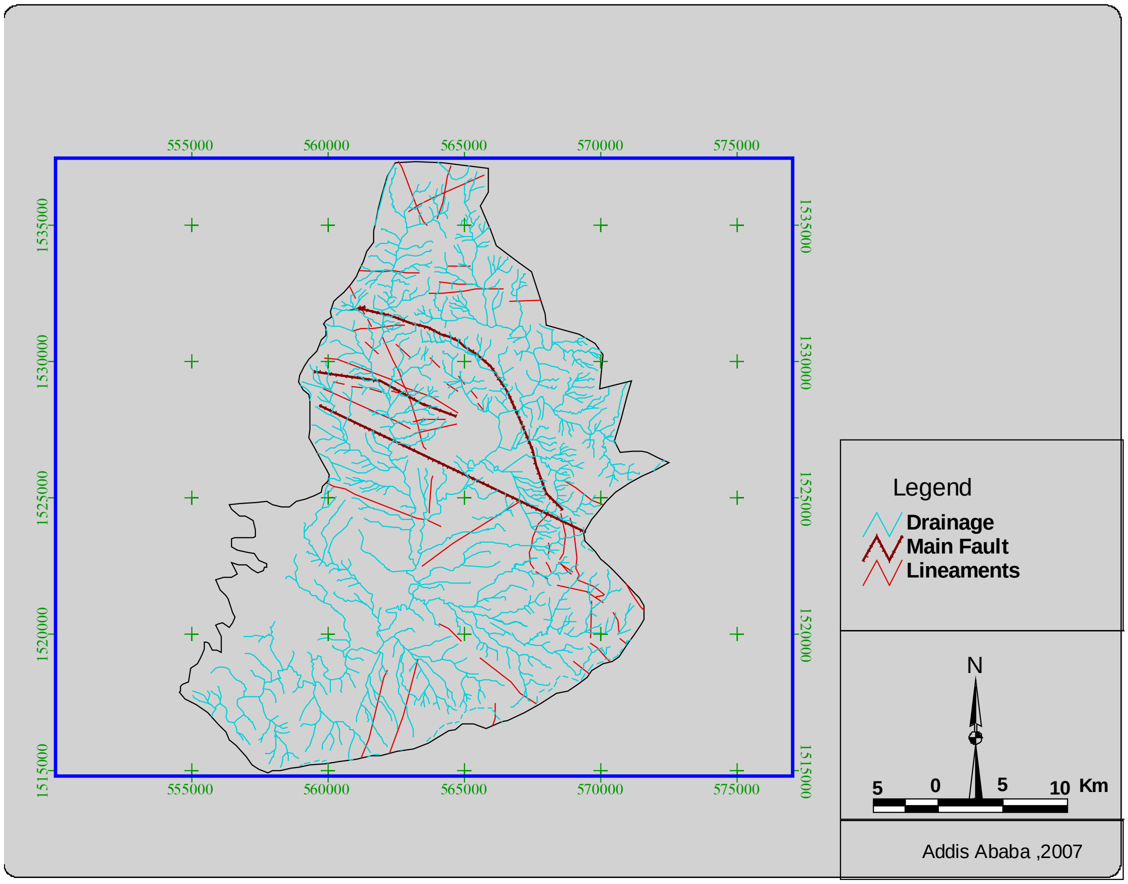


Figure 2-10 Structural and Drainage Map of the study area

CHAPTER 3

3 Hydrometeorology

Hydrometerological data plays a great role in the analysis of groundwater resources evaluation of an area for a given period of time. Thus the collection of available Hydrometerological data and careful computation of each component will be required in order to obtain a more reasonable result.

Although the National Meteorological Service Agency(NMSA) has the duty to provide data which are more accurate with no or very small missing data ,the rain fall data collected from the agency has many missing data for rainfall, especially for wukro and Hawzien .Therefore, Rainfall are compiled from Mekelle Water supply project report (Tahal consultant group 2005). The data from Tahal consulting group is for about 40 years by correlation method .Thus using this data analysis of recharge and runoff and other parameters that are crucial for groundwater resources are evaluated.

The meteorological stations used for this study are : Class A for Senkata and Atsbi ;and three ordinary type for Hawzien , Wukro and Agulae.The station for Agulae is not functional at present ,but the rainfall data collected from 1975-1980 are correlated using regression method and also the station for Atsbi is newly opened last year ,Hence the data of one year is considered.

River discharge of Genfel River is obtained from Ministry of Water Resource (Federal Bureau) for the durations of 1991-2006.

Table 3-1Metrological Station Distribution In the area

STATION	Easting(UTM)	Northing(UTM)
Wukro	564710	1524508
Senkata	560396	1553251
Hawzien	546376	1545513
Agulae	563630	1513645
Atsbi	580091	1534940

3.1 Precipitation

As the there is elevation difference in the study area, the spatial distribution of rainfall is variable in different parts of the area. Thus, the computation of areal depth precipitation is inevitable to obtain a more reasonable result that could represent the whole study area.

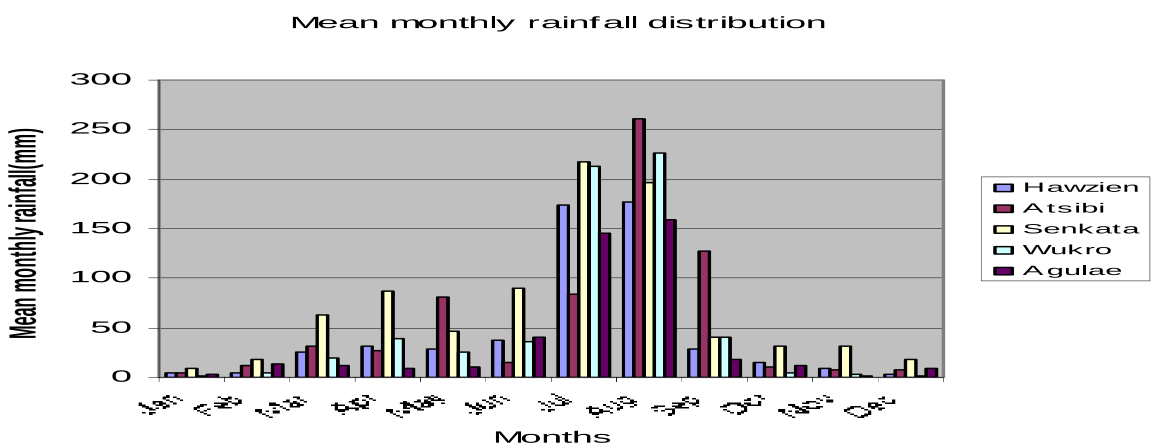


Figure 3-1 Mean monthly rainfall

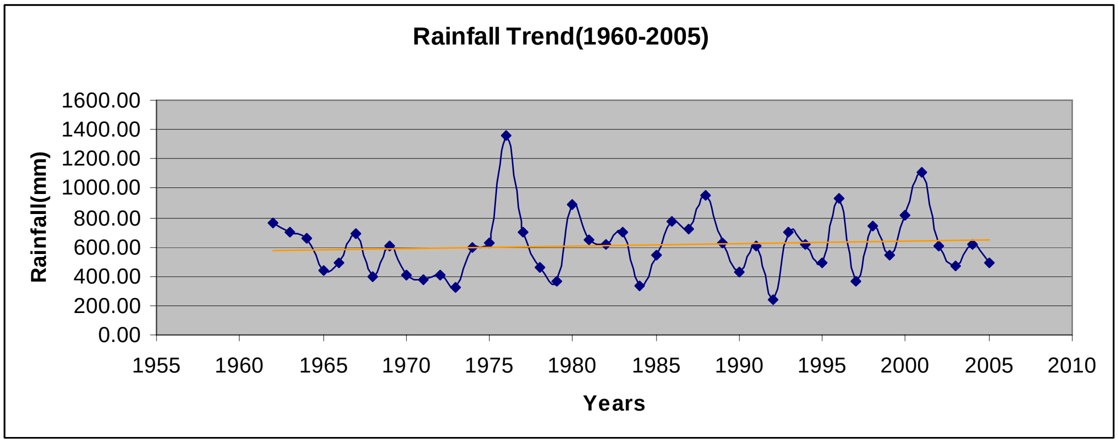


Figure 3-2 Trend of Rainfall

The rainfall trend observed from the figure indicates that there is very small increasing trend especially, from the year 1981 on ward.

The meteorological stations available are five and are unevenly distributed in areas which have elevation differences, therefore, the Arithmetic mean method is not good enough to give reasonable result as Thesien Method and Isohytal methods. But for the seak of comparison the arithmetic method will be analyzed.

3.1.1 Thesien Polygon Method

Thesien Polygon Method gives good result when the rain gauges are not evenly distributed over the area, in flat and hilly terrains. Thus Thesien polygon method defines areas represented by each gauge in order to weigh the effects of non-uniform rainfall distribution.

The only disadvantage of this method is that it doesn't account the topographic influence of the area.

The areal depth precipitation is calculated using the following formula.

$$P_{av} = \frac{A_1P_1+A_2P_2+A_3P_3+\ldots+A_nP_n}{A_1+A_2+A_3+\ldots+A_n}$$

$P_{av} = W_1P_1+W_2P_2+W_3P_3+\ldots+W_nP_n$

In which $P_1,P_2,P_3 \ldots P_n$ represents precipitation at stations 1,2,3,…,n and $A_1,A_2,\ldots A_n$, represents the area of polygons representing the corresponding stations. A is the total area of the basin which is the sum of all the polygons and $W_1, W_2, \ldots W_n$ are thiessen weights computed as $W_1= A_1/A$, $W_2= A_2/A$ … $W_n=A_n/A$ Such that $W_1+W_2+\ldots +W_n=100$

Table 3-2Areal depth precipitation of the study area calculated by Thiessen method.

Stations	Area (sq –km)	Area Percentage (%)	Annual Precipitation	Weighted Areal depth Precipitation.
Wukro	181.991	80	614.4	494
Agulae	44.453	20	433.6	85
Total	226.444	100	1048	579

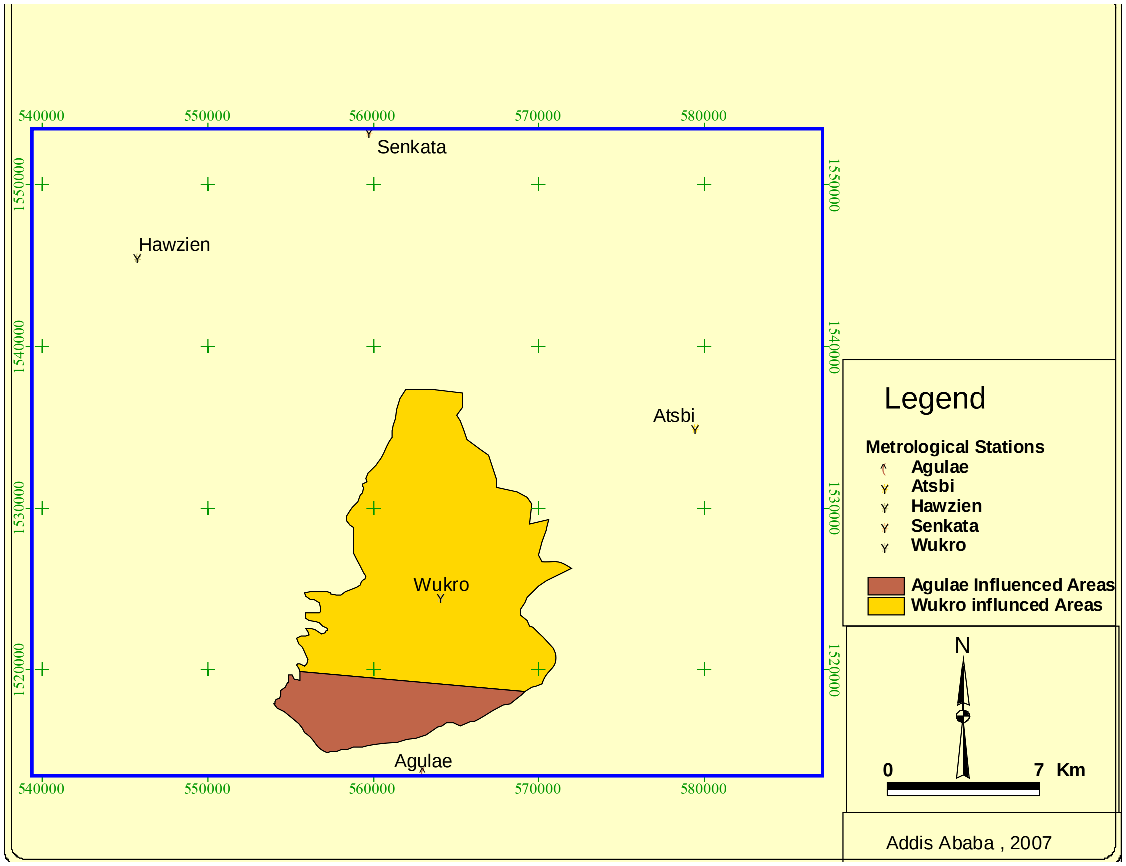


Figure 3-3 Thesien polygon

Thus the areal depth precipitation of the study area using the theissen method is 579 mm.

3.1.2 Arithmetic Mean

The Arithmetic mean is used to calculate the areal depth precipitation of the areas having uniformly distributed rain gauges and the individual gauge catches do not vary much from the mean. It is the simplest form in which the average depth of precipitation over the given basin is obtained by taking simple arithmetic mean of all the gauged amounts with in the basin. This method gives a rough estimate of the average areal precipitation.

This method doesn't account for the topographic and other influences. Here it will be employed for better understanding of the depth of precipitation result in the study area comparing with other methods.

The formula is given as follows:

$$P_{av} = \frac{P_1+P_2+P_3+\ldots+P_n}{n}$$

where $P_1, P_2, P_3, \ldots, P_n$ are the precipitation recorded by n number of gauges while P_{av} is the average precipitation.

Table 3-3 Mean monthly Areal depth precipitation

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Wukro	1.0	4.4	19.2	38.7	26.0	35.6	213.3	227.0	41.0	4.1	2.8	1.3	614.4
Hawzien	4.2	3.9	26.2	31.9	28.2	38.1	173.7	177.3	29.2	14.7	9.6	3.3	540.3
Senkata	9.7	17.9	63.2	87.1	46.8	89.6	217.1	196.4	39.9	31.1	31.4	17.8	848.0
Agulae	3.4	14.0	12.1	8.6	9.8	40.0	145.0	159.0	18.4	12.3	1.5	9.5	433.6
Atsbi	4.0	12.1	31.5	27.0	81.7	14.4	84.3	260.4	128.2	10.7	7.5	7.8	669.6
Total	22.3	52.3	152.2	193.3	192.5	217.7	833.4	1020.1	256.7	72.9	52.8	39.7	3105.9
Mean	4.46	10.46	30.44	38.66	38.5	43.54	166.68	204.02	51.34	14.58	10.56	7.94	**610.14**

3.1.3 Isohyetal method

This method is used in cases where the orographic effect is believed to have resulted in non uniform rain fall distribution in an area. Thus it is effective in mountainous terrains. Likewise the area of theissen polygons the areas between two Isohyets are considered as representative area for the rain gauge available in that area. The result is obtained by Summing of all the products of the area bounded between isohyets and the average of the two adjoining precipitation of isohyets divided by the total area of the basin.

It is calculated using the following formula

$$P_{av} = \frac{A_1(P_1+P_2)/2 + A_2(P_2+P_3)/2 + \ldots + A_{n-1}(P_{n-1}+P_n)/2}{A_1+A_2+A_3+\ldots+A_{n-1}}$$

In which $P_1, P_2, P_3 \ldots P_n$, are the isoheytal values such that P_1 and P_2 bound the area A_1, P_2 and P_3 bound the area A_2 and so on. Sum of all such sub basin bounded by all isoheyts,i.e, $A_1+A_2+\ldots+A_n$,is the total area of the basin.

Table 3-4 Areal depth precipitation by Isoheytal Method

No	**Area(sq-km)**	**Precipitation among Isohyets**	**Weighed Precipitation**
1	2.718	700.000	8.402
2	48.894	675.000	145.747
3	59.138	625.000	163.225
4	39.545	575.000	100.415
5	40.511	525.000	93.923
6	26.008	475.000	54.556
7	9.630	425.000	18.074
Total	**226.444**	**4000.000**	**584**

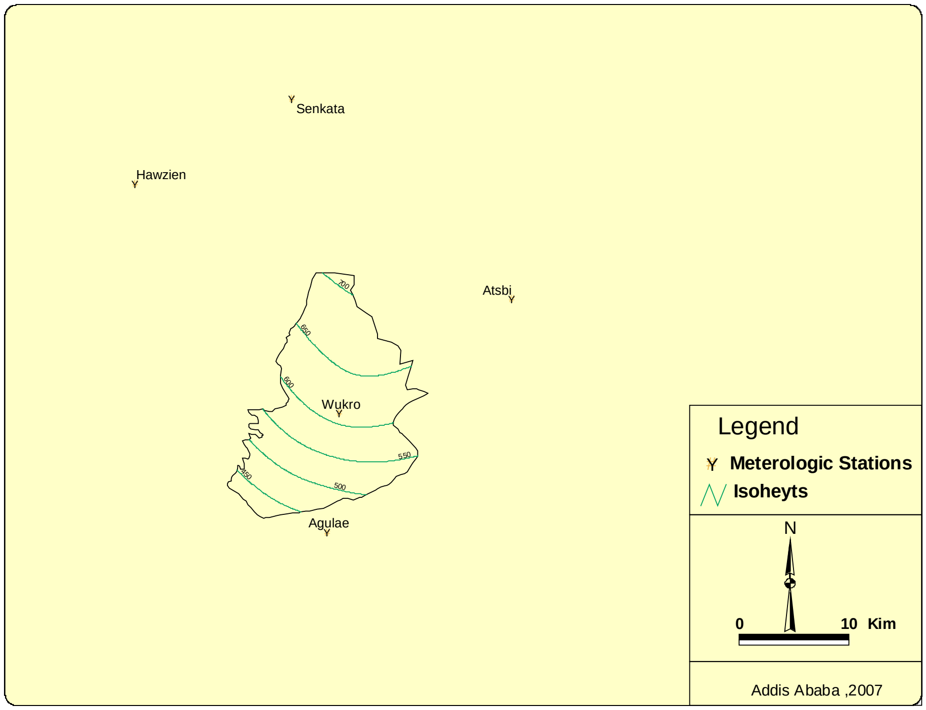


Figure 3-4 Isohyets of the study area

The weighed average areal precipitation obtained by isoheyt method is 584 mm/year. The results obtained by both theissen and Isohyets is 579 and 584 mm respectively. Therefore, the value 584 mm will be the representative areal depth precipitation of the study area. Because the Isohyets method fulfils the major parameters, that considers the topography and uneven distribution of the stations.

3.1.4 Relationships between elevation and depth of precipitation

The depth of precipitation is highly affected by topographic differences of an area. In most of low lands the precipitation is lower than that of high lands .Thus the study area depth of precipitation has also reflected the same characteristic feature of being unevenly distribution of precipitation with respect to topographic variations (elevation).Therefore, the rainfall and surface runoff and recharge contribution of these sub areas of the study area is quite different taking geology into consideration.

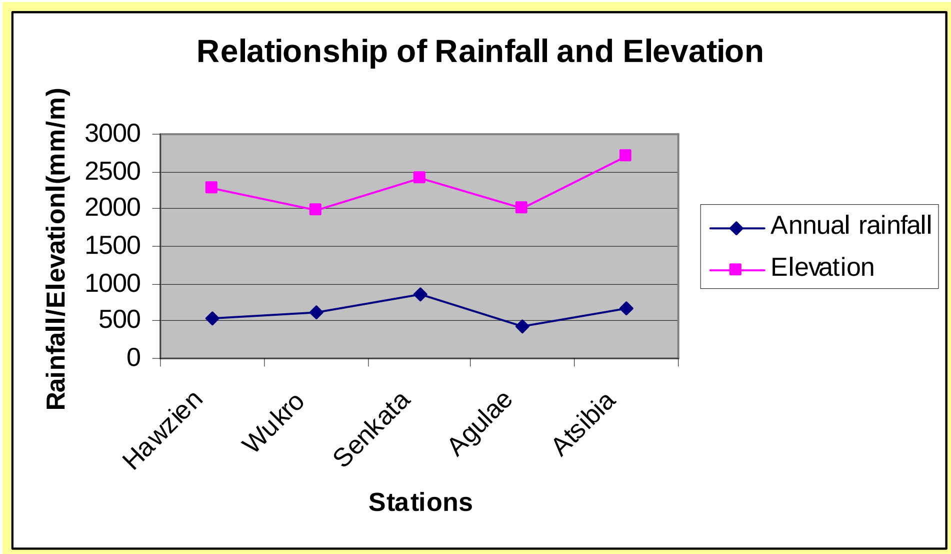


Figure 3-5 Relationship of precipitation with surface elevation

3.1.5 Seasonality of Rainfall

The seasonality of rainfall of a given area is dependent on the calculation results of rainfall coefficients of that area. The rainfall coefficient is the ratio between the mean monthly and one-twelfth of the annual mean rainfall.

The formula is given as

$R_c=P_m/(P_Y/12)$

R_c stands for rainfall coefficient,

P_m stands for mean monthly rainfall,

P_y stands for mean annual rainfall.

The value of this rainfall coefficient distinguishes rainy from dry months of the seasons.

Table 3-5 The rainfall coefficient of the study area

components	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
P_m	2.18	8.03	20.41	29.96	34.22	32.24	171.77	219.08	54.23	7.35	3.62	4.42
$P_{y=584}$												
R_c	0.04	0.16	0.42	0.61	0.70	0.66	3.51	4.47	1.11	0.15	0.07	0.09

Thus, according to (Daniel Gemechu., 1977), months with rainfall coefficient less than 0.6 are dry and months with values 0.6 and over are rainy. The six months(April ,May ,June ,July ,August and September) are rainy months while the remaining six months(January ,February ,March ,October ,November and December) are dry months.

Table 3-6 Classification Scheme of Monthly Rainfall Values (Modified from Daniel 1977)

	Designation	**Rainfall coefficient (standard)**	**Study area rainfall coefficients**	**Months**
1	Dry	Less than 0.6	0.04-0.42	Jan.,Feb.,Mar.,Oct.,Nov. and Dec.
2	Rainy months	>0.6	0.61-4.47	Apr.,May.,Jun.,Jul.,Aug. and Sep.
2.1	Small rains	0.6-0.9	0.61-0.70	April, May and June
2.2	Big rains	>=1	1.11-4.47	July, August and September
2.2.1	Moderate concentration	1-1.9	1.11	September
2.2.2	High concentration	2-2.9	-	
2.2.3	Very high concentration	>=3	3.51-4.47	July and August

The areal depth precipitation contribution of the dry months is 7.83% while the rainy months are 92.17% of which 67% is only from July and August.

3.2 Temperature

Temperature of the air and ground are important components in order to increase evaporation rate. The capacity of air to absorb water vapor increases as the temperature of the air raise.

Table 3-7 Mean Minimum and Maximum Temperature of the study area

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Mean minimum temperature	6.61	7.31	9.43	11.39	11.57	11.89	12.56	10.53	10.61	10.36	7.96	6.94	11.28
Mean maximum temperature (c^0)	22.11	22.75	23.23	25.25	25.77	30.07	24.99	22.83	25.65	25.38	20.96	21.21	26.49
Average	14.36	15.03	16.33	18.32	18.67	20.98	18.77	16.68	18.13	17.87	14.46	14.07	18.88

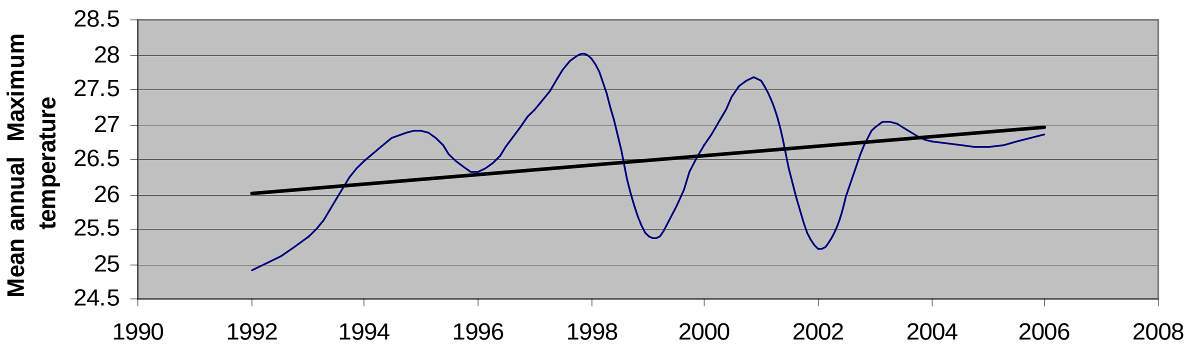


Figure 3-6 Increasing trend of Mean annual maximum temperature

3.3 Relative Humidity

Relative humidity is the most important parameter in determining evaporation and condensation of water molecules. It is also dependent on absolute humidity (the number of grams of water per cubic meter of air) and saturation humidity (the ability of the air to hold a maximum amount of moisture at a given temperature) .Thus relative humidity of an air mass is the percent ratio of the absolute humidity to the saturation humidity for the temperature of the air mass. Relative humidity has inverse relationship with evaporation.

The study area has 3 order stations which do not measure relative humidity. Therefore, as Mekelle has similar elevation and temperature, the mean monthly relative humidity of Mekelle station is considered. The mean monthly relative humidity at 0600 lst is higher relative to noon at 1200 LST and evening at 1800 LST .These clearly shows the inverse relationship of temperature and relative humidity. The maximum mean monthly relative humidity is observed in 0600Lst, especially in the months of July and August. The mean annual relative humidity is 53.01%.

Table 3-8 the mean Annual Relative humidity %

Local Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
AT 0600 LST	68	58	64	68	59	64	76	86	78	78	63	64	68
At 1200 LST	39	31	35	32	28	35	64	71	43	37	33	32	40
At 1800 LST	58	47	52	46	34	40	70	77	48	45	42	47	51
Average	55	46	50	49	40	46	70	78	57	51	46	48	**53**

3.4 Wind Speed

As water vaporizes into the atmosphere, the boundary layer between earth and air becomes more and more saturated so that the water vapour has to be removed and replaced with drier air continually in order the rate of evaporation to increase. The movement of the air depends on the speed of the wind that pass taking vapor from water, soil and plant surface. Evapotranspiration has a direct relation with the wind speed.

When importing wind speed data from another station, the regional climate, trends in variation of other meteorological parameters and relief should be compared.(FAO,No

56).Therefore, Mekelle wind speed is considered for the area. As they have similar elevation and temperature. The mean annual wind speed of Mekelle is 2.7m/s .But according to FAO irrigation and drainage paper 56, missing wind speed is obtained by a conversion factor. Thus, the wind speed in the study area using the factor which is based on elevation difference and the measured wind speed in the near by station is 2.16m/s.

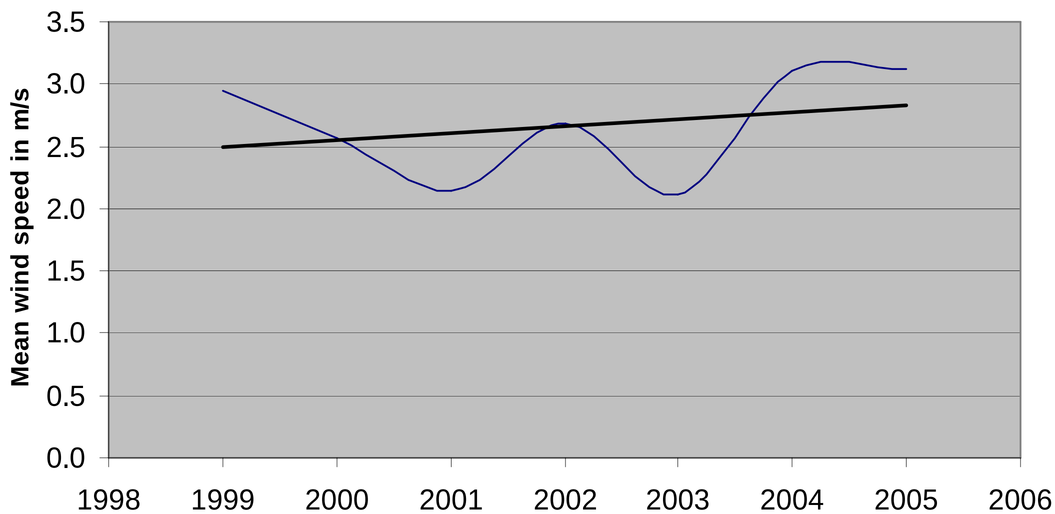


Figure 3-7 Increasing trend of wind speed

3.5 Sunshine Hours

The sunshine hours are the maximum hour sunshine in a day. When there is no obstacle for the radiation of the sun to reach the ground, the mean sunshine hours is about 8.1 hours. But during cloudy days the sunshine detected is very small. And also during rainy season the clouds and the precipitation obstruct the sun radiation from reaching the earth. Thus, there will be smallest sunshine hours that are as low as 4.1 hours. While in the dry months the sun shine hours reach as high as 10 hours.

3.6 Evapotranspiration

Evapotranspiration is the evaporation that takes place from surface water, shallow groundwater table by capillary activity and from soils whereas transpiration takes place from plants leaf openings called Stomata. When plants grow on soils, it is difficult to distinguish between evaporation and transpiration. Thus, the two components take place at the same time and named as evapotranspiration.

The amount of water required for water supply and other agricultural or industrial purposes are the water left after evaporation and transpiration requirements are met.
Thus, it is one of the major components for determining the water resource evaluation of an area for a bit longer durations in an area.

The direct measurement of evapotranspiration is difficult, as it involves many and complex factors and the difficult involved in measuring them, many empirical formulae have been devised to estimate potential losses.

3.6.1 Potential Evapotranspiration

Potential evapotranspiration is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water and with out advection or heat storage effects (Lawrence Dingman, 1993 cited in water balance-program manual).Different empirical formulae have been employed to calculate the potential Evapotranspiration.This following are some of the formula most often used.

3.6.1.1 Penman combination (Penman –Mentioth) method.

This method requires the use of mean temperature, Mean relative humidity, sunshine hours and wind speed to calculate the potential Evaporation. This method combines both energy budget and mass transfer approaches, thus the name penman combination is given.

Using FAO from the original Penman-Monteith equation and the equations of the aerodynamic and canopy resistance, the FAO Penman-Monteith equation is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where

ET_o reference(Potential) evapotranspiration [mm day^{-1}],[mm month^{-1}]
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
$e_s - e_a$ saturation vapour pressure deficit [kPa],
Δ slope vapor pressure curve [kPa °C^{-1}],
γ psychometric constant [kPa °C^{-1}].

Equations that are used during the calculation of potential evapotranspiration.

a. Pressure

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26}$$

Where
P is pressure [Kpa]
Z Elevation from mean sea level [m]

b. Saturation vapour pressure at the air temperature $e^0(T)$

$$e°(T) = 0.611\exp\left(\frac{17.27T}{T+237.3}\right)$$

where:

$e°(T)$ saturation vapour pressure function [kPa]
T air temperature [°C]

C.Psychrometric Constant (γ)

$$\gamma = \frac{c_p P}{\varepsilon \lambda} \times 10^{-3} = 0.00163 \frac{P}{\lambda} \quad (3\text{-}10)$$

where:

γ psychrometric constant [kPa C^{-1}]
c_p specific heat of moist air = 1.013 [kJ kg^{-1} °C^{-1}]
P atmospheric pressure [kPa]: equations 2 or 4
ε ratio molecular weight of water vapour/dry air = 0.622
λ latent heat of vaporization [MJ kg^{-1}]

***d. Slope of saturation vapour pressure curve** (Δ)*

$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \quad (13)$$

Where

Δ slope of saturation vapour pressure curve at air temperature T [kPa °C^{-1}],
T air temperature [°C],
exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

F. Mean saturation vapour pressure (e_s)

$$e_s = \frac{e°(T_{max}) + e°(T_{min})}{2}$$

g. Actual vapour pressure (e_a)

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e°(T_{max}) + e°(T min)}{2}\right]$$

RH_{mean} mean relative humidity

Net radiation (R_n)

$R_n=R_{ns}-R_{nl}$

R_{ns} net solar radiation[MJ m^{-2} day^{-1}]
R_{nl} net long wave radiation [MJ m^{-2} day^{-1}]

h. Solar or shortwave radiation (R_s)

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a$$

where R_s solar or shortwave radiation [MJ m^{-2} day^{-1}],

n actual duration of sunshine [hour],

N maximum possible duration of sunshine or daylight hours [hour],

n/N relative sunshine duration [-],

R_a extraterrestrial radiation [MJ m^{-2} day^{-1}],

a_s+b_s fraction of extraterrestrial radiation reaching the earth on clear days (n = N).

i. Clear-sky solar radiation (R_{so})

$R_{so} = (0.75 + 2\ l0^{-5}z)R_a$

Where

z station elevation above sea level [m].

j. Net solar or net shortwave radiation (R_{ns})

The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$R_{ns} = (1- \quad)R_s$ (38)

Where

R_{ns} net solar or shortwave radiation [MJ m^{-2} day^{-1}],

α Albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop [dimensionless],

R_s the incoming solar radiation [MJ m^{-2} day^{-1}].

R_{ns} is expressed in the above equation in MJ m^{-2} day^{-1}.

***k. Soil heat flux* (*G*)**

For monthly periods:

When assuming a constant soil heat capacity of 2.1 MJ m^{-3} $°C^{-1}$ and an appropriate soil depth, Equation can be used to derive G for monthly periods:

$G_{month,\ i} = 0.07\ (T_{month,\ i+1} - T_{month,\ i-1})$

or, if $T_{month,\ i+1}$ is unknown:

((R_a) Extraterrestrial radiation is taken from standard plot for 14 N (Northern Hemispher)

R_s/R_{so})   Relative shortwave radiation

(R_{nl}) Net longwave radiation

(R_n) Net radiation

Table 3-9 Results of the Penman Mentioth combination Method.

Components	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	
T ©	14.36	15.03	16.33	18.3	18.67	20.98	18.77	16.68	18.13	17.87	14.46	14.07	
H(%)	78.34	65.68	71.52	72.23	63.68	74.30	98.36	110.48	88.11	79.70	68.68	70.17	
U_{2}(Km/day)	116.11	145.00	143.46	126.43	98.56	74.31	69.15	59.86	67.08	89.79	89.79	76.37	
n(Hrs)	9.50	9.73	8.10	8.26	8.86	6.76	4.21	4.40	7.91	9.55	9.88	9.91	
N(Hrs)	9.80	10.70	11.70	12.91	13.90	14.40	14.20	13.40	12.20	11.10	10.10	9.60	
n/N	0.97	0.91	0.69	0.64	0.64	0.47	0.30	0.33	0.65	0.86	0.98	1.03	
D (Kpa c)	0.09	0.11	0.12	0.13	0.13	0.15	0.14	0.12	0.13	0.13	0.11	0.10	
R_s(mm/day)	5.25	6.50	7.05	8.30	9.28	8.25	6.63	6.32	7.38	6.83	5.64	5.03	
$e_{a(Kpa)}$	1.28	1.12	1.33	1.52	1.37	1.85	2.13	2.10	1.83	1.63	1.13	1.13	
$e_{s(Kpa)}$	1.82	1.90	2.015	2.28	2.34	2.83	2.31	2.03	2.29	2.25	1.78	1.76	
e_s- e_a	0.54	0.77	0.69	0.76	0.97	0.98	0.18	-0.07	0.45	0.62	0.64	0.63	
R_a(mm/day)	7.14	9.22	11.83	14.57	16.32	17.01	16.65	15.26	12.85	10.04	7.63	6.57	
$R_{so(mm/day)}$	35.04	45.26	58.07	71.49	80.10	83.50	81.70	74.89	63.08	49.26	37.45	32.24	
$R_{n(mm/day)}$	3.12	2.88	2.13	1.66	1.28	1.03	0.96	1.15	1.97	2.85	3.24	3.30	
Rns(mm/day)	9.77	14.15	17.96	22.30	25.16	26.20	25.67	23.40	19.82	15.16	11.51	9.72	
G(mm/day)	0.04	0.04	0.06	0.01	0.07	-0.06	-0.06	0.04	-0.01	-0.10	-0.01	-0.40	
PET(mm/month)	164	180	148	123	119	88	66	62	81	100	134	128	1392

((R_a) Extraterrestrial radiation is taken from standard plot for 14 N (Northern Hemisphere)

R_s/R_{so}) Relative shortwave radiation

(R_{nl}) Net longwave radiation

3.6.1.2 Thornthwaite Equation

Thornthwaite (1948) developed an exponential relationship between mean monthly temperature and mean monthly consumptive:

$$PET = 1.62 R_f \frac{(10T_m)^a}{T_e}$$

Where R_f is the reduction factor is taken from standard table which consists of months with respective latitudes.

T_m is the mean monthly temperature in C^0 , a is a constant which can be computed from the relation

$$a=0.4923+0.01792T_e-0.0000771T_e^2+0.000000675\,T_e^3$$

Where

T_e is the annual temperature efficiency index

$$T_e = \sum_{j=1}^{12} \frac{(T_m)^{1.514}}{5}$$

Table 3-10 Results of Potential evapotranspiration by Thornthwaite Method

altitude	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	
$R_f(10^0N)$	1	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	0.98	0.99	
PET(Cm)	11.40	10.44	11.99	12.33	12.99	13.25	13.01	12.52	12.17	12.13	11.18	11.25	144.66
PET(mm/month)	114	104	120	123	130	132	130	125	122	121	112	113	1446

3.6.1.3 Masmstrom method (1969)

A simplified method calculated using the saturation vapour pressure of the atmosphere.

$PET = 0.409x[e_{sat}(T_a)]$

Where

PET (cm/month)

$E_{sat}(T_a)$ saturation vapour pressure of the atmosphere(Kpa)

T_a means monthly air temperature (c^0)

$$e_{sat}(T_a) = 6.11\exp\frac{(173T)}{(T+237.3)}$$

Table 3-11 Comparison of Potential evapotranspiration results obtained from Three methods

Methods	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual PET
Penman Mentioth	163.89	179.64	147.93	122.98	119.08	87.98	66.16	62.20	80.87	99.68	133.98	128.18	1392.57
Thornwaite	113.96	104.40	119.95	123.27	129.94	132.47	130.15	125.16	121.73	121.27	111.79	112.53	1446.62
Masmstrom	67.06	70.03	76.12	86.34	88.26	101.87	88.84	77.84	85.32	83.93	67.50	65.83	958.96
Mean Total													1266.05

Although the results of Penman-Mentioth and Thornwaite are very quite similar than the Masmstrom method , the Penman-Mentioth is considered as the representative of the study area potential Evapotranspiration.This is because ,it comprises of many components compared to the two methods which they use not more than two parameters. Moreover, the Thornwaite method gives higher potential evapotranspiration during the wet month of the year, which in actual sense decreases in these months. Thus the potential evapotranspiration of the study area is 1393mm/year.

3.6.2 Actual Evapotranspiration

Actual Evapotranspiration is defined as the evapotranspiration from a vegetal cover under the natural or given condition of supply of water. Actual evapotranspiration is equal to Potential evapotranspiration when all rainfall for that period is to satisfy the evapotranspiration needs.

Estimation of actual evapotranspiration is employed for the reason of estimation of water balance/recharge of the study area. The methods used to estimate actual evapotranspiration are the following:

3.6.2.1 Turc Method (1961)

Based on the parameter of rainfall, temperature and evaporation data, Turc has developed equation for the computation of Actual Evapotranspiration.

$$\overline{E} = \frac{\overline{P}}{\sqrt{0.9 + \left(\frac{\overline{P}}{J}\right)^2}}$$

Where:

$J = 300 + 25T + 0.05\,T^3$

$\overline{P}$: Mean annual precipitation in millimetre

$\overline{E}$: Mean annual actual evapotranspiration in millimetre

T : Mean annual air temperature in ^{0}C

$\overline{P}$ =583.5mm; T = 18.89 ^{0}C ; J = 1103.28 and $\overline{E}$ = 537.79 mm/year

3.6.2.2 Soil Water Balance (Thornthwaite and Mather, 1957)

The soil water balance (WATBAL) use average monthly effective precipitation, potential evapotranspiratation and available water capacity of the soil, which is equal to the rooting depth and the water holding capacity of the soil. It generates actual evapotranspiration soil moisture and soil moisture surplus (recharge).

The soil type with respective to water holding capacity for Mekelle area according to Macdonald et al.,(1975) is used for determining the available water capacity for the study area , as Mekelle and wukro are found in the Mekelle outlier ,moreover , the temperature and rainfall have good similarities.

Table 3-12 Soil type and Field capacity of Mekelle area adopted from Macdoland et.al (1975)

Percent of frequency in the study Area	**Soil type**	**Field capacity(mm)**
91.6	clay loam	328
1.4	sand	250
7	Silt clay	241

Thus the area coverage and the soil moisture content of each soil are utilized to determine the weighted average soil moisture content of the total sub basin, and is calculated to be 321 mm.According to the analysis done by Macdonald et al., the rooting depth, up to which evaporation is effective is 0.70m which is very close to the modified clay root depth by (Dunn and Leopold, 1978)0.67m for clay soil of grass.

Therefore, the available water capacity at field capacity is (0.7*290) =225mm/m

The potential evapotranspiration and actual evapotranspiration are related to the difference of soil moisture.As the supply of water to the soil of a vegetated area is with out limit the potential evapotranspiration is equal to the actual evapotranspiration but when the supply of water is limited to the natural condition PET will be greater than AET.

Results of Thornwaite and Mather model

According to the results obtained from the model indicates that during the first six months the potential evapotranspiration is much higher than the actual evapotranspiration and hence, there is soil moisture deficit from January to June but between July and August months there is an increase of precipitation and actual evapotranspiration which implies decreasing of soil moisture deficit. At the mid of July to mid of September actual evapotranspiration and potential evapotranspiration becomes equal which indicates unlimited supply of precipitation that enable the soil moisture recharge / surplus and runoff to take place. And finally from mid of September to the mid of December soil moisture utilization takes place. (See table 3-14 and Figure 3-8)

Soil water balance of Wukro-Genfel Sub-basin (Thornwaite and Mather 1957)

Assumed Average monthly runoff =50%

Water capacity of root zone=225mm

Table 3-13 Thornwaite and Mather soil Water balance computation results

mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	2	8	20	30	34	32	172	219	54	7	4	4	584
PET	164	180	148	123	119	88	66	62	81	100	134	128	1393
P-PET	-162	-172	-128	-93	-85	-56	106	157	-27	-93	-130	-124	-807
Actpot Wls	-536	-708	-836	-929	-1014	-1070	0	0	-27	120	-250	-374	
SM	21	10	5	4	2	2	108	225	200	132	74	43	
dSM	-22	-11	-5	-1	-2	0	106	117	-25	-68	-58	-31	
AET	24	19	25	31	36	32	66	62	79	75	62	35	546
D	140	161	123	92	83	56	0	0	2	25	72	93	847
S	0	0	0	0	0	0	0	40	0	0	0	0	40
TL Avail	1	0	0	0	0	0	0	40	20	10	5	2	
RO	1	0	0	0	0	0	0	20	10	5	3	1	40
DET	0	0	0	0	0	0	0	20	10	5	2	1	

P=Mean monthly precipitation (mm/month)

PET = Potential evapotranspiration (mm/month)

P-PET = The difference of precipitation and potential evapotranspiration which is equal to the moisture deficit when precipitation is less than potential evapotranspiration.

AET = Actual Evapotranspiration

Act pot Wls =Accumulated potential water loss (the sum of the negatives of potential evapotranspitation starting from the dry month to the beginning of wet month)

SM=Soil Moisture for each wet month is obtained by adding the excess of the current month to the soil moisture of the month before.

dSM = Difference in soil moisture is the difference between precipitation and actual evapotranspiration of each months. The positive values indicate the soil moisture recharge.

D = Soil moisture deficit is negative values of the difference between precipitation and potential evapotranspiration.

S =Soil moisture is the amount of water that can be stored.

Ro =Runoff is assumed to be 50% of the surplus moisture of successive months.

Tavil = Total available for runoff is the moisture surplus of month M,eventually increased in with the detention of month M-1.

DET = Detention is the amount of water left after 50% of the moisture surplus of each moisture surplus months.

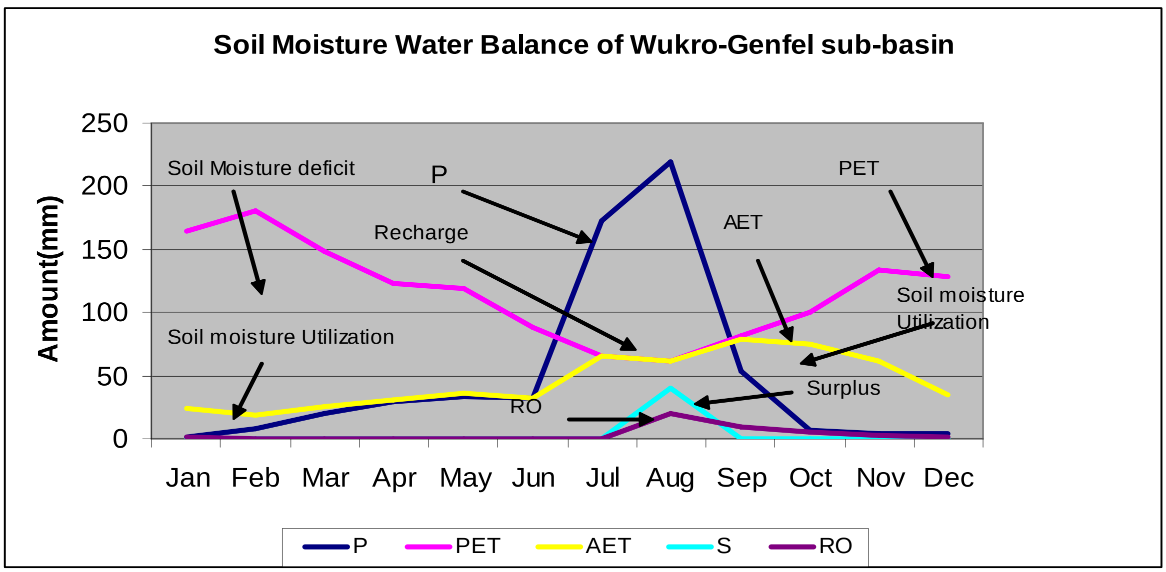


Figure 3-8 soil moisture water balance of the study area.

The Results of actual evapotranspiration obtained from Turc empirical formula and soil water balance of Thornwaite and Mather 1957 are 537.79 mm/year and 546mm/year respectively.

The results obtained from both Turc and Soil water balance methods are close to some degree therefore the average value of the two methods is taken. Hence, (AET = 542 mm/year) is considered.

The annual recharge is determined by the soil water balance that can be represented by

G_r = P-AET+Ds-RO

Where

G_r = Annual recharge

P = Mean annual Precipitation

AET =Annual Actual evapotranspiration

Ds ==Annual change in soil storage which is zero on annual bases

RO = Annual Runoff

Therefore, the annual surplus is 40mm and about 6.13mm/year is with drawn by water pumps and submersible pumps for irrigation and water supply respectively from the basin. Thus the total recharge of the sub-basin that is retained in the soil and down to groundwater is 33.87mm.

In addition to the annual recharge calculated by the model, there may be direct recharge through preferential paths in metamorphic rocks where the rocks are exposed and fractured. There is also a possibility of getting inflow from the near by catchment of suluh river that is in the southwest of the catchment .As the geology of the area is fractured thinly bedded limestone that could facilitate horizontal flow from the river.

CHAPTER 4

4 Surface and Groundwater Interaction.

4.1 Stream Flow

The total runoff consisting of surface flow, subsurface flow, ground water or base flow and the precipitation falling directly on the stream is the stream flow or the total runoff of a basin. For the steam flow to be practical the following factors plays the main role .These are grouped into climatic factors which comprises intensity, duration, aerial distribution and Evapotranspiration of the precipitated water; basin characteristics comprising size, shape, slope, drainage density , topography; Basin geology; Basin infiltration characteristics.(Patra.,2001)

The study area is characterized by low intensity rainfall through out the year with the exception of June to August .Even during these months the rain fall distribution is erratic in spatial and temporal.

The northern and eastern parts of the study area are covered with relatively elevated mountains where the runoff is higher during rainy months, especially, the north eastern part where the in let of the genfel river is found is bounded by steep weakly metamorphosed metasediments with foliations against to the river flow, there are also lineaments trending East to west which is also perpendicular to stream flow direction but this area comprise less than 10% of the total length of the steam. The drainage density near this area is highly dense compared to the drainage densities of the middle and far in the out let. The remaining part of the study area where the river passes through is covered by Mesozoic sediments.
The river is crossed with two major faults one in the contact between metamorphic terrain and the Paleozoic sediments and the second in Mesozoic sediments that brought in contact Adigrat sandstone and Antalo limestone, near the gauging station..

It has been attempted to measure the discharge using a current meter but due to over exploitation of the upstream for irrigation by the farmers and also the survey time was end of the dry season, the amount available in the river is not measurable .Down 1 km far from this inlet of the basin, there was no any water observed on the bed of the stream. Even the gauging station didn't measure at this time.

The gauging station of river discharge covers 481 Sq km in area. But the study area included with in this considered area is 12 %(58.436 sq km). And the data obtained is from1992-2006, but the only data with complete discharge value is 1996.While the remaining years 1992-1995 records only have two or three months daily records of the year. Even after 1996, the only data with greater than seven month's records are 1997 and 2001. Therefore, it has been attempted to use wukro(Genfel) incomplete nine months daily record river discharge data and annual daily rainfall of 2001, as the year is the closest year of all the possible available data to the time of study. In addition to this the missing data are in the dry seasons with very small river discharge.

The field survey indicated that the farmers are using more than 30 small and big motor pumps which can yield 15 l/s and 20l/s from base flow that is below the sandy soils of the river bed, by digging to some meters. The data obtained from the upstream and down stream and even the town water supply is tabulated below.

Table 4-1 Annual withdrawal from the Genfel river and the basin as a whole.

Classification	**Type**	**Quantity**	**Yield**	**Pumping hrs./day**	**M^3/year**
Upstream	Small pumps	14	15l/s	4	272160
	Big pumps	-	-		0
Down Stream	Small pumps	15	15 l/s	4	291600
	Big pumps	7	20 l/s	4	181440
Sub total					**7452000**
Town Water supply	Bore hole	4	59 m^3/hr	23	579255
Child care(school)	Borehole	2	12.3		64648.8
Total					**8841103.8**

Considering irrigation activities to take place for 6 months of the year and all the pumps are functional for the whole year, and the irrigation time is every two days for 4 hours ,the total amount exploited annually is estimated 1.389104 MCUM or 6.13mm/year of which 3.58mm is withdrawn for the town water supply and child care(orphan) and the remaining 2.55 mm is withdrawn for irrigation purpose .Some of the water withdrawn for irrigation purpose may be involved for recharging of the catchments.

4.1.1 Hydrograph analysis of Genfel River

Hydrograph is a method where by river discharges measured at gauging station are plotted with time to extrapolate the possible surface runoff and base flow using different methods. The base flow and runoff are the main hydrograph components that determine the groundwater recharge of a catchments and water resource evaluation.

4.1.2 Hydrograph component separation

The individual elements that participate in flow formation, theoretically divided into; flow formed by direct precipitation over the surface of the stream, surface runoff collected by the stream, interflow and groundwater inflow. But it is difficult to separate all this components thus they are reduced to an estimation of base flow and surface runoff.

Base flow separation by Timeplote method is employed for this work as it gives more reliable value and simple compare to other methods. This method uses daily discharge values and attenuation coefficient (0.9-0.995) that depend on the climate, topography, geology and land use to account degree of runoff .The following results are obtained from the time plot model .

Table 4-2 River Discharge of The Genfel river

Year	Total flow		Baseflow		Runoff	
	m^3/s	mm	m^3/s	mm	m^3/s	mm
2001	4.475	140.36	0.970	41.04	2.303	111.69
1996	52.609	3449	1.263	83	3.116	204

An estimated average flows of 1996 is highly exaggerated compared to the remaining flows and also it is measured 11 years ago, in addition to this the annual precipitation of that year is as high as 912mm, almost half of the calculated mean annual precipitation of the study area. .Hence, the 2001 is more reliable although it comprises of only nine months (except October, November and December) which could have very low flow. And with mean annual precipitation of 622.35mm that is close to the mean yearly precipitation.

Results

Using the Time plot method the daily river discharge for the year 2001 was calculated and the following results are obtained:

The base flow of the catchment is 0 .970m^3/s or 41.01mm and the annual runoff is 2.30m^3/s or 111.69mm.The study area is 12% of the total hydrograph basin. Therefore, the contribution of the study area to the hydrograph is 4.8 mm for base flow and 13.4mm for runoff. The runoff obtained from soil moisture water balance which is 40mm is far greater than 13.4mm obtained from hydrograph analysis. Stream flow hydrograph of Genfel River in 2001 (for nine months)(see figure 4-1)

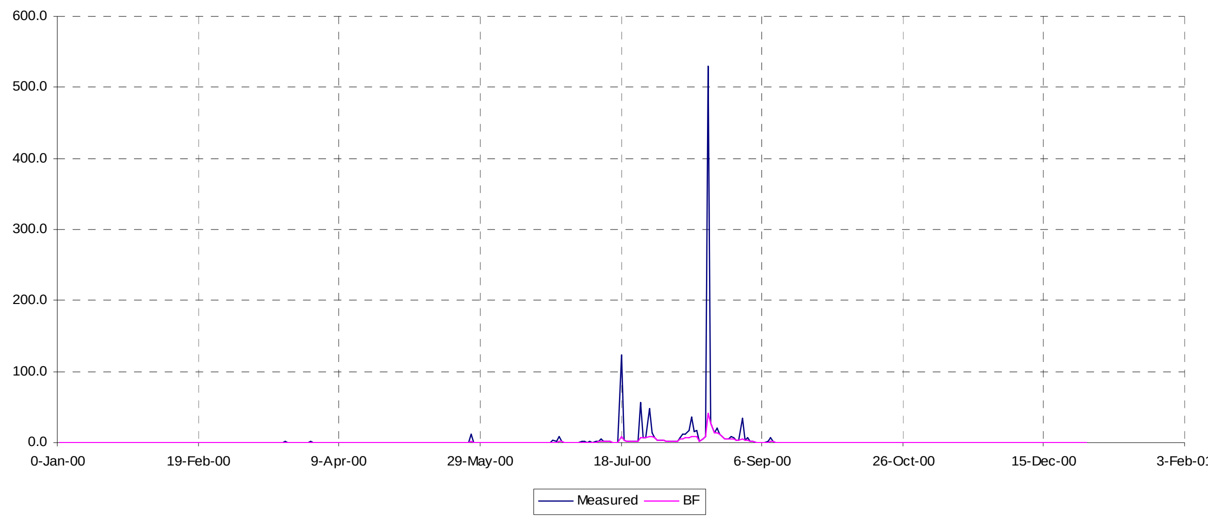


Figure 4- 1 Hydrograph of Genfel (2001)

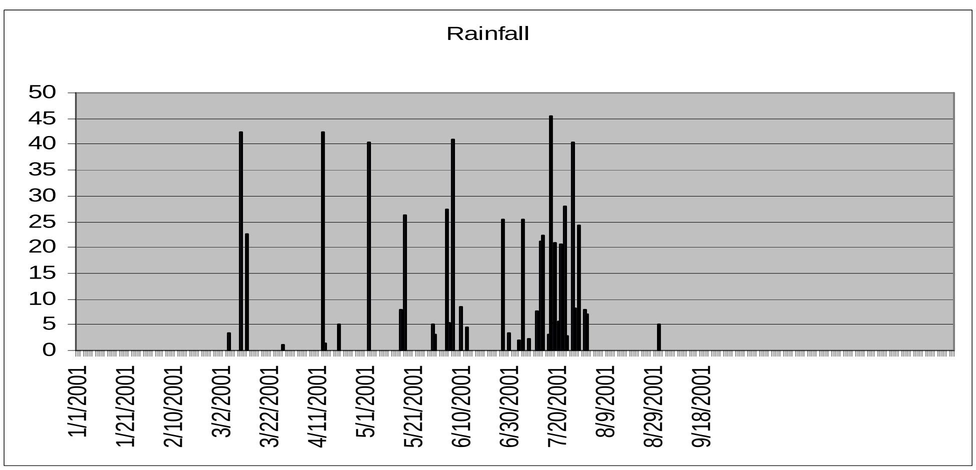


Figure 4-3 Rainfall of Wukro in (2001)

4.1.3 Seasonal recession Method

This method is a simple way for estimating groundwater recharge .It assumes that the catchment has no dams or other surface or groundwater extraction and it also assumes the groundwater discharge from basin storage has constant values through groundwater year. It utilizes stream hydrographs from two or more consecutive years.

The equation $Q=Q_0e^{-at}$

Where Q is the flow at some time t after the recession started

Q_0 is the flow at the start of the recession

a is a recession constant for the basin(1/T)

t is the time since the start of the recession

Indicates Q varies logarithmically with time (t). A plot with time in arithmetic scale and discharge on logarithmic scale will yield a straight line with a slope value of (α) .This line can be used to separate the base flow just doing a parallel shifting the master line till it touches the lower part of the hydrograph .The sum of the differences of the shifting lines of different discharge values gives total recharge of the basin storage. Thus

the volume of water ,which remains in the water bearing formations (aquifers),can be obtained from:

$$V_t=Q_t/\alpha$$

Since the discharge measurement at genfel for the last eleven years is not complete except for the year 1996.The determination of groundwater recharge of the basin by the recession curve method is not practical. Because it requires two or more consecutive years of the river discharge values.

4.2 Groundwater Recharge

The amount of moisture that will eventually reach the water table is natural groundwater recharge. Quantification of the rate of natural groundwater recharge is pre-requisite for efficient groundwater resource management. Although the estimation of recharge by whatsoever method is normally subjected to large uncertainties and errors.

The amount of recharge depends upon hydrometer logical, soil moisture conditions, the water table depth, soil type and thickness, the vegetation, geology and topography.

4.2.1 Water Balance using Stream Hydrograph

Recharge is estimated as the residual of all other water balance components. The water balance for catchments is calculated with groundwater inflow and outflow. But the study area has river with inlet and outlet. However, as it is mentioned previously, the upstream inlet water is very small to measure due to over exploitation of the in coming water and similar to the upstream the down stream is also highly depleted and the remaining water flows below the sandy bed of the river. Hence, it is good to consider, as there is no inflow and outflow as the available water is being consumed with in the catchment, the withdrawal from town water supply intake are also considered in this calculation.

Case 1

Therefore the water balance equation is given by

$$G = P - Ro - AET - W$$

Where P is mean annual precipitation mm/year

Ro Runoff mm/year

AET Actual Evapotranspiration mm/Year

W is withdrawal from the basin

For annual case the change in storage is zero, therefore Ds is excluded from the calculation.

Hence the 2001 river discharge is considered for this purpose. Therefore, the total surface run off is 13.4 mm/year. Precipitation is 584 mm/year and the AET is 542 mm/year, with 6.85 mm with drawl annually. Therefore, recharge for the case of the study area is 21.75 mm/year is the recharge of the catchment.

This shows that the total recharge of the sub-basin is only 3.7 % of the mean annual precipitation. The recharge value is 18.23 mm less than the amount obtained from the soil water balance method which is 40mm/year. The discrepancy could be due to the irrigation recharge being not included from the withdrawn water and also there could be inflow through the two major faults that crosses the river and lineaments of the area.

Case 2

The flow from the 88 %(part of the hydrograph) is considered as inflow to the catchment, that is 123.5mm and the out flow is calculated from the Darcy's law:

Q_{out} =TWI

Where

Q_{out} = outflow from the sub-basin

T= Transmissivity of the aquifer

W =width of the aquifer

I= Hydraulic gradient (change in height /change in length)

Therefore, a total amount of 108.56mm is goes out of the sub-basin annually. Now it is possible to make a water balance budget for the sub-basin taking recharge as a residual.

$P+Q_{in}$ =AET $+Q_{out}$+ change in storage withdrawal

$R=AET-P-Q_{in}+W-RO+Q_{out}$

Where

R =recharge

PET =Potential Evapotranspiration

P = Mean annual precipitation

Q_{in} =Ground water inflow

Q_{out} = Ground water outflow

RO =Surface runoff

W= withdrawal from the sub-basin.

Based on the sub-basin water budget method the total recharge is 32.37 mm annually. When this result is compared to the previous results obtained from soil water balance is very much higher than the soil water balance while the groundwater recharge considering no inflow and outflow except surface runoff is close in values. Which indicate that the recharge from the surrounding catchments in the southwest (suluh River) watershed.

Table 4-1 Summary of water balance

Method	**Recharge/Surplus(mm/year)**
Soil moisture Water balance	33
Water Balance using Steam Hydrograph	
Case 1 considering no inflow and outflow	21.75
Case 2 considering inflow and outflow	64

CHAPTER 5

5 Hydrogeology

5.1 General

The hydrogeologic setting of an area is dependent on the geological (structure), metrological, hydrological and geomorphologic interaction and relation. The northern part of the area forms ridge and hill to gentle slope forming topography from which dense drainage pattern tributaries of the Genfel River are originated .The geology of this area is weakly metavolcanic and metamorphosed meta-sedimentary rocks. Sharp contacts with metasediments and metavolcanic marked by very important tectonic lineaments(Vernier, 1993).While the central and south southwestern part of the area is covered with cliff forming, low-lying sandstone, and also cliff ,gentle and plain forming limestone and shale.

The study area consists of only nine borehole logs and 8 pump test data that are not spatially distributed in the area. Therefore, Hydrogeology of the study area will be analyzed and presented based on the available pump tests, log data, qualitative field observation and other relevant data.

5.2 Groundwater storage and Movement

The portion of a rock that could be occupied by groundwater is voids, interstices and pore spaces. It is characterized by their shape, irregularity and distribution in an area.
These pores are primary or secondary in character; the primary porosity is the porosity that is created during deposition or formation of sedimentary or igneous rocks while the secondary porosity is formed due to reworking, faulting, fracturing and physical or chemical effects.

The permeability of a rock or soil defines its ability to transmit a fluid with an appreciable velocity under a pressure gradient and depends on the shape and size of the voids, therefore, it plays a great role in transporting the stored groundwater in the voids medium. Similar to porosity the permeability of rocks are of primary or secondary. The advantage or disadvantage of the primary and secondary permeability depends on the change in storing and transporting water through them.

In nut shell, the over all movement of groundwater is dependent on hydraulic parameters of the medium such as transmissivity, storativity and hydraulic permeability which directly or indirectly related to the characteristics of the fore mentioned parameters. Hydrostratigraphy of the lithology of the area will presented below.

5.3 Hydrostratigraphy

5.3.1 Metamorphic

According to the geological setting of the study area, the metamorphic rocks are grouped into four Hydrostratigraphic units:

5.3.1.1 Metasediments

These rocks are found on the middle and NNW of the Negash syncline composed of slate and dolomite; pebbly slate, weakly metamorphosed black limestone phylite and schist. The slate and dolomite intercalation consists of highly interconnected fractured with interbedding of thin beds of dolomite and highly foliated slate. The boreholes located in this part of the area (BH22 and BH35) are characterized by highly fractured, weathered and water saturated dolomite and slate. The depth of fracturing and weathering reach to depths of 31meter and cavities saturated with water are found with depths 14-25 m. The aquifer is semi-confined in both of the boreholes drilled in this area, because there is rise of water above the depth of water strike and also the constant discharge test log-log time –drawdown graph fit with the modeled graph of confined fractured aquifer. The safe yield of the wells in this area ranges from 0.5 to 6.5l/s.The main source of groundwater is secondary structures and solution cavities and weathering. The slate dominated formations found near the metavolcanic are relatively better aquifer than metavolcanic rocks. One well sunk in this formation give 1l/s and transmissivity of 0.049m^2/d with saturated thickness 9m. The potential of both the dolomite dominated slate and slate dominated aquifers is limited to the center of the synclines where plane to gentle sloping areas are found.(See figure 5-1).

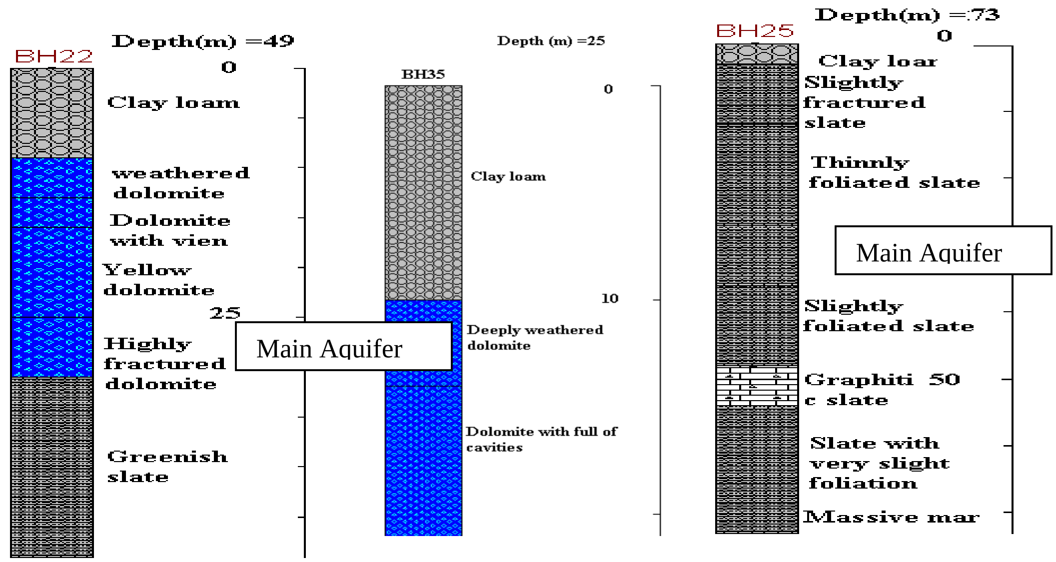


Figure 5- 1 Borehole log of the Dolomite dominated slate

The slate and black limestone consists of thickly to thinly bedded with thinly to widely spaced joints and foliations. In some part where black limestone is found, there are solution driven travertine through which springs flow and also karts caves are also observed. There is low lying land on the side of the genfel river that are highly productive dug and drilled wells ,but the rocks which are found out of this valley are undulated ,thus except near by to the river there are no boreholes and dug wells that could give information about the rock characteristic nature. The aquifer is of unconfined type with low extended (localized) aquifer for the hand dug wells. According to (Zekiai Sen, 1995), fractured black limestone is good aquifer

The phylite and schist rocks are moderately jointed in the exposured areas. The phylite is intruded with small dyke in the direction of foliation .There are hand dug wells and boreholes in the area which serve for rural water supply. The depth of the hand dug wells (HDW1, HDW14 and HDW15) is 8 – 15 m with water strike of 4-10 m respectively. While the borehole (BH37) depth is 54m and static water level of 7m.Which indicates shallowness of the groundwater.

In general, phylites, slates and schists have very poor water storage and transmission properties (Zekia Sen, 1995)

5.3.1.2 Metavolcanics

There are metavolcanics and metavolcanoclastics in this group. The fracturing in the metavolcanic is highly interconnected as it seen on the surface and also in the dug wells observed during the field work .Most of the hand dug wells are drilled to depths of 6-12m and provide enough water to the rural communities. Moreover, the water table is in the range of 3-5m from the surface. Therefore, the aquifer type is unconfined with thick saturated thickness in the dug wells. There is only one borehole (BH31) drilled in this formation with a depth of 45m and static water table of 4m.The static water is very shallow similar to hand dug wells.

The metavolcanoclastics are highly fractured and less foliated rocks. Similar to the metavolcanics, it is good aquifer for shallow dug wells as it is observed on the field, but the area is not good aquifer for borehole as there are failed boreholes with only small shallow aquifer water (Discussion with farmers) .Even the dug wells in this area are generally as deep as 8m because beyond this depth it is massive.

5.3.2 Edaga arbi glacial

The formation is dominated by highly compacted shale; marl and silt with out fracturing .Wells drilled in this formation fail to strike water .But beanth these formations a big amount of water is obtained from Enticho sandstone. When the water is stricken, it has raised to near surface, thus the edaga arbi glacial has acted as aquitard confining the groundwater below it. Its lateral extent is controlled by the ridge forming sandstones and also by the wukro fault belt in the north and south. The average thickness of this rock is 90m in the study area. Therefore, the area has no hydro geologic significance except for very shallow seepage dug wells which collects small amount of water over night that can be used for very small plot watering.

5.3.3 Enticho sandstone

Enticho sandstone is a white fine to coarse grained sandstone with calcite cementing. The primary porosity and permeability is characterized by the compact cementation of the sandstone, but due to the solution effect of the calcite cementing material, there is development of secondary permeability. Moreover, the thin coarse grained and fractured beddings are the main source of groundwater as it is observed from BH36 .Due to the overlaying Edaga Arbi glacial, it is semi-confined aquifer. The hydraulic conductivity of this formation is 7m/d and a yield of 259.2m^3/day (3l/s).The lateral extent is also controlled by the two faults bounding the area and other small lineaments. The average thickness of the aquifer in the area is 10-20m

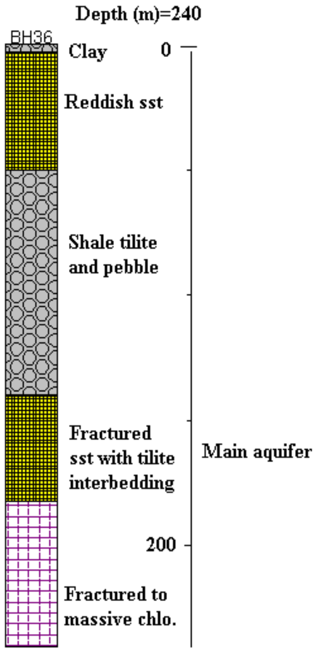


Figure 5- 2 Log representing Enticho Sandstone

5.3.4 Adigrat sandstone

Adigrat sandstone comprise fine to medium with some coarse matured and well sorted grain. In some areas it is highly compacted due to cementing material property. Thickly bedded and jointed yellow sandstone are found on the west of the plain called metseko. And also there are thickly bedded massive sandstone inclined to ward west with wide plane of bedding among them and wider intermittent joints having 2-5 cm spacing through which indicates the possible groundwater flow. While in some part of the area there are inter beds of reddish silts, clay (laterite), shales and mudstone which could act as confining beds. The most important aquifer which are found in Mesozoic rocks are adigrat sandstone which is medium to coarse, red to brown ,non-calcareous, well sorted, and cross-bedded sandstone with average thickness of about 800m (Tamiru Alemayehu,1993) The Adigrat sandstone is highly affected by two main wukro fault belts (see Figure 2-8) and associated lineaments. Therefore, the aquifer is characterized by bedding plane and fracturing and Intergranular contributions. Potential aquifers may be found with in the most superficial horizons where weathering has taken place within the coarse conglomeratic base (Tamiru Alemayehu, 1993).Boreholes (BH 45, BH46 and BH9) are located in this unit which have intercalations of gravel, mudstone and siltstone .Especially BH45 is located in mudstone dominated formation that resulted in low yielding (1l/s) than the remaining ones. Contrary to this there is BH44 located just in the main fault that brought Juxtaposition limestone and adigrat sandstone which has the second high yield borehole. It is about 30m far from the low yield borehole (BH45).This indicates that the hydraulic conductivity is highly controlled by structures than Intergranular porosities. The aquifer has limited extent due to its limited occurrence in the area. The hydraulic conductivity of this aquifer is in the range of 8.81-11.87 m/d and a yield of 5-6.9l/s. The average thickness of the aquifer is about 15 m. (See figure 4-1)

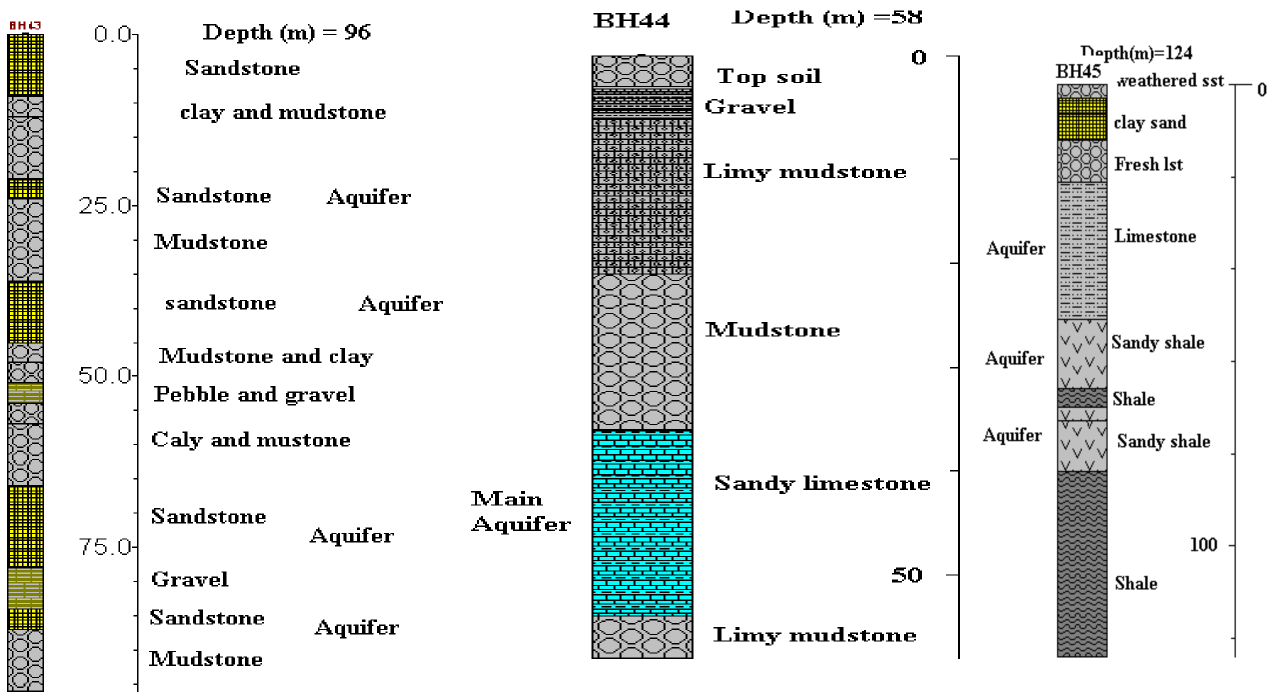


Figure 5- 3 Lithological Log representing Adigrat Sandstone

5.3.5 Limestone

The largest portion of the study area is covered with limestone. The limestone is of different in type. Some are thick with interconnected jointed bedding. And some are thinly bedded limestone with intercalation of thinly bedded shale in the SSW and others are thinly jointed beds intercalated with different in color shale, dolomite and mudstone.

There is also highly fractured and thickly bedded black limestone in the south-south eastern part of the study area with a yield of 2 l/s, this data is obtained from personal communication of the driller and the geologist who were involved in the work. Therefore, from the borehole data (BH27 and another borehole 200m far) obtained in the area, there is multilayered aquifer system which is fractured and weathered containing solution cavities that resulted in a semi confined nature of the aquifer. It contains extended aquifer. The yield is 2, 6.96 and 8.51l/s and Transmissivity of 65 and 96.5 m^2/day.

This area covers more than 50% of the area but it has only two boreholes with complete pump test and log data .Therefore, resistivity method is conducted in two traverses comprising 4 and 5 Vertical electrical sounding each. The measurement is conducted with SAS300 ABEM Terrameter. The geographic locations of the Vertical electrical Soundings are listed below.

Table 5-1 Lists of the conducted Vertical Electrical Sounding

VES	UTM		Elevation	Direction
	Northing	Easting		
1	1520585	563838	1991	N 140 W
2	1519692	563618	1983	N140W
3	1521423	563967	1975	N 160 W
4	1521225	565301	1993	N160W
5	1520727	565066	1993	N140 W
6	1522701	564126	1976	N 140 W
7	1522689	565241	1994	E_W
8	1529129	562391	2040	N-S
9	1517210	563155	1996	N140W

The resistivity data are analyzed with a user friendly software called Rezix-Ip.The analysis result and interpretation results are given in table form below.

Table 5-2 Summery of VES traverses in the study area

No	Traverse line	Ap. Resistivity (ohm-meter)	Thickness (meter)	Lithology
1	VES 7,10, 4, 2, 3	214-299	0.2-1.25	Clayey soils
		10- 68	1.25 - 27	Loam soil
		10-28	27-57	Saturated fractured limestone
		68-99	57-188	Marl
		9-23	infinitity	Saturated fractured limestone
2	(VES 8, 6, 5,)	5-19	0-2.5	Limestone
		178-366	0.2-4.5	Marl/mudstone
		0.7-33	1.5-36	Saturated fractured limestone
		117-762	13-55	Marl/mudstone
		33-68	infinity	Limestone

The results of the analysis indicates the moist lithology varies from very shallow(1.5 around the genfel river) to as deep as 27-57m in areas east of the road Mekelle-Wukro .The borehole log data of (BH27) is in good agreement to the results obtained from the VES. The water strike level of BH27 is 13 and 26m while the estimated depth to water depth from the work is 1.5-27m.

In general the aquifer is laterally and vertically extended to the area covered with limestone.

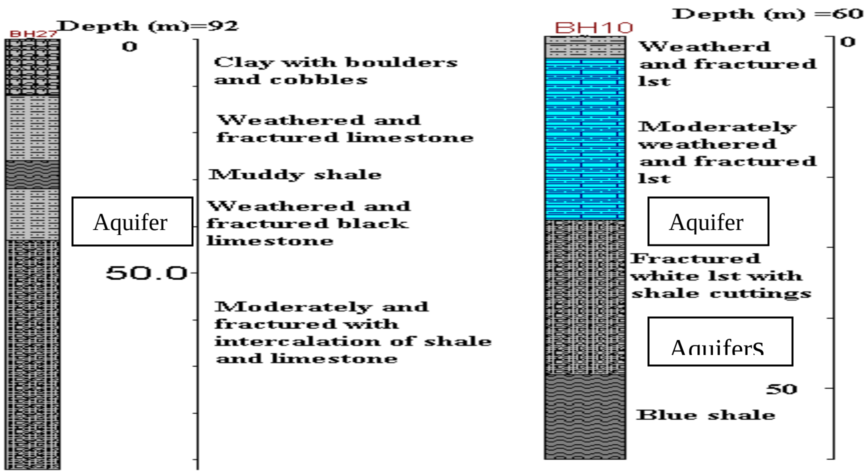


Figure 5- 4 Lithologic Log Representing the Limestone

5.3.6 Agulae Shale

It is shale dominated limestone that overlies the Antalo limestone. The exposure of this unit is found in the south east and southern and southwest in a Kebele called Debrebrhan and in the boundary between the study area and agulae town. It is friable and fissile when exposed and compact and intercalated with thinly bedded limestone. According to the borehole data BH39 and BH48 similar to previous well, the well near the boundary (extreme south) BH39 provide as high as 5 l/s. The Hydrostratigraphic of nearby area indicates the shale is highly weathered with intercalation of highly fractured limestone. The maximum thickness of this aquifer in the area is 33m. According to the log data the well could be drilled to a much deeper depth with increasing yield from the inter-beddings. The water level is 4m from surface which shows semi-confining nature.

5.3.7 Alluvial Deposits

As the result of weathering processes and transportation, there are alluvial deposits in the study area although the distribution and thickness is not appreciable. In the metamorphic terrain the deposition is from in suite weathering and reaches to depths of 2-3meter while in the sedimentary area, the deposition is both institute and on the river sides transport deposits .The thickness of the alluvial deposit reach to depths of 6- 12 meters. Those especially with thick silt to sand deposition are good source of very small irrigation practices. But there is no extended shallow aquifer and even the available aquifers are directly dependent on yearly rainfall.

Table 5-3 General classification of aquifers on the basis of qualitative and quantitative data

Type and degree of Permeability				
Type	**High**	**Moderate**	**Low**	**Very Low**
Intergranular Permeability	Alluvium	Alluvium	Alluvium,Agulae shale,Edaga Arbi glacials	
Fracture Permeability		Dolerite Trap vol. Adigrat sst Enticho sst		Dolerite Metavolcanic Metasediment
Fractured and karstic permeability	Limestone	Antalo lst,Alst-2 Antalo lst,Alst-5 Meta-carbonates	Antalo lst, Alst-4	

Source: Ezana Mining Develepment Plc.(1999)

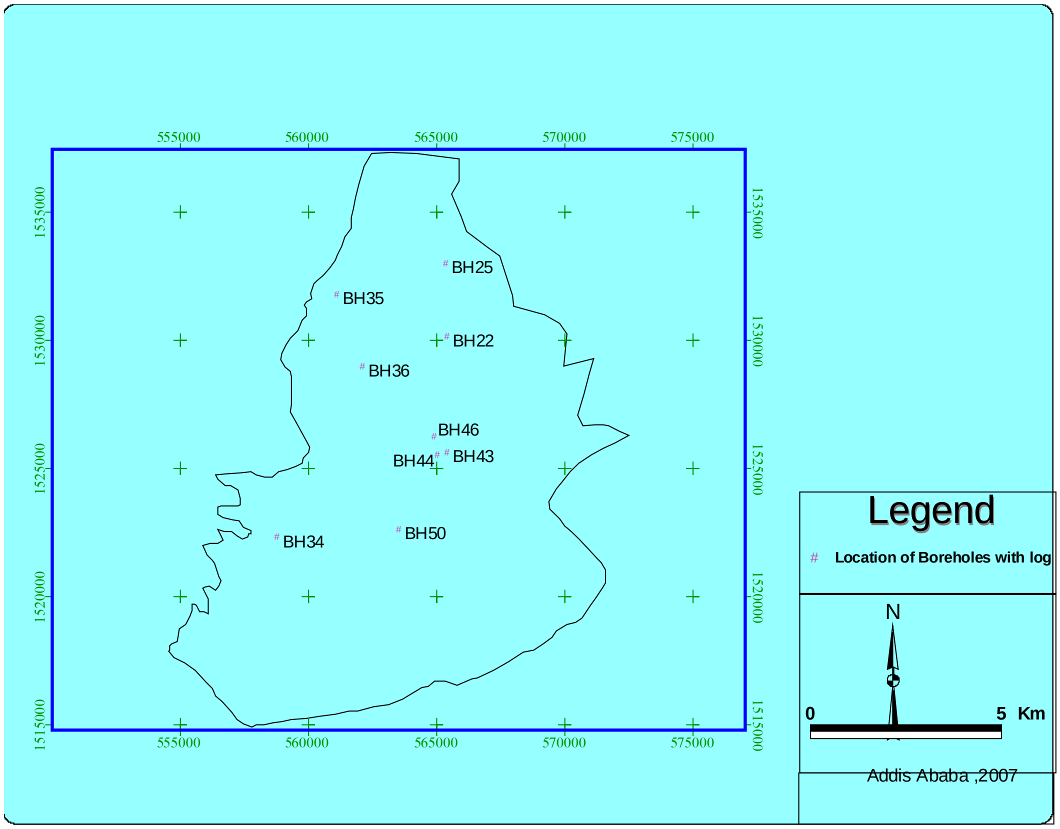


Figure 5- 5 Location of Borehole with Logs

5.4 Groundwater Recharge and Discharge Conditions

5.4.1 Direct Recharge

The study area has denser drainage in the metamorphic part where rock exposure is common and the soil type are clay loam to silty .The aperture, spacing ,interconnection ,orientation and thick soil cover of the metamorphic rocks enable the recharge to be facilitated in the rocks. Recharge in hard rock is dependent on nature of precipitation, the nature and thickness of the top soil, weathered zone and the topographic features.(UNESCO,2004). As the study area basement rock is highly affected by faulting and associated lineaments, the possibility of preferential recharge from flowing tributaries and the river that crosses the main wukro fault belts is high. In supporting this idea, the study conducted in one of the kebelles of the area (REST, 2001), the saturated hydraulic conductivity by permimeter of the sandy silt is as high as 0.0085826 cm/sec that indicates the possibility of high recharge through 3-6m thick soils which is found on the vicinity of the upper genfel river. Moreover, the solution cavities and kaverns observed on the area and the wide joints on the limestone are also the main source of direct recharge from precipitation.

5.4.2 Indirect Recharge

There are three small ponds which are distributed in the north, southwest and south of the study area. Among the three ponds only one is still holding a good amount of water. The two are failed to hold water due to the subsurface geologic structure. Therefore, the water percolated to the ground indicates that the recharge to the subsurface groundwater is not only controlled by soil moisture surplus (recharge) but from indirect recharge.

During the calculation of the soil water balance method the surplus was very much lower than the river hydrograph base flow .So the cause of this difference is due to the preferential recharge and indirect recharge which are not accounted in the soil water balance.

In addition to this, the out flow calculated with Darcy method is also higher than the inflow contributed by the study area of the big hydrograph basin. Thus, this is due to inflow from surrounding catchments which are adjacent to the sub-basin. Because groundwater flow from the adjacent catchment is controlled by the laterally extended limestone and shale intercalated beds.

5.4.3 Discharge

As the discharge area is plane to gentle in topography, there are shallow dug wells which strike water at depths shallower than 3 meters and also there are some semi perennial springs observed in the most south of the study area.

The recharge and discharge conditions are indicators of groundwater flow direction. This is also observed by the rise in groundwater level conditions in the shallow unconfined aquifers and the distribution of electrical conductivity and pH (see figure 6-2 and 6-3).

5.5 Groundwater Flow

Groundwater flow is determined from piezometeric levels of 31 boreholes from the study area and 4 from near by representative areas. The Piezometeric level wasn't measured at field but taken from the completion data sheets of different organizations. The Piezometeric level point data is plotted using Surfer and interpolated to create water level equipotentiometric and vector flow direction is plotted perpendicular to the potentiometer surface. But due to the difference in pressure affected by the intense tectonic in the area, the flow is quite exaggerated. Therefore, the most representative piezometeric level is taken to draw manually considering the drainage, the structure and the topography.

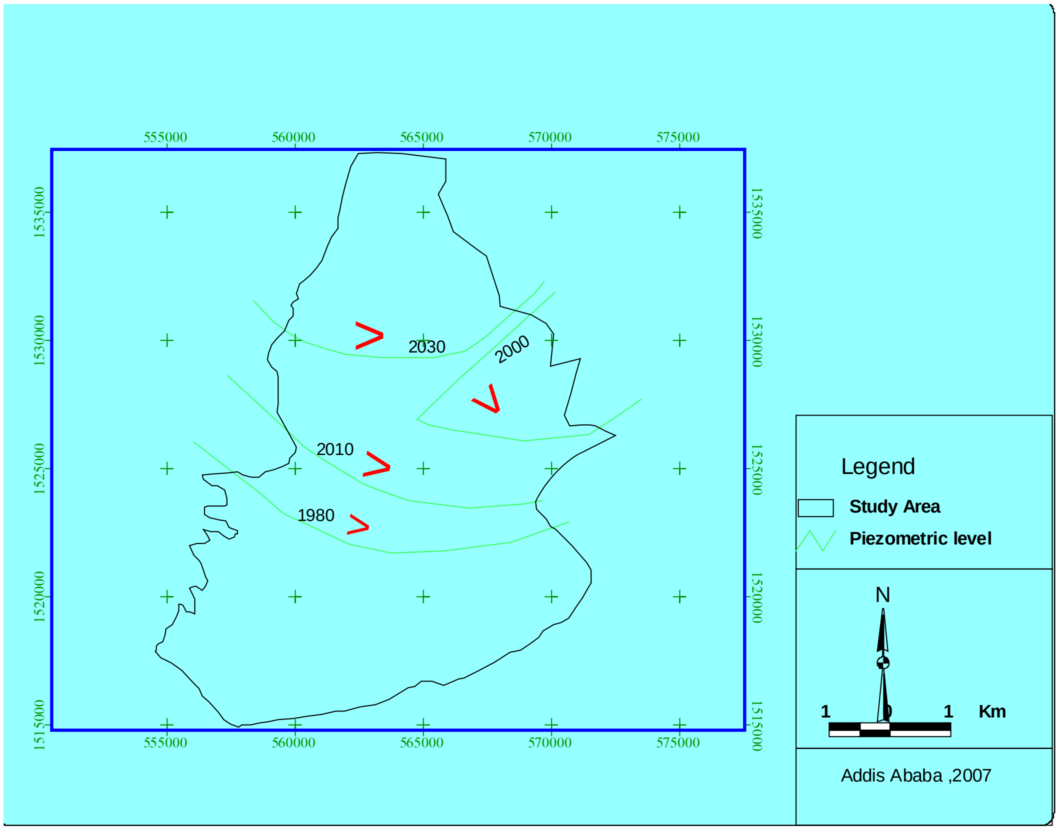


Figure 5- 6 Groundwater Flow Direction

5.5.1 Structural Control of Groundwater Flow

The metamorphic part of the area is highly affected by tectonics that resulted in wukro fault belts and the lineaments that trend in similar orientation against to the direction of flow the major faults. (See figure 2-10). The direction of flow of the tributaries are aligned to some degree to the lineaments while the genfel river crosses the main faults in an angle less than 90^0, the general trend of the fault is NW-SE while the river is NE-SW Therefore, the groundwater movement in these metamorphic rocks is controlled by the minor and major structures complementing Intergranular pore spaces.

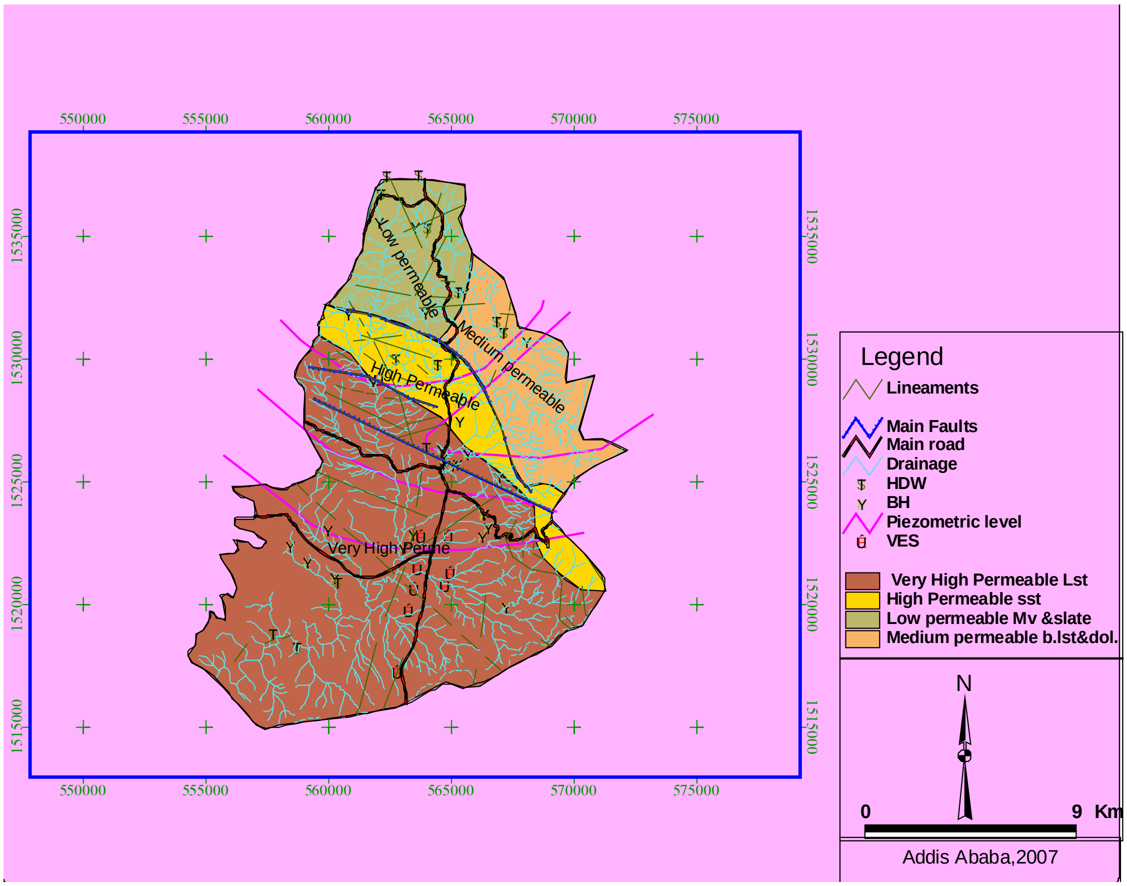


Figure 5- 7 Hydrogeological map of the study area

5.6 Water Sources

There are some boreholes and hand dug wells in the study area. But most of them don't have recodes of log, pump test and other important information. Hence, it is attempted to use the few in number wells which have completely fulfilled the necessary data. And it is complemented with qualitative field observation data.

There are four productive wells that supply water to wukro town, located in the Adigrat sandstone and limestone. The borehole(BH44) that is drilled in the limestone is in the vicinity of the wukro main fault that crosses the genfel river and also brought in contact limestone with adigrat sandstone(see fig. 2-10).Where as the remaining are drilled in the Adigrat sandstone in 1992-1993 by the then WASA. Other two wells are from Alshaday Children's Village, wukro for orphan school. They have well completed document. Two from Ezana Mining Development for rural water supply ,one from Tigray Water Works Construction Enterprise and one from Relief Society of Tigray and also one from Tekeze water wells drilling Enterprise..

The rest boreholes and dug wells are for rural water supply scattered in many kebelles .Some of the boreholes are tested with compressor for estimation of yield.

In general, about 39 boreholes and 17 Hand dug wells are used during this work to understand, the overall hydrogeological characteristics of the geologic formations.

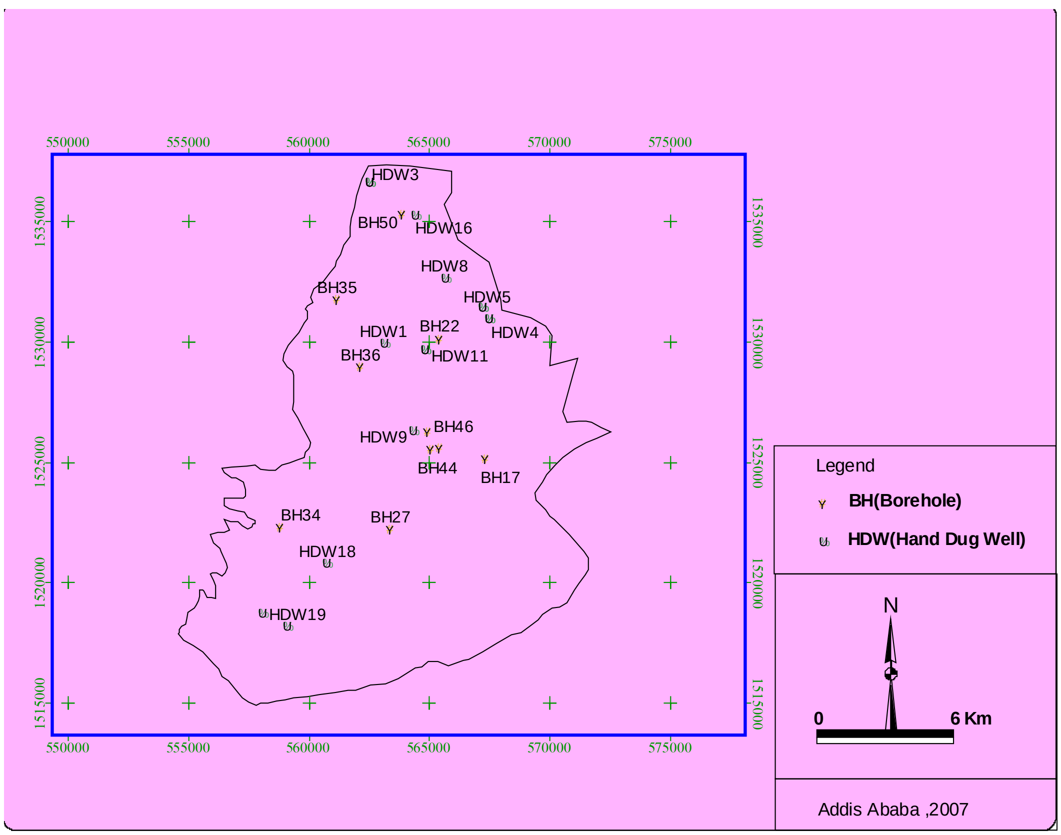


Figure 5- 8 Water point location map

5.7 Aquifer Characterization

Most of the borehole data obtained form the study area lack log and the pump test data, the yield is measured by compressor, therefore, the need of qualitative field data is important to get reasonable decision for the aquifer characterization.

The water level and piezometeric measurement results obtained from the different wells in the sub-basin indicates that the aquifer type comprising of unconfined in the hand dug wells dug in the alluvial underlined by weathered and fractured rocks; confined to semi-confined in almost all the wells drilled in the sub-basin irrespective of geological variation. The northern, central part of the area is under single semi-confined fracture aquifer while the Southern part that is dominated by limestone and shale are multilayered leaky aquifers. The water table that penetrates the permeable layer stands above or below the water table in the aquitard, which means that there is an exchange of water between the two layers (Boonstra.,1997).That is there is down or upward seepage from the aquitard.

The characterization of aquifer is dependent on the nature of Hydraulic conductivity, Transmissivity, storativity and specific discharge of the wells found in the area of interest.

5.7.1 Hydraulic Conductivity

Hydraulic conductivity of an aquifer is the volume of water that will move through a porous medium in a unit time under a unit hydraulic gradient through a unit area measured at right angle to the direction of flow, it has any unit of length and time (meter/day) .It is also the constant of proportionality in Darcy’s law. (Kruseman 1990). The hydraulic conductivity of fracture rocks depends largely on the density of the fractures and the width of their aperture. The hydraulic conductivity of carbonate rock is mostly depending on the fractures and associated secondary porosity .In most cases the hydraulic conductivity ranges 10^{-3}-1 m/d while for fractured or weathered rock is almost 0-3 x10^{2} m/d.

The hydraulic conductivity of the study area in the semi-confined fractured aquifers is dependent on the double porosity that is aquifer matrix blocks and aquifer fractures. (Kruseman, 1990).

The hydraulic conductivity of the hard rock formations of the study area is generally very low in hydraulic conductivity. The available data of one borehole drilled in metavolcanic formation has 0.02m/d and also one well (BH25) in the metasediment have 0.049m/d.

While for leaky aquifer the hydraulic conductivity is controlled by Intergranular porosity, hydraulic resistance(c) and Leakage factors (L). (See table 5-6)

The hydraulic conductivity of the limestone intercalated with shale is higher when it is compare to the other types of formation. The hydraulic conductivity of this formation ranges from 0.15-11.87m/d.

5.7.2 Transmissivity

It is defined as the rate of flow of a unit volume of water under a unit hydraulic gradient through a cross section of unit width over the whole saturated thickness of the aquifer. It indicates how much water will move through the formation. It can also define as the product of average hydraulic conductivity "K" and the saturated thickness 'd' of the aquifer.(Zekia Sen.,1975) the transmissivity of the double porosity is dependent on the transmissivity of the rock matrix and fracture rocks .These media have their own characterstics property. Where as the transmissivity of leaky aquifers are also dependent on transmissivity of the aquifer and the aquitard.The wells drilled in the study area is ranging from the moderate to weak except the wells in metavolcanic that are grouped as negligible.Zekai Sen (1995) has classified aquifers potential based on Transmissivity values(See table 5-4)

Table 5-4 Aquifer potentiality

Transmissivity (m^2/day)	**Potentiality**
T>500	High
50<T<500	Moderate
5<T<50	Low
0.5<T<5	Weak
T<0.5	Negligible

5.7.3 Specific capacity

The specific capacity of a well is defined as the ratio of discharge "Q" to the drawdown "s_w" in the pumping well (Q/s_w). It gives some information about the behaviors of the well and its productivity. Wells are said to be productive if small drawdown are coupled with high discharges. The larger the specific capacity of a well the better is the well. (Zekai Sen., 1995).The wells drilled in the study area have Moderate to low productivity. For instance, the wells in Antalo limestone are (0.32-6.19) l/s/m and metamorphosed carbonates (2.29) (l/s)/m, metavolcanic rock have the lowest productivity from the wells in the area. (See table 4-5)

Table 5-5 Classification of wells based on their specific capacities (Zekai Sen, 1995).

Specific capacity (Q/s_w) in [(l/s)/m]	**Well productivity**
$Q/s_w > 5$	Highly productive
$0.5 < Q/s_w < 5$	Moderately productive
$0.05 < Q/s_w < 0.5$	Low productive
$0.005 < Q/s_w < 0.05$	Very low productive
$Q/s_w < 0.005$	Negligibly productive

Although it is not complete, the following table is presented to compare hydraulic parameters and help in characterizing the aquifer of the study area.

Table 5-6 Hydraulic data of quifers taken from the available boreholes.

Formation	**Yield (l/s)**	**Sp.capacity (l/s/m)**	**Transmissivit y (m^2/d)**	**Permeability (m/d)**
Alluvium				
Agulae shale	5	Not Available	Not Available	Not Available
Antalo lst	0.25,3,4,8.23,4	0.32,6.19,0.92	65,261.42	0.15,0.38,11.87
Adigrat sst	0.54,3.17,3.3,3.88,6.59,5	0.4,0.03,0.75,	6.25,100,196.05,	0.18,8.81
Edagarbi glacial	Not Available	Not Available	Not Available	Not Available
Enticho sst	3,0.7	0.79,0.83	42,110	7,3.14
Metacarbonates	3	2.29,		
Metasediment	4,1	0.1	0.049	0.0054
Metavolcanics	3,.05	0.007	0.144	0.02

The 8 available wells with pumping test results are tested with constant discharge and draw down data are collected from the pumping well. The two boreholes of (Alshaday Child care) are tested for 24 hrs, three wells of (Water Wells Drilling Enterprise).for 42hrs , one of Ezana Mining Development plc for 1.5 days and one from Tekeze water well drilling plc for 48hrs. And one from Relief Society of Tigray. All tests do not reach to the equilibrium condition. When the log-log and the semi log-linear time-drawdown are plotted and compared to the log-log and semi-log of the model curves of consolidated fractured aquifers, borehole BH35 and BH25 from the metamorphic rocks have good similarities to the model curves. That indicates the boreholes are drilled in confined fractured aquifers. The graph also looks like the graph of unconfined aquifer with delayed yield. Because the water first contribution is from the fractured aquifer and later the contribution from matrix blocks after some delay time which make both the unconfined and hard aquifers similar. This is the first step in choosing the methods for calculating the aquifer parameters. Moreover, the boundary conditions should be clearly identified; otherwise the methods used may give erroneous results. (See figure 4-7 semi log time-draw-dawn curve).

The sedimentary rocks cover the largest part of the area. All the water levels collected from this geologic setting shows semi-confined, having aquitard as confining layer both in the sandstone, limestone and shale.

The method that comprises the conditions for calculating transmissivity for confined leaky aquifer is the Hantush method for (leaky confined aquifer, no aquitard storage).

This method works with the principle that most confined aquifers are not totally isolated from source of vertical recharge, less permeable layers, either above or below the aquifer can leak water into the aquifer under pumping condition. The equation given by Hantush is later modified to give the following equation

$S = Q/4\Pi T\ W(u,r/L)$ Hantush and Jacob solution(1955)

Where

$U = r^2/4\Pi T\ 4$

There are many assumption mentioned for this equation please refer the aquitest help manual for further information.

Using the available time –drawdown of constant discharge tests for the confined fractured aquifers and for the multilayered semi-confined leaky aquifers .The radius of the well is considered as the observation well. Because the equation requires observation well. The Transmissivity and storativity are calculated by the user friendly waterloo Hydrogeologic aquitest soft ware. And the results of the software and the response of the wells to draw-dawn and recovery tests are observed. The wells in the confined fractured aquifer except the dolomite dominated slate, have very slow recovery compared to the semi confined leaky aquifers. This is resulted because, the lateral and vertical extent of the limestone aquifers is much extensive than the hard rock aquifers and similarly the Paleozoic Enticho sandstone confined by Edagarbi glacial shale, tilites response to recovery is a bit slower than the limestone aquifer.

In crystalline rocks, the maximum depth to get fractures is 100m ;(Clark, 1988) even it is shallower if there is no fracturing and siling of the fractures by weathering products. Accordingly the maximum depth of fracturing in the hard rock of the northern part of the study area is not greater than 70m.

Jacob straight line method for confined fractured aquifer of unsteady state is used to determine hydraulic parameters using the simplified equation for single well pumping condition.

$KD = 2.3\ Q/4\Pi KD$

for a single well test in confined aquifer

$t > 25 r_c^2 / KD$

If this time condition is met, the effect of well-bore storage can be neglected:

The Jacob straight line method can be applied for this case when the following conditions and assumption are satisfied.

1. The aquifer is penetrated fully
2. The aquifer is confined and infinitely latterly extend
3. The aquifer is homogeneous, isotropic, and uniform thickness over the area influenced by the test.
4. the piezometeric surface is horizontal
5. The aquifer is pumped at constant discharge rate.

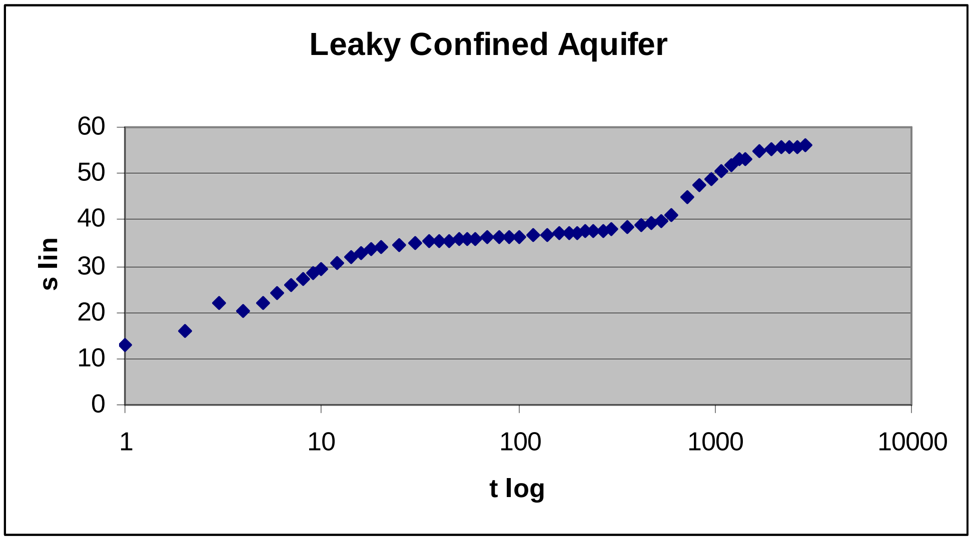


Figure 5- 9 Semi-log time –draw-dawn graph of the southern part of the study area

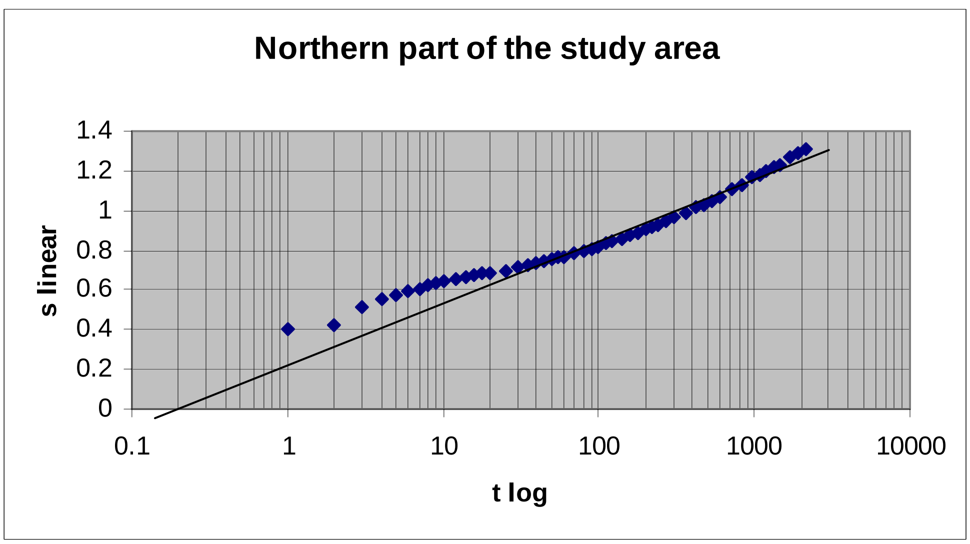


Figure 5- 10 Semi-log time-drawdown of the Northern part of the study area

The hydraulic parameters, Transmissivity, Permeability are determined only for some of them because there were wells having low yield and stopped pumping early.

Due to lack of enough and evenly distributed wells that can give information on the saturated thickness of the aquifers, all the wells are considered as water table aquifer and the saturated thickness is the thickness from the water strike to the end of the aquifer depth of the well. Kruseman (1990), also expressed that multilayered aquifer system consists of two or more aquifers, each with its own hydraulic characterstics, and separated by interfaces that allow unrestricted crossflow is analogous to that of a single layered aquifer whose transmissivity and storativity are equal to the sum of the transmissivity and storativity of the individual layers.

The study area is divided in to Four groups of potential areas based on permeability,Transmissivity and storativity data obtained from pump test analysis and from actual qualitative field observations .As the aquifers are limited in extent the reserve of the sub-basin could not be calculated for the whole aquifer represented by a single thickness of the confined fractured and semi confined leaky aquifers ,therefore, the aquifers are considered as water table aquifers with saturated thickness measured down from water strike level to the depth of penetration of saturated thickness of each four areas .Moreover, for the identification of the lower saturated thickness screen casing are also considered. Using this approach water available is calculated for each groups of hydro geologic environment. Therefore, available water available is calculated using saturated thickness, Areal coverage of each aquifer and specific yield given in the following (table5-7)

The specific yield is synonymy to effective porosity and is referred to as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table .The specific yield are used from the table developed after Johnson,1976

Available Water = specific Yield ($S_{y)}$ X saturated average thickness (D) X Areal coverage of the Aquifer (A)

$$= S_y \, XDXA$$

Table 5-7 Representative Value of Specific yield.

Formations	**Specific Yield (%)**
Gravel, coars	23
Gravel, medium	24
Gravel, fine	25
Sand, coarse	27
Sand medium	28
Sand, fine	23
Silt	8
Clay	3
Sandstones, fine grained	21
Sandstones, medium grained	27
Limestone	14
Dune sand	38
Schist	26
Siltstone	12
Tuff	21

Source: Freeze and cherry, 1979(Representative value of specific yield (after, Johnson, 1976)

The available water is calculated as follows

Table 5-8 Total Available water

No	Formation	Specific yield	Average saturated thickness(m)	Areal coverage(m^2)	Total available(m^3)
1	Sandstone fine to medium grained	0.24	15	25510785.596	91838826
2	Limestone	0.14	25	144079984.5	50427993
3	Phylite& Schist	0.26	9	25341980.632	59300233
4	Carbonate slate	0.14	15	125649992.342	26386498
Total					227953550

Therefore, the total available water of the wukro- genfel-sub-basin is estimated 227,953,550 m^3.

CHAPTE 6

6 Hydrochemistry

6.1 General

All groundwater originates as rain water that infiltrates through soils or fractured rocks into flow system in the underlying geological materials. (Fetter, 1979). Groundwater flow as subsurface base flow from recharge to discharge area, it undertake a series of geochemical reactions and processes.

The main objective of the hydrochemistry analysis is to determine the source, concentration and fate of dissolved constituents with in the physical frame work of flow and transport (UNESCO, 2004). Moreover, determine the quality of the water for human, agriculture and industrial use.

The analyzed water samples are of primary and secondary. Primary data are collected from representative parts of the study area, in terms of water bodies (points) and the geological setting and recharge and discharge conditions. Accordingly 4 boreholes, 1 pond, 2 Hand dug wells and 1 river water samples are collected. While the secondary chemical data are obtained from Ethiopian Water Well Drilling Enterprise(three well data), two well data from Ezana Mining Development Plc. And two well data from Child care Orphan School. In addition to water sampling, field measurements of EC, Temperature, and Salinity are conducted. (Figure 6-1). During sampling and measurement all safety precautions for sampling and handling are undertaken with great care in order to minimize the possible contamination and other relevant problems

The analyzed water is interpreted through user friendly waterloo software Aquachem 4.0. Before the start of graphical representation of the cations and anions, the Electrical neutrality that is the equilibrium interaction between water and geologic material is determined. Based on the Electrical neutrality (EN) problem about 4 water samples are rejected because the EN is much greater than 5%.

A variety of graphical methods (Piper, Collins and schoeller) are used .Statistical mean are also used to understand type of water available and the dominant cations and anions.

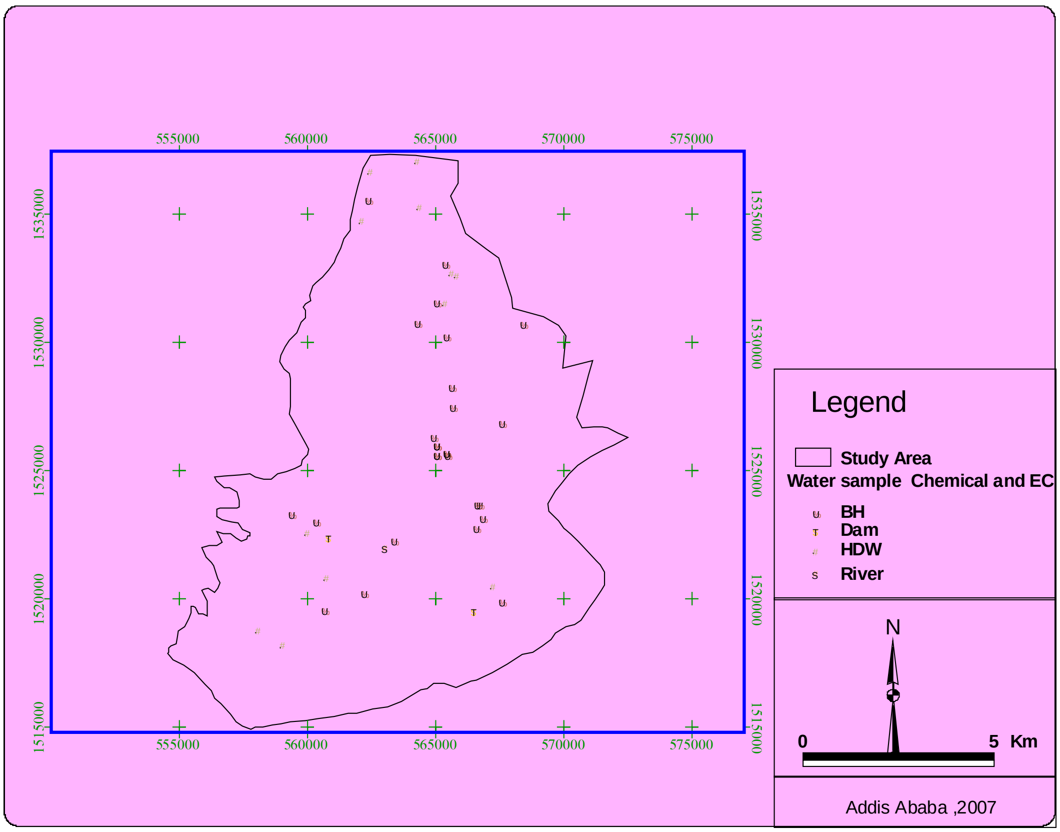


Figure 6-1 Water sample sites

6.2 Field Measured Parameters

6.2.1 pH

pH is the negative base ten logarithm of hydrogen ion activity in mole pre liter. It is the measure of ionic activities of H^+ and OH^-.Water with PH less than seven is acidic ,with greater than seven is alkaline and with equal to seven is neutral. 18 PH measurements is conducted in 6 Hand Dug Wells, 11 boreholes and 1 dam with minimum and maximum range of 6.8-7.8, 6.4-7.4 and 8.2 respectively in different parts of the area. The main reason for collecting the PH data is to understand the relation of PH to different geological materials. The emphasis is given to limestone that covers the majority of the area .When sufficient amount of carbon dioxide from atmosphere and unsaturated porous soil is available. Carbondioxide reacts continuously to produce H_2Co_3 and this weak acid dissolve the carbonate under specific PH conditions between 7-8.That indicates the dissolution of inorganic carbonates is under open system condition. Weathering reaction is associated with shifts in the acid/base equilibrium. Consider the dissolution of Ca-carbonate in carbonic acid

$$CaCO_3 + H_2CO_3 \rightleftarrows Ca^{2+} + 2HCO_3$$

As the pH value rise in open system with in the given range the H_2Co_3 consumed and HCo_3^- increase. For the case of closed system inorganic carbonate rocks in saturated media have limited supply of H_2CO_3 from the unsaturated and from the reaction of groundwater with rock. Thus, most of the hydrogen ions are consumed and enriched with $CO^{2-}{}_3$. In this case pH is mostly above 8.

Only one dam is 8.2 pH while the remaining 17 of the sampled wells are in pH range of 6.4-7.8. Thus the dissolution of the inorganic carbonate is under open system condition. In addition to this, PH is a good indicator of salinity that is a pH value of 8.5 or more with Na-saturation of 15%. Or more water is Salian. (HM Raghunath, 1982).

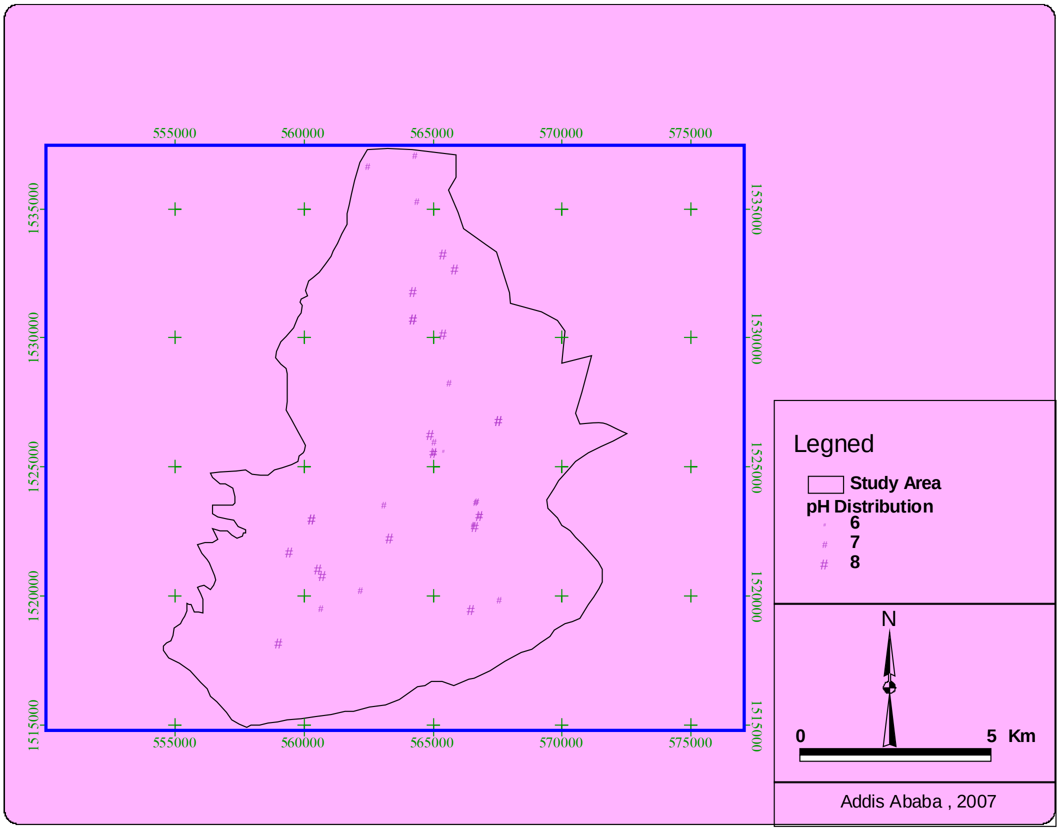


Figure 6-2 PH Distribution

6.2.2 Temperature

Temperature of the unsaturated and saturated area play a great role in the chemical evolution of groundwater while it moves from upstream to down stream. The dissolution of inorganic carbonate in shallower depth is higher as the low temperature favors the dissolution of inorganic carbonates. That is recharge areas in inorganic carbonates are saturated with calcite or dolomite , as it goes deep more precipitation will be observed while reaching the discharge area dissolution starts to increase as the water level get shallower and the temperature is low. But the deeper the well the less will be the dissolution of calcite or dolomite because the temperature increases with depth in most of the time.

Temperature of 13 HDW, 17 BH, 2 Dam and one river is measured with the amount of 19-22.9C^0, 20.6-25.5C^0 ,21^0 and 22^0 respectively. The temperature variation does not result an appreciable change among the wells as all are under similar open system influenced condition.

6.2.3 Electrical Conductivity

Electrical conductivity is the ability of a dissolved substance to transfer electric current. Thus Electrical Conductivity is directly related to the ionic concentration in water so as to conduct electric as faster as possible.

The electrical conductivity in the area differs from site to site and from area to area. In a radius of 2 Kms, a big difference between wells is observed that is attributed to a fault that brought in contact sandstone on the one side and limestone in the other side. And there is a general increasing trend to ward the limestone and even more toward the shale and limestone intercalation from recharge to discharge area. .In the study area the main factor for the increment of Ec is mainly concentration of cations and anions in the given geology and residence time. (See figure 6-2)

A total of 27 samples are measured for electrical conductivity among which 12 are HDW, 15 BH and 2 Dam. And the maximum and minimum concentration are tabulated (see table 6-1)

Table 6-1 the Maximum and Minimum EC Distribution

Type	Maximum	Minimum
BH	2952	0.00771
Dam	353	305
Hand Dug Well	1227	429

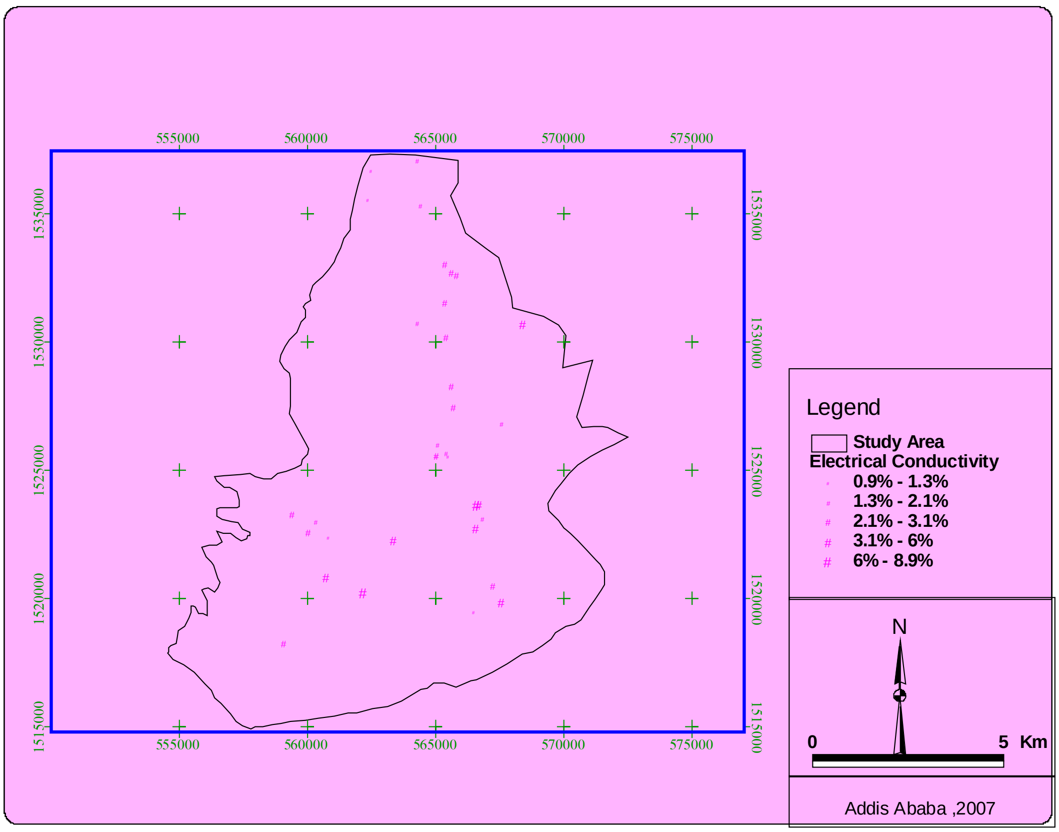


Figure 6-3 Electrical conductivity Distribution

6.2.4 Total Dissolved Solid (TDS)

Total Dissolved Solid is the measure of the solute that dissolved in water, this parameter is dependent on many geochemical and Hydrometerological and geological processes. It has been observed in ground investigations in many parts of the world that shallow groundwater in recharge areas is lower in dissolved solids than the water deeper in the same system and lower in dissolved solids than water in shallow zones in the discharge areas(Freeze and Cherry,1979)

In the study area, the TDS variation is mainly governed by the carbonate rock dissolution although the metamorphic terrains also contribute for the over all increase down to discharge from the recharge,

TDS wasn't measured at field level and even at laboratory because the sample stayed for some time during transport and it is feared the calcium will precipitate with in the sampling glass. There is strong correlation between electrical conductivity and Total dissolved solid (Tenalem and Tamiru, 2001), .As the result the concentration of dissolved salts can be estimated on the basis of electrical conductivity using the formula,

S=AK

Where K is electrical conductance in micromhos, S is a dissolved solid in mg/l and A is a conversion factor. For most groundwater the specific conductance multiplied by a factor 0.55 to 0.75 gives reasonable estimate of TDS.But the factor varies for saline and acid solutions.

Using the above minimum and maximum conversion factor, the minimum and maximum TDS of the study area is in the range of 43 and 2214mg/l respectively The acceptable limit for human use is 500 mg/l but is not objectionable up to 1500 mg/l. so the groundwater of the study area is below the objectionable limit except Boreholes WP 18, WP 19 and Wp 29 which have above 1900 mg/l total dissolved solid in the limestone, dolomite. And even for irrigation consumption it is a bit higher than the upper limit(see table) .But for industrial purpose, it depends on the type of industry and type of product is producing (HM.Raghunath,1982), the bore holes in the sandstone , metamorphic rocks and dug wells in the shallow aquifers are very low in TDS .

6.3 Laboratory Measured Geochemicals

The evolution of major cations (Ca, Mg,Na and Mg)and anions(HCO_3,SO_4,NO_3 and Cl) are mainly depend on the overall geochemical processes , Geomorphologic and Hydrometerological characterstics of the area .For water resource studies ,priority need to be given to the analysis of this major ions which constitute around 99% of the mineral content of most of the natural water. The physical and chemical processes that take place in the geological materials are the driving factors for geochemical evolution of saturated part of the subsurface. Therefore, the understanding of these factors helps in interpreting the spatial variation in water chemistry and defining groundwater flow paths and characterization of the hydrologic system.

Water sample for chemical analysis are collected from 6 BH, 2 HDW, 1river and 1 dam. Moreover, six analyzed chemical data are collected from previously sampled water by two different companies.

6.3.1.1 Graphical presentation of the Laboratory Measured samples

Graphic representations are useful for display purposes, for comparing analysis, and for detecting the mixing of water of different compositions and in identifying chemical processes occurring as groundwater moves. (Freeze and Cherry, 1979)A lot of graphic techniques has developed and make ease the understanding of evolution, facies changes and interactions of hydrochemicals.

6.3.1.2 Piper's Trilinear Diagram (1953)

The diagram consists of two lower triangular fields and a central diamond –shape field. All the three fields have scale reading in 100 parts. The percentage reacting values of the cations and the anions are plotted as a single point at the lower left and right triangles rescpectively.These are projected upwards parallel to the sides of the triangles to give a point in the rhombus. This point represents the chemical characteristic of the water and it is possible to determine the type of water under question.

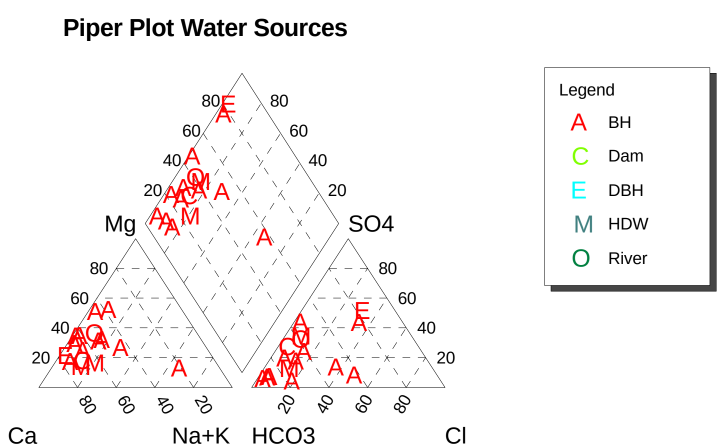


Figure 6-4 Piper's trilinear diagram of All water source

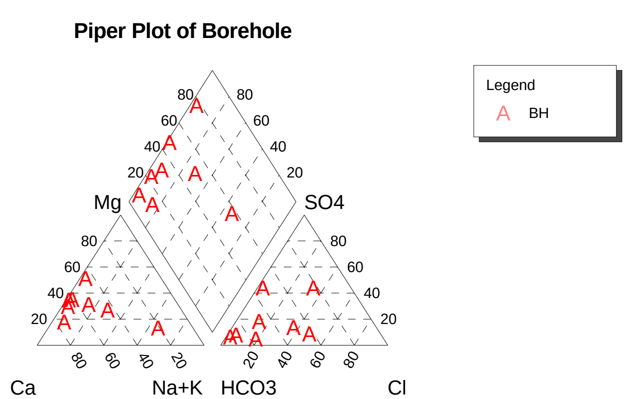


Figure 6-5 Bore hole piper plot

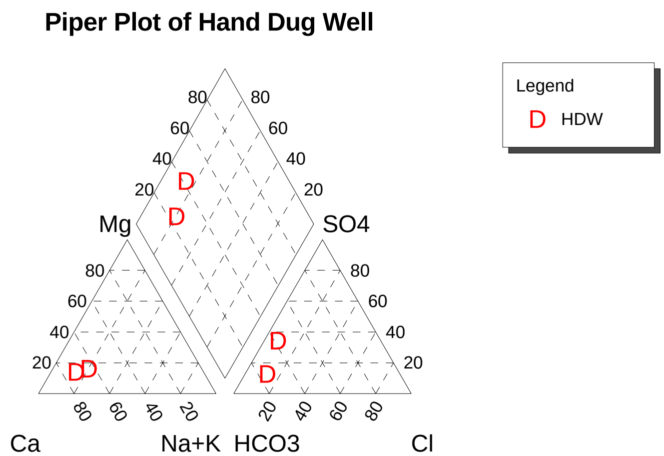


Figure 6-6 Hand Dug Well Piper Plot

From the piper's diagram we can observe that the over all composition dominating the area water source is Mg-Ca-HCO_3 and Ca-Mg-HCO_3 and type water, and water samples from the Metavolcanic rocks are Mg dominated Mg-Ca-HCO_3 Facies .These types of water are found in the northern part of the study area (recharging area).This may be related to the Magnesium and Calcium rich minerals of the metavolcanic rocks or else due to the magnesium and Ca rich carbonate low grade metamorphic rocks. Moreover, there are Mg-Na-HCO_3 and Mg-Na-Ca-HCO_3-Cl type water in BH50 and BH51 which shows a mixing and early cation exchange. Some Deep borehole having Ca-Mg-So_4-Cl in the discharge area are observed, the cause of this facies change in the water is related to the joint effect of the geochemical evolution of groundwater while it is moving from the recharge to this area and the geologic formation of the discharge area. But the dominant factor is the geology and time of residence of the groundwater. The mentioned type of facies is found in fossiliferous limestone with shale intercalation.

6.3.1.2.1 Anion

Anions in groundwater tend to evolve chemically along flow path and increasing age. It starts with carbonate to carbonate –sulphate then to sulphate-carbonate and then to sulphate- chloride and finally to chloride-sulphate and chloride. But this facies change is dependent on scale and geology of the specific setting with allowance for interruption and incompleteness.Cheboranev (1955) cited in (Freeze and Cherry, 1979).

Although there is variation of anions comprising of Carbonate, carbonate-sulphate, sulphate-carbonate and sulphate-chloride anions distribution in the study area but does not follow the mentioned groundwater flow path and age sequence from recharge to discharge areas. Because the area is highly affected by tectonic structures that brought stratigraphically different lithologies into juxtaposition more over the presence of different in age and geology rocks from site to site. The northern part where the metavolcanic rocks dominated are HCO_3 dominant as it is the recharge area with excess atmospheric carbondioxide under open system and chloride and sulphate ions are not significant constituent of silicate rocks and there is no tendency toward development of sulphate and chloride anions facies as groundwater moves along flow paths in these rocks. (Freeze and Cherry, 1979)while in one borehole (BH 50) Northeast of the area with a unique sulphate anion containing groundwater is observed in the metamorphosed black limestone dominated area. This occurrence may indicate the presence of sulphate containing protelite sediment for the metamorphosed black limestone in that locality. Sulphate originates from the oxides of sulphide ores or the solution of gypsum anhydrite. (Boonstra, 1997).There is carbonate –chloride anions in two boreholes (BH46 and BH43) as there are clay and mudstone intercalation with sands in the borehole log which have chloride in their component. Where as wells (BH27 and BH26) that are very close to the previous wells have only Carbonate anion. This is resulted from the limestone and sandstone rocks that are observed in the logs.

The dominant anion in southern part of the study area where the dominant rock type is fossiliferous limestone intercalated with shale is Carbonate-sulphate. Although there is limitation of borehole logs in this area, the analysis indicates the presence of sulphate containing rock in the layers. Even the river water sampled in this vicinity clearly shows similar anion constituent. The anion concentration of one well (BH27) drilled to relatively deeper depth (92m) than the other wells in the vicinity has Sulphate- chloride anion constituent. This stage shows clear facies change to a depth that could be expressed in relation to residence time and dominant fossiliferous and chloride rich mineral presence at depth. (See figure map of 6-7)

6.3.1.2.2 Cations

As the chemical evolution of groundwater in carbonate rocks the dissolution of feldspare, micas and other silicate minerals is strongly influenced by the chemically aggressive nature of water caused by dissolved $CO_{2,}$ when CO_2 charged waters that are low in dissolved solids encounter silicate minerals high in cations, aluminia and silica, cations and silica are leached, the cations released to the water are Na, K, Mg, and Ca (Freeze and Cherry, 1979). And according to (UNESCO, 2004) the dominant cations in Feldspare, oliven, pyroxene amphiboles, mica and Mg-calcite are Ca, Mg, and Na. K is immobile and rarely observed in groundwater. The groundwater type (WP4) of the upper most north of the area is dominated by Ca^{2+} anion where the area is covered by metasediment (schist and phylite) rocks. The possible source of this cation is the protelite carbonate, gypsum and feldspars. The central part is dominated by Mg-Ca, where the dominant logged lithologies are metavolcanic (Feldspare, oliven pyroxene and mica), black limestone (Mg-calcite or dolomite) and then follows by mixed type of Mg-Ca, Mg –Na-Ca, Ca-Na and Ca. which varies with in short distance. This part of the area is located where the tectonic structures are highly concentrated causing stratigraphic difference that brought up or down the young or old formations. The lithologies found in the logs of the boreholes drilled indicate sandstone, sandstone with thin interlayer of shale/clay and mudstone and thickly bedded limestone. Thus the introduction of Na in to the system is related to the ion exchange result of Ca and Mg with Na. Far to south the dominant cations are Ca-Mg and Ca .This is directly related to the geological formations present in this area that is fossiliferous limestone (BH27 and WP 8). (Figure of 6-7)

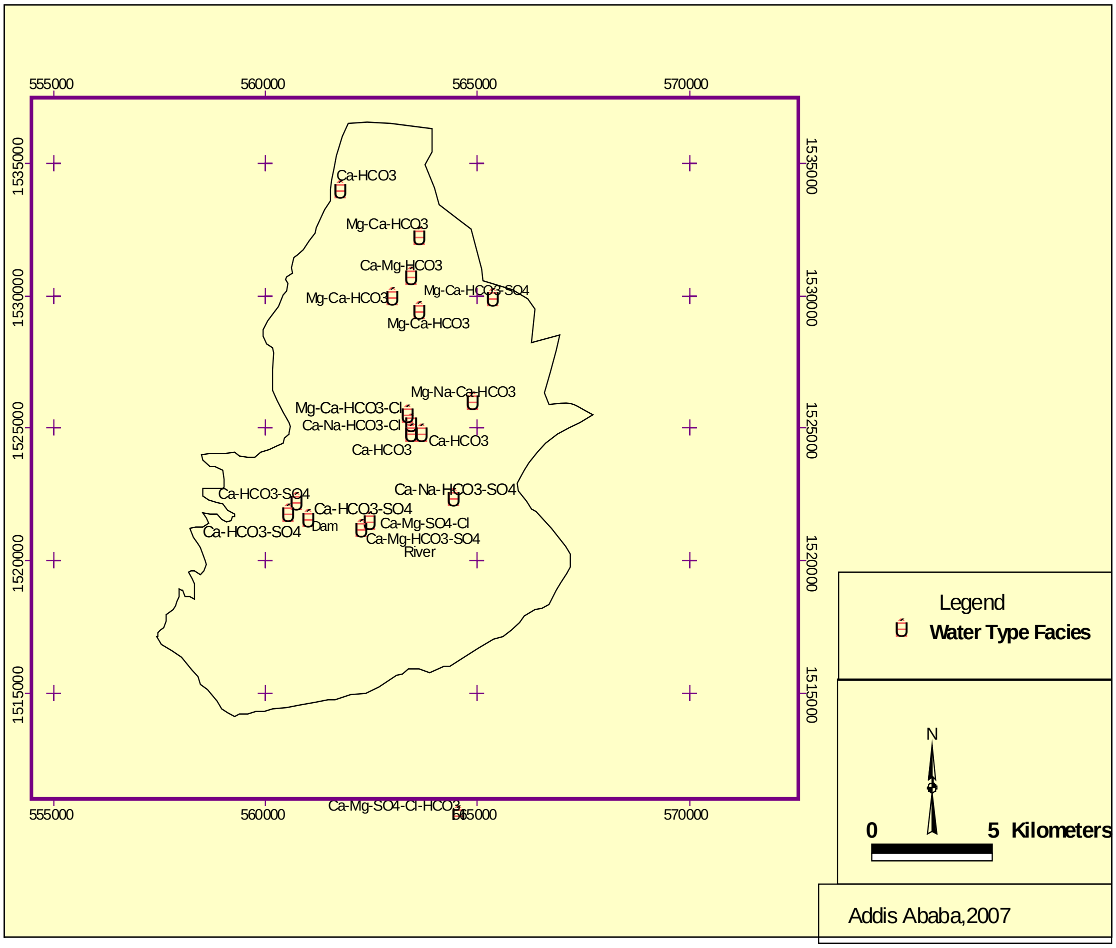


Figure 6-7 Water type Distribution

The following figure (6-8) shows the relation of cations with respect to the Total Dissolved Solid. Thus, The K versus TDS relation is not in a way that enriches the dissolution and is not co relatable with increasing TDS.While for the case of Na verses TDS, There is a tendency of increasing with increasing TDS but not appreciable. The relation of Ca Versus TDS has linear relationship that indicates the total dissolved solid increase with increasing Ca ions, Moreover, Mg versus TDS has also show linear relationship although it is not equal to Ca. In general, the dominant contributor of dissolved solid came from Ca and Mg with very small amount from Na and K

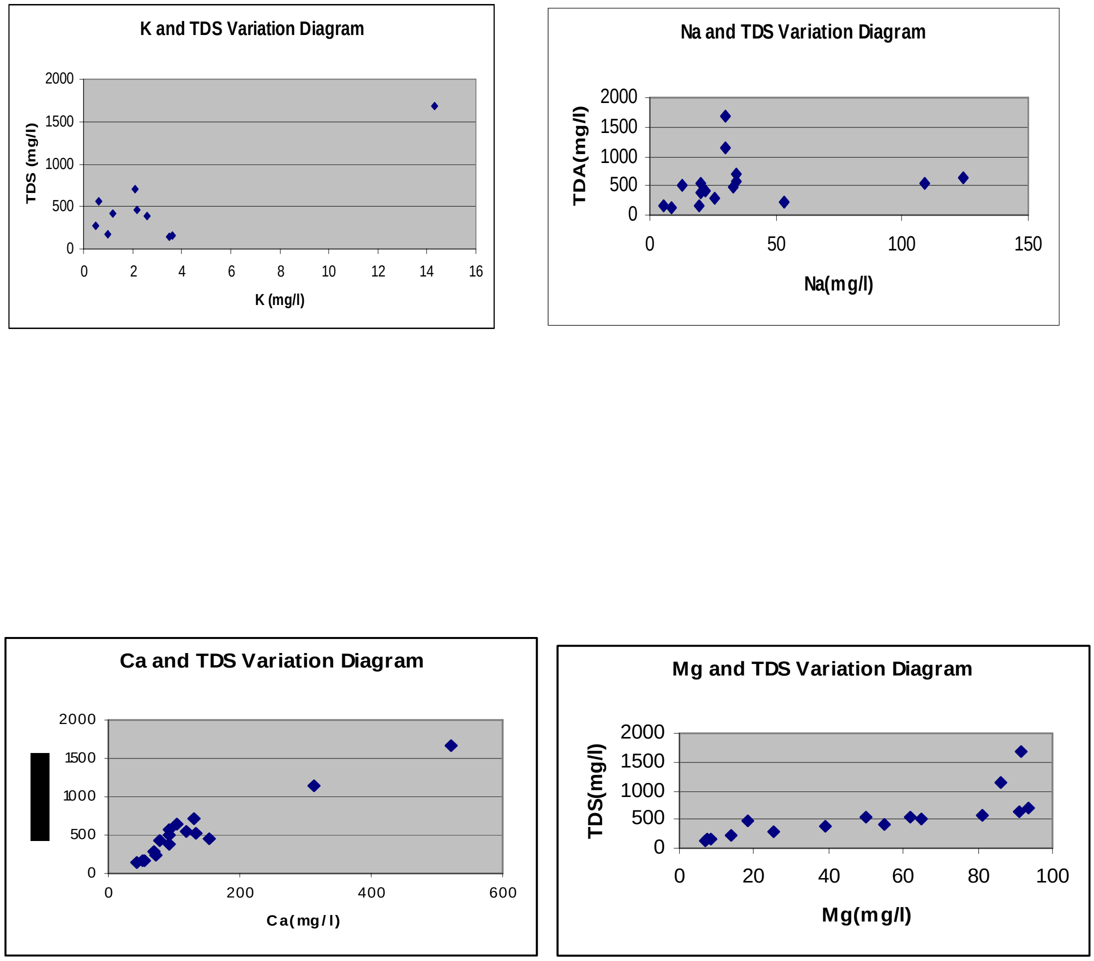


Figure 6-8 Variation Diagram of Cations with TDS

6.3.1.3 Schoeller plot

Schoeller Plot gives well organized and easy to understand relations of cations and anions concentration. Thus enable to determine the possible water type of the study area from dominant cations and anions.

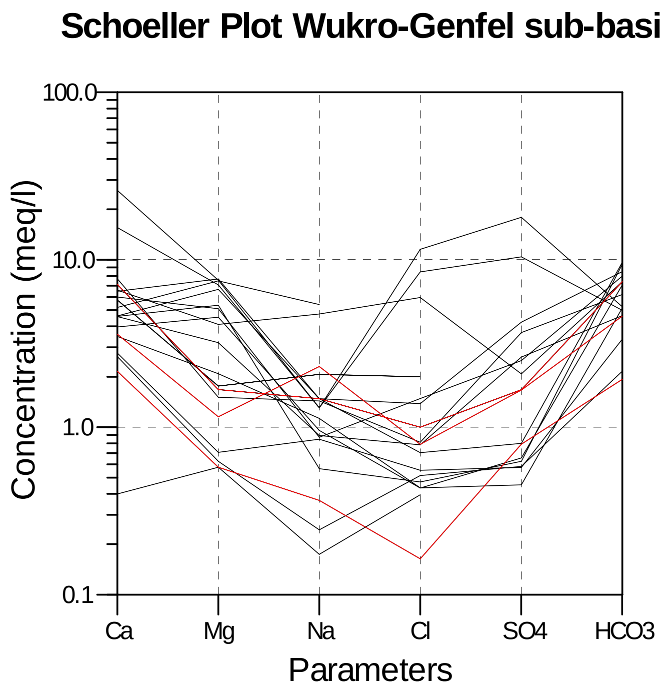


Figure 6-9 Schoeller plot of cation and Anion Concentration

6.4 Sodium Adsorption Ratio (SAR)

The classification of water for irrigation is based on the sodium concentration because sodium reacts with soil to reduce its permeability. Sodium saturated soil will support little or no plant growth. The presence of sodium with carbonate predominant anion is termed alkali soils. (Todd, 1995). The salinity laboratory of the US department of agriculture recommended the SAR as an index for sodium hazard and defined it as:

$$SAR = \frac{Na}{\sqrt{ca + Mg/2}}$$

Where the concentration of the constituent are expressed in miliequivalent pre liter

Out of the 18 samples only three are in the range 1-2.1 while the remaining 15 samples are below 1.Generally, the groundwater is good enough for irrigation in terms of SAR. (See figure on Salinity)

According to Driscol (1986), adjusted SAR is calculated from the following equation:

$$Adj.SAR = \frac{Na}{\sqrt{ca + Mg/2}} [1+(8.4 - pHc)]$$

Where Na, Ca and Mg are in meq/l from the water analysis. A nomogram for determining

$\frac{Na}{\sqrt{ca + Mg/2}}$ is used .The pHc (a theoretical calculated pH of the irrigation water in contact with lime and in equilibrium with soil CO_3) and is calculated using the following equation:

$$pHc = (pK'_2 - pK'c) + p(Ca + Mg) + p(Alk)$$

where

$(pK'_2 - pK'c)$ is obtained from the standard table using the sum of Ca +Mg in meq/l.

p(Ca +Mg) is obtained from the standard table using the sum of Ca +Mg in meq/l

p(Alk) is obtained from the standard table using the sum of $CO_3 + HCO_3$ in meq/l.

(annex)

The sample water of the study area do not have CO_3. Thus, the calculation of adjusted SAR was not applied.

The Values of pHc above 8.4 indicates a tendency to dissolve lime from the soil through which the water moves; a value below 8.4 indicates a tendency to precipitate lime from the water applied.

6.5 Salinity

Salinity is the total dissolved solids expressed as parts per thousand of unit weight of water (UNESCO,2004).The US Regional Salinity Laboratory has constructed a diagram for classification of irrigation waters, with reference to SAR as an indeed for sodium hazard S and Ec an an Index of salinity hazard C.

Table 6-2 Quality Classification of irrigation Water

Water Class	Salinity Hazard		Alkali hazard(SAR)	RC in Me/l
	Ec in micro mhos/cm at 25c0	Salt conc,in me/l		
Excellent	<250	<.25	Upto 10	<1.25
Good	250-750	0.25-7.5	10-18	1.25-2.5
Medium	250-2250	7.5-22.5	18-26	>2.5 poor
Bad	2250-4000	22.5-40	>26	
Very Bad	>4000	>40		

Source: HM Raghunath, 1982

Thus according to the IS 2296-1963 cited in HM Raghunath the following chemical parameters are also included: Cl<600, So4 <1000 Ppm and Exchangeable sodium percentage (ESP) <15, B<250 micromhos/cm.

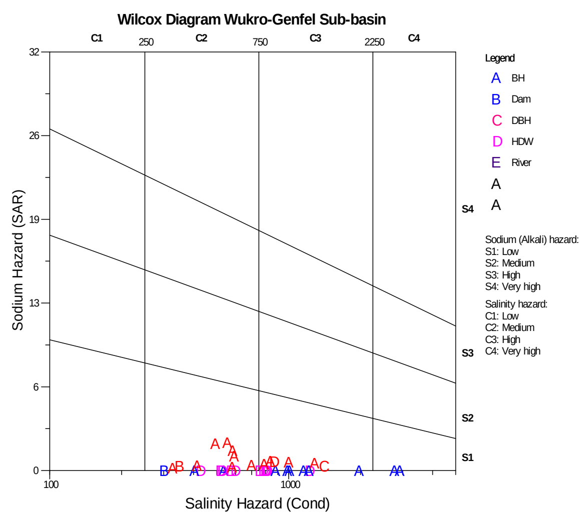


Figure 6-10 Salinity and Sodium Hazarded Plot

Where

C_1: Low salinity hazard — S_1: Low sodium hazard

C_2: Medium salinity hazard — S_2: Medium sodium hazard

C_3: High salinity hazard — S_3: High sodium hazard

C_4: Very high salinity hazard — S_4: Very high sodium hazard

N.B. only the extremes are labelled in the Wilcox plot.

Therefore, the water of Wukro-Genfel sub basin falls in sodium hazard class of S_1 which is low in sodium hazarded. But the Salinity hazard falls in the class of C_2-C_4 that is medium to very bad water class. Therefore serious follow up is required while it is used for irrigation purpose. Soil Stalinization in arid-semi arid regions is directly related to the depth to groundwater and the salinity of the groundwater. (Boonstra, 1997).

According to Driscol (1986) the medium salinity (C_2) water of the study area can be used where a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases with out special practices for salinity control But high salinity (C_3) can not be used on soils that have restricted drainage. With adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected. Moreover, very high salinity water (C_4) is not suitable for irrigation under ordinary conditions. If used, the soils must be permeable, drainage must be adequate, considerable excess irrigation water must be applied and very tolerant crops should be selected.

The low sodium water (S_1) of the study area can be used with little danger on nearly all soils. Sodium –sensitive crops such as avocado which may accumulate injurious concentration of sodium.

6.6 Hardness

Hardness results from the presence of divalent metallic cations, of which calcium and magnesium are the most abundant in groundwater. The hardness in water is derived from the solution of carbon dioxide, released by bacteria action in the soil, in percolating rain water. The low Ph condition develops and leads to the solution of insoluble carbonates in the soil and in limestone formations. (Todd, 1995)

Hardness is usually expressed as

$$H_T = Ca \text{ X } CaCo_3/Ca + Mg \text{ X } CaCo_3/Mg$$

Where, H_T,Ca, and Mg are measured in milligram per liter and the ratios in equivalent weights

$$H_T = 2.5Ca + 4.1\ Mg$$

Table 6-3 Hardness Classification of Water (after Sawyer and McCarty)

Hardness, mg/l as $CaCo_3$	Water Class
0-75	Soft
75-150	Moderately hard
150-300	Hard
Over 300	Very Hard

Only one percent of the sampled water is in the range of hard but the remaining 99 percent are in the very hard range. Therefore, ion exchange has to be used for softening the water in order to use for domestic purpose.

CHAPTER 7

7 Synthesis

The Hydrometerological parameters; precipitation, wind speed, relative humidity, temperature and sunshine hours are employed to calculate the mean annual potential evapotranspiration of the study area using Penman-Mentioth combination method, Thornthwaite equation and Masmstrom method (1969) . Since the penman-Mentioth method comprises of many component parameters and also the Thornwaite potential evaporation gives higher values even during the wet season, on practical cases, there would be excesses supply of water which equates the PET to AET. Hence, Penman Mentioth method is used preferably which is 1392mm/year.

Using the PET result and the weighed average areal precipitation Thornthwaite and Mather (1957)soil moisture water balance is calculated using the previous studies around Mekelle on soil moisture Field capacity of different soil types of the Mekelle outlier and the maximum effective root depth that evapotranspiration could take place determined by Macdonald et al (1975).From this work water capacity of root zone is determined to be 225mm.The modeled soil water balance results for AET,Surplus and Runoff are 546,40 and 40 respectively. The recharge months of the study area are mid of July to mid September while the remaining 10 months are soil moisture deficit months and soil moisture utilization.

Water budget is also determined from the results of hydrograph analysis, base flow and surface runoff and the parameters calculated in the previous sections. The inflow is calculated from weighed percentage contribution of the big basin of the hydrograph to the sub-basin and the out flow is also calculated using the Darcy’s law .Thus the final recharge o f the sub-basin is estimated 64 mm per year.

The results of soil moisture water balance method and water budget balance have very large gaps .This discrepancy are attributed by the preferential recharge through fractured rocks and subsurface inflow from the near by catchments.

The geology of the area is of low grade metamorphic and Paleozoic and Mesozoic sediments. Among the low grade metamorphic rocks, the black limestone and the dolomitic slate are the main aquifers having highly interconnected fracture and solution cavities that help to increase the yield of wells in the area. While the metavolcanic and the slates are low in productivity. The northern part of the sedimentary rocks are also highly affected by intense faults and lineaments that resulted in less hydraulic interconnection between near by formations .And even the southern part dominated by limestone are jointed and fractured with solution cavities and interbedding layers of limestone and shale. This formation is the most productive aquifer of the study area as it has laterally extended multi-layered aquifer.

The recharge and discharge conditions of this area are governed by fracturing, solution cavity and Intergranular pore spaces.

The water levels collected from different wells in the area indicates, the aquifer type of the area is semi-confined as the water level is shallower than the strike water level. This result and the intense fracturing and faulting of the area have made the piezometeric level to be quite variable from site to site. Although the piezometeric level of the wells vary from site to site, especially in the central, the general trend of the flow considering only the major productive wells, drainage and structure of the area is from north to south .

The area is classified in to four hydrogeological units depending on the hydraulic parameters and field qualitative data. The very high permeable area is limestone while the low permeable area is the metavolcanic unit.

The available water is determined taking each of the four groups separately because it is difficult to get a single laterally extended aquifer for the whole basin. The calculation for determining of the available water is performed using the saturated thickness, specific capacity and Areal coverage of each similar aquifers. The saturated thickness is considered from the water strike level to the end of the aquifer as it is compared from the screen casings arrangement .The specific capacity is taken from the predetermined values of each lithology by Johnson (1976). Thus the total annual available water in the sub-basin is estimated 227,953,550 $m^{3.}$

.

Hydrochemistry of the area is attempted to know through field measurement of Electrical conductivity, PH and temperature; laboratory measurements of primary and collection of previously measured samples. The samples of the primary are collected from representative water source of the study area. The samples are bottled with plastic bottles with great care from being contaminating. The primary and secondary sample analysis is checked for electrical neutrality, the ones with much greater than 5% area rejected.

The cation and anion are analyzed using waterloo hydrogeolocic.inc Aquachem 4.0 and are plotted on the Piper trilinear and schoeller graphical representations. The information obtained from this representation indicate that the water type is dominated by $Mg\text{-}Ca\text{-}HCO_3$ and $Ca\text{-}Mg\text{-}HCo_3$ .This types of water type is found in almost all part of the area. A different water sample type is found in the shale and limestone intercalated; the carbonate and slate formations are consisting of $Ca\text{-}Na\text{-}HCO_3$ and $Mg\text{-}Na\text{-}HCO_3$ .Where partial ion exchange is taking place. In one deep borehole in the limestone intercalated with shale BH27 and in the extreme southern part where agulae shale is found, $Ca\text{-}Mg\text{-}SO_4\text{-}Cl\text{-}HCO_3$ is found. This indicates that the former is caused due to evolution of geochemicals in response to residence time and the later due to the agulae shale with thin layers of gypsum is possible explanation for their occurrence.

Therefore, the hydrochemistry is highly influenced by the geological variations than flow interaction with the groundwater. The Electrical conductivity result also indicates that the concentration is controller by the geological formation. This is caused as the result of the intensive structures that give rise to the complexity of the geology.

The Electrical conductivity is in the range of 0.008-2800 micro Siemens/cm, in the boreholes and 429-1227 micro Siemens /cm in the hand dug wells. The results of Dams are below 320 micro Siemens/cm. The permissible limit for drinking of TDS is 500mg/l and up to 1500 is not objectionable but values above this are not good for drinking .But the wells in the southern part of the study area have greater than 1500mg/l.So attention should be given on its use. In addition to this the PH is measured to be 6.4-7.9 in the wells that indicates the environment of the sub-basin is acidic to alkaline which is influenced by open- system with surplus supply of $HCO_{3.}$

The area is in the range of medium to very high salinity range which is very hazardous range for plant growth. Hence a series of follow up is required while using water for irrigation purpose.

CHAPTER 8

8 Conclusion and Recommendation.

8.1 Conclusion

The trend of the temperature and wind shows rapid increasing trend. While the precipitation increasing trend is very small that indicates the direct relation ship of the former two components with precipitation. The trend of the three metrological component generally indicates the sub basin is getting wet relatively although the potential evaporation could equally increase.

The wukro-Genfel Sub-basin hydrogeology is very complex in aquifer relationship between the different formations resulted from intense tectonic activities that take place in the Northern and central part of the study area while the southern part that is controlled by eastern escarpment is limestone intercalated with thin layers of shale where the groundwater flow is controlled by the interbedding of limestone and shale.

In most part of the area, the yield, transmissivity and hydraulic conductivity varies in less than 150 meters. Therefore, this may lead to a conclusion that the flow of the groundwater is highly dependent on the nature of the formations. This idea is strengthened by hydrochemical cation and Anion concentration distribution in the formations. In the upper part of the sub-basin that is dominated by low grade metamorphosed rocks, the hydrochemical analysis of the water samples has showed that the water type determined are Mg-Ca-HCO_3 and Ca-Mg-HCo_3 and also the shallow Hand dug wells and boreholes in the south have similar water type to the northern part but in the deep wells and far south to the shale dominated area the water type facies changes to Ca-Mg-SO_4-Cl. In some wells of northern and southern there is an early cation exchange that gives to the water type Ca-Na-HCo_3 and Mg-Na-Ca-

HCO_3. Therefore, The water type facies change is controlled to the large extent by the geological formation and structure than the evolution that occur while the groundwater is moving.

The quality of the water for water supply is dependent on the nature of geological formations and the structures that affect them, for instance , boreholes drilled in the northern(metamorphic and Paleozoic dominating) part are soft and hard with in a radius of 100meters.while in the southern (limestone dominated) the shallow wells have relatively low hardness than the deeper once. This is related to the residence time of the water in this formation for a longer time so that the favorable reactions get time to react and give the highest hardness of the basin.

Irrigation practice along the river flow and even from shallow dug wells is common in the area. The water expelled is through pumps with out control. Although the shallow wells and river flow are relatively lower in salinity, the trend as it is seen from the Wilcox graph (Figure 7-10), the area is in the medium to very high salinity conditions. Therefore, the uncontrolled use of water will result salinity of the soil.

In general, the geological, hydrogeological and hydro chemical factors are in support to each another. The potentiality of the study area is classified in to Four based on the hydraulic parameters and field qualitative observation of hydrogeological features.

8.2 Recommendation

- A lot of hand dug wells and boreholes are constructed in the area but there is no well organized database management bank that helps in providing complete well completion report for further study. Therefore, a well organized data base bank is required.

- Frequent measurement of water level of wells, especially , those that provide water for the town has to be measured at least every one hydrogeological year. In order to know the well response to the discharge and take early measures.
- The northern part of the area is dominated by hard rock formations. And according to UNESCO (2004) the whole system (hard rock) is very sensitive to the availability of recharge during the rainy season and the runoff is a bit higher. Therefore, recharge mechanisms such terracing and flow break trenches has to be strengthen so as to furnish un interrupted recharge to water supply wells
- The hydrological station (stream gauging station) is not functional or not recording for the last five years .In order to determine the groundwater and surface water resource of the area the need of stream flow is crucial. Therefore, urgent repairing of the gauging station is required.
- The sub-basins surface water is over exploited by water pumps for irrigation in the upper and down steam. Hence, water management system has to be developed for the area as soon as possible.
- The water supply for the town is supplied with four wells. The wells are mined at once for 23 hours a day with only one hour recovery time. If this condition continuous for some time, the wells could be depleted .Thus, more wells have to be drilled in order to increase the recovery time.
- The hydrochemistry of the area is quite variable from wells to wells in very small area. Therefore, Isotope hydrochemistry has to be conducted in this area to understand the source, movement and interactions of the groundwater.
- The groundwater in the southern part of the area is medium to very high saline. Hence, there must be a series of monitoring of the soil and watering conditions to minimize the possible danger of salinization of the soil.

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Annex 3-1 Wukro monthly Rainfall

Wukro Station Rainfall (mm)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1962.00	***0.00***	***0.00***	***39.79***	***82.39***	***11.65***	***5.47***	***239.43***	***310.19***	***67.84***	***0.00***	***2.31***	***1.73***	760.81
1963.00	0.00	0.00	8.40	34.90	12.00	13.30	304.90	276.20	***18.74***	***0.00***	33.50	0.00	701.94
1964.00	5.30	0.00	4.30	***57.44***	8.20	37.30	236.40	262.40	23.00	0.00	0.00	27.50	661.84
1965.00	13.30	0.00	26.50	6.30	1.00	***16.98***	180.60	192.20	1.50	0.00	3.00	0.00	441.38
1966.00	0.00	39.80	6.10	***49.51***	0.00	***7.79***	***166.90***	168.70	37.80	10.90	0.20	0.00	487.70
1967.00	0.00	0.00	5.50	20.80	35.60	32.60	284.50	***285.73***	***14.20***	0.40	7.90	0.00	687.23
1968.00	0.00	0.20	0.00	10.60	1.10	1.30	224.80	147.20	***1.96***	0.00	5.50	***0.00***	392.66
1969.00	***6.10***	***0.88***	***82.38***	***41.58***	***37.48***	***0.00***	***198.46***	***187.97***	***47.63***	***0.00***	***0.00***	***0.00***	602.49
1970.00	0.00	10.60	5.40	26.50	***3.17***	***12.45***	153.50	113.70	***78.74***	***0.00***	***0.00***	0.00	404.06
1971.00	0.20	0.00	25.80	20.60	41.60	3.10	82.90	167.10	***25.59***	0.00	5.40	***0.00***	372.29
1972.00	0.00	***2.96***	***15.22***	59.40	***7.13***	***100.16***	***212.73***	12.80	0.00	0.00	0.80	0.00	411.19
1973.00	0.00	0.00	0.00	0.00	0.00	0.00	209.60	62.00	***56.94***	0.00	0.00	***0.00***	328.54
1974.00	0.00	0.00	15.00	***2.22***	7.70	51.00	186.50	259.50	70.70	0.00	0.00	0.00	592.62
1975.00	0.00	14.50	0.90	31.70	0.00	59.80	183.80	229.90	104.40	0.00	0.00	0.00	625.00
1976.00	0.00	0.00	25.90	41.20	144.30	7.30	544.30	361.00	231.60	***1.73***	***2.05***	***0.00***	1359.38
1977.00	***0.00***	***0.00***	***13.47***	***5.22***	***61.02***	***65.72***	***221.16***	***256.06***	***77.02***	***4.73***	***0.00***	***0.00***	704.41
1978.00	***0.00***	***0.00***	***15.57***	***0.00***	***0.48***	***37.92***	***195.43***	***207.54***	***6.86***	***0.00***	***0.00***	***0.72***	464.52
1979.00	***0.00***	***0.00***	***1.75***	***39.55***	***82.25***	***35.83***	***68.42***	***99.90***	***34.90***	***0.00***	***0.00***	***0.00***	362.60
1980.00	***0.00***	***43.10***	***0.00***	***108.60***	***34.47***	***48.97***	***220.89***	***415.80***	***21.67***	***0.00***	***0.00***	***0.00***	893.50
1981.00	***0.00***	***0.00***	***16.34***	***5.42***	***8.95***	***0.00***	***377.25***	***209.28***	***28.04***	***0.00***	***0.00***	***0.00***	645.27
1982.00	***0.00***	***12.65***	***31.55***	***68.47***	***7.77***	***9.31***	***208.19***	***211.11***	***70.78***	***0.00***	***0.00***	***0.00***	619.83
1983.00	***0.00***	***5.71***	***3.21***	***26.59***	***84.24***	***2.09***	***264.07***	***260.04***	***42.86***	***1.32***	***11.16***	***0.00***	701.29
1984.00	***0.00***	***0.00***	***9.91***	***2.13***	***0.00***	***11.28***	***127.23***	***99.18***	***61.72***	***0.00***	***16.62***	***2.38***	330.44
1985.00	***0.54***	***4.11***	***17.24***	***122.62***	***29.64***	***16.98***	***139.87***	***184.30***	***25.23***	***0.00***	***0.00***	***0.00***	540.53
1986.00	***0.00***	***2.79***	***12.26***	***47.75***	***18.32***	***133.01***	***225.13***	***310.07***	***24.71***	***0.80***	***0.00***	***2.09***	776.93
1987.00	***0.00***	***1.04***	***55.57***	***35.97***	***100.40***	***65.84***	***191.54***	***224.46***	***44.45***	***1.56***	***0.00***	***0.00***	720.84
1988.00	***0.00***	***15.20***	***0.00***	***9.77***	***29.80***	***7.79***	***411.08***	***402.55***	***72.25***	***0.00***	***0.00***	***0.00***	948.43
1989.00	***0.43***	***3.72***	***25.98***	***56.87***	***0.81***	***20.82***	***212.47***	***230.17***	***58.54***	***2.77***	***0.00***	***10.73***	623.33
1990.00	***0.76***	***8.43***	***27.79***	***40.07***	***1.89***	***0.00***	***171.13***	***106.28***	***71.15***	***0.92***	***0.00***	***0.00***	428.42
1991.00	***0.15***	***2.98***	***21.35***	***5.30***	***22.85***	***37.36***	***213.48***	***220.49***	***34.53***	***43.69***	***0.00***	***0.00***	602.19
1992.00	0.00	0.00	0.00	6.50	20.90	6.80	56.60	95.80	0.00	28.50	20.40	3.20	238.70
1993.00	***3.52***	***3.99***	***44.61***	***130.55***	***59.19***	***80.26***	***234.78***	***108.56***	***18.61***	***16.46***	***0.00***	***0.00***	700.54
1994.00	0.00	0.00	0.00	22.10	0.00	53.30	176.10	248.10	113.10	0.00	0.00	0.00	612.70
1995.00	0.00	11.30	33.50	6.50	14.50	0.00	184.90	198.10	37.60	0.00	0.00	0.00	486.40
1996.00	0.00	0.00	115.40	60.50	73.50	88.80	178.00	389.70	0.00	20.90	0.00	1.00	927.80
1997.00	0.00	0.00	31.70	72.20	10.80	19.40	185.30	5.30	23.00	4.70	***10.07***	***0.00***	362.47
1998.00	***3.01***	***0.62***	***0.00***	47.40	0.00	65.00	285.00	283.00	***38.82***	***18.10***	***0.00***	***0.00***	740.95
1999.00	***6.61***	***0.16***	***7.61***	***0.00***	***0.00***	0.00	167.30	352.60	13.60	0.00	0.00	0.00	547.88
2000.00	0.00	0.00	0.00	30.00	0.00	135.00	233.60	409.00	0.00	4.50	0.00	0.00	812.10
2001.00	0.00	0.00	69.50	43.80	83.00	115.40	385.60	405.20	4.60	0.00	0.00	0.00	1107.10
2002.00	0.00	0.00	11.30	0.00	***18.23***	44.30	106.40	384.40	41.30	0.00	0.00	***0.43***	606.36
2003.00	0.00	4.90	0.00	40.70	0.00	14.30	156.60	237.10	11.10	1.90	0.00	4.80	471.40
2004.00	2.00	0.00	0.00	145.00	42.00	67.20	166.00	171.50	4.80	14.00	0.00	0.00	612.50
2005.00	0.00	2.80	12.60	61.70	1.30	9.50	183.40	206.40	15.60	0.00	0.00	0.00	493.30
Mean	**0.97**	**4.41**	**19.23**	**38.71**	**25.95**	**35.61**	**213.32**	**227.03**	**40.97**	**4.14**	**2.77**	**1.27**	**614.39**

Annex 3-2 Agulae Monthly Rainfall

Year	Station		Element		Rainfall	(mm)				
	Jan	Feb	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1962	0.0	0.0	6.0	161.1	221.2	33.4	0.0	0.9	7.3	481.7
1963	2.1	3.3	30.2	180.9	118.6	9.2	0.0	3.9	50.7	434.3
1964	7.0	0.0	47.1	235.6	166.5	17.1	34.4	0.0	11.0	541.4
1965	0.0	34.7	18.7	105.1	206.6	8.7	0.0	0.0	0.0	393.0
1966	0.7	19.7	8.6	112.3	158.5	15.6	2.3	0.0	0.0	333.3
1967	0.0	0.0	49.1	145.9	203.8	7.0	12.8	0.5	0.0	442.0
1968	15.0	0.0	78.5	142.6	103.4	1.0	0.0	0.0	0.0	353.4
1969	20.1	4.3	0.0	133.6	134.0	23.5	0.0	0.0	0.0	396.3
1970	2.6	14.9	13.7	181.7	192.1	38.8	0.0	0.0	0.0	460.4
1971	0.0	0.0	43.2	66.8	149.0	12.6	0.0	0.0	0.0	306.1
1972	0.0	14.4	110.5	143.2	60.8	27.7	6.9	9.6	0.0	404.9
1973	0.0	0.0	35.4	155.9	106.0	28.1	5.0	0.0	0.0	346.6
1974	0.0	0.0	25.7	123.7	173.0	10.8	0.0	0.0	0.0	357.2
1975	8.2	19.1	51.9	60.0	191.2	62.0	0.0	0.0	0.0	415.9
1976	0.2	12.9	22.5	131.0	149.4	0.0	0.1	5.5	0.1	341.6
1977	0.2	0.0	40.1	142.3	174.7	39.8	41.4	0.0	9.5	476.7
1978	0.0	1.7	59.5	237.1	84.1	0.4	3.4	0.3	8.2	420.9
1979	12.2	0.0	23.4	38.0	151.4	15.8	12.0	0.0	25.0	313.9
1980	0.0	69.4	39.2	235.6	205.7	0.0	0.0	1.2	0.0	589.3
1981	0.0	0.0	0.0	253.9	149.2	13.8	0.0	0.0	0.0	433.0
1982	0.0	61.8	10.3	140.1	150.5	34.9	0.0	0.0	0.0	438.7
1983	0.0	27.9	2.3	177.7	185.4	21.1	3.7	4.3	0.0	468.5
1984	0.0	0.0	12.4	85.6	70.7	30.4	0.0	6.4	10.0	222.6
1985	1.8	20.1	18.7	94.1	131.4	12.4	0.0	0.0	0.0	333.4
1986	0.0	13.6	146.7	151.5	221.1	12.2	2.2	0.0	8.8	584.2
1987	0.0	5.1	72.6	128.9	160.1	21.9	4.4	0.0	0.0	482.8
1988	0.0	74.2	8.6	276.7	287.1	35.6	0.0	0.0	0.0	697.8
1989	1.4	18.2	23.0	143.0	164.1	28.9	7.7	0.0	45.3	463.0
1990	2.5	41.2	0.0	115.2	75.8	35.1	2.6	0.0	0.0	301.2
1991	0.5	14.6	41.2	143.7	157.2	17.0	121.7	0.0	0.0	521.3
1992	8.6	5.3	8.0	102.4	169.4	0.8	4.8	13.3	50.7	391.9
1993	11.6	19.5	88.5	158.0	77.4	9.2	45.8	0.0	0.0	497.9
1994	0.0	13.4	86.7	107.6	231.0	42.3	0.0	4.4	12.2	508.7
1995	0.0	14.9	8.7	195.1	172.8	31.0	6.9	0.0	132.4	592.7
1996	1.4	0.0	61.5	79.4	162.8	4.3	0.0	7.7	6.7	386.5
1997	0.0	0.0	41.6	176.9	73.1	9.8	137.3	3.9	0.0	470.1
1998	9.9	3.0	61.6	210.2	231.7	19.1	50.4	0.0	0.0	596.3
1999	21.7	0.8	9.5	213.6	261.1	13.8	2.1	0.0	0.0	527.5
2000	0.0	0.0	6.9	146.5	132.3	9.5	5.0	2.5	21.4	335.4

2001	*0.0*	*0.0*	*84.0*	*194.9*	*164.5*	*5.6*	*6.6*	*0.0*	*0.0*	479.2
2002	*12.3*	*0.0*	*78.0*	*69.5*	*150.2*	*16.9*	*0.0*	*0.0*	*1.8*	354.1
2003	*0.0*	*65.6*	*112.3*	*91.4*	*146.7*	*13.5*	*1.6*	*0.0*	*6.7*	460.5
2004	*7.3*	*9.4*	*32.6*	*46.8*	*160.7*	*0.8*	*7.1*	*2.0*	*0.0*	290.2
2005	*0.0*	*3.5*	*23.4*	*80.4*	*228.3*	*20.7*	*0.0*	*0.3*	*0.0*	394.8
Mean	3.4	14.0	40.0	145.0	159.0	18.4	12.3	1.5	9.5	433.6

Annex 3-3 Relative Humidity

Element — Mean Monthly Relative Humidity At 0600 L.S.T in %

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	80	85	90	89	84	76	95	98	86	73	77	88
1996	94	81	86	87	79	84	91	96	83	70	72	70
1997	78	73	75	76	69	81	96	94	83	88	90	86
1998	89	76	81	73	61	64	94	98	89	77	68	71
1999	78	55	74	62	53	59	93	96	87	84	75	82
2000	72	55	67	69	61	60	87	94	83	88	81	79
2001	84	75	79	69	67	75	93	94	83	83	x	x
2002	91	68	75	68	43	69	88	94	81	77	74	90
2003	82	75	80	73	58	66	x	86	93	75	75	78
2004	x	x	x	x	x	x	x	x	x	x	x	x
2005	x	x	x	83	80	67	95	96	89	74	79	60

Element — Mean Monthly Relative Humidity At 1200 L.S.T in %

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	37	44	40	50	40	36	73	77	47	37	35	43
1996	47	37	42	24	43	49	59	70	44	33	39	34
1997	36	31	34	32	31	45	68	62	33	42	47	35
1998	44	33	33	29	28	28	69	76	48	36	28	29
1999	36	20	28	24	20	26	72	75	47	45	39	42
2000	30	21	34	29	26	30	63	73	44	42	38	35
2001	38	29	37	29	24	38	70	77	44	38	x	x
2002	49	31	34	27	20	33	56	68	41	40	34	43
2003	31	32	35	34	24	35	59	69	42	30	31	31
2004	37	32	30	36	18	33	53	68	38	34	35	38
2005	40	27	37	34	36	33	64	65	46	34	36	24

Mean Monthly Relative Humidity
At 1800 L.S.T in %

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	50	55	54	59	45	40	78	79	50	38	43	64
1996	65	53	57	65	46	53	66	76	48	37	52	47
1997	58	48	55	51	35	47	74	64	33	53	62	54
1998	67	50	53	43	33	30	76	86	56	48	37	42
1999	50	32	49	31	22	26	77	80	49	57	45	55

2000	48	38	46	37	30	33	66	77	48	56	55	55
2001	58	48	56	35	35	52	77	81	53	49	x	x
2002	72	47	52	37	27	42	55	69	47	40	41	67
2003	54	53	54	46	26	41	67	94	55	36	42	46
2004	62	50	41	54	24	39	60	73	41	41	44	59
2005	58	48	56	45	49	37	74	72	54	40	47	34

Annex 3-4 Maximum Temperature

Station: WUKRO

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	27.4	28.4	29.1	29.4	29.8	30.5	26.6	27.0	27.6	27.4	26.1	27.5
1996	28.1	29.4	29.1	28.2	29.2	28.0	25.4	24.6	28.1	27.5	26.4	26.6
1997	28.2	28.2	29.2	29.0	29.6	30.9	26.2	30.1	27.6	27.6	x	x
1998	26.9	31.0	30.9	32.2	30.7	x	x	x	x	x	x	x
1999	x	x	x	x	x	33.1	27.1	25.9	26.0	26.5	25.7	26.8
2000	28.3	26.7	28.8	28.3	28.7	29.9	28.5	28.0	26.1	27.1	28.0	26.8
2001	27.8	28.6	29.3	31.5	30.5	29.8	27.2	26.0	28.4	26.9	26.0	25.6
2002	27.6	29.2	28.8	28.8	x	24.2	27.4	26.9	27.9	27.6	26.9	x
2003	28.9	29.6	29.3	29.3	31.4	30.6	26.4	25.6	28.2	26.7	26.2	26.0
2004	29.3	27.7	28.2	29.5	31.4	30.0	26.9	26.2	27.6	25.9	26.1	27.0
2005	27.7	29.2	29.2	29.1	30.1	40.1	26.2	26.5	27.9	26.3	25.6	25.5

Annex 3-4 Minimum Temperature

Element:
Monthly Min Temp. In ^{o}c

Station: WUKRO

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	6.4	8.1	11.5	12.3	12.6	10.6	12.8	11.6	11.3	11.2	7.1	5.4
1995	6.2	8.4	10.7	12.4	12.9	12.9	11.7	12.6	9.2	7.5	6.2	7.5
1996	9.3	9.9	11.9	11.6	11.7	11.5	13.7	12.8	10.6	9.6	8.7	7.4
1997	6.4	7.8	11.9	13.3	13.9	13.7	13.8	11.2	12.4	12.3	x	x
1998	14.7	8.7	13.2	14.8	14.4	13.7	14.5	x	x	9.8	7.4	6.4
1999	x	x	x	x	x	12.8	13.6	13.0	12.3	12.4	10.4	8.8
2000	8.1	9.7	10.7	13.7	11.9	12.7	13.6	13.1	12.7	10.6	10.3	8.5
2001	6.5	7.6	11.0	11.7	11.3	12.0	11.5	12.0	9.8	x	x	x
2002	4.8	7.0	7.3	x	x	8.3	4.5	4.9	4.9	11.0	10.0	x
2003	7.9	10.8	12.4	15.4	15.7	13.9	14.2	14.0	12.2	10.4	9.5	8.3
2004	8.9	9.7	11.6	14.5	12.4	13.5	13.9	13.6	10.6	10.2	10.0	8.6
2005	8.6	10.4	13.5	14.8	14.5	13.5	14.2	13.5	12.3	10.4	10.1	6.6

Annex 3-5 Sunshine

Station: MEKELLE Obs.												
Element:												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	10.3	8.9	9.3	8.8	9.3	9.2	5.4	5.1	8.7	9.8	10.0	9.4
1996	8.9	9.6	8.2	9.1	8.4	5.9	6.1	5.8	7.7	9.8	9.0	9.9
1997	9.4	9.8	8.5	9.1	9.6	8.0	6.0	6.5	8.4	8.1	10.0	10.0
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	x	10.3	10.0	7.2	4.1	5.5	8.0	9.2	10.3	9.9
2000	10.1	10	10.0	7.8	9.6	7.7	x	x	7.0	9.0	9.0	9.4
2001	9.6	9.7	6.4	9.6	x	x	x	x	8.6	9.3	10.2	10.1
2002	9.2	9.9	8.9	x	10.7	7.4	5.8	6.4	8.4	10.1	9.8	9.5
2003	9.9	9.4	9.4	8.9	10.4	6.9	3.8	4.1	7.8	10.3	10.1	9.9
2004	9.7	9.9	9.9	8.8	10.7	6.6	5.3	5.8	7.4	10	10	9.9
2005	9.6	10.6	9.4	9.1	9.4	8.2	4.9	5.1	7.9	10.3	10.1	10.7

Annex 3-6 Wind Speed

Element	Monthly Wind Speed At 2mt's In m/s											
Region	Tigray											
Station	Mekele											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	3.5	4.2	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	3.0	2.3	2.1	1.9	1.7	2.8	3.1	x
2001	2.8	3.5	3.2	3.7	2.7	1.9	1.7	1.6	1.8	2.8	x	x
2002	3.2	3.5	3.1	3.5	2.5	2.0	1.6	1.5	1.9	3.0	3.3	3.1
2003	2.9	3.2	3.8	3.6	3.2	2.0	2.0	2.0	2.6	x	x	x
2004	3.1	4.5	4.8	3.8	2.5	1.9	2.0	1.5	2.0	3.3	4.0	3.9
2005	3.3	4.8	4.5	4.6	2.3	2.2	2.1	1.5	1.5	2.8	3.6	4.2

Annex 5-1 Borehole Water Level

Kushet	Easting	Northing	Elev.	Type	Depth (m)	SWL (m)	Strike WL(m)	Water level Elev.(m)
kalhable	565880	1532640	2250	BH1	31.5	2		2248
Girida	563800	1522800	1970	BH10	60	21		1949
Mai Tewaru	560330	1522970	2000	BH11	43	14		1986
AdiAkawih	560600	1521030	2010	BH13	37	12		1998
Adiworema	559460	1521680	2026	BH14	30	4		2022
Mokoh	567320	1525180	1940	BH17	43	14	15	1926
L. Wukro	566000	1526070	1900	BH2	48	20	24,33	1880
Belesa	565425	1530151	2105	BH22	49	7	13,25,28	2098
Gonga	568420	1530659	2074	BH24	17	11		2063
kalhable	565389	1533014	2343	BH25	73	8.79	12,36	2334.21
L. Wukro	566689	1525535	2223	BH26	42	12.5		2211
Tsaedanaele	565699	1527421	2013	BH28	48	12		2001
L. Wukro	565599	1525684	2017	BH29	60	15		2002
Belesa	565635	1528231	2035	BH30	40	10		2025
Negash	563860	1535340	2383	BH31	45	4		2379
Wukabet	572930	1511580	2279	BH32	28	7	8	2272
Tsebat	572980	1510460	2244	BH33	48	7	9	2237
Mai-tewaru	558800	1522320	2030	BH34	30	9		2021
Felegisha	561150	1531790	2208	BH35	25	8.7	10-14,14-25	2199
Tsahelo	562150	1528983	2043	BH36	240	13.68		2029
Megadien	562401	1535529	2337	BH37	54	7		2330
Korir	567582	1519835	2052	BH38	59.4	8.08		2044
Adengur	568132	1514770	2046	BH39	42	4		2042
Kumbirto	554450	1525000	1970	BH4	65	38		1932
Gurahutsa	566719	1523624	2031	BH40	48	24		2007
Gurahutsa	566653	1523613	2031	BH41	48	20		2011
Endaselasie	566611	1522714	2028	BH42	48	36		1992
L. Wukro	565419	1525624	2007	BH43	96	16.5		1990.5
Dedbit(1)	565060	1525549	1999	BH44	58	7.58		1991
Dedbit(2)	565074	1525941	1998	BH45	124	52		1946
Sifra geganu	564926	1526266	2001	BH46	105	12.35		1988.65
Eusurti				BH48	42			
Dongolo 2	563557	1522617	1967	BH50	92	8.62	13,26,52	1958
Gera Hatsera	566840	1523100	2040	BH6	39	8	15,24	2032
Felegisha	564290	1531810	2110	BH7	49	11	15	2099
Wukro	565050	1525960	1910	BH9	58	12.8		1897

Annex 5-2 Water Level of Hand Dug Wells

no	Tabia	Easting	Northing	Elevation (m)	Type	Depth (m)	STW (m)	Str. water level (m)	Water Level Elevation(m)
1	Gemada	563100	1529950	1980	HDW1	6_7	2	0	1978
2	Gemad	562489	1536644	2345	HDW2	15	9		2336
4	Adi Kisandid	564800	1529700	1980	HDW4	7	1.5	2	1978.5
5	Adi Kisandid	567190	1531460	2020	HDW5	18	2.8	2	2017.2
6	Adi Kisandid	567480	1530980	2000	HDW6	7	0.8	2.8	1999.2
7	Negash	565637	1532675	2211	HDW8	11	8		2203
8	Genfel	564340	1526330	1920	HDW9	6.3	5.8	5.8	1914.2
9	Gemad	562700	1537380	2353	HDW10	9	1.5		2351.5
10	Adi Kisandid	564800	1529700	1980	HDW11	7	1.5	2	1978.5
12	Adi Kisandid	567480	1530980	2000	HDW13	7	0.8	2.8	1999.2
13	Gemad	564030	1537450	2384	HDW14	8	4		2380
14	Gemad	562492	1536646	2345	HDW15	12.4	10		2335
15	Negash	564408	1535269	2358	HDW16	12	6		2352
16	Mesanu	569755	1514156	2059	HDW17	10	4		2055
17	Aynalem	560747	1520793	1978	HDW18	8	3		1975
18	Aynalem	559071	1518186	1926	HDW19	9	3		1923
19	Aynalem	558081	1518745	1912	HDW20	7	3.2		1908.8

Annex 6-1 Cations and Anions In mg/l

Type	ID	Location	Easting	Northing	Na	K	Ca	Mg	Cl	HCO3	SO4
BH	BH42	Genfel	566840	1523100	53		72	14	28	281	80
BH	BH44	Dedebit	565070	1525550	20		120	62	52.5	488	120
BH	BH48	Belesa	564290	1530700	13		92	65	16.695	573	30
BH	BH50	Adikisand	567580	1526780	124		104	91		464	
BH	BH51	Aynalem	560330	1522970	109		132	50	211.05	451	100
BH	BH52	Mesanu	567030	1511140	30		312	86	300.3	305	500
BH	WP1	Adikisandid	565425	1530151	34	0.6	92.6	81	24.96	589.3	38.4
BH	WP2	Adikisandid	565066	1531503	26	0.5	69.7	25.4	15.4	314.3	21.7
BH	WP3	Adikisandid	568420	1530659	34	2.1	129.7	93.4	48.96	519.1	203.14
BH	WP5	Negash	565389	1533014	22	1.2	79.38	55.1	15.36	432.12	31.4
BH	WP6	Adikisandid	565489	1525535	5.6	3.6	52.9	7.6	18.2	131.9	28
Dam	WP7	Aynalem	560848	1522357	8.4	3.5	43.2	7	5.8	117.8	38
DBH	WP11	Genfel	563376	1522230	30	14.3	520.38	91.8	408.96	319.9	861.2
HDW	WP4	Gemad	562131	1534725	19.5	1	55.57	8.6	19.6	204.8	27.61
HDW	WP8	Aynalem	560029	1522543	33	2.2	154.3	18.36	28.8	378.8	176.69
River	WP10	Aynalem	563047	1521970	20.5	2.6	91.7	38.9	27.8	283.4	125.9

Annex 6-2 Electrical Conductivity distribution

Type	Location	Station ID	Easting	Northing	EC(ms/cm
BH	Genfel	BH42	566840	1523100	590
BH	Dedebit	BH44	565070	1525550	419
BH	Belesa	BH48	564290	1530700	587
BH	Adikisand	BH50	567580	1526780	560
BH	Aynalem	BH51	560330	1522970	498
BH	Mesanu	BH52	567030	1511140	706
BH	Adikisandid	WP1	565425	1530151	1011
BH	Adikisandid	WP17	565699	1527421	1020
BH	Genfel	WP18	566719	1523624	1993
BH	Genfel	WP19	566653	1523613	2800
BH	Wukro	WP23	565419	1525626	540
BH	Wukro	WP24	565060	1525549	847
BH	Wukro	WP25	565074	1525941	598
BH	Genfel	WP26	566611	1522714	1167
BH	Adikisandid	WP27	565635	1528231	998
BH	Adikisandid	WP3	568420	1530659	1296
BH	Gemad	WP33	562401	1535522	408
BH	Genfel	WP35	567582	1519835	1229
BH	Aynalem	WP36	560666	1519514	0.00771
BH	Negash	WP5	565389	1533014	799
BH	Adikisandid	WP6	565489	1525535	330.7
BH	Aynalem	WP9	559405	1523266	890
Dam	Genfel	WP28	566508	1519450	305
Dam	Aynalem	WP7	560848	1522357	353.4

DBH	Genfel	WP11	563376	1522230	1416
BH	Aynalem	WP29	562213	1520190	2952
HDW	Negash	WP12	565637	1532675	800
HDW	Negash	WP13	565830	1532590	815
HDW	Adikisandid	WP14	565372	1531516	758
HDW	Adikisandid	WP15	568614	1531511	519
HDW	Adikisandid	WP16	567250	1520448	810
HDW	Aynalem	WP20	560747	1520793	1227
HDW	Aynalem	WP21	559071	1518186	782
HDW	Negash	WP30	564314	1537056	528
HDW	Gemad	WP31	564030	1537450	574
HDW	Gemad	WP32	562492	1536646	429
HDW	Negash	WP34	564408	1535269	599
HDW	Aynalem	WP8	560029	1522543	871

Annex 6-3 pH Distribution

Location	Station ID	Easting	Northing	pH
Genfel	BH42	566840	1523100	8
Dedebit	BH44	565070	1525550	8
Belesa	BH48	564290	1530700	8
Adikisand	BH50	567580	1526780	8
Aynalem	BH51	560330	1522970	8
Mesanu	BH52	567030	1511140	8
Adikisandid	WP1	565425	1530151	8
Genfel	WP18	566719	1523624	6.8
Genfel	WP19	566653	1523613	6.8
Wukro	WP23	565419	1525626	6.4
Wukro	WP24	565060	1525549	6.8
Wukro	WP25	565074	1525941	6.8
Genfel	WP26	566611	1522714	7
Adikisandid	WP27	565635	1528231	7
Genfel	WP35	567582	1519835	7
Aynalem	WP36	560666	1519514	6.6
Genfel	WP28	566508	1519450	8.2
Genfel	WP11	563376	1522230	8
Aynalem	WP29	562213	1520190	7
Aynalem	WP20	560747	1520793	7.6
Aynalem	WP21	559071	1518186	7.8
Negash	WP30	564314	1537056	6.8
Gemad	WP31	564030	1537450	6.8
Gemad	WP32	562492	1536646	7.4
Negash	WP34	564408	1535269	6.8
Aynalem	BH1	563120	1523500	7.4
Aynalem	BH2	559460	1521680	7.7
Aynalem	BH3	560600	1521030	7.5
Genfel	BH4	566840	1523100	7.4
Genfel	BH5	566660	1522700	7.5

Dedebit	BH13	565070	1525550	6.9
Dedebit	BH14	564930	1526260	7.6
Negash	BH25	565880	1532640	7.6
Negash	BH26	565430	1533250	7.6
Belesa	BH27	564290	1530700	7.6
Adikisandid	BH28	564290	1531810	7.9
Adikisandid	BH31	567580	1526780	7.6
Aynalem	BH35	560330	1522970	7.9
Mesanu	BH37	567030	1511140	7.6

Annex 6-4 Water Type

Sample ID	Water Type	Station ID	Location	Geology	Easting	Northing	Elevation
BH	Ca-Na-HCO3-SO4	BH42	Genfel	ALST	566840	1523100	2040
BH	Ca-Mg-HCO3-SO4	BH44	Dedebit	ALST	565070	1525550	1870
BH	Mg-Ca-HCO3	BH48	Belesa	DFM	564290	1530700	2221
BH	Mg-Na-Ca-HCO3	BH50	Adikisand	DFM	567580	1526780	1950
BH	Ca-Na-Mg-HCO3-Cl	BH51	Aynalem	ALST	560330	1522970	2000
BH	Ca-Mg-SO4-Cl-HCO3	BH52	Mesanu	ALST	567030	1511140	2130
BH	Mg-Ca-HCO3	WP1	Adikisandid	Slate	565425	1530151	2105
BH	Ca-Mg-HCO3	WP2	Adikisandid	Slate	565066	1531503	2101
BH	Mg-Ca-HCO3-SO4	WP3	Adikisandid	Bslate	568420	1530659	2074
BH	Mg-Ca-HCO3	WP5	Negash	Hfslate	565389	1533014	2343
BH	Ca-HCO3	WP6	Adikisandid	Asst	565489	1525535	2223
Dam	Ca-HCO3-SO4	WP7	Aynalem	Lst	560848	1522357	1977
DBH	Ca-Mg-SO4-Cl	WP11	Genfel	Lst	563376	1522230	1971
HDW	Ca-HCO3	WP4	Gemad	Mv	562131	1534725	2339
HDW	Ca-HCO3-SO4	WP8	Aynalem	Lst	560029	1522543	1986
River	Ca-Mg-HCO3-SO4	WP10	Aynalem	Lst	563047	1521970	1955
BH	Ca-Na-HCO3-Cl	W1	Dedebit	Lst	565074	1525941	1998
BH	Mg-Ca-HCO3-Cl	W4	Dedebit	SSt	564926	1526266	2001
BH	Ca-HCO3	W3	Dedebit	Lst	565060	1525549	1999