

**ADDIS ABABA UNIVERSITY**  
**SCHOOL OF GRADUATE STUDIES DEPARTMENT OF**  
**EARTH SCIENCES**

**HYDROGEOLOGICAL AND HYDROGEOCHEMICAL**  
**CHARACTERIZATION OF BELES RIVER BASIN,**  
**NORTHWESTERN ETHIOPIA**



**By: - Girma Addisu**

**A Thesis Submitted to the School of Graduate Studies of Addis Ababa  
University in Partial Fulfillment of the Requirements for the Degree of  
Master of Science in Hydrogeology**

**June, 2010**

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**By**

**Girma Addisu**

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**(Examiner)**

**This work is dedicated to my sister**

**Ayalnesh Addisu**

## DECLARATION

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

Candidate: Girma Addisu

June, 2010

Signature: \_\_\_\_\_

Date of Submission: \_\_\_\_\_

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

Advisor: Tenalem Ayenew (Prof.)

Signature: \_\_\_\_\_

Date of Approval: \_\_\_\_\_

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## **Abstract**

Beles River Basin is part of northwestern lowlands and its adjacent highlands. It is found in the southwestern direction of Lake Tana, It has the total areal coverage of 14,200 sq. Km and elevation varies from 500 to 2,700masl. The Basin has all climatic zones, except alpine. The objective of the thesis work was characterizing the hydrgeology and hydrogeochemistry of the basin using integrated methodology and approaches. Secondary data has been collected from the respective institutes and organizations and primary data of water samples for water chemistry was analyzed in the laboratory.

The rainfall pattern of the Basin is unimodal. It has an aerial depth of precipitation of 1352.9mm/yr that was computed using isohyetal cotour map method. The precipitation condition has high orographic effect. The hydrograph of the two main rivers reflects the unimodality of the rainfall. The variation of these rivers discharge is very high from dry to rainy season that shows the infiltration of the Basin is low.

The Basin has geology of Precambrian basement complex, undifferentiated formations, tertiary and quaternary volcanic and quaternary sediments. It has lithological units of gneiss and associated high-grade metamorphic rocks, low-grade supra-crustal metamorphic rocks, syn- and post-tectonic intrusive of acidic to intermediate composition, Cenozoic volcanic rocks, and quaternary sediments. The most important tectonic settings are dominantly aligned N-S and NE-SW direction.

Hydrogeological map of the Basin was produced based on previous reports and maps and field observations of geology, topography and water point inventory, weathering and fracturing condition of the formations. Accordingly the hydrogeological characterization of the area revealed; porous aquifers (alluvium, colluviums), fissured and karst aquifers (marble), fissured aquifers (sandstone and volcanic rock), fissured aquifers of low potential (some non-carbonate metamorphic and intrusive rocks) and aquitards (some non-carbonate metamorphic and intrusive rocks). Accordingly the aquifer of the basin was classified in to very low, low, intermediate, intermediate to high and high productive formations.

The regional recharge zones are the highlands of the Basin Such as; Wombera, Balay, Dangur and Kar mountains and highlands areas of Dangila and Achefer. The discharge areas are intimately linked with groundwater flow lines and the regional groundwater flow direction is to the southwest following the topographic gradient.

Hydrochemical data shows that evolution of major ions, water types, and direction of groundwater flow. It shows a general trends increasing total ion concentration along flow direction.

Graphical presentations of the physical and chemical parameters of the water samples provide a good deal of information on the characteristics of ground water flow systems, recharge and discharge zones, and evolution of major ions in the basin. The general natural water type of the basin is Ca dominated cation and HCO<sub>3</sub> dominated anion (Figure6.9) and has low (fresh

water range) TDS values. The TDS can be relatively grouped in to three groups (figure 6.9) low medium and high. But there are a very few samples with Na dominated cations and Cl dominated anions. In general the dominance of bicarbonate ions shows the groundwater of the area is shallow.

## **CHAPTER ONE**

### **1. Introduction**

#### **1.1. General**

The study area, Beles River Basin is one of the Abay River sub Basins. It is found in the southwest direction from Lake Tana, in Amhara and Benishngul Gumuz National Regional states. The two main perennial rivers in the basin are Main Beles and Gilgel Beles. These rivers join in the middle of the basin to form Beles River. There are also other small perennial and intermittent rivers. In this basin surface and ground water are the most important water supply for the community. But information on ground water recharge, storage, circulation and chemical evolution is barely known. A picture of ground water recharge and factors that influence ground water circulation and its chemical evolution is lacking. The ground water development in this basin is being conducted without a good understanding of its role in the hydrology of the basin.

Because of volcanic and tectonic processes, the area contains varying topographic features. Characterization of hydrogeology and hydrogeochemistry of the Basin is the main objective of this research work.

In situ water quality measurements have been conducted in the field together with sampling of water to get physico-chemical analysis resulted from laboratory.

Although most of the farmers of the community depend on seasonal rain, irrigation in small skim techniques are being developed to cultivate farmlands close to Perennial Rivers. But currently there is a big project (Tana-Beles Hydropower Project) in this Basin starting its function, which generates hydropower and used for irrigation purpose too. This project has a great contribution for the development of the country. The lowland parts of the basin has a potential to be irrigable, and currently there is a promising irrigation project like Hiber Sugare S.C., by using the surface water from out late of the Hydropower project.

The volcano tectonic processes results different environments and complex geological formations, which is from Achaean age basement complex rocks to tertiary volcanic and alluvial deposits. Occurrence of ground water in basement terrain is limited to zones of fracturing and weathering. But in volcanic terrain the formation of water bearing zone can depends on primary porosity and secondary porosity. Successful identification of this water bearing geologic layers requires application of different techniques and methods.

In this research work both primary and secondary data are used for hydrogeological and hydrogeochemical characterization of the basin.

## 1.2. Previous Works

Almost all of the Abay River sub-basins are less investigated and perhaps Beles River Basin is the least investigated of all both from hydrogeochemical and hydrogeological point of view. The investigation carried out so far in the area are either to general (on a regional scale ) or hydrogeological and geophysical investigations for specific institutions, organizations, private limited companies and town water supply, for locating borehole sites without considering all the catchments and geological setups of an area.

- Among the important geological, hydrogeological and hydrogeochemical investigations are:- Unpublished investigation reports on hydrochemistry of natural water of northern Ethiopia by Ketema Wagari, Fetanegest W/mariam and Nikodimos Kassaye (January 2005), covers only small area upstream part of the basin.
- Abay River Basin Integrated Development Master Plan project Phase 2, volume 1 by BCEOM-French Engineering consultants-in association with ISL and BRGM 1998. Geology, morpho-lithologic and morpho-structural investigation; 1:250,000 scale maps
- Hydrogeological Study of the Tana-Beles River Sub-Basins by SMEC International, pty Ltd (2008). It was limited to small area of upstream part.
- Rapid-Groundwater resources assessment in Lake Tana sub-basins and adjacent areas, by Engda Zemedagegnehu, Dr. Yilma Sileshi and Albert Tuinhof (January 2007). It was limited to small area in the upstream part of the basin.
- Regional hydrogeological investigation of Northern Ethiopia, GSE Hydrogeological map with scale 1:2,000,000, Compiled by Bayissa Asfaw (2003). This investigation was in regional scale and covers the upper part of the basin.
- Explanatory notes to the hydrogeological and hydrogeochemical map of Abu Ramla area, GSE (2003), Compiled by Yohanes Belete, Demis Alamirew, Dawit Birhan, Robert Michek, Jiri Sima and Irena Volna. It covers the lower northwestern part of the basin with hydrogeological and hydrogeochemical maps of scale 1:250,000.
- Explanatory notes to the hydrogeological and hydrogeochemical map of Assosa-Kurmuk area, GSE (2004), Compiled by Yohannes Belete, Demis Alemirew, Andarge Mekonen, Melaku Tesfaye and Kefale Tilahun. It covers the lower southwestern part of the basin with hydrogeological and hydrogeochemical maps of scale 1:250,000.

### **1.3. Objectives**

The general objective of the research is to describe and give detailed picture of the hydrogeologic characteristics and hydrogeochemical characteristics of the basin.

This research was carried out with the following specific objectives.

- Description and characterization of the major aquifer systems and aquifer units in the study area, to identify the origin and mechanisms of recharge for groundwater potential and to show the general groundwater flow direction in the basin.
- Producing geological and hydrogeological map of the area.
- Characterizing the variation in natural hydrogeochemistry in the basin.
- Correlating the relation between hydrogeology and hydrogeochemistry of the basin.

### **1.4. Approach and Methodology**

This research work has began with primary secondary data collection in the field and secondary data collection from and all relevant available data related to geology, hydrogeology, hydrology, hydrochemistry and well data inventory has been acquired.

The activities undertaken included:-

- Reviewing the available literatures related to the title.
- Reviewing the available previous works in the basin.
- In situ testing of water sample for pH, TDS, EC and temperature.
- Collecting and analyzing of primary and secondary data.
- Application of software such as Aquachem, Arcview, Arcgis, Digrares, Global mapper and other computer codes to make ease of bulk data management and facilitate the analysis, synthesis and interpretation of results.
- Using Shuttle Radar Terrain Mission (SRTM) Digital Elevation Model (DEM) data with 30m resolution for structural and topographic setup of the basin.
- Characterization of the chemistry of water samples collected from different sources within and adjacent to the catchment.
- Understanding and mapping of the geologic and hydro geologic set-ups and the natural ground water chemistry of the basin.

### **Materials Used in the field**

The 1:50,000 scale topographical maps and Garmin GPS map 60c5x will be used for navigation during the field work so that accurate locations of the observation data and sampling points.

PH, EC, and TDS water proof family HI 98129-HI98130 used for measuring pH, Sampling materials for water chemistry testing in the lab.

Geological and Hydro geological maps of scale 1: 2,000,000.

## CHAPTER TWO

### 2. STUDY AREA DESCRIPTION

#### 2.1. Location, Aerial Extent and Accessibility

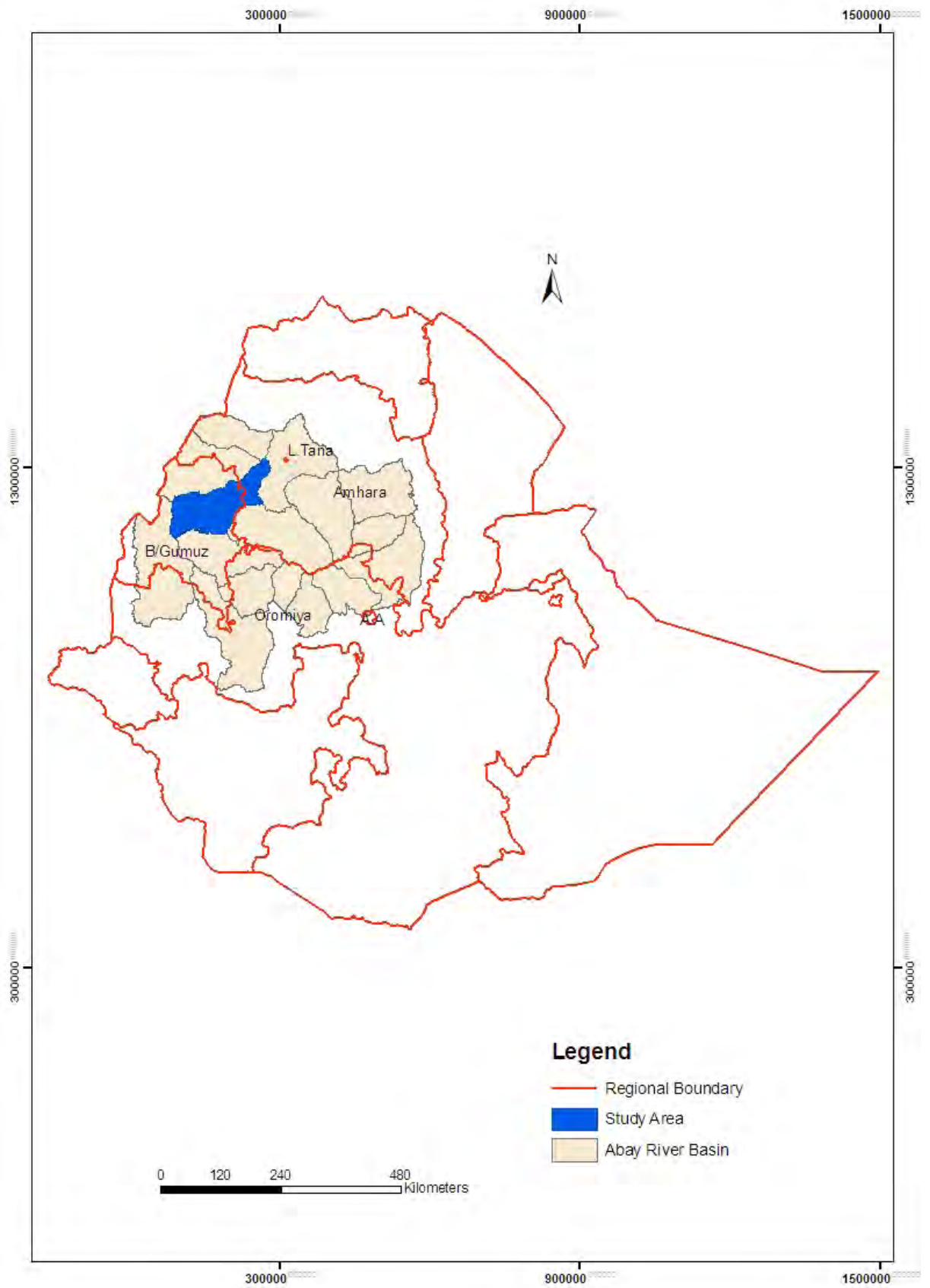
The study area, Beles River Basin is located in the northwestern part of Ethiopia. The area is within Benishangul Gumuz and Amhara Regional States (in Metekel Zone in Benishangul Gumuz and Awi, West Gojam, and South Gondar zones in Amhara regional states). It is about 550km northwest of Addis Ababa on the way Addis Ababa to D/Markos, Kosober, Chagni, Gilgel Beles and Pawe towns.

Geographically it is bounded within the limit of 1159010m to 1319728m N latitude and 78565m to 281251mE longitude and has an elevation of 2,720masl, highest at Balaya Mountain and 500masl, lowest at the confluence of Beles and Abay River.

It is one of Abay River sub Basins and delineated based on surface water divide. It comprises parts of the two Regions; Benishangul Gumuz regional state and Amhara regional state with a total surface area of about 14,200.13 km<sup>2</sup> and perimeter of 704.53Km. The area can be accessed through asphalt up to Kosober (440Km) on the way Addis Ababa-D/Markos-Kosober-Dangila-Durbete-B/Dar. At Kosober it is divided in to two routes for upper part and lower part of the basin. The upper part of the is accessed from Dangila (which is 490km from Addis Ababa) town and then to the west 30Km with all weathered dry season road, from Durbete (which is 510km from AA) to NW direction 65Km to Tana-Beles Hydropower project area (Kunzila small town) and it is then to the west around 30 to 40 Km to the outlet of the project tunnel. The lower part of the basin is accessed from Kosober to Chagni (60Km) with all weathered road and then also divided in to two to the west 150Km with all weathered gravel road up to Wombera high land and to north from Chagni-Gilgel Beles-Pawe-Jawi (100Km). It is also from G/Beles to the west (140Km) with all weathered gravel road to Mambuk-Gublak-Guba areas.

In general, the area is covered with plateau basalts in the northern in Balaya and Dangur Mountains, in the eastern and northeaster parts in Amhara Regional state highlands and some lowlands of Jawi, Pawe and Dangur Woredas, in the escarpment of Mandura Woredas and volcanic and intrusive rocks in Wombera plateaus. The rest low land is covered by basement complex with marble exposure in some low lands of Wombera, Guba and Bulen Woredas.

There is alluvial and colluvial sediments in some low lands of the study area at the sides of Beles River and its tributaries.



**Figure2.1. Location map of the study area**

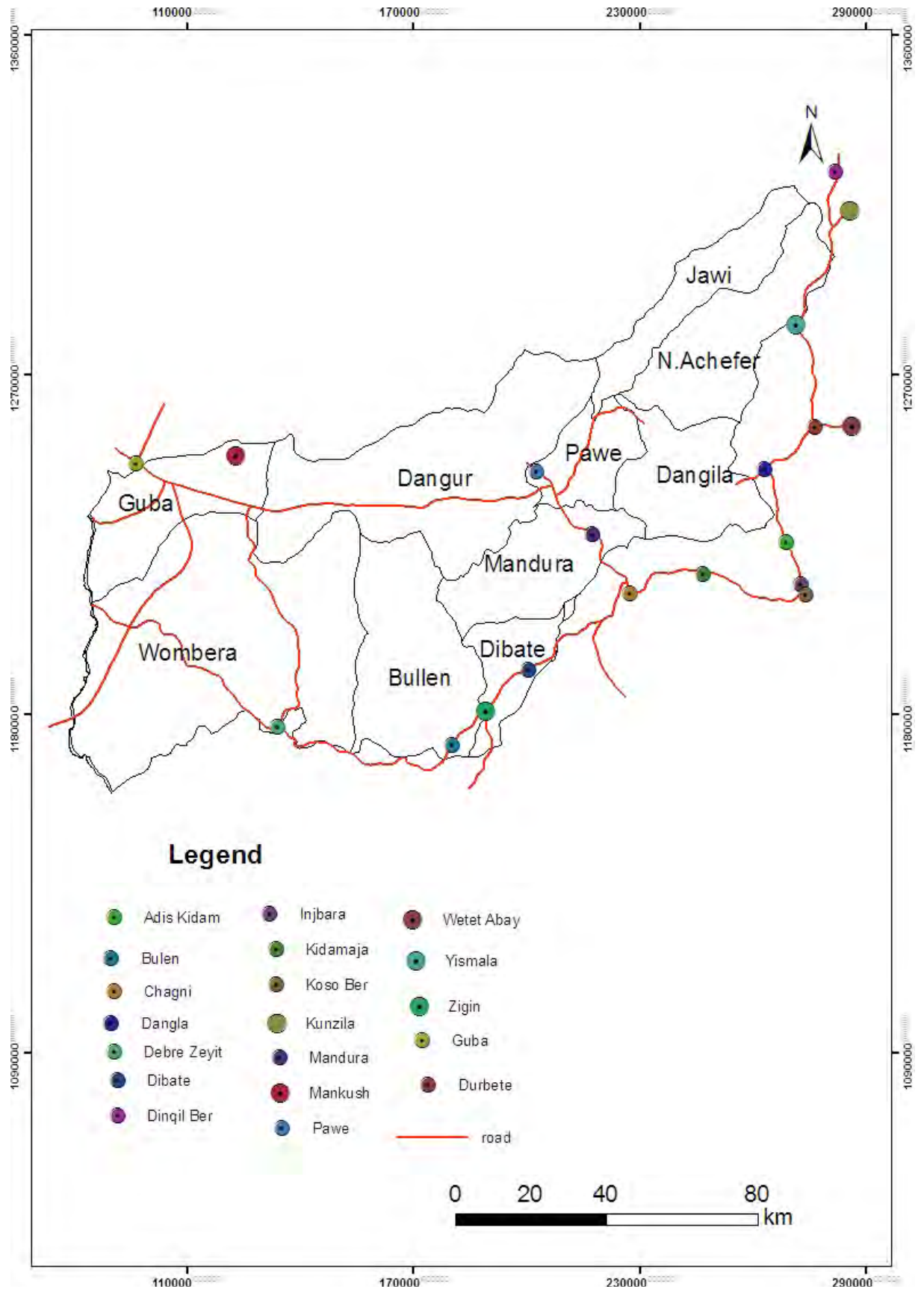


Figure .2.2 Map of Woredas in the Area

## 2.2. Climate

Due to large topographic differences the climate of the area is highly variable from place to place. The area above 1500masl is generally cool and gets more rain than the area below 1500 m, which is dry and hot. The topographic difference is dramatic. Elevation ranges from a little above 2720 masl at Balaya Mountain up to less than 500 masl at Abay River.

In general most of the lowlands of the region can be classified as arid and semi-arid. Daniel Gamachu (1977) classified the climate of Ethiopia (based on the system introduced by Thorthwait), as shown in table 2.1. According to this classification, the region has all climatic zones except Kur. Balaya, Wombera and some parts of Dangila areas and few mountainous areas of Mandura (Kar Mountain), North Achefer and Dangur areas can be categorized in Dega and the transitional escarpments of all Woredas as Woinadega. The lowlands are categorized as Kolla and Berha. Bereha characterizes the extreme western lowlands near to Abay River.

<i>Mean annual Temperature</i>	<i>Climatic classification</i>		<i>Region altitude (m.a.s.l)</i>
Less than 10°C	Kur	Alpine	Above 3300
10- 15 °C	Dega	Temperate	2300 - 3300
15-20°C	Weina Dega	Subtropical	1500 - 2300
Greater than 30°C	Kolla	Tropical	800 - 1500
Above 40°C	Bereha	Desert	less than 800

**Table2.1. Climatic Classification (Daniel Gamachu, 1977)**

## 2.3. Topography and drainage

### 2.3.1. Topography

The study area is part of the northwestern lowlands, with limited highland areas to the southwest Wombera Plateau; to the north Dangur and Balaya Plateau, North Achefer and Kunzila areas and Dangila areas; and to the east Kar mountain of Mandura Woreda escarpments. The basin is predominantly flat to undulating. Figure 2.1 shows the Elevation map from DEM of the area extracted from the SRTM-DEM data (30m resolution). The geomorphology of the area is generally the outcome of repeated tectonics, with associated volcanism and intrusion followed by denudation and erosion processes forming the flat plains

covered with Quaternary deposits. The drainage density and pattern are also partly or wholly controlled by the volcano-tectonic activities and denudation processes of the region.

Most of the major rivers are tectonically controlled and follows regional and sub-regional lineaments. As in the case of rivers major high-discharge springs are aligned along regional faults.

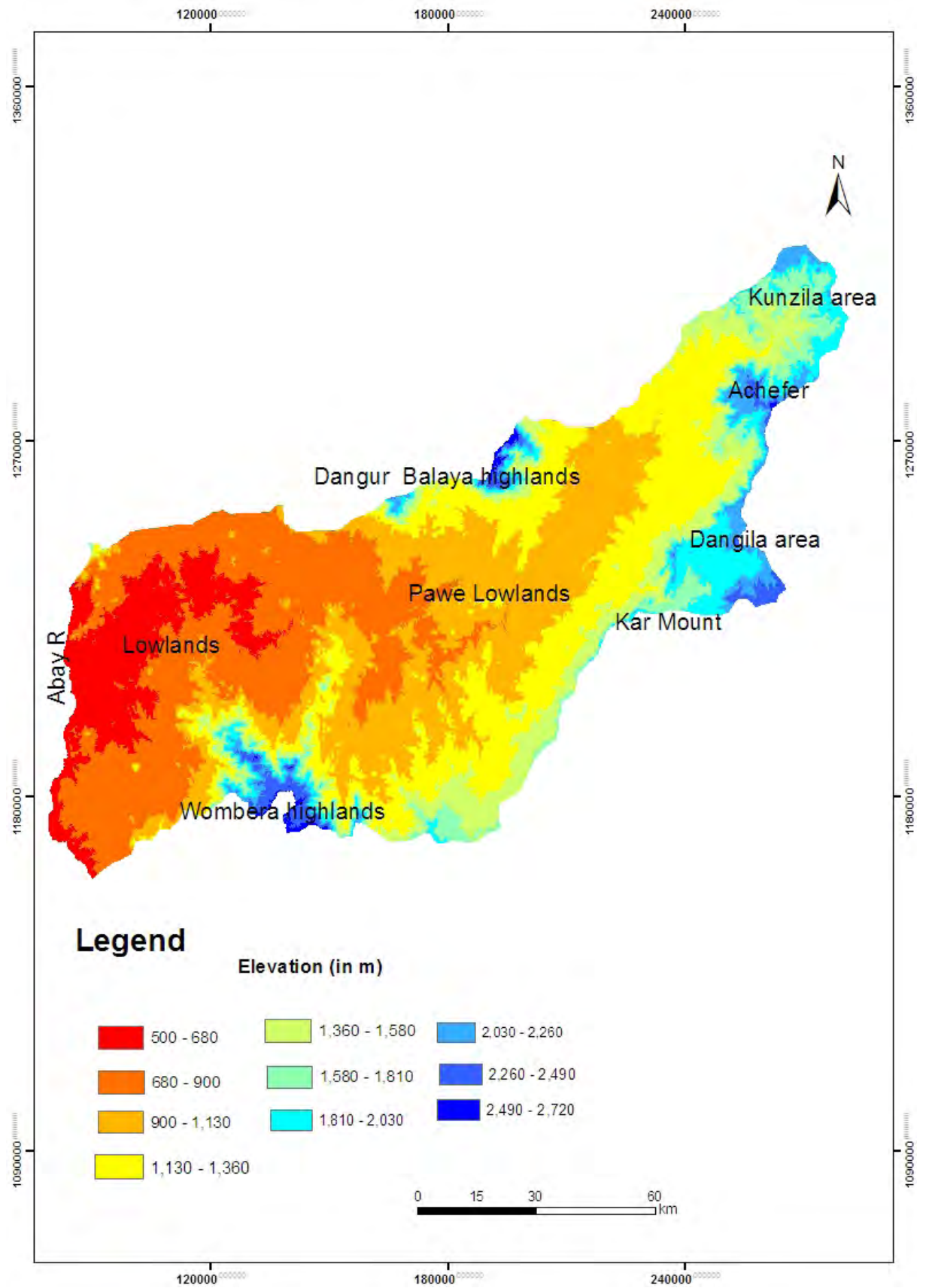
The mountainous areas in Balaya, Dangila, Kunzila and Wombera, lie between 2300 and 2720 masl, and in Kar Mountain and Dangur lie between 2000 and 2400m.a.s.l. In Balaya and Wombera areas Tertiary and Quaternary basalts form a flat-topped area lying between 2000 and 2700 m a.s.l. The area above 2500 m forms a plateau covered with basalt underlain by basement complex metamorphic rocks.

The lowland area towards the Beles River and Abay generally has a flat to rolling topography with an elevation ranging from 500m to 1000m above sea level. The lowest area lies at about 500m above sea level at the confluence of Beles and Abay Rivers. Most of the central part of the area lies between 800 to 1400 masl. The area with an elevation of 1400 to 2000masl found as an escarpment at Wombera, Balaya, Dangila, Dangur, Alefa and Kar Mountains.

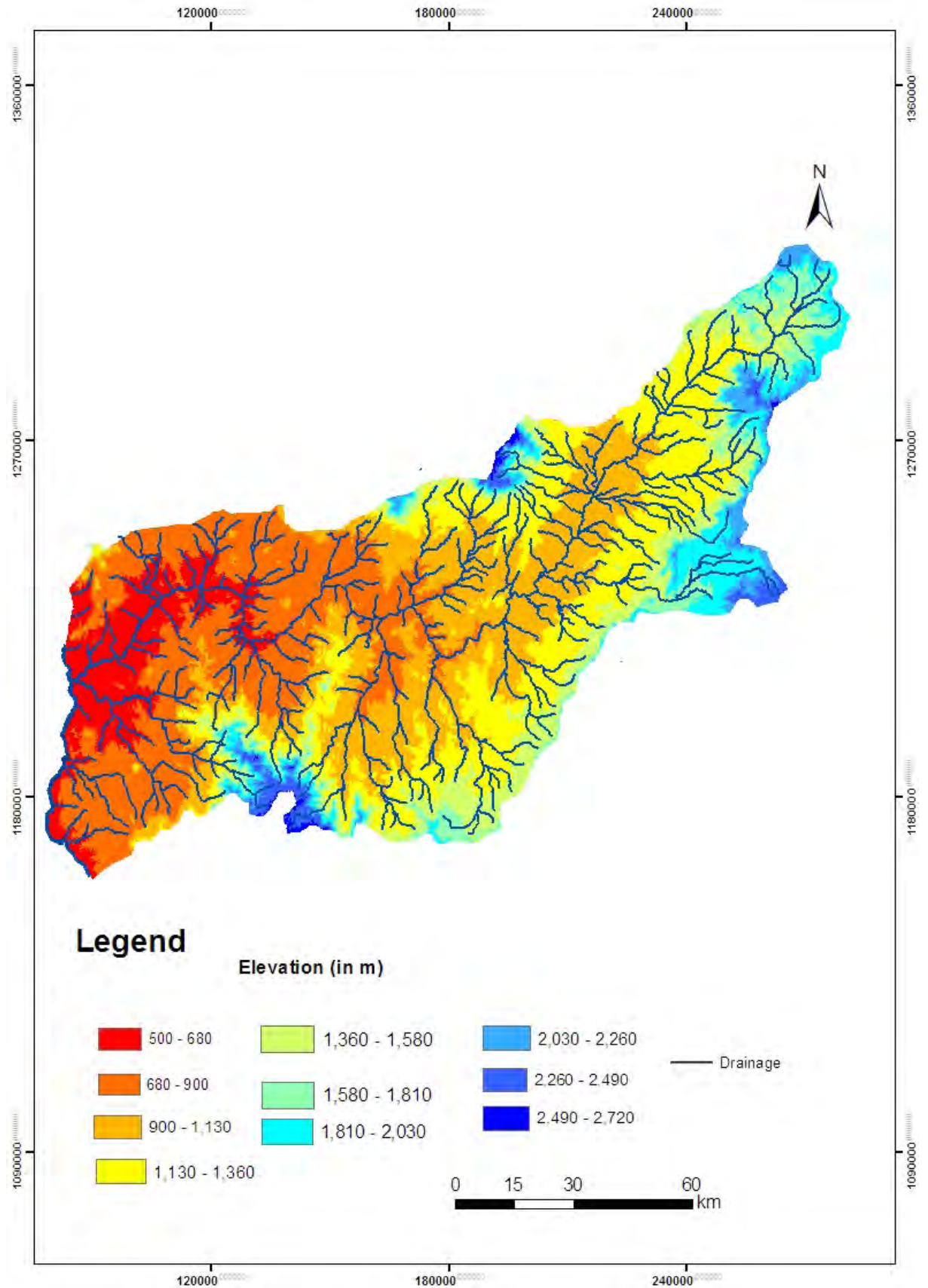
### **2.3.2. Drainage**

The drainage density is higher in the relatively elevated areas especially when the weathered section is thick or when the pattern of structures crossing the rocks is higher. In general, narrow deep to shallow gorges are found in the highland. In the lowlands, relatively wider river channels are found. These river channels and tectonized terrains form the lowest or flat lying areas in the map sheet. Most of the major rivers are tectonically controlled and follows regional and sub-regional lineaments. As in the case of rivers major high-discharge springs are aligned along regional faults. The lowest elevated areas are found near to the Abay River, at the confluence of Beles and Abay rivers.

In general, the direction of flow of these rivers is controlled by the topography. The highlands, from where the streams flow, are in general humid and rugged and the surrounding lowlands, in to which the streams flow, are mostly arid and relatively flat. These topographic differences induce rapid run off, low retention in soil layers and soil erosion on the highlands.



**Figure 2.3 Topographic Map of the Area**



**Figure 2.4** Drainage Map of the Area

## **2.4. Settlements**

The area is a part of the Benishangul-Gumuz and Amhara National regional states. The population distribution is variable from place to place due to several factors. The main factors are the suitability of the climate, the presence or absence of perennial water bodies, the suitability of the land for farming, cattle breeding and the proximity of the villages to roads and markets, etc. A relatively large number of people live in highlands in Wombera plateau, Dangur and Balaya Mountains and Dangila areas and lowlands in Pawe and Dangur and along or nearby water sources in the other lowlands. The Shinasha, Agew, Amhara and Gumuz, are the major tribes in the area whereas the Oromo represent a minority. The people of Gumuz tribe inhabit only the lowlands and these people sometimes engage in subsistence farming, cultivating sorghum and maize. Sesame and cotton are grown for local consumption. They raise goats and occasionally pan for gold along some of the rivers in the area. People also harvest wood to produce incense and produce honey. The Oromo, Shinasha, Amhara and Agew people populate the highlands and lowlands. They grow Teff and barley and raise cattle, sheep and goats. Coffee is the common cash crop in the subtropical area of Wombera.

## **2.5. Soil characteristics and vegetation cover**

### **2.5.1. Soil characteristic**

According to the National Atlas of Ethiopia 1981, the majority of the basin is covered by nitosol soil. The soil thickness and type in the eastern part of the area is variable from place to place. The soil cover is generally thin on the highland plateau and even at some places soil cover is absent. On the low-lying plains a relatively thick soil cover is observed. Its thickness is greater and fertility much better in the low-lying plains than at the flat-topped areas. The soils occurring over most of the area, especially on the gentle to moderately steeping terrains, is considered to be non-calcareous at least to a depth of 20 to 50 cm. (GSE Abu Ramla area). They are mainly weathered products of the underlying rock and mainly overlie the weathered mantle material. These soils are mainly constituted by unconsolidated silty clay to silty sand material and possess weak or no development of soil horizons (Eutric Regosols). They show changes in color, structure and constituents from area to area as the source (weathered material) is variable. The thickness of such soils is variable due to variation in the susceptibility of the bedrock to weathering and the morphology of the area.

The soils covering the Wombera plateaus and their surroundings are classified as lava plateau soils grouped as II-N which contains shallow, red, yellow, gray, black clays (Mesfin Woldemariam (1969). These soils have been termed as Nitosols and are characterized by an argillic B-horizon where the percentage of clay does not decrease from its maximum amount by as much as 20% within 150 cm from the surface (National Atlas of Ethiopia, 1981). The thickness of this soil is also variable reaching up to 20 m at the thickest portion. There are also soils covering the margins of river channels and some low-lying plains near the rivers. These are fluvisols, connotative of flood plains and alluvial deposits. These soils have been developed from recent alluvial deposits and mostly occur along the lower reaches of rivers (streams).

### **2.5.2. Vegetation cover**

Extensive vegetation and/or forest cover is not present in the study area. The vegetation cover decreases towards the low-lying areas because of deforestation activities (like forest fire) by the local people for farming. The natural vegetation in the lowland part of the study area in general is characterized by a variety of shrubs, bush with woody trees and elephant grass undergrowth and localized bamboo forests. The highland part of the study area is covered by moderately dense eucalyptus trees. Most of the area underlain by a crystalline basement and is apparently unsuitable for agriculture. In the Highland part of the Basin, agriculture is practiced on the Tertiary basalt cap. Incense is harvested from the gum of a few types of trees. Stream valleys are characterized by an overgrowth of a special type of palm tree whose leaves and fibers are used for making baskets and household furniture.

Woodlands and deciduous trees cover a large part of the area. Local people depend on the forest for making charcoal, collecting honey and harvesting material for producing incense. Improper utilization of the forest in the form of burning to clear land for agriculture is endangering both the forest and the wild animals living in it.



**Plate 2.1 Deforestation (Mandura area)**

## CHAPTER THREE

### 3. HYDRO-METEOROLOGY

#### 3.1. Hydrometeorology

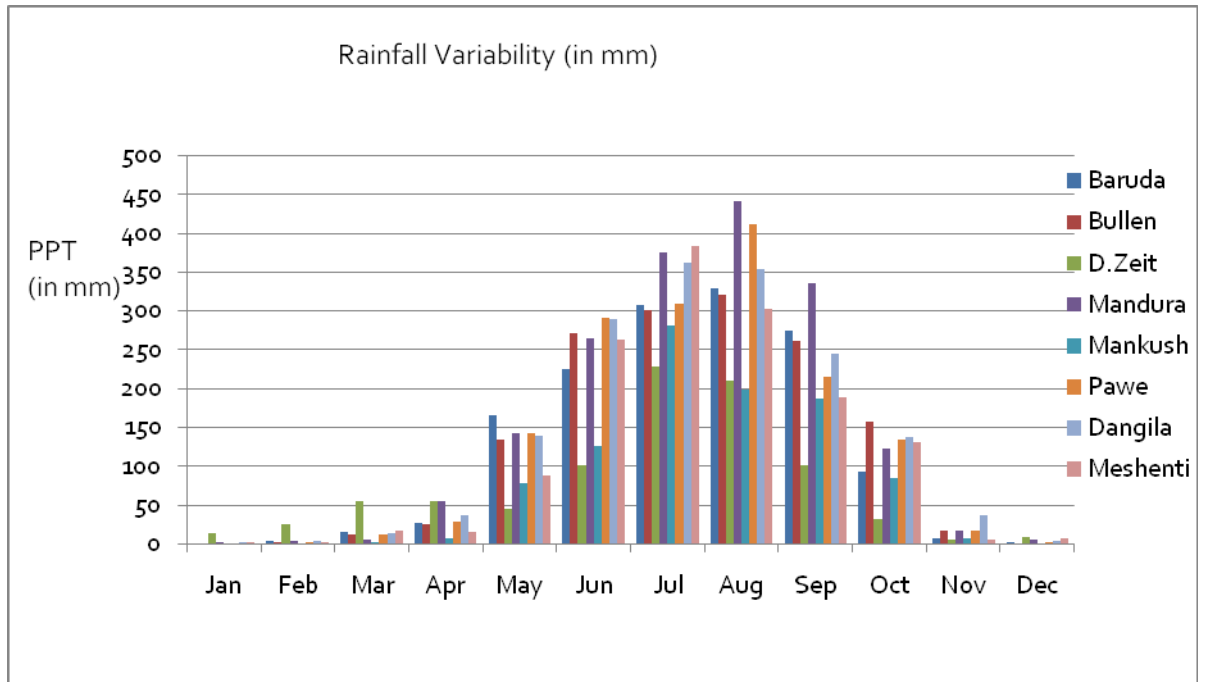
Based on limited data attempt was made to present the general overview of the hydrometeorology and surface water resources of the study area in this chapter. The data availability (both in space and time) do not permit to make analysis of the detailed account of the climate and hydrology of the region. Here hydrometeorological data is used mainly to understand the role of the various climatic and hydrological factors in recharging the groundwater system.

There are quite a number of meteorological stations in the area. Based on the scarce and incomplete climatic records, the hydrometeorology is characterized. The meteorological stations are located in few urban centers Monthly river discharge data was obtained from the Ministry of Water Resources only for two rivers with gauging stations (Main Beles and Gilgel Beles rivers). The data displays large variations in discharge. This is due to extreme topographic differences, precipitation condition, vegetation covers and infiltration condition.

##### 3.1.1. Precipitation

In general the distribution and amount of precipitation varies significantly owing to various factors. Among others the most important ones are topography, circulation of the moisture patterns, distance from the moisture sources and temperature. The former two are the major factors influencing the amount and distribution of precipitation in the Basin. The rainy season in the area is from June to September, which forms a uni-modal character that matches with the hydrograph of Beles Rivers.

Generally, the seasonal distribution of precipitation over the country is governed by the position of inter tropical convergent zone (ITCZ). Accordingly; the rainy season from June to September is controlled by ITCZ which lies to the north of Ethiopia at this time. Hence the study area intercepts most of the monsoon precipitation from Atlantic and Indian Ocean during this time. The dry period from October to February represents the time when the ITCZ lies to the south. In these months, the northeasterly trade wind traversing Arabia dominates the region and therefore produces very little or no precipitation. During March, the ITCZ is located in the south of Ethiopia moving northward. At this time low pressure is developed in the Sudan and Arabia while high pressure develops over the Gulf of Aden and Indian Ocean The high pressure generated a moist easterly air current over southeast Ethiopia producing spring (Belg) rain from March to May. But, the Basin gets very little precipitation. As shown in Figure3.1 the temporal variability of precipitation strongly correlates with the position of the ITCZ.



**Figure 3.1 Mean monthly long term precipitation graph of the area**

Precipitation of the study area was analyzed based on the record of eight stations found in and around the study area. The data of these stations is incomplete for some months. The data gaps of these stations are filled by averaging results obtained at the same station in different years of the same months and the other nearby stations. Table 3.1 shows the long-term average monthly precipitation of the selected stations.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Baruda	0.34	3.15	14.38	26.8	165.64	224.63	307.69	328.87	274.68	92.52	6.8	1.43	1446.93
Bullen	0.65	1.6	11.39	24.43	134.38	270.64	299.63	320.6	261.03	156.48	16.04	0.25	1497.12
D.Zeit	12.44	24.77	54.67	54.98	45.1	100.57	227.82	209.56	100.13	31.45	5.08	8.47	875.04
Mandura	2.02	3.53	4.51	54.81	142.33	264.25	374.71	441.11	334.9	121.59	15.71	4.88	1764.35
Mankush	0	0	1.9	7.29	77.72	126.21	280.21	197.33	185.76	83.91	6.78	0	967.11
Pawe	0.27	1.42	11.81	27.86	142.39	290.27	308.4	410.71	215.28	134.43	17.25	1.81	1561.9
Dangila	0.94	2.48	13.13	35.64	137.48	288.84	360.96	352.12	244.09	137.04	35.444	2.533	1610.7
MESHENTI	2.19	2.09	16.69	15.46	86.76	263.06	382.58	301.28	187.52	130.96	4.412	6.844	1399.84

**Table3.1 means monthly long term precipitation of the area.**

Precipitation in the study area shows significant variation. High altitude area like Wombera Plateau with elevation around 2500 m receives mean annual precipitation of 875 mm; while the low altitude area like Pawe with elevation around 1000 m receives an average annual precipitation of 1560mm and Mankush with an elevation of about 800 m receives average annual precipitation of 965 mm. Highest annual rainfall depth was recorded at Mandura station (1735mm).

In general the long-term average annual precipitation of the region is over 1300 mm. Attempt was made to calculate the aerial depth of precipitation based on Isohyetal methods. . Because the area has Orographic effect and the stations are not evenly distributed the Isohyetal method gives good result, Tenalem Ayenew and Tamiru Alemayhu, 2001.

**Isohyetal Contour Map method:** - it consists of drawing lines of equal rainfall depth (Isohyets) by interpolation between observed rainfall depths at observed points. The average depth of precipitation is given by:

$$pA = \frac{P_{1,2} \cdot a_{1,2} + p_{2,3} \cdot a_{2,3} + \dots + P_{n-1,n} \cdot a_{n-1,n}}{At}$$

Where  $p_{1,2}$  is rainfall between isohyets 1 and 2,  $a_{1,2}$  is area enclosed by successive isohyets of 1 and 2. The estimated depth of precipitation using Isohyetal contour map method is 1352.9mm. The values obtained from these methods indicate quite high rainfall compared with the average elevation. The rainfall of the region is by far higher as compared to the southern, northwestern and eastern lowlands of Ethiopia which receive less than 600 mm annually. One can generally conclude that the precipitation of the Basin is higher, despite lowland dominated system in Northwestern Ethiopia. This is partly attributed to the moisture source. Ethiopia receives the main rain from the Atlantic Ocean from June to September. Much of Ethiopia including the study area receives the Belg (summer) precipitation from the Atlantic Ocean. The amount of the Belg precipitation decreases as one goes from southwestern Ethiopia to northwestern Ethiopia. Beles Basin is the transition zone between the two extremes.

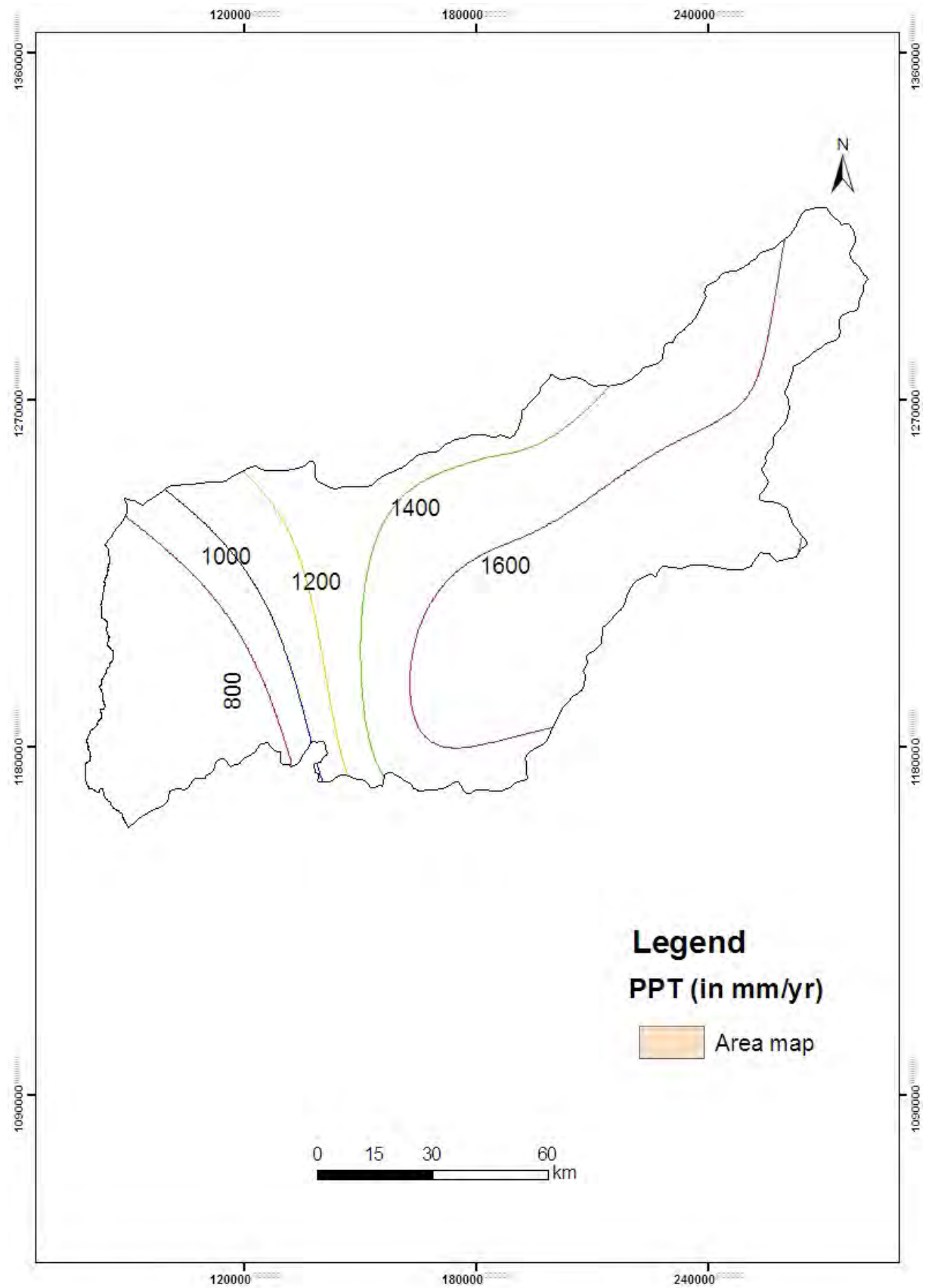
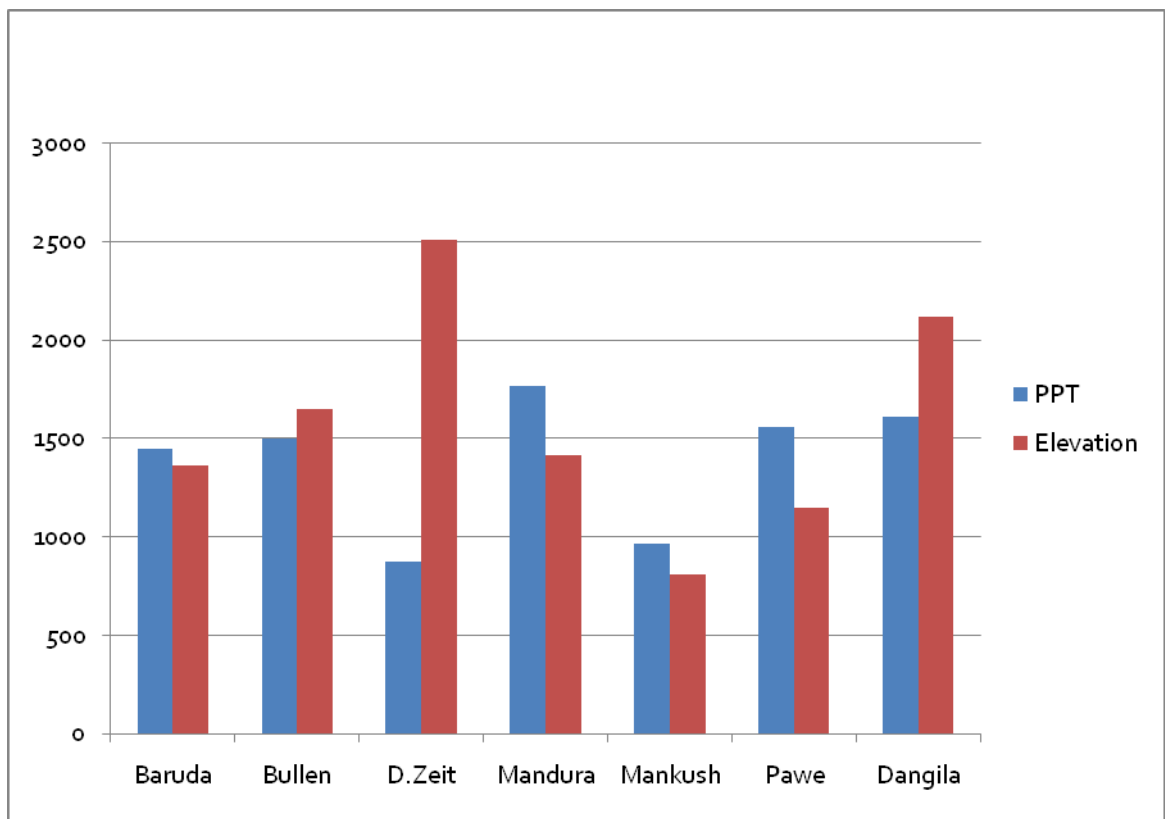


Figure3.2. Isohyetal Map of the Area

It is worth noting from the data the unusual precipitation variability in the region. There is no strong correlation between altitude and precipitation. The two variables show poor correlation coefficient. Usually, precipitation increases with altitude. This is not the case in the region. It can be exemplified by the data of Pawe and Wombera (Debrezeit) stations. This is most likely related to the Orographic effect. The presence of large elevated plateau (Wombera) and such mountains as Belaya Northwest of Pawe, Dangila East of Pawe and Kar southeast of the Basin may affect the distribution and amount of precipitation. Orographic effect on rainfall distribution is evident



**Figure3.3 Altitude-precipitation graph of the basin**

Despite the low correlation coefficient of precipitation and altitude, the Geological Survey of Ethiopia has established altitude – precipitation relations based on limited data obtained in western Ethiopia. The relation is given by:

$$P = 0.6 A + 303$$

Where, P is annual precipitation in mm and A is altitude in meter.

This relation appears to be not valid for the study area. This is apparent from the very low correlation coefficient ( $r=0.4$  in figure3.3). Therefore, generating precipitation data from

altitude based on limited recording stations in areas where there is Orographic effect requires careful consideration and assessment of precipitation variability both in space and time.

### 3.1.2. Temperature

In the study area there are seven stations recording daily maximum and minimum temperature which was averaged to mean monthly value. These stations are found in both the highlands and lowlands.

As in the case of precipitation temperature varies highly with altitude and seasons. Highest mean monthly temperature was recorded at Mankush during April (31<sup>0</sup>C) and the lowest at Debrezeit during December is (17<sup>0</sup>C). Table 3.3 summarizes the 10 years monthly average temperature of selected stations.

Station Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bullen	20.5	22.6	23.7	24.6	23.2	20.8	19.3	19.7	19.8	20.2	20	20.1
D/Zeit	18.4	19.9	20.6	21.2	21.2	20.5	19.1	19	19.2	18.7	17.6	17.4
Mandura	24.1	25.8	27.4	28.1	26.7	23.1	21.7	21.2	21.1	22.2	23.3	23.7
Mankush	26.8	29.1	30.9	30.9	29.5	26.2	24.6	24.1	24.4	24.7	25.9	25.9
Pawe	23.5	25.7	27.6	28.4	26.5	24	22.6	22.6	23.2	23.4	23.1	23
Chagni	19.3	21.6	22.8	23.7	22.8	20.5	19.6	19.6	19.7	20.1	20.1	19
Dangila	15.4	17.4	18.4	19.4	19	17.7	16.9	16.9	17.1	16.7	15.8	15.2

**Table 3.2. long term mean monthly temperature of the area**

### 3.1.3. Evapotranspiration

Evapotranspiration is the loss of water to the atmosphere through evaporation from all surfaces; including evaporation from free water surfaces, soil, and man-made surfaces and transpiration from plants. It is customary to divide evapotranspiration in to free water evaporation and evapotranspiration from plants and soil. Although the deriving climatic forces behind the two processes are the same, evapotranspiration from soil and plants is more complex. This is due to the fact that the nature of evaporating surface of soil and plants is influenced by various physiological and aerodynamic factors as well as the availability of water.

There are two types of evapotranspiration (AET and PET).

**1. Potential evapotranspiration (PET)** - the evapotranspiration from a vegetal cover if sufficient water supplied to obtain optimum growth or the maximum amount of vapour which might be transferred under the existing meteorological conditions (water is not the limiting factor).

**2. Actual evapotranspiration (AET)** - the evapotranspiration from a vegetal cover under the natural or given conditions of supply of moisture or the actual amount of vapour which might be transferred to the atmosphere, depends also on the availability of water to meet the atmospheric demand.

Estimation of evapotranspiration demands data of many variables as the process is affected by various factors. Accurate estimation of actual evapotranspiration is more difficult. However, there are many simple empirical and semi-empirical relations that can be used to estimate evapotranspiration. In this case very general pictures of evapotranspiration are given based on two simple methods.

The potential evapotranspiration was estimated using Thornthwaite method. The result indicates that the annual potential evapotranspiration in the basin ranges from 1400 to 1800 mm annually. The method is given by the following relation.

$$PE^x = 1.6 \left[ \frac{10t}{J} \right]^a$$

$$a = 675 \times 10^{-9} J^3 - 771 \times 10^{-7} J^2 + 178 \times 10^{-4} J + 0.49239$$

t: mean annual temperature ( $^{\circ}\text{C}$ )

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

$$j = \left[ \frac{t_n}{5} \right]^{1.514}$$

$t_n$ : average monthly temperature in  $^{\circ}\text{C}$

$$PE = PE^x \cdot \frac{ST_z}{30 \times 12}$$

PE : potential evapotranspiration in cm of a standardized month of 30 days and 12 hours between sunrise and sunset.

$PE^x$ : total potential evapotranspiration of the month under consideration

S : number of the days of the month in question

$T_z$  : average number of hours in the days between sunrise and sun set in the month

The actual evapotranspiration is estimated based on the formula of Turic, Langbein and Wundit. This method estimates the mean actual evapotranspiration of river basins based on

precipitation and temperature records. This method has limitations as evaporation is treated only based on two variables.

$$\bar{E} = \frac{\bar{P}}{\sqrt{0.9 + \frac{\bar{P}^2}{[L(t)]^2}}}$$

$$L(t) = 300 + 25t + 0.05t^3$$

P: mean annual precipitation in millimetre

E: mean annual evapotranspiration in millimetre

t: mean annual temperature in °C

The result obtained from this method indicates that the mean annual evapotranspiration ration in the Beles River basin is 675. It should be noted that the data obtained from these methods may have limited practical importance for detailed water resources potential evaluation and management. Actual evapotranspiration estimation demands accounting all important factors such as temperature, wind speed, humidity, land use and land cover, etc.

The summary of the other meteorological records is given in Table 3.3. This record is only for Class A meteorological stations. Only Pawe station has complete meteorological record in the studied area. To provide regional picture other stations in adjacent areas are included.

In general potential evapotranspiration is expected to be by far higher than the corresponding annual precipitation in the lowlands. It is expected that the highlands may have lower value but relatively higher actual evapotranspiration. As precipitation increases with altitude, the temperature decreases. Evapotranspiration also decreases. Therefore highlands are more humid than lowlands. Putting together both relations it is possible to approximate the hinge point, the altitude where precipitation is equal to evapotranspiration.

This relation between mean annual precipitation and mean annual potential evapotranspiration (PET) and altitude is established by the Geological Survey of Ethiopia for Assosa area. The hinge point of equal precipitation and evapotranspiration lies at an elevation of 1600masl. for this region. It means that the localities lying at altitudes higher than 1600masl have surplus of water on annual basis, while localities under altitude of 1600masl are drier. However, this may be affected by the geological and hydrogeological factors as discussed in the following chapters.

Station Name	Altitude (m)	Data	Months											
			J	F	M	A	M	J	J	A	S	O	N	D
Chagni	1,620	T	19.1	20.2	22.1	22.7	21.8	19.9	19.1	19.0	19.3	19.6	19.1	18.7
		H	60	62	58	77	71	79	83	83	81	75	68	64
		W	1.4	1.5	1.6	1.6	1.6	1.4	1.2	1.1	1.0	1.0	1.0	1.2
		S	8.9	8.6	8.0	8.4	6.3	5.0	3.3	3.1	4.4	5.9	8.4	8.8
		Rf	3.4	6.9	12.6	28.2	158.8	277.4	349.9	356.8	295.7	181.3	29.3	3.6
		ETP	3.6	3.9	4.4	4.3	3.9	3.3	2.8	2.7	3.0	3.2	3.4	3.3
Dangella	2,100	T	15.7	17.1	17.4	18.3	18.2	17.7	16.5	16.6	17.0	17.0	16.7	15.8
		H	65	61	59	58	70	81	88	90	88	83	74	68
		W	1.4	1.5	1.6	1.6	1.6	1.4	1.2	1.1	1.0	1.0	1.0	1.2
		S	9	9.7	7.9	9.1	7.5	5.2	3.6	5.1	6.5	7.1	9.1	7.9
		Rf	16.8	18.3	45.5	49.9	107.3	227.8	301.7	334.7	227.3	96.1	46.2	8.7
		ETP	3.3	3.8	4.0	4.4	3.8	3.1	2.6	2.9	3.2	3.2	3.3	3.0
Mankush	810	T	26.3	25.4	28.7	27.5	27.6	25.1	25	21.7	23.3	24.6	25.5	23.4
		H	30	31	32	41	46	67	78	77	73	66	45	35
		W	0.9	1.1	1.4	1.3	1.4	1.4	1.1	0.9	0.9	0.7	0.6	0.7
		S	9.4	9.4	9	8.7	7.6	5.5	4.8	7.4	6.1	7.7	9.3	8.9
		Rf	0	0	7.5	10.5	83.4	177.6	266.1	157.2	211.8	53.7	6.5	0
		ETP	4.2	4.7	5.5	5.4	5.1	4.1	3.5	4.0	3.6	3.9	3.8	3.6
Pawi	1,150	T	23.5	25.7	27.6	28.4	26.5	24.0	22.6	22.6	23.2	23.4	23.1	23.0
		H	52	48	60	39	63	80	85.0	88	86	82	64	51
		W	0.9	1.1	1.4	1.3	1.4	1.4	1.1	0.9	0.9	0.7	0.6	0.7
		S	9.8	9.3	8.8	9.2	8.7	6.5	5.1	5.2	6.2	6.8	8.3	10.1
		Rf	0.3	1.4	11.8	27.9	142.4	290.2	308.4	410.7	215.3	134.4	17.3	1.8
		ETP	4.1	4.5	5.0	5.5	5.0	3.9	3.3	3.2	3.4	3.4	3.2	3.7

**Table 3.3 Long term mean monthly meteorological data.**

Note: T =mean monthly temperature in °C; H =mean relative humidity in %; W = mean wind speed in m/s; S = average daily sunshine duration in hr; Rf = mean monthly precipitation in mm; ETP = potential evapotranspiration (Penman-Monteith) in mm/day

### 3.2. Surface water resources

Groundwater and surface water interaction is a natural phenomenon drifted by the fact that the two are critical component of one system linked intimately by hydrologic cycle. Groundwater discharged to the surface through natural springs, transpiration by plants, seepage under river and stream. On the other hand, groundwater is recharged by surface water from direct precipitation and indirectly from loosing rivers and streams.

As a matter of fact, any groundwater resources assessment requires evaluation of surface water systems. Surface waters include rivers, lakes, ponds and artificial reservoirs.

In the study area there are two major rivers which have gauging stations. These are Main Beles and Gilgel Beles rivers. These gauging stations are at middle of the study area and the hydrological system is assessed only using limited data. This basin shows its distinct

hydrogeological characteristics being controlled by geology, slope, soil, climate and also the upstream catchment area. Here attempt is made to provide the general picture of the hydrology of the Basin based on limited river hydrographs and quantitatively based on field observation of the hydrogeological and geomorphological features.

### 3.2.1. Hydrographic characteristics of major rivers

As sated above, only Main Beles and Gilgel Beles have automatic river gauging stations. The drainage density is higher in the highlands and lower in the lowlands. The drainage pattern is dominantly dendritic in the highlands and sub-parallel in the lowlands. The high drainage density in the highlands is attributed to steep topography and high rainfalls. In these mountainous areas streams start as high discharge springs at the foot of hills and ridges. Good example to this is Ali spring in Pawe woreda, Abatachin spring in Mandura woreda and Gisa spring in Dangila woreda. They emanate along the line of regional faults and flow as perennial stream downstream. The details of these water points are presented below. Figure3.1 shows selected water points of hydrological importance.



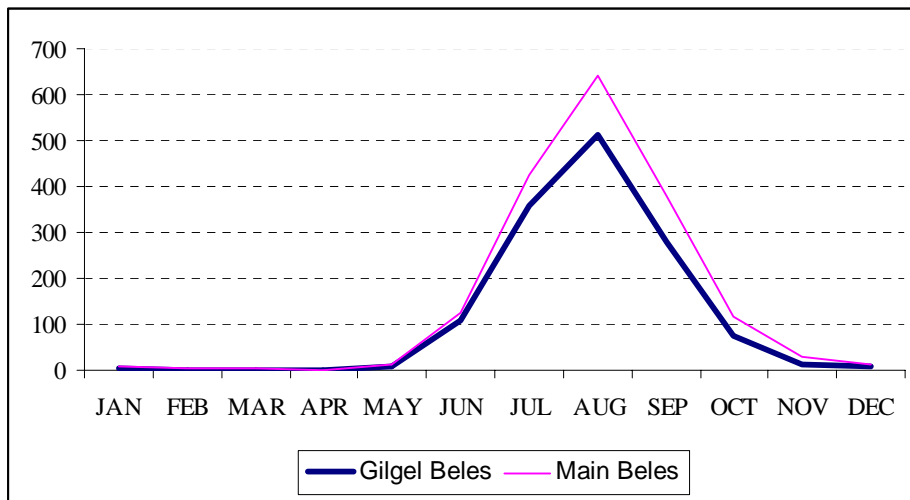
**Plate3.1. some water points of hydrological significance.**

[Note: Upper left is Beles River crossing close to the town of Pawe; upper right is Gisa spring on construction at Dangila; lower left is dammed Ali Spring north of Pawe, and lower right is Diga dam close to Pawe town]

As revealed from the discharge record of the Beles River there is strong seasonal and interannual variability of discharge. This is also the case for precipitation.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Main Beles	7.5	4.7	3.4	2.3	9.3	85.0	362.9	812.1	356.5	258.2	52.1	17.6	1971.5
Gilgel Beles	6.8	3.4	3.3	2.9	6.2	34.0	102.5	178.3	124.0	82.3	26.0	11.7	581.6

**Table 3.4 Ten year average monthly discharge of Beles Rivers (in mil.mc)**



**Figure 3.4. Long-term average monthly discharge graph**

As shown above (Figures 3.4) the hydrographs have one major peak discharge season. This covers the wet season between June and September. As compared to the wet season flows, the dry season base flow is very low. Therefore, any surface water development plan should target towards tapping the wet season flow. As revealed from field observations, spring discharges change also significantly with rainfall. The discharge of large springs varies substantially. This is often the typical character of springs emanating along major faults and contact springs.

### 3.2.2. Existing water supplies

The water supply coverage of the Basin is very low. Most of the rural community uses traditional unprotected surface waters and springs. However few areas have better water supply sources. These are mainly localized in Mandura, Pawe and some areas of Dangila and Dangur woredas. The great majority of the population depends on springs and hand dug wells. In extreme lowlands in Bullen, Dangur, Jawi and Wonbera woredas, people use river water.

As is usually the case, surface water systems are preferred to be used for water supply when groundwater sources are scarce or absent. However, due to pollution using surface waters for drinking is a risk business. Because surface waters (rivers and lakes) are usually liable to be polluted easily. As a matter of fact, development of surface waters for water supply demands some kind of water treatment system. This in turn requires money. Establishment of water treatment plant for utilizing surface water sources is mostly economically feasible for larger

communities which are leaving in major urban centers or for rural community which settles in areas which are economically and technically feasible for the construction of hydraulic structures. Diga dam is one of such structures constructed for water supply purpose in pawe woreda by diverting Gilgel Beles River.

### **1. Main Beles and Gilgel Beles Rivers**

These two rivers emerge from the highlands of North Achefer and Dangila woredas respectively and join to form Beles River in Pawe woreda. The livelihood of the great majority of the population depends on these rivers. They are being used for irrigation in few areas of Pawe, Jawi, Dangila and Mandura woredas and in some cases for drinking in the extreme southwestern part of the lowlands. Diga Dam is the only hydraulic structures that have been constructed on Gilgel Beles River for water supply purposes for some parts of Pawe woreda.

### **2. Diga Dam**

The Beles river basin has been a focal point for large scale development since the 1980s. Large irrigation projects have been proposed and partly implemented in Pawe area during the Derg Government. Still the Tana Beles project is undergoing mainly for the generation of hydroelectric power and irrigation project.

One of the results of the Tana-Beles irrigation project is the construction of the Diga Dam close to the town of Pawi (see Figure 3.1). After the construction of the dam, the Tana Beles Project was suspended. This dam has been constructed for irrigation and generation of hydropower. Its use for water supply remains to be seen. At the moment there is a structures present for water supply system for the pawe woreda community only during dry season. Because the structure has no treatment plant it is not functional during rainy season. In the long-term, Diga Dam can be used for such a purpose for large rural and urban communities residing downstream.

### **3. Ali Spring**

Ali spring is located east of Pawi town right at the border of Metekel Zone and the Amhara Regional State. The spring has high discharge (Estimated yield of 40-50l/s). The great majority of the population within the Pawi woreda depends on Ali Spring. The spring has been developed and diverted by a pipeline to the different villages and towns established during the resettlement program during the Derg Regime and the overflow water used for small scale irrigation downstream of the spring. Unfortunately much of this system is not functional. Most of the reservoirs are not functional. Only the main pipeline that connects the spring with towns (Pawe and Almu) is functional. Even the existing pipeline has substantial leakage problem. This spring has a great sanitation problem. Because the dam is unprotected and has no any treatment mechanisms. According to the information from the community the spring discharge is decreasing from time to time.



**Plate3.2 Ali spring. The left hand side picture is the spring over flow, with non functional irrigation pipelines. The right side is the dam from the spring.**

#### **4. Abatachin Spring**

Abatachin spring is located about one km east of the small town of Genete Mariam. It emanates along a large north-south running regional fault that passes at the base of the Kar Mountain Ranges. The spring is the source a local river that flows towards the Beles River.

The spring supplies water to the towns of Gente Mariam (Mandura) and the Zonal capital Gilgel Beles town. More than 75 percent of the water of the two towns comes from this spring. The spring water is pumped to a reservoir located at Genete Mariam town and flows by gravity to Gilgel Beles town which is around 12km from Genete Mariam. Both towns have water shortage still.

#### **5. Gisa spring**

This spring is located 20km in the west of Dangila town in Dangila woreda. The spring has 11 points in total area of around  $0.05\text{km}^2$  and has an average discharge of 30l/s (information from woreda water bureau). The area has a geological formation of highly weathered porphyritic basalt (Figure3.1). Three of these springs are on construction for water supply of small towns and rural community around there through pipelines. According to the information from the woreda water bureau the three spring discharge increase from 5l/s in rainy season(summer) to 8l/s in dry season(winter). But now after development its average discharge increases to more than 10l/s. The probable reason for this increment of discharge in dry season is its recharge area may be far from the discharge area (the spring).

## CHAPTER FOUR

### 4. GEOLOGY

#### 4.1. Regional geology

Generally the geology of Northwestern Ethiopia is very complex. This vast lowland region, adjoining the western and northwestern highlands is characterized by basement complex Precambrian rocks with relatively wide coverage of Quaternary Sediments. The elevated adjacent highlands and transitional areas are covered with Tertiary and Quaternary Volcanic rocks.

The general regional succession of rock from the oldest to the youngest is Precambrian rocks, Triassic sandstone, Mesozoic sediments, Tertiary basalts, Cretaceous sandstone, Quaternary basalt and recent alluvial sediments. Age of geological unit in this report is according to Mengesha Tefera et.al 1996.

According to GSE Report Abu Ramla area, the geology of the basement rocks of the Northwestern Ethiopia can be divided into three litho-structural domains based on lithological associations, the style of deformation, and the degree of metamorphism. Low, medium and high-grade metamorphic rocks and intrusive bodies are evident in all the domains.

The lithological units can be divided into five major groups as follows:

- Gneiss and associated high-grade metamorphic rocks,
- Low-grade supra-crustal metamorphic rocks; which are mainly metavolcanics, metasediments and associated ultramafic rocks,
- Syn- and post-tectonic intrusive of acidic to intermediate composition,
- Cenozoic volcanic rocks, and
- Quaternary sediments.

Regionally, the basement complex rocks have been divided into three major domains showing differences in lithology, structure and degree of metamorphism. Central high-grade domains lie between western and eastern domains. It consists of high-grade gneisses and covers the majority of Dibate and Bullen Woredas. Gneisses of middle to upper amphibolite facies are migmatitic and are thought to be Archaean or early Proterozoic in age. These rocks outcrop in patches in Dibate, Bullen, Wonbera and Mandura Woredas. This gneissic unit borders large outcrop of felsic to mafic metavolcanics with intercalated metasediments and occurrences of altered ultramafic bodies of upper green-schist to lower amphibolite facies. The contact between these two units is of tectonic origin. Both units have been intruded by a succession of

plutons which are foliated mafic to felsic intrusions to post-massive tectonic bodies. Low grade schists are also common.

The Precambrian rocks are covered with Tertiary volcanics in elevated areas. Alluvial, elluvial and colluvial sediments cover extensive areas along the lower reaches of the Abay River and its major tributaries and at the confluence point of the Abay and Beles Rivers.

## **4.2. Geology of the area**

Characterization of different geological units was done based on various geological maps, their explanatory notes and reports and field observations.

The general description of the lithostratigraphic units of all the rocks in the Basin is given below. Most of this description has been taken from the geological map of Ethiopia compiled at the scale of 1:2,000,000 (Mengesha, 1991) and Abay River Basin Master plan Integrated Development Master Plan Project by Ministry of Water Resources at the scale 1:250,000.

### **Stratigraphy**

The older rocks outcropping in the Beles River Basin are Precambrian. They can be more simply divided from base to top into three lithological types corresponding to the three main metamorphic facies of the lithosphere: Granulite (Lower Complex), amphibolites (Adola Group), green-schist (Tsaliet and Tambien Group).

### **Achaean age formations**

#### **Lower Complex**

High grade metamorphic rocks of the Pan-African Mozambique Belt with amphibolite to granulite facies that includes mainly gneisses. Although usually coarse-grained and well foliated, the gneisses and migmatites merge into more homogeneous varieties of granitic appearance. In the Blue Nile basin, this group includes rocks which, generally, have not been assigned to a particular lithologic unit. Only the Konso Gneiss was differentiated and mapped in the south of the Dangur Mountains in the western part of the Beles basin. It consists of dark, weakly foliated, pyroxene, amphibole-pyroxene and pyroxene-garnet gneiss.

#### **Adola Group**

This group is typically developed at Adola in Sidamo Province where it consists of amphibolites of intrusive and volcanic origin and an assemblage of basic and ultrabasic rocks, with beds of chlorite and graphite phyllite and iron-bearing and graphitic quartzites. In this research area the Adola Group is residual in a small tectonic basin in the lowland of north-west of Wombera plateau.

**Marble:** – Extended marble belt is evident in Bullen, Guba and Wonbera woredas. This unit is aligned along N-S and NW-SE tectonic line. The unit occurs as resistant ridges that can easily be delineated from aerial photographs and satellite images. These rocks are fine grained and dark green, weathering to brown or yellow. In few places they can easily be identified as white patches. Generally they are massive and dense and cut by numerous quartz veins.

**Tsaliet Group;** Low grade metamorphics, with greenschist facies: chloritic and sericitic schists including some volcano-sedimentary rock.

This Group contains two major rock associations:

The mainly volcanic rocks of northern Ethiopia (a), consisting of propylitised andesites and diabases, tuffaceous slates and greywackes totalling over 2,000 m in thickness;

The sedimentary and volcanic group of Wellega Province (b), consisting of quartzites, chloritic and sericitic phyllites with interbedded iron-bearing quartzites, graphitic rocks and acid and intermediate volcanic rocks (Birbir Group).

In the study area it outcrops in the escarpment of Wombera plateau.

### **Tsaliet and Tambien Group clastics:-**

Phyllites and carbonates (oncolithic limestone and dolomite, "marble"), and quartzite.

Developed mainly in a broad area of Tigray Province in the north of Ethiopia, this group merges into the underlying Tsaliet Group. Slate and shale (which is commonly graphitic) with interbedded limestone are the main rock types. An important unit in this group is a black limestone containing algae, including probable oncolites. It outcrops in the central part of the area in northeast of Wombera plateau, in south of Balaya plateau and north of Bullen woredas.

The undifferentiated lower complex exposed lowlands of north of Dibate, in some parts of Pawe, Mandur escarpment adjoining with the high lands. This formation is low grade supra-cristal metamorphic rocks, which are mainly metavolcanics, metasediments and associated ultramafic rocks.

### **Intrusive and ultramafic rocks younger than the Tambien Group**

- **Basic and ultrabasic rocks**, such as gabbros, dolerites, pyroxenites, dunites, peridotites, and serpentinites often metamorphosed.
- **Granitoids and quartzo-diorites**
  - **Syntectonic granitoids:** grano-diorites and granites.

Granodiorites and granites formed during a major episode of folding and metamorphism are included in this group.

The grey granodiorites are the end product of extreme metamorphism and are typically medium to coarse-grained rocks forming bodies with foliated margins and massive centres. They consist of oligoclase-andesine and orthoclase feldspars with or without quartz and biotite and contain remnants of amphibolitic metavolcanics and metasediments.

Syntectonic granites generally form large massifs aligned parallel to the trend of the surrounding rocks. They are commonly pink or yellowish-grey and are sometimes porphyritic, containing large crystals in a finer grained matrix. They locally contain abundant fragments of the surrounding rocks and are often foliated near their margins. These formations outcrops in the western part of the area in lowlands of

Wombera, Dangur and Guba woredas around and at the confluence of Abay and Beles Rivers..

- **Post-tectonic granitoids:**

These occur as crosscutting intrusive bodies in western Ethiopia. The granite vary in composition and texture and have been dated as from 690 to 450 my. The granite typically contains microcline, a smaller amount of plagioclase, quartz and a little biotite. It outcrops in lowlands of northwest of Wombera plateau.

## **Cenozoic (Tertiary and Quaternary) volcanics**

**Ashangi Group (basalt)** (Blanford, 1870; Paleocene-Oligocene-Miocene).

Olivine basalts, tuffs and intrusive rocks: alkaline granite and syenite (S).

**Ashangi Basalts** (~ 55 to 24 My, Eocene-Oligocene)

Poorly defined and deeply weathered basalt flows with scarce tuffs; sometimes tilted with respect to the younger volcanics. This group includes outcrops in the periferi of the area Balaya and Dangur plteau, jawi, North Achefer and Dangila.

**Amba Aibà Basalts** (~ 36 to 18 My)

Flood basalts in thick flows with rare basic tuffs. Wolkefit basalts and trachybasalts. It has been identified in the North east of Jawi.

**Tarmaber Basalts** (~ 27 to 5 my, ~ 1000 m thicker at the volcanic centres).

Lenticular basalts with a large amount of tuffs, scoriaceous lava flows and typical red paleosoils. This unit overlies unconformably the Amba Alaji Rhyolites and, westward, the Amba Aibà Basalts and the Ashangi or the Blue Nile Basalts. According to Zanettin and others (1974), the Termaber Basalts show a southward age shifting from Lower to Upper Miocene. They were erupted from central volcanoes of hawaian type. The Mangestu volcano, which is the largest and the best preserved, has a diameter of about 100 km and rises a further 1,500 m above the plateau. This formation outcrops in the upper most part of the study area.

**Wellega basalts** (~ 15-13 My and 7 My, Zanettin, 1978; 200-400 m). Predominantly columnar basalt flows with intercalations of acidic tuffs and loose fluvio-lacustrine clastics. Phonolite plugs are quite frequent. This unit outcrops in the Wombera highlands. And the basalts related to volcanic centres outcrops around the periphery the stud area in Dangila and North Achefer woredas.

## **Eluvial, colluvial and alluvial deposits (Pleistocene to Present)**

They are concentrated in the alluvial flats extending in the west of the basin, close to Abay River. This colluvial deposits exposed in Guba woreda, at the periphery of the study area covering very small areas. Alluvial deposits in the west of Wombera at the confluence of Abay and Beles Rivers.

### **4.3. Structural geology and tectonic setting**

The main structural and tectonic trends are E-W, N-S, NE-SW and NW-SE. The most important ones are two sets of lineaments. These are the N-S and NE-SW sets. The majority of stream and river courses are parallel to these lineaments. The sheared zones (Wombera escarpments), often running N-S, are usually 50 to 500 m wide and contain highly strained rocks (GSE Assos-Kurmuk Report). Numerous E-W trending lineaments traverse the area. Springs are common along these major regional structures.

Few folds have been identified. Major folds occur in the western and south-central parts of the region. Bedding in the meta-sedimentary schists is parallel to foliation, indicating isoclinal folding. The folds are clearly evident in the escarpments bounding the Wonbera Plateau.

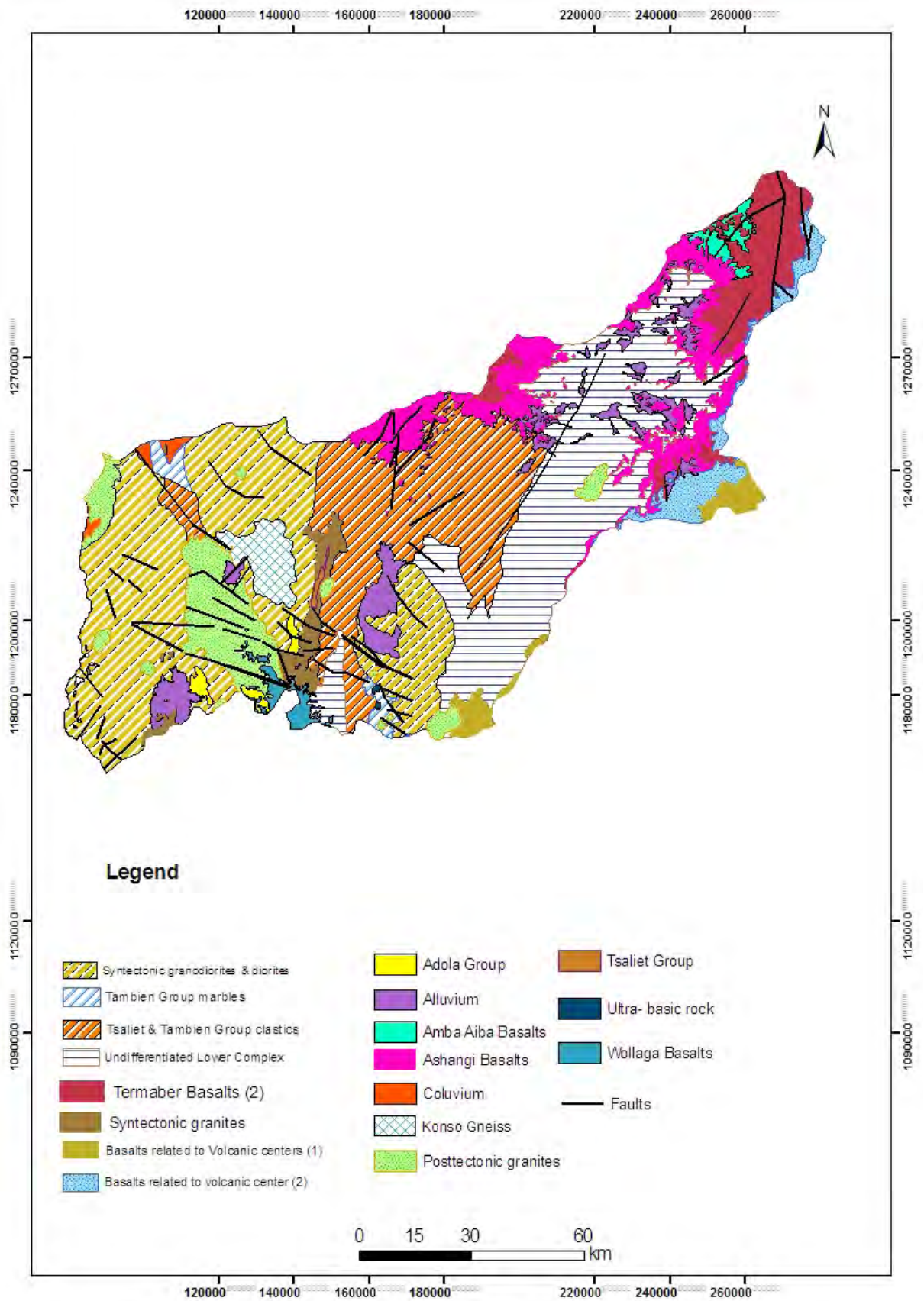


Figure 4.2. Geological map of the area (From Abay River Basin Master Plan Project)

## **CHAPTE FIVE**

### **5. HYDROGEOLOGY**

#### **5.1. General**

The occurrence and distribution of groundwater in the Basin was systematically analyzed. The hydrogeology of the study area is essentially controlled by the geological setting, morphogenesis of the terrain, distribution of rainfall and the movement of groundwater through interconnected primary and secondary porosity of the formations constituting the aquifer system.

The geological/lithological descriptions and field observation are very important tools in the assessment of the aquifer productivity. Hydrogeological field observations such as the distribution and magnitude of spring discharges, the degree of fracturing of the rock units, the thickness of the formations, the grain size, rounding and sorting, extent of weathering are some of the significant field observations which provided indirect evidence as to whether a rock unit is likely to be an aquifer of low, moderate or high productivity. In order to reinforce the indirect hydrogeological observations, other methods such as pumping test data should be utilized, however, such data are not available for the study area. Therefore the aquifer classification is made only by indirect hydrogeological field observations, such as distribution and magnitude of discharge of springs, degree of fracturing of rocks, grain size and rounding, depth and extent of weathering and available previous studies are taken in to consideration.

Groundwater inevitably occurs in geological formation. The occurrence of the groundwater depends upon the water bearing characteristics of a rock, which in turn depends primarily on their origin and/or geological process. Based on the qualitative evaluation of the water bearing characteristics, different hydrogeological units were identified in the study area.

These include fissured and fractured aquifer of basalt, fractured and karsts openings of marble, weathered and fractured parts of crystalline basement rocks and slightly weathered and locally fractured crystalline basement rocks.

## 5.2. Hydrogeological units of the area

The aquifer system has been defined based on the hydrogeological characteristics of the lithological units described by the geological maps and hydrogeological map of the area in scale 1: 250 000 and 1:1,000,000 by GSE, data from the field inventory and other unpublished groundwater investigation reports. The hydrogeological characterization of the area revealed the following aquifer / aquitard system:

- Porous aquifers (alluvium, colluviums) – The groundwater accumulates in the pores of the unconsolidated material. The bases of the mountain slopes are fringed by alluvial fans composed largely of great porosity gravel and sand. The effective porosity of the fan deposits, as well as the hydraulic gradients decrease away from the mountain margin. The consequences are the deterioration of water, quality and decreasing groundwater potential.
- Fissured and karst aquifers (marble) – The groundwater is stored in fissures of the whole thickness of marble body and the permeability can be enhanced by karstification along some fissures. Solution phenomena and karstification in the underground drainage of carbonate rocks are controlled by the base level, which may be a perennial draining stream and/or an impervious formation inside (graphite schist, intrusive rocks) and/or underlying the carbonate aquifer where it is in contact with the water table.
- Fissured aquifers (sandstone and volcanic rock) – The groundwater is stored in fissures and pores of the whole thickness of sandstone and conglomerate layers and / or in fissures and joints of the whole thickness of lava flows. The most favorable structure for groundwater accumulation is that which is mostly found in stratified sedimentary rocks.

Porosity of sandstone ranges from less than 5 % to a maximum of 30 % (GSE). Geological time is an important factor of the hydrogeological properties of volcanic rocks. Both porosity and permeability tend to decrease with geological time. The porosity of young lava flows may be quite high, but the permeability is largely a function of a combination of the primary and secondary structures within the rock. Pyroclastic rocks associated with lava flows are generally porous but not very permeable because of poor sorting and an abundance of fine material. Volcanic ash beds of large extent may form semi-horizontal barriers to water movement. The aquifers are expressed in the hydrogeological map.

- Fissured aquifers of low potential (some non-carbonate metamorphic and intrusive rocks) – The groundwater in the hard rock's is practically all stored in the fractured zones and the weathered mantle called overburden or regolith. The depth of fractured aquifer zones is generally no more than 50-70 m below the surface. The fractures will tend to close at depth. The faults and joints in igneous rocks are nearly vertical, except for narrow fractures, which are more or less parallel to the rock surface, sheeting and exfoliation. The greatest permeability is found in the sub-soil zone within the partially

decomposed rock. Wells tapping this zone have yields roughly an order of magnitude greater than in the unweathered (fresh) rock. The aquifers are expressed in model of the hydrogeological map (Figure5.1).

- Aquitards (some non-carbonate metamorphic and intrusive rocks) – The groundwater in the hard rock is practically all stored in the fractured zones and the weathered mantle called overburden or regolith. The rocks having a large amount of mafic minerals tend towards clayey weathering. The fractures will tend to close not only in increasing depth, but also because they are blocked by clay material. The aquitards are expressed in the model of the hydrogeological map (Figure5.1).

### **5.3. Aquifer Formation**

Based on the hydrogeological characteristics of the rocks the area can be divided into six rock units with different occurrence of groundwater:

- Precambrian marbles
- Non-carbonate Precambrian stratified and intrusive rocks
- Mesozoic sandstone
- Tertiary volcanic
- Quaternary volcanics
- Quaternary sediments

Unfortunately the less productive rock unit – Precambrian crystalline basement rocks, occupy the largest portion of the map sheet (more than 50%). Marbles, volcanic and others that have potentially productive aquifers form only little bit below 50 % of the map area. The general hydrogeological settings of the area and hydrogeological scheme of the area are shown in Figure 5-1

According to Hydrogeological report of GSE (Abu Ramla and Assosa-Kurmuk area); which cover half of the lower part of the study area the geological map consists of 31 geological units. These units were classified into the aquifer – aquitard systems as follows:

## **5.4. Aquifer classification of the area**

### **5.4.1 Extensive and highly productive fissured and karstic aquifers**

#### **-Precambrian marbles**

This unit outcrops in the northwestern (Guba woreda southeast of Mankush town) part and southern part (around Bullen-Wombera border) of the study area. At some places it is jointed and shows solution holes. The spring in this formation (southeast of Mankush town) has multiple eyes with a low yield during the peak of the dry season (GSE Abu Ramla report). According to information from locals, the yield increases during the rainy season. From a geomorphological point of view, this outcrop is part of the lowlands with poor possibility of recharge. The groundwater is believed to be stored in fissures of the whole thickness of marble body and the permeability has been enhanced by karstification along some fissures.

Well-jointed marble with significant solution holes is observed on elevated ground outside the study area to the south (GSE Asosa-Kurmuk, NC36-7 and NC36-8, sheets). It appears to have very good recharge and several cold springs with a maximum discharge of over 15 l/s.

Therefore, based on field observation and spring yield, the fractured and karst aquifer in the marble can be considered as having moderate productivity.

- **Quaternary Basalt:** - it covers the northeastern part of the study area which is an extension of quaternary basalt of Bahir Dar, generally show high discharge for small draw down, while around Dangila show high draw down for small discharge indicating that the productivity decrease south ward. This rock unit includes lava flows connected to volcanic centers and young lava fields from aligned spatter cones. They are scoraceous and faulted. The interconnected pore space accompanied with the fracturing has increased the value of rock as aquifer.

Taking all the above conditions in to consideration Precambrian marbles and Quaternary basalts are generally grouped as aquifer with good productivity.

According to GSE this formation has ranges of aquifer parameters of: -  $T > 100$  sq.m/d,  $q > 1$  l/s.m and  $Q > 5$  l/s.

### **5.4.2 Aquifer with moderate to high productivity**

This formation has fractured and intergranular aquifer with an average of  $T = 100-10$ sq.m/d,  $q = 1-0.1$ l/s.m and  $Q = 5-1$ l/s (GSE report).

- **Ashagi Basalt:** -this unit is exposed around the northern periphery and the escarpment of northeastern highlands of the study area. Ashangi Basalts is fissural flood basalts commonly injected by Dolerite dykes and sills. It is thick, deeply weathered and fractured. Merla (1979). The discharge of springs in this unit varies from place to place from 0.5l/s to 10l/s and mostly it is greater than 2l/s. Therefore this unit is considered as moderate to high productivity aquifer.

### 5.4.3 Moderately productive fissured aquifers

#### Tertiary volcanic rock

These formations, which occur mainly in the eastern, northeastern and northern part of the study area has a formation of Tarmaber Basalt and Aiba Basalt.

**-Tarmaber Basalt:** - this unit covers the upper most area in North Achefer and wide area of Jawi and to the north around the escarpment of Dangur and Balaya Mountain and their lowlands. Generally it lies in various topographic areas. It is moderately jointed and weathered. Tarmaber basalt is generally classified as aquifer of moderate productivity.

**-Aiba Basalt:**-this unit is found around the periphery northeastern part of the area. It covers small area. This unit is jointed and highly weathered. The Aiba basalt due to fracturing and weathering can be a good aquifer having moderate productivity water yield zones.

### 5.4.4 Low productive fissured aquifers of basement

This aquifer is developed in some non-carbonate metamorphic and intrusive rocks. This aquifer system constitutes the Precambrian basement rocks, which consist mainly of high grade and low-grade metamorphic rocks with granitic intrusions. Unfortunately, the less productive rock unit of the crystalline basement rocks occupies the largest proportion of the study area covering (see Figure 5-1). In this area, ground water potential is considered to be poor because of very low permeability of the hard rocks and very low recharge in low altitude. On the escarpments and valley slopes at the southern part and southwestern of the study area. It also covers large area in the low land and escarpments in Mandura and Dangila woredas, which has a lithology of metabasalt, metaandesite and greenschist. This formation drains groundwater quickly away and at low lands the recharge is almost negligible.

Groundwater in the crystalline basement rocks only occurs along their fractures and weathered zones. In particular, the basement rocks located nearer to volcanic plateau have some groundwater potential due to recharge contributions from the volcanic aquifers. These units are generally considered as aquifer of low productivity aquifer. This formation has  $T=10-1\text{sq.m/d}$ ,  $q=0.1-0.011/\text{s.m}$  and  $Q=1-0.5/\text{s}$ .

### 5.4.5 Aquitards

This aquifer is developed in some non-carbonate metamorphic and intrusive rocks. This group includes meta-tonnalite and gneisses, which outcrop at the lower western and in some southern part of the study area. This formation mostly occurs as massive outcrop, characterized by a very low permeability and can be grouped as aquitards and/or regional aquicludes with a much localized aquifer in its slightly weathered part. It has aquifer parameters of  $T=0.1-1\text{sqm/d}$ ,  $q=0.001-0.011/\text{s.m}$  and  $Q=0.5-0.05/\text{s}$ .

## **5.5. Aspects of groundwater recharge and discharge**

### **5.5.1. Recharge**

Groundwater recharge can be defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. Recharge may occur naturally from precipitation, rivers, canals, lakes, and as man induced phenomena (irrigation, urban recharge).

**There are three types of recharge.**

Direct recharge - water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone.

Indirect recharge: - it is percolation to the water table following runoff and localization in joints, as ponding in low lying areas or through the beds of surface water sources such as rivers, lakes and reservoirs.

Localized recharge: - resulting from horizontal surface concentrations of water in the absence of well-defined channels.

Assessment of the mechanism and amount of recharge is fundamental for sustainable groundwater resources utilization and management. However, estimating the different recharge processes is not simple. It requires understanding the various processes that affect recharge and quantifying the spatial and temporal variability. Unfortunately, there is no direct means of measuring groundwater recharge at regional and sub-regional level.

Recharge estimation requires accounting the different factors. These include:

- Topography and geology
- Precipitation (magnitude, intensity, duration, spatial distribution)
- Runoff and ponding of water
- Irrigation effects (nature of irrigation scheduling, losses from canals and water courses, etc.)
- Rivers (rivers flowing into and leaving out of the area under consideration, rivers gaining water from or losing water to the aquifer, etc.).
- Soil zone (nature of the soil, depth, hydraulic parameters, variability of the soil spatially and with depth, rooting depth of the soil, and cracking of soil on drying out or swelling due to wetting)
- Unsaturated zones between soil and aquifer (flow mechanism through unsaturated zone, zones with different hydraulic conductivity, etc.)
- Ability of aquifer to accept water and variation of aquifer condition with time

Here attempt is made to give the general picture of the recharge process at regional and sub-regional scale. All the three types of recharge can be identified in the region. However, direct recharge and indirect recharge from rivers are the most important ones.

### **Recharge from precipitation**

The ultimate source of groundwater recharge is precipitation. As discussed in Chapter 3 the precipitation in the area varies significantly both in space and time. Generally precipitation increases with altitude. However, due to orographic effects this relation does not hold true in this Basin. The maximum precipitation is in the northern area (Mandur Dangila, and Pawi). The lowlands of Pawe get exceptionally high precipitation. Despite the high altitude of the Wonbera plateau, the precipitation is relatively low.

Generally areas with high precipitation get more groundwater recharge under favorable geological and topographic conditions. The most important recharge zones are the elevated mountain ranges and plateau. The major regional recharge zones are the Wombera plateau ranges to the southwest, Balay and Dangur mountains to the northeast, highlands areas of Dangila and North Achefer woredas to the north and northeast and Kar Mountain Ranges to the east. These elevated mountain ranges have low groundwater potential due to topographic constrains. However, the permeable volcanic rocks provide sustained supply to the high-discharge springs emanating at the base of the mountains and to the shallow and intermediate aquifer systems of the undulating and lowland plains.

In most cases the potential evapotranspiration is by far higher than the precipitation in the lowlands. This means that direct recharge from precipitation in the lowlands is insignificant. However, during extreme wet months of July and August direct recharge can be of significant in highly fractured rocks and permeable quaternary deposits. The plains of Pawe are exceptional. They have relatively thicker permeable quaternary deposit and fractured basalts. Added with the exceptionally high precipitation, the area may significantly get direct recharge. This is evident from the existence of high discharge springs and perennial rivers.

The Wonbera plateau and Dangur Mountains are large regional recharge zones. Although, the precipitation seems to be not very high, the existence of highly fractured basalts with underlying fractured basement complex rocks favor groundwater recharge. These highlands plateau are bounded by steep escarpments in all directions. The recharged water forms many springs along the contact line of the volcanic and the basement rocks. The remaining groundwater drains towards the lowlands of Bullen and Wonbera woreda in the case of Wombera and to lowlands of Dangur woreda, Gublak area in case of Dangur Mountain. The Balaya Mountains, highlands of NorthAchefer, Dangila and Kar mountains are good regional recharges of the basin. These recharge area form high yield spring at the foot of Balaya Mountain around Manbuk town, lowlands of Pawe such as Ali spring which has an estimated yield of more than 40l/s, at the escarpment of Kar mountain (Abatachin spring) and many others, most of which aligned with regional faults and lineaments.

### **5.5.2. Groundwater Discharge**

Natural groundwater discharge occurs when the groundwater flow (streamlines) intersect the land surface. Discharge of groundwater is manifested as springs, seepage zones and base flow of rivers. Often groundwater discharge areas are present in the lowlands, local and regional

depressions, and along the banks of rivers. Discharge areas are intimately linked with groundwater flow lines and the existence of geological structures.

The regional groundwater flow direction is to the south, west and southwest following the topographic gradient. The shape of groundwater contours seems to be subdued replica of topographic contours.

The discharge of groundwater in the region is manifested by the occurrence of springs and increase in the base flow. Many of the springs are localized along major regional faults and the contact of the volcanic with the basement rocks. Almost all high-discharge springs in the Basin are controlled by faults. No large seepage zones exist.

With regard to base flow there is limited information. As shown in Chapter 3.4, the hydrograph of the Beles and Gilgel Beles rivers is dominated by base flow. The surface runoff component is less than 40% of the total flow. In most cases groundwater discharge is minimal, except outflow as large spring discharges and base flows of rivers in the highlands.

On the contrary groundwater recharge from rivers is dominant in the lowlands. In general the contribution of groundwater to rivers is higher in the highlands. As the rivers drain towards the lowlands, they are expected to lose substantial amount of water in to the groundwater system through permeable quaternary sediments and fractured rocks (both the volcanics and the basement). The existence of recharge from rivers is evident by the general decrease of river discharge downstream. The discharge of the perennial rivers decreases in the lowlands towards the southwest. Some small rivers cease to flow in the lowlands, while having large discharges in the elevated highlands.

Some of the wider streams that contain relatively thick sand cover in their bed have continuous flow of water under the sand during the dry season. A considerable inflow of groundwater is seen in the rivers where the riverbed contains permeable rocks or sediments. Further downstream water infiltrates again into permeable streambed and totally dry sand is seen on the same streams further downstream.

### **Some important water points**

#### **-Hand dug wells and springs**

A plenty of Hand Dug wells and springs are found within the study area for public & livestock consumption, for small scale irrigation and washing purposes are springs and rivers. More than 100 HDW and 30 were from developed springs were inventoried during field work. Abstractions of these HDWs are carried out by hand. Depths of the dug wells vary from 10-20m with average static water levels of 5m - 15m.

The dominant aquifer formation is known to be thick overburden soil in most of highlands and, alluvial deposits in the lowlands. Highly weathered volcanic rocks in lowlands of Pawe are also productive sites for HDWs

Most of the dug wells provide a perennial source of water and however, yield is substantially decreasing during dry season. The seasonal fluctuation of the static water levels in most of the wells is highly attributed to the direct recharge condition from precipitation into the well which intern indicates the unconfined nature of the aquifers. Most of the springs are around the escarpment area.

**-Bore Holes**

Both deep and shallow boreholes are drilled in the study area by Governmental, non Governmental and private Drilling Company. There are about 6 deep boreholes where the depth varies between 61-150m and 50 shallow boreholes of 25-60m depth range.

Deeper boreholes are fitted with submersible electrical pumps and the others boreholes are equipped with Indian mark II, III, and Afrideve hand pumps. The main aquifer formations of the boreholes are, weathered and fractured basalt and basement rocks variable thickness and variable weathering and fracturing intensity.

Type	UTM E	UTM N	Elevation	Type	UTM E	UTM N	Elevation	Type	UTM E	UTM N	Elevation
CS	248608	1237564	1895	SW	823963	1243574	779	CS	802266	1172939	2514
HDW	245658	1237046	1855	CS	225000	1280000		CS	783419	1179455	2050
CS	271746	1307994	1630	CS	215450	1255635	1048	CS	782549	1178801	2035
CS	270928	1306722	1578	SW	213650	1252570	1056	CS	797329	1179696	2380
CS	274639	1309533	1704	SW	212249	1250460	1056	CS	799116	1178043	2460
CS	280119	1300617	1877	SW	209540	1246859	1063	CS	820004	1173602	1305
CS	218200	1226932	1363	CS	235187	1258242	1200	CS	821860	1172611	1330
SW	220549	1224609	1475	HDW	224731	1260325	1130	CS	800313	1180548	2290
SW	220962	1224760	1485	SW	228598	1262455	1137	CS	801276	1181755	2000
CS	221297	1229731	1370	HDW	225763	1255387	1117	CS	790553	1183752	2250
SW	218631	1227650	1406	HDW	231737	1257679	1181	CS	791648	1183792	2330
HDW	213384	1228940	1230	HDW	218213	1240618	1171	DBH	826693	1236669	900
SW	207991	1222490	1185	SW	217871	1244595	1109	DBH	781528	1248710	800
SW	208011	1222878	1172	SW	222006	1246621	1145	SW	768017	1218809	1000
HDW	208200	1224433	1143	HDW	222033	1251244	1147	SW	769294	1231314	670
Sw	208666	1231558	1080	HDW	222056	1249978	1152	SW	806123	1243127	860
SW	209078	1234661	1030	HDW	223785	1252380	1126	SW	794303	1247643	929
SW	210640	1233792	1060	SW	223319	1252501	1107	SW	803102	1235104	830
SW	214823	1242340	1097	SW	228496	1253871	1127	HDW	215795	1229954	1267
HDW	214958	1241986	1094	HDW	214542	1248506	1054	HDW	216323	1229252	1309
HDW	214309	1242180	1076	HDW	217353	1240715	1141	CS	217160	1226863	1377
SW	193404	1246633	1163	HDW	216478	1251921	1103	HDW	217468	1229008	1350
Sw	187390	1243832	1028	SW	217471	1256700	1056	HDW	217497	1229109	1351
SW	186286	1241519	997	HDW	206173	1254433	1191	HDW	217502	1229751	1332
SW	182168	1238835	972	HDW	206138	1254238	1195	HDW	218083	1224865	1405
Sw	822926	1237366	890	HDW	201448	1245149	1185	HDW	218583	1227484	1410
DBH	826712	1236653	863	HDW	213090	1244602	1049	HDW	219593	1227578	1383
Sw	200626	1248542	1191	HDW	206213	1253828	1181	HDW	219703	1227811	1369
CS	199515	1249099	1166	SW	205976	1242399	1058	HDW	220880	1225403	1463
SW	197759	1250205	1210	HDW	204914	1243138	1090	SW	220971	1224754	1487
DBH	198509	1250018	1200	SW	205264	1248383	1114	HDW	225331	1229463	
HDW	217989	1251209	1104	SW	213428	1245018	1037	HDW	226206	1228899	1423
CS	235168	1258268	1194	CS	187829	1227125	1082	HDW	226324	1229462	1433
DBH	214827	1246461	1069	HDW	207064	1218813	1234	HDW	226877	1229521	
SW	213421	1245024	1040	HDW	208305	1221937	1182	CS	226881	1232416	1275
HDW	212015	1242508	1035	HDW	208888	1234643	1016	HDW	226882	1229508	1427
SW	205980	1242411	1050	HDW	208933	1234682	1016	SW	828258	1184382	1150

SW	201453	1245154	1182	HDW	209070	1234663		SW	821255	1192030	1060
CS	201748	1245870	1177	HDW	209120	1231098	1079	CS	795013	1179896	1420
SW	209541	1246857	1064	CS	209122	1232336	1053	CS	818988	1170890	1447
HDW	214701	1255651	1062	SW	209226	1234916	1016	CS	818004	1172037	1341
SW	213651	1252573	1054	HDW	209472	1234667		HDW	213706	1229133	
HDW	217188	1259505	1077	HDW	209667	1234045		HDW	214329	1216650	
HDW	226225	1280040	1213	HDW	209890	1235019		HDW	215566	1229237	
DBH	225865	1279316	1201	HDW	210066	1233500		HDW	215660	1230119	1260
HDW	220497	1269599	1137	SW	212735	1228886	1208	HDW	215688	1229535	1283
HDW	796984	1170412	2500	HDW	212747	1228632	1200				
SW	813488	1199853	1000	HDW	213109	1229175					

**Table 5.1 Water point inventory data**

### 5.6. Groundwater flow system

Groundwater moves into various soil and rock formations by means of infiltration and percolation through interconnected void spaces, along micro cracks between grain boundaries and in large-scale fractures in response to differences in fluid pressure and elevation after the water comes from recharging area and/or from the precipitation processes. These movements are governed by well-known Hydrogeologic parameters like hydraulic conductivity and hydraulic principles of Darcy’s Law.

Groundwater flow system could be local, intermediate or regional flows depending on different factors like recharge area, lateral & vertical extent and thickness of aquifers. In turn it depends on effective porosity and permeability of the aquifers itself.

Extent of flow system is depend on the recharging area, in which recharge area may be discharged in the nearest topographical low area as local flow.

Thickness and extent of aquifer can also limit or extend the ground water flow system as local or regional. If the geological formation of the aquifer is laterally and vertically extends with the necessary effective parameters, the ground water flow system could be regional, or else it could be local.

Regarding to the depth, regional groundwater flow is in most case deeper than that of the local flow system. In the flow system of water in the subsurface whether it is local or regional, there may be an ideal vertically impermeable layer as a boundary called Groundwater divide across which there is no flow. For the case of surface water divide, the principle is the same, but in this case, topographically elevated area can be considered as surface water divide.

As of the hypothesis, ground water flow may follow the slop of surface morphology, if so, in most case, surface and ground water divide overlaps.

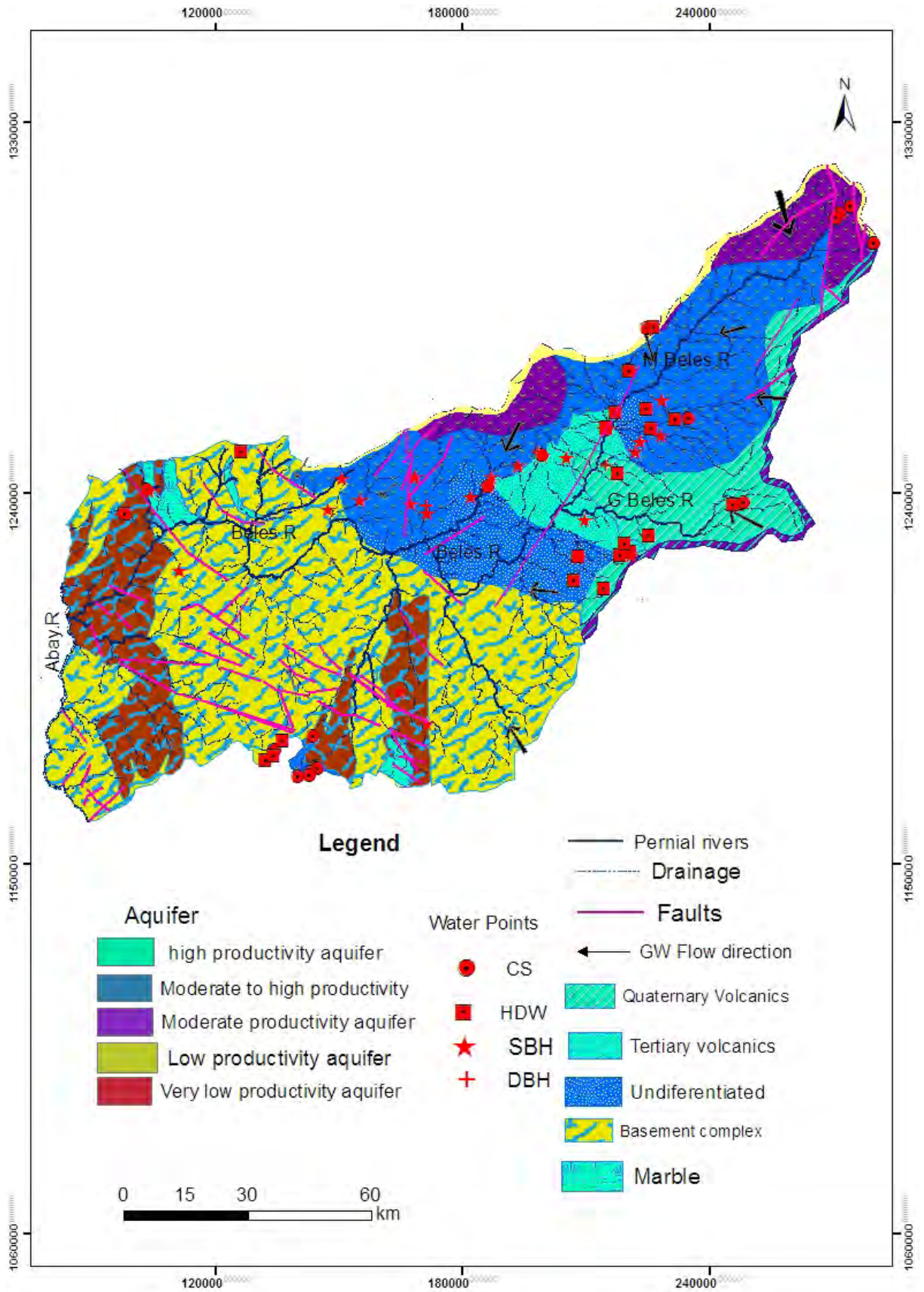


Figure 5.1 Hydrogeological map of the area

## CHAPTER SIX

### 6. HYDROGEOCHEMISTRY

#### 6.1. General

Nearly all groundwater originate as rain that infiltrates through soil into flow systems in the underlying geological materials. But the chemical composition of ground water varies both spatially and temporally. This is because of The chemical substances in natural waters are derived from many different sources of solutes, including gases and aerosols from the atmosphere, weathering and erosion of rocks and soils, solution and precipitation reactions existing below the land surface, and effects resulting from human activities. The ways in which solutes are taken up or precipitated and the amounts present in solution are influenced by many environmental factors, especially climate, structure and position of rock strata, and biochemical factors associated with the life cycle of plants and animals

The soil zone has unique and powerful capabilities to alert the water chemistry, as infiltration occurs through this thin, biologically active zone. In recharge area the soil zone undergoes a net loss of mineral matter to the flowing water. As groundwater moves along flow lines from recharge to discharge area, its chemistry will be altered by the effects of a variety of geochemical processes. As groundwater moves along its flow paths in the saturated zone, it increases in its total dissolved solid and the shallow groundwater in recharge area 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 area. The concentrations, relative proportions and rates of transport of dissolved substances in water samples reflect their sources, paths and interactions with different substances.

Geochemical reactions along ground-water flow paths can lead to regional variations in water composition that evolve in the direction of flow. According to Chebotarev (1955) and two hydro geologist in the Soviet Union developed groundwater tend to evolve chemically toward the composition of seawater. They observed that this evolution is normally accompanied by the following regional changes in dominant anion species:

**Travel along flow path ----->**



**Increasing age----->**

These changes occur as the water moves from shallow zone of active flushing through intermediate zones into zones where the flow is very sluggish and the water is old.

This water chemistry variation along its flow paths is very important for generation of hydrochemical data which are applicable for the conceptualization of groundwater flow pattern (dynamics), Standardization of water quality in various natural geological and hydro geological systems.

Conceptualizations of groundwater flow systems in small watersheds has been demonstrated by Toth (1963) which has importance to hydrochemical analysis in hydrogeology along with simple two dimensional numerical groundwater flow model.

Winter (1978) presented the use of Groundwater flow models coupled with hydrochemical methods in understanding the groundwater-surface water interactions in Lake Watershed systems. A more comprehensive coverage of the study and interpretation of chemical characteristics of natural waters and their use in hydrological studies have been provided by Hem (1970), Stumm & Morgan (1970) and Appeleo and Postman (1993), Plumer(2005), Wolley (2005) and McDonnel (2005).

Standardization of water quality based on World Health Organization can also generated on the basis of Hydrochemical data which in turn helps to categorized water for human, industrial and irrigation purpose.

In this chapter attempt is made to provide the hydrogeochemical characteristics of the area form the point of view of spatial natural compositional variation and water quality for different uses. With the exception of some basement complex rocks, in the majority of the places the general physico-chemical characteristics of natural waters may not vary, since the geology, hydrometeorology and other related factors do not vary much.

As an objective of this section, the Pysico-chemical analysis, which is considered as hydrochemical data results from different water source like boreholes, Hand dug wells and spring water are helps for the determination of ground water flows along Beles River basin. In its approach, as ground water moves from place to place, the chemistry of water changes due to, displacement & replacement reaction between ions, duration and interaction between rock and water. Variation of ionic concentration in this aspect soundly important for determination of flows, among these ions Na, Cl and TDS are the most common.

The analysis also crucial for the recommendation of water quality of the study area for human consumption comparing to WHO standard.

## **6.2. SAMPLING SITES AND METHOD**

Samples were collected from deep borehole, shallow borehole, hand-dug wells, springs and rivers. The distribution of sample sites highly depends on accessibility, availability of water points and population distribution, because of all these reasons there was no sample site at lower most part of the study area near to the confluence of Abay and Beles rivers. But efforts have been made to distribute the sample sites evenly to identify reference areas, to give a representative geographical and hydro geological sample distribution. Their distribution consisted of a total of 74 from which 47 samples are primary and 27 are secondary samples from GSE (Abu Ramla and Assos-Kurmuk area hydrogeological reports). All of these samples are from recharging, discharging and transition Zone.

The method involves the withdrawal of water from pumping boreholes sufficiently in order to insure that the sample represents the groundwater that feeds the well and in situ measurements of pH, EC, TDS and Temperature has been conducted. Samples are batch type collected at particular time and places. These kinds of samples represent the composition of the source at that particular time and place. However, when a source is known to be fairly constant in composition over a considerable period of time or over substantial distances in all directions, then the sample may be said to represent a longer time period or a large volume, or both, than the specific point at which it was collected. Accordingly, the physico-chemical analysis which analyzed by the previous studies are also included in this study.

The samples are collected by plastic bottle which has the advantage of not breaking when they are completely filled as can be the case with glass bottles after temperature changes and were reached to the laboratory at easier risk within few days and laboratory measurements are then carried out in the laboratory of water Works, Design and Supervision Enterprise.

### **6.3. IN-SITU MEASURED PARAMETERS**

Parameters, like pH, Temperature, Conductivity and TDS are easily altered by the environment or surrounding atmosphere, and are need to be determined in the field. The relative quality of analytical data can be determined through use of properly calibrated and functioning field meters. PH, Temperature, Conductivity and TDS all change to some degree from the time the sample is collected to the time it is analyzed in the laboratory. Therefore, a field determination is important and quality assurance; comparing these values with the laboratory one will be made.

#### **6.3.1 PH (hydrogen ion activity)**

According to Hem, 1992, Hydrogen ion of natural waters mainly fall between 6 to 8.5 and it is controlled by interrelated chemical reactions that produce or consume hydrogen ions. The dissociation equilibrium for water is always applicable to any aqueous solution, but many other equilibrium and many non equilibrium reactions that occur in natural water among solute, solid and gaseous, or other liquid species also involve hydrogen ion. Field PH values generally are higher or lower than laboratory PH values by as much as  $\pm 1$ PH unit or more (Pyne et al. 1995). Field values are commonly lower than laboratory values because collection, transport, or storage causes a release of dissolved carbon dioxide from the water into the head space of the sample and a release to the atmosphere when the sample is opened.

#### **6.3.2. Electrical conductivity (EC)**

Electrical conductivity of water is its ability to conduct an electric current at a specified temperature and it is usually measured in micro Siemens per centimeter or micromhos per centimeter (Weast, 1968). The values of EC increase with temperature, between 20<sup>0</sup>c and 30<sup>0</sup>c, an increase in 10c, increases the EC by two percent on the average (Hem, 1992).

The presence of charged ionic species in solution makes the solution conductive. As ion concentrations increase, conductance of the solution increases; therefore, the conductance measurement provides an indication of ion concentration.

Specific conductance values measured in field and in the laboratory should agree within approximately 5 to 10% unless there has been a chemical reaction following the collection of the water sample and prior to its analysis. Accordingly, except two samples one from Dangila woreda (Gisa spring) and one from Mandura woreda (Gilgel Beles SW) all samples agree with in the range. Laboratory EC value of these samples are greater than in situ test. This is probably due to the dissolution of residue from a sample container.

### **6.3.3. Total dissolved solids (TDS)**

Total Dissolved Solids concentration is approximately equal to the sum of the concentrations of all dissolved ions. The TDS should be both measured and calculated, and the difference should be within approximately 5%. The measured value is typically larger for surface water, which commonly contains suspended organic and inorganic matter. Shallow groundwater in recharge areas is lower dissolved solids than the water deeper in the same system and lower in dissolved solids than water in shallow zones in the discharge areas (Freez and Cherry 1979). This implies that as the water goes from the highland through fractured and unconsolidated sediments it acquires dissolved solids more and more depending on all the parameters that govern the evolution of groundwater chemistry. As it is related to the sum of the concentration of all ions, it is directly related to the electrical conductivity. TDS of natural water range from less than 10ppm of dissolved solids for rain and snow, to more than 300,000ppm for some brine. Thus, the total concentration of dissolved solids can be used for simple classification of water.

### **6.3.4. Temperature**

Temperature is also other parameters measured in the field. In most case, shallow ground water are normally characterized by a temperature which is strongly affected by the type of overlying surface environment. The ground water of the area in general is classified as cold water. In this area, although there are few samples from deep wells, the temperature variation is only due to surficial climatic situations and time of sampling. The lowest temperature was 21°C recorded at Dangil (Gisa spring) which is classified as subtropical environment and the highest at Gublak 30°C which is tropical.

## **6.4. CLASSIFICATION AND PRESENTATION OF LABORATORY MEASURED PARAMETERS**

The spatial variability observed in the composition of the major ions can provide highlight to aquifer heterogeneity and connectivity as well as the physical and chemical processes controlling water chemistry. Generally the approach is to divide the samples in to hydro chemical groups, which are group of samples with similar chemical characteristics that can then be fitted with location. Variations along the flow path are related to reactions between ground water and surrounding formation which can provide the hydro chemical evolution trend for the Beles River basin. This variation of natural water chemistry defines ground water flow direction along the Basin and characterization of the hydrologic systems. By using Aquachem Software and tried to use some of the many available graphical and statistical methods it was tried to classify the water samples including Piper diagram, Pie Chart, Box & whisker, Stiff diagram, and Schoeller plot.

### Quality assurance

Mass balance between cations and anions was the method used for quality assurance. It can be calculated for both the cations (positively charged ions) and the anions (negatively charged ions) in units of mill equivalents per liter (meq/L). This unit of measurement takes into account both the differences in gram atomic weight (molar) units of each ion and the valence or charge units for each ion. The meq/L difference should be compared using the following equation:

$$\% \text{charge balance (CB) error} = \frac{\sum zmc - \sum zma}{\sum zmc + \sum zma}$$

Where z is the absolute of the ionic valance, mc is the molality of cation species and ma is the molality of anion species.

The error should be within 5% for a high quality analysis. A 10% error is allowed if TDS is less than approximately 100 or more than 5000 mg/l. an error equal to or greater than 20% is not acceptable for meaning full interpretation of aquifer geochemistry. In this research work about 27 water chemistry samples were secondary data and 47 water chemistry samples were primary data from laboratory. All of these primary data pass the highest quality assurance check (5%) using mass balance method which means all primary data have CB error less than or equal to 5%. 63% of the secondary data passes the highest quality assurance (5%) and 85% of these data passes CB error of 10%. But those with CB error greater than 10% have small amount of TDS values (<140mg/l). But all the total data 9Primary and secondary passes quality assurance with BC error 20%.

#### 6.4.1. GRAPHICAL PRESENTATIONS

Presentation and compilation of chemical data is an important task in groundwater investigation in a convenient manner for visual inspection. According to Hem (1998) cited in Cuneyt et al. (2002), most of the graphical methods are designed to simultaneously represent the total dissolved solid concentration and the relative proportions of certain major ionic species. For this purpose several commonly used graphical methods are available such as Stiff diagram, Pie chart, Box-whisker, and piper diagram & Schoeller. In addition to this, the spatial variability observed in the composition of the major ions (as natural tracers) can provide insight into aquifer heterogeneity and connectivity as well as the physical and chemical processes controlling water chemistry. Generally the approach is to divide the samples into hydrochemical groups (facies) that is group of samples with similar chemical characteristics that can then be correlated with location and flow direction. Verification that systematic variations along the flow path are related to reactions between groundwater and the aquifer provides the hydrochemical evolution trend for the area. This information provides the context for interpreting the spatial variations in water chemistry and defining groundwater flow paths and characterization of the hydrogeologic system.

##### 6.4.1.1 Piper Diagram and water types

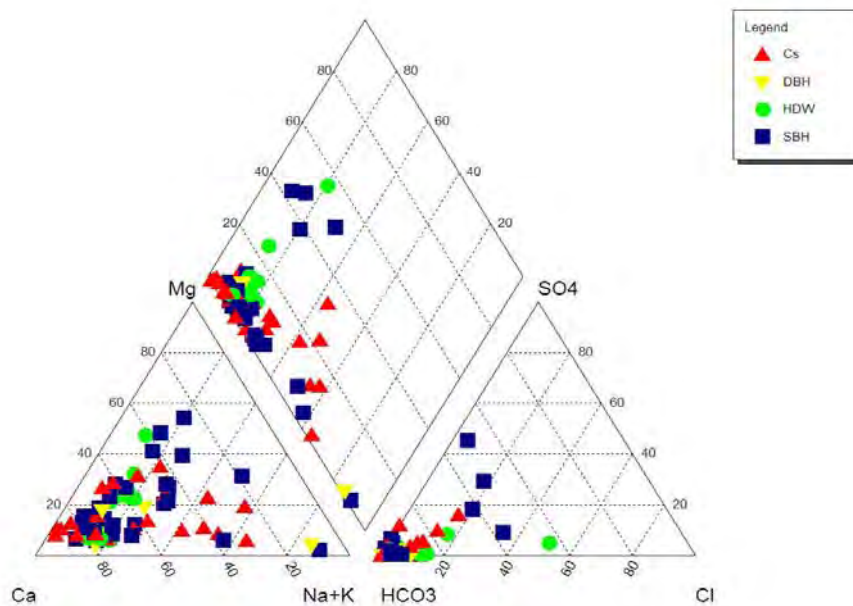
The Piper diagram is the most widely used graphical form of data presentation. It permits the cations and anions composition of many samples to be represented on a single graph in which major groupings or trends in the data can be discerned visually and also showing the effects of mixing two or more waters from different sources. The diagram displays the relative concentrations of the major cations and anions on two separate trilinear plots, together with a central diamond plot where the points from the two trilinear plots are projected. The central

diamond-shaped field (quadrilateral field) is used to show overall chemical character of the water.

The intersection of lines extended from the two sample points on the triangles to the central rectangle gives a point that represents the major-ion composition on a percentage basis.

From this point, lines extending to the two adjacent scaled rectangles provide for representation of the analysis in terms of two parameters selected from possibilities, in this case, total major-ion concentration.

Piper diagram of the area clusters the water sample into different water types; from which Ca-CHO<sub>3</sub> is dominant one (37% or 28 samples) of the total 74 samples. Ca-Mg-HCO<sub>3</sub> 15 sample, Ca-Na-HCO<sub>3</sub> 6 samples, Na-Ca-HCO<sub>3</sub> 5 samples, Mg-Ca-HCO<sub>3</sub> 3 samples, Na-HCO<sub>3</sub> 2 samples, Ca-Mg-Na-HCO<sub>3</sub> 2 samples, Ca-Mg-NO<sub>3</sub>, Mg-Ca-Na-HCO<sub>3</sub>, Na-Mg-HCO<sub>3</sub>, Ca-K-Na-HCO<sub>3</sub>, Ca-HCO<sub>3</sub>-NO<sub>3</sub>, Ca-Na-HCO<sub>3</sub>-SO<sub>4</sub>, Ca-HCO<sub>3</sub>, NO<sub>3</sub>-SO<sub>4</sub> and CA-HCO<sub>3</sub>-Cl are the water types.



**Figure 6.1 Piper plots of all water samples**

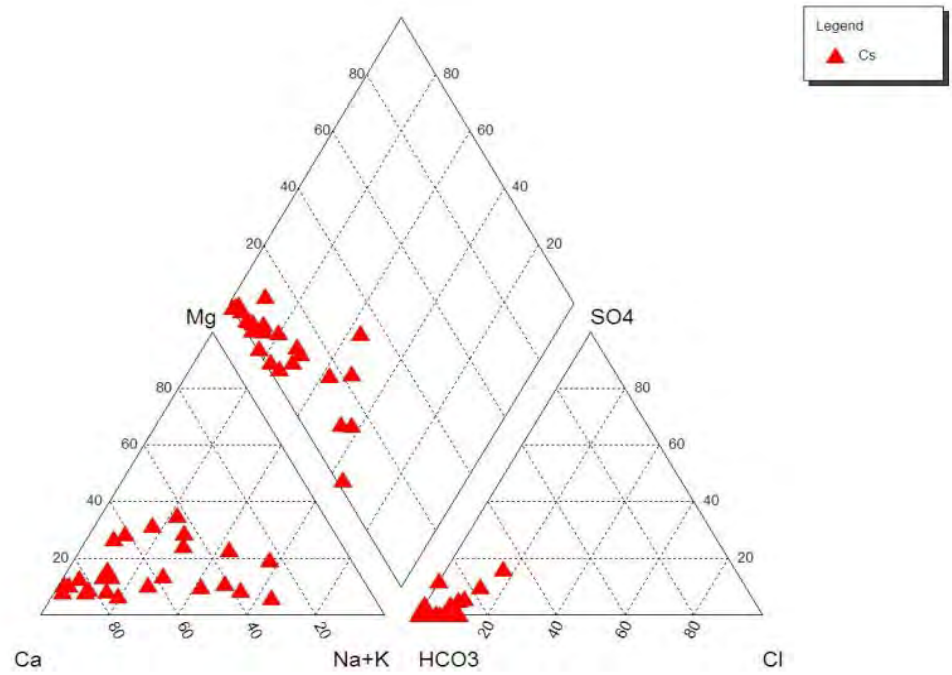
In addition to displaying all water sources together, piper diagram is also important to display each water source of more than one sample. In the figure below, four piper plots observed which are representing springs, shallow boreholes, deep boreholes and hand dug well.

Spring Samples position on the piper plot (Figure 6.2) represents the fresh waters. The dominant cations in these spring waters are calcium followed by sodium and magnesium, and the dominant anion is bicarbonates. These spring waters fall in the Ca-HCO<sub>3</sub> and Ca-Na-Mg-HCO<sub>3</sub> type in the Piper plot.

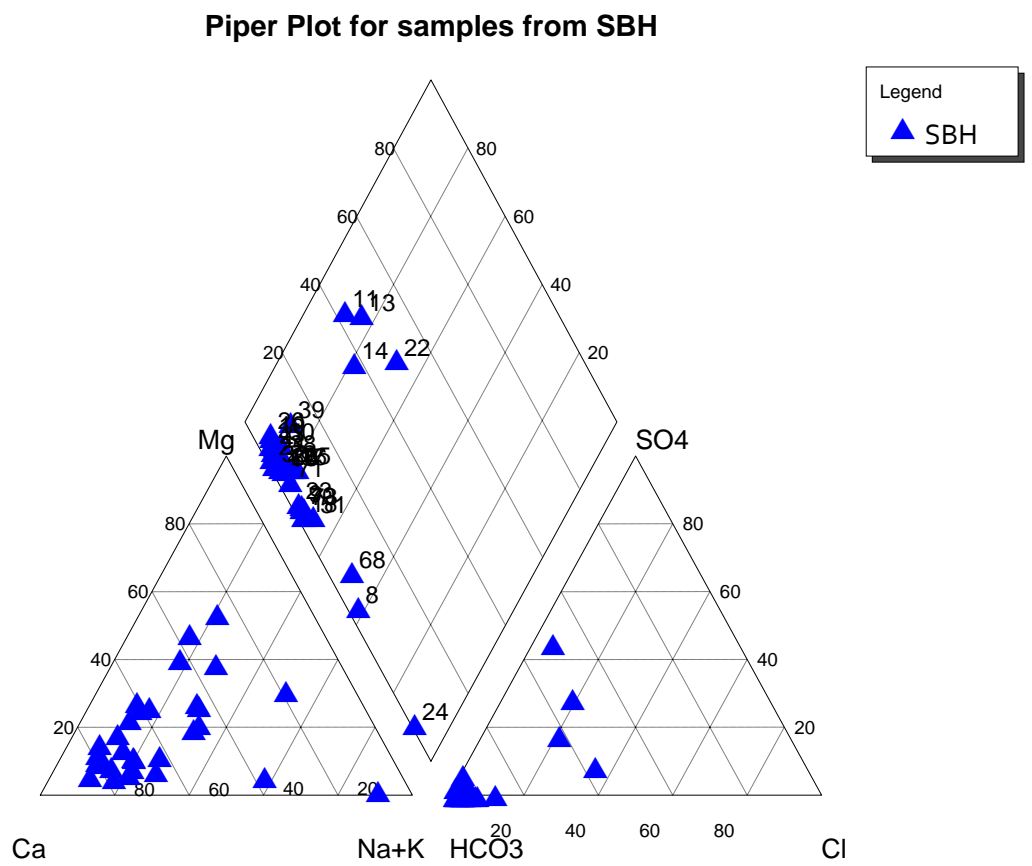
In deep bore holes water samples (Figure 6.4) the dominant cation is calcium with the exception of one sample which is sodium type and the dominant anion is bicarbonate. The water types of samples from deep bore holes are Ca-HCO<sub>3</sub> and K-HCO<sub>3</sub> types.

In the piper plot of shallow bore holes the dominant cation is calcium followed by magnesium and sodium. The dominant anion is bicarbonate and minor sulphates. The dominant water types are Ca-HCO<sub>3</sub>, Ca-Mg-Na-HCO<sub>3</sub> and Ca-Mg-HCO<sub>3</sub> types.

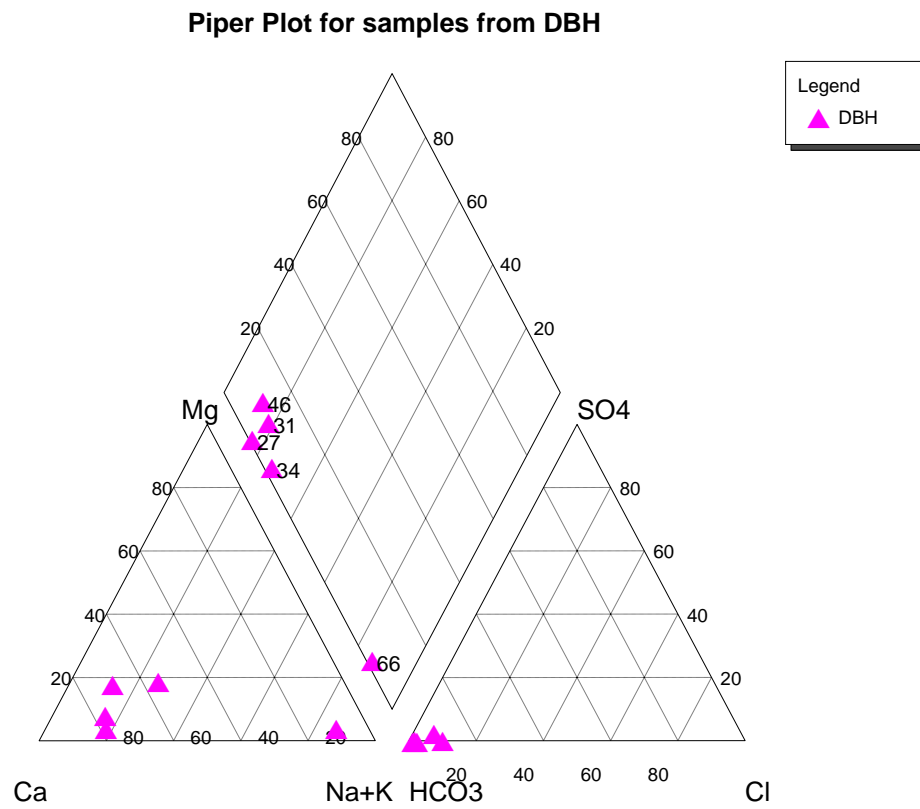
In the majority of waters from dug wells (Figure 6.5); Calcium dominate their cations species followed by magnesium and bicarbonate dominate their anions. There is one exception where nitrate dominate its anion. Thus, the water samples from HDW fall in the Ca-HCO<sub>3</sub> and Ca-Mg-HCO<sub>3</sub> type in the Piper plot.



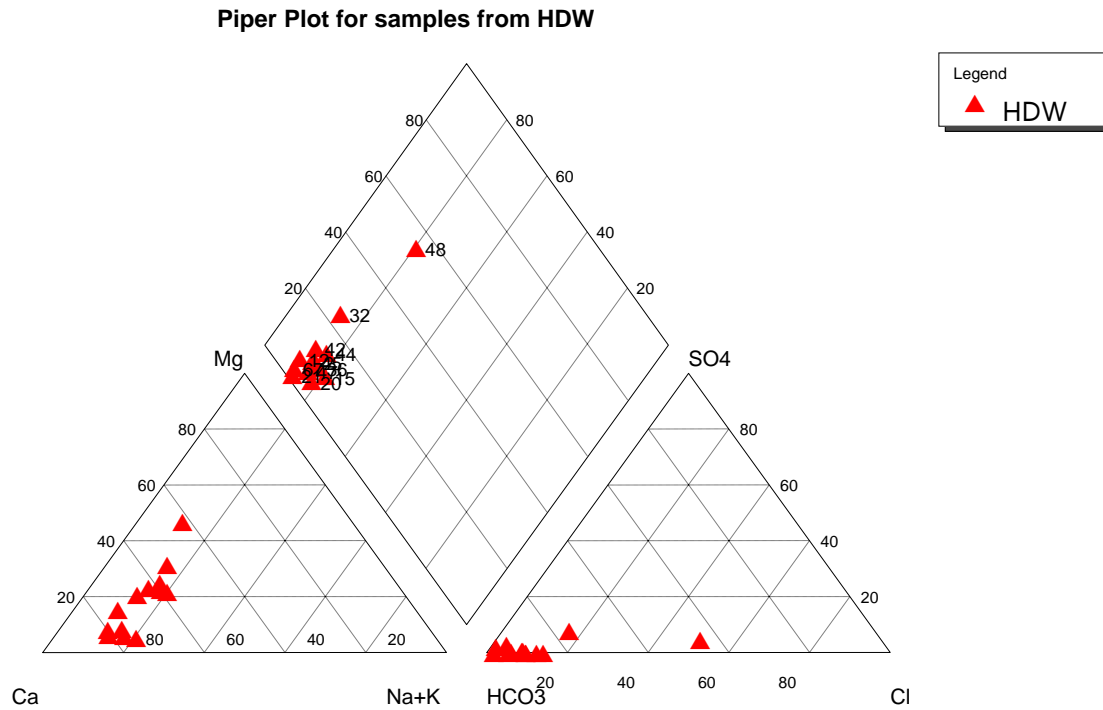
**Figure 6.2** piper plots of samples from springs



**Figure 6.3. Piper plots of samples from shallow boreholes**



**Figure 6.4. piper plots of samples from deep boreholes**



**Figure 6.5 Piper plots of samples from HDW**

#### **6.4.1.2. Box and Whisker for Major ions chemistry**

Almost all ground water is naturally balanced in terms of the existing major cation and anion (Na, K, Ca, Mg & CL, SO<sub>4</sub>, CO<sub>3</sub>, and HCO<sub>3</sub>). But because of its distribution, occurrences and movements with in geological formation, the neutrality of water disturbed. On the study area, variable dissolved solids observed together with major ions concentration.

Major ions concentration in the ground water shows variation as can be seen in the figures below, which shows that the minimum, maximum and mean concentrations of the major cations and anions of ground waters (from boreholes, cold springs and dug wells) in the study area.

From the samples in the basin (figure 6.6) calcium is the dominant cations followed by sodium and magnesium, and bicarbonate is the dominant anions which also followed by Cl and SO<sub>4</sub>.

Major cations concentration of ground water in the basin descends uniformly from Ca to Na to Mg.

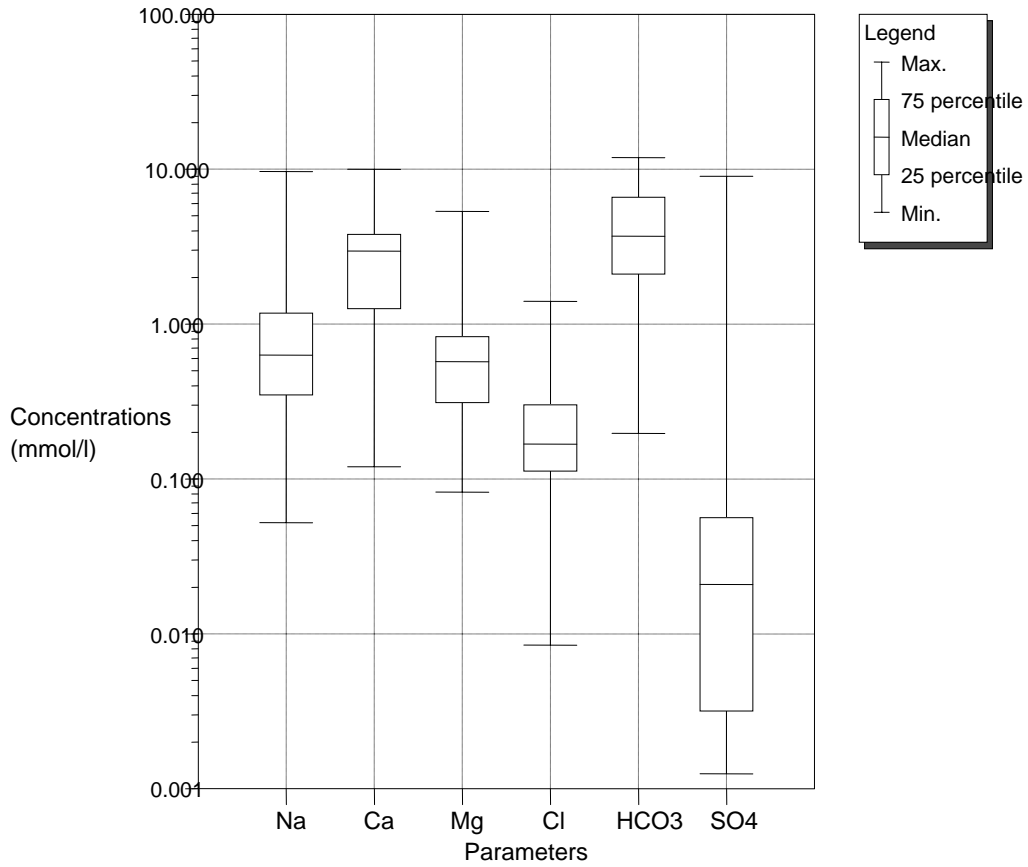
The dominance of calcium in the study area is likely from igneous rock minerals especially in the silicates of pyroxene, amphibole and feldspars; it is mainly sourced from Ashangi group of olivine basalt, Tarmaber basalts lava flow, Amba Aiba flood basalt Wollega basalt, columnar basalt, and Adola group amphibolites of intrusive and volcanic assemblage of basic and ultrabasic rocks.

Magnesium is typically a major constitute of the ferromagnesian minerals such as olivine, pyroxene and amphiboles, which from basic rocks and has small concentration in the area. The concentration of sodium is from acidic rocks especially from basement complex rocks, like sodium feldspars, mainly in the center and lower parts of the basin.

The dominance of bicarbonate in the study area is likely due to the reaction of dissolved CO<sub>2</sub> with rocks, which is especially occurred in the shallow ground water zones; and most of the samples from the area are shallow ground water.

Other anions, CL and SO<sub>4</sub> mostly occurred with an association of sedimentary rocks. This probably attributed to the effect of local alluvial and colluvial deposits.

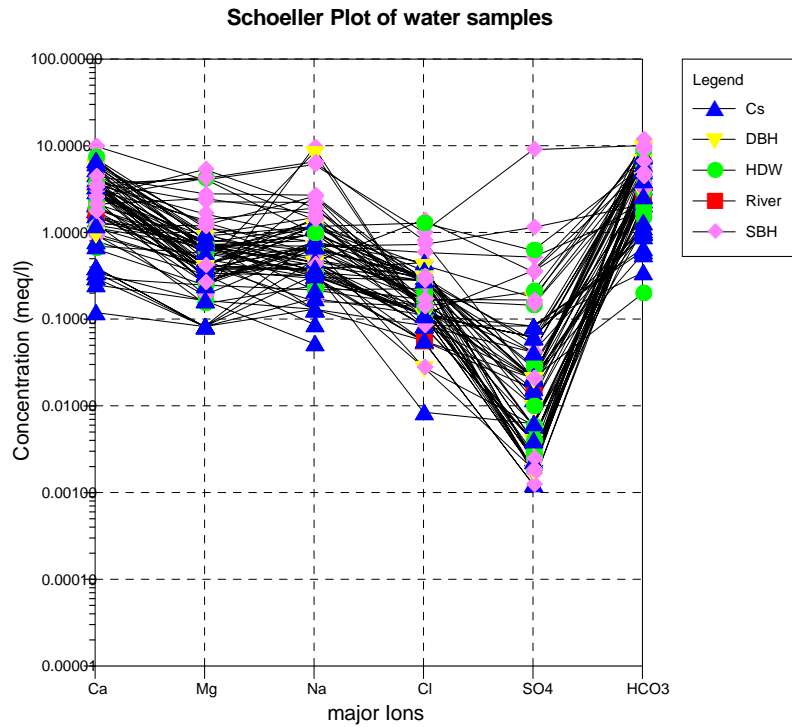
Therefore, there is a variation of dominant cation and anion species in groundwater which can reflects the existence of different hydrogeological process that is crucial to trace groundwater flow paths in the basin.



**Figure6.6. Box and whisker plots of water samples**

#### 6.4.1.3. Schoeller semi-logarithmic diagram

The Schoeller semi-logarithmic diagram shows the total concentration of cations and anions and it allows the major ions of many samples to be represented on a single graph, in which samples with similar patterns can be easily discriminated



**Figure 6.7** schoeller plots of water samples

From the diagram above (Figure 6.7) Calcium from cations and Bicarbonate from anions are dominant ions. That is also confirmed by other diagrams. Magnesium from cations and Sulphate from anions are the least dominant concentration.

## 6.4.2. The Spatial Distributions of Major Ions in the basin

### 6.4.2.1. Stiff Diagram

The spatial variations of the natural hydrochemistry in Beles Basin has clearly demonstrated by preparing Stiff Pattern plots on the study area map using all scattered hydrochemical data (Fig 6.8). Stiff patterns used to visually trace the flow paths on the map (Stiff, 1995). (Fig.6.8) shows that there is spatial variation in the major cation and anion concentrations of ground water following its flow directions. This variation is due to the rock-water interactions; which is related to lithology and groundwater residence time, and the structural and geomorphologic settings.

The evidence that the systematic variation along the flow paths related to reaction between groundwater and the rock provide the hydrochemical evolution model for the area. In this basin because most of the samples were from shallow groundwater zone there is a great relation of water chemistry with local lithology. In the area ionic composition of the water samples induces relatively variable chemical evolutions; for cations calcium is the most dominant, sodium is the second and magnesium is the least one. For anions bicarbonate is the most dominate the second is Chloride and sulphate is the least one.

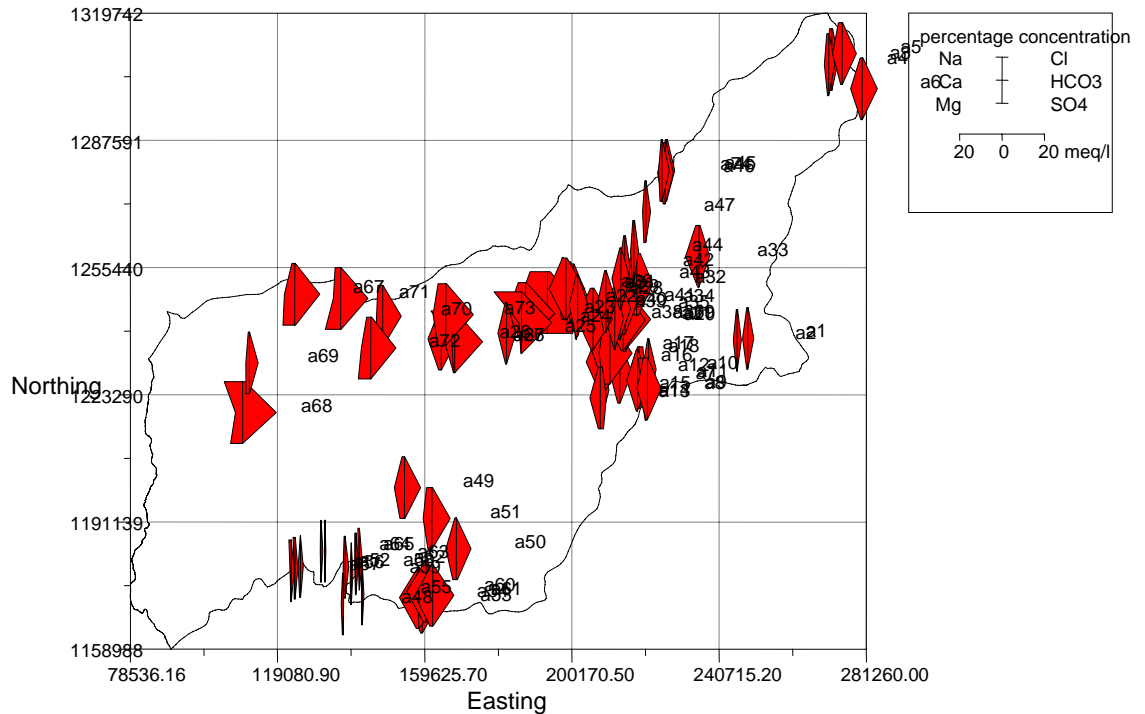
Calcium is dominant cation in almost all samples. But the concentration of sodium increase from east towards the west in the basin. The concentration of magnesium observed in central part of the basin and highlands of Wombera.

Bicarbonate is the dominant anion in all samples. Chloride and sulphate concentration observed in the central part of the basin and around Wombera areas.

The relative size of the stiff symbol demonstrates the evolutionary history of the groundwater (Fig.6.8).

The size of the stiff symbol (which corresponds with the ionic concentration in the waters) is used to show the groundwater flow pattern in the area. The variation in the symbols size is related with the variations in the major ionic compositions of ground water.

The increasing trend in the size of the symbol from the eastern and northeastern highlands toward the western and northwestern and from highlands of Wombera towards lowlands of Baruda area indicates the groundwater flows along the increment of the size of Stiff symbols. The low concentration of major ions in the recharge area due to absence of high rock-water interaction and fast circulation of groundwater and these symbols enlarge away from the recharge to the discharge to indicate groundwater flow paths.



**Figure 6.8** study area map from stiff diagram

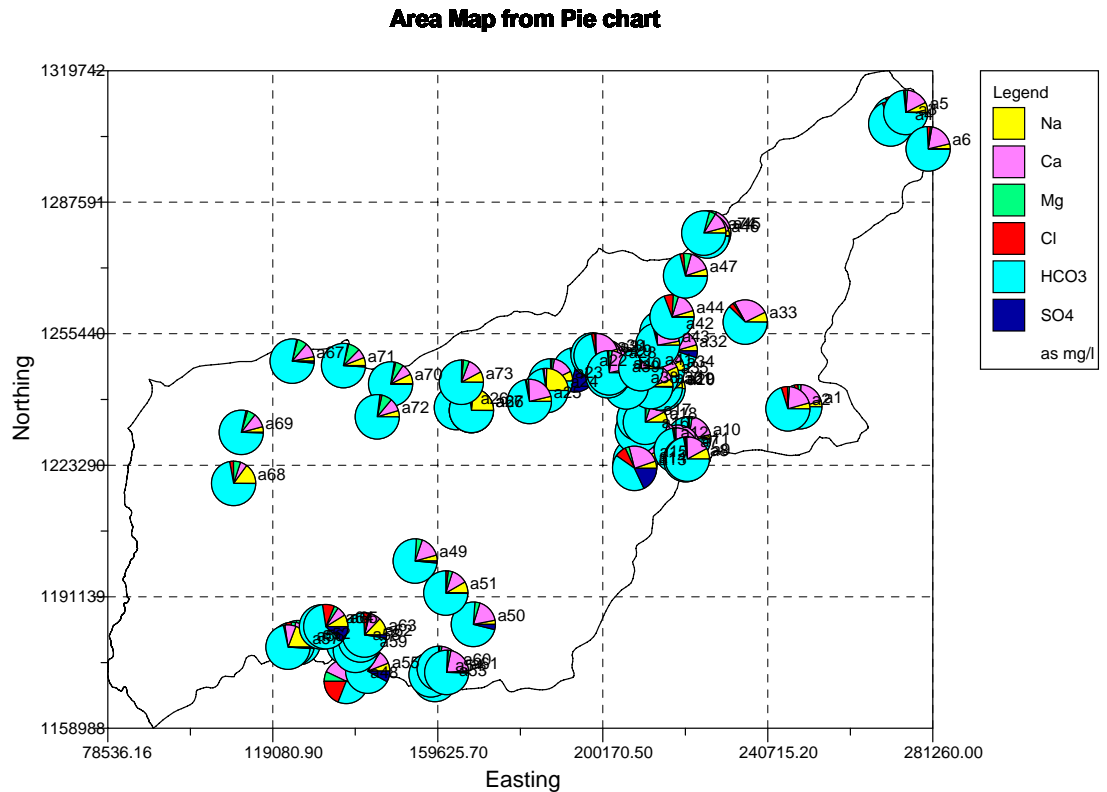
#### 6.4.2.2. Pie chart

Hydrochemical facies of spatial distribution can also be observed by using pie charts which clearly show the concentration and distribution of major cations and anions together with their observable variation along the Beles River Basin. Clear variation and distribution of the concentration of major ions are very crucial for the determination of recharge and discharge areas, groundwater residence time, flow paths, and neutrality of water.

Figure 6.9 below shows pie charts representing the water sample with its major ion concentration. The total distribution of major ions in the Beles River Basin is dominated by Ca and HCO<sub>3</sub> as major cations and anions, respectively. Na, due to replacement and displacement reactions by Mg & K, and because of its small radius, allows to increase its concentration along the groundwater flow paths. However, there is one special case where Na concentration is high in the Wombera plateau, which may be the result of local lithology.

Cl is also represented by a specific color like the others in the pie chart.

According to hydrochemical evolution process, Cl is most conservative ion which is not active to react with others, as the result, its concentration increases along the ground water flow paths. But in this basin significant concentration of Cl observed in samples from central part of the study area around Pawe and samples from Wombera plateau. This may be resulted from anthropogenic sources because these areas are highly populated and cultivated.



**Figure6.9.Study area map from pie chart**

### 6.4.3. SPATIAL TRENDS OF THE CHEMICAL PARAMETERS OF WATER

#### SAMPLES IN THE STUDY AREA

The chemistry of natural groundwater can be affected by many factors. The most important one are lithological and hydrological properties of the geologic unit, a series of chemical reactions that have dissolved material from another phase, have altered previously dissolved components, or have eliminated them from solution by precipitation or other processes, the source and chemical composition of recharge water, and the amount of time the water has remained in contact with the geologic unit (residence time). All of these factors can affect the type and quantities of dissolved constituents in groundwater.

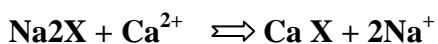
The spatial trend (evolution) of the cations and anions for each of the sources are plotted on figure 6.9, and analyses are made on the basis of the trending direction and patterns so as to determine their contribution on the ground water flow direction.

**Chloride:** - chloride is known by its conservative nature in the chemical evolution process and good indicator of the relative age of ground water compare to other major ions. The common source of Cl is association with sedimentary rocks. But volcanic gases from geothermal fields may also introduce in the ground water system and in some rift lakes (Tenalem Ayenew, 2005)

In the study area, Cl is observed only in few areas and its concentration is relatively small and it is observed in Wombera highlands and Pawe lowland areas. For the Pawe lowlands it may follow groundwater flow direction. But for the highland it may be from anthropogenic sources.

**Sodium:** - Na is one of the major cations characterized ion exchange chemical reaction during evolution process by Ca and Mg. Cations exchange is the chemical reaction frequently cited to explain the high percentage of sodium compared to calcium and magnesium in water (Lee, 1981; Woessner et.al., 1981, Wilson et.al., 1986). Cations exchange is a reaction in which the calcium and magnesium in the water are exchanged for sodium that is adsorbed to aquifer solids such as clay minerals, resulting in higher sodium concentrations (Hem, 1985).

The generalized reactions are as follow (Hem, 1985)



Unlike other ions, Na not shows trend in the studied area especially in the northwestern part of the area that follows the flow direction. But a significant amount of sodium concentration observed in Wombera highlands which may be from cation exchange in in clay minerals, because this area has thick soil deposits.

**Bicarbonate:** - the concentration of bicarbonate is high in all samples. This is because of most of the samples are from shallow groundwater and there is an exchange of carbon dioxide.

## CHAPTER SEVEN

### 7. Conclusion and recommendation

#### 7.1. Conclusion

Secondary data, primary water sample data as well as previous reports and existing maps were used for characterization of the hydrogeology and hydrogeochemistry of the Beles River Basin.

The Basin has unimodal pattern of rainfall (June to September), which is highly influenced by its topographic setting (orographic effect) and has mean annual rainfall of 1350mm.

Interpretations of the graphical analysis coupled with the chemical analysis results of the hydrochemical data and results from analysis of recharge-discharge condition of the area are critically showed the hydrodynamics of the Basin. From this approach the following conclusions have been made

- The aquifer in the study area is dominantly shallow. This aquifer formation has a depth range of 40-60m and in some areas may be up to 70-90m (which covers the central parts, at the foot of northeastern escarpments where the geology is volcanic rocks). It is confirmed from few deep wells and some structural controlled high yield springs.
- Aquifer formations are classified into six hydrostratigraphic units: Precambrian marbles, Non-carbonate Precambrian stratified and intrusive rocks, Mesozoic sandstone, Tertiary volcanics, Quaternary volcanic and quaternary sediments.
- The productivity of aquifers show variation and have been classified as very low, low, moderate, moderate to high and high yields. This is because the basin has almost all types of geological formations, from Archean age basement complex to recent alluvial and colluvial deposits.
- The order of the productivity of the aquifer from high to very low is; Precambrian marble and Quaternary volcanic -> Tertiary volcanic and quaternary sediments -> Mesozoic sandstone -> Non-carbonate Precambrian stratified and intrusive rocks.
- The controlling factors for the productivity of the formation in the Basin are Geology, recharge and catchment area, from which geology is the main controlling factors. This was confirmed from the fact that the lower part of the Basin with large catchment area is the least productive.
- The main recharges for the lowlands of the basins are the eastern, northeastern, northern highlands and southwestern, highlands by considering their annual precipitation and topographic difference. Relatively the south western highlands (such as Wombera) may be considered as lowest recharge area. Because of its low annual rainfall in comparison with other areas and geological formations (which has at the escarpments of metamorphic rocks).
- The possibility of groundwater movement in the study area is the subdued replica of surface water because most of the aquifer is shallow system.

- The field measurement of pH of the Basin range between 6 to 8.5 pH values. Therefore, pH values of water in the area can be considered as neutral.
- Electrical conductivity (EC) values do not show significant variations with the different sources of water. But it shows spatially variations depending on the lithology and recharge –discharge condition of the area.
- TDS distribution of the area shows distribution varies with in the area (Figure6.8). Generally it increases with the groundwater flow direction.
- Stiff diagram (Figure6.8) shows, the sizes of the stiff symbol is corresponding with major ionic concentration in the sample water that are sum up to gives TDS.
- The TDS distribution can be relatively grouped in to three; low, intermediate and high TDS. Wombera highlands has the least TDS, Pawe, Mandura and their escarpments have intermediate TDS values and the other lowland areas especially Wombera lowlands and the western and northwestern areas have High TDS values.
- The TDS distribution clearly shows recharge-discharge condition and the general groundwater flow path. The representative stiff symbols in the highlands of Wombera and northeastern escarpments indicates low concentration of major ions due to absence of high rock-water interaction and fast circulation of groundwater but the symbols being enlarge when away from the highlands, indicating groundwater flow paths.
- Field temperature measurements confirmed that the groundwater in the basin is cold water. The temperature variation is due to the surficial environmental condition.
- Ca and HCO<sub>3</sub> are the dominant cations and anions respectively for all types of ground water samples in the Basin. The major water types in the studied area are of Ca-HCO<sub>3</sub> and Ca-Na-Mg--HCO<sub>3</sub>.
- This dominance of bicarbonate type anion shows the groundwater in the basin is generally shallow and has small residence time.
- Hydrochemical facies of spatial distribution can also observed by using pie chart which clearly shows concentration and distribution of major cations and anions together with their observable variation along the basin (Figure6.9) Which are very crucial for the determination of recharge and discharge area, groundwater residence time, flow path and neutrality of water.
- Generally the groundwater in of this Basin is neutral, cold and fresh water which is recommendable for drinking, irrigation, and other domestic uses.

## 7.2. Recommendation

For more detail understanding of the objective of the study, following recommendations are presented.

- Stable isotope method is significant tool for potential hydrogeological and hydrogeochemical investigation, especially in the upper part of the study area where high yield, structural controlled springs emerge. It is used to trace regional ground flow system and recharge-discharge condition.
- Detail physicochemical, biological and trace element analysis is proper to see extent of pollution from human effect and natural impact.
- Further detailed large scale hydrogeological and hydrogeochemical studies will provide more detailed information about the area.
- Paying attention to structural and tectonic effect is highly recommended which suppose to be in charge of groundwater evolution to larger extent.
- Well compilation report should be properly compiled to get sufficient data on borehole history of the studied area.
- Regional major ions evolution (including the study area) needs to be conducted to observe variation of water types which strongly indicated groundwater flow direction.
- Water point inventory data should be recorded properly for detailed of the hydrogeological and hydrogeochemical investigation of the basin.
- It is better if rain gauge stations are installed in representative stations.
- It is highly recommended if river discharge gauging stations are installed for all rivers, especially at the confluence of Beles and Abay Rivers for water balance estimation of the Basin.

## References

- Amenti Abraham (1987): Tectonic History of the Pan-African Low Grade Belt of Western Ethiopia.
- Antonio Vernier et.al, January (1985): Preliminary analysis of Groundwater resource possibilities in Precambrian rocks in Ethiopia.
- Bayissa Asfaw (2003), Regional hydrogeological investigation of Northern Ethiopia. GSE, unpublished report.
- BCEOM (1996): Abay River Basin Integrated Development Master Plan Project; Phase 1 Reconnaissance, Section III. - Sectoral studies Volume II. Water resources, part 3 Hydrogeology - French Engineering Consultants in association with BRGM and ISL.
- BCEOM (1998) Abay River Basin Integrated Development Master Plan project, phase 2 data collection - site investigation survey and analysis section 2-sectorial studies, volume 1. Natural resources, part 1
- Chebotarev II (1955) Metamorphism of natural waters in the crust of weathering. Parts 1–3. *Geochim Cosmochim Acta* 8:22–48,137–170, 198–212
- Craig E. Divine. Jeffrey J. McDonnell (2005). The future of applied tracers in hydrogeology. *Hydrogeol J.* 13:255–258
- Daniel Gemechu (1977): Aspect of climate and water balance in Ethiopia. Addis Ababa University press, Addis Ababa, 79pp.
- Engda Zemedagegnehu, Dr. Yilma Sileshi and Albert Tuinhof (2007): Rapid Groundwater resources assessment in Lake Tana sub-basins and adjacent areas.
- Frans R. P. Kalf. Donald R. Woolley (2005), Applicability and methodology of determining sustainable yield in groundwater systems *Hydrogeol J.* 13:295–312
- Freeze R. Allan and Cherry John A. (1979): *Groundwater*. Prentice – Hall, New Jersey. 616pp.
- Getahun Seyid (2002): Geology of the Abu Ramla area.
- GSE-AQUATEST, 2003a: Explanatory notes to hydrogeological and hydrochemical maps of the Abu Ramla area. Geological Survey of Ethiopia, unpublished Report. 43pp.
- GSE-AQUATEST, 2003b: Explanatory notes to hydrogeological and hydrochemical maps of the Assosa –Kurmuk area. Geological Survey of Ethiopia. Unpublished Report. 66p.
- Hem D. John (1992): Study and interpretation of chemical characteristics of natural water. Third edition. United States Geological Survey water supply paper 2254, United States government printing office, Washington, 264pp.

- Hem, J.D (1970): Study and interpretation of the chemical characteristics of natural water. United States Geological Survey, Water Supply Paper 1473.
- Hem, J.D. (1970). Study and interpretation of the chemical characteristics of natural waters, US. Geol. Surv. Water Supply Paper 1473, 363 pp.
- Hem, J.D. (1985): Study and Interpretation of the Chemical Characteristics of natural Water. 3<sup>rd</sup> edition. U.S. Geological Survey, Alexandria, 263pp.
- Kazmin V. (1972): The Geology of Ethiopia (1:2,000,000 Scale), Ethiopian Institute of Geological Survey, Ministry of Mines, Addis Ababa.
- Mengesha Tefera et.al (1996): Geological map of Ethiopia, Addis Ababa.
- Mengesha Teferra (1991): Geology of the Kurmuk and Assosa area. – MS (digital version) EGS, Addis Ababa.
- Mesfin Woldemariam (1969): An Atlas of Ethiopia.
- National Atlas of Ethiopia, (1981), Ethiopian mapping agency
- Pierre D. Glynn. L. Niel Plummer (2005), Geochemistry and the understanding of groundwater systems Hydrogeol J 13:263–287
- SMEC international pty Ltd (2008), Hydrogeological study of the Tana-Beles Sub-Basins
- Tenalem Ayenew (2005): Major ions composition of the groundwater and surface water systems and their geological and geochemical controls in the Ethiopian volcanic terrain. Journal of Radioanalytical and Nuclear Chemistry, Vol. 257, No. 1, 11–16 pp. SINET: Ethiop. J. Sci. 28(2): 0379–2897.
- Tenalem Ayenew and Tamiru Alemayhu (2001): Principle of hydrogeology. Department of geology and geophysics, Addis Ababa University, 125pp.
- Tesfaye Chernet (1985): Hydrogeology of Ethiopia (Explanation of the Hydrogeological Map of Ethiopia 1:2000000): MS EIGS Note 225, Ministry of Mines and Energy, Addis Ababa. (Library No).
- Tesfaye Chernet (1993): Hydrogeology of Ethiopia and Water resources Development. - MS EIGS, Ministry of Mines and Energy, Addis Ababa. (Library EIGS 880-051-17).
- Toth, J., (1963): A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research, 68 (16):4795-4812.
- Vu Thi Minh Nguyet (2006), Hydrogeological characterization and groundwater protection of tropical mountainous karsts area in NW Vietnam.
- Weast, R. C., ed., 1968, Handbook of chemistry and physics (49th ed.): Cleveland, Ohio, Chemical Rubber Co., p. A1-F286.

Zanettin B., Justin- Visentin E., and Piccirillo E.M. (1978): Volcanic succession, Tectonic and magmatology in central Ethiopia. Mem. Acc. Patovina SS..LL.AA., vol. 19, 1-9.

Annex 1. Parameters measured in the field

Woreda	Village	Type	Sample ID	UTME	UTMN	Elevation	TEMP(°c)	pH	EC(µs/cm)	TDS(mg/l)	
Dangila	Gisa	Spring	1	248608	1237564	1895	21.8	6.22	180	90	
	Gisa	HDW	2	245658	1237046	1855	23.3	5.86	175	80	
North Achefer	Chanmar	Dokmit Spring	3	271746	1307994	1630	25.5	6.44	245	110	
	Chanmar	Dusman Spring	4	270928	1306722	1578	25	6.27	230	110	
	Degera	degera Spring	5	274639	1309533	1704	22.6	6.54	455	220	
	Beles	Beles Spring	6	280119	1300617	1877	21.25	7.5	470	230	
	Mandura	G/Mariam	Abatachin spring	7	218200	1226932	1363	23.75	6.8	380	190
		Jigda	SW	8	220549	1224609	1475	25.5	7.19	365	180
Jigda		SW	9	220962	1224760	1485	25.25	7.39	400	200	
Jigda		D. Spring	10	221297	1229731	1370	25.25	6.29	225	110	
G/M School		SW	11	218631	1227650	1406	25.1	6.18	425	220	
Kebele 2		HDW	12	213384	1228940	1230	26.5	6.32	395	200	
Duanz Baguna		SW	13	207991	1222490	1185	27.25	6.05	470	260	
Duanz Baguna		SW	14	208011	1222878	1172	26.5	6.1	365	190	
Duanz Baguna		HDW	15	208200	1224433	1143	26.5	6.3	285	140	
G/Beles		Sw	16	208666	1231558	1080	26.5	6.73	615	340	
G/Beles		SW	17	209078	1234661	1030	26	6.57	515	270	
G/Beles		SW	18	210640	1233792	1060	26.4	7.07	630	340	
Menjari		SW	34	214823	1242340	1097	25.75	6.63	595	300	
Menjari		HDW	35	214958	1241986	1094	24.5	6.57	365	170	
Menjari		HDW	36	214309	1242180	1076	26.5	6.75	460	220	
Dangur	Gitsi	SW	19	193404	1246633	1163	27.25	6.87	730	380	
	Dabotloker	Sw	20	187390	1243832	1028	27.25	6.33	305	140	
	Dirsembicokel	SW	21	186286	1241519	997	27	6.66	620	320	
	Jimtia	SW	22	182168	1238835	972	28	6.39	1455	770	
	Jurasis	Sw	23	822926	1237366	890	27.4	6.87	810	420	
	Gublak	BH	24	826712	1236653	863	30	7.73	865	440	
	Shibeshi school	Sw	25	200626	1248542	1191	31.5	6.5	365	180	
	Mambuk	D Spring	26	199515	1249099	1166	26.25	6.72	525	260	
	Kitli	SW	27	197759	1250205	1210	28.5	6.56	400	190	
	Mambuk	BH	28	198509	1250018	1200	31	7.05	410	200	
	Pawe	Mender 30	HDW	29	217989	1251209	1104	27.5	6.58	365	180
Ali		Spring	31	235168	1258268	1194	27.25	7.04	190	90	
Adari School		BH	32	214827	1246461	1069	28	7.09	615	290	
Mender 4		SW	33	213421	1245024	1040	28.7	6.82	850	410	
Medin		HDW	37	212015	1242508	1035	29	6.5	415	200	
G.B.River		River	38				27	7.79	215	100	
Mender 49		SW	39	205980	1242411	1050	26	6.72	680	330	
Mender 46		SW	40	201453	1245154	1182	27	5.8	120	50	
Mender 46		D.Spring	41	201748	1245870	1177	25.85	7.02	355	170	
Mender 4		SW	42	209541	1246857	1064	27.6	6.52	360	170	
Mender 7	HDW	43	214701	1255651	1062	28.5	6.33	270	130		
Mender 6	SW	44	213651	1252573	1054	28.5	6.74	340	160		
Mender 8	HDW	48	217188	1259505	1077	28.35	6.23	185	90		
Jawi	Jawi	HDW	45	226225	1280040	1213					
	Jawi	BH	46	225865	1279316	1201					
	Hilala Abo	Artesian	47	220497	1269599	1137	26.75	6.73	380	180	

Annex 2. Lab. Results for water samples

Object	UTME	UTMN	TDS	EC	PH	NH3	Na	K	Ca	Mg	Fe	F	Cl	NO3	HCO3	SO4
Cs	248608	1237564	150	217	6.5	0.17	7.3	1	36.5	4.14	0.02	0.45	5	16	128	0.12
HDW	245658	1237046	106	162	6.06	0.097	5.6	0.8	25.8	1.84	0.08	0.47	6	11	92.2	0.13
Cs	271746	1307994	176	251	6.57	0.102	18.5	2.7	27.4	8.76	0.04	0.58	11	21	144	0.29
Cs	270928	1306722	170	239	6.39	0.11	16	3.9	31.9	4.6	0.02	0.74	6	24	128	0.67
Cs	274639	1309533	304	458	6.71	0.1	31	2.2	68.4	6.9	0.06	0.46	5	15	307	0.76
Cs	280119	1300617	310	480	7.42	0.87	16	4.2	82.1	5.52	0.04	0.55	9.9	7.8	328	1.05
Cs	218200	1226932	250	393	6.76	0.16	8.9	1.1	76	4.6	0.02	0.27	4	2.7	243	0.19
SBH	220549	1224609	270	390	7.27	0.11	60.5	1.7	35	3.22	0.03	0.19	5	16	269	0.12
SBH	220962	1224760	280	434	7.52	0.17	33	1.8	72.2	5.06	0.05	0.43	5	0.4	300	0.09
Cs	221297	1229731	156	248	6.57	0.12	6.8	1.3	42.6	4.6	0.02	0.62	2	1.3	164	0.06
SBH	218631	1227650	312	476	6.39	0.19	10.4	1.2	82.1	3.68	0.03	0.3	50	55	141	16.9
HDW	213384	1228940	284	435	6.66	0.22	12	0.9	71.4	9.2	0.04	0.41	6	30	256	6.95
SBH	207991	1222490	350	528	6.31	0.23	16	2.4	73	8.74	0.02	0.53	26	98	128	54.9
SBH	208011	1222878	272	409	6.33	0.13	16.5	3.6	59.3	3.22	0.02	0.58	21	65	110	25
HDW	208200	1224433	204	307	6.42	0.11	15	1.6	49.4	2.3	0.04	0.18	11	30	169	0.12
SBH	208666	1231558	464	710	6.95	0.42	34	4.6	116	11.5	0.03	0.46	4	1	451	17.4
SBH	209078	1234661	378	576	6.8	0.26	27	2.1	91.2	9.2	0.08	0.54	9.9	42	350	2.76
SBH	210640	1233792	450	699	7.3	0.61	51	10	76	27.6	0.02	1.06	5	2.1	479	0.12
SBH	214823	1242340	532	800	7.1	0.43	18	0.5	144	13.8	0.02	0.37	16	37	551	0.11
HDW	214958	1241986	210	317	6.54	0.3	14	2.3	43.3	10.1	0.04	0.36	7	11	198	0.09
HDW	214309	1242180	436	670	6.85	0.3	22	0.3	124	7.82	0.04	0.38	6	4.6	474	0.14
SBH	193404	1246633	1190	1674	6.82	3.05	140	6.8	200	49.2	0.03	1.46	36	21	615	433
SBH	187390	1243832	546	880	7.1	0.52	60	0.7	128	14.7	0.02	0.62	9	1.5	630	0.09
SBH	186286	1241519	586	900	7.81	0.189	222	2.1	19	2.3	0.02	0.49	4	0.6	653	0.09
SBH	182168	1238835	250	385	6.75	0.159	10.2	0.6	60.8	4.6	0.04	0.4	2	56	200	0.06
SBH	164225	1237366	360	568	6.92	0.39	11.1	0.2	95	11.5	0.02	0.51	11	39	346	0.08
DBH	167910	1236653	278	426	6.86	0.2	16	0.8	72.2	4.6	0.06	0.51	1	23	282	0.09
SBH	200626	1248542	280	428	7.21	0.15	18	0.4	74.5	3.22	0.05	0.5	6	13	287	0.09
Cs	199515	1249099	250	381	6.71	0.25	8.7	0.4	68.4	4.6	0.02	0.44	16	35	205	0.11
SBH	197759	1250205	140	205	7.12	0.25	7.6	0.5	30.4	7.82	0.02	0.21	1	4.2	141	0.29
DBH	198509	1250018	428	650	7.22	0.18	28	3.6	119	3.7	0.02	0.84	15	0.5	410	8.57
HDW	217989	1251209	574	880	7.02	0.43	27	2	147	7.36	0.02	0.6	46	102	351	29.8
Cs	235168	1258268	376	586	6.66	0.208	27	2.4	95	5.06	0.03	0.41	13	100	231	0.57
DBH	214827	1246461	244	382	6.56	0.26	27	1.9	53.2	11	0.05	0.15	3	1.7	261	0.19
SBH	213421	1245024	310	478	6.72	0.199	23	0.7	72.2	5.06	0.02	0.5	9.9	64	226	0.19
HDW	212015	1242508	268	413	6.6	0.301	15.5	1.6	63.1	3.22	0.21	0.32	11	50	190	1.33
River			150	228	7.63	0.23	7.2	1.9	31.9	8.3	0.06	0.37	2	1.5	146	0.76
SBH	205980	1242411	452	693	6.82	0.24	22	4.2	114	7.82	0.01	0.67	11	44	418	2.5
SBH	201453	1245154	84	125	5.92	0.16	3.7	0.6	18.2	5.06	0.04	0.26	5	9.8	64.1	0.29
Cs	201748	1245870	244	372	7.16	0.18	10.7	0.4	59.3	7.82	0.02	0.41	3	36	225	0.19
SBH	209541	1246857	250	378	6.62	0.195	10.4	0.3	57.8	9.2	0.05	0.49	4	36	218	0.19
HDW	214701	1255651	180	282	6.51	0.159	8	1.3	38	7.36	0.03	0.62	9.9	42	118	0.19
SBH	213651	1252573	222	349	6.82	0.159	8.5	0.7	63.8	5.06	0.01	0.33	4	42	200	0.09
HDW	217188	1259505	116	177	6.33	0.159	7	1	22.8	5.98	0.11	0.58	9.9	7.6	103	0.28
HDW	226225	1280040	182	281	6.97	0.22	9.6	1.5	38	8.74	0.41	0.59	9.9	0.7	179	1.43
DBH	225865	1279316	250	398	6.76	0.248	10.5	0.7	53.2	8.3	0.06	0.59	11	48	179	0.48
HDW	220497	1269599	130	201	6.4	0.14	7.2	0.7	22.8	8.3	0.06	0.18	4	20	103	0.48
HDW	137136	1170412	112	607	5.8		5	0.4	13	3		0	8	58	12	1
SBH	154088	1199853	507	535	6.8		20	4	72	20		0.2	0	0	347	7
SBH	168362	1184382	476	523	7.8		13	5.4	75	16		0.1	0	2.2	317	17
SBH	161608	1192030	644	608	7.1		44	6.4	62	17		0.7	9	2.7	395	2
CS	125423	1179896	124	77.5	6.8		2	0.4	16	4		1	0	6.7	60	1
CS	158949	1170890	520	521	7.3		3	0.3	107	6		0	2	0	368	1
CS	157992	1172037	666	643	7.4		3	0.2	137	10		0.2	0	0	482	1
CS	142420	1172939	78	68	6.9		3	1	5	2		0	0	9.3	37	4
CS	123906	1179455	159	160	6.3		16	1.2	6	3		0.1	4	14	65	3
CS	122834	1178801	143	108	7.1		19	1.3	8	1		0.1	0	0.4	70	1
CS	137704	1179696	139	141	6.7		8	0.7	14	7		0	0	6.7	79	1
Cs	139416	1178043	56	63	6.4		1.2	0.3	7	2		0	0	0	34	1
CS	159996	1173602	640	690	7.3		5	1	137	10		0.3	5	0	455	2
CS	161816	1172611	643	696	7.2		8	1.2	125	12		0.3	4	1.3	457	3
CS	140650	1180548	121	89	7.3		7.4	1	8	1		0.1	4	0	55	3
CS	141630	1181755	137	100	7		11	1	7	1		0.2	3	0.4	62	2

Lab. Results for water samples.

CS	131050	1183752	87.8	76	6.7		4	7	6	1		0.1	4	2.2	40	4
CS	132132	1183792	54.5	34	6.5		3	1	2.4	1		0.1	3	0	21	4
DBH	167892	1236669	860	888	8.23		193	1.7	19.5	5		0.13	4	0	599	1
HDW	123836	1248710	774	795	7.61		22.5	1.3	73.5	50.5		0.17	5	3.1	538	10
SBH	109485	1218809	1041	1489	7.71		150	11	51	51		0.73	29	11	726	1
SBH	111336	1231314	266	301	7.93		10	2.3	25	14.5		0.17	3	0.9	190	1
SBH	148028	1243127	552	585	8.08		38	2.6	42.5	30		0.18	5	0.9	403	1
SBH	136464	1247643	803	847	7.72		45	1.8	51.5	65		0.17	6	0.4	590	8
SBH	144766	1235104	775	822	7.65		32.5	1.5	66.5	53		0.21	11	4	545	1
SBH	165415	1243574	848	832	7.69		62	5	90	34		0.23	10	5.3	598	1
CS	225000	1280000	204		6.6		8.4	1.2	24.5	9.1		0.1	0.3	0.5	160	0.3

Annex 3. % Error values for Lab. Data (primary & secondary Data)

Sample No	Schem	UTME	UTMN	ALT	TDS (mg/l)	%Error
1	Spring	248608	1237564	1895	150	1
2	HDW	245658	1237046	1855	106	-5
3	Spring	271746	1307994	1630	176	-1
4	Spring	270928	1306722	1578	170	1
5	Spring	274639	1309533	1704	304	1
6	Spring	280119	1300617	1877	310	-4
7	spring	218200	1226932	1363	250	5
8	SW	220549	1224609	1475	270	-1
9	SW	220962	1224760	1485	280	4
10	Spring	221297	1229731	1370	156	0
11	SW	218631	1227650	1406	312	1
12	HDW	213384	1228940	1230	284	-2
13	SW	207991	1222490	1185	350	-4
14	SW	208011	1222878	1172	272	0
15	HDW	208200	1224433	1143	204	-3
16	Sw	208666	1231558	1080	464	3
17	SW	209078	1234661	1030	378	-2
18	SW	210640	1233792	1060	450	3
19	SW	214823	1242340	1097	532	-5
20	HDW	214958	1241986	1094	210	0
21	HDW	214309	1242180	1076	436	-2
22	SW	193404	1246633	1163	1190	1
23	Sw	187390	1243832	1028	546	-2
24	SW	186286	1241519	997	586	0
25	SW	182168	1238835	972	250	-5
26	Sw	822926	1237366	890	360	-4
27	DW	826712	1236653	863	278	-4

% Error values for Lab. Data (primary & secondary Data)

28	Sw	200626	1248542	1191	280	-3
29	Spring	199515	1249099	1166	250	-3
30	SW	197759	1250205	1210	140	2
31	DW	198509	1250018	1200	428	1
32	HDW	217989	1251209	1104	574	1
33	Spring	235168	1258268	1194	376	5
34	DW	214827	1246461	1069	244	4
35	SW	213421	1245024	1040	310	0
36	HDW	212015	1242508	1035	268	-2
37	River				150	2
38	SW	205980	1242411	1050	452	-4
39	SW	201453	1245154	1182	84	5
40	Spring	201748	1245870	1177	244	-4
41	SW	209541	1246857	1064	250	-2
42	HDW	214701	1255651	1062	180	1
43	SW	213651	1252573	1054	222	-1
44	HDW	217188	1259505	1077	116	-4
45	HDW	226225	1280040	1213	182	-3
46	BH	225865	1279316	1201	250	-3
47	HDW	220497	1269599	1137	130	0
48	HDW	796984	1170412	2500	111.58	-10
49	SW	813488	1199853	1000	506.54	3
50	SW	828258	1184382	1150	476	2
51	SW	821255	1192030	1060	644.28	-2
52	Spring	795013	1179896	1420	123.95	3
53	Spring	818988	1170890	1447	520.14	-1
54	Spring	818004	1172037	1341	666.27	1

% Error values for Lab. Data (primary & secondary Data)

55	Spring	802266	1172939	2514	77.95	-19
56	Spring	783419	1179455	2050	158.7	-7
57	Spring	782549	1178801	2035	143.08	6
58	Spring	797329	1179696	2380	138.61	7
59	Spring	799116	1178043	2460	55.99	0
60	Spring	820004	1173602	1305	640	2
61	Spring	821860	1172611	1330	642.5	1
62	Spring	800313	1180548	2290	121.21	-13
63	Spring	801276	1181755	2000	137.31	-11
64	Spring	790553	1183752	2250	87.75	-10
65	Spring	791648	1183792	2330	54.48	-18
66	DW	826693	1236669	900	859.87	1
67	DW	781528	1248710	800	774.07	-2
68	SW	768017	1218809	1000	1041.41	2
69	SW	769294	1231314	670	265.86	-5
70	SW	806123	1243127	860	552.17	-4
71	SW	794303	1247643	929	802.91	1
72	SW	803102	1235104	830	774.7	-1
73	SW	823963	1243574	779	847.55	0
74	Spring	225000	1280000		204	-6

Annex 4. Field Vs Lab. Measured values of water samples.

Station	Schem	UTME	UTMN	Elevation	TEMP	Field pH	Lab PH	Fiel TDS	Lab TDS	Field EC	Lab EC
Gisa	Spring	248608	1237564	1895	21.8	6.22	6.5	90	150	180	217
Gisa	HDW	245658	1237046	1855	23.3	5.86	6.06	80	106	175	162
Chanmar	Spring	271746	1307994	1630	25.5	6.44	6.57	110	176	245	251
Chanmar	Spring	270928	1306722	1578	25	6.27	6.39	110	170	230	239
Degera	Spring	274639	1309533	1704	22.6	6.54	6.71	220	304	455	458
Beles	Spring	280119	1300617	1877	21.25	7.5	7.42	230	310	470	480
G/Mariam	spring	218200	1226932	1363	23.75	6.8	6.76	190	250	380	393
Jigda	SW	220549	1224609	1475	25.5	7.19	7.27	180	270	365	390
Jigda	SW	220962	1224760	1485	25.25	7.39	7.52	200	280	400	434
Jigda	Spring	221297	1229731	1370	25.25	6.29	6.57	110	156	225	248
G/M School	SW	218631	1227650	1406	25.1	6.18	6.39	220	312	425	476
Kebele 2	HDW	213384	1228940	1230	26.5	6.32	6.66	200	284	395	435
Duanz Baguna	SW	207991	1222490	1185	27.25	6.05	6.31	260	350	470	528
Duanz Baguna	SW	208011	1222878	1172	26.5	6.1	6.33	190	272	365	409
Duanz Baguna	HDW	208200	1224433	1143	26.5	6.3	6.42	140	204	285	307
G/Beles	Sw	208666	1231558	1080	26.5	6.73	6.95	340	464	615	710
G/Beles	SW	209078	1234661	1030	26	6.57	6.8	270	378	515	576
G/Beles	SW	210640	1233792	1060	26.4	7.07	7.3	340	450	630	699
Gitsi	SW	193404	1246633	1163	27.25	6.87	7.1	380	532	730	800
Dabotloker	Sw	187390	1243832	1028	27.25	6.33	6.54	140	210	305	317
Dirsambicokel	SW	186286	1241519	997	27	6.66	6.85	320	436	620	670
Jimtia	SW	182168	1238835	972	28	6.39	6.82	770	1190	1455	1674
Jurasis	Sw	822926	1237366	890	27.4	6.87	7.1	420	546	810	880
Gublak	DW	826712	1236653	863	31	7.73	7.81	440	586	865	900
Shibeshi school	Sw	200626	1248542	1191	31.5	6.5	6.75	180	250	365	385

Field Vs Lab. Measured values of water samples.

Mambuk	Spring	199515	1249099	1166	26.25	6.72	6.92	260	360	525	568
Kitli	SW	197759	1250205	1210	28.5	6.56	6.86	190	278	400	426
Mambuk	DW	198509	1250018	1200	31	7.05	7.21	200	280	410	428
Mender 30	HDW	217989	1251209	1104	27.5	6.58	6.71	180	250	365	381
Ali	Spring	235168	1258268	1194	27.25	7.04	7.12	90	140	190	205
Adari School	DW	214827	1246461	1069	29	7.09	7.22	290	428	615	650
Mender 4	SW	213421	1245024	1040	28.7	6.82	7.02	410	574	850	880
Menjari	SW	214823	1242340	1097	25.75	6.63	6.66	300	376	595	586
Menjari	HDW	214958	1241986	1094	24.5	6.57	6.56	170	244	365	382
Menjari	HDW	214309	1242180	1076	26.5	6.75	6.72	220	310	460	478
Medin	HDW	212015	1242508	1035	29	6.5	6.6	200	268	415	413
G.B.River	River				27	7.79	7.63	100	150	215	228
Mender 49	SW	205980	1242411	1050	26	6.72	6.82	330	452	680	693
Mender 46	SW	201453	1245154	1182	27	5.8	5.92	50	84	120	125
Mender 46	Spring	201748	1245870	1177	25.85	7.02	7.16	170	244	355	372
Mender 4	SW	209541	1246857	1064	27.6	6.52	6.62	170	250	360	378
Mender 7	HDW	214701	1255651	1062	28.5	6.33	6.51	130	180	270	282
Mender 6	SW	213651	1252573	1054	28.5	6.74	6.82	160	222	340	349
Jawi	HDW	226225	1280040	1213			6.33		116		177
Jawi	DW	225865	1279316	1201			6.97		182		281
Hilala Abo	HDW	220497	1269599	1137	26.75	6.73	6.76	180	250	380	398
Mender 8	HDW	217188	1259505	1077	28.35	6.23	6.4	90	130	185	201

Annex 5. Water point inventory data

Scheme type	UTM E	UTM N	Elevation
CS	248608	1237564	1895
HDW	245658	1237046	1855
CS	271746	1307994	1630
CS	270928	1306722	1578
CS	274639	1309533	1704
CS	280119	1300617	1877
CS	218200	1226932	1363
SW	220549	1224609	1475
SW	220962	1224760	1485
CS	221297	1229731	1370
SW	218631	1227650	1406
HDW	213384	1228940	1230
SW	207991	1222490	1185
SW	208011	1222878	1172
HDW	208200	1224433	1143
Sw	208666	1231558	1080
SW	209078	1234661	1030
SW	210640	1233792	1060
SW	214823	1242340	1097
HDW	214958	1241986	1094
HDW	214309	1242180	1076
SW	193404	1246633	1163
Sw	187390	1243832	1028
SW	186286	1241519	997
SW	182168	1238835	972
Sw	822926	1237366	890

DBH	826712	1236653	863
Sw	200626	1248542	1191
CS	199515	1249099	1166
SW	197759	1250205	1210
DBH	198509	1250018	1200
HDW	217989	1251209	1104
CS	235168	1258268	1194
DBH	214827	1246461	1069
SW	213421	1245024	1040
HDW	212015	1242508	1035
SW	205980	1242411	1050
SW	201453	1245154	1182
CS	201748	1245870	1177
SW	209541	1246857	1064
HDW	214701	1255651	1062
SW	213651	1252573	1054
HDW	217188	1259505	1077
HDW	226225	1280040	1213
DBH	225865	1279316	1201
HDW	220497	1269599	1137
HDW	796984	1170412	2500
SW	813488	1199853	1000
SW	828258	1184382	1150
SW	821255	1192030	1060
CS	795013	1179896	1420
CS	818988	1170890	1447
CS	818004	1172037	1341
CS	802266	1172939	2514
CS	783419	1179455	2050

CS	782549	1178801	2035
CS	797329	1179696	2380
CS	799116	1178043	2460
CS	820004	1173602	1305
CS	821860	1172611	1330
CS	800313	1180548	2290
CS	801276	1181755	2000
CS	790553	1183752	2250
CS	791648	1183792	2330
DBH	826693	1236669	900
DBH	781528	1248710	800
SW	768017	1218809	1000
SW	769294	1231314	670
SW	806123	1243127	860
SW	794303	1247643	929
SW	803102	1235104	830
SW	823963	1243574	779
CS	225000	1280000	
CS	215450	1255635	1048
SW	213650	1252570	1056
SW	212249	1250460	1056
SW	209540	1246859	1063
CS	235187	1258242	1200
HDW	224731	1260325	1130
SW	228598	1262455	1137
HDW	225763	1255387	1117
HDW	231737	1257679	1181
HDW	218213	1240618	1171
SW	217871	1244595	1109

SW	222006	1246621	1145
HDW	222033	1251244	1147
HDW	222056	1249978	1152
HDW	223785	1252380	1126
SW	223319	1252501	1107
SW	228496	1253871	1127
HDW	214542	1248506	1054
HDW	217353	1240715	1141
HDW	216478	1251921	1103
SW	217471	1256700	1056
HDW	206173	1254433	1191
HDW	206138	1254238	1195
HDW	201448	1245149	1185
HDW	213090	1244602	1049
HDW	206213	1253828	1181
SW	205976	1242399	1058
HDW	204914	1243138	1090
SW	205264	1248383	1114
SW	213428	1245018	1037
CS	187829	1227125	1082
HDW	207064	1218813	1234
HDW	208305	1221937	1182
HDW	208888	1234643	1016
HDW	208933	1234682	1016
HDW	209070	1234663	
HDW	209120	1231098	1079
CS	209122	1232336	1053
SW	209226	1234916	1016
HDW	209472	1234667	

HDW	209667	1234045	
HDW	209890	1235019	
HDW	210066	1233500	
SW	212735	1228886	1208
HDW	212747	1228632	1200
HDW	213109	1229175	
HDW	213706	1229133	
HDW	214329	1216650	
HDW	215566	1229237	
HDW	215660	1230119	1260
HDW	215688	1229535	1283
HDW	215795	1229954	1267
HDW	216323	1229252	1309
CS	217160	1226863	1377
HDW	217468	1229008	1350
HDW	217497	1229109	1351
HDW	217502	1229751	1332
HDW	218083	1224865	1405
HDW	218583	1227484	1410
HDW	219593	1227578	1383
HDW	219703	1227811	1369
HDW	220880	1225403	1463
SW	220971	1224754	1487
HDW	225331	1229463	
HDW	226206	1228899	1423
HDW	226324	1229462	1433
HDW	226877	1229521	
CS	226881	1232416	1275
HDW	226882	1229508	1427

## Annex 6. Mean Monthly discharge of main rivers (in mil. mc)

### 6.1. Main Beles River

year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1995	3.45	1.6	1.4	0.68	9.4	109	359	511.8	277.5	76.61	14.3	6.72
1996	3.2	1.5	1.4	0.9	8.9	72.5	224	1505	356.5	258.2	52.1	17.6
1997	5.6	2.9	1.8	0.94	6	45.7	250	381.8	207.6	274.3	84.6	15.4
1998	5.6	2	0.9	0.15	1.7	51.5	382	669.3	433.7	279.5	46	15.4
1999	6.88	2.6	1.6	1.04	16	67.5	242	605.1	244.3	237	39.6	15.2
2000	8.96	3.5	1.7	2.78	33	153	351	1604	300	552.7	73.2	18.9
2001	9.57	5.1	3.6	0.99	4.8	99.2	342	848.5	344.7	261.5	63.8	18.6
2002	9.25	4.2	2.6	1.11	0.5	43.6	256	472.7	358	132.6	43.4	22.5
2003	15.3	11	8.9	4.79	2.1	98.7	546	826.5	603.9	258.2	52.1	17.6
2004	7.53	13	10	9.19	10	108	675	696.4	438.6	251.4	51.9	28
Average	7.53	4.7	3.4	2.26	9.3	85	363	812.1	356.5	258.2	52.1	17.6

### 6.2. Gilgel Beles River

year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1994	6.85	1.29	1.81	1.3	2.33	17.5	67.4	130.1	100.25	41.08	15	7.86
1995	3.89	2.1	1.39	0.9	2.45	45.7	107	169	106.72	56.06	13.8	8.6
1996	4.43	1.59	1.17	1.9	6.24	40.1	122	200.2	163.69	51.62	17	9.09
1997	5.05	3.19	4.76	4.1	11.5	50.2	117	148.3	77.666	96.49	38.3	12.1
1998	6.85	2.78	4.81	4.6	6.17	39.2	99.7	233.3	146.88	105.3	34.3	11.7
1999	8.75	4.32	3.17	2.4	8.9	38.4	85	212.3	114.9	131.9	29.6	12.9
2000	7.77	4.46	2.91	3.1	13.4	33.6	76.7	237.4	134.82	127.8	43.4	16.5
2001	9.93	5.05	3.84	2.6	4.19	32.3	103	130.5	130.4	61.45	28.1	14.9
2002	8.73	4.5	4.54	6.7	4.79	21.2	53.2	178.3	124.04	82.25	26	11.7
2003	6.21	4.63	4.94	1.8	2.45	22.1	193	143.3	141.06	68.58	14.7	11.7
Average	6.84	3.39	3.33	2.9	6.24	34	102	178.3	124.04	82.25	26	11.7

Annex 7. Mean monthly precipitation (in mm).

Station name	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Baruda	1985	3.4	0	28	85	161	260	389	329	200	109	32	0	1597
Baruda	1986	0	1.4	15	15	33	302	280	329	533	87	0	0	1595
Baruda	1987	0	0	18	62	312	165	256	192	292	112	0	10	1418
Baruda	1988	0	13	0.2	0	168	198	377	212	193	172	0	0	1334
Baruda	1989	0	0	41	48	164	224	308	329	275	93	6.8	1.4	1489
Baruda	2002	0	3.1	14	26	170	225	308	329	138	39	3.8	0	1255
Baruda	2003	0	4.4	2.1	0	180	220	236	387	293	36	4.6	0	1364
Baruda	2004	0	3	12	4.7	150	228	308	315	275	93	6.8	1.4	1395
Baruda	2005	0	3.3	15	27	160	226	308	329	275	93	6.8	0	1442
Baruda	2006	0	3.3	0	0	158	198	308	539	275	93	6.8	1.4	1581
Bullen	1997	0	4	11	38	275	202	299	268	281	176	4	0	1559
Bullen	1998	0	0	1.9	5	142	219	380	462	432	352	7.7	0	2001
Bullen	1999	2.8	0	0	24	264	364	210	279	270	212	13	0	1639
Bullen	2000	0	0	11	45	137	299	372	308	153	183	14	0.3	1523
Bullen	2001	0	0	0	40	138	228	391	320	165	132	5.1	1.6	1421
Bullen	2002	3.5	0	2.2	17	47	260	250	304	226	105	18	0	1232
Bullen	2003	0	9	6.5	7.7	64	308	333	378	297	41	5.1	0	1449
Bullen	2004	0.2	0.2	9.6	52	76	267	222	409	238	77	37	0	1388
Bullen	2005	0	0	71	9.8	64	334	240	204	288	131	40	0.3	1382
Bullen	2006	0	2.8	0	5.3	137	226	299	274	261	156	16	0.3	1378
D.Zeit	1998	32	51	14	77	42	77.7	206	294	97.6	93	0	0	984.7
D.Zeit	1999	0.5	0	37	0	10	177	299	259	48.7	31	0	0	861.4
D.Zeit	2000	0	0	28	8.6	50	65.4	77	244	139	31	23	3.4	671.3
D.Zeit	2001	0	4.6	166	22	104	79.5	242	143	64.3	38	0	0	864.5
D.Zeit	2002	8.6	0	48	35	11	109	179	178	58.4	0	0	21	648.3
D.Zeit	2003	38	55	64	100	21	81.4	278	286	120	6	3.6	35	1089
D.Zeit	2004	12	28	68	120	2	134	173	209	73.6	23	10	0	851.2
D.Zeit	2005	22	0	122	77	87	96.7	168	187	153	0	2.9	0	915.3
D.Zeit	2006	5	109	0	52	32	108	329	141	123	78	5.2	16	999.2

Mean monthly precipitation (in mm).

D.Zeit	2007	5.8	0	0	58	92	77.4	327	155	123	13	5.4	8.5	865.3
Mandura	1987	8.4	0	3.6	15	282	303	188	297	204	75	4.6	0	1381
Mandura	1988	0	20	2.9	0	216	284	456	356	443	128	0	0	1906
Mandura	1989	0	0	20	45	158	310	514	509	383	211	0	0	2149
Mandura	1990	6.4	0	0	0	93	124	398	690	325	48	0	0	1685
Mandura	1991	0	0.8	0	290	142	264	375	441	335	122	16	4.9	1990
Mandura	2002	2	3.5	4.5	55	142	252	234	351	160	157	31	0	1392
Mandura	2003	0	5.7	9.3	2.5	53	312	292	304	408	15	37	4.9	1443
Mandura	2004	0	1.5	0	111	52	264	538	581	422	219	37	29	2254
Mandura	2005	2	3.5	4.5	2.5	142	264	375	441	335	122	16	4.9	1712
Mandura	2006	1.4	0	0	27	142	264	377	441	335	122	16	4.9	1730
Mankush	1985	0	0	15	21	159	136	319	177	232	92	42	0	1192
Mankush	1986	0	0	0	0	7.3	126	280	197	186	84	6.8	0	887.5
Mankush	1998	0	0	2	7.5	78	126	280	0	0	0	6.8	0	500.4
Mankush	1999	0	0	0	0	0	128	221	161	188	149	0	0	847.4
Mankush	2000	0	0	2	13	195	100	291	222	121	117	4.5	0	1065
Mankush	2001	0	0	0	7.5	78	155	280	310	225	189	0	0	1244
Mankush	2002	0	0	0	0	68	112	271	169	219	63	0	0	901.8
Mankush	2003	0	0	0	18	71	179	321	263	273	38	1	0	1164
Mankush	2004	0	0	0	6.5	43	74.1	258	277	228	24	0	0	911.2
Mankush	2006	0	0	0	0	78	126	280	197	186	84	6.8	0	957.9
Pawe	1993	0	0	8.2	35	112	321	371	291	168	97	32	0	1434
Pawe	1994	0	0	0	14	155	207	291	305	215	78	49	0	1313
Pawe	1995	0	1	35	15	93	413	233	434	248	92	0	1.4	1565
Pawe	1996	0.2	0	43	57	99	207	371	533	272	134	12	0	1728
Pawe	1997	0	0	2.1	31	147	180	331	383	176	170	17	1.4	1439
Pawe	1998	0	0	9.8	9.6	154	511	385	367	243	147	5.6	0	1831
Pawe	1999	2.2	0	0	36	181	281	286	359	224	135	19	4.3	1526
Pawe	2000	0	0	2.1	61	189	265	201	365	177	224	17	2	1503
Pawe	2005	0	2	18	3	142	290	308	411	215	134	3.2	4.5	1532
Pawe	2006	0.3	11	0	18	153	227	308	660	215	134	17	4.5	1749
Dangila	1997	0	0	36	53	210	206	351	380	175	164	91	3.4	1667

Mean monthly precipitation (in mm).

Dangila	1998	0	0	23	14	186	289	282	343	254	148	5.8	0	1545
Dangila	1999	2	0	0	36	244	281	389	371	330	264	36	7.8	1959
Dangila	2000	0	7.1	7.5	77	135	344	313	436	238	265	70	2.5	1896
Dangila	2001	0	0	15	14	157	318	390	259	150	98	3.3	7.1	1411
Dangila	2002	0	3.6	12	15	52	279	299	352	183	123	30	2	1350
Dangila	2003	0	4.5	7.5	2.2	23	331	339	279	302	27	55	0	1369
Dangila	2004	0.5	9.1	2.3	91	61	231	488	364	267	95	21	0	1628
Dangila	2005	4	0.5	29	7.4	48	271	319	345	321	54	7.3	0	1405
Dangila	2006	2.9	0	0	48	259	340	440	393	222	133	35	2.5	1876
MESHENTI	1997	0	0	65	6.3	208	113	375	170	124	154	12	0	1229
MESHENTI	1998	0	0	48	1.8	144	305	271	309	157	134	0	0	1368
MESHENTI	1999	4.3	0	0	14	82	349	432	329	194	169	3.2	1.1	1576
MESHENTI	2000	0	0	0.3	56	30	266	323	365	244	248	4.4	0.4	1538
MESHENTI	2001	0	1.2	6.8	8	96	293	282	437	184	82	0	16	1405
MESHENTI	2002	6.9	6.1	13	12	80	257	255	254	140	139	2.1	26	1191
MESHENTI	2003	0	3.9	8.3	1.3	2.1	321	506	265	278	71	4.5	18	1479
MESHENTI	2004	10	7.3	3	19	5.9	194	445	270	139	93	1.7	0	1187
MESHENTI	2005	0.5	0	23	17	44	161	384	244	228	89	12	0	1203
MESHENTI	2006	0	2.4	0	21	176	372	553	371	188	131	4.4	6.8	1824

Annex 8. Mean monthly temperature (in °c)

Station Name	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bullen	1997	20.5	22.6	23.4	23.9	21.7	21	20	20	20.7	20.6	20.4	20.9
Bullen	1998	20.55	21.5	24.4	26.3	23.5	21	19.6	19.7	20.5	20.6	20	19.6
Bullen	1999	20.3	23.2	22.4	25	21.6	20	19.1	19.2	20.3	20	19.8	19.8
Bullen	2000	20.65	22.2	23.4	23.1	23.2	20	19.3	19.1	19.5	19.4	19.1	20.1
Bullen	2001	19.7	22.6	23.5	24.6	23.2	20	15.2	19.7	20.2	20.2	20	20.1
Bullen	2002	20.5	22.6	23.4	24.7	23.2	21	20.6	19.9	20.6	20.7	20.3	20
Bullen	2003	20.95	22.8	24.9	25	25.3	21	19.7	19.9	20.3	20.2	20.1	19.7
Bullen	2004	20.55	22.2	24.4	23.9	23.7	21	19.9	19.9	20.1	20	20.6	20.5
Bullen	2005	20.5	23.4	23.9	25.6	23.2	21	19.8	20	20.6	20.4	19.9	20.1
Bullen	2006	21	23.3	23.6	24.6	23.2	21	20	19.6	14.9	20.2	20	20.1
D/Zeit	1998	19.7	21	21.6	22.7	22.1	21	19.6	19	19.4	19	17.1	16.5
D/Zeit	1999	18.35	19.5	20.7	22	21.9	21	18.6	18.9	19.2	18.7	16.6	17
D/Zeit	2000	17.85	19.3	21.1	21.9	21.2	20	19.3	18.8	19.2	18.4	18	17.9
D/Zeit	2001	18.35	20.2	20.8	21.5	21.3	20	19.3	19.1	19.8	19.8	18.4	18.9
D/Zeit	2002	19.3	20.9	21.8	22.4	22.6	22	20.6	19.6	19.9	20.1	19.1	19.5
D/Zeit	2003	19.15	21	21.5	21.5	22.2	21	18.9	19.2	19.4	18.9	18.9	17.4
D/Zeit	2004	18.05	20	19	19.2	19.8	19	18.6	18.6	18.7	17	16.5	16.9
D/Zeit	2005	17.15	18.5	20	20.5	20.1	20	18.4	19.3	19.1	17.6	16.7	14.9
D/Zeit	2006	17.5	19.3	19.2	19.7	20.2	20	19.1	19	17.9	18.7	17.3	18.1
D/Zeit	2007	18.35	20	20.5	20.9	21.2	20	19.1	18.3	19.2	18.7	17.6	17.5
Mandura	1987	24	26.4	27.5	28.1	25.5	22	22	21.5	21.7	22.4	23.9	24.5
Mandura	1988	24.9	26.2	28.2	29.4	26.7	23	21.2	20.7	21.9	22	22.6	24.8
Mandura	1989	24.1	25.2	27	28.7	27.1	25	22.8	23.1	22.6	22.4	23.6	22.8

Mean monthly temperature (in °c)

Mandura	1990	24.35	25.7	26.5	29.3	27.4	25	22.2	21.7	21.2	23.4	24.4	25.2
Mandura	1991	24.9	27	29.2	28.4	26.1	23	21.7	21.2	21.2	22.3	23.3	23.8
Mandura	2002	24.1	25.8	27.4	28.1	26.7	23	21.3	20.6	21.1	21.7	22.5	22.2
Mandura	2003	22.9	25.3	26.8	27.3	27.2	22	20.4	20.4	20.2	22.1	22.6	23.8
Mandura	2004	23.55	24.4	27	27.9	27.3	23	20.8	20.6	19.3	21.9	23.7	23
Mandura	2005	23.3	25.8	27.4	28.5	26.7	23	21.7	21.2	21.2	22.3	23.3	23.8
Mandura	2006	24.45	26.2	27.1	25.8	26.7	23	23.4	21.2	21.2	22.3	23.3	23.8
Mankush	1986	27.65	25.9	28.8	28	28.2	25	26.7	23.7	22.8	22.7	24.5	24.8
Mankush	1998	24.9	27	29.7	30.9	29.4	26	24.7	24.5	24.4	26.2	25.9	26.7
Mankush	1999	27.25	29.7	30.6	30.7	28.8	27	23.3	22.5	23.7	24	24.9	25.9
Mankush	2000	26.8	29.1	30.9	26	25.3	26	24.2	23.6	24.9	24.8	25.9	27.1
Mankush	2001	26.3	28.4	30.9	30.9	29.5	25	24.2	24.5	24.8	25.3	25.5	27.1
Mankush	2002	26.15	30	30.9	32.7	31.4	27	24.8	24.8	25.5	22.8	27	27.4
Mankush	2003	27.95	30.5	32.3	32.3	32.2	26	24.4	24.6	24.7	25.9	26.5	27.3
Mankush	2004	27.5	29.2	31.7	31.4	31.5	27	24.8	24.7	24.7	25.8	27	27.5
Mankush	2005	26.7	31.8	31.9	33.7	29.5	26	24.7	24.1	24.4	24.7	25.9	26.7
Mankush	2006	26.8	29.1	31.4	32.4	29.5	26	24.7	24.1	24.4	24.7	25.9	18.2
Pawe	1990	23.9	24.4	27.3	28.4	27.9	24	22.7	22.6	22.7	23.5	23.4	23.3
Pawe	1991	23.85	25.9	27.7	28.4	26.5	24	22.7	22.6	23.2	23.4	23.1	23.1
Pawe	1995	23.55	25.5	26.4	28.2	27.6	24	22.5	23	23.3	23.9	23	23.3
Pawe	1996	22.85	26.2	27.3	27.7	25.8	23	22.6	22.4	23	23.5	22.8	22.8
Pawe	1997	23.05	25.4	28.1	27.4	25.8	24	22.8	23	24	23.4	23.3	23.4
Pawe	1998	23.3	24.3	28.3	30.1	27.4	24	22.7	22.6	23.2	23.4	23.1	23.1
Pawe	1999	23.55	25.7	27.7	28.4	25.6	24	22.4	22.4	23.3	23.1	22.7	22.8
Pawe	2000	23.95	25.5	28.4	27.5	26.8	24	23	22.4	23.2	23.2	23.1	22.7
Pawe	2005	23.15	27.5	28.1	29.8	26.5	24	22.7	22.6	23.2	23.4	23.5	23.1
Pawe	2006	24.25	26.5	27.4	27.9	25.8	25	22.7	22.9	23.2	23.4	23.1	23.1
Chagni	1992	19.29	21.6	22.8	23.8	22.8	20	19.6	19.6	19.8	20.1	21.1	19

Mean monthly temperature (in °c)

Chagni	1998	19.29	21.6	22.8	23.8	22.8	21	19.7	20	20.2	20.2	21	18.9
Chagni	1999	19.1	21.9	22.8	24	21.4	20	18.1	19.5	19.6	19.9	18.9	18.6
Chagni	2000	19.5	21	22.7	22.7	21.8	20	19.7	19.1	19.8	20.2	19.4	18.8
Chagni	2001	18	21	21.7	23.7	22.8	20	19.7	19.7	19.5	20.4	19.1	19.4
Chagni	2002	19.3	21.6	23	23.9	23.4	21	20.5	19.6	20	20.4	20	18.8
Chagni	2003	19.5	22.1	23.4	23.8	25.2	21	20	19.9	19.7	20	20.2	19.3
Chagni	2004	20	21.4	23.2	23.3	23.3	20	19.5	19.7	19.2	19.8	20.1	19.3
Chagni	2005	18.65	22.2	23	24.6	22.6	21	19.6	19.4	20	20.1	19.9	18.7
Chagni	2006	20.3	22.1	22.6	23.9	22.2	21	20.1	19.5	19.8	20.1	21.1	19
Dangila	1997	14.5	15.8	18.3	18	17.5	17	16.2	16.4	17	16.3	15.8	15.1
Dangila	1998	15.35	17.4	19.7	20.7	19.6	18	16.9	17	17.5	17.3	15.6	14.5
Dangila	1999	15.05	17.8	16.4	19.3	18.1	17	15.8	16.1	16.1	16	14.6	14.4
Dangila	2000	14.9	15.8	17	16.9	17.6	16	15.5	15.2	15.9	15.7	14.7	15.1
Dangila	2001	14.35	17.4	17.8	20.1	18.9	18	17.2	17.2	17.3	17.6	15.9	16
Dangila	2002	15.95	17.9	18.9	19.5	20.1	18	18.1	17.2	17.2	16.8	16.1	15.1
Dangila	2003	15.45	18.1	19.7	19.5	21	19	17.6	17.7	17.6	17.3	16.9	15.6
Dangila	2004	16.15	17.1	18.9	19.6	19.6	18	17.4	17.5	17.3	16.6	16.8	15.9
Dangila	2005	15.4	18.6	19.3	21	19.4	19	16.9	17.3	17.6	17.3	16.1	15
Dangila	2006	16.4	18.3	18.6	19.4	18.9	18	17.6	17.5	17.4	16.5	15.8	15.2