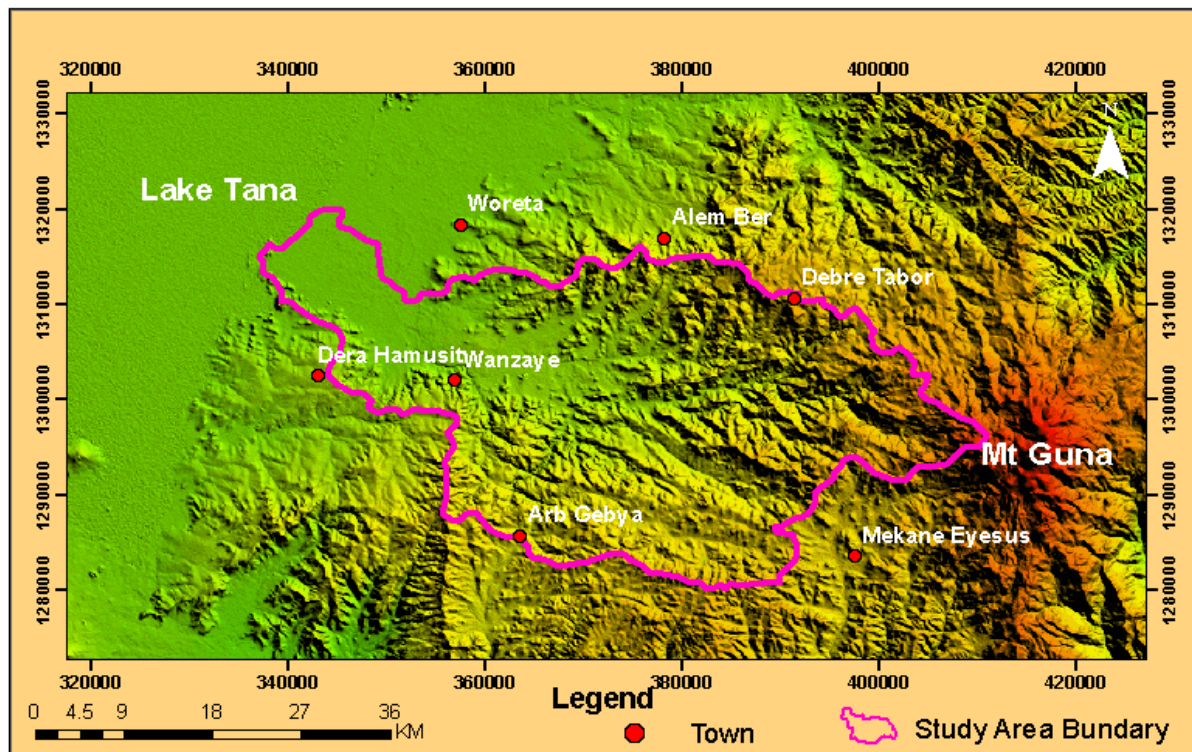




ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES
GROUND WATER POTENTIAL ASSESSMENT OF GUMARA
RIVER CATCHMENT, NORTH WEST ETHIOPIA



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

By

Zelalem Leyew

June, 2009

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Abstract

The development of balanced plan for water resource utilization requires assessment of the water resources in terms of quality, quantity, spatial distribution and the land use land cover condition of the entire catchment area. The Gumara River catchment is located in North West part of Ethiopia particularly in south Gonder zone and enclosed between Mount Guna from the east and Lake Tana in the west. The area is generally characterized by two pronounced topographic features. The high land which comprises of about 80% of the study area is covered by Tarmaber formation of Miocene age and the remaining low land area consists of Quaternary volcanics, alluvial and lacustrine deposits.

Different approaches have been used to quantify the main hydrometeorological components and estimate the recharge amount of the catchment. The annual rainfalls of point data from different nearby stations of the catchment are analysed using arithmetic, Thiessen polygon and Isohyetal methods. All the three methods provide nearly closer value. The analysis result of Thiessen polygon method which is more or less the average value (1377 mm) of three methods is used as the annual average rain fall of the study area. The actual evapotranspiration of the catchment is calculated by evaluating the land use land cover type, soil texture and their areal proportion and is computed to be 764 mm per year. The annual recharge of the catchment is estimated using base flow separation and water balance methods of which the water balance method (267 mm) is preferred to be the annual recharge of the catchment.

Weathered and fractured basalt are the major aquifers of the area. The ground water potential recharge-discharge condition and ground flow system of the area is generally controlled by the amount of rain fall, topographic feature and prevailing structure. The general ground water flow direction is from the eastern towards west with minor irregularities reflecting local topographic variation, existence of deep well and prevailing structure.

Aquachem software has been employed to identify the different water types. From the analysis of hydrogeochemical data different water types are identified of which the Na-HCO₃-CO₃ and Na-CO₃-CO₃ are thermal springs in Guramba and Wanzaye area. The dominant water type of the area is Ca-Mg-HCO₃. Waters of the area generally evolves from Ca-HCO₃ and Ca-Mg-HCO₃ in the recharge area to Na-Ca-HCO₃ discharge area. Such evolutionary trend is controlled by dissolution, precipitation, cation exchange and Hydrolysis of silicate minerals.

CHAPTER ONE

INTRODUCTION

1.1 Background

Water is possibly the most important natural resource affecting human survival, economic development and environmental enhancement. It is indispensable for domestic and is of vital importance in the development of agriculture and industries. It can also be used to generate electrical energy in case where a large quantity of surface water exists. Generally it plays a very significant role in every aspect of human life. The need for water is strongly ascending from time to time as it is fundamental for all development activities. Any development is directly or indirectly dependent upon utilization of water resources. Persistent drought and population growth together with the need for water to domestic, irrigation and industrial development brings high demand in water resources. With time due to population expansion, higher per capital demand and pollution, water resources become scarce. It is therefore of great importance that they should be developed and used in a sustainable manner so as to maintain adequate water resources and preserve the environment.

Groundwater is the only reliable sources of water compared to surface water though there is temporal and spatial variation in quality and quantity. It is the main source of water supply development in Ethiopia covering about 85% (Getachew, 2004). Ground water can also be non-renewable, at least when viewed with in a human time frame and its exploitation is subjected to supply and demand (Domenico, 1998). Such high demand of water urges different researchers to conduct research work so as to identify potential sites for further development activities.

Gumara river catchment, which is one of the catchments of Tana sub-basin, is found in the North West part of the country (South Gonder). The catchment is drained by Gumara River and its tributaries covering parts of Dera, Fogera, Farta and Estie. Most of the residents living there are rural people whose livelihood is dependent mainly on agriculture (mixed farming) with poor water supply and sanitation services. The area is partly affected by recurrent drought and even by flooding especially adjoining to Lake Tana. The catchment is characterized by undulating and erosion prone topographic feature especially in the upper (eastern) part of the study area. In this part of the study area, settlement and agricultural

activities are insignificant due to unfavorable topographic settings. The lowland area (western part) on the other hand is plain and is suitable for settlement and agricultural practices.

The federal government of Ethiopia has recently opened one development project entitled 'Gumara Irrigation Project'. Though the project is in its feasibility stage, it is intended to be implemented in the near future so as to improve traditional agricultural practices and increase productivity and generating better income. The project thus, will progress the way of life of people in the area in particular and the country in general. However, the displacement of people from reservoir and command areas will create problem. According to the feasibility study report, 30,234 people have to leave their indigenous village. Development project that displace people involuntarily entails sever economic, social and environmental problems as production system and income sources will be dismantled. To compensate the problem, new settlement program is proposed with better infrastructures and social services. The resettlement program can create additional population pressure and the demand for potential water resources will be higher. The above mentioned and other related problems in the area generally need water for various purposes including drinking.

1.2 Previous Studies

Because of the importance of the Abay, different studies had been carried out concerning the basin (Abay basin). Though there was no any specific and separate study of Gumara catchment exclusively in relation to water resource potential assessment, all the studies were undertaken pertaining to Lake Tana, Abay or the country as a whole. The review of previous studies are presented in the following paragraphs of which most of the studies are related to geological and geomorphologic set up of the area, flood control, irrigation and land resources development in a general sense.

Chorowicz et al, 1998 had studied Tana basin inter-plateau uplifting and subsidence. The study emphasized on structural and tectonic setting, morph-tectonic analysis such as regional uplift, dikes and plugs, faulting and graven, subsidence and micro tectonics. Pik et al, 1998 and Kiffer et al, 2004 stressed on the North West Ethiopian flood basalt and shield from Ethiopian magmas in African supper wells.

EVDASA (1980) Rib and Gumara flood project studied the surrounding area so as to control the flood damages caused by Rib and Gumara rivers and thereby ensure safe agricultural

production. During that time river engineering works and internal drainage systems were introduced. In this study the condition of Rib and Gumara rivers in the project area were analyzed. Valuable figures and reflections about average and maximum discharge of Rib and Gumara rivers were found.

The country wide master plan studies were also carried out for country wide water and land resource development covering all river basins including the Abay basin. These were primarily desk studies for identifying potential irrigation and hydropower site based on country wide data collection and analysis coupled with detailed map studies.

BCEOM-French Engineering Consultants (1999) have studied the Abay basin. The study entitled ‘The Abay River Basin Integrated Development Master Plan Project’ has been carried out with the objective of: preparation of river basin development master plan that will guide the development of the basin resources potential with respect to occurrence, distribution, quality and quantity of water resources for the coming 30-50 years. The study is also aimed at preparing water allocation and utilization plan under alternative development scenarios and to generate data information and knowledge that will contribute to the future water allocation.

A recent project by Water Works Design and Supervision Enterprise in association with Intercontinental Consultants and Technocrats India PVT LTD (2008) has studied the feasibility of Gumara irrigation from different point of view. However the study is highly emphasized at the dam and surrounding area, little is dealt about the rest of the catchment

1.3. Objective

The general objective of this research is to evaluate the hydrogeology in Gumara river catchment with particular emphasis to ground water potential condition of the area.

The specific objectives of the study are:

- To quantify major hydrologic components and estimate the recharge of the catchment
- To characterize the aquifer and establish hydrogeological map of the area
- To assess the spatial variation of hydrochemistry as well as evaluate the water quality
- To determine groundwater flow direction
- To delineate potential sites for further development activities

1.4 Methodology

The rainfalls data collected from different meteorological station have been estimated by arithmetic, Isohyetal, Thiessen polygon methods of which the Thiessen method is preferred. Other meteorological data such as temperature, relative humidity, sunshine hour, wind speed were organized in a way suitable for analysis. They have been put into Penman modified method for calculation of potential evapotranspiration (PET). The actual evapotranspiration (AET) which uses rainfall and PET as an input is calculated by Thornthwaite and Mather soil water balance model. The annual recharge of the catchment on the other hand has been estimated by base flow separation method using Time Plot and general water balance method.

The hydrogeology of the area has been evaluated using qualitative and quantitative parameters. Physical observation and description of the nature of geologic materials, degree of weathering /fracturing, porosities, discharge conditions, sustainability of water points, lithological log etc are some of the sources of important qualitative parameters. A few of the pump test data have been put into Aquitest Software for execution of aquifer parameters (storativity, Transmissivity).The hydraulic conductivity is then determined from transmissivity as the aquifer thickness is known.

Representative water samples were collected from selected water points (river, spring, hand dug well and boreholes). Field parameters of the samples (pH, EC, Temperature) were measured at the time of sampling .Such measurements are always important for confirmation between field and laboratory measurements and are good indicators about sample preservation or change of chemical constituents during transportation. Physico-chemical analysis has been carried out in the laboratory. The geochemical data from the laboratory analysis result have been utilized for the assessment of ground water spatial variation (evolution), flow system and overall quality of the water for specific purposes.

Generally the collected data (both primary and secondary) have been analyzed using relevant softwares like ArcGIS, Surfer, Global Mapper, Aquitest, Aquachem, etc. Digital elevation maps, topographic, hydrogeological and geological maps, combined with primary data acquired from field investigation and laboratory analysis have been integrated under GIS environment and related softwares to make rational interpretations that meet the objectives of the research.

CHAPTER TWO

OVERVIEW OF THE STUDY AREA

2.1 Location and Accessibility

The study area is enclosed between 1280002m and 1320755m N latitude and 337073m and 411064m E longitude and covers a total area of 1532 km². It is located northwest part of Ethiopia particularly in the south Gonder zone which is about 624 km from Addis Ababa. The main asphalted road from Bahir Dar to Gonder crosses the western part of the study area. The area is also accessed by weathered roads particularly from Ambessamie via Arbgebya to Debretabor and to Mekaneselam. Wanzaye on the other hand is accessed by vehicles from Wereta. However, most of the area is inaccessible to vehicles due to undulating topographic feature especially the eastern part of the study area.

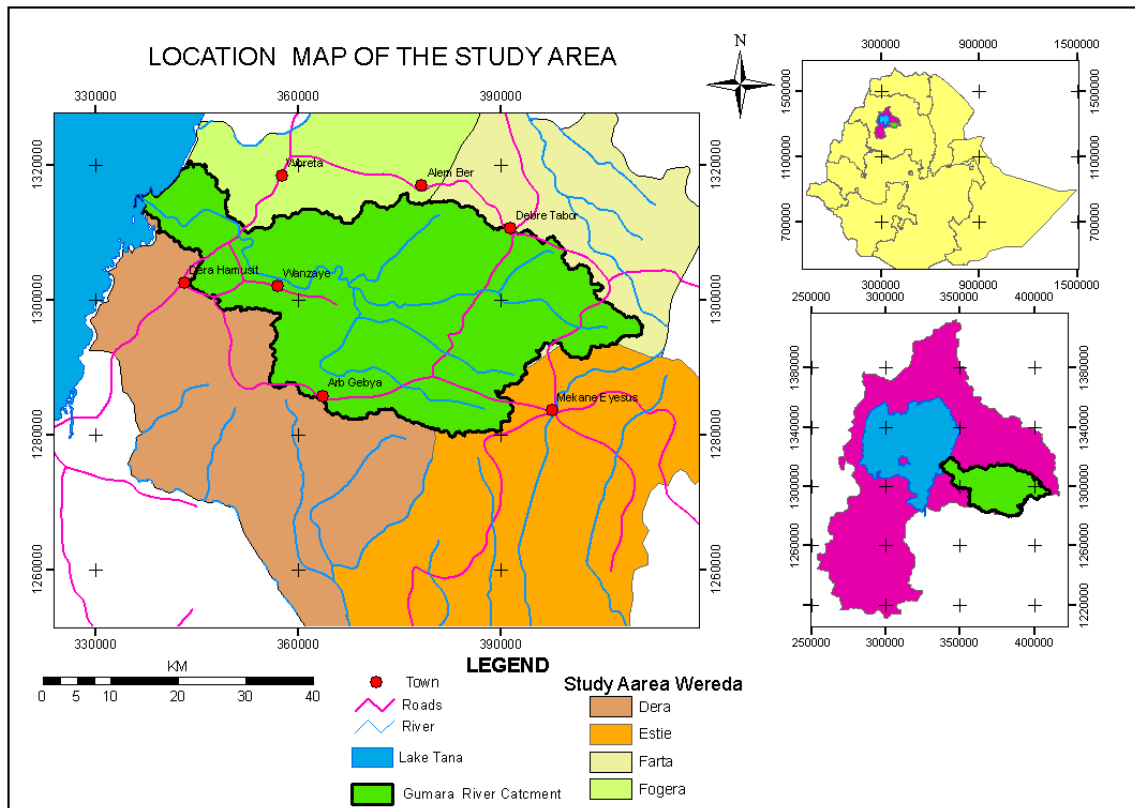


Figure 2.1 Location Map of the Study Area

2.2 Topography and Drainage

Gumara River is one of the main streams on the east side flowing to Lake Tana. The river along with its tributaries, originate from high mountain ranges. The river generally flows in the western direction and joins Lake Tana. The catchment consists of the main river and its

tributaries like Kintit Gumara, Sendya Gumara and Mentray. The lower down plain reach of the sub-catchment near to the upstream of Gumar's confluence with Lake Tana is subjected to flood inundation in the wet seasons. This is because of the prevailing flat slopes further worsened by back water effect of Tana which is at a higher level during flooding. The flat low land of the study area has an average elevation of about 1800m. It includes the lacustrine and alluvial deposits consisting clay and silt soils and undifferentiated clay to gravel size materials. Some parts of the flat lands have been believed to be part of Lake Tana once upon a time. The upper reach of the river consists of hilly and mountainous undulating topography comprises of volcanic lava flows. The area generally has east to west slope descending from mountain chain of Guna in the east that rises to more than 3500m above sea level to lake Tana that has about 1786 m above mean sea level

Figure 2.2 Topography and Drainage

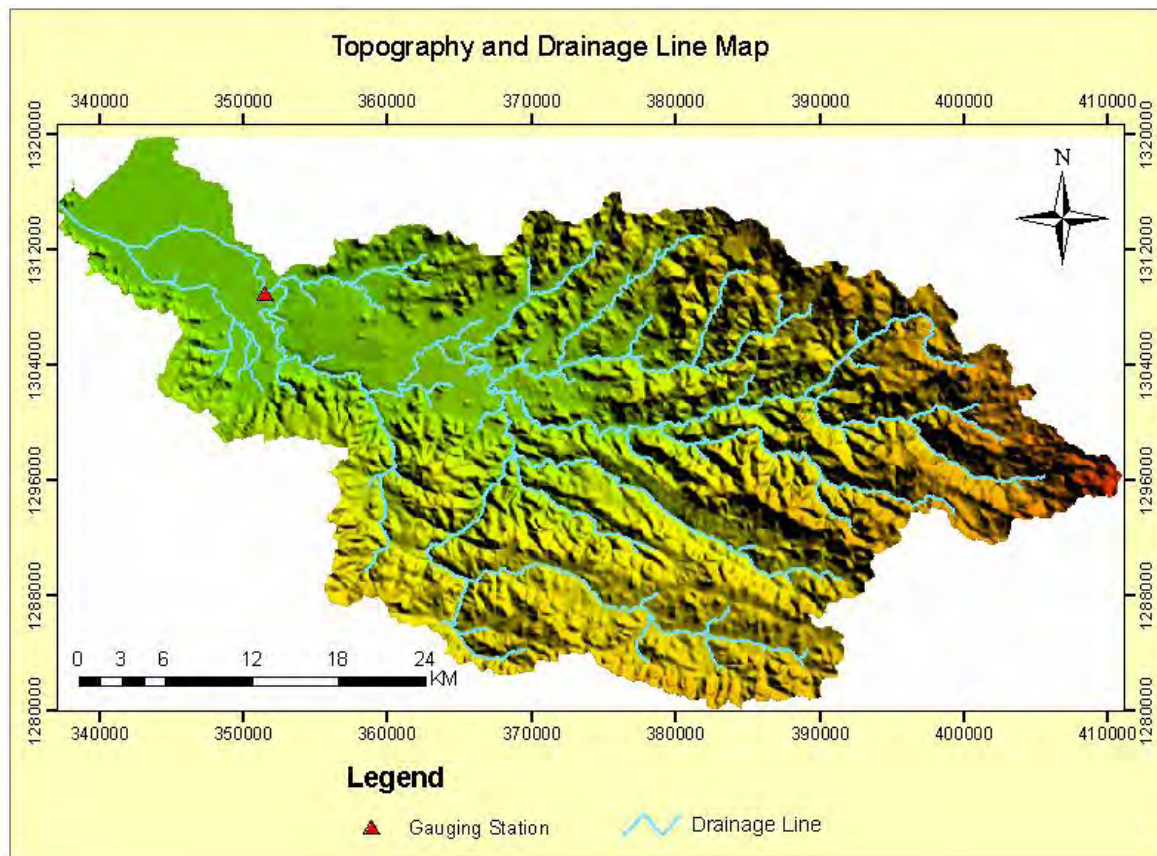
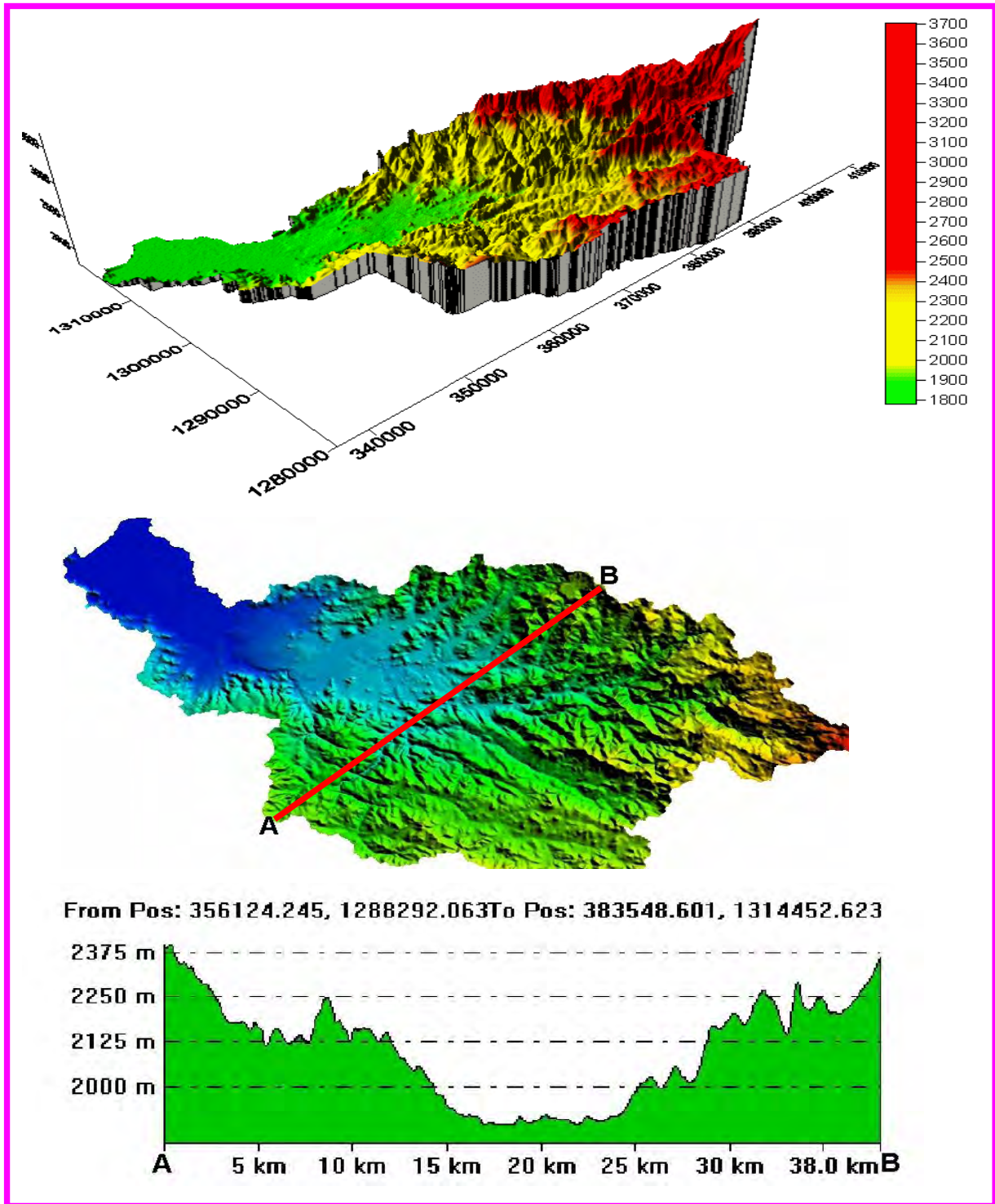


Figure 2.3 Topographic variations in 3D and Cross-sectional view



2.3 Soil

Classification of soil unit is based on the combined description of geomorphic and soil characteristics. The major soil units of the area fall into four main groups. This classification is on the basis of FAO supplemented with related literatures and field visits. According to FAO four major groups of soil are recognized in the study area and their corresponding texture and drainage condition is displayed in table 2.1 below.

Haplic and Chromic Luvisols: Luvisols are soils having an argillic horizon which have a base saturation of 50% or more at least in the lower part of B horizon within 125cm of the surface. Such soils are the most widely distributed and covering more than 80 % of the study area. They are derived from various volcanic rocks and depicted as brown to reddish brown with friable to firm, sticky and slightly plastic nature. The soils show surface horizon depletion in clay and clay accumulation in the surface and are characterized by clay to silty clay texture with moderate to well drainage condition.

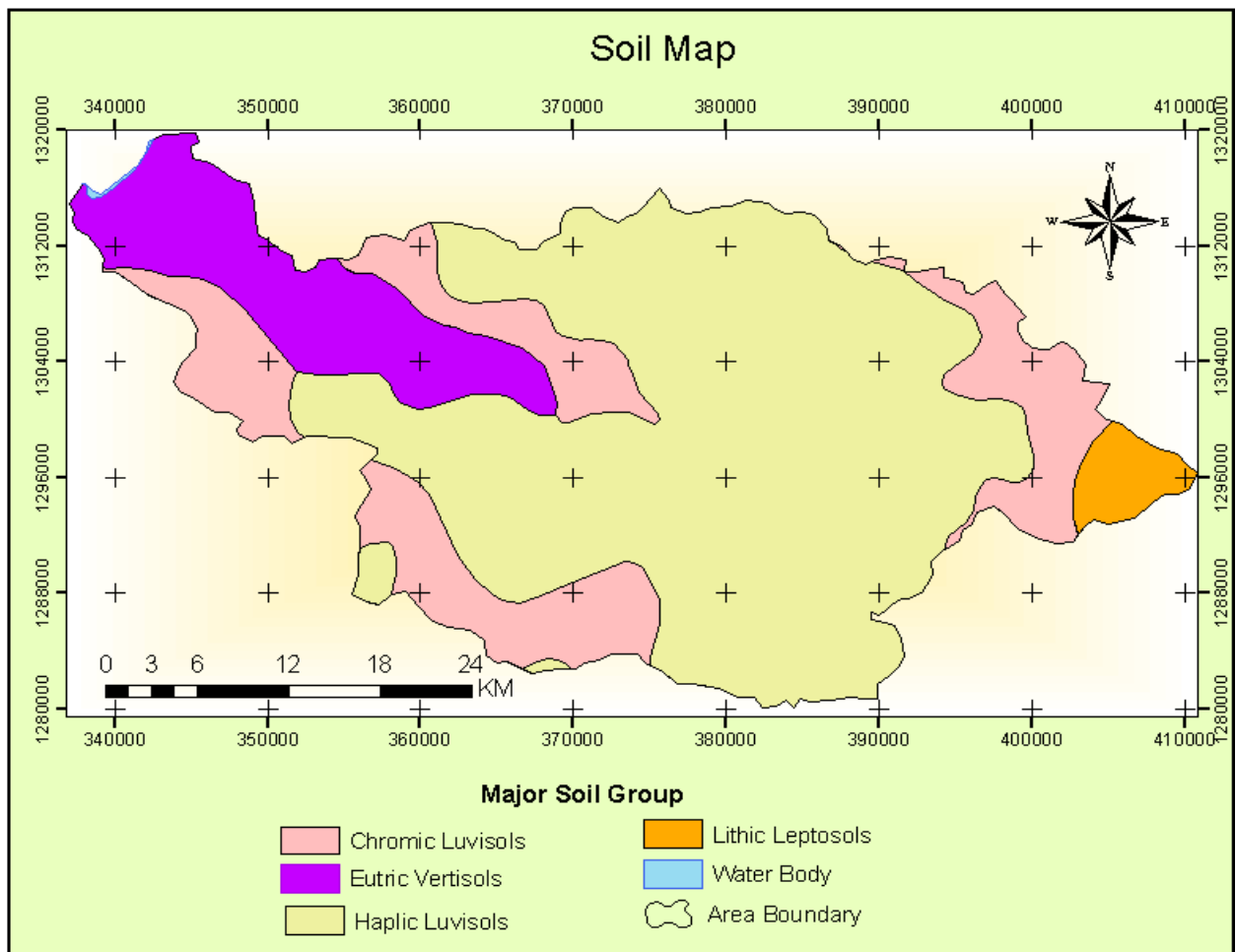
Eutric Vertisol: Eutric Vertisol soils are often referred to as problematic soils owing to the behaviour of creating difficulties during cultivation and construction despite the soil have high agricultural potential. These soils are dark, montmorillonitic clay soils, which expand and contract with changes in moisture content and consequently show wide vertical cracks when dry. They prevail in the flat lowlands especially in Fogera and Dera weredas fluvo-lacustrine deposits and comprise 13.3% of the area. These soils are generally characterized by high clay content, poor drainage and very low hydraulic conductivity.

Lithic Leptosol: Leptosols are very shallow soils limited in depth by continuous hard rocks. They are commonly occurring on highly eroded areas undulating and steep slopes and are developed on relatively young surfaces origin. Since these soils occur on steep slopes, they are exposed to a high degree of erosion which is responsible for a further decrease in depth. They are commonly characterized by low in clay, medium in silt and high in sand content.

Table 2.1: Major soil group their texture and Drainage condition

Major soil group	Soil texture	Drainage Condition
Eutric Vertisol	Clay loam	Imperfectly to poorly drained
Lithic Leptosol	Sandy loam	Well drained
Chromic Luvisol	Clay	Moderately well to well drained
Haplic luvisol	Clay to silty clay	Well drained

Figure 2.4 Soil Map of the Study area



Source: FAO

Table 2.2 Major soil Group and their areal coverage

Major Soil Group	Area (Km ²)	Weighted Area (%)
Chromic Luvisols	341.50	22.30
Eutric Vertisol	203.53	13.29
Lithic Leptosols	36.05	2.35
Haplic Luvisols	949.15	61.98
Water Bodies	1.23	0.08
	1531.46	100.00

2.4 Land use /Land cover

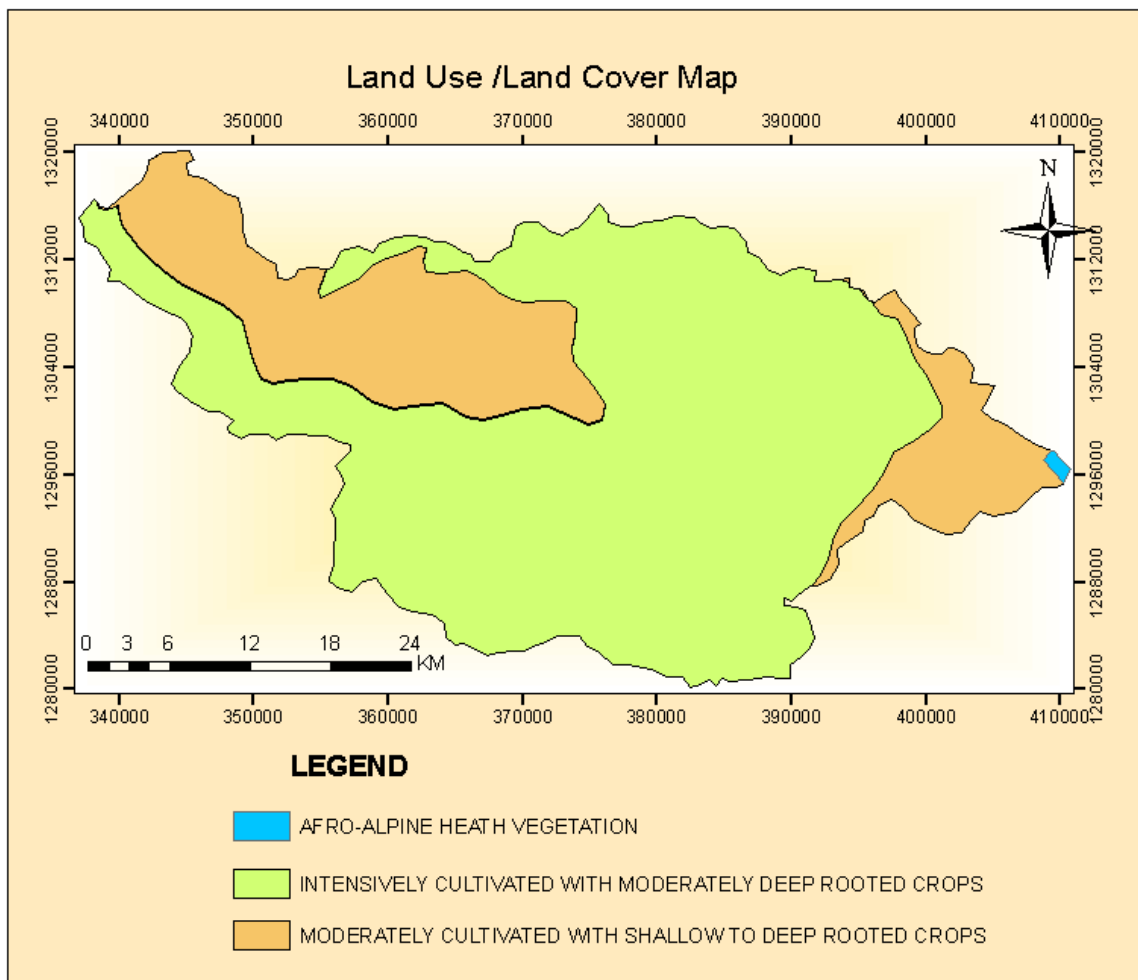
The Land cover of an area is governed by its geographic, climatic and ecological conditions. The study area has not pronounced natural forest coverage, most indigenous vegetation cover are observed around churches and deliberately projected areas as in Gelawdiwos. The eastern extreme high land area near mount Guna has very small coverage as it has been seen in the map. However, the land coverage at the moment is dramatically changing due to fast population growth and the demand for utilization of the land for agricultural practices. Due to this fact more than 95% of the area is employed for agricultural activities. Currently even scatter shrubs and grass lands are being cleared and the land is utilized for food security purpose. Base on the type of covering material of the area with their present services, major land use/land cover units of the study are described. The description is based on previous reports and slight modification of the changes as a result of natural observation during the field visit.

1. Intensively cultivated with moderately deep rooted crops of cereal type like maize, sorghum, millet, teff, barley, wheat etc
2. Moderately cultivated with shallow to deep rooted crops like onion, beans peas as well as some prevailing grass and shrubs
3. Afro-alpine heath vegetation

Table 2.3: Land use Land cover Areal Proportion

Land use /Land Cover	Area (Km ²)	Weighted Area (%)
Intensive cultivated with moderately deep rooted crops	1120.804	73.18
Moderately cultivated with shallow to deep rooted crop	408.341	26.55
Afro-alpine Heath Vegetation	2.324	0.15
Total	1531.469	100

Figure 2.5 Land use Land/Land cover



CHAPTER THREE

GEOLOGY

3.1 Regional Geological Setting and Structures

The Ethiopian plateau is not a simple, undeformed structural block. In the North West, it contains the Tana basin, a faulted depression located between the Erosional escarpment overlooking the Sudan plains to the west and, to the east, the tectonic escarpment of the plateau margin overlooking the Afar depression (Chorowicz et al, 1998).

As Chorowicz et al, 1998 study, the Tana basin lies at the convergence of three grabens: the Debre Tabor graben from the east, the Gondar graben from the north-northwest, and the Dengel Ber graben from the south-southwest. The grabens are impressed in the mid-Tertiary flood basalt pile; lack of exposure of the sub-volcanic terrain hides evidence for any earlier structural history. Zanettin et al. (1980) propose that Eocene pre-Afar graben faulting extended northwest across what is now the N Ethiopian plateau to the Sudan border. This 'Ashanghi graben' is considered to have formed a westward projection of an Eocene Gulf of Aden rift.

The northern sector of the Tana basin is an asymmetric graben (the Gondar graben), the western boundary fault zone being framed by clearly defined NNW–SSE- to N–S-trending faults. Farther north, the Gondar graben is cut by the West Tana escarpment. In its southern sector the Gondar graben floor preserves olivine basalt flows and overlying lignitiferous lacustrine sediments. Together these form a thin cover upon faulted mid-Tertiary basalts (Tezera and Heeman, 1983). The younger basalts have yielded an 8–10 Ma radiometric apparent-age range (Yemane et al., 1985). They mantle older faults that now lack morphologic expression, whereas the youngest faults cut across these mid-Tertiary flows and retain identifiable scarps. The southern sector of the Tana basin comprises the Dengel Ber graben. Its western border is framed by NE–SW- to NNE–SSW-striking faults. The graben is largely masked by the profuse volcanism that has built up the Danghila plateau. Grabham and Black (1925) report outcrop of probable Mesozoic sandstone on the eastern flanks of Mt. Belaya, consistent with this discovery. The indication is therefore one of shoulder uplift along the western side of the Dengel Ber graben, in concert with observed block faulting. This shoulder uplifts favoured location of the West Tana erosional escarpment along the western border of the graben, resulting in inversion of the graben topography. The southward continuation of the Dengel Ber graben remains to be elucidated.

Over the eastern side of the Tana basin, alluvial cover partly masks the Debre Tabor graben. North of Debre Tabor, E–W-striking faults with a morphologic expression indicating southerly downthrows, can be traced farther east; here they turn to ESE–WNW before termination against the Guna shield volcano. The faulting then reappears on the south eastern flanks of the shield. On the opposing, other side of the Debre Tabor graben, a complementary set of E–W faults veers to the east-southeast farther east, and is downthrown to the north.

According to the description made to Mohr, P.A report ‘The geology of Ethiopia, 1961’ immediately following and contemporaneous with the major uplift of the continental mass, immense quantity of lava were extruded from fissures and volcanic centres. Although considerable denudation of Mesozoic rock had also taken place before the eruption of the volcanic rocks, the area was not deeply eroded.

The plateau volcanics or the Trap series essentially predates the rift faulting and therefore forms the high Ethiopian and Somali plateaus. The Aden (Younger) volcanic series post dates the rift faulting and largely confined to the floor of the rift valley, the Lake Tana basin and to younger, manifestly fresh lava volcanic cones, and explosion crater which in some places are still active.

The Lake Tana sub basin is formed by structural deformation, erosion and extrusions of volcanic rocks. It is surrounded by volcanic mountains, consisting primarily of basaltic lava flows associated with tuff, trachytic and rhyolite rock types. Some of the tectonic features associated with the formation of lake Tana basin are northeast south west faults and dykes of the lake; down warped, faulted, and steeply dipping volcanic rocks along the south western side of the lake and rift-fault structures NW of the Lake Tana which cut through the structural basins in which are deposit of lake beds (WAPCOS report, 1990).

3.1.1 Mesozoic Sedimentary Rocks

The Abay River Basin regionally shows a thick succession of Mesozoic sedimentary rocks. These generally horizontal beds of sedimentary rocks are exposed in the numerous valleys within the Abay Basin. The succession is made up of the Adigrat Sandstones, Gohatsion Formation, Lagajima Limestones, Mughher Mudstones and Debre Libanos Sandstones (Getaneh, 1981, 1991; Russo *et al*, 1994).

Although they are not exposed in the area of the Lake Tana basin, at least a part of the Mesozoic sequence is expected to be encountered at great depth below the volcanic strata.

The northern extent of the individual Mesozoic formations is not clearly defined or observed, implying that maybe not all the units have reached the area of Tana basin. Graham and Black (1925) report outcrops of probable Mesozoic sandstone on the eastern flanks of Mt. Belaya. This sequence, in turn rests on the basement complex that includes Precambrian granites, gneisses, schists, marble and phyllites

3.1.2 The Volcanic Rocks

The rocks in the vicinity of Lake Tana are mainly extrusive volcanic rocks representing three or more phases of volcanic activity. To a limited extent fluvo-lacustrine sediments are also represented. The three major divisions or phases of volcanism that are recognized are:

The ‘Plateau Volcanic’ Rocks: The ‘Plateau volcanic’ consisting of extensively, horizontally bedded, massive generally basaltic lava flows that cover the plateau. They are the lower and the oldest of the Tertiary age volcanic rocks that comprise the bulk of the flat-lying beds. The series is a unit of very thick lava flows, mostly of basaltic composition; with more silicic differentiates near the top. A division is made between the lower, thick, massive Ashangi group of plateau basalt which are extraordinary uniform in composition, and the upper, more silicic lavas of Magdela group. Disconformity between the two groups has not been definitely proven. A slight unconformity is indicated between the Trap Series and underlying Mesozoic sedimentary rocks as well as irregular contacts due to erosion of Mesozoic sediments. The age of the Ethiopia Trap Series, based on paleontology, is between the end of cretaceous and Pliocene.

The greater portion of the Ethiopian plateau is covered by the extensive volcanic rocks. In general these rocks crop out or underlie the surface in all parts of the country where altitude exceed 2400 meters. “Plateau Basalt” usually described them chronologically as “Old Volcanic formation”.

The ‘Volcanic Mounts’ Rocks: Late phase volcanic mounts and intrusive dikes, plugs etc. are more acidic varieties of tracyitic or rhyolite, phyroclastics of tuff and breccias etc. These rocks generally associated with high mountains or intrusion penetrating the lower ‘Plateau’ volcanic rocks. Some of these intrusive rocks are in, or they are resting on, Precambrian rocks. They are perhaps remnants of extrusive erosion and are believed to be related to the some later phase of volcanic activity that formed the high mountains and intrusion.

The 'Volcanic Mounts' generally have steeper dips rising to the vent areas (The higher mountains rising above represent the dying, explosive and more acidic viscous phases of volcanism. Associated with this phase numerous dikes and plugs generally of trachytic composition.) .These rocks occur on the east, north and west side of Lake Tana. West of the lake, the generally flat beds have been tilted so, as to dip about 30° south easterly the basin.

Quaternary Volcanic Rocks: 'Younger' very late phase recent eruption of volcanic rocks has occurred in numerous places in the Blue Nile river basin. In the Lake Tana sub-basin basaltic lava from numerous small, widely spaced craters and cinder cones covers an area of several hundred kilometres, particularly on the south and southwest side of Lake Tana and extend downstream along the Blue Nile valley. Other recent flows are located on the east and north sides of the Lake. This younger (Aden) volcanic series is clearly more recent than the Tertiary Trappean series. It is characterized by its extensive distribution

This volcanic series is rather diversely constituted, mostly of basaltic and andesitic rocks, more or less alkaline, sometimes plagioclase-olivinitic, often doleritic, with titaniferous augite etc. The occurrence is commonly marked by acid lavas of tracyitic or rhyolite type. The 'Younger Volcanics' lava flows, which have been occurred after a long period of erosion, such as the lava at the southern end of Lake Tana is the youngest phase of volcanic activity in the Lake Tana sub basin. The Present Lake was formed primarily by this younger volcanism which dammed off the previously eroded valley and drainage system, impounding a broad, relatively shallow body of water.

Pliocene and Pleistocene Sediments: The Chilga continental rift basin, located in northwest Ethiopia, consisting of sediments composed of claystones, siltstones and silty sandstones, volcanic ashes, lignite beds, and vertebrate and plant fossil-rich sandstones provides ample information for such a sequence stratigraphic interpretation.

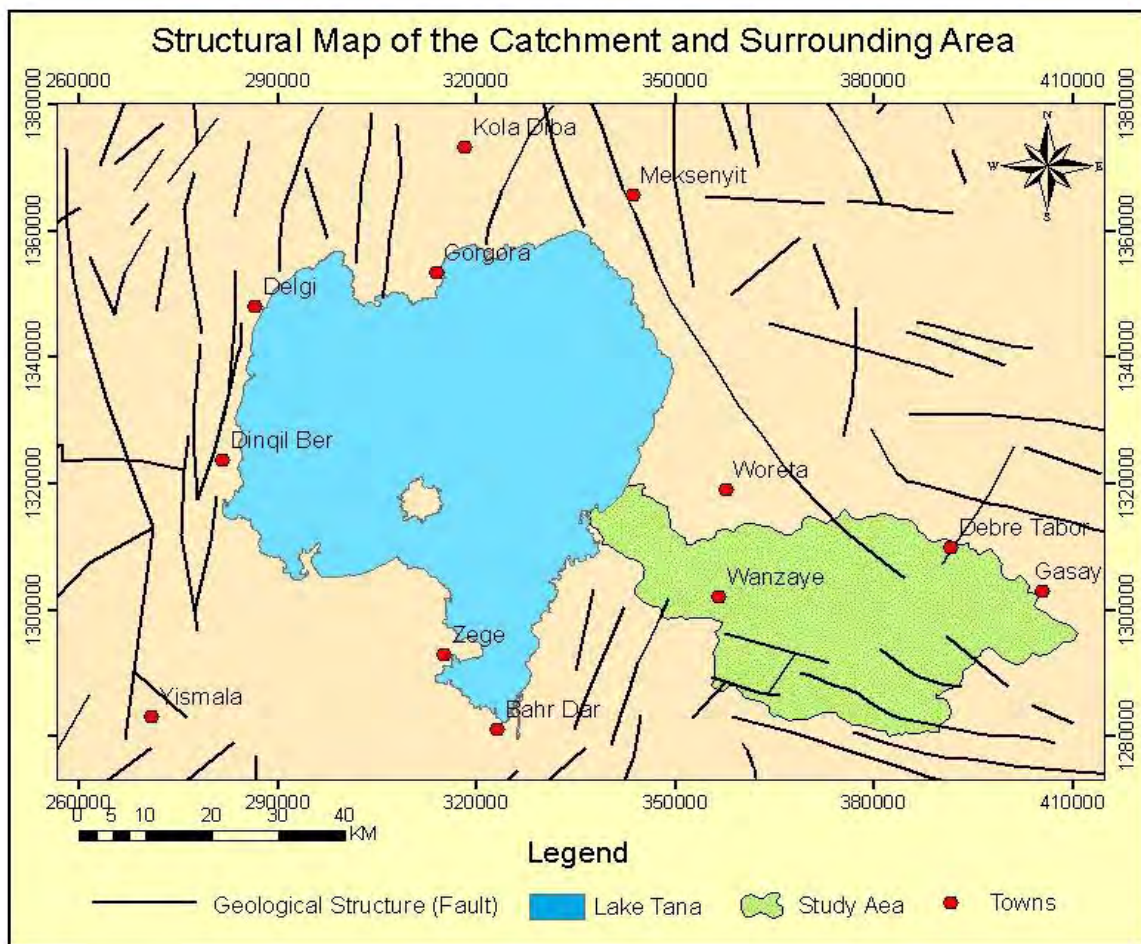
Radio isotopic and paleomagnetic dating techniques were used to constrain the age of the basin filling sediments and the underlying basaltic rocks. Results indicate that the Chilga sediments were deposited between 27–28 Ma (Mulugeta Feseha et al., 2001; Mulugeta Feseha, 2002).The Results also indicate that the Chilga sediments are composed of framework grains of mainly unaltered plagioclase, potassium feldspars, and volcanic rock fragments; the matrix is commonly enriched in kaolinite and illite-montmorillonite; and the cement is mainly composed of authigenic siderite and some iron oxide coatings. Interpretations of these characteristics suggest that the Chilga sediments were deposited in

alluvial-lacustrine environment with a nearby fine-grained sediment source indicating a reducing diagenetic environment (Mulugeta Feseha, 2002).

The Chilga Lake Beds, several hundred feet thick, consist mostly of clays, water lain ash beds, siliceous shale, sandstone and lignite beds. They have been cut off sharply by rift type faults.

Fig. 3.1 The regional Structural Map of the Study area

Source: Geological Survey of Ethiopia



3.2 Geological Setting of The study Area

The geology of Gumara river catchment is dominated by huge volcano system named Guna ‘Terara’ shield volcano. It corresponds to the eruptive events that occurred during the early Miocene to Pliocene period and classified in the shield group basalt (BCEOM, 1999 and Kieffer et al., 2004). The common litho type for this material is basalt with large amount of interbedded scoriaceous lava, volcanic ash and other acidic rock such as rhyolite and trachyte.

At the western end of the catchment bordering Lake Tana, the area is completely covered by lacustrine and alluvial deposits. These deposits consist of small portion relative to volcanic rocks. Recent volcanic flow belonging the Quaternary eruption events have been noted north east of the above mentioned deposits. But the largest portion of the study area is covered with Tarmaber formation

3.2.1 Tarmaber Basalt

The age of Tarmaber formation becomes younger towards southern plateau (with ages ranging 16-13 millions years). About 80% of the study area is covered with this unit. It is typically alkaline in nature and composed of various basalts erupted from shield volcanoes on the plateaus. Usually individual basaltic flows in this formation are easily recognizable and paleosol and scoraceous horizons are seen in many places at the base of individual flows. Pyroclastic deposits are highly associated with this existing massive basalts indicating cyclic eruption of magma. Such pyroclastic deposits are commonly exposed in Debretabor areas especially in the south and south west of the town.

Figure 3.2 Tarmaber formations (lava flow and phyroclastics intercalation)



3.2.2 Quaternary Volcanics

Quaternary volcanic rocks in the study area are exposed in Bebeks, part of Meneguzer, Wanzaye and surrounding areas. They are characterized by the existence of pronounced vesicles. Such kind of volcanic rocks are prominent in Bahir Dar town, south ward extension

and surrounding areas. They are highly scoriaceous erupted from numerous small cones. Detail explanation of the rocks has already been mentioned above in the regional geological setting.

Vesicles

Figure 3.3 Quaternary Volcanic rocks (vesicular in nature)



3.2.3 Lacustrine Deposits

This part of the area is found at the lowest part of the catchment adjoining Lake Tana. It is believed that Lake Tana has covered large areas around the area of the present lake position. Regression of the lake has left lacustrine deposits exposed in the surrounding areas. The variation in thickness of such deposit is controlled by distances from the present lake position as the thickness decreases away from the lake. This unit is mainly composed of silt, silty sand and clay.

3.2.4 Quaternary sediments /Alluvial Deposit

Quaternary sediments are commonly exposed along the river course. The spatial and temporal variation of such deposit is dependent on the amount and velocity of the river flow. Despite this deposit is found along the river course, pronounced deposit is exposed in the lower course of the river where flow energy is minimal. The alluvial deposit varies in size from clay to boulder. The lower part of the deposit near to the lake is dominated by silt to clay size particles. A bit in the upper part of such deposit sand to bolder size deposits are prominent. All these deposits are derived from weathered parent rock materials in the hillside catchment as a result of erosion and transportation.

Figure 3.4 Gumara rivers upstream of the gauging station and parts of the alluvial deposit (Photo taken on 16/03/2009)



3.3 Geologic structures

Three structural features observed in the catchment area are linear features (lineaments), faults and fractures. The detection of linear features was performed by preliminary interpretation of satellite images on the basis of tonal variation, via close observation of three dimensional digital elevation maps of the study area and from topographic map of the area supported by physical observation of different features during the field investigation. These features are traced from river channels devoid of water body, continuously elevated or depressed land escapes, alignment of ridges and alignment of naturally grown vegetation in certain direction possibly showing structurally weak zones. Almost all clearly observed lineaments in the study area are concentrated only in Tarmaber basalt. The quaternary volcanics also shows some linear features as observed in the field but are not significant and mapable. The structures maybe obscured and detail investigation is required.

The prominent orientations of lineaments in the study area are WNW-ESE and NNE-SSW. Minor orientations also prevail in the E-W and N-S direction. The overall all drainage pattern of the study area is controlled by WNW-ESE and NNE-SSW trending lineaments and faults. The faults in the area are traced by reading various supportive literatures in relation to the

regional structural set up supplemented with DEM, satellite image, top map and field observation. The area is also controlled by various fractures in different orientation controlled by lithology, surface and subsurface conditions.

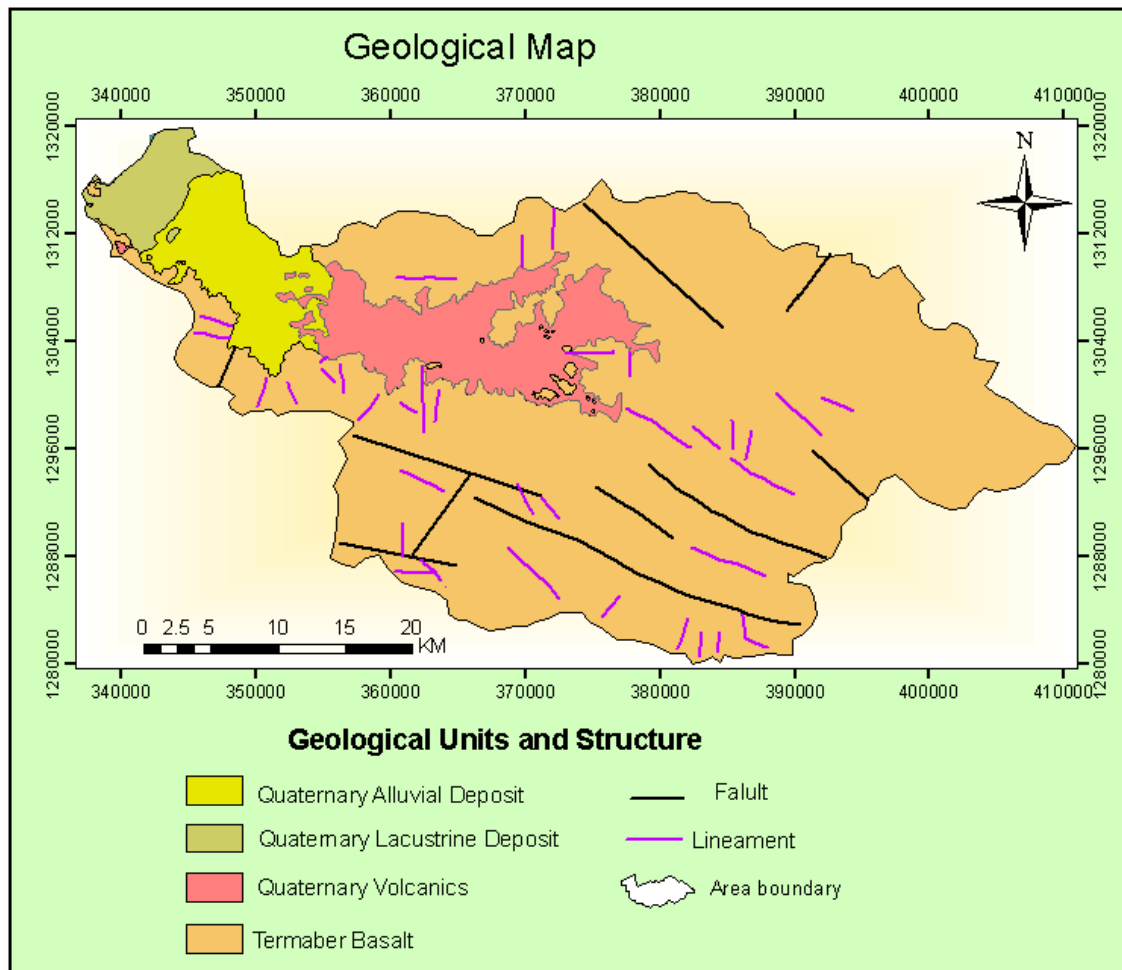


Figure 3.5 Geological Map of the Study Area

Source: Water Works Design and Supervision Enterprise with slight modification

CHAPTER FOUR

HYDROMETEOROLOGICAL DATA ANALYSIS AND RECHARGE ESTIMATION

4.1 General

Hydrometeorology is given by world meteorological organization in stating that it is concerned with the study of atmospheric and land phases of the hydrologic cycle with the emphasis on inter-relationship involved. Hydrometeorological data play an important role to solve different problems, such as forecasting of precipitation for reservoir operation and in the spill way design, for the design of dams and other structures, determination of temperature for evaluating water resource potential etc (Jayarami, 1992). Hydrometeorology is the study of the two fundamental phases in the processes of hydrological cycle (precipitation and evaporation) within the atmosphere and at the earth's surface or atmosphere interface (Shaw, 1988).

4.2 Hydrometeorological data

Long term measurements of Meteorological parameters such as precipitation, temperature, wind speed, relative humidity, sunshine hours, evaporation, atmospheric pressure and radiation are essential to understand the atmospheric phenomena. Though it is generally difficult to make short term weather prediction, observation over a period of time would render long term prediction on statistics basis. To analyze various hydrologic cycle components, long term meteorological data have been taken from National Meteorological Service Agency (NMSA) and Amahara Region meteorological service Bureau. The river discharge data on the other hand is taken from Ministry of Water Resources. The Gumara River gauging station is located above the bridge of Hamusit to Woreta road and is the only station that controls the whole catchment run off.

The meteorological station within the study area and the vicinity is displayed in the following table and all the stations are active at the moment. Meteorological data are taken from the station based on their availability within the recording year. The stations are not evenly distributed and some time lack continuous meteorological records. However, long term records of values of meteorological parameters are enough for the purpose of this study.

Table 4.1: Location of Meteorological Stations and data recording years

Meteorological Stations and Data recording Years					
		Location UTM			
No	Station	Northing	Easting	Altitude	Record Year
1	Dera Hamusit	1303396	343321	1930	1987-2005
2	Arb Gebya	1286488	363734	2228	1993-2006
3	Wanzaye	1303114	355634	1821	1984-2007
4	Woreta	1318144	357993	1819	1961-2007
5	Debre Tabor *	1311926	390536	2612	1954-2007
6	Mekaneyesus	1283263	396867	2374	1994-2007
7	Alem Ber	1317169	378683	2051	1977-2006
8	Bahir Dar *	1282722	321186	1800	1961-2006

*Meteorological stations recording all meteorological variables (first order stations)

Debre Tabor and Bahir Dar record all meteorological parameters: Rainfall, Temperature Relative humidity, wind speed and sunshine hour. All the other stations record rainfall and temperature except Arb Gebya and Dera Hamusit which record only rainfall. Debre tabor, Wanzaye and Arb Gebya are located within the catchment; all other stations are situated around it. This makes the catchment to have an uneven station distribution.

4.3 Precipitation

Rainfall is the most important part of the atmospheric precipitation in the hydrologic cycle that falls on the earth surface in the form of water droplets and its amount is one of the most fundamental factors to determine the density and distribution of vegetation. The rainfall in Ethiopia varies from less than 200mm in arid zones to 2000mm in the southwest part of the country. This is due to altitude variations over the country from about 120m below sea level in Dallol depression up to 4620m above mean sea level in Ras Dashen in the Semien Mountain Massif (Tamiru, 2006).

The spatial and temporal variation of rainfall in Ethiopia is controlled by the movement of position of inter tropical convergence zone (ITCZ) (Tenalem and Tamiru, 2001). The principal rainy season from June to September is controlled by ITCZ which is located north of Ethiopia. During this time South west winds bring rain from the Atlantic Ocean and the

study area intercepts pronounced rainfall in these months. The dry period from October to February occur when the ITCZ lies south of the country. In these months the north easterly trade winds traversing Arabia dominates the area and produces little or no rainfall. During March, the ITCZ is located south of the country moving northwards. At that time low pressure is developed in Sudan and Arabia while high pressure is developed in Gulf of Aden and Indian Ocean. The high pressure generates south east winds which bring the small rain from the Indian Ocean.

4.4 Determination of Areal Depth of Precipitation

Since most hydrological problems require knowledge of average depth of rainfall over a significant area such as river basin, some procedures must be used to connect rainfall measured at individual rain gauges to the areal averages (Subramanian, 1994). Of all the components of the hydrologic cycle, precipitation is the most commonly measured. It would appear to be a straight forward procedure to catch as it falls. The rainfall obtained from a single rain gauge station is the point rainfall or station rainfall. Precipitation for a given duration over a particular area rarely produces uniform depth over entire area. It is never possible to determine the exact average depth of rain fall because rain gauges give a very small sample. There are three methods of treating the average records to arrive at an approximate result and the three methods give three different approximations.

4.4.1 Arithmetic Mean Method

Arithmetic mean method is the simplest of the three methods and the result is obtained by dividing the sum of the rainfall amounts recorded at all the rain gauge stations which are located within the area under consideration by the number of station.

$$P = \frac{P_1 + P_2 + \dots + P_n}{n}$$

Where P_A is the average depth of precipitation of the area and $P_1, P_2,$ and P_n are the rainfall records at the stations 1,2, etc. This method relatively requires flat topographic terrain. If the distribution of such records over the area is uniform and the variation in the individual gauge's amount is not large, then this method gives reasonably good result (Wilson, 1990). The conditions mentioned above are not fully implemented in the study area for the very reason that there are only three stations within the catchment with uneven distribution and different topographic variation. In spite of all these, the variation between precipitation amounts in each gauging station is not this much significant. The arithmetic average precipitation of the three stations within the catchment gives 1395 mm.

Table 4.2: Long term mean monthly precipitation of the stations in and around the catchment

Long term mean monthly precipitation (mm)													
Station	Jan	Feb	Mar	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Debre Tabor	6.8	4.4	27.0	37.6	89.9	184.4	422.1	420.7	190.9	85.6	32.9	12.1	1514.3
Alem Ber	1.0	3.7	13.1	29.2	83.2	184.9	391.4	370.4	159.0	93.8	17.2	3.8	1350.7
Wereta	0.2	1.0	5.3	19.3	67.4	183.1	397.0	394.2	188.1	64.8	11.0	3.1	1334.4
Wanzaye	1.0	0.7	8.6	27.1	78.9	192.1	417.7	389.8	230.5	77.8	10.2	2.4	1436.7
Dera Hamusit	0.0	1.5	11.0	17.7	77.7	213.1	452.6	415.3	214.6	91.5	12.5	2.8	1510.4
Arb Gebya	1.7	7.8	14.4	36.0	29.3	204.7	365.9	341.9	151.2	65.9	12.4	3.6	1234.7
Mekane Yesus	5.0	4.8	38.9	54.1	65.8	190.0	365.7	300.8	172.6	68.0	32.9	12.0	1310.4

4.4.2 Thiessen Polygon Method

The method of Thiessen polygons consists of attributing to each station an influence zone in which it is considered that the rainfall is equivalent to that of the station. The influence zones are represented by convex polygons. These polygons are obtained using the perpendicular bisector of the segments which link each station to the closest neighboring stations (Figure 4.1 below). This method is more accurate than that of the simple arithmetic mean method.

The method is given by : $P = \frac{P_1A_1+P_2A_2+\dots+P_nA_n}{\sum A_i}$ where P_1, P_2, \dots, P_n are mean annual rainfall recorded at each rainfall stations and A_1, A_2, \dots etc. are polygonal areas around each gauging stations enclosed in the catchment (Figure 4.1). The result obtained from using this method is displayed in table 4.3 below. Accordingly the averaged annual precipitation of the study area using this method is 1377 mm. Bahir Dar can also be used as additional station as the average monthly mean precipitation is similar to the result of the three methods. However, the Thiessen polygon method doesn't sense the station as Dera Hamusit which is much closer to the area mask and takes most of the influential area. Due to this reason data from Bahir Dar meteorological station have not been used for estimation of areal depth of precipitation. However, for other purpose and use of other meteorological parameters, the station data have been used

Figure 4.1 Thiessen Polygon Map of the Area

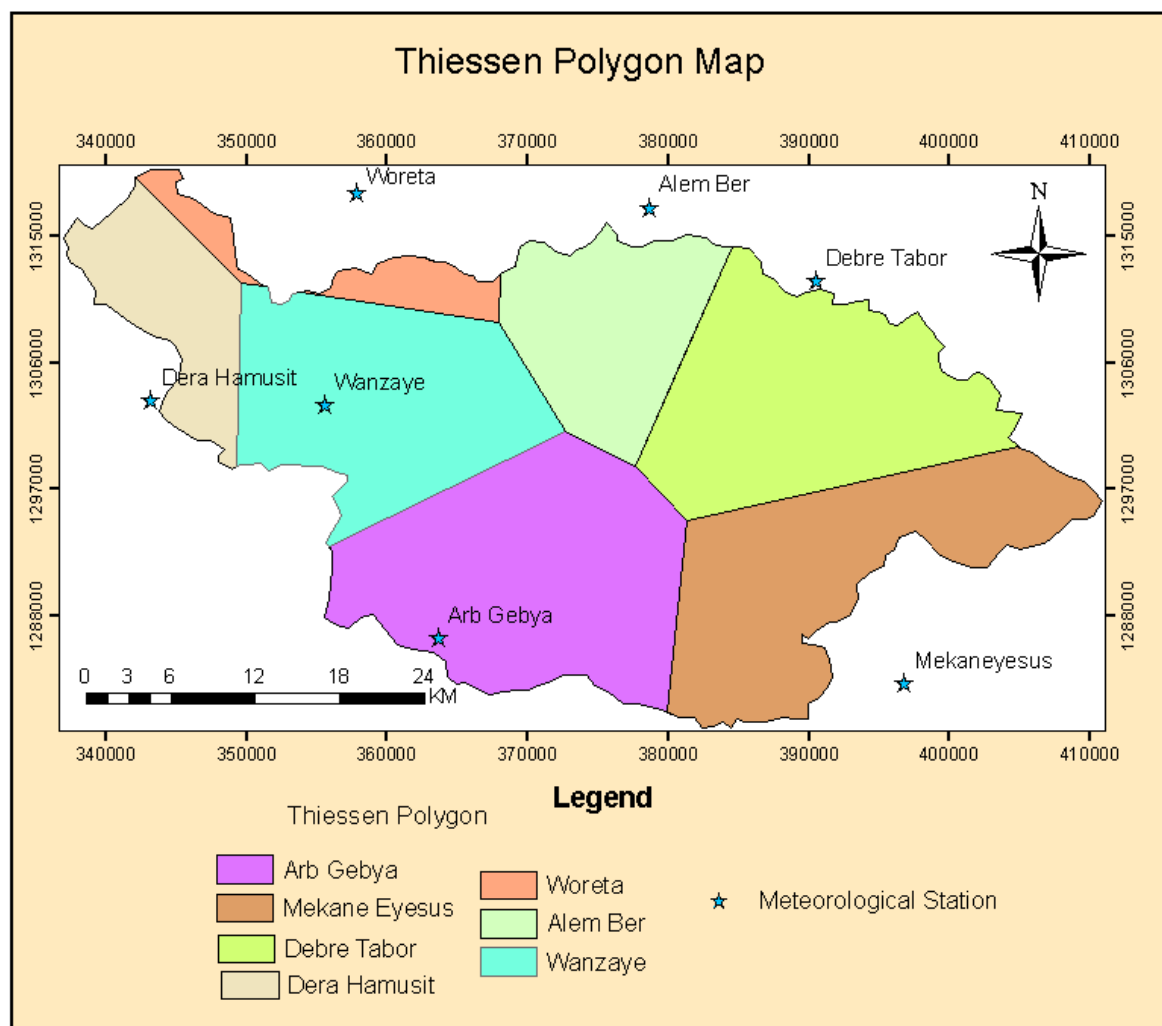


Table 4.3 Thiessen Polygon Method of Calculating Annual Rainfall

Station	Thiessen Polygon Method of Rainfall Calculation			
	Area (KM ²)	Weighted Area (%)	Rainfall (mm)	Weighted RF(mm)
Dera Hamusit	121.11	8	1510	119.41
Arbe Gebeya	336.34	22	1235	271.23
Wanzaye	266.81	17	1437	250.35
Woreta	55.54	4	1334	48.38
Debre Tabor	300.31	20	1514	296.88
Mekane Eyesus	279.99	18	1311	239.69
Alem Ber	171.37	11	1351	151.17
Total	1531.47	100		1377.11

4.4.3 Isohyetal Method

The areas between successive isohyets are measured and assigned an average value of rainfall. The overall average for the area is thus derived from weighted averages. This method is possibly the best of the three and has the advantage that the isohyets may be drawn to take account of local effects like prevailing wind and uneven topography (Wilson, 1990). According to (Shaw, 1988), this method allows the influence of physiographic parameters to be taken into account. These parameters include elevation, slope and distance from the coast and exposure and rain bearing winds.

The method is employed by preparing station locations and their respective rainfall amounts in a suitable chart and plotting the isohyets. The area enclosed between successive isohyets and the average rainfall amounts are considered for the final execution of weighted rainfall. According to this method the annual precipitation in the catchment is 1372 mm (Table 4.4).

Figure 4.2 Rainfal Isohyetal map

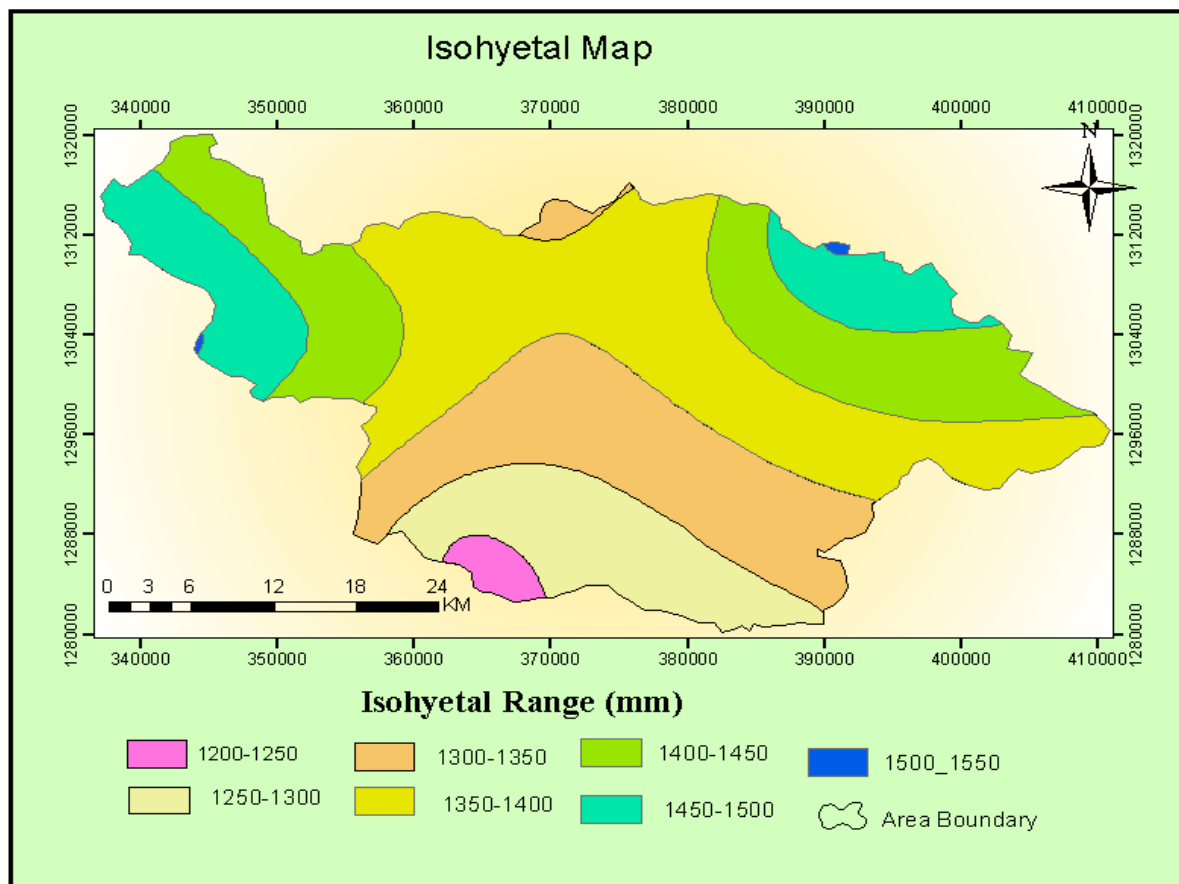


Table 4.4. Isohyetal Method of Calculating Annual Rainfall

Isohyetal Method					
Id	Isohyetal Range (mm)	Average Isohyets	Enclosed Area(KM ²)	Weighted Area (%)	Weighed Rainfall
1	1200-1250	1225	23.32	1.52	18.64
2	1250-1300	1275	191.51	12.50	159.35
3	1300-1350	1325	325.07	21.21	281.09
4	1350-1400	1375	490.88	32.04	440.49
5	1400-1450	1425	314.68	20.54	292.65
6	1450-1500	1475	184.87	12.06	177.96
7	1500-1550	1525	1.96	0.13	1.95
	Total		1532.29	100	1372.14

As it has been observed from all the three methods, the results obtained are very much closer to each other. The mean and the median of the three methods have not any significant difference. The average value of the three methods is nearly similar to the Thiessen polygon method; no considerable difference will result if one can use the average value of the three methods or the Thiessen polygon method for further analysis. As a result the value from Thiessen polygon method is selected for further use of the rainfall data in this research.

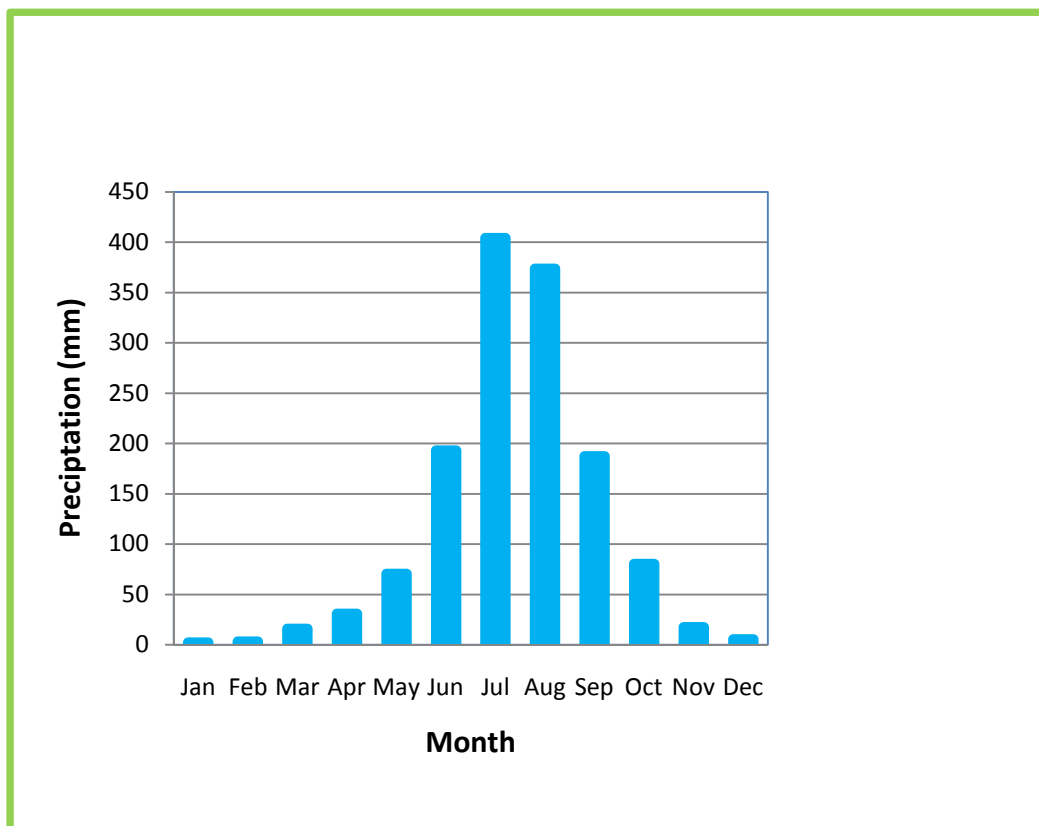
4.5 Rainfall Characteristics

The precipitation process is essentially random in nature. We cannot predict with certainty what would be the rainfall for any given period of time. The rainfall magnitude can be estimated only with some probability attached to it. Therefore the analysis of the rainfall data obtained over a long period in the past would help to make reasonable probabilistic estimates of rainfall to be used in various development activities.

Table 4.5 Long terms mean monthly rainfall (mm) of all stations

Station	Long Term Mean Monthly Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Debretabor	6.8	4.4	27.0	37.6	89.9	184.4	422.1	420.7	190.9	85.6	32.9	12.1	1514.3
Alem Ber	1.0	3.7	13.1	29.2	83.2	184.9	391.4	370.4	159.0	93.8	17.2	3.8	1350.7
Wereta	0.2	1.0	5.3	19.3	67.4	183.1	397.0	394.2	188.1	64.8	11.0	3.1	1334.4
Wanzaye	1.0	0.7	8.6	27.1	78.9	192.1	417.7	389.8	230.5	77.8	10.2	2.4	1436.7
Bahir Dar	1.8	2.5	9.6	25.1	70.3	192.5	419.4	354.2	191.9	94.2	11.3	2.5	1375.2
Dera Hamusit	0.0	1.5	11.0	17.7	77.7	213.1	452.6	415.3	214.6	91.5	12.5	2.8	1510.4
Arb Gebya	1.7	7.8	14.4	36.0	29.3	204.7	365.9	341.9	151.2	65.9	12.4	3.6	1234.7
Mekaneyesus	5.0	4.8	38.9	54.1	65.8	190.0	365.7	300.8	172.6	68.0	32.9	12.0	1310.4

Figure 4.3 Long-term monthly precipitation distribution of Gumara River Catchment



The rainfall distribution in the study area ranges from 1235mm to 1514mm. The highest rainfall is recorded in Debretabor highland area and the lowest rainfall is from Arb Gebya. As it is depicted in the precipitation bar graph, the maximum rainfall is recorded in the month of July and the minimum in the month of January. The majority of rainfall in the catchment is concentrated during Ethiopian wet season (‘Kiremt’) and the rain fall is of unimodal in nature. 84% of the total annual rainfall is covered in July to September.

The rainfall trend from 1992-2006 where data are relatively available is depicted in figure 4.4 below. It is generally a decreasing trend though the change is relatively slight.

Table 4.6 Mean average annual rain fall (1992-2006)

Mean Average Annual Rainfall (mm)															
Year	1992	1994	1995	1996	1997	1998	1999	2000	2001	2001	2002	2003	2004	2005	2006
RF	157	127	131	104	134	115	125	133	131	106	106	120	102	117	134

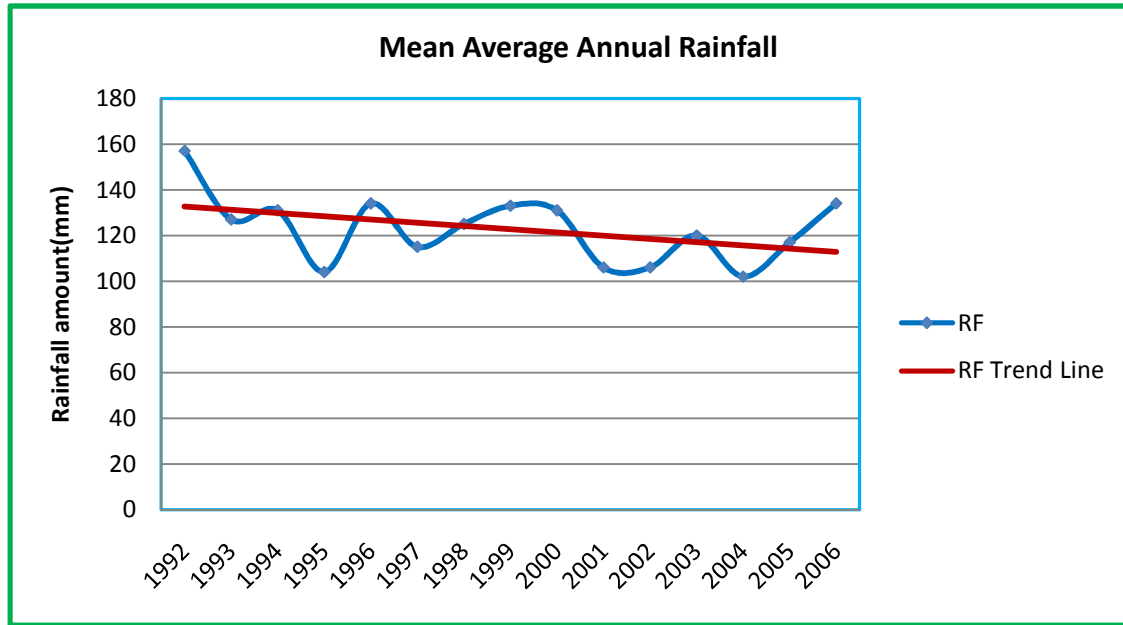


Figure 4.4 Annual Rainfall trend from 1992-2006

4.6 Evapotranspiration

In studying the hydrologic balance for a catchment area, one is usually concerned with the total evaporation or Evapotranspiration. Evaporation is important in all water resource studies. It affects the yield of a given river basin, the necessary capacity of reservoirs, the consumptive use of water by crops and the yield of underground supplies (Wilson, 1990). In field condition, it is practically impossible to differentiate between evaporation and transpiration if the ground is covered with vegetation. The two processes are commonly linked together and referred to as evapotranspiration.

Water evaporates from land, either bare soil or soil covered with vegetation, and also from trees, impervious surfaces like roof and roads, open water body and flowing streams. The rate of evaporation varies with the colour and reflective properties of the surfaces (the albedo) and is different for surfaces directly exposed to or shaded from solar radiation. The amount of moisture that a land area loses by evapotranspiration depends primarily on the incidence of precipitation and climatic factors of radiation, temperature, relative humidity, wind speed, sunshine hours and secondly on the type, manner of cultivation and extent of vegetation.

4.6.1 Temperature

Energy input is necessary for evapotranspiration to proceed. It will advance more rapidly when the temperature of air and ground is high as heat energy is readily available. The

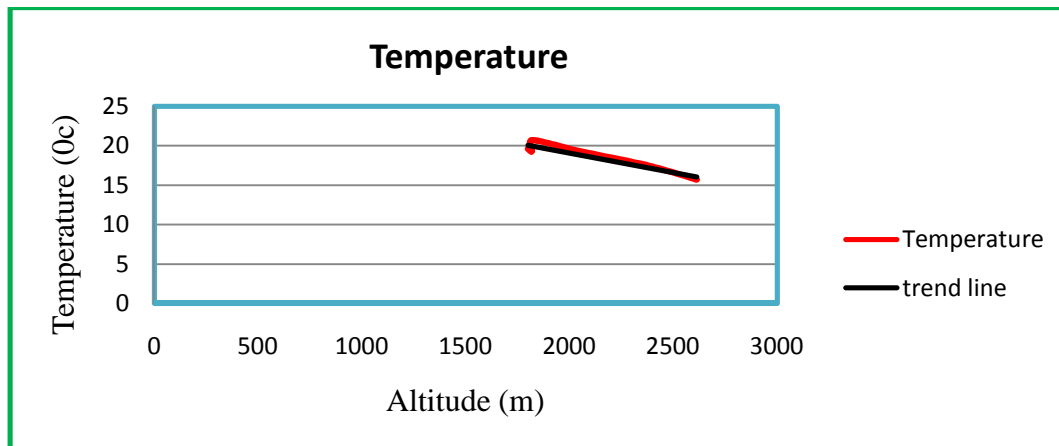
capacity of air to absorb water vapour increases as its temperature rises, so air temperature has a double effect on how much evaporation takes place, while ground and water temperature has a single direct effect (Wilson, 1990).

As it has been show in the table and displayed in the graph temperature provides negative relation with altitude. The temperature decrease with increase in altitude; the correlation coefficient between temperature and altitude is 0.897 (Figure 4.5)

Table 4.7 Spatial variation of temperature with altitude

Station	Spatial Variation of Temperature with Altitude					
	Bahir Dar	Woreta	Wanzaye	Alem ber	Mekane Eyesus	Debre Tabor
Altitude (m)	1800	1819	1821	2051	2374	2612
Temperature(0c)	19.6	19.3	20.7	19.3	17.5	15.7

Figure: 4.5 General Decreasing trend of Temperature with Altitude



Temperature data in the study area are taken from six stations and the minimum mean monthly temperature (°c) is recorded in the month of December and maximum in April (table

Table 4.8 Mean monthly average temperature of the stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	17.4	19.0	21.1	22.1	22.0	20.6	19.1	18.9	19.2	19.7	18.8	17.2
Wereta	18.5	20.0	21.1	20.8	20.9	19.8	18.6	18.1	18.6	18.1	18.8	18.0
Amed Ber	19.0	20.2	21.4	21.7	21.1	19.4	17.7	17.5	18.0	18.6	18.7	18.6
D/ Tabor	15.6	16.7	17.4	17.7	17.3	16.4	14.1	14.1	14.4	14.7	14.8	14.6
Mek.yesus	15.8	18.0	18.9	19.5	19.3	17.8	16.6	16.9	16.9	16.9	16.8	16.1
Wanzaye	19.2	20.1	22.6	23.1	22.9	21.2	20.0	19.8	19.9	20.8	19.7	19.2
Average	17.6	19.0	20.4	20.8	20.6	19.2	17.7	17.5	17.9	18.1	17.9	17.3

Figure 4.6 Mean monthly Average Temperature in year of the study Area

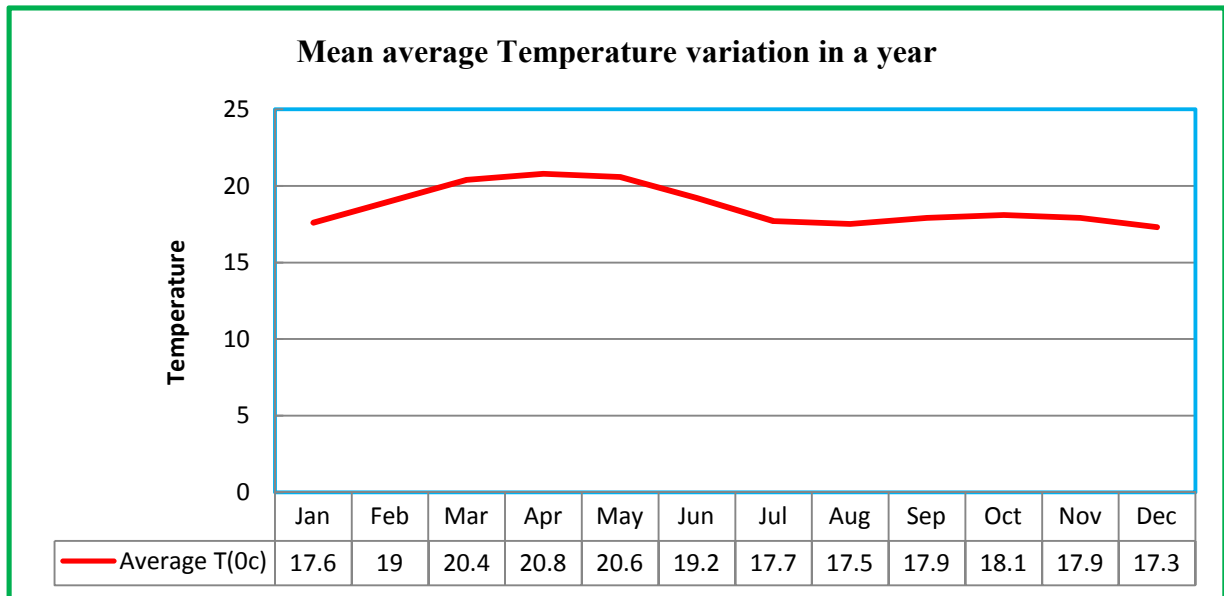
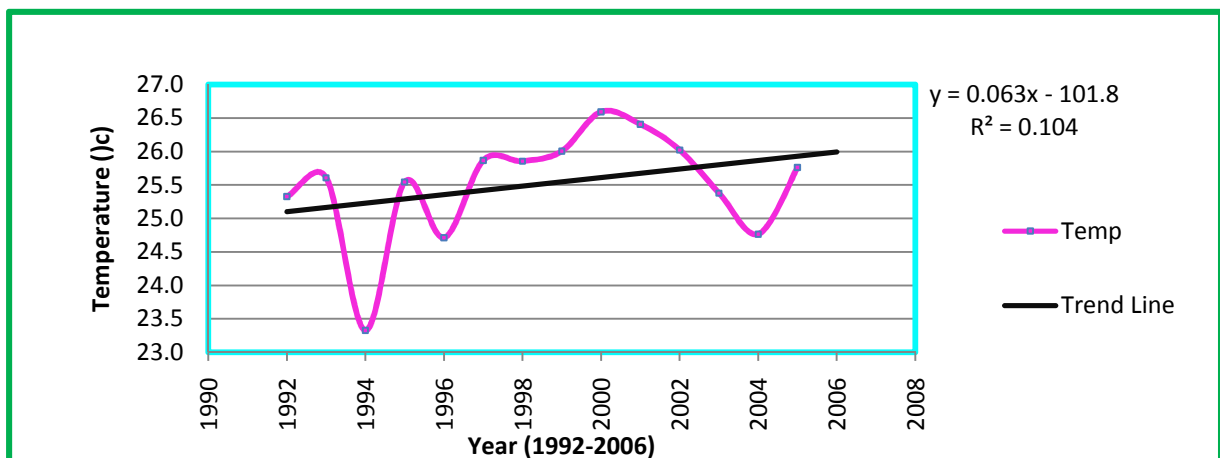


Figure 4.7 Temperature Variation From (1992-2006)



4.6.2 Relative Humidity

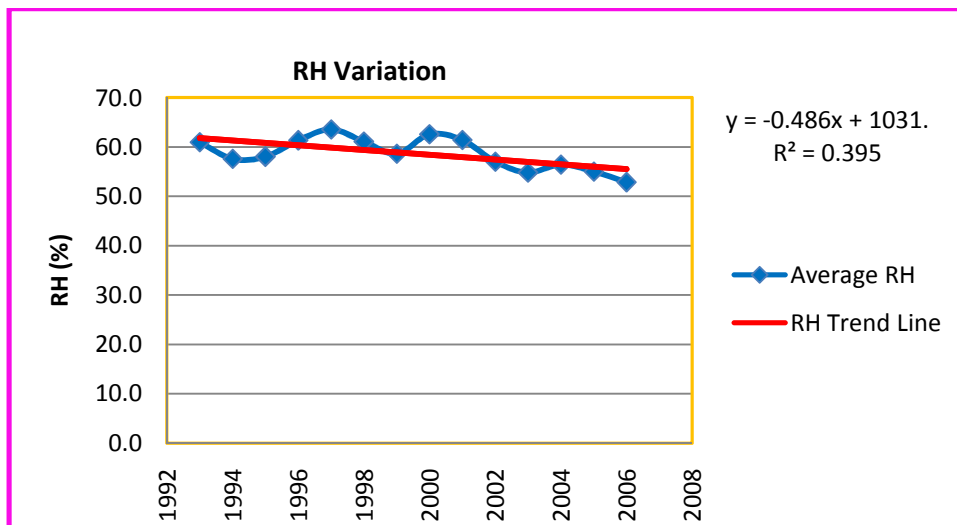
Relative humidity (RH) is the relative measure of the amount of moisture in the air to the amount needed to saturate the air at the same temperature (Shaw, 1988). It expresses the degree of saturation of air as a ratio of actual (e_a) to saturation (e_s) vapour pressure at the same temperature, which is $RH=100(e_a/e_s)$. RH is dimensionless and commonly given as percentage. This meteorological parameter affects evaporation in such a way that as air humidity increases its ability to absorb more water vapour decreases and the rate of evaporation slows.

Available data of relative humidity are taken from Bahir Dar and Debre Tabor. Table 4.9 below reveals that the maximum and minimum values of relative humidity exist in July and February and this is attributed to rainy and dry season of Ethiopia.

Table 4.9 Mean monthly relative humidity

Station	Mean Monthly Relative Humidity (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
B / Dar	51.1	45.1	42.3	42.8	52.5	66.8	76.0	77.1	72.3	63.2	56.2	52.0
D/Tabor	41.7	38.9	42.1	47.5	55.3	72.7	85.1	83.1	75.4	63.2	54.0	48.3
Average	46.4	42.0	42.2	45.1	53.9	69.7	80.5	80.1	73.9	63.2	55.1	50.2

Figure 4.8 Average Annual Relative Humidity Variations



4.6.3 Wind Speed

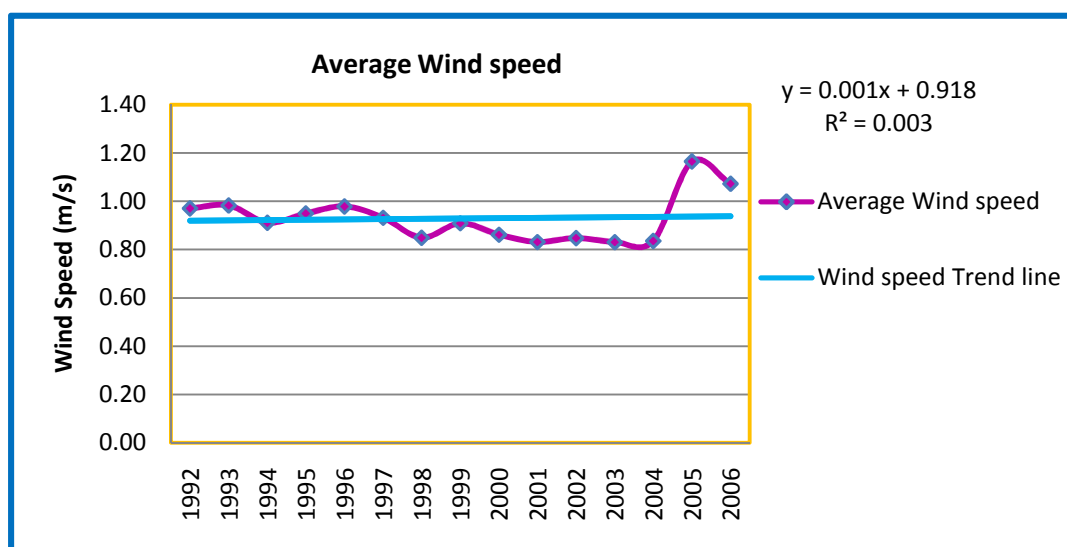
When water vaporises into the atmosphere, the boundary layer between earth and air or water body and air becomes saturated. This layers must be removed continuously and replaced by dried air if evaporation to proceed. If the boundary layer is still, it will get saturated with vapour and the evaporation ceases. On the other hand, higher wind speed cause higher evaporation as the wind is great enough to remove all the vapour. Therefore, wind generally affects evapotranspiration and the rate is a function of wind speed and turbulence.

Wind speed varies with height above the ground. The speed at any height can be approximately obtained from known wind speed at the known heights of observation. Wind speed in the study area and nearby station is measured at 2m above the surface of the ground

Table 4.10 Mean Monthly Wind Speed (m/s)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	0.6	0.6	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.7	0.6	0.5
Debre Tabor	1.1	1.2	1.3	1.3	1.3	1.3	1.1	1.2	1.1	0.9	1.0	1.0
Average	0.9	0.9	1.0	1.1	1.1	1.1	0.9	0.9	0.9	0.8	0.8	0.8

Figure 4.9 Average Annual Wind Speed Variations



4.6.4 Sunshine Hour

Sunshine hour refers to the duration of sunshine in a day. It plays a significant role in affecting evapotranspiration. Longer sunshine hour within a day increases the evaporation rate and amount which in turn is dependent on the intensity of solar radiation.

Table 4.11 Mean Monthly Sunshine hour

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	9.6	9.7	9.0	8.9	8.3	7.0	4.6	4.5	6.5	8.5	9.5	9.4
D/Tabor	7.4	7.2	7.1	6.3	6.4	6.0	4.4	4.8	6.9	7.3	8.1	8.1
Average	8.5	8.4	8.0	7.6	7.4	6.5	4.5	4.6	6.7	7.9	8.8	8.8

4.7 Evaporation and Evapotranspiration Estimation

Evaporation and evapotranspiration are two of the most important and most complicated phases of the hydrologic cycle. These phases redistribute heat energy between the surface and the atmosphere. Estimations of evaporation and evapotranspiration are required in the design of many water resource projects, irrigation systems, scheduling the frequency of irrigation and water balance and simulation studies (Subrahmanya, 1994)

Evaporation is the process by which water from liquid or solid state passes into vapour state and is diffused into the atmosphere. The nature of evaporating surface affects evaporation by modifying the wind pattern. Over a rough, irregular surface, friction reduces wind speed but has a tendency to cause turbulence so with an induced vertical component in the wind, evaporation is enhanced. Over an open water surface, strong winds cause waves which provide an increased surface for evaporation in addition to causing turbulence. As wind passes over smooth, an even surface there is little friction and turbulence and evaporation is affected predominantly by horizontal velocity (Shaw, 1988).

There is no direct measured value of evaporation from open water body or pan evaporation in the study area as a result calculation related to pan evaporation is not used. Though there are different methods of estimating evaporation from water body, Penman combined method is used because of limited meteorological data.

4.7.1 Penman Combined Method for Evaporation Estimation

This method combines two approaches to evaporation calculation: the mass transfer method and energy budget method. The basic equations are modified and rearranged to use meteorological components and measurement of variables made regularly at climatological stations.

$$H = E_0 + Q \dots \dots \dots (3.1). \text{Simplified energy balance method}$$

$$E_0 = f(u)(e_s - e_d) \dots \dots \dots 3.2. \text{Mass transfer method.}$$

Where H is available heat, Q-energy for evaporation, E₀-energy for evaporation or rate of evaporation. e_s - saturated vapour pressure of air at the water surface (saturated)

e_d -saturated vapour pressure of air above the water surface (actual)

e_s - e_d -saturation deficit and f(u) is a function of wind speed

After rearranging the different parameters based on the above two methods, equation (3.1) and (3.2), penman arrive at the final equation for open water evaporation.

$$E_0 = \frac{\left(\frac{\Delta}{\gamma} H + E_a\right)}{\left(\frac{\Delta}{\gamma} + 1\right)} \dots \dots \dots (3.3) \text{ Where } E_0\text{-evaporation rate (mm/day)}$$

Δ- slope of the curve of saturated vapour pressure plotted against temperature

γ -hygrometry constant (0.27mm Hg)

$H = R_I(1 - r) - R_0 \dots \dots \dots (3.4)$ Where R_I is incoming solar radiation, R_0 -outgoing solar radiation and r is albedo ($r = 0.05$) for water.

$$R_I(1 - r) = 0.95R_a f_{a(n/N)} \dots \dots \dots (3.5)$$

$$f_{a(n/N)} = 0.18 + 0.55 n/N \dots \dots \dots (3.6)$$

Where R_a solar radiation at the atmosphere is fixed by (latitude and season), n is bright sunshine hour per day and N is maximum possible sunshine hour obtained from standard meteorological tables.

$$R_0 = \sigma T_a^4 (0.56 - 0.09\sqrt{e_d})(0.10 + 0.9 n/N) \dots \dots \dots (3.7)$$
 Where,

σT_a^4 - The theoretical black body radiation at the temperature T_a of air

σ -Stefan -Boltzmann constant ($5.67 \times 10^{-8} \text{wm}^{-2}\text{k}^{-4}$), T must be converted to ^0k

e_d -mean vapour pressure for the same period

Next E_a in equation (3.3) is found using the coefficients derived by the experiment for open water which is $E_a = (0.5 + U_2/100)(e_a - e_d) \dots \dots \dots (3.8)$ where,

U_2 -mean wind speed at 2m above the surface in miles per day

e_a -saturated vapour pressure at air temperature and e_d -actual vapour pressure at dew point that is t_d =actual vapour pressure. Saturated vapour pressure (e_a) can be found from the standard curve drawn for the relation between temperature and saturated vapour pressure or from standard table. But empirically it can be obtained as:

$$e_a = 6.11 \exp\left(\frac{17.3T}{T+237.3}\right) \dots \dots \dots (3.9)$$
 , Where T is temperature in ^0c and e_a in mmHg.

Actual vapour pressure (e_d) on the other hand can be calculated from the relation of relative humidity and ratio of actual to saturated vapour pressure, $RH\% = e_d / e_a \dots \dots \dots (3.10)$.

The slope of saturated vapour pressure curve corresponding to the air temperature (Δ) can be obtained from approximate equation, $\Delta = \frac{4098e_a}{(237.3+T)^2} \dots \dots \dots (3.11)$ (Jayarami, 1996).

Where e_a is in mmHg and T in $^{\circ}\text{C}$. Hygrometric constant (γ) has a typical value of 0.4859 mmHg/ $^{\circ}\text{C}$ (Maidment, 1993). Therefore using all relationships mentioned above the evaporation rate of Gumara catchment can be calculated to be 1330.5 mm/year

4.7.2 Potential Evapotranspiration (PET) Estimation

PET refers the evapotranspiration which could occur if there is always an adequate water supply available to fully vegetated surface. It is the upper limit of evapotranspiration for a crop in a given climate. Potential Evapotranspiration is controlled essentially by meteorological factors. PET tends to increase as temperature, sunshine, wind speed increases and as humidity decreases. For calculating PET, there are different formulae but for this research Penman modified and Thornthwaite methods are employed based on the prevailing data.

Penman Modified Method: Resulting from later experience, the evaporation rate formula was modified to allow conditions under which evaporation plus transpiration takes place from a vegetated surface (Shaw, 1988) and is given by:

$PET = \frac{(\frac{\Delta}{\gamma} H_t + E_{at})}{(\frac{\Delta}{\gamma} + 1)}$ (3.12), where the extra subscript t signifies inclusion of transpiration effect in equation (3.3).

$H_T = R_I(1 - r) - R_0$ (3.13), where r is the reflective coefficient for incident radiations, the albedo for the basin or catchment depending on the nature of the surface. The possible albedo value for Gumara river catchment considering the land cover is close to 0.23. This value has been used for calculating the potential evapotranspiration.

$E_{at} = (1 + U_2/100)(e_a - e_d)$ (3.14). This is similar to equation (3.8) except 0.5 is replaced by 1 to allow for extra roughness in the wind speed function.

$R_I(1 - r) = (1 - r)R_a f_{a(n/N)}$ (3.15). In addition to albedo modification of equation (3.5) to equation (3.15), equation (3.6) takes the form:

$$f_{a(n/N)} = 0.16 + 0.62 n/N \dots \dots \dots (3.16)$$

For latitude south of 54.5°N , the empirical equation for the outgoing radiation in the calculation takes the form:

$$R_0 = \sigma T_a^4 (0.47 - 0.075 \sqrt{e_d}) (0.17 + 0.83 n/N) \dots \dots \dots (3.17)$$

Albedo of any basin can vary widely with time of day, season latitude and cloud cover. Considering the land use and land cover condition the albedo 0.23 has been used and accordingly $R_I(1 - r)$ will become: $R_I(1 - r) = 0.77 R_a f_a(n/N) \dots \dots \dots (3.18)$.

By using the above empirical relations potential evapotranspiration is calculated and displayed in table 4.12

Table 4.12 Calculated Potential Evapotranspiration of Gumara River Catchment using penman Modified Method

Month	Temp	e_a	RH%	e_d	U_2	T_k	n	N	n/N	$f_a(n/N)$	R_a	$RI(1-r)$	σT_a^4	R_o	H_t	E_{at}	Δ/γ	PET	
Jan	17.6	14.17	0.46	6.52	45.65	290.6	8.5	11.54	0.74	0.62	12.60	6.00	13.9	3.04	2.96	3.9	1.84	102.02	
Feb	19.0	16.46	0.42	6.91	49.94	292.0	8.4	11.76	0.71	0.60	13.75	6.36	14.18	2.94	3.42	5.01	2.11	110.08	
Mar	20.4	17.97	0.42	7.55	54.24	293.4	8.0	12.00	0.67	0.58	14.72	6.52	14.45	2.77	3.75	5.63	2.28	134.02	
Apr	20.8	18.43	0.45	8.29	58.00	293.8	7.6	12.34	0.62	0.54	15.2	6.37	14.53	2.45	3.92	5.61	2.33	132.83	
May	20.6	18.20	0.54	9.83	57.46	293.6	7.4	12.64	0.59	0.53	15.07	6.10	14.49	2.25	3.85	4.61	2.31	126.47	
Jun	19.2	16.68	0.70	11.7	57.46	292.2	6.5	12.76	0.51	0.48	14.9	5.46	14.21	1.8	3.66	2.76	2.14	101.2	
Jul	17.7	15.17	0.81	12.6	47.79	290.7	4.5	12.66	0.36	0.38	14.99	4.42	13.92	1.33	3.09	1.32	1.97	77.32	
Aug	17.5	14.99	0.80	12	50.48	290.5	4.6	12.44	0.37	0.39	15.04	4.51	13.89	1.39	3.12	1.58	1.95	80.54	
Sept	17.9	15.38	0.74	11.4	47.79	290.9	6.7	12.12	0.55	0.50	14.76	5.69	13.96	1.9	3.79	2.07	1.99	96.44	
Oct	18.1	15.59	0.63	9.80	42.96	291.1	7.9	11.8	0.67	0.58	14.07	6.23	14.00	2.39	3.84	2.88	2.01	109.15	
Nov	17.9	15.38	0.54	8.31	42.42	290.9	8.8	11.56	0.76	0.63	12.92	6.28	13.96	2.84	3.44	3.52	1.99	104	
Dec	17.3	14.80	0.48	7.10	41.89	290.3	8.8	11.44	0.77	0.64	12.29	6.03	13.85	3.03	3.00	3.82	1.93	101.68	
Total																			1275.75

Where e_a =saturated vapour pressure (mmHg) , e_d = actual vapour pressure (mm Hg , RH= Relative Humidity (%) , U_2 =wind speed(Mile/day)

n = daily mean bright hour (hr/day), N =Max. Possible sunshine hour determined by Latitude and season (11^0) in case of Gumara f_a =function of sunshine hour, R_a = Solar radiation dependent latitude and season (mm of water/day), R_I = incoming solar radiation (mm/day) =albedo (reflection coefficient for incoming radiation is 0.05 for water and 0.23 for land cover in Gumara, Stephphan Boltzman constant= $5.67 \times 10^{-8} \times Wm^{-2} T^4$, T =temperature(0c) T_k = temperature in Kelvin, R_o =out going solar radiation(mm/day) , H = available heat(mm/day) E_{at} = energy for evapotranspiration(mm/day), σT_a^4 = theoretical black body radiation(mm/day), Δ =slope of saturated vapour pressure plotted against temperature, γ =the hygrometric constant (0.27mmHg/ 0c), PET= potential evapotranspiration (mm/month

Thornthwaite Method of PET Estimation: An estimate of potential evapotranspiration on the monthly basis (PET_m) is given by:

$PET_m = 16N_m \left(\frac{10T_m}{I}\right)^a mm$, where m is the months 1, 2, 3...12, N_m is the monthly adjustment factor related to hours of the day light. It is found from standard table by dividing possible sunshine hours for the appropriate latitude (11^0 N) of the study area (Gumara river catchment) by twelve. T_m is the monthly mean temperature (0c), I is the heat index for the year given by: $I = \sum i_m = \sum \frac{(T_m)^{1.5}}{5}$ for $m=1, 2, \dots, 12$, a is an exponent given by:

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} + 0.4$$

Accordingly PET_m on the Thornthwaite method is 836.36.mm

Table 4.13 Thornthwaite Method of PET calculation

Thornthwaite Method of PET Calculation													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Ann
N_m	0.96	0.98	1	1.03	1.05	1.06	1.06	1.04	1.01	0.98	0.96	0.95	
$T_m(^0c)$	17.6	19	20.4	20.8	20.6	19.2	17.7	17.5	17.9	18.1	17.9	17.3	
i_m	6.55	7.41	8.4	8.49	8.36	7.53	6.66	6.55	6.77	6.89	6.77	6.44	
$a = 1.91$													
$I = 86.82$													
PET_m	59.2	70	81.8	87.4	85.5	77.23	66.1	63.5	64.4	63.78	61.2	56.7	836.8

The limitation of the using Thornthwaite method of calculating PET is its dependency only with two parameters: temperature and sunlight adjustment factor. Thus, the PET calculated by Penman modified method is employed as it considers various parameters for estimating PET. From the above two results, the PET obtained from Penman combination seem to be representative. The Thornthwaite method underestimates the values. As a result, the catchment's PET which is 1275.75mm is used for further analysis.

4.7.3 Actual Evapotranspiration Estimation

Actual evapotranspiration refers to the evaporation from vegetable cover under given or natural condition of supply of moisture. It helps to describe the amount of evaporation that occurs under field condition and depends on the availability of water to meet the atmospheric demand. There are different methods of estimating actual evapotranspiration of which the Turc method and soil water balance model are employed in this paper.

Turc Method: Turc used formula to estimate annual AET for catchment areas in 1954,1955.Turc showed that the formula could be applied in humid or arid climate either hot or cold (Shaw,1998). According to him precipitation and temperature are the dominant factors that govern AET.

$$\text{The empirical formula that Turc used is: } AET = \frac{P}{(0.9+(P/L)^2)^{1/2}} \text{ mm/year}$$

Where P is the annual precipitation and T is the mean air temperature ($^{\circ}\text{C}$)

$L = 300+25T+0.05T^3$. Therefore, the AET of the catchment with $P =1377.11\text{mm}$ and $T =18.67^{\circ}\text{C}$ is 872 mm/year. But this method is commonly used for calculation of AET for large basin and seems over estimating the value AET.

Soil Water balance Method: As it has been mentioned earlier, PET is controlled by meteorological factors. AET is controlled by plant and soil factors in addition to meteorological parameters. The value of actual evapotranspiration (AET) over a catchment is often obtained by first calculating the potential evapotranspiration. AET is used to describe the amount of evapotranspiration that occurs under field conditions. When vegetation is unable to abstract water from the soil, the actual evapotranspiration becomes less than the potential.

When soil is saturated, it will hold no more water. In this condition actual evapotranspiration is equal to potential evapotranspiration ($AET=PET$) (Shaw, 1988). If there is no rain to replenish the water supply, the soil moisture gradually becomes depleted by demand increase of vegetation to produce a soil moisture deficit (SMD).As soil moisture deficits, actual evapotranspiration becomes increasingly less than potential evapotranspiration. The value of soil moisture deficit and AET vary with soil type and vegetation. The availability of water supply is largely determined by the extent of root zone and the climatic regime. If the extended periods without rainfall during the growing season are characteristic of an area, the deep rooted forest cover will transpire freely much of the time when the supply to shallow rooted plants have been exhausted. In area where climatic conditions are such that shallow rooted plants have adequate supply, evapotranspiration is less affected by the extent of root zone (Lensley, 1975)

A soil moisture budget can be made on the monthly basis for various types of vegetation classified according to their root constants which define the amount of moisture that can be extracted without difficulty by given vegetation. Therefore to evaluate the actual evapotranspiration over the catchment area, the proportion of different types of vegetation and soil covering the catchment are identified from soil, land use land /land cover maps. Accordingly the study area has been classified to four soil textures with their corresponding vegetation cover. Based on these categories and meteorological data the actual evapotranspiration of the catchment is calculated using Thornthwaite and Mather soil water balance model. The result of the analysis of the model will be described in the following section.

Since there are different land use/land cover categories and soil texture in the study area, the model provides different independent results. The methodology steadily follows the Thornthwaite and Mather, 1957. The description and estimation mechanisms of the main components that govern the balance are presented in the following table (Table 4.14- 4.17).

Table 4.14 Calculated AET using soil water balance model for silty loam soil covered with moderately deep rooted crops and available water capacity of the root zone 200mm

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
P	3	4	20	35	68	193	397	369	184	77	20	7	1377
PET	102	110	134	133	126	101	77	81	96	109	104	102	
P-PET	-99	-106	-114	-98	-59	92	320	289	87	-32	-84	-95	
APWL	-310	-416	-530	-628	-687					-32	-116	-211	
SM	42	25	14	9	6	99	200	200	200	171	112	70	
Δ SM	-27	-17	-11	-5	-2	92	101	0	0	-29	-58	-42	
AET	30	22	30	41	70	101	77	81	96	107	79	49	783
SMD	72	88	104	92	57	0	0	0	0	2	25	53	
S	0	0	0	0	0	0	218	289	87	0	0	0	595
TAR _o	18	9	4	2	1	1	218	398	286	143	72	36	
Ro	9	5	2	1	1	0	109	199	143	71	36	18	594
D	9	4	2	1	1	0	109	199	143	72	36	18	

Description to symbols and values (all units in mm):-

P = the mean rainfall of the catchment (Thiessen Polygon method).

PET = the potential evapotranspiration calculated from Penman modified method

P-PET is the difference between precipitation and potential evapotranspiration. Positive values are indicatives of the addition of moisture to the soil while the negative values are

showing the monthly demand of moisture by the vegetation which is not satisfied by the monthly rainfall.

APWL is accumulated potential water loss, which is obtained by cumulating the negative values of the differences between monthly precipitation and evapotranspiration as shown in the above table.

S_m is the soil moisture. Accumulated potential water loss is used to calculate S_m for the dry months using the following relation:

$$S_m = W * \exp\left(-\frac{APWL}{W}\right), \text{ Where } S_m \text{ is the soil moisture during the}$$

month M (mm), APCL is the accumulated potential water loss and W is the available water capacity of the root zone (mm). Soil moisture values for each wet month are obtained by adding the excess rain of the current month to the soil moisture of the month before. But, the sum may or may not exceed the available water capacity. If the soil moisture value exceeds the available water capacity of the root zone, the excess moisture is recorded as moisture surplus.

AET is the actual evapotranspiration. $AET = PET$ if P of that month is greater than the respective PET . Otherwise, $AET_m = P_m + S_{m-1} - S_m$, where m stands for month and S_{m-1} and S_m are soil moisture during the month **m-1**(earlier month) and **m** (current Month) respectively.

SMD is the soil moisture deficit obtained by deducting AET from PET .

S is the soil moisture surplus which is in excess of soil moisture values(S_m) especially in wet season.

TAR₀ refers to the total amount of water available for runoff. The value is determined starting from the first month of the water surplus period. It is simply equal to the amount of soil moisture surplus for the first month ($TRO = S$) in the month of July in case of Gumara river catchment) but the value for consecutive coming months is obtained by adding the surplus of the month and the detained amount of water in the preceding month as this detained water is thought to be readily available for run off for the coming month. According to Thornthwaite and Mather assumption , 50% of the surplus is detained (**D**) in sub soil, ground water, channels of the catchment and available for run of for the next month and the remaining 50% is the run off (**R₀**) that is as river discharge.

On the basis of the relationship of the soil water balance components described above, the calculated AET is different for different available water capacity of the root zone (Table 4.15,16 and 17)

Table 4.15 Calculated AET using soil water balance model for clay loam soil covered with shallow rooted crops and available water capacity of the root zone 100m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
P	3	4	20	35	68	193	397	369	184	77	20	7	1377
PET	102	110	134	133	126	101	77	81	96	109	104	102	
P-PET	-99	-106	-114	-98	-59	92	320	289	87	-32	-84	-95	
APWL	-310	-416	-530	-628	-687					-32	-116	-211	
SM	5	2	0	0	0	92	100	100	100	73	31	12	
ΔSM	-8	-3	-1	0	0	92	8	0	0	-27	-42	-19	
AET	11	7	21	35	68	101	77	81	96	104	62	26	689
SMD	91	103	113	97	59	0	0	0	0	5	42	76	
S	0	0	0	0	0	0	312	289	87	0	0	0	688
TAR _o	19	10	5	2	1	1	312	445	310	155	77	39	
Ro	10	5	2	1	1	0	156	222	155	77	39	19	688
D	10	5	2	1	1	0	156	222	155	77	39	19	

Table 4.16 Calculated AET using soil water balance model for clay soil covered with moderately deep rooted crops and available water capacity of the root zone 150 mm

Awc 150mm-clay

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
P	3	4	20	35	68	193	397	369	184	77	20	7	1377
PET	102	110	134	133	126	101	77	81	96	109	104	102	
P-PET	-99	-106	-114	-98	-59	92	320	289	87	-32	-84	-95	
APWL	-310	-416	-530	-628	-687					-32	-116	-211	
SM	19	9	4	2	2	94	150	150	150	121	69	37	
ΔSM	-18	-10	-5	-2	-1	92	56	0	0	-29	-52	-33	
AET	21	14	25	37	68	101	77	81	96	106	72	39	738
SMD	81	96	109	96	58	0	0	0	0	3	32	63	
S	0	0	0	0	0	0	263	289	87	0	0	0	640
TAR _o	19	9	5	2	1	1	263	421	298	149	74	37	
Ro	9	5	3	1	1	0	132	210	149	74	37	19	639
D	10	5	2	1	1	0	132	210	149	74	37	19	

Table 4.17 Calculated AET using soil water balance model for fine sandy loam soils covered with dominantly with matured forest and available water capacity of the root zone 300 mm

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
P	3	4	20	35	68	193	397	369	184	77	20	7	1377
PET	102	110	134	133	126	101	77	81	96	109	104	102	
P-PET	-99	-106	-114	-98	-59	92	320	289	87	-32	-84	-95	
APWL	-310	-416	-530	-628	-687					-32	-116	-211	
SM	107	75	51	37	30	123	300	300	300	270	204	149	
Δ SM	-42	-32	-24	-14	-7	92	177	0	0	-30	-66	-55	
AET	45	36	43	49	74	101	77	81	96	108	86	62	859
SMD	57	74	91	83	52	0	0	0	0	2	18	40	
S	0	0	0	0	0	0	142	289	87	0	0	0	519
TARo	17	8	4	2		0	142	360	267	134	67	33	
Ro	8	4	2	1	0	0	71	180	134	67	33	17	518
D	8	4	2	1	1	0	71	180	134	67	33	17	

The AET which is strongly dependent on land cover, soil type and meteorological variables, is finally calculated by relating the model results of AET with respective areal coverage. Accordingly, the weighted PET is summed up and AET of the Catchment area is 764mm (Table 4.18). Surplus, detention and run off can be weighted in a similar way.

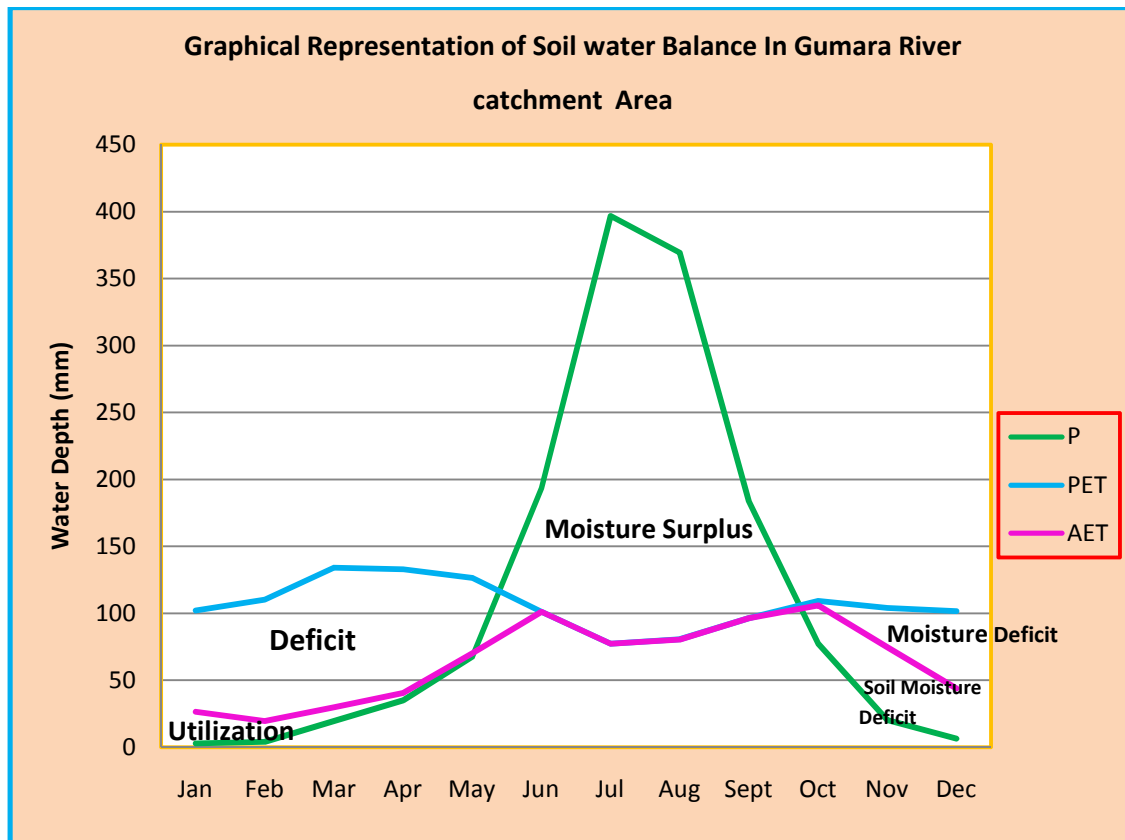
The calculated AET of the study area based on the model incorporates various parameters. The Turc method of AET calculation, which depends only on precipitation and temperature, on the other hand is not as reliable as the water balance model. Therefore, the value of AET obtained using soil water balance method is used for further analysis especially of recharge estimation.

The graphical representation of Thornthwaite water balance components especially the relationship between precipitation, potential evapotranspiration, actual evapotranspiration as well as the respective moisture surplus and deficit of Gumara river catchment is depicted in figure 4.10 below.

Table 4.18 Relation between soils type, land use/ land cover and actual evapotranspiration

Soil Texture	Land use /Land cover	Aw (mm)	Areal proportion	AET (mm)	Weighted AET(mm)
Clay	Moderately to intensively cultivated cereal crops (moderately deep rooted)	150	0.223	738	165
Clay Loam	Moderately cultivated crops of shallow rooted variety like onion	100	0.133	689	92
Silty loam	Intensively cultivated with various crops and scattered shrubs and grass	200	0.620	783	486
Sandy loam	Moderate cultivation and Afro-alpine heath vegetation(Matured forest)	300	0.024	859	21
Total		1.00			764

Figure 4.10 Graph of Annual Soil Water Balance in Gumara River Catchment



4.8 Ground Water Recharge Estimation

The amount of water that is extracted from an aquifer without causing depletion is primarily dependent upon the ground water recharge. Thus, a quantitative evaluation of spatial and temporal distribution of ground water recharge is a pre-requisite for operating ground water resources system in an optimal manner. Quantification of the rate of natural ground water recharge is basic for efficient ground water resource development and management. It is particularly important in regions with large demands for ground water supplies, where such resources are the key to economic development.

Rainfall is the principal means for replenishment of moisture in the soil water system and recharge to ground water. Moisture movement in the unsaturated zone is controlled by capillary pressure and hydraulic conductivity. The amount of moisture that will eventually reach the water table is defined as natural ground water recharge. The amount of this recharge depends upon the rate and duration of rainfall, the subsequent conditions at the upper boundary, the antecedent soil moisture conditions, the water table depth and the soil type.

Estimation of ground water recharge is a major problem in many water resources investigations. It is a complex function of meteorological conditions, soil, vegetation, physiographic characteristics and properties of the geologic material within the paths of flow. Soil layering in the unsaturated zone plays an important role in facilitating or restricting downward water movement to the water table. The depth to the water table is important in ground water recharge estimations, too. Of all the factors controlling ground water recharge, the antecedent soil moisture regime is probably the most important. There is no single comprehensive recharge estimation technique, yet recharge can be evaluated with different methods of which base flow separation, soil moisture balance and the general water balance methods are used to represent the recharge amount of the catchment in this paper.

4.8.1 Base Flow Separation Method

The main Gumara river catchment doesn't have a stream gauge at its mouth that is at the entrance or near to Lake Tana. Due to this reason the catchment area is categorized into Gauged (88.2%) and ungauged (11.8%). So as to be rational and reasonable, the Gauging station should be extrapolated towards the mouth of the main river that is very close to Lake Tana. This can be achieved by using area ratio and relating it with the discharge of the gauging station.

The approach is made by scaling up the stream flow values from the gauged sub catchment to the drainage area of the projected site. Scaling up is made by calculating the proportionality (drainage area ratio) between the projected site drainage area (total area of the catchment) and the drainage area of the gauged sub catchment. The estimation is made by considering the following conditions: Similarity in topography, climate, patterns, soil characteristic, land use and land cover. Gumara river catchment nearly fulfils the above mentioned requirements (conditions). Accordingly the discharge data at gauging station near Gumara village is extrapolated to the mouth of the river near Lake Tana with a location of 339237E and 1313222N on the basis of drainage area ratio as follows:

$$Q_{\text{mouth}} = (A_2/A_1) Q_{\text{gauged}}$$

where A_1 is the drainage area of the gauging station

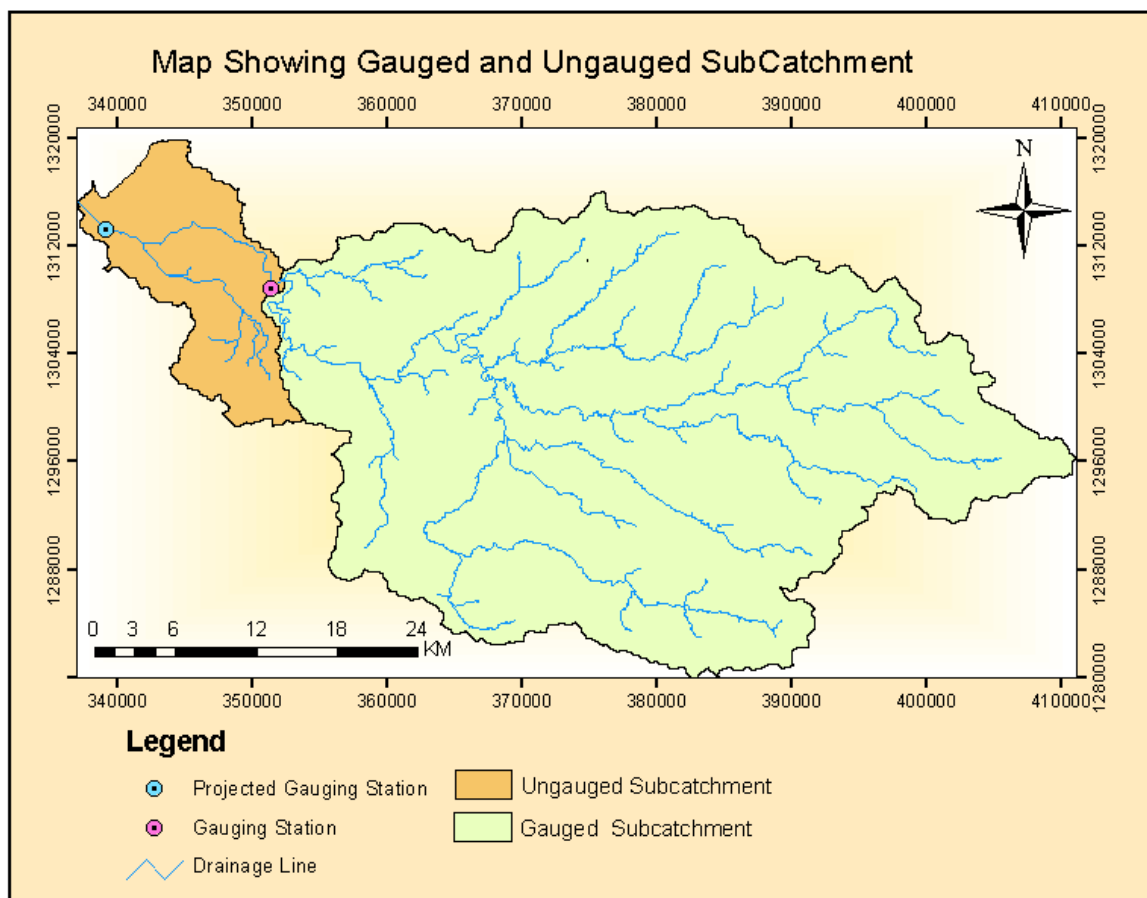
A_2 is the total drainage area of Gumara River Catchment

Q_{gauged} is the stream flow in m^3/s of the gauged river

Q_{mouth} the discharge in m^3/s at the mouth of the river

Thus the extrapolated river discharge data is used for further analysis.

Figure 4.11 Gauged and Ungauged Sub-catchments with Projected Gauging Station



Base flow separation techniques use the time-series record of stream flow to derive the base flow signature. Base flow from a catchment is an indirect measure of recharge as it represents the drainage of ground water from aquifer storage after ground water recharge has occurred. The study area river gauging station which is located at 351489E and 1308804N, records daily river flow data. These data after organized and projected is the prime input for TIMEPLOT software developed by Gabriel Parodi which uses daily flow and attenuation coefficient ranging between 0.9-0.995. The software separates total flow into base flow and runoff component values supplemented with hydrographs depicting the components. Despite there are some gaps in daily discharge data 15 years (1992-2006) data are used for base flow separation and 15-35 for other analysis.

Ground water recharge estimation from base flow separation method is based on the following assumption:

- Surface water divide coincide with the groundwater divide and there is no inflow or outflow of water from the catchment.
- There is no loss of water below the river bed at the measuring site.
- There is no (or negligible) diversion or addition of water in to the river.

However, Gumara River Catchment may not fulfil all the above assumption. There is small diversion using dewatering pump by the local people for irrigation practice (not this much significant). The assumption that no ground water inflow or outflow into or out of the basin is uncertain as subsurface features is complex and obscured from physical observation. The relative nearly constant base flow trend irrespective of slightly decrease in rain fall and increase in temperature may be attributed to ground water inflow in to the catchment or related to the limitation of the time plot itself. The base flow of Gumara River is 491mm per year. This figure is relatively high compared to the recharge amount obtained from water balance method.

Figure 4.12 Base flow separation of Gumara River from daily discharge

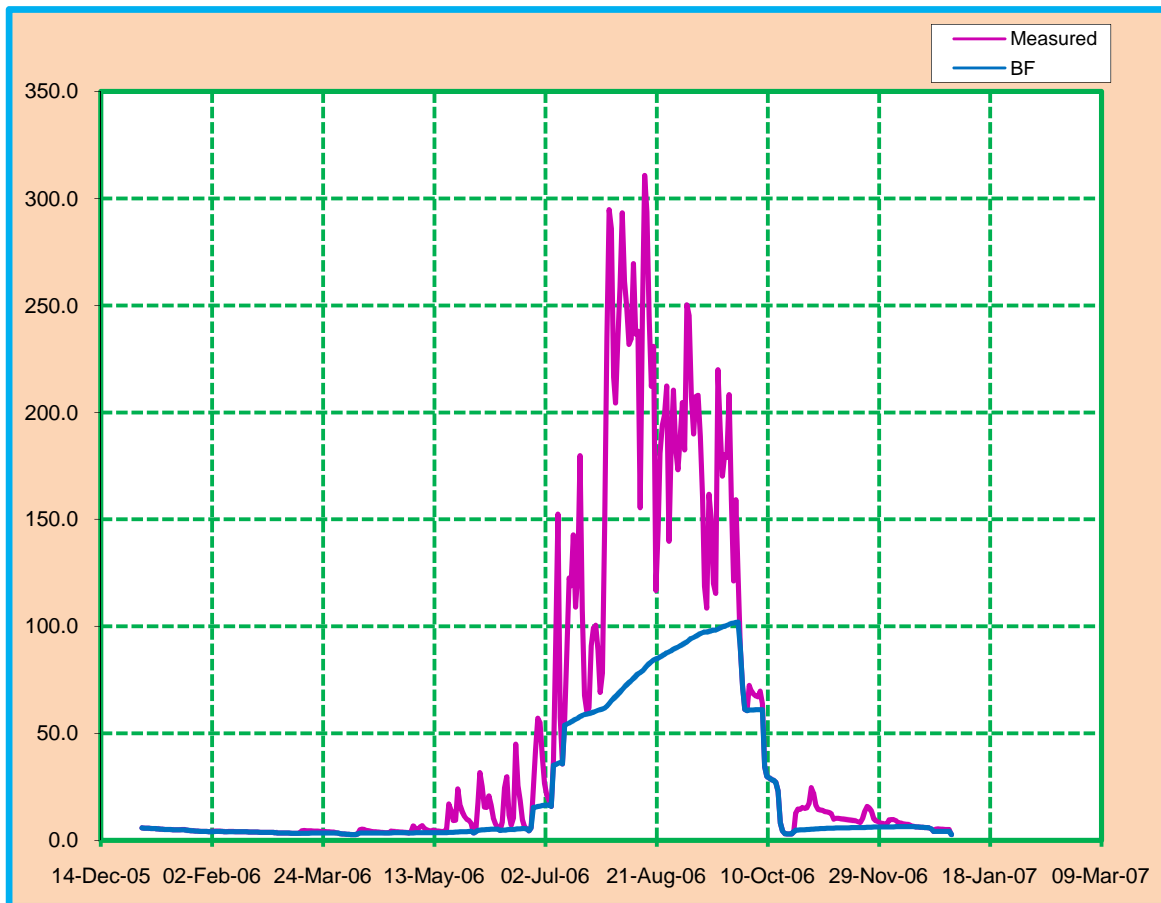


Table 4.19 Base flow separation Result

Base flow Separation Result (1992-2006)													
Q (m ³ /s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Avg
Total Flow	5.18	3.51	3.15	2.33	3.42	20.19	103.38	177.26	105.63	39.74	15.99	8.65	40.70
Base Flow	5.18	3.50	2.79	2.17	2.72	18.37	47.82	66.87	76.22	37.07	15.12	8.58	23.87
Run off	0.00	0.00	0.36	0.16	0.70	1.82	55.56	110.39	29.41	2.67	0.87	0.07	16.83

4.8.2 Water Balance Method

The hydrologic equation is based on the law of conservation of matter as applied to the hydrologic cycle, define the total water balance. Ground water balance deals with aspect of balancing or budgeting various component of ground water supply (recharge) and disposal (discharge) with change in ground water reservoir.

Water balance techniques are the means of solutions of important theoretical and hydrological problems. On the basis of water balance approach, it is possible to make a

quantitative evaluation of water resources and their change under the influence of man's activities. It assists the prediction of the consequences of artificial changes in the regime of streams, lakes and ground water basins. It is also extremely important for studies of hydrologic cycle. With water balance data, it is possible to compare individual sources of water in the system over different periods of time and to establish the degree of their effect on variations in the water regime. Furthermore, water balance studies provide an indirect evaluation of an unknown water balance component from the differences of known parameters.

The ultimate objective of balancing the hydrologic components that exist in the study area is to estimate the amount of ground water recharge. For natural catchment, measurements of the precipitation and river discharge may be made satisfactorily with some degree of precision. However, the measurement of ground water movement in to or out of the drainage area cannot be made straightforwardly. In this specific research the catchment is assumed to be closed.

The general water balance equation can be expressed as:

$$\text{Inflow} = \text{outflow} \pm \text{change in storage}$$

$$P + G_i = AET + SRO + R + G_o \pm \Delta S, \text{ Where,}$$

P = Annual precipitation; ΔS = change in water storage and

G_i = Ground water inflow R = Ground Water recharge

AET = actual evapotranspiration G_o = ground Water out flow

SRO = Annual surface run-off.

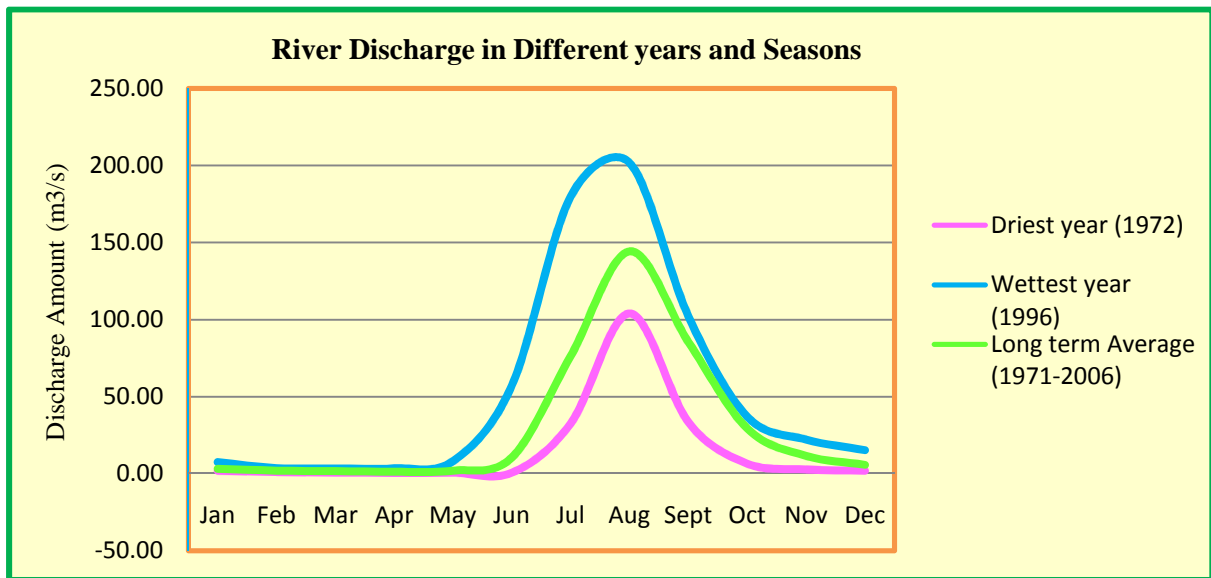
The basic assumption as mentioned earlier is that the surface water divide coincides with the subsurface drainage basin. There is no inter aquifer flow (inflow or out flow of the ground water). The change in storage (ΔS) of ground water in annual basis is negligible. As a result of this the above equation is simplified to:

$$R = P - (AET + R_o)$$

Where P = 1377 mm, AET = 764 mm and R_o = 346 mm (from base flow separation result table). Therefore the recharge amount obtained from Gumara river catchment based on this relationship is 267 mm per year.

Comparing the three recharge estimation methods, base flow separation method over estimates the recharge amount as the recharge corresponds to the base flow. But the water balance method provides reasonable result. Hence the annual recharge amount of the catchment is 267 mm per which is 19.4 % of the total annual rainfall.

Figure 4.13 River discharge in Different Years and Seasons



The river discharge in Gumara generally varies from 100m³ to above 200m³ in the wettest season particularly between July and August with in the given year. The driest year within the recording years corresponds to 1972 and the wettest 1996. The variation of the river in different years is possibly attributed to variation in rain fall amount

CHAPTER FIVE HYDROGEOLOGY

5.1 Introduction

The assessment of groundwater resources entails broad understanding of various parameters in relation to ground water occurrence, movement, distribution in prevailing hydrogeologic environment. It involves identification and characterization of hydrogeologic units, recharge-discharge conditions, aquifer type, property and set up, ground water flow system as well as surface and ground water interaction. It is so broad that it is difficult to get complete hydrogeologic information from this research in this portion. The hydrogeologic properties of geologic formations are complex and vary in space and time. Due to this fact it is rarely possible to have comprehensive information about all features with short period of time. However, identification of essential features which strongly influences ground flow and overall interaction with the geologic media is of paramount importance.

An interaction of geologic and geomorphic factors governs the movement of water from the time it reaches the land surface till the time of leaving it. Geomorphic features control the distribution and amount of precipitation that contributes to run off and ground water recharge. The nature, distribution and structure of geologic formation control the occurrence, movement and availability of ground water. Of all, the primary importance is the occurrence and distribution of aquifers and their relationship with the associated relatively impermeable beds that act as leaky or non leaky confining layers and barriers to ground water movement. The geologic structure has a marked influence on the lateral and vertical extent of aquifers and associated less permeable rocks. The surface and subsurface run off are governed, in part, by geology on which depend the development of land forms, infiltration characteristic of zone of aeration and transmissive characteristics of aquifers. The porosity and permeability of consolidated rocks are attributed to process of rock fracturing and weathering controlled by topography, lithology, structure and climate. The depth of fracturing and weathering as well as the nature of weathered product, together determine availability of ground water and its supply to wells.

The principal hydrogeologic properties of rocks are porosity, effective porosity or specific yield and permeability. These properties control the entrance of water in the water bearing formations. Hydrogeologic properties depend chiefly on porosity, size of openings or interstices and their shape arrangement, interconnection, continuity. Rock formations and the

openings there in are the results of primary geologic processes which form the rocks and secondary processes that modify them by either increasing or decreasing their porosity and permeability.

Volcanic rocks predominantly cover the study area. These rocks exhibit greater variation in their water bearing properties. Basic volcanic rocks like basalts are generally rich in cavities and pyroclastic rocks associated with lava flow are generally porous. However, their permeability varies depending on the inter connection of pore spaces. Opening in volcanic rocks include gas cavities, porous flow texture and structures. Fractures are the principal openings in such rock types. Large fractures, usually few in number are produced by deep seated earth stresses and may extend to a great depth and small near surface fractures may occur in great number.

The aquifers of the study area in relation to potential production are not evaluated significantly. This may be due to the fact that there are insufficient and unevenly distributed boreholes to make quantitative evaluation of the aquifer system. In spite of all these limitations, existing geologic, geomorphic and structural information, borehole (well log), some pumping test and spring discharge data are used as a basis for classification of the aquifer with some degree of certainty.

5.2 Hydrogeological Units and Aquifer Classification

Volcanic rocks which comprise almost more than 90% are the major hydrogeologic unit of the area. The main aquifer of the area is weathered and fractured basaltic lava flows, pyroclastic materials, and paleosol and scoraceous layers. As it has been observed from different bore holes of the area fracture plays a dominant role for the existence of water bearing formation although weathering effect still exists. About 15 boreholes are bored to a maximum depth from 45m-124m in and very near to the study area. In almost all the bore holes the dominant water bearing formation observed is fractured and weathered basalt. Weathering horizon, scoraceous layer as well as undifferentiated alluvial and lacustrine deposits also prevails but the relative thickness of such aquifer is small. These rocks have both primary and secondary porosity. The thickness of Quaternary alluvial and lacustrine deposits especially along the river courses and low land areas of the catchment shows high variability. In the low land areas the thickness is pronounced relative to areas far away from the deposits

The main controlling factors for ground water occurrence and circulation of the area are of different types. The geologic control of the ground water circulation is related to formation of volcanic rocks and their temporal and spatial variation. The volcanic rocks are highly affected by primary porosity. They are characterized by the presence of vesicles. The vesicles in turn are intensively affected by fracture and weathering and produce high permeability zone. Unconsolidated pyroclastic materials of variable size interbedded with lava flow help for lateral migration of ground water. Therefore, the existence of porous and permeable zone in the geologic media controls the overall distribution and circulation of ground water.

The prevailing topography of the area affects the distribution precipitation, movement of ground water as well as discharge - recharge areas and location of productive wells. The precipitation amount is high in Debretabor highland massifs in comparison to other intermediate and low land areas. There is relatively high recharge in the north east and south east part of the study area. Different springs are observed emerging from Debretabor highland areas but their discharge amount is not this much pronounced. Their appearance is due to local ground water flow intercepted by depression, geologic structures and lineaments. Shallow and deep boreholes are localized in the low and intermediate altitude area. The depth to water table is very shallow in low land areas ranging from 0.5m- 6m. The different hydrogeological units and their degree of hydraulic characteristics will be discussed below

5.2.1 Aquifer with Very High Productivity / Quaternary volcanics

The Quaternary volcanics include volcanic lava flows connected to volcanic centre. This volcanic rock is vesicular basalt of plain topography with very low drainage network, indicating that this formation is highly pervious. Such formation is exposed in low lands especially of Bebek, Meneguzer and surrounding areas. These units are highly vesicular and affected by intensive weathering and fracturing. The springs emerged from aquifer are so huge that instant volumetric measurement is impossible. The springs discharge in three different sites in which all the springs are emerging from highly weathered and fractured vesicular basalt. The discharge measurement of the springs from one site (Bahire timket) measured on irrigation canal shows that the average spring discharge is 1045 l/s from the combination of on spot appearance of two springs at the same place. Springs from Bebek emerge from the aquifer in three different localities and their discharges are enormous. These high yield springs are attributed to geological structures especially of faults (WWDSE, 2008)

.Most of the local irrigation project in Fogera plain of that specific area is utilized by these springs. The high productivity of such aquifer is verified west of Bahir Dar where the same aquifer produces about 200 l/s on which Bahir Dar town water supply system depends

The static water level of many hand dug wells in Bebeks and surrounding area is less than 7m. Close physical observation of different hand dug well in the area during the field investigation confirms that the ground water level is shallow. Based on the information from the villagers and Kebele people in the area, there is no any problem in drying of the water in the hand dug well even in adverse climatic conditions.

The main characteristic of this aquifer is the existence of high porosity and permeability. The primary porosities mainly the vesicles are interconnected by the effect of weathering. The primary porosities enhanced by weathering and create favourable condition for the occurrence, movement and considerable discharge of the springs (Figure 5.1A, B and C). The anomalous discharge of the springs may possibly enhanced by other secondary structures like tectonic fractures and fault as well as by primary structures like lava tubes despite there is no clear observation about these structures from surface. The other major diagnostic feature of the area in general is the existence of high concentration of natural ever green vegetation in all the discharge areas of the aquifer

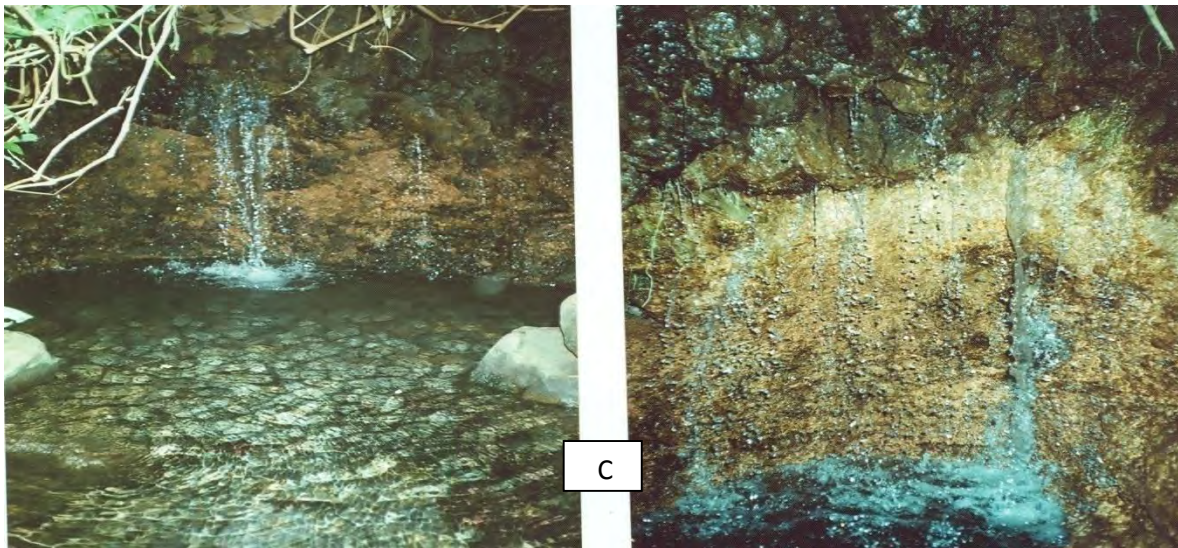
The Wanzaye borehole which is drilled to a depth of 124 m taps the thermal water. The static water level of the well is 0.4 m. During field investigation it is found that the water is flowing out of the well breaking the well head with pressure. The borehole log data shows that the lithology is highly fractured basalt with vesicles filled with greenish pigment or secondary materials (silica precipitates)



A



B



C

Figure 5.1 A, B, C different springs emerging from highly weathered and fractured vesicular basalt in Bebeks area

5.2.2 Aquifer with high productivity /Alluvial and Lacustrine Deposit

Lacustrine and alluvial deposits prevail at the lower elevation of the study area. These deposits are characterized by high permeability porosity and transmissivity. The Shobel deep well located in this formation does not fully represent the alluvial-lacustrine deposits as the well is very close to Tarmaber basalt on the surface. However, well log data from Wereta which fully represents the formation shows that the well log comprises gravel, gravelly clay and sandy clay with significant clay layer at the top and fractured basalt at the bottom. The lower part of the study area before Lake Tana is completely overlain by recent flood materials which are mainly formed by silt to clay deposits (BCEOM, 1999). As it is shown from different borehole log, the underlying rock formation below these lacustrine and alluvial deposits is the basalt lava flow and pyroclastics with moderate weathering. The area occupied by this formation is hydraulically interconnected with the surrounding rock this condition is clearly manifested by the presence of productive wells in Shobel and Wereta with a range of 6l/s-7 l/s. Draw down test from Wereta town showed significant discharge (7 l/s) with 4m draw down. The thickness of alluvial and lacustrine deposit varies from place to place but it is less than 60 m on average. Based on lithological arrangement, piezometric surface condition and pumping test curve the aquifer is confined to semi-confined with clay to silty clay layer at the top and massive basalt flow at the bottom. The discharge and specific capacity of Shobel deep well in this aquifer system is 6.4l/s and 18.4m²/day respectively. The transmissivity and conductivity of the well are 15.64m²/d and 0.4 m²/day correspondingly. But the Wereta deep well has better hydraulic parameter than the Shobel due to the spatial variation of the aquifer.

5.2.3 Aquifer with Moderate and low Productivity /Tertiary Basalt (Tarmaber basalt)

Tarmaber basalt is usually thinning out from their volcanic mount sources (Guna). Thus, the formation provides variable hydraulic properties both vertical and lateral with short distances. This scoriaceous Tertiary basalt is widely distributed in the study area; it covers 80% of the whole catchment. The ground water in this formation is relatively deep as compared to Quaternary basalt. The water bearing nature of this formation is attributed to fractures, weathering and porous pyroclastic materials. The depth to water table in this aquifer varies between 12 m-59 m within the study area. The moderate productive and low productive zone of this aquifer is identified and demarcated in the hydrogeological map. The moderate productive zone consists of Arb Gebya and Jibasra deep wells and Gelawdiwos area shallow

wells. The borehole log data from the deep and shallow wells indicate that weathered and fractured basalt are the main water bearing formations. Pumping test results of Arb Gebya deep well shows that the total draw down of the well is 4.37m with high transmissivity and conductivity but with low storativity ($164.2\text{m}^2/\text{d}$, 7.8 m/d and 1.33×10^{-5} respectively). The existence of this productive well in moderately productive aquifer is attributed to the location of the well with respect to the orientation of lineaments. Field observation of the well site during sampling indicates that the well is located at the junction of two lineaments. The lineaments are grooved surfaces covered with grasses and vegetation and slopping towards the well. Similarly, the well in Jibasra Mariam has similar effect. It is structurally controlled deep well with discharge conductivity and transmissivity of 10 l/s , 2.2 m/s and $64.4\text{ m}^2/\text{d}$ respectively. The existence of this productive well in the area doesn't mean that the aquifer is more productive. It is the locations of the well with respect to the prevailing structure that make the well productive. However, further assessment of the deep wells with the same formation in Dera Hamusit and Debretabor Hamusit shows very poor production less than 3 l/s and is depleting through time.

In the low productive aquifer of the same formation there is no location of deep wells as the geomorphology of the area doesn't allow to doing so or it is costly to get water from the water bearing formation as the area is dominantly in the recharge zone. Different springs are found emanating from hill sides and even in depressed areas near to the rivers. The discharge of the springs in this area is totally below 1 l/s .

5.3 Identification of Aquifer Types

Identification of the different aquifer types existing in the area needs thorough investigation of the aquifer system with integrated investigation techniques. However, the investigation in this research merely depends on borehole log records and pumping test data analysis of draw down versus time in the in the log-log scale and comparison of the draw down behaviour with different theoretical models. Despite the borehole lithological data is very useful for aquifer identification; it is not consistent to identify the type of aquifer with full confidence. The main reason for this is that it is not always possible to get accurate and representative samples of the formation. Such problem is more pronounced especially during drilling with mud. The second reason is that lithological log at the well site may not fully represent the large extent lateral variation of the aquifer system. The aquifer at the well site may be very thick and comprised of only one lithological unit or may be pinched out and is

different from other borehole logs in the nearby area as subsurface geologic formations are a bit complicated with internal processes during the formation of the geologic units.

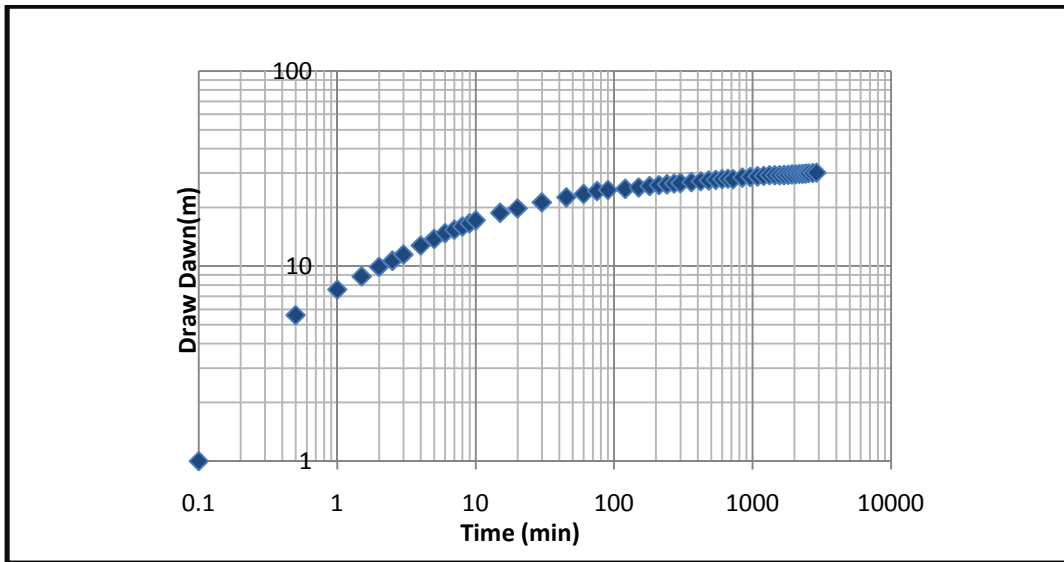
Regardless of these problems, the bore hole and hand dug well data dictates the existence of different aquifer systems in the area. Most of the hand dug wells constructed at the time of field investigation in different sites show unconfined aquifers. The ongoing and completely finished hand dug well lithological data around Gassay, Awzet and Debretabor highland areas show that the top soil is followed by highly weathered volcanic ash and pyroclastic material. This is a clear indication of the existence of shallow unconfined and perched aquifers. The bore hole lithological data on the other hand shows a bit deeper stratification of the aquifer. The common top layer of most of the deep and shallow wells of the area is clay with variable thickness from 2m in hard rock area to about 30m in alluvial deposits. The alternative change of the bore hole log data of clay with weathered and fractured basalt at relatively upper horizon and the alternate variation of highly weathered and fractured volcanic rocks and pyroclastic materials with massive basalt in relatively deeper zones of the well give rise to confined aquifers of multiple layers. Examples include Shobel, Hamusit and Arb Gebya boreholes. As the layer between the aquifer may not be hundred percent impermeable, the aquifer possibly acts as a semi-confined aquifer, too.

The existence of Wanzaye borehole that abstracts thermal water is another indication of the existence of a deep aquifer system. The aquifer in this well is a confined fractured aquifer as it is indicated from the borehole data as well as the plot of the pump well data and comparing it with the theoretical curves (Figure 5.2b). However, generally it is possible to say that the shallow, intermediate and deep aquifers exist. Shallow unconfined aquifers are common as shown from many hand dug wells. Leaky and confined aquifers also exist especially from shallow and deep boreholes.

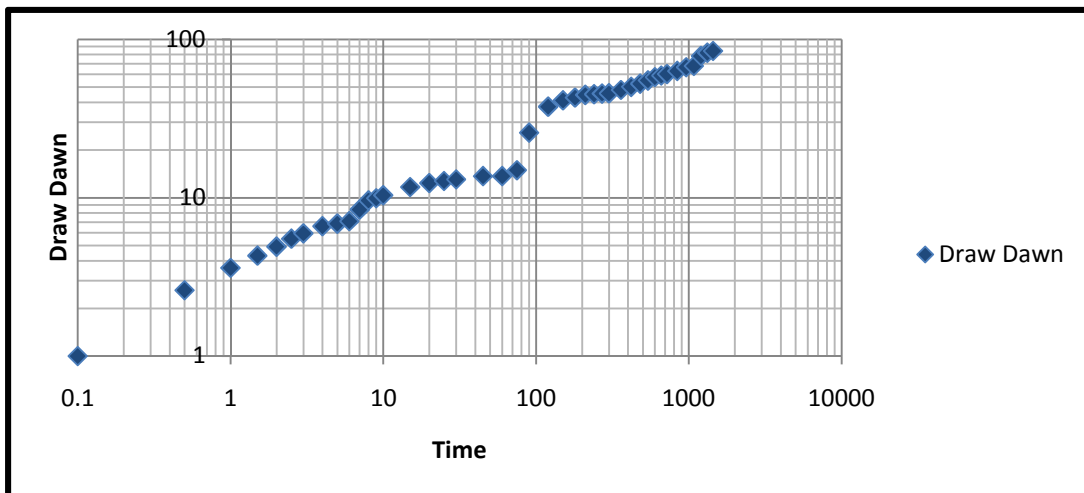
The identification of aquifer from the draw down versus time also gives some highlights about the type of the aquifer despite it is not complete by itself. The plots from pumping well data of four boreholes are displayed below. The three boreholes except Wanzaye show more or less similar curves and the aquifer corresponding to them clings to confined type. It also resembles semi-confined too, as the graph for both is nearly similar. The aquifer in Wanzaye borehole is a confined fractured aquifer type.

Figure 5.2 Draw down Vs time plot of deep wells

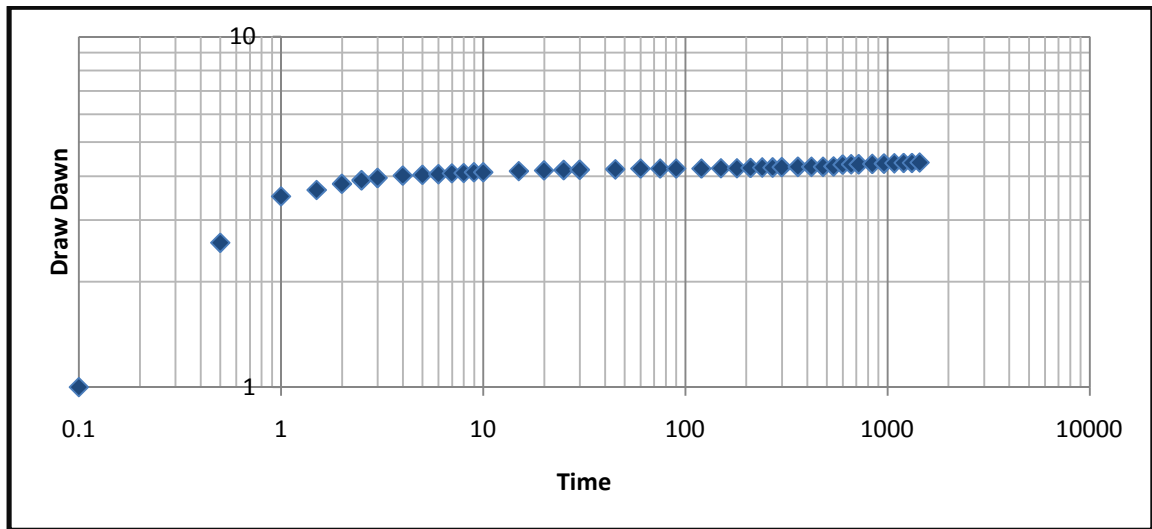
a) Draw Dawn Vs Time plot of Shobel deep well



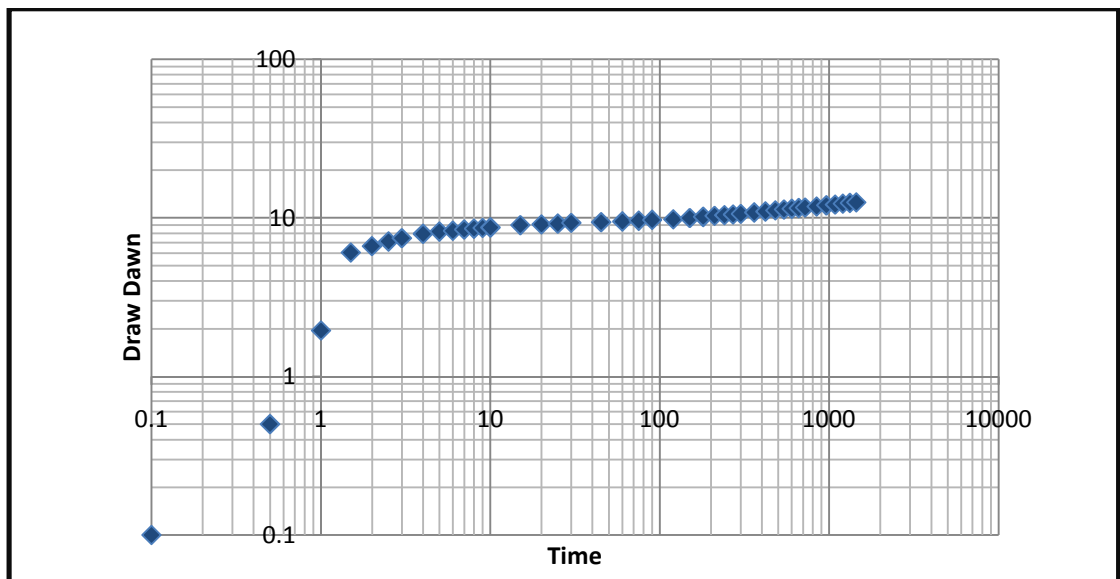
b) Draw dawn Vs Time plot of Wanzaye bore hole



C) Arb Gebya Deep well



D) Draw Dawn Vs Time Plot of Jibasra Maria Deep Well



As described above the aquifer characterization is more of qualitative in that the data for quantitative characterization is limited. Characterizing the aquifer with respect to aquifer property and mapping of the area with different hydraulic conductivity zones needs sufficient borehole data. To compensate such problems field observation of the different hydrogeological parameters such as degree of weathering and fracturing, grain size of the geological materials, primary and secondary porosities, water resources distribution, discharge amount and consistency of the schemes have been used.

5.4 Ground Water Recharge and Discharge Condition

Ground water recharge refers to the entry into the saturated zone of water made available at the water-table surface and groundwater discharge is the removal of water from saturated zone across the water table surfaces. Water enters ground water systems in recharge areas and moves through them, as dictated by hydraulic gradients and hydraulic conductivities to discharge areas. These two processes are so much interrelated that they cannot be taken part independently. It has already been mentioned that recharge of ground water depends on many factors, such as permeability of the formation, vegetation cover and slope.

The major source of ground water recharge in the study area is rainfall. Rainfall entering the soil at the surface (infiltration) replenishes the soil-moisture deficiency and excess water percolates and reaches the ground water table. The infiltration depends upon intensity and duration of rainfall, topography, soil types, vegetation cover, land use, initial soil moisture contents and depth of water as it has been mentioned earlier. The rainfall accounts about 1377 mm/year on average but the high land area of Debretabor receives Rainfalls fall amount up to 1514mm.

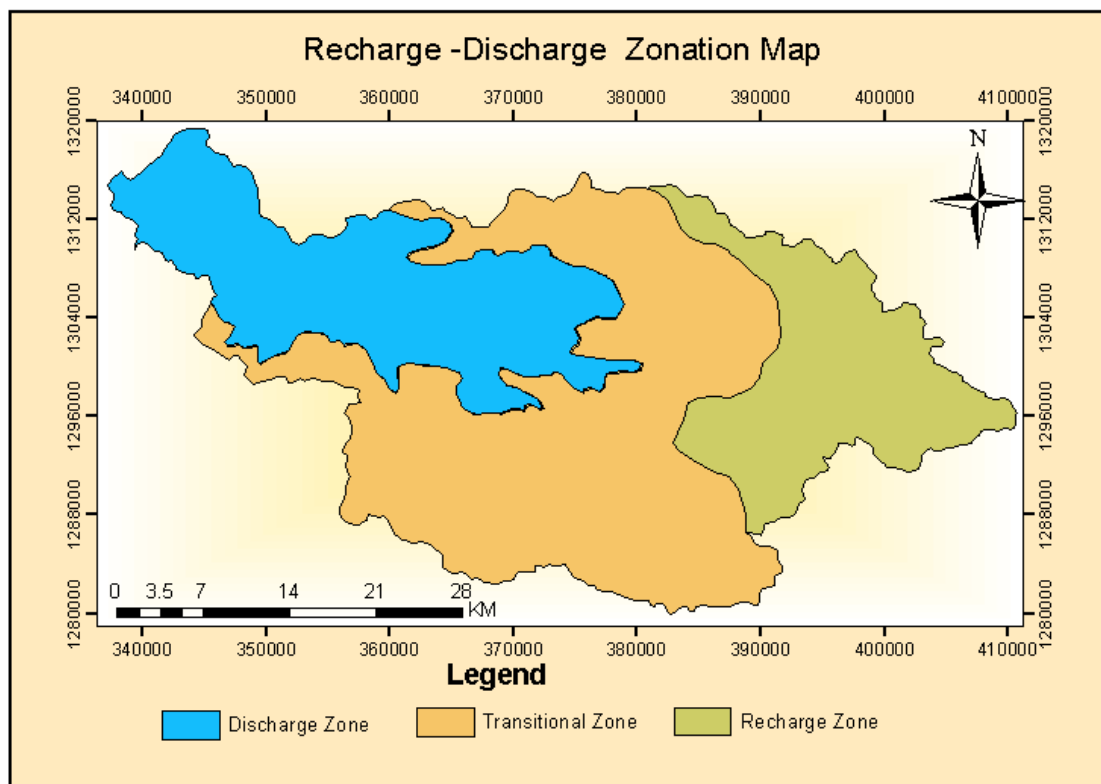
Ground water is discharged by springs of high land areas especially from Tarmaber formation. The single discharge amount of the springs is not pronounced despite there are many springs discharged in various places of high land area of this formation. Significant discharge is found in low land area in the form of seepage and potential spring discharge. The natural discharge from ground water system includes not only the flow of sprigs and flow of water into streams or wet lands but also evaporations from upper parts of capillary fringe where ground water is very close to the surface. The condition is expected in the study area of low lands where the ground water level is very close to the surface.

The groundwater recharge areas for both the deep and the shallow aquifer are mainly the mountain chain of Guna and Debretabor highland areas. Recharge areas are usually topographically high land areas and the discharge zones are the respective low lands. In recharge areas there is often a rather deep unsaturated zone between the water table and the land surface. In contrast, the water table is found either close to or at the land surface in the discharge areas. Shobel and Wanzaye deep wells static water levels are very close to the surface in the discharge area. There may be physical manifestation of the discharging ground water which can take the form of spring or water indicator vegetations (Fetter, 1994). The recharge and discharge areas are relative terms and are identified based on various parameters

of which topography and depth of static water level play more significant roles. It is rare that there is absolute discharge and recharge areas. From direct field observation, deep wells are not developed in highland areas of Debretabor such as Mynet, Awzet, Sores and surrounding Kebele. People utilize natural springs and develop hand dug wells from shallow perched aquifer of pyroclastic and highly weathered lava flows. Water supply problem in Debretabor town is resulted from lack of sustainability from boreholes unlike Wereta which is provided with sufficient amount of water from wells not more than 60 m deep. This is due to the fact that Debretabor is situated in recharge area relative to Woreta.

The recharge, discharge as well as intermediate zones in the study area are delineated by using different parameters. Topography one major factor which has to be considered. High land areas are a clear indicator of recharge areas as ground water always moves away from this area. The second important parameter that has been considered is the ground water flow patterns which will be discussed in the coming section. The divergence and convergence of vector flow lines is indicator of the recharge and discharge areas respectively in general. Lastly the depth of static ground water level which has been inventoried also contributes for the demarcation of the recharge, transitional and discharge zones.

Figure 5. 3 Recharge Discharge Zonation Map



5.5 Ground Water Flow System and Direction

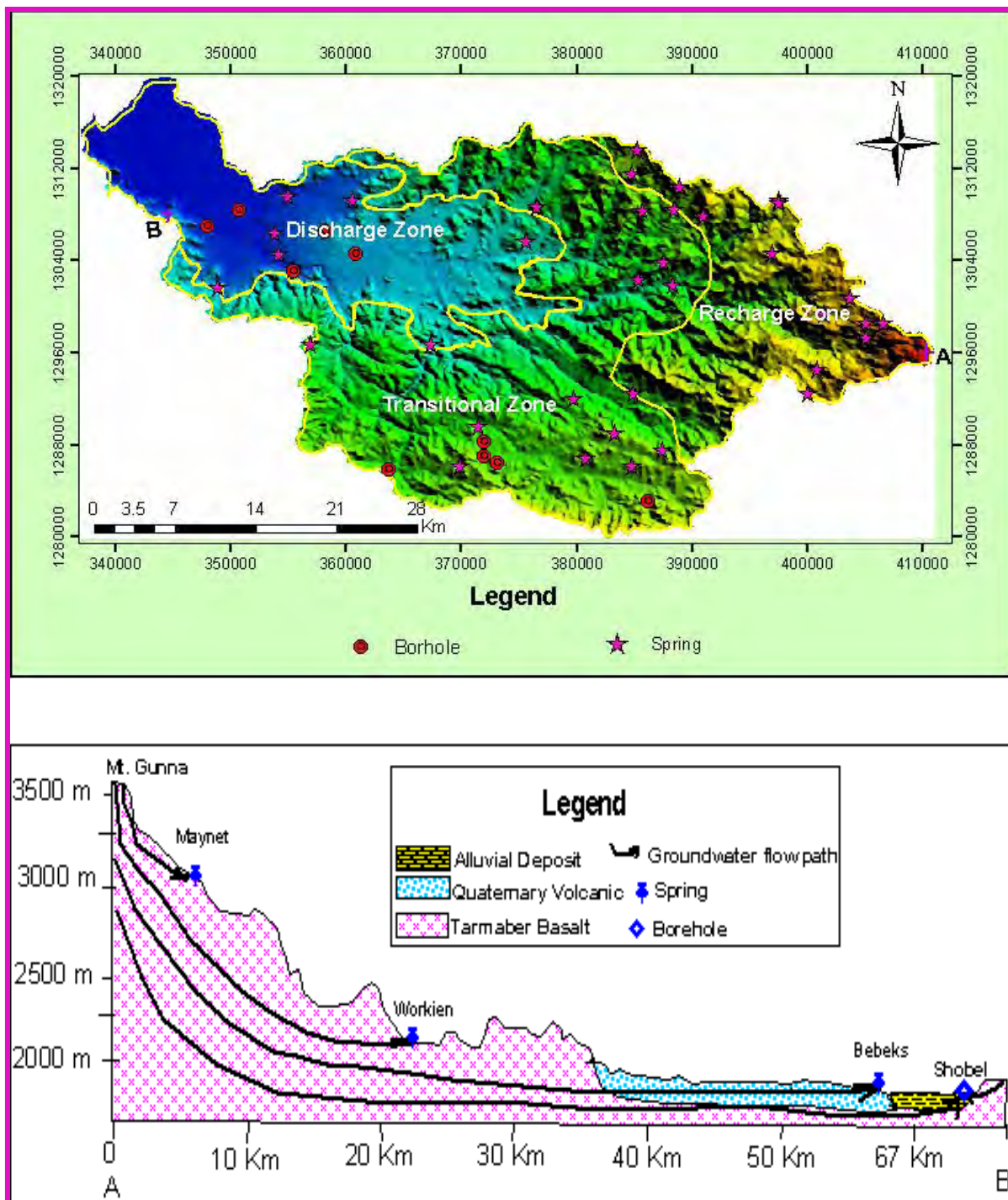
It is important to determine the position of the water level and the direction in which ground water moves because many water related projects and constructions are highly influenced by ground flow system. Ground water is driven by lateral variation in topography in water table or phreatic aquifers. Local relief in topography is high that causes local system of ground water flow. Due to pronounced local relief various condition of ground water flow in local and intermediate flow systems possibly exists. However in phreatic aquifer the regional system of ground water flow may be considered similar to surface water flow condition. In the study area the flow system generally follows the topographic variation. The local ground flow direction varies within small areas depending on the topographic effect at the shallow depth where as the regional ground water flow shows the general direction at a depth.

Unlike many sedimentary basin aquifers, which are characterised by similar groundwater flow pattern and continuity over vast regions; the groundwater dynamics and recharge mechanism in volcanic terrain remains challenging system. This is confirmed by the presence of highly variable groundwater flow patterns, chemistry, groundwater depths, occurrences, and discharge mechanisms. The general implication is that the dominant and even in some cases the sole source of recharge to the aquifers or thermal waters of the area comes from groundwater inflow from the surrounding highlands. Wanzaye and Guramba thermal springs located in the area indicate the presence of variable groundwater chemistry, depth and groundwater occurrence in the region. This implication put forward a complex groundwater dynamics. Because of disruption of the lithologies by faults, often aquifers are laterally discontinuous, and flow paths are the function of interplay between tectonic features and secondary permeability related to volcanic structures (Seifu Kebede et al., 2007)

The uniform topography produces a single flow system, but hilly topography produces different sub systems. The study area comprises of different topographic relief as a result the three major flow systems exists as a result of this variation. Field observation of the different water scheme shows that there exists variable discharge amount, difference in the sustainability of the scheme in different topographic features. The Debretabor highland area is characterized by low discharge springs emanated from hillsides. In some localities of the springs dry out and the developed scheme remains without service. At intermediate altitude the springs provide better discharge than the highland ones. The low topography springs of

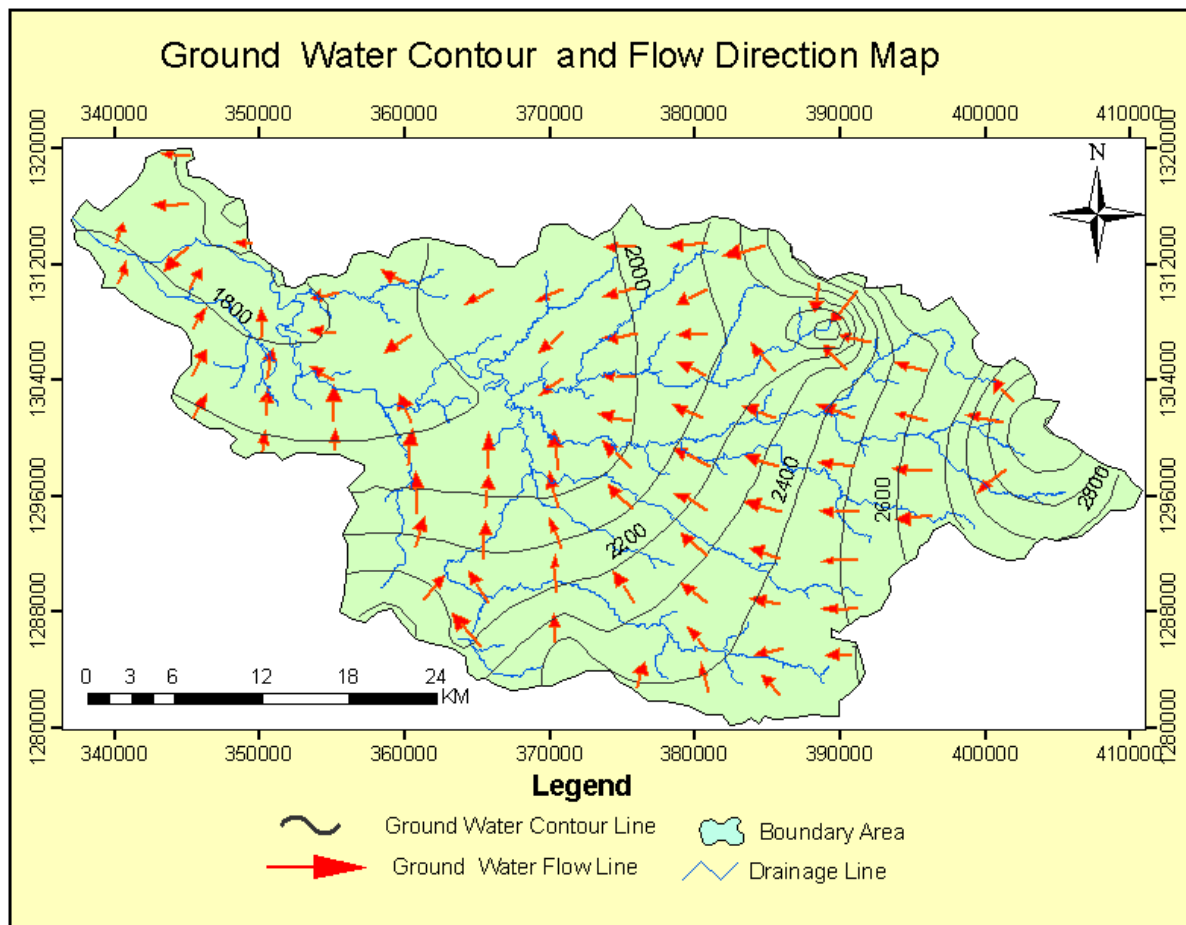
Bebeks area deliver very significant amount reflecting the regional ground water flow system. The local, intermediate and regional ground water flow system from recharge to discharge area is conceptualized in figure 5.4 below.

Figure 5.4 Conceptual ground water flow system from recharge to discharge area (local, intermediate and regional flows along A-B Cross section)



Ground water is normally hidden from physical observation; as a result many people have difficulty in visualizing its occurrence and movement. This difficulty affects their ability to understand and to deal effectively with ground water related problems. The problem can be partly solved through the use of ground equipotential lines and flow directions (lines). The relationship between equipotential lines (ground water contours) and flow directions of Gumara river catchment is displayed in ground contour and flow direction map figure.5.5 below. It is clearly depicted that the general flow direction is from east to west reflecting the surface topographic feature. The local irregularity is due to local topographic variations, discharge zones, deep wells and no flow boundaries. Close observation from the contours and flow direction map indicates that vector lines below 2000m are dominantly converged indicating the discharge zones.

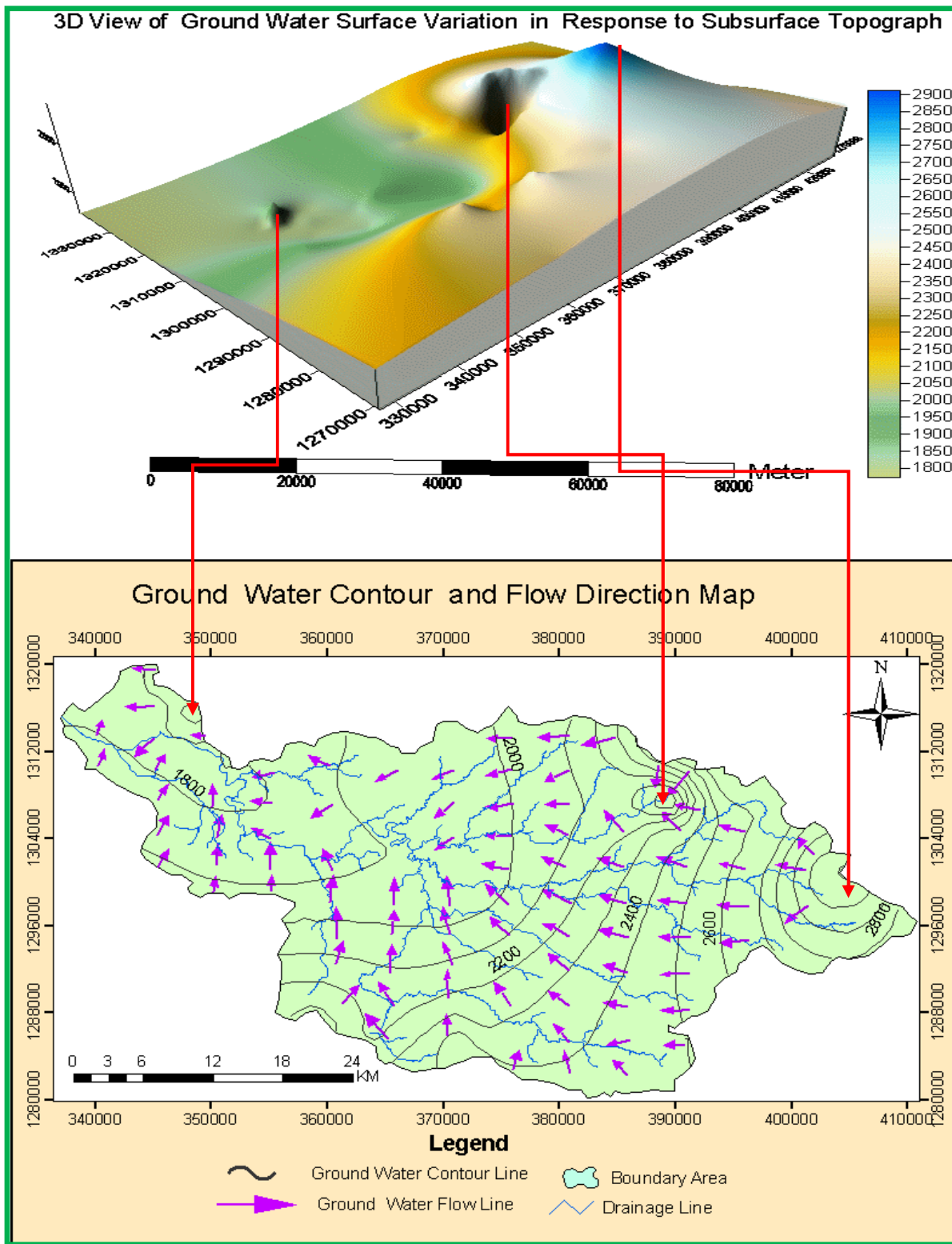
Figure 5.5 Ground Water Contour and Flow direction Map



Further investigation in identifying the controlling factors in the nature and flow patterns of ground water flow enables to visualize the ground water surface and its relationship with surface and subsurface topographic features. In two dimensional ground water contour and

flow direction map abrupt change in flow direction is observed by convergence and divergence of the flow lines. However the three dimensional view provides a clear picture and shows the controlling factors which affects the pattern. Accordingly, a high peak near Gassay, a gorge near Debretabor and a small peak in the low land area are found which significantly affects the flow pattern of ground water along its flow path (Figure 5.6).

Figure 5.6 Effect of subsurface topography on ground water flow pattern



5.6 Ground Water Surface Water Interaction in the Catchment

Ground water and surface water are closely interrelated components of the hydrologic system. They interact in a variety of physiographic and climatic landscapes. In many regions surface water and ground waters are interconnected and exchange their constituents as a result the quality of one resource can therefore affects the other.

Interaction between the stream and groundwater in the area needs detail assessment of the entire catchment. However, there is no observed data of ground water level changes and stream discharge rates, ground water data for extraction boreholes, peizometric transects, stream hydrographs, stream bed and static water level of neighbouring well in the area under investigation. Due to such reasons, the interaction of surface and ground water is evaluated using the basic principle and relationship that govern ground water surface water interaction. The principle is based on theoretical back ground which indicates the interaction of streams with ground water. Streams gain water from inflow of ground water through the stream bed (gaining stream), they lose water to ground water by out flow from the stream bed (losing stream and/or do both along the course of travel or sometimes they may not interact at some portion of stream reach.

The relationships can easily be displayed from ground water flow lines. Ground water flow lines converge towards the streams in gaining streams, moves away from the stream in losing streams and moves parallel to the stream whenever there is no interaction between the surface and ground water. As it is depicted from the flow pattern, at the higher elevation in the recharge areas and intermediate or transitional zone the interaction between the streams and ground water is not significant. This may be attributed to the existence of linear features which run parallel to the river courses. In the low land areas, however, vector lines are found to direct towards the stream indicating gaining reach of the stream and moves away from the river course which shows the losing stream reach.

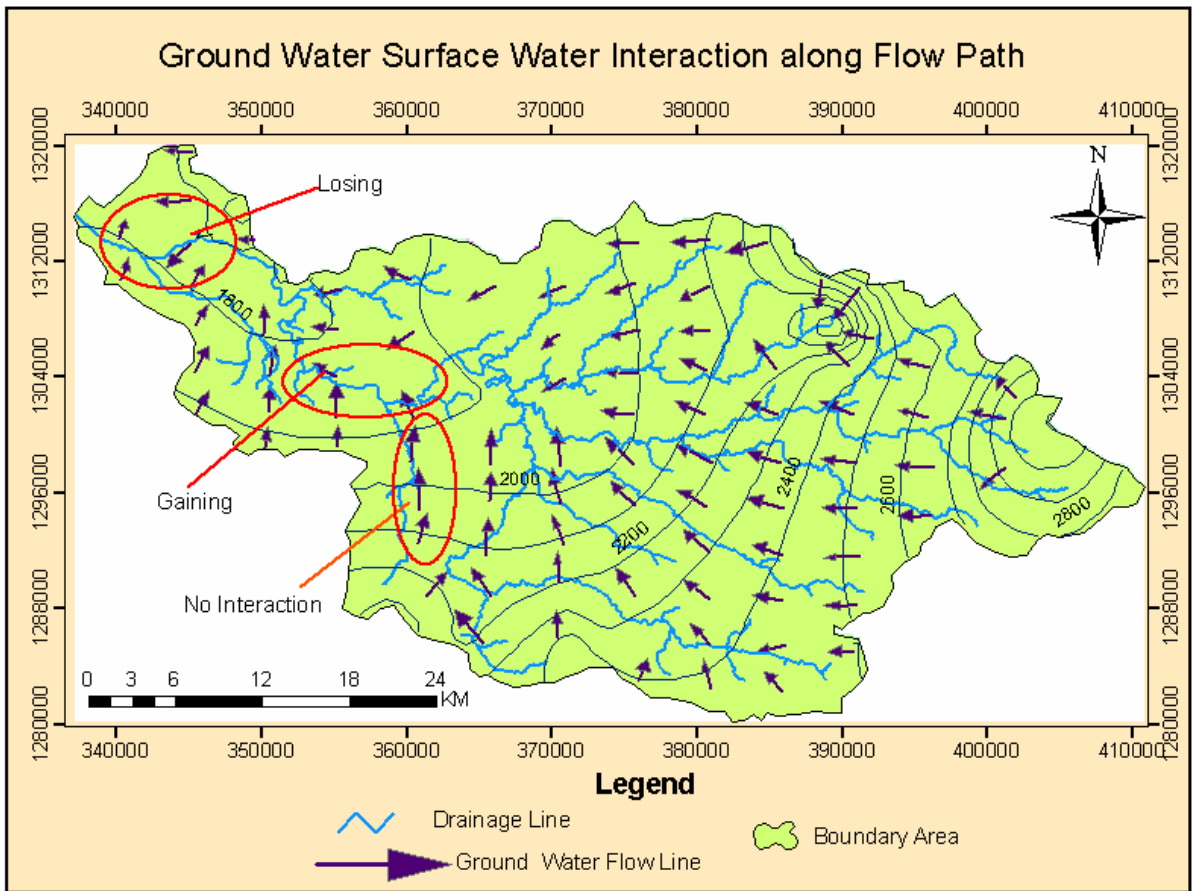


Figure 5.7 Ground water surface water interactions along the flow path

5.7 Water Points

Secondary data on springs, hand dug wells and boreholes have taken from different organizations. Actual field observation, georeferencing and measurements of the various schemes of the water points supplement and fill the gap of secondary data. There are lots of springs and hand dug wells in the study area. Of all the springs a few are inventoried and used for further analysis of the data. The number of hand dug wells in the area is very great due to availability of shallow ground water especially in Dera and Fogera plains. The number of boreholes in the area is very small compared to springs and hand dug wells. Additional borehole data in the vicinity of the catchments which possibly provide further information regarding the aquifer, ground water flow, and the chemistry of the water are also acquired. Despite the existence of numerous springs and hand dug wells only some of them which are considered to be representative are selected and examined.

5.7.1. Boreholes

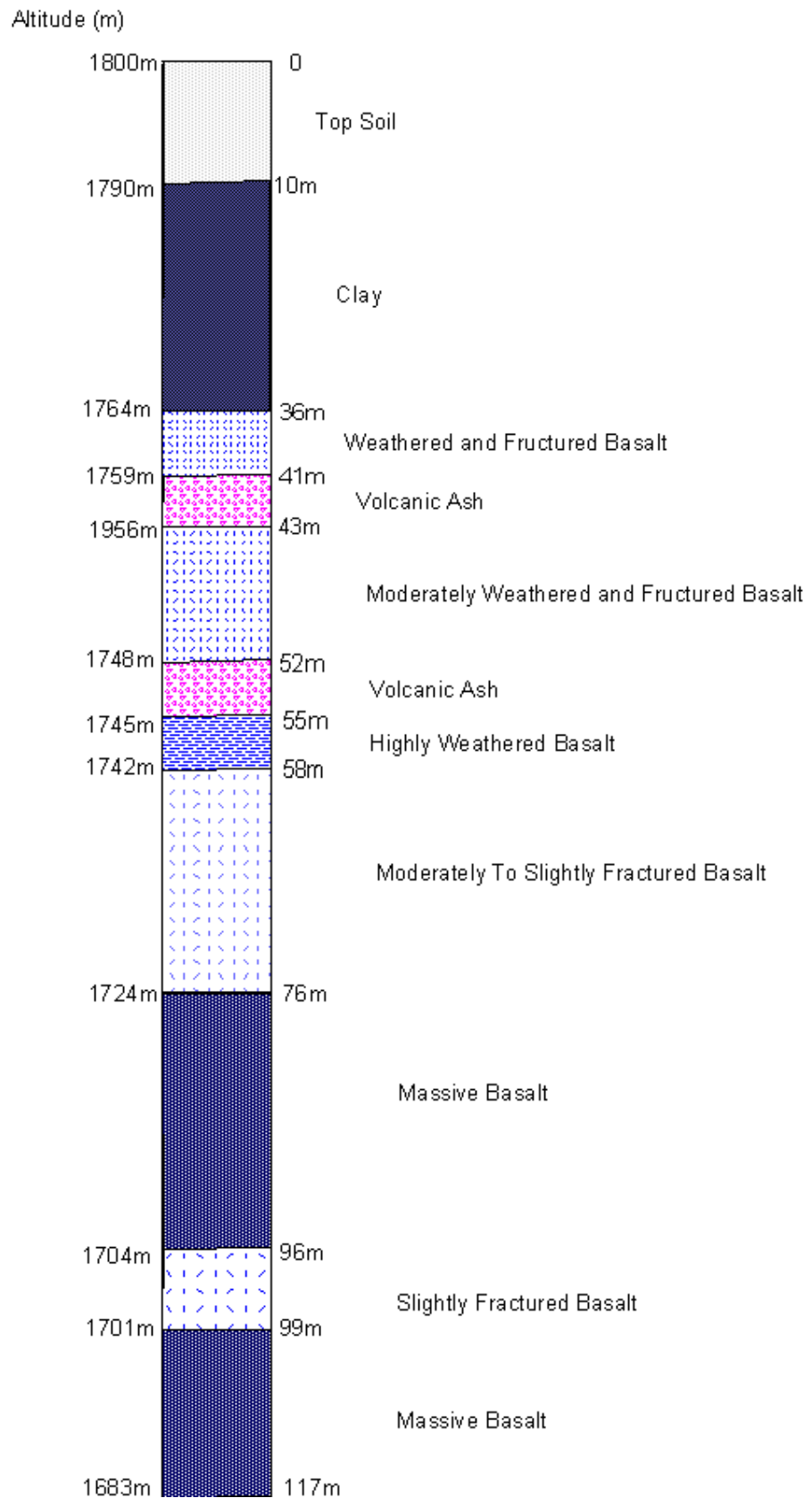
Most of the boreholes in the study area are localized in places where public concentration is high especially in or near towns. Hamusit, Arb Gebya, Wanzaye and Jibasra deep wells are constructed to supply the people in the town or village with available water. The rural people are devoid of such service except the prevailing hand dug wells and recently drilled shallow boreholes especially in Dera areas by world vision development program. There are ten boreholes in the study area of which four are deep and the remaining are shallow. Two of the shallow boreholes in Aba Kiros Kebele are not functioning during field investigation due to current technical problems. Due to such problems, it is impossible to sample the despite the water exists in the borehole. The borehole in Wanzaye area is different from others because of the appearance of geothermal water in this well. The well was drilled to provide domestic water for the people there; however the geothermal water is tapped and come to the surface easily. The total depth of the well is 124m and the static water level was 0.4m during the construction of the well. It has been observed during the field investigation that the water from the well is flowing to the surface with pressure. The in situ hydrochemical field measurements (T^0 , pH and EC) show that the water has the same parameter as the adjoining thermal springs.

Figure 5.8 Wanzaye Borehole (thermal water)



The static water level in the boreholes generally ranges from 0.4m in Wanzaye to 59.02 in Arb Gebya. The Static water in shallow boreholes of Gelawdiwos (near Arb Gebya) varies between 25m and 40m indicating that water level in relatively elevated area is deeper. As the borehole log data display, the bore hole especially of deep wells intercept various strata and aquifers. Unconfined, semi-confined and confined aquifers are intercepted by a single well indicating the existence of multilayer aquifers irrespective of insufficient information about the vertical and lateral variations of the aquifers with limited data sources. The hydraulic properties of the wells are displayed in the hydrogeological map (Figure 5.12)

Lithological Log of Shobel Borehole



5.7.2. Springs

Of all the springs in the area only about 35 are used. These springs have relatively better information and some of these are checked during the field investigation.

Most of the springs in the study area issue from Tarmaber formation in the highland area of Debre Tabor. The springs in this formation commonly produce less than 2 l/s and dominantly contact and depression springs. Springs from quaternary volcanic rocks on the other hand are located in flat topographic terrain and have very high discharge. Three spring sites from Bebeks Kebele individually produce more than 20 l/s. Of the three springs the one entitled Bahir timket (two springs from common source) produce 1045 l/s. This is equivalent to a small river that produce a discharge of $1.045\text{m}^3/\text{s}$. The springs emanate from highly weathered vesicular basalt and seem structurally controlled though the structures are not clearly viewed on the surface. Springs are generally evenly distributed in volcanic rocks but are rare in lacustrine and alluvial deposits in the study area.

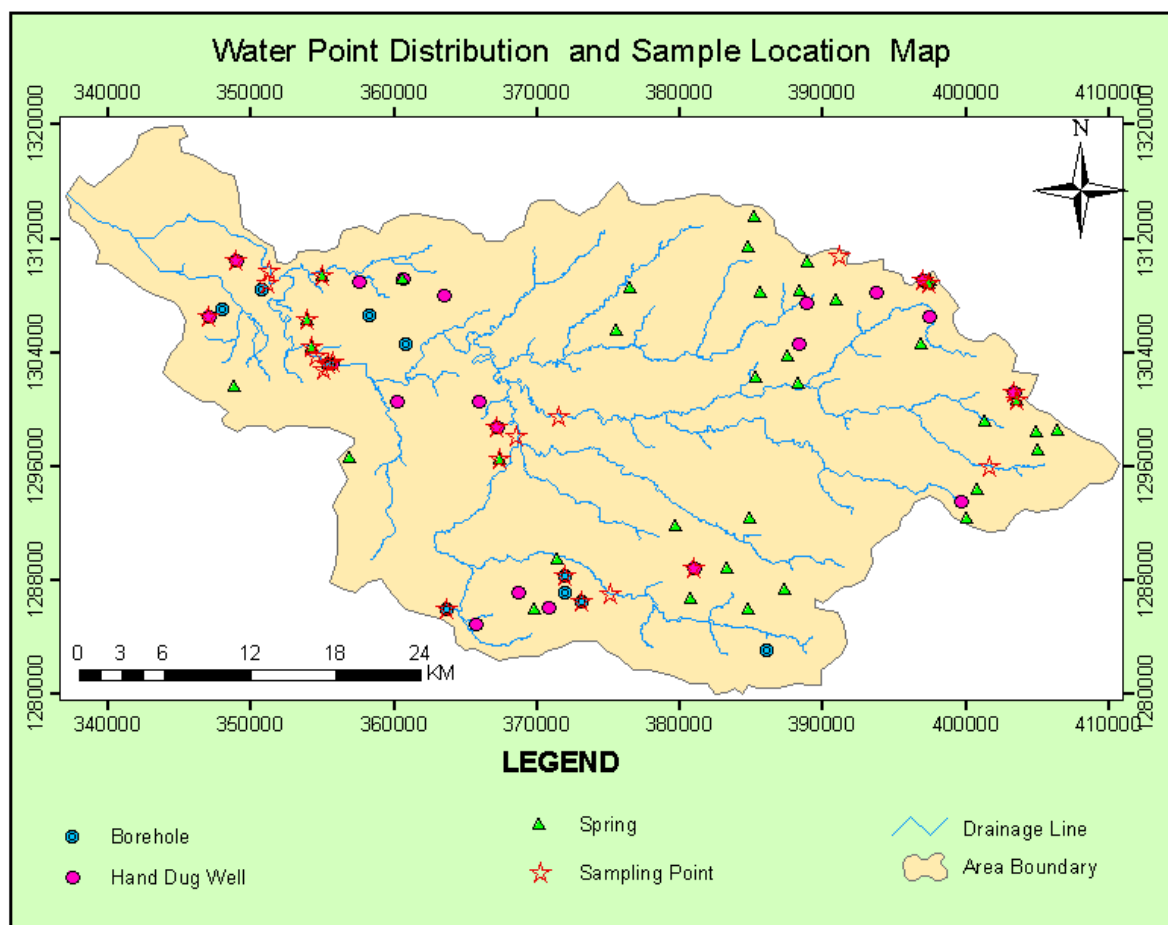
Figure 5.9 High discharge spring from Bebeks (Bahire Timket)



5.7.3 Hand Dug Wells

They are widely distributed in all part of the study area regardless of variation in latitude. Of all hand dug wells, more than 80 are inventoried in this study. More productive dug wells are located in Quaternary volcanics and alluvial and lacustrine deposits. The existence of many dug wells with static water level not more than 6m and minimum fluctuation in Bebeks area shows that the ground water is close to the surface. Most dug wells in Debre Tabor highland areas are localized in weathered pyroclastic deposits. This deposit is relatively good water bearing for shallow aquifer system. The depth of Dug wells in the study area range from 6m to 19m and the static water level ranges from 1 to 8m.

Figure 5.10 Water point Distribution and sample location Map



5.8 Hydrogeological map

The hydrogeological map of the study area has been prepared by evaluating various hydrogeologic parameters. There is no sufficient lithological log and pumping test data that enable for quantitative evaluation of the various aquifer parameters and preparation hydraulic

conductivity map. Instead field evaluations of the hydrogeological units in terms of porosity permeability degree of weathering as well as the assessment of the various schemes of the area regarding the discharge, sustainability and depth to water level have been carried out. Such evaluation is supplemented by few pump test data of the area and nearby area or adjacent catchment. The pump test data after analysed with Aqua test Software provide the aquifer parameters of existing wells in the area. The hydraulic properties of the wells are demonstrated in figure 5.12 below. Such figure is part of the hydrogeologic map, but insufficient space to represent all information in a single map made the preparation of two separate maps.

Figure 5.11 Hydrogeological Map of Gumara River catchment

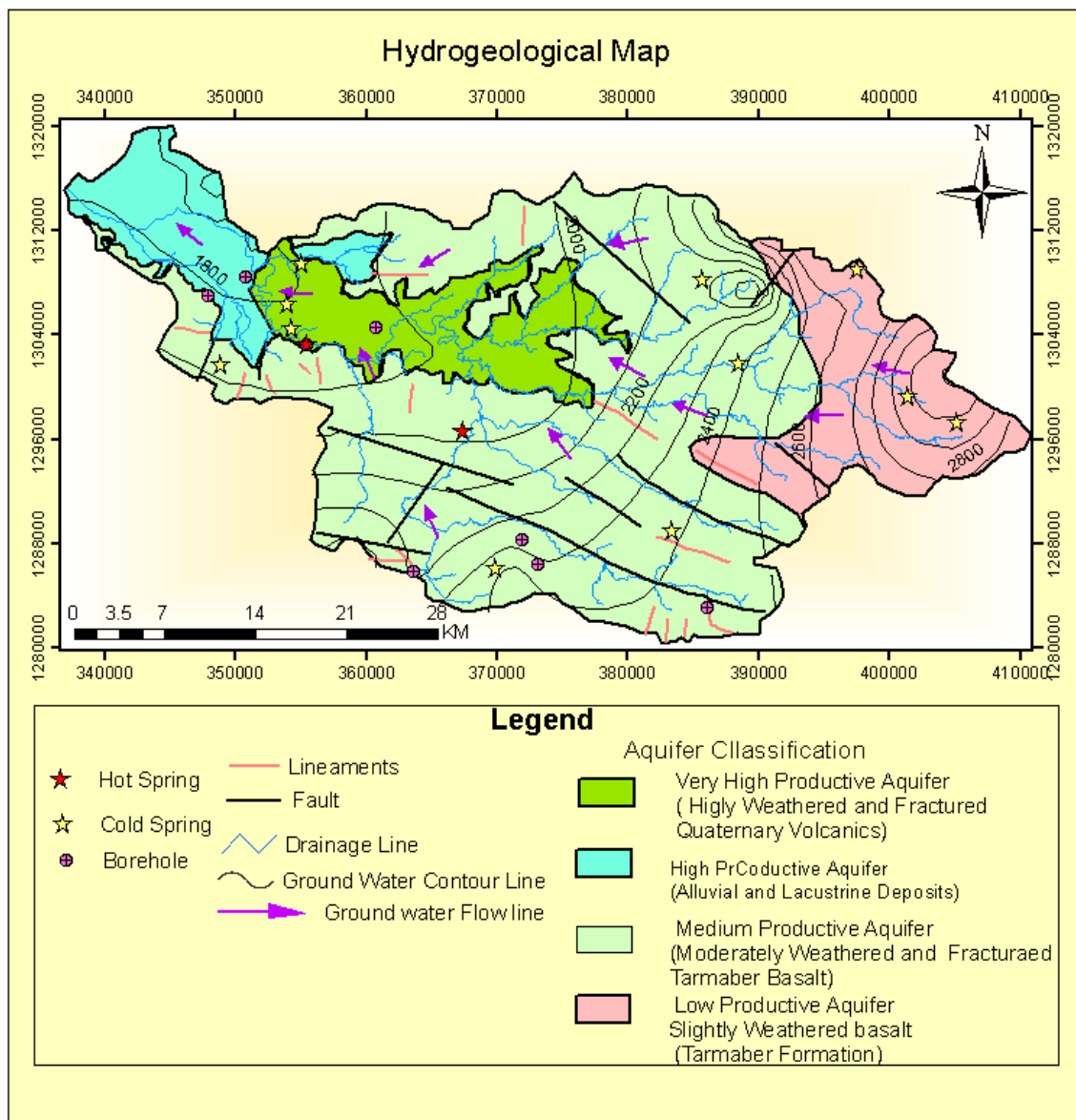
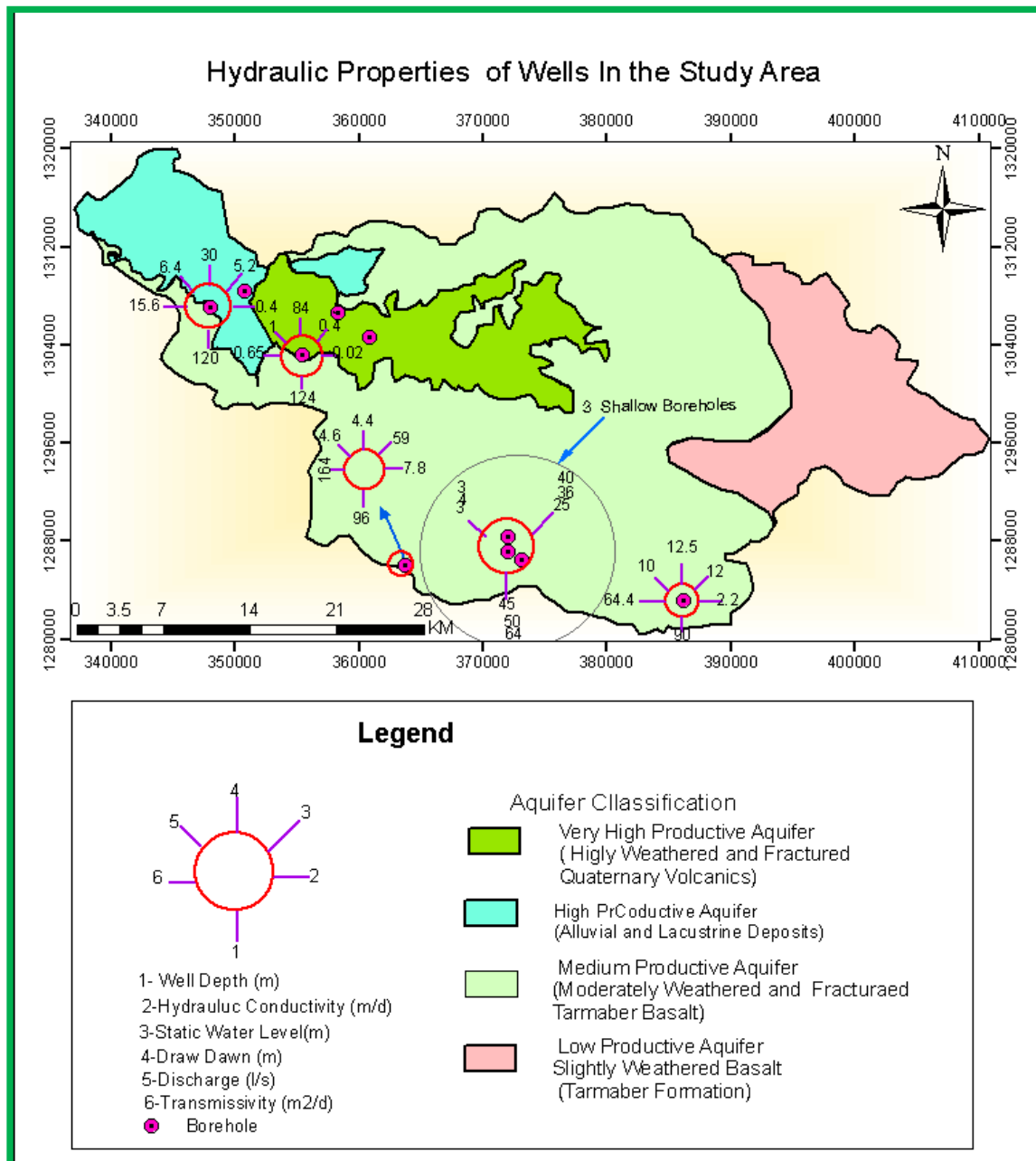


Figure 5.12 Hydraulic properties of existing wells (Boreholes)



CHAPTER SIX

HYDROCHEMISTRY

6.1 Introduction

In ground water potential assessment studies, evaluation of the quality of ground water is an important as the quantity in such a way that the usability of ground water available is determined by its chemical, physical, and bacteriological properties.

The geochemical properties of ground water generally depend on those of the recharge water and on the subsurface geochemical processes. These control the water quality during the course of its underground movement by raising or lowering the amount and kinds of dissolved solids (Matthess, 1982). The scale of changes of the dissolved constituents is dependent on the physical and chemical properties of the surrounding rocks, the water temperature, salinity of water and its chemical content, the volume of water in movement and its velocity, periodic change of recharge water and the hydrologic and human factors. The way in which solutes are taken up or precipitated and the amount present in solution are influenced by many environmental factors, especially climate ,structure and position of the rock strata and biochemical effect associated with life cycle of plants and animals, both microscopic and macroscopic (Hem,1992). Freeze and Cherry (1979) had also described the effect of geochemical processes on ground water in altering the natural ground water chemistry as the water moves from recharge to discharge areas.

As it has been described above the geochemical properties of ground water varies due to various factors both natural and manmade. The variations in ground water properties cannot be easily understood unless physic-chemical analysis of the water samples is carried out. Physico-chemical analysis forms the basis of interpretation of the quality of water in relation to source, geology, climate and use. In a given basin or catchment the chemistry of ground water varies spatially and the spatial variations possibly produce an impact on different water utilization programs such as domestic water supply, irrigation, industry etc. Therefore, to visualize over all variations, sampling of representative water points, in situ measurements of certain parameters of the water (T^0 , EC, TDS, pH, etc) and laboratory analysis results of the collected samples are mandatory tasks to be accomplished prior to interpretation of the geochemical data.

6.2 Water Sampling and Analysis

The sampling of water points in the study area has been carried out first by selecting representative sites in which the water point exists. Twelve duplicate samples have been collected from different sources and are supplemented with previously collected secondary geochemical data. The samples consists of four samples from springs, three from boreholes, three from Hand dug wells and one form river and one from rainfall but rejected due to significant reaction error. Each sample is taken with a one litre plastic bottle. Representative samples have been taken from each water sources at different locations (Figure 5.10). A total of 25 samples together with the secondary geochemical data taken from WWDSE have been used for interpretation and evaluation of the geochemical spatial variation of the study area. The primary samples are analyzed in the laboratory and the analysis result supplemented with secondary data can make the data liable for hydrochemical interpretation. The accuracy of the analytical results of the chemical data was examined for reaction error prior to the interpretation. Nearly all data are within the limit of acceptable error (< 5%) only two samples are between -5 % to -10 % and are used for the purpose of data processing. Reaction errors are determined as a method to assess data quality with the following relationship.

$$Reaction\ Error = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 \dots \dots \dots (6.1)$$

The Natural water is sampled in view of carrying out various analyses on it. In the study area secondary samples are collected from different water supply schemes that are found within the catchment.

Field and laboratory measurements of pH, EC, TDS and Temperature have been conducted. Measurement index parameters such as pH, EC and Temperature are measured with pH-meter, EC-meter and Hannan immediately during sampling. The main objective of measuring EC and pH is to assure the change in chemical constituent of the sample between sampling and laboratory analysis. If the sample is not well preserved or if there is problem during transportation, then certain chemical reaction or precipitation of certain constituent ions will possibly take palace. The measurement of field parameters like pH and EC is helpful to approve the degree of changes of the sample constituents that are not analysed but as important as common measured ions. EC measurement helps for example if some of the major ions are precipitated between sampling and analysis. It is also used to determine if there are dissolved ionic constituents that are not analysed but as important as common measured ions. The closer the result between the fields measured values and the

corresponding laboratory measurements the better is the sample preservation. During field measurement, no significant change is observed within each parameter spatially except an abrupt change in temperature and pH measurement that occurred in Wanzaye borehole and spring. The temperature in these samples rise to 38.4⁰c unlike all other measurements which are below 25⁰c. The water in these two samples is thermal water which possibly comes from a deeper horizon via deep structures.

Recharge at around Guna shield volcanoes, flow of Ca-HCO₃ type water through a metamorphosed zone of the Miocene lignite bed and sink of CO₂, exchange of Ca for Na and K in the zone, formation of high pH and high SiO₂ water plume, emerge Na-HCO₃ water at low TDS and pH (Seifu Kebede et al.,2005)

6.3 Temperature, pH, EC and TDS

Temperature, pH, electric conductivity and total dissolved solids are some of the parameters that are measured both in the field during sampling and in the laboratory. The overall effects of these parameters and their contribution on the chemistry of water in general and water of the study area in particular will be discussed the following section.

6.3.1 Temperature

Water temperature is an important property that determines water suitability for human use, industrial applications and aquatic ecosystem functioning. Water temperature can affect the dissolved oxygen content, an important water characteristic that strongly affects many aquatic organisms. The temperature of water is controlled primarily by climate. Field measurement evidence shows that the temperature recorded in relative high elevation (2924m) areas of Debretabor (Awzet) is 15.98⁰c and relatively lower elevated (2220m) area of Arbgebya is 24.6⁰c.

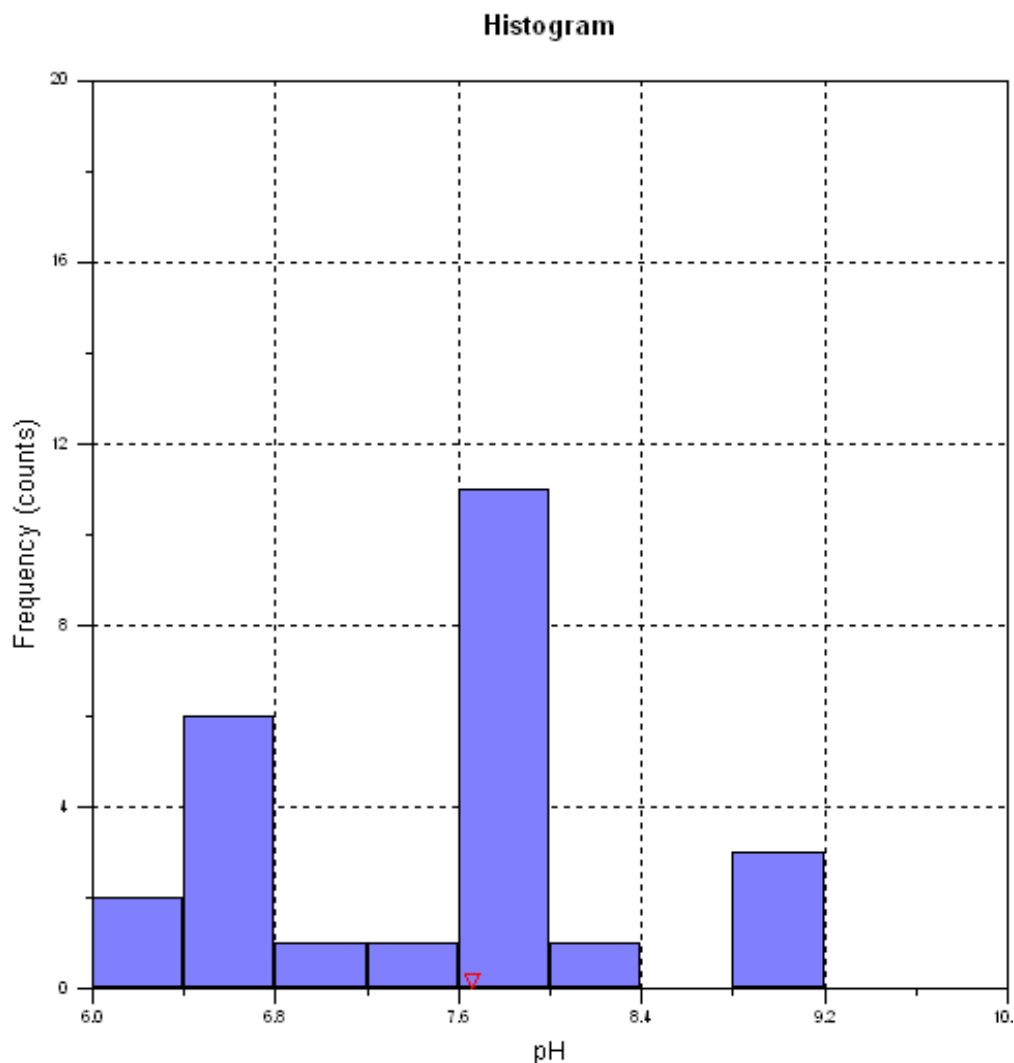
A number of parameters such as turbidity, colour, odour, etc are affected by temperature directly or indirectly. Temperature also affects pH, electrical conductivity, the rate of Chemical reaction as well as the concentration of the reactants and the products, and Solubility of gases in the water.

6.3.2 pH

The hydrogen ion activity in an aqueous solution is controlled by interrelated chemical reactions that produce or consume hydrogen ion and hence, the pH of natural water is a useful index of the status of equilibrium reactions in which the water participates. pH is a

measure of the hydrogen ion concentration of the water. The pH of water indicates whether the water is acid or alkaline. Drinking water with a pH between 6.5 and 8.5 is generally considered satisfactory. Acid waters tend to be corrosive to plumbing and faucets, particularly if the pH is below 6 where as alkaline waters are less corrosive. The pH value of the samples in the study area ranges from 6.7 of Janmeda spring in Debretabor area to 9.18 of Wanzaye spring. Nearly all field measured water points have a pH value within the limit of 6.5-8.5 except Wanzaye borehole and spring which provide 9.15 on average. These are thermal waters as mentioned earlier. The waters are associated with a faulted area in the eastern part of Lake Tana graben (Seifu Kebede et al., 2005)

Figure 6.1 pH frequency histogram



6.3.3. Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

The term TDS describes all solids (usually mineral salts) that are dissolved in water. The TDS is usually measured in mg/l. Water naturally contains a number of different dissolved

inorganic constituents. Several processes may cause an increase in TDS content of ground water. These could include movement through rocks containing soluble mineral matter, concentration by evaporation, contamination due to influx of sea water, industrial and municipal waste water disposal (Karkaranth, 1987).

The major cations are (calcium, magnesium, sodium and potassium , major anions (chloride, sulphate, carbonate, and bicarbonate) and silica though not in ionic form constitute the bulk of the mineral matter contributing to total dissolved solids. In addition there may be minor constituents present, including iron, manganese, fluoride, nitrate, strontium and boron.

The presences of all these chemical constituents give water the ability to conduct electricity. Thus, the electrical conductivity (EC) of water is an indirect measure of its dissolved constituents. In practice, EC is often expressed in terms of mill Siemens (ms) and micro Siemens. The TDS and the EC are in a close connection. The more salts are dissolved in the water; the higher is the value of the electric conductivity. EC does not give specific information about the chemical species present in water, but it enables for determination of TDS, which is an acceptable indicator of water quality. As natural waters commonly contain several salts in solution, no definite relation exists between EC and TDS and the conversion factor ranges from 0.5-1. However, for waters in a given area characterized by a distinctive family of salts, the relationship between EC and TDS is more exact and the value of the factor ranges between 0.6 and 0.7 for most ground waters (Karkaranth, 1987). In the study area the average conversion factor to relate the two parameters is found to be 0.65 as it is indicated in the figure 6.2 below. Accordingly the relation can be defined as, $S = AC$ where, $S = TDS (mg/l)$, $C = EC$ and A (unit less) is the conversion factor which is 0.65 in this particular case (Gumara river catchment) produce best fit correlation with ($r = 0.994$)

Figure 6.2- The relationship between EC and TDS from the laboratory Measurement

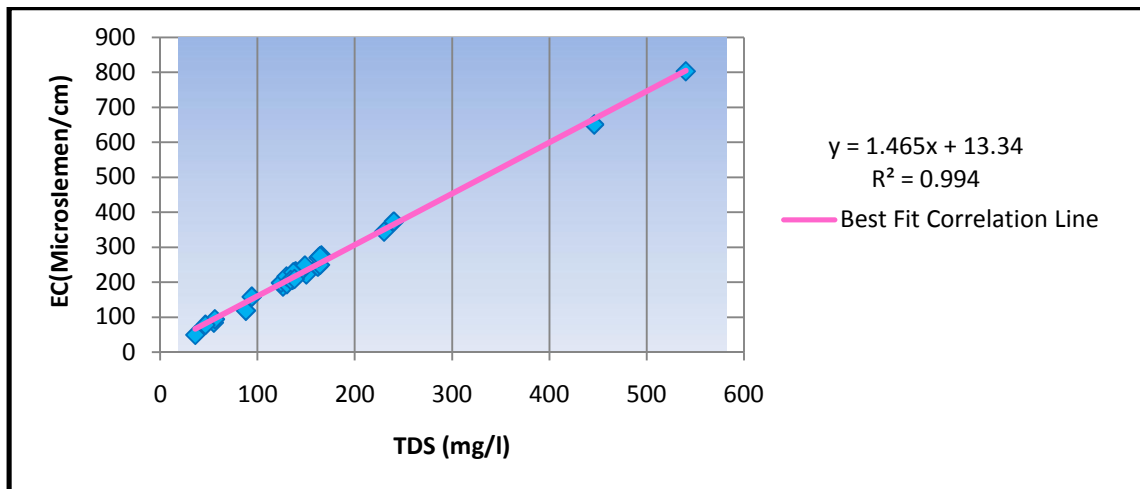


Figure 6.3 Electrical Conductivity Isohyetal Map

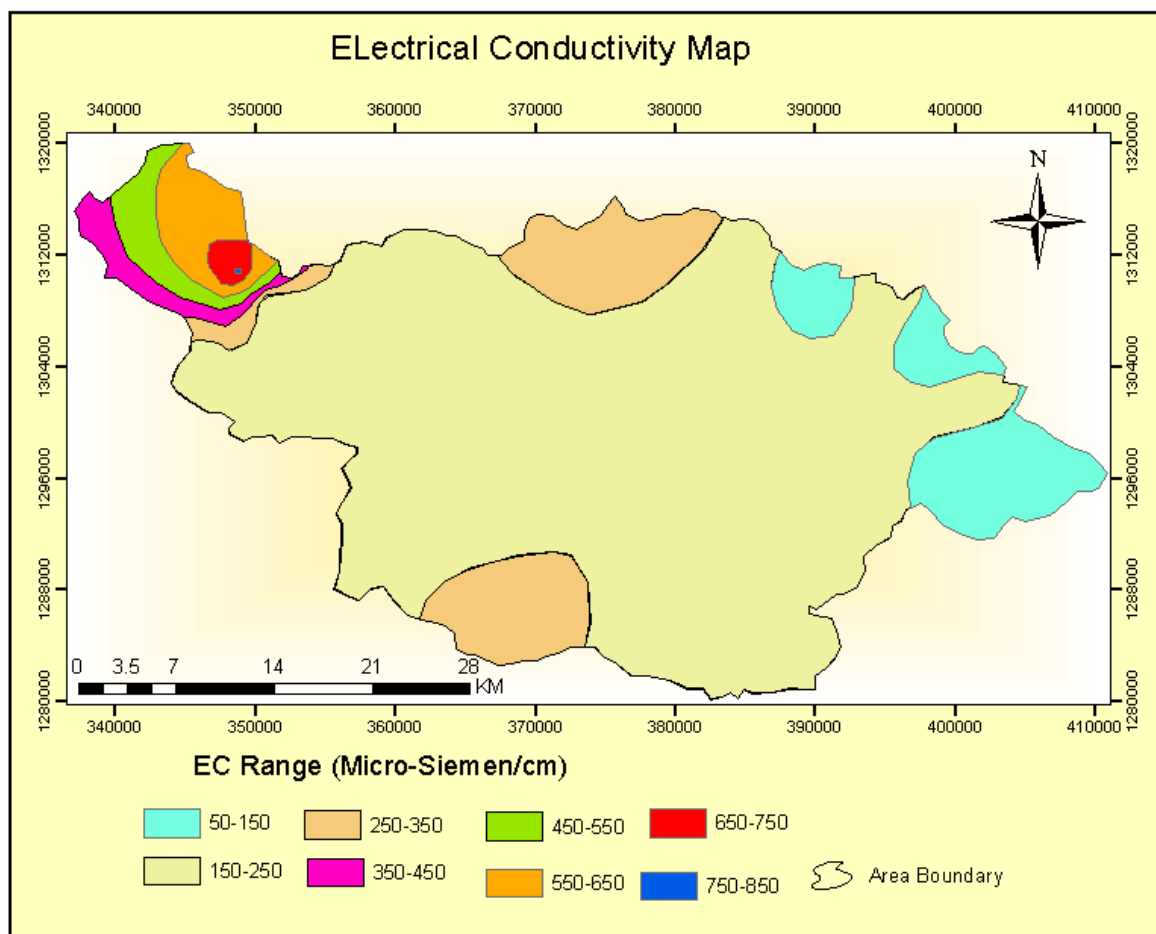


Table 6.1 Classification of Water based on the Total Dissolved Solids (Fetter, 1994).

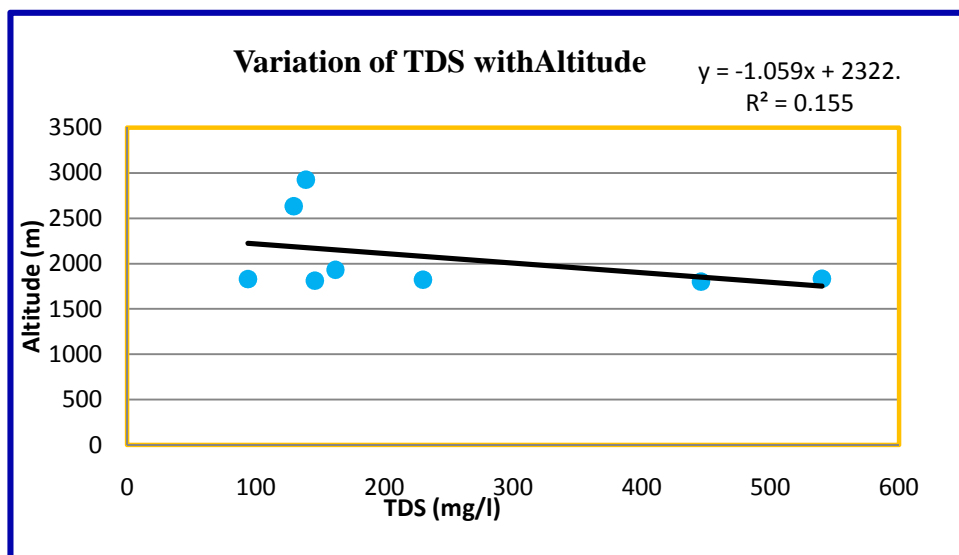
Water Type	Total Dissolved Solids (mg/l)
Fresh Water	0-1000
Brackish Water	1000-10,000
Saline Water	10,000-100,000
Brine Water	>100,000

Table 6.2 Classification of Gumara River Catchment based on TDS values

Water source	Minimum	maximum	average	Water Type
Borehole	124	165.4	152	Fresh
Hand dug Well	94	540	224.8	Fresh
Spring	51.1	164	115.5	Fresh
River	55	240	117.3	Fresh

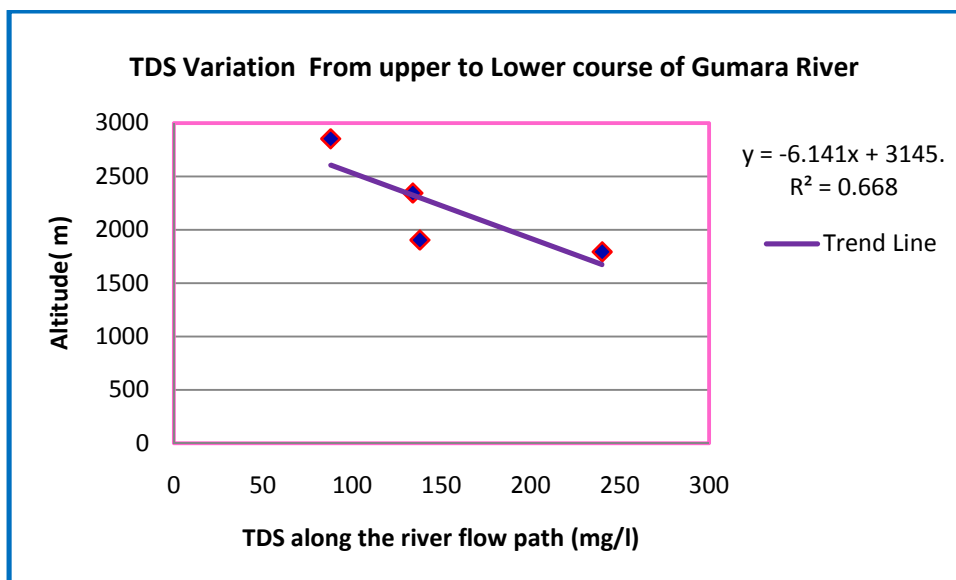
Based on Tables 6.1 and 6.2 all the water source in the catchment is fresh. The total dissolved solid in ground water of the study area generally varies from 46.3 mg/l in highland area of Debretabor to 540mg/l in Zara Jigna of the low land area. This variation is also displayed in the TDS Isohyetal Range Map (Figure 63). The increase in TDS from high land area to lowland is attributed to the increase in evapotranspiration of the low lands and possibly the dissolution of mineral constituents by ground water during its movement through geologic media

Figure- 6.4 Altitudinal Variation of TDS in Hand dug wells



TDS also Varies along the flow path of the river from high land (upper course of Gumara River via the middle course to lower course of the river. Such general spatial variation of the TDS along the flow path or the river course is related to the variation in topography. The upper course of the river is commonly situated in the area of erosion as well as in a relatively high rainfall and minimum evapotranspiration rate. The other condition for the increase in TDS in the lower course of the river is the possible interaction of the ground water with the river as there is no isolated hydrological component.

Figure 6.5 TDS Variation along the River Course



6.4. Graphical Presentation of Laboratory Measured Geochemical data

Geochemical studies often involve synthesis and interpretation of mass of analytical data. The objective of interpretation is to classify waters of different geochemical characteristics and visualize any similarity and/or differences among waters from different sources and render possible geochemical evolutionary trend. Variation in groups of water from existing data for example can provide insight to chemical difference between types of flow system and the accompanied chemical changes as well as the aquifer heterogeneity and connectivity.

The examination of tabular geochemical data of a large number of samples is monotonous and tiresome process. For such a reason analytical data are better represented by diagrams. Multi variant diagrams bring together the result of analyses of different water samples and permit direct comparison of various ground water types and genetic and classification statements. By the use of different symbol, it is possible to distinguish evolutionary status.

Several commonly used graphical methods are available of which Piper and Schoeller and s Stiff have been used in this particular research.

6.4.1 Water Type and Piper Diagram

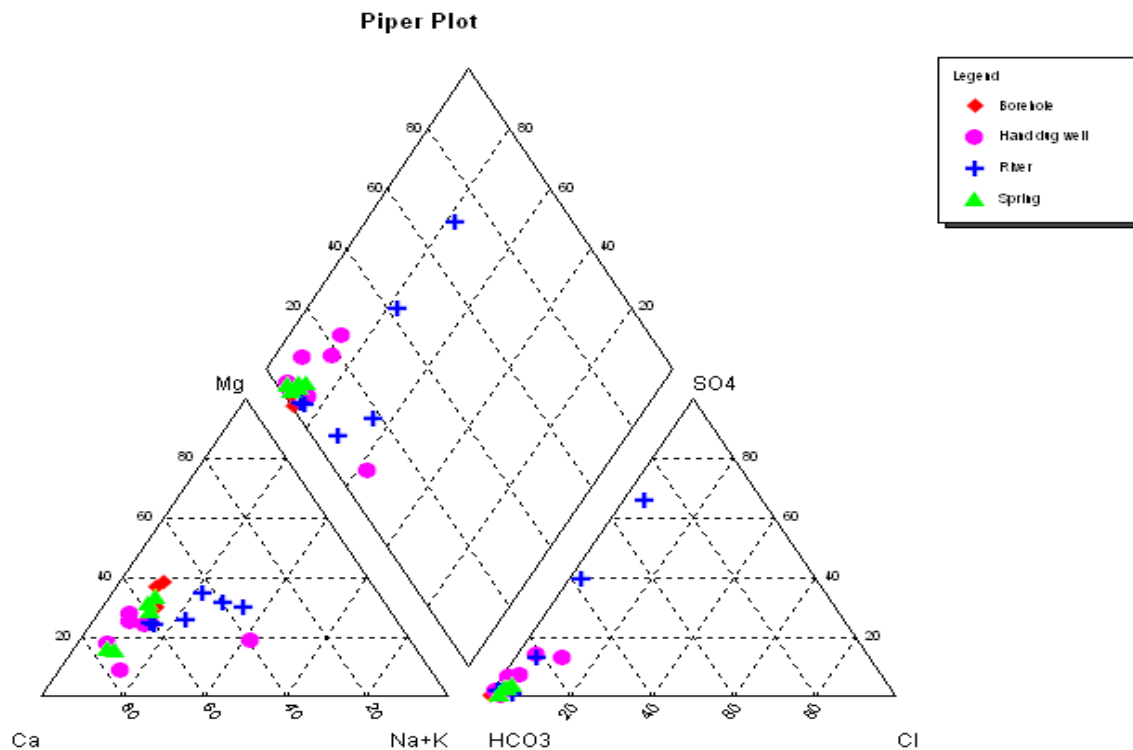
Piper diagrams permit the cations and anions composition of many samples to be represented on a single graph in which major groupings or trends in the data can be discerned visually. Piper trilinear diagram plots the major cations and anions as percentage of milli-equivalent on two separate base triangles, and project the plotted points from the two base triangles on one central diamond plot. It is convenient for showing the effect of mixing two waters from different sources; the mixture of two different water will be plotted on the straight line joining the two points (Freeze and Cherry, 1979). The different water types which are generated as a result of Aquachem Software analysis are plotted on piper diagram

Table 6.3 Water Types in the study area

Site	Source	Easting	Northing	Altitude	Water Type	Remark
Guramba	River	368325	1297896	1918	Ca -Mg-So ₄ - HCO ₃	
Guramba	Spring	367449	1296565	1940	Na-CO ₃ -HCO ₃	Thermal
Guramba	Hand dug well	367264	1298770	1930	Ca -Mg- HCO ₃ -NO ₃	
Wanzaye	Borehole	355516	1303185	1827	Na-HCO ₃ -CO ₃	Thermal
Wanzaye	Spring	355783	1303278	1838	Na-HCO ₃ -CO ₃	Thermal
Wanzaye	Hand dug well	355129	1302836	1828	Ca-Mg-Hco ₃	
Bebeks	Spring	354299	1304392	1808	Ca-Mg-Hco ₃	
Bebeks	Spring	353967	1306286	1802	Ca-Mg-Hco ₃	
Bebeks	Spring	355074	1309388	1805	Ca-Mg-Hco ₃ -NO ₃	
Jigna Zara	Hand dug well	349036	1310444	1800	Na-Ca-Hco ₃	
Jigna Zara	River	351267	1308819	1807	Ca-Mg-Hco ₃ -So ₄	
Jigna Zara	Hand dug well	347109	1306534	1822	Ca-Hco ₃	
Awzet	Hand dug well	403424	1301214	2924	Ca-Mg-Hco ₃	
Awzet	Spring	403734	1300666	2910	Ca-Hco ₃	
Hiruy Abarega	Spring	397542	1308887	2625	Ca-Hco ₃	
Hiruy Abarega	Hand dug well	397071	1309085	2631	Ca-Hco ₃	
Bebeks	River	354642	1303771	1796	Ca-Mg-Hco ₃	
Gindatemem	Hand dug well	381085	1288870	2377	Ca-Mg-Hco ₃	
Gelawdiwos	Borehole	373206	1286508	2336	Ca-Mg-Hco ₃	
Gelawdiwos	Borehole	372073	1288388	2297	Ca-Mg-Hco ₃	
Arb Gebya	Borehole	363789	1285991	2220	Ca-Mg-Hco ₃	
Mynet	River	401749	1295986	2853	Ca-Mg-Hco ₃	
Near Licha	River	375239	1287122	2345	Ca-Mg-Hco ₃	
Jigna	River	351414	1309680	1794	Ca-Mg-Hco ₃	
Dam site	River	371605	1299548	1905	Ca-Mg-Hco ₃	

The dominant Water type in the catchment is Ca-Mg-HCO₃. It is widely distributed in the study area especially in the transitional and discharge zones. Almost all river samples are dominated with this water type except two river samples which provide Ca-Mg-SO₄-HCO₃ and Ca-Mg-HCO₃-SO₄. Calcium bicarbonate water Ca-HCO₃ is Prominent in the highland area of Debretabor particularly in Awzet, Hiruy Abarega and surrounding areas. Samples from different springs and hand dug wells reveal that Ca²⁺ and HCO₃⁻ are the governing cation and anions respectively. Magnesium on the other hand appears in one sample from recharge zone, in all schemes in the transitional zone and partly in Discharge areas. The only exceptional Water Schemes which are devoid of any calcium and magnesium are Guramba and Wanzaye thermal springs as well as Wanzaye deep well. The water of this scheme is entirely different from neighbouring and adjacent schemes. A clear evidence from the hydrochemical analysis of Wanzaye area shows that the hand dug well adjacent to the borehole and thermal spring water has different Chemistry. Both Ca²⁺ and Mg²⁺ which disappear in the thermal spring and borehole prevails in the hand dug well. This tells us that at least there is a different aquifer with different Hydrochemistry and possibly connected with deeper horizon. In the lowland areas especially of alluvial deposit the water is dominated with sodium ion. The water in Zara Jigna Ayngib is Na-Ca-HCO₃ in which calcium still prevail with significant amount unlike the thermal waters.

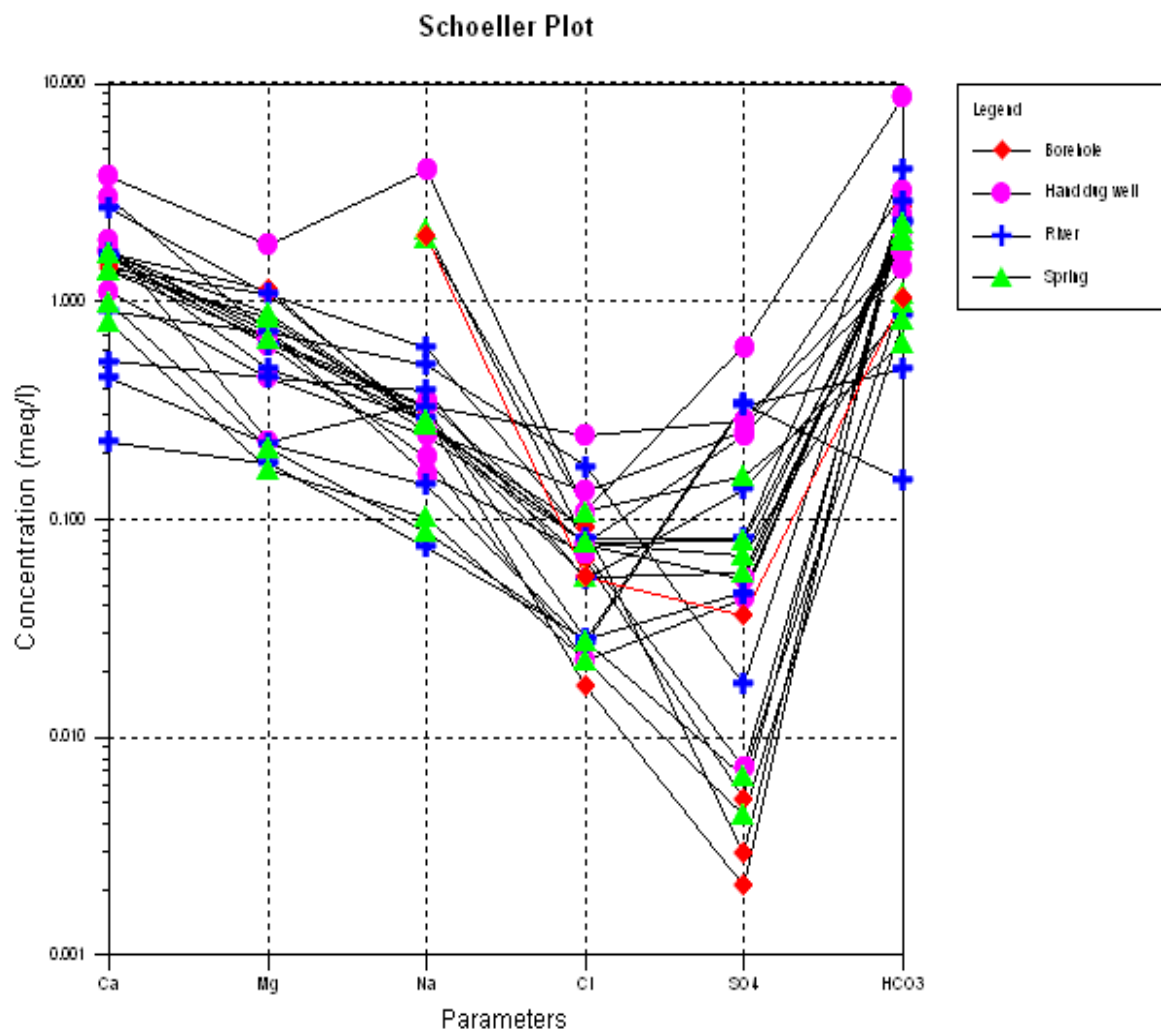
Figure 6.6 Piper Diagram



6.4.2 Stiff and Schoeller Diagrams

Stiff diagram is easy to construct and provide a quick visual inspection of individual chemical analysis unlike Schoeller which permits comparison of many samples to be represented on a single graph and displays the total concentration of anions and cations. The Wanzaye Plot Stiff plot is different because of the absence of calcium and total dominance of Na ion in the water sample.

Figure 6.7 Schoeller Diagram

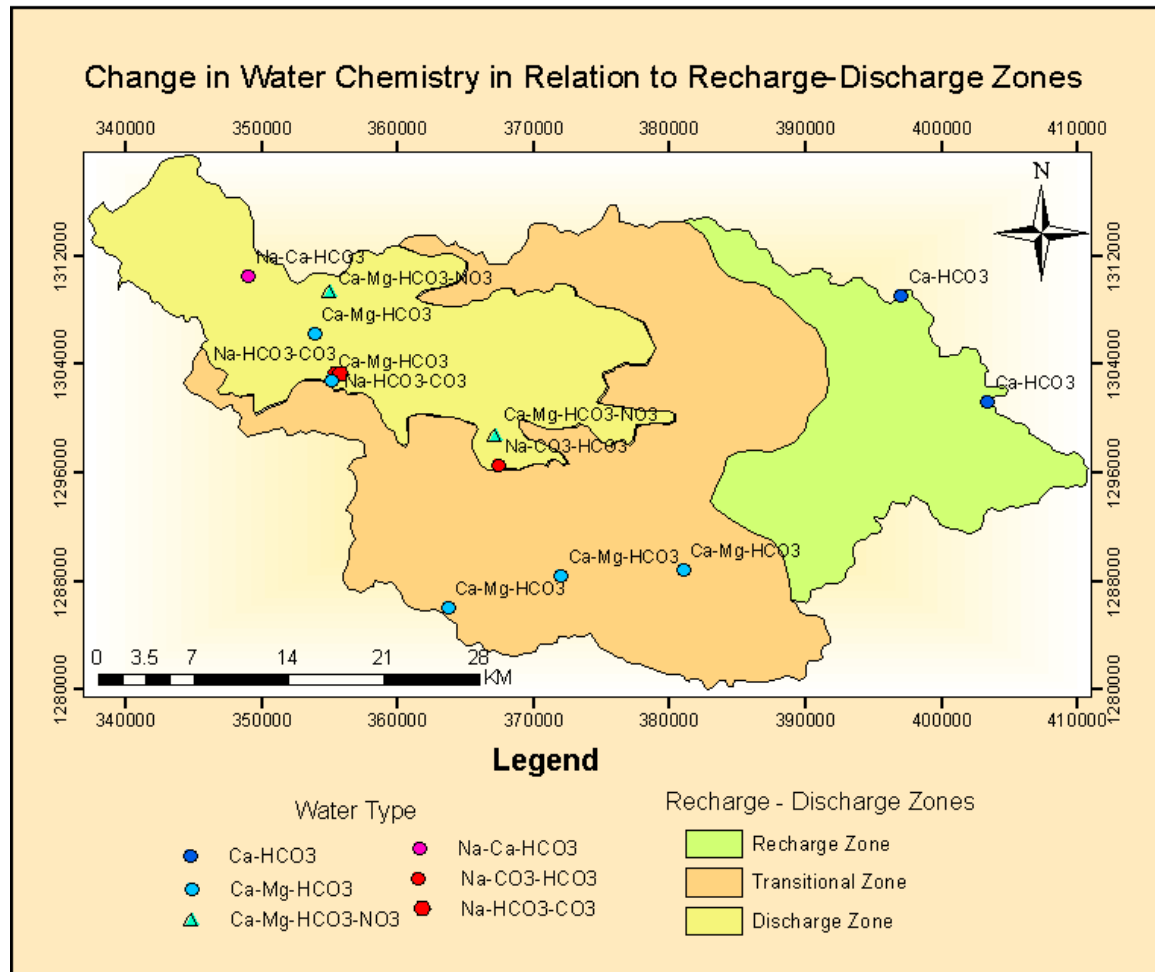


6.5 Evolution of Major Ions and Their Possible Governing Factors

As ground water flows from an aquifer from point of recharge to appoint of discharge, it undergoes change in water quality. The evolution of water chemistry in ground water proceeds from near surface oxidizing condition typically producing calcium bicarbonate water chemistry to deep ,reducing condition producing sodium chloride water chemistry (Pyne,1995). The evolution involves cation exchange such as between dissolved calcium and

dissolved sodium, oxidation of inorganic materials to carbon dioxide and water, chemical weathering (digenesis), dissolution and leaching of inorganic substances from soil and sediment particles creating a relatively stable mineralogy compatible to water chemistry.

Figure 6.8 Quality of water in recharge, transitional and discharge Zones



6.5.1 Evolution of Major Cations (Ca²⁺, Mg²⁺, Na⁺, K⁺)

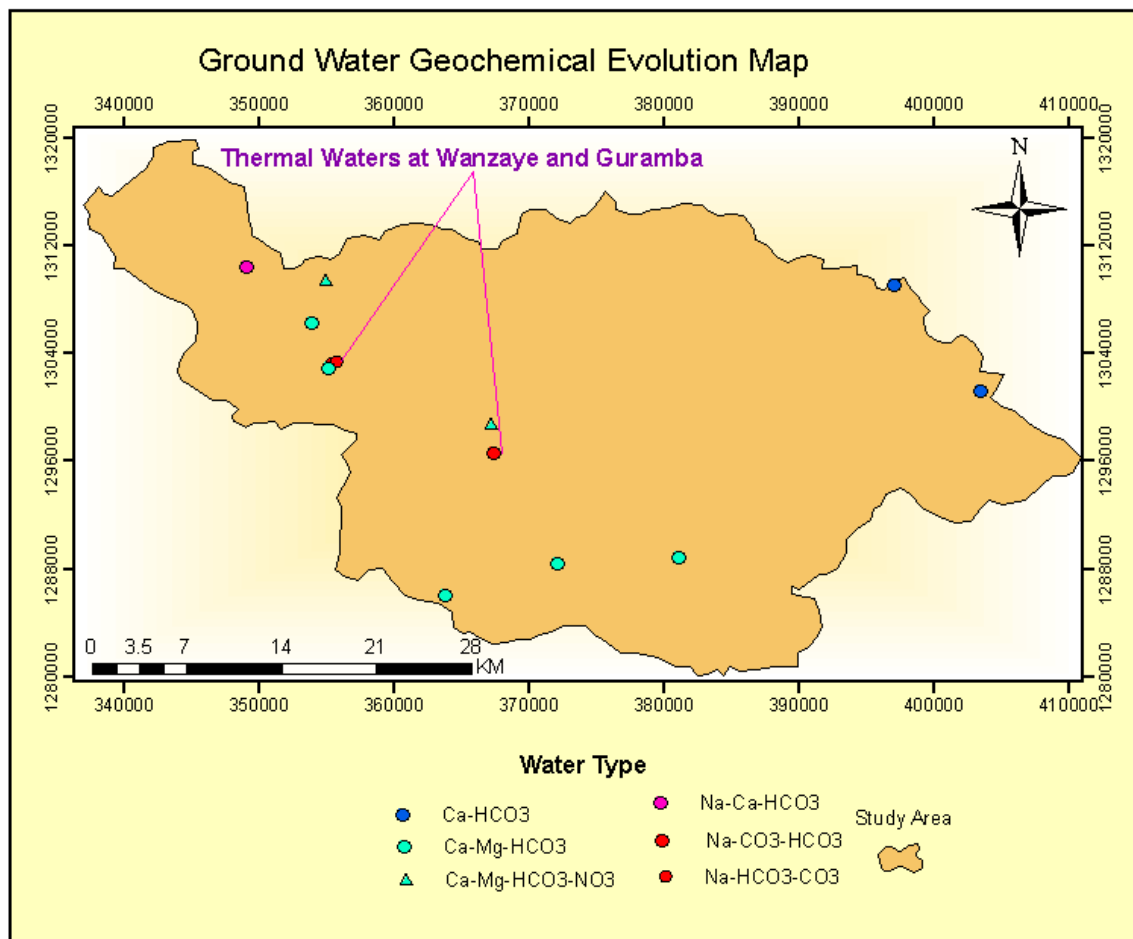
In the study area progressive change in the chemical character of the ground water is noticed from point of recharge to point of discharge. During the prolonged contact of ground water with the reservoir rock geo-chemical process leads towards the attainment of equilibrium between the mobile constituents of the rock mineral and the solute in ground water. The geochemical processes which possibly take place include dissolution, precipitation, ion exchange and Hydrolysis of the silicate minerals. What is actually observed from the analysed chemical data and the change in the water type is the replacement of calcium by

sodium ion through the flow path. This is governed by the interrelated above mentioned processes of which hydrolysis and cation exchange plays a dominant role.

As it has been shown from the ground water chemical evolution map, the Ca-HCO₃ water type from the recharge area is progressively changed along the flow path till calcium is dominated by Na- rich water type that is Na-Ca-HCO₃. Therefore, with the exception of geothermal water the evolution in relation to cation generally becomes:

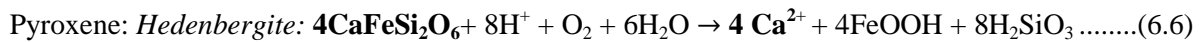
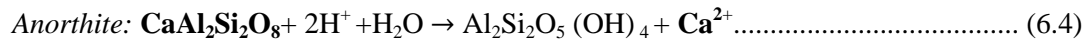
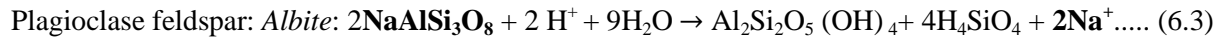
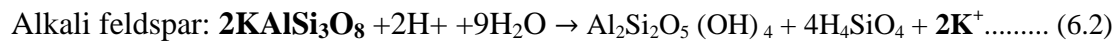


Figure 6.9 Ground Water Chemical Evolution Map



Hydrolysis of silicate minerals: The breakdown of mineral under the influence of H⁺ and OH⁻ in the water is known as Hydrolysis (Matthess, 1982). Hydrolysis attack the surface of minerals which are relatively insoluble and cause the formation of new mineral as the same time as the removal of Ca²⁺, Mg²⁺, Na⁺ and K⁺ ions in solution. The hydrolysis process which is responsible for the removal of cations from their parent rock (alkali feldspars, plagioclase

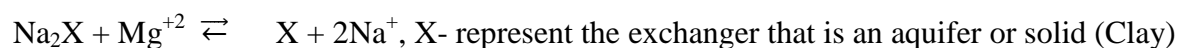
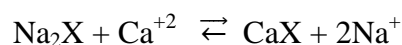
feldspar (albite and anorthite), pyroxene as well as olivine and amphibole is shown in the following equations



Since the study area is dominated by volcanic rocks, the above silicate minerals are expected to undergo hydrolysis reaction which is responsible for the evolution of cations. Thus, hydrolysis is one of the factors which control the evolution.

Dissolution and Precipitation: Dissolution and precipitation of soluble minerals play a fundamental role for the evolution of cations along ground water flow direction. The evolution is dependent on the availability and solubility of the minerals. During the course of its flow ground water picks up dissolved solids, dissolution continues to proceed until saturation takes place between the ground water and the mineral phase. Under saturation of the ground water with respect to the mineral result in the net dissolution provided the mineral is present. Super saturation on the other hand results in precipitation of the minerals. Therefore the spatial variation and evolution of the ions in ground water is a function of nature of the mineral and reaction with the ground water.

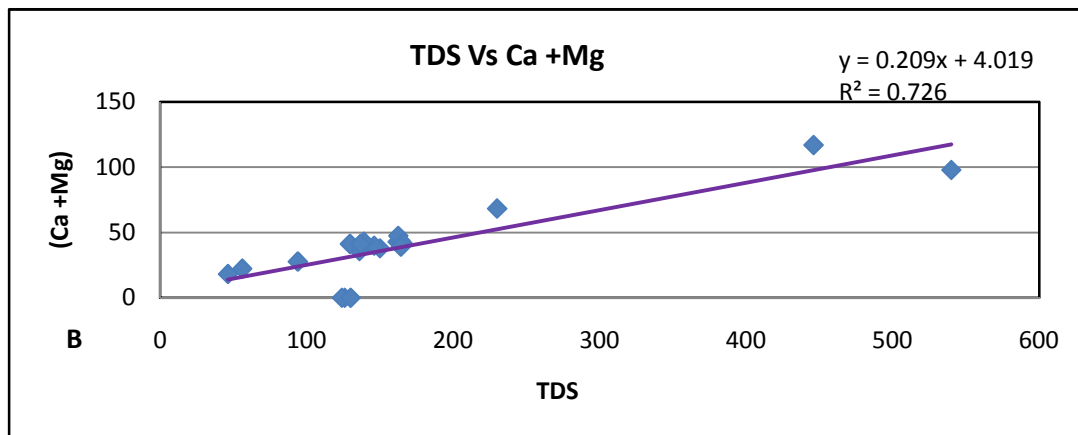
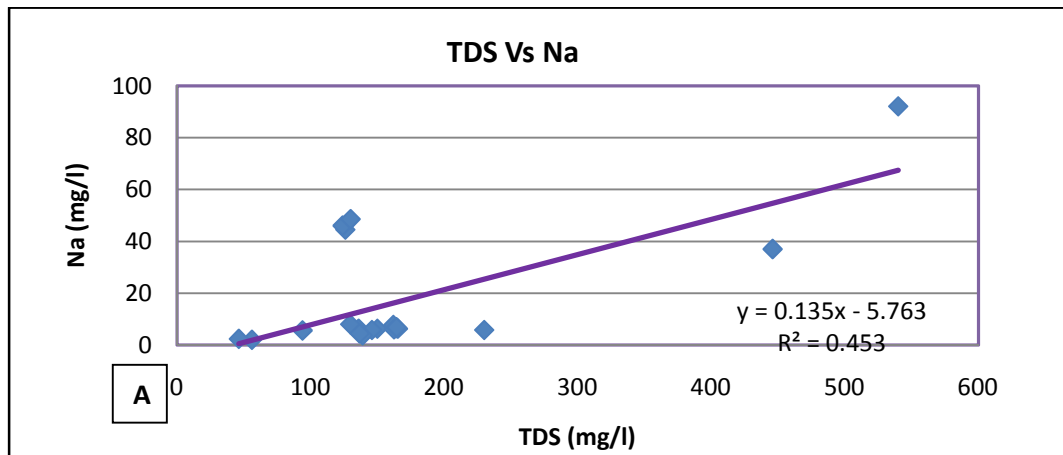
Cation exchange: The extent and velocity of an ion exchange process depend on the kind of dissolved substances, their properties, their ionic composition and the type and concentration of dissolved ions and their accompanying complementary ions (Matthess, 1982). Cation exchange process is a chemical reaction in which the calcium and Magnesium ions in water are exchanged for sodium that is adsorbed to aquifers solids such as Clay minerals, resulting in higher sodium and lower Calcium and Magnesium concentration in water. The exchange between Na^+ , Ca^{+2} and Mg^{+2} which are important in many natural groundwater systems is given by equation:

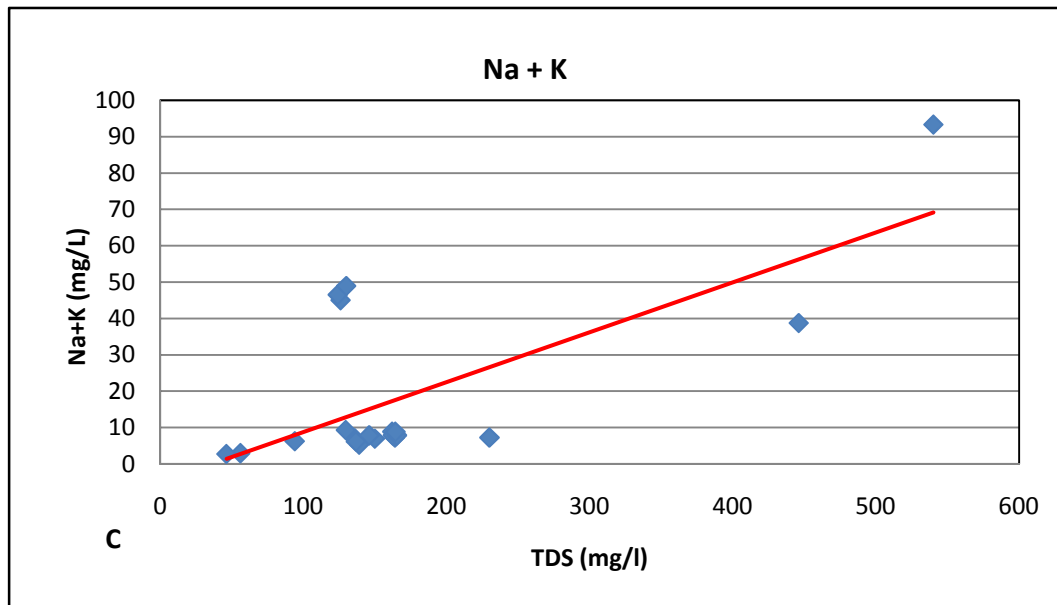


Progressive change in the geochemical characteristic of a large number of samples can best be studied by plotting selected constituents on bilinear and trilinear diagrams. Such diagrams

show the relationship between concentrations of various constituents. For this purpose a bilinear diagram of Ca, Ma, Na and potassium or their sum or ratios against TDS is used to assess the evolutionary trends. Some bilinear plot of cations, sum of cations and ratio of cations which indicate evolutionary trend is plotted in the diagrams below. A few numbers of geochemical data (insufficient data source) make the evolution no to be pronounced.

Figure 6.10 Evolutionary Trend of major cations, using the cations, their sum, ratio Vs TDS (A, B, C)





6.5.2 Major Anions (HCO_3^- , CO_3^{2-} , SO_4^{2-} , Cl^- , F^-)

Nearly all the ground water in the area is the bicarbonate rich type and there is no clear evolutionary change among anions. The main possible source of bicarbonate ion in the study area is the dissolved carbon dioxide. The source of CO_2 that produce HCO_3^- ion in water is the CO_2 gas fraction of atmosphere or atmospheric gases between the land surface and the water table. The water located in Guramba hand dug well and Bebeks (Tankua Gebriel) contain relatively pronounced nitrate ion which are related to human impact of the resource. A clear evidence from the field visit shows that the spring is used as a Holy Water and many people from different area come and jam to use it consistently. Similarly, the Guramba dug well is due human poor handling of the resource.

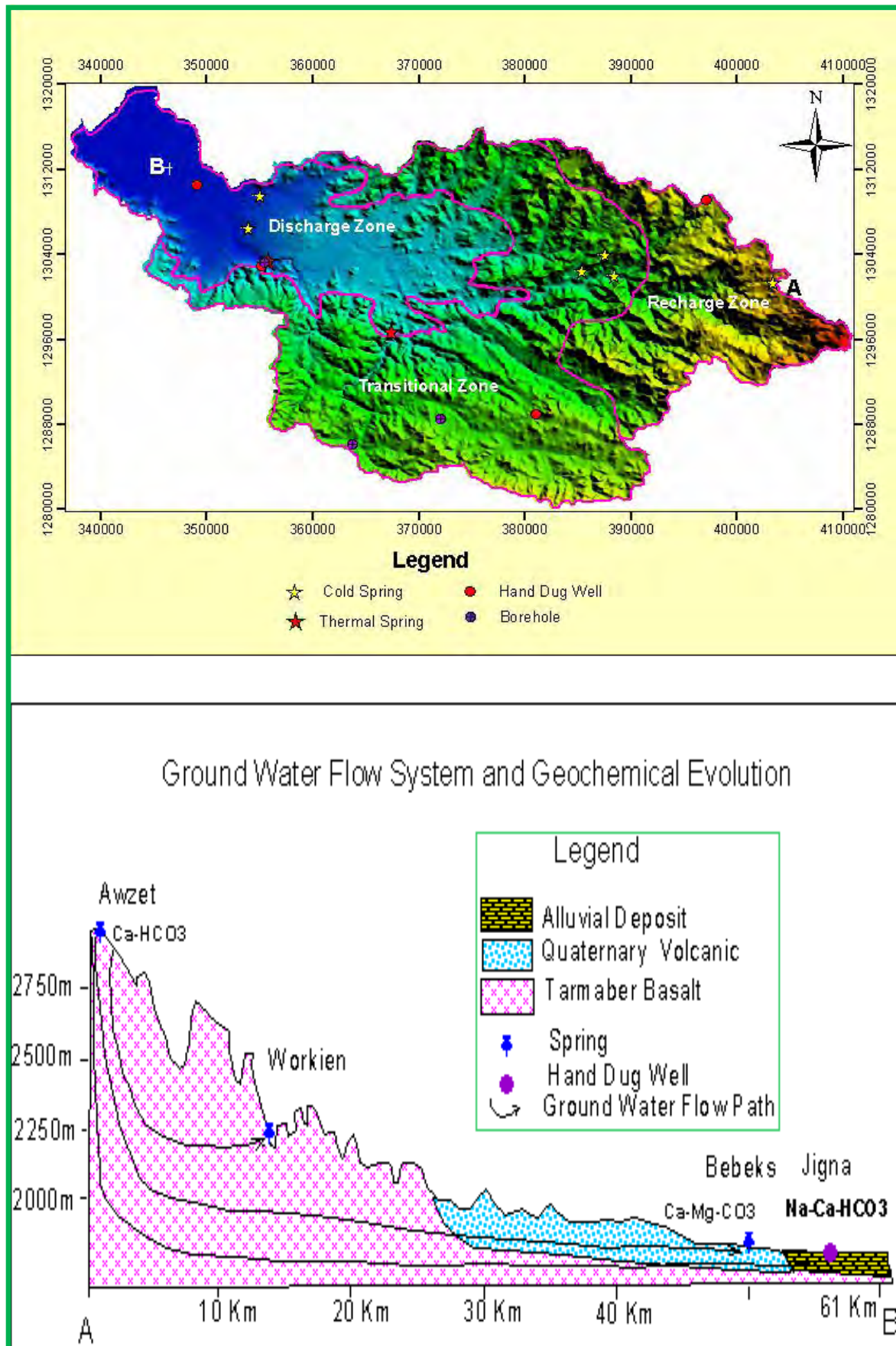
6.6 Conceptual Flow System and Associated Evolutionary Trend of Ground Water from Recharge to Discharge Areas

The chemical variations along the flow paths and systems are depicted from the water types existed in different zones of the study area. The highland areas of Debretabor is dominated by calcium rich water types spring from Awzet (Gossie) and Hiruy(Janmeda) as well as hand dug well from Hiruy have Ca-HCO_3 . Only one hand dug well from Awzet (Amagaw) has Ca-Mg-HCO_3 . The geology of these areas is Tarmaber basalt flow and pyroclastic materials associated with it. Most schemes developed in the highland area of Debretabor have a local flow system. The springs, hand dug wells and even boreholes developed in the transitional

zone have Ca-Mg-HCO₃ type water where the geology remains the same. Water in Gelawdiwos boreholes and Gindatemem hand dug well and spring have this water type.

The discharge area experiences Variety of water types compared to the recharge and transitional zones and the geology of this zone is also different from the other two zones. Bebek's springs are fully situated in Quaternary volcanic rocks (vesicular basalt) and Wanzaye thermal spring is nearly in the same geology but very close to the contact with Tarmaber basalt. The discharge zone comprises Ca-HCO₃, Ca-Mg-HCO₃, Ca-Mg-HCO₃-NO₃, Na-Ca-HCO₃, Na-HCO₃-CO₃ and Na-CO₃-HCO₃ water Types. The relatively high TDS Ca-HCO₃ water in this discharge zone (Zara Jigna School) is related to the relative recharge of water from the neighbouring hill composed of pyroclastic materials. The high discharge Bebek's springs composed of Ca-Mg-HCO₃ and Jigna Aynjib Hand dug which is located in the alluvial deposit is Na Ca-HCO₃ water type. Such variation of the water type from that of the recharge area is due to regional water flow system accompanied by geochemical evolution governed by different factors mentioned above. The conceptual flow system and the accompanied geochemical evolution along the A-B Cross section from recharge to discharge area is displayed in Figure 6.11 below.

Figure 6.11 Ground water flow system and geochemical evolution along the flow path



6.7 Water Quality Assessment

Ground water can be classified with regard to their suitability on human use for domestic, agricultural and industrial purposes. Statements about water quality offer an important base in this context. Water quality guidelines is established to safe guard the health of users and thus eliminate adverse effect or reduce to a minimum of water constituents. A guideline value represents the level or concentration of constituents that ensure aesthetically pleasing water that does not result in any significant risk to the consumers. In this viewpoint, quality refers to fitness for a purpose. Hence, for practical application, it is very useful to assess and evaluate the quality of water resources of the area for intended purposes. Despite all the constituents of ground water are not identified in the analytical laboratory, the analysis results of major and important parameters have been used to assess the suitability of waters of the study area for intended purposes especially of domestic and irrigation. .

6.7.1. Water Quality for Domestic Use

Water guide line for drinking purpose is established taking into consideration the socioeconomic status, availabilities of alternative water resources, geographical location (climate condition) and dietary condition of the people (Fetter, 1994).

Water that is to be used for drinking must meet high standard of physical, chemical and biological purity. According to Punimia (1995), the water quality should fulfil the following criteria.

- ✓ It should be colourless and sparkling clear. It must be free from solid in suspension and must not deposit sediments on standing.
- ✓ It should be of good taste and free from odour
- ✓ It should be free from disease causing bacteria and organism
- ✓ It should be free from objectionable dissolved gases
- ✓ It should be free from harmful salts
- ✓ It should be free from objectionable minerals such as iron, manganese lead, arsenic and other poisonous metals
- ✓ It should be free from radioactive substances such as radium and strontium,etc
- ✓ It should be reasonably free from phenolic compounds, fluorides and iodine
- ✓ It should not lead scale formation and should not be corrosive

Therefore to evaluate water chemistry of Gumara river catchment, World Health Organization (WHO) guide line is basically used.

Table: 6.4 Water chemistry of study area in comparison with WHO guide line

WHO Guide Line		Gumara River Catchment Chemical Value				
Water Constituent	WHO	Borehole	HDW	Spring	River	Remark
TDS (mg/l)	1000	154.05	204.47	115.49	119.94	
Na (mg/l)	200	16.29	18.18	16.64	7.72	
K (mg/l)	10	1.44	1.27	0.56	3.26	
Mg (mg/l)	30	12.13	9.07	6.75	6.51	
Ca (mg/l)	100	30.59	44.11	24.77	22.99	
Cl (mg/l)	250	2.01	3.72	2.27	2.32	
SO ₄ (mg/l)	250	0.56	10.27	3.04	6.81	
F (mg/l)	2.5	0.21	0.21	0.32	0.18	
NO ₃ (mg/l)	50	7.17	7.82	7.16	0.81	
Mn(mg/l)	0.1					
Fe(mg/l)	0.3					

According to the WHO guide line and the Ethiopian standards, the study area water is below the maximum permissible limit and will not have any problem for domestic application.

6.7. 2. Water Quality for Irrigation

According to (Karkarant, 1987), several chemical constituents affect the suitability of water for irrigation. Some of these are:

1. Total concentration of soluble salts (which is broadly related to the specific conductance of water)
2. The relative proportion of sodium to Calcium and Magnesium
3. The concentration of boron
4. The relative proportion of bicarbonate to calcium and magnesium

Water quality, soil types, and cropping practices all play a role in successful irrigation. Good quality water permits maximum yields consistent with proper soil and water management. Study of soil types determines the infiltration rates that can be expected for certain soils, thereby providing some guides to the amount of leaching of mineral salts that can be anticipated; leaching is essential to reduction of salinity in top soils. Equally important, the tolerance for certain elements must be determined before specific crops can be selected.

Water quality problems in irrigation include salinity and toxicity. Excessive salinity occurs when there is an accumulation of salts in top soils. These salts can affect crop production because crop roots, especially in the upper root zone, have great difficulty in extracting enough water and nutrients from saline solution. Soil permeability can be reduced significantly by the build up of salts in the soil, zone. Salts may harm plants growth by limiting the uptake of water through modification of osmotic process or chemically by metabolic reaction such as those caused by toxic substances (Todd, 1980). Consequently, crop production is limited because sufficient water cannot reach the root zone. Toxicity is also a problem in maintaining good yields. Some waters contain high enough concentrations of certain elements to retard or even eliminate the growth of some plants. Boron, chlorides, and sodium are common toxic substances.

The two principal effects of sodium are reduction in soil permeability and hardening of the soil. Both effects are caused by the replacement of calcium and magnesium ions by sodium on clay soil and colloids. The total dissolved solids content measured in terms of electric conductance gives the salinity hazard of irrigation waters. Besides the salinity hazard, excess sodium content in water renders it unsuitable for soils containing exchangeable calcium and magnesium ions.

If the percentage of sodium ion to calcium, magnesium and sodium is considerably above 50 in irrigation water, soil containing exchangeable calcium and magnesium take up sodium for calcium and magnesium and causes deflocculating and impairment of the tilth and permeability of soil (Karkarant, 1987). Such condition alters the physical characteristic of the soil and can even lead to growth retardation. Clay that take up sodium becomes sticky and slick when wet and has low permeability. When dry, the clay shrinks and form pronounced cracks that are difficult to cultivate. Even worse, high concentrations of sodium salts can produce alkali soils in which little or no vegetation can grow. On the other hand, when the same clay carries excess calcium or magnesium ions, it tills easily and has good permeability. The sodium hazard in irrigation water is expressed by determining the Sodium Adsorption Ratio (SAR) by the relation;

$$SAR = \frac{Na}{\sqrt{\frac{(Ca+Mg)}{2}}} \dots \dots \dots 6.2$$

Where all ionic concentrations are expressed in milli-equivalent per litre.

Most classification system of irrigation water includes limits on specific conductance (expressing total dissolved solids), sodium content, and boron concentration. Soils containing large proportion of sodium with carbonate as the predominant anions are termed as alkali soils; and those with chloride and sulphate as the predominant anions are Saline soils (Todd, 1980). Sodium content is usually expressed in terms of percent sodium (sodium percentage) defined by $\%Na = \frac{(Na+K)100}{Ca+Mg+Na+K} \dots \dots \dots 6.3$, where all the concentrations are expressed in milli equivalent per litre

Table 6.5 Quality classification of water for irrigation (after Wilcox) cited in Todd (1980)

Water Class	SAR	(%Na)	Specific Conductance ($\mu S/cm$)	Boron (mg/l)		
				Sensitive crops	Semi-tolerant Crops	Tolerant Crops
Excellent	<10	< 20	< 250	< 0.33	<0.67	< 1.00
Good	10-18	20-40	250- 750	0.33-0.67	0.57-1.33	1.00-2.00
permissible	18-26	40-60	750-2000	0.67-1.00	1.33-2.00	2.00-3.00
Fair						
Doubtful	>26-poor	60-80	2000-3000	1.00-1.25	2.00-2.50	3.00-3.75
Unsuitable		>80	> 3000	> 1.25	> 2.50	> 3.75

Table 6.6 Irrigation Water Quality of Gumara River Catchment

Parameter	Borehole	Hand dug well	Spring	River
SAR	0.63	0.65	0.76	0.35
Water Class	Excellent	Excellent	Excellent	Excellent
%Na	23	22	29	20
Water class	Good	Good	Good	Good
Ec	255	319	176	184
Water class	Good	Good	Excellent	Excellent

Therefore, based on the analysis of existing data and comparison of the water sources of the study area with the above listed standard (Table 6.5), the catchment area has apt water quality for irrigation water hence best for agricultural practices. There is no sodium hazard which will possibly affect agricultural activities in the area.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

Gumara river catchment is located in the Lake Tana basin. It has a total area of 1532km² and is characterized by flat, gentle slope to hills of undulating topographic feature. More than 80% of the area is covered by Tertiary volcanic rocks (Tarmaber formation). The remaining 20% comprises of Quaternary volcanics, alluvial and lacustrine deposits.

The catchment possesses temperate climatic zone with long-term mean annual precipitation of 1377. The precipitation is unimodal in nature with the rainy (wet) season between June to September and the other remaining months correspond to the dry season. The potential evapotranspiration which is estimated by Penman modified method and the actual evapotranspiration with Thornthwaite and Mather soil water balance model is 1276 mm and 764 mm respectively.

The estimated annual direct groundwater recharge of the catchment is 267mm. This figure is found using water balance method unlike the base flow separation method which relatively exaggerates the recharge. The ground water recharge and discharge condition of the area is controlled by the topography, the prevailing geologic set up especially the existence of weathered and fractured geologic materials, the associated geological structures and rainfall amount. The main recharge of study area is from the highlands of Debretabor, west of Guna and surrounding areas which slopes towards Gumara river catchment.

The major aquifer in the study area is the weathered and fractured tertiary and quaternary volcanic rocks. The existence of alluvial and lacustrine deposits in the area provides additional potential aquifer. However, this aquifer coverage in terms of areal proportion is very small compared to the associated volcanic rocks. Furthermore, the depth of this aquifer is limited and varies from place to place and the maximum depth is less than 60 m. The aquifer by itself is not purely lacustrine or alluvial but intercalated with the existing weathered and fractured volcanic lava flows and pyroclastic deposits. The alluvial and lacustrine deposits are dominantly covered by clay layers on the top surface; minimum direct recharge to the aquifer prevails and the recharge is from associated volcanic rocks exposed out of the deposits in the surrounding areas.

Based on the observation of the characteristics of the nature of geologic material, degree of weathering and fracturing of volcanic rocks and associated pyroclastic materials and alluvial deposits, the aquifer of the study area is classified into four categories. These are aquifer very high productivity, high productivity, medium productivity and low productivity zones. The justification for such classification is the few pre-existing boreholes and their hydraulic characteristics, the discharge of different ground water points, consistency and nature of springs emanated from aquifer, reliability of hand dug wells in delivering water during the whole dry season and so on.

The ground water of the study area generally flows from east to west direction. A minor local irregularity of the flow pattern is attributed to existence of geologic structures, boreholes and no flow boundaries. The ground water surface water interaction of the catchment in this specific study is not based on collection of all pertinent data that enable to grasp the overall interaction rather it relies on the general principle of ground water surface water interaction as a result of head variation of the ground water and the river water. Accordingly, the interaction is simply visualized by the change in orientation of the flow line towards or away from the stream course in gaining and losing stream reaches.

The hydrochemistry of the study area is a bit complicated in that two entirely different water types exist at the same place as in Wanzaye thermal spring and/ or borehole and neighbouring hand dug well. This is evidence that waters of these schemes are not in the same aquifer system. Thermal spring also exists in Guramba area and the chemistry of the two springs is nearly similar except the order of carbonate and bicarbonate ions. The two thermal water are characterized by the total dominance of the Na^+ and absence of any Ca^{2+} and Mg^{2+} ions and relatively higher pH value of 9.15. Such waters may have deep source connected with deep structure which brought to the surface. The prominent water of the study area obtained from different water sources is Ca-Mg-HCO_3 . It prevails from recharge to discharge areas with great frequency in transitional zone.

Graphical representations using piper has been used to identify the prevailing water type and visualize the distribution and evolution in the diagram. Schoeller has also been employed to see the relative concentration of each major ionic constituent from the plot of the whole sample in a single diagram.

Ground water generally evolves from Ca-Hco₃ and Ca-Mg-Co₃ to Na-Ca-Hco₃ as it passes along the flow path from recharge to discharge areas and the evolution is accompanied with increment of total dissolved solids. The factors that govern such evolutionary trends are dissolution-precipitation; ion exchange and hydrolysis of silicate .The evolutionary trend is clearly observed with respect to change in cations but the evolution of anions is insignificant as carbonate is the dominant anion throughout the study area.

The water source of the study area with respect to potential use for irrigation and domestic application is proved to be suitable. There is no sodium hazard that hinders full utilization of the water resources for irrigation activities.

7.2 Recommendations

- Surface run off in the catchment erodes varieties of soil and geological materials from adjacent elevated areas of the catchment and deposited on the lowland areas. These poorly graded eroded materials hinder infiltration rate of the catchment and water logging is a common phenomenon in low land areas. Therefore soil water conservation program should be endorsed and implemented especially in the high land and gentle slope areas.
- There exist few and unevenly distributed boreholes even in a ground water potential zone. The rural people will benefit more if additional boreholes are drilled in rural areas which in turn help for further quantitative characterization of the aquifer system
- Due to the existence of high topographic variations between low land and high land areas, the meteorological stations existing in and around the study area are not sufficient. Therefore at least one or two first order meteorological stations which will measure all meteorological parameters should be established to supplement the only pre-existing first order Debretabor rain gauge station.
- Local irrigation activity has already been practiced using dewatering pump from Gumara River. Such practice will possibly restrain the river flow provided the numbers of beneficiaries are increasing from time to time. Therefore utilization of ground water for irrigation purpose should be practiced and used by drilling deep wells in agriculturally feasible local areas.
- To know the actual source of thermal springs in Guramba and Wanzaye, detail integrated geophysical and hydrogeochemical analysis is recommended.
- The lateral and vertical extent, nature of the aquifer and any discontinuities prevailed which will affect the ground water system had better be mapped by using integrated ground water investigation techniques.
- To better understand the geochemical evolutionary trend, much more geochemical data with even distribution and minimum spacing is recommended
- Controlling mechanism should be taken during well site location, construction and utilization of any water resources to avoid anthropogenic sources of pollution.
- Different governmental and nongovernmental organizations that entail in the preliminary and detail study of the water resources as well as construction of water wells should develop the habit of data base management system. The responsible government or department of the data base had better deliver the data upon legal request.

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Annexes

Annex 1: Precipitation Data

Annex 1a: Rainfall of Wereta station

Monthly Rain Fall (mm) Woreta Station												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	*	*	*	*	*	*	368.7	225.5	156	52.3	19.8	0
1981	0	0	0	0	67.8	163.5	397.9	455.1	108	28.4	23.3	0
1982	0	0	5.5	33.7	18.3	147.6	395	428.2	117	80.6	0	0
1983	2.5	0	0	0	42.5	36.4	314.4	388.6	149	58.2	0.1	0
1984	0		4.1	1	127	159.5	276	238.3	146	0	0	14.7
1985	0	0	0.2	24.9	126	64.6	486.6	360.5	193	33.4	5.2	0
1986	0	0	7	9.6	8.9	219.7	347.6	357.7	159	26.6	0	0
1987	0	0	14	6.5	176	*	368.8	548.4	96.6	194	35.2	0
1988	0	11.7	0	0	41.4	164.1	728.2	339.9	316	125	5	0.5
1989	0	0	12	16	163	169.1	465.9	361.9	295	88.2	2.1	1.2
1990	1	0	18	5	25.4	106.2	333.7	354	234	3.4	*	*
1991	0	0	0	99.5	150	492	356.9	357.7	295	41.7	*	*
1992	*	*	0.8	67	29.2	241.8	641.2	820.7	235	90.1	26.4	*
1993	*	*	*	4.9	67.8	43.2	257.2	479.9	99.8	9.9	0	0
1994	0	0	0	0	19.3	236.6	641.5	471.6	186	0	0	3.2
1995	0	0	0	0	89.3	178.9	357.1	282.9	120	0	16.1	18.1
1996	0	0	36	55	87.5	353.2	439.9	286.9	*	*	*	*
1997	0	0	1.5	8.9	71.1		217.1	205.8	144	110	15.5	0
1998	0	0	0	0	13.3	119.5	589.8	417.3	237	57.2	0	0
1999	0	0	0	6.2		109.8	451.4	480.5	178	269	0	2.9
2000	0	0	2	81.1	110	122.2	453.5	373.5	121	156	24.1	0
2001	0	0.5	4	14.2	39.7	176.5	335.8	270.7	159	97.9	26.5	6.5
2002	0	0	0	18.7	22.8	309.1	327.3	335.4	115	13.5	0	0
2003	0	0	0	2.6	0	251.2	298.4	397.4	293	9.5	6.3	5.2
2004	1.3	5.9	6.7	37.5	3.2	163.1	382.1	410.2	133	55.6	29.5	0
2005	0	0	27	0	37.9	262.1	261.8	461.6	271	44.6	22.4	0
2006	0.0	4.8	0.0	3.7	195.7	118.9	388.7	503.0	180.3	96.6	0.0	22.7
2007	0.0	0.0	0.0	24.0	19.0	167.5	232.3	425.0	346.7	7.0	16.5	0.0

Annex 1b: Rainfall of Bahir Dar Synoptic Station

Monthly Rainfall (mm) at Bahir Dar Synoptic Station												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	0.0	0.0	6.0	0.0	43.0	230.1	643.8	257.4	147.2	197.9	15.0	4.8
1978	1.8	0.0	9.4	67.9	41.1	266.7	350.0	212.4	200.8	123.2	23.9	0.1
1979	9.9	0.0	0.1	1.3	97.1	180.2	463.4	284.2	163.2	110.3	0.1	0.2
1980	0.0	4.4	16.1	51.8	27.9	136.1	349.2	320.5	153.5	55.5	3.2	0.0
1981	0.0	0.0	0.0	68.5	45.3	66.0	636.4	382.7	132.3	57.7	8.0	0.0
1982	4.7	0.1	42.8	9.1	35.4	78.4	266.9	261.5	116.7	73.0	6.0	0.0
1983	0.0	0.3	0.0	0.5	27.5	124.2	336.0	457.6	170.3	126.8	14.1	0.0
1984	0.0	0.0	4.4	0.3	66.3	234.8	381.0	310.4	209.6	0.0	0.1	9.8
1985	3.5	0.0	2.9	66.3	128.8	186.5	451.5	385.3	177.8	56.4	4.0	0.0
1986	0.0	0.3	5.1	16.5	9.4	212.4	410.7	273.2	170.8	115.9	0.0	0.0
1987	0.0	0.1	0.8	8.3	197.6	234.5	208.1	302.4	133.3	97.2	9.3	0.0
1988	1.2	26.9	0.0	0.0	31.7	164.9	467.3	273.6	192.2	113.6	31.0	8.8
1989	0.0	0.0	7.9	9.8	123.0	169.6	412.4	513.0	269.2	76.0	16.4	3.3
1990	4.6	6.3	1.0	19.8	15.9	83.6	559.5	463.3	224.2	40.0	0.0	0.0
1991	0.0	0.1	*	*	*	196.1	557.2	368.1	245.0	100.5	0.9	1.8
1992	0.0	0.0	4.3	63.7	49.9	114.4	290.5	446.8	154.1	209.6	65.3	0.0
1993	5.5	0.0	12.2	27.3	106.3	207.8	476.5	362.8	252.0	114.9	18.9	0.0
1994	0.0	0.8	0.0	21.7	103.5	190.3	314.1	272.0	145.6	19.2	3.7	5.6
1995	0.0	4.1	8.4	19.2	76.5	261.4	417.5	259.5	106.2	20.5	8.4	4.7
1996	0.0	0.7	28.0	49.0	99.2	261.6	295.2	359.3	211.9	48.4	26.7	0.0
1997	0.0	0.0	19.4	29.1	237.5	121.7	233.5	217.5	179.7	145.5	23.4	10.1
1998	0.0	0.0	18.8	0.6	107.6	196.5	384.1	358.0	240.6	115.3	1.1	0.0
1999	9.0	0.0	0.0	8.1	50.5	130.9	393.6	485.7	196.3	197.3	3.0	0.0
2000	0.0	0.0	0.3	90.3	61.2	153.7	314.2	517.2	225.8	173.3	27.8	0.0
2001	0.0	0.0	1.0	22.7	54.8	249.3	380.6	562.1	142.5	92.7	12.5	16.9
2002	0.0	1.2	8.2	15.9	2.0	437.2	465.0	405.0	154.9	17.8	0.5	1.0
2003	0.0	0.0	0.3	0.0	1.2	239.2	616.2	451.1	258.3	74.2	5.2	5.7
2004	8.7	20.5	5.1	39.2	7.3	144.3	503.3	294.5	232.0	89.9	7.4	0.0
2005	0.7	9.0	85.6	9.9	74.6	188.8	533.3	247.5	278.0	52.8	7.4	0.0
2006	3.1	0.2	0.1	6.7	151.2	225.5	563.9	364.1	211.0	153.7	0.0	3.7
2007	*	*	1.1	29.2	35.1	279.5	325.6	311.0	254.7	50.9	8.2	0.0

Annex 1c: Rainfall of Debretabor Station

Monthly Rainfall(mm) at Debretabor Station												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	71.4	25.5	2.6	18.8	39.6	269.0	399.5	502.4	129.4	0.0	0.0	0.0
1976	0.0	0.0	13.6	9.7	59.8	137.9	298.2	400.0	224.4	94.2	134.9	6.1
1977	0.0	0.0	50.6	3.5	134.9	343.5	595.9	532.5	254.9	314.3	3.3	32.1
1978	2.6	7.0	8.8	26.1	72.3	493.0	573.7	406.1	241.0	57.6	67.7	32.1
1979	6.6	2.0	0.0	5.2	158.1	144.8	555.7	462.2	260.2	182.5	0.0	0.0
1980	0.0	10.1	25.4	103.8	37.6	166.7	586.6	489.1	225.4	97.6	141.1	0.0
1981	0.0	0.0	0.0	7.2	26.0	137.1	462.7	464.9	247.3	155.7	58.0	0.0
1982	14.3	0.6	57.9	3.9	78.6	90.3	266.5	670.6	201.8	182.6	67.9	0.0
1983	0.0	0.0	0.0	20.8	89.6	51.0	474.0	516.7	186.4	50.6	46.3	0.0
1984	0.0	0.0	0.0	6.2	155.1	197.6	*	262.6	116.7	0.0	13.0	0.0
1985	5.0	10.0	12.8	44.8	100.9	177.3	338.2	259.4	146.7	16.2	15.7	11.0
1986	3.3	2.3	42.0	15.6	5.6	347.5	447.5	444.6	192.6	46.8	0.0	22.9
1987	16.1	0.3	58.3	21.4	155.8	146.7	273.8	369.6	56.1	65.1	27.2	0.0
1988	0.1	5.4	3.6	17.2	54.9	*	*	*	*	*	*	*
1989	6.2	*	84.3	45.8	94.8	85.3	304.7	425.5	139.3	103.6	6.6	37.7
1990	10.8	*	*	*	*	*	*	*	*	*	*	*
1991	*	*	*	*	*	*	*	*	*	1.7	36.1	2.1
1992	0.0	0.0	12.8	86.0	38.6	115.9	329.5	393.4	133.8	99.7	68.1	5.9
1993	0.8	2.0	86.3	74.5	199.4	137.2	429.8	289.9	208.8	118.6	23.3	1.1
1994	1.8	9.1	7.7	17.0	89.7	237.7	493.8	631.5	248.0	10.0	24.8	31.7
1995	0.0	0.0	22.7	34.6	100.4	73.0	399.7	403.6	186.9	5.0	23.4	25.3
1996	4.3	1.2	49.4	92.1	146.1	187.0	369.4	374.0	155.4	30.6	76.2	4.4
1997	3.4	0.0	73.7	43.1	197.6	215.1	439.7	359.0	197.0	305.0	12.3	82.5
1998	13.6	0.0	21.2	6.9	203.6	126.2	399.6	410.8	245.4	75.9	0.5	0.0
1999	34.5	0.0	0.0	9.5	44.3	181.4	476.5	345.7	182.1	275.0	11.2	19.5
2000	0.0	0.3	6.3	118.3	61.1	168.1	423.6	462.4	232.2	137.8	35.1	0.5
2001	0.0	1.3	17.2	24.0	95.4	197.5	496.7	410.0	184.8	60.1	4.5	7.2
2002	0.4	0.0	60.2	45.1	47.2	203.3	256.6	313.4	132.8	2.9	16.0	18.8
2003	0.0	13.9	24.1	28.1	10.5	86.2	435.7	396.8	221.7	16.7	33.3	14.8
2004	0.5	37.6	33.7	75.5	19.1	141.0	333.7	295.2	120.8	85.8	42.5	12.7
2005	1.3	0.0	34.1	10.3	56.3	224.4	473.6	436.0	216.2	5.0	29.7	0.0
2006	0.0	1.4	6.8	63.2	147.3	170.0	482.2	452.5	255.0	47.5	0.0	7.9
2007	19.9	0.5	22.2	87.8	65.6	281.4	424.7	439.1	183.1	8.1	0.0	0.0

Annex 1d: Rainfal of Dera Hamusit and Alem Ber Station

Monthly Rain Fall at Alem ber Station												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	0	0	17.4	37.3	64.8	215	372.4	314.2	146	54.6	49.4	11.6
1979	0	0	0	13.3	97.2	178.4	356.2	369.1	147	73.3	0	0
1980	0	39	18.5	121	24	116.3	442.7	382.8	187	351	18.1	1
1981	16	0	0	25.8	58.9	140.8	469.1	487.5	166	71.4	25.6	0
1982	0	0	89.4	12	55.4	49.2	300	380.7	122	127	34	0
1983	0	0	0	2.2	81	*	302	428.9	109	79.7	26.4	0
1984	0	0	9.4		91.2	196.3	364.3		188	0	2	6.6
1985	1.3	0	2.7	22.1	174	215.2	413.9	351.2	133	34.8	36.7	0
1986	0	1.1	6.9	22.9	44	252.6	394.5	373.4	181	55.7	0	1.9
1987	0	0	17.6	64	261	134.3	293	279.2	69.7		0	0
1988	0		0	4.6	49.4	202.2	806.4	392.7	209	155	9	0
1989	*	3.5	34.9	*	146	71.6	269.1	412.2	157	136	16.7	32.6
1990	*	5.4	15.5	1	*	*	*	*	*	*	*	*
2000	0	0	0	65.6	116	143.2	381.9	342.6	212	111	14.4	0
2001	0	0	8.8	15.2	30.5	378.1	443.5	329.1	80.1	92.8	33.2	4.2
2002	0	0	8.4	12.1	8.4	219.5	274.2	292.3	135		6.9	5.9
2003	0	8.9	5.7	26	3.9	245.7	405.2	490.2	234	10.6	7.3	2.3
2004	1	11.6	9	63.5	14.2	226.6	340.2	274.5	138	104	16.7	1.7
2005	0	0	18.6	6.2		211.4	352.1	400.2	249	44.2	12.4	0
2006	0	0	0	11.7	177	132.3	456.6	366.3	*	*	*	*
Monthly Rainfall at Dera Hamusit												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	*	*	*	*	*	*	*	*	*	9.1	2.8	0
1988	0	8.7	0	0	75.8	14.6	792.6	463.2	250	228	15	0
1989	0	0	9.1	0	90.8	128	476	449	192	114	4.1	0
1990	*	*	*	*	*	*	*	*	*	*	*	*
1991	*	*	*	*	*	*	*	*	*	*	*	*
1992	*	0	0	27.6	51.6	182.4	426.3	570.8	141	195	42.8	2.5
1993	0	0	26.6	27.4	56	244.9	390.7	356.5	385	70.5	0	4.5
1994	0	5.2	0	16.2	120	316.1	591.8	621.9	252	36.9	14.5	21.3
1995	0	0	42.2	23.9	90.1	160.3	636.9	266	120	14.8	27.3	13.7
1996	0	2.3	47	65.3	159	386.8	409.8	363.8	210	25.7	18.5	0
1997	0	*	14.6	22.8	145	281.8	344.5	263.3	220	249	16.6	0
1998	0	0	*	3.5	92.8	176.1	*	522.4	246	204	0	0
1999	*	*	0	0	42.6	118.1	455.9	435.2	175	177	0	0
2000	0	0	0	10.6	90.2	185.3	420.2	535.4	136	143	21	0
2001	0	0	0	34.3	52.7	149.5	*	460.9	*	0	0	0
2002	0	0	6.4	0	6.5	239.6	322.9	440.3	170	25.5	0	0
2003	0	0	3.2	0	12.7	229.1	491	389.4	314	21.9	15.1	6.1
2004	0.1	3.6	5.3	8.9	150	457.4	279.6	216.7	127	22.8	0	0
2005	*	*	*	42.7	8.7	138.8	298.3	290	283	18.7	34.4	0

Annex 1e: Rainfall of Wanzaye Station

Monthly Rainfall at Wanzaye												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984	*	*	*	*	*	*	*	*	*	*	0.0	25.0
1985	*	*	*	*	*	*	*	*	*	*	*	*
1986	*	*	1.1	0.0	4.1	216.4	586.8	281.8	183.8	111.5	0.0	0.0
1987	0.0	0.0	20.4	21.1	215.5	165.6	400.6	368.9	192.1	121.2	*	0.0
1988	0.0	12.9	0.0	0.0	88.5	208.8	691.7	266.4	232.0	129.2	13.7	4.2
1989	0.0	0.0	16.0	9.2	110.7	170.9	395.5	418.0	*	113.3	4.5	1.0
1990	*	*	*	*	*	65.8	340.6	523.2	295.0	7.8	0.0	0.0
1991	0.0	*	*	*	*	*	*	*	256.5	36.7	0.0	0.0
1992	*	*	*	*	*	164.2	194.1	477.6	200.1	161.7	2.0	0.0
1993	0.0	0.0	1.0	14.6	*	*	425.1	404.9	437.7	62.3	18.4	0.0
1994	0.0	0.0	0.0	6.6	70.0	332.8	329.3	423.5	222.3	21.8	0.0	0.0
1995	0.0	0.0	37.9	51.9	68.7	141.1	458.8	380.8	164.9	0.0	18.5	12.2
1996	0.0	0.0	42.6	97.4	102.4	315.6	375.0	404.3	207.3	7.9	42.8	0.0
1997	0.0	0.0	1.8	15.2	197.0	222.2	258.7	201.1	180.2	101.7	33.1	0.0
1998	9.2	0.0	1.4	2.3	99.0	226.6	408.6	496.6	283.2	103.0	0.0	0.0
1999	5.9	0.0	0.0	0.0	33.0	217.9	437.9	495.9	227.8	176.1	0.0	0.0
2000	0.0	0.0	0.0	76.5	45.6	218.9	551.2	393.3	202.0	171.7	5.6	0.0
2001	0.0	0.0	0.0	0.0	75.8	142.6	718.8	260.9	150.1	33.0	0.0	0.0
2002	0.0	0.0	0.0	29.0	0.0	202.1	310.4	461.1	210.3	6.0	48.8	*
2003	*	0.0	*	*	*	*	*	*	*	*	*	*
2004	0.0	0.0	3.0	24.5	0.0	117.9	378.8	256.4	211.1	87.2	9.8	0.0
2005	0.0	0.0	27.8	0.0	54.7	136.8	334.1	289.0	299.8	45.5	9.8	0.0
2006	2.9	0.3	2.1	99.0	111.7	82.0	413.1	599.4	199.4	77.8	0.0	8.8
2007	0.0	0.0	0.5	39.7	64.0	301.9	344.0	393.0	253.8	57.5	7.4	0.0

Annex 1f: Rainfall of Mekaneyesus and Arb Gebya

Monthly Rainfall At Arbgebya												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	*	*	*	*	*	*	*	*	*	*	*	0.4
2001	0.0	0.1	13.4	42.2	86.4	243.1	416.1	505.2	179.1	63.5	25.1	16.1
2002	0.0	0.0	47.3	61.0	18.3	248.0	246.9	388.7	162.7	88.5	3.3	1.2
2003	0.0	19.0	18.8	25.2	8.9	*	*	*	*	*	*	*
2004	*	27.7	6.6	56.1	12.6	184.3	466.1	287.3	188.8	111.5	21.2	0.4
2005	*	0.0	0.0	13.1	20.5	143.5	334.5	186.3	*	*	*	*
2006	6.8	0.0	0.0	18.4	*	*	*	*	74.0	0.0	0.0	0.0

Monthly Rainfall At Mekaneyesus												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	*	*	*	*	*	182.1	356.6	295.2	219.0	18.2	30.0	2.3
1995	0.0	1.0	26.1	68.8	102.4	44.5	296.5	222.9	133.0	0.2	7.2	24.2
1996	20.3	12.5	83.9	79.8	124.2	183.9	511.5	345.2	257.5	19.6	32.0	5.4
1997	0.3	0.0	65.2	32.6	99.9	184.0	363.3	334.0	129.2	102.5	100.5	5.6
1998	2.9	0.0	35.1	16.9	75.3	265.0	301.1	263.2	249.2	100.0	1.2	0.0
1999	24.3	0.0	0.0	72.2	24.5	125.8	365.0	349.5	184.6	193.5	7.9	30.8
2000	0.0	0.0	26.9	67.4	40.2	183.3	426.7	279.2	143.1	145.2	73.0	27.7
2001	0.0	4.7	52.2	79.5	58.9	260.6	377.0	452.2	64.9	73.6	0.0	12.1
2002	3.0	1.2	51.6	34.5	5.8	191.1	344.3	362.8	207.1	14.6	10.0	3.6
2003	*	16.5	*	*	*	*	*	*	*	*	*	*
2004	5.2	8.3	11.2	57.7	23.2	132.2	415.1	194.2	103.1	44.7	22.3	2.4
2005	3.9	3.6	56.6	*	35.8	115.8	330.2	257.1	*	*	*	*
2006	0.0	2.9	16.5	42.2	125.1	257.4	310.8	277.2	219.7	65.1	40.4	30.0
2007	0.0	11.1	41.1	43.8	73.9	343.9	355.4	278.0	160.3	39.1	70.0	0.0

Annex 2: Temperature, Relative Humidity, Wind Speed and Sunshine hours

Maximum, Minimum and average Monthly Temperature of the Stations													
Station	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
B/Dar	Min	8.2	10.1	12.8	14.3	15.1	14.6	13.9	13.8	13.2	13.1	11.0	8.7
	Max	26.6	28.0	29.5	29.9	29.0	26.7	24.2	24.1	25.3	26.4	26.6	25.6
	Aver	17.4	19.0	21.1	22.1	22.0	20.6	19.1	18.9	19.2	19.7	18.8	17.2
Wereta	Min	8.0	10.4	12.0	12.3	12.9	12.7	11.9	12.0	11.6	10.4	11.2	8.5
	Max	29.0	29.6	30.2	29.4	28.9	26.9	25.3	24.2	25.7	25.8	26.4	27.5
	Aver	18.5	20.0	21.1	20.8	20.9	19.8	18.6	18.1	18.6	18.1	18.8	18.0
Alem Ber	Min	10.6	11.9	13.2	13.4	13.6	12.7	12.0	11.8	11.5	11.2	10.6	10.2
	Max	27.3	28.5	29.6	30.0	28.6	26.2	23.5	23.2	24.5	26.0	26.8	27.0
	Aver	19.0	20.2	21.4	21.7	21.1	19.4	17.7	17.5	18.0	18.6	18.7	18.6
Debre Tabor	Min	8.9	9.9	10.9	11.3	11.3	10.4	9.7	9.6	9.2	8.9	8.5	8.2
	Max	22.3	23.4	23.9	24.1	23.4	22.4	18.6	18.6	19.7	20.6	21.2	21.0
	Aver	15.6	16.7	17.4	17.7	17.3	16.4	14.1	14.1	14.4	14.7	14.8	14.6
Mekane yesus	Min	4.6	6.4	8.5	10.0	10.3	10.5	11.1	11.0	9.3	7.2	5.5	4.8
	Max	27.0	29.5	29.4	29.0	28.2	25.0	22.2	22.7	24.5	26.5	28.2	27.5
	Aver	15.8	18.0	18.9	19.5	19.3	17.8	16.6	16.9	16.9	16.9	16.8	16.1
Wanzaye	Min	9.2	9.2	13.2	13.9	14.2	13.8	14.2	13.7	13.3	12.7	10.5	9.5
	Max	29.1	31.1	32.0	32.3	31.5	28.6	25.9	25.9	26.5	28.9	28.9	28.9
	Aver	19.2	20.1	22.6	23.1	22.9	21.2	20.0	19.8	19.9	20.8	19.7	19.2

Relative Humidity												
Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	51.1	45.1	42.3	42.8	52.5	66.8	76.0	77.1	72.3	63.2	56.2	52.0
Debre Tabor	41.7	38.9	42.1	47.5	55.3	72.7	85.1	83.1	75.4	63.2	54.0	48.3
Average	46.4	42.0	42.2	45.1	53.9	69.7	80.5	80.1	73.9	63.2	55.1	50.2

Wind Speed												
Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	0.56	0.63	0.75	0.85	0.79	0.84	0.69	0.66	0.64	0.67	0.61	0.51
Debre Tabor	1.14	1.23	1.27	1.32	1.34	1.30	1.09	1.22	1.15	0.93	0.97	1.04
Average	0.85	0.93	1.01	1.08	1.07	1.07	0.89	0.94	0.89	0.80	0.79	0.78

Sunshine Hour												
Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bahir Dar	9.6	9.7	9.0	8.9	8.3	7.0	4.6	4.5	6.5	8.5	9.5	9.4
Debre Tabor	7.4	7.2	7.1	6.3	6.4	6.0	4.4	4.8	6.9	7.3	8.1	8.1
Average	8.5	8.4	8.0	7.6	7.4	6.5	4.5	4.6	6.7	7.9	8.8	8.8

Annex 3: Ground Water Source Inventory Data

Annex3a Boreholes and Hand Dug Wells

Ground Water source inventory Data (Borehole and Hand Dug well)											
Wereda	Easting	Northing	SWL	Alt	Source	Wereda	Easting	Northing	SWL	Alt	Source
Dera	370897	1286091	8.7	2456	HDW	Fogera	343061	1316215	5.3	1801	HDW
Dera	368763	1287203	6.0	2271	HDW	Fogera	343604	1315980	2.9	1801	HDW
Dera	371795	1283100	7.9	2455	HDW	Fogera	348558	1314297	3.5	1803	HDW
Dera	347354	1300075	6.0	1918	HDW	Fogera	351213	1313110	2.4	1804	HDW
Dera	348963	1301585	2.4	1871	HDW	Fogera	351449	1313588	2.0	1802	HDW
Dera	363047	1284820	16.5	2246	HDW	Fogera	352610	1314001	3.7	1800	HDW
Dera	365825	1284974	8.4	2282	HDW	Fogera	349280	1313478	3.9	1799	HDW
Dera	358899	1287510	5.9	2357	HDW	Fogera	349327	1313707	3.4	1798	HDW
Dera	350980	1287172	12.1	2246	HDW	Fogera	349172	1313814	4.0	1800	HDW
Dera	355706	1303186	7.3	1832	HDW	Fogera	349156	1313798	4.1	1801	HDW
Fogera	389496	1313043	6.0	2621	HDW	Fogera	349174	1313720	4.3	1800	HDW
Fogera	378277	1316806	6	2065	HDW	Fogera	348890	1313865	3.9	1799	HDW
Fogera	377797	1316518	7.0	2051	HDW	Fogera	348870	1313901	3.9	1799	HDW
Fogera	357592	1308923	11.0	1838	HDW	Fogera	348904	1314011	3.9	1799	HDW
Fogera	388922	1307465	7.5	1850	HDW	Fogera	348893	1314208	3.5	1797	HDW
Fogera	366018	1300550	6.0	1911	HDW	Fogera	344941	1315500	3.6	1797	HDW
Fogera	360295	1300535	9.0	1903	HDW	Fogera	345626	1313161	3.7	1801	HDW
Fogera	363580	1307953	9.0	1944	HDW	Fogera	345680	1313315	4.8	1800	HDW
Fogera	360728	1309146	7.0	1945	HDW	Fogera	345673	1312893	3.9	1802	HDW
Este	399804	1293607	9.0	2741	HDW	Fogera	345642	1312884	3.7	1800	HDW
Este	381085	1288870	9.0	2377	HDW	Fogera	345672	1312847	3.9	1802	HDW
Farta	397529	1306460	4.5	2598	HDW	Fogera	345706	1312810	3.8	1799	HDW
Farta	393849	1308192	9.0	2648	HDW	Fogera	346248	1312849	4.3	1798	HDW
Farta	397106	1309736	9.5	2635	HDW	Fogera	346238	1312809	3.5	1797	HDW
Farta	405325	1304126	9.0	2827	HDW	Fogera	346238	1312809	3.8	1804	HDW
Farta	402163	1300529	9.6	2893	HDW	Fogera	347398	1312693	3.7	1802	HDW
Farta	388442	1304640	13.0	2362	HDW	Fogera	347407	1312959	3.5	1802	HDW
Farta	405029	1301052	7.0	2924	HDW	Fogera	347442	1312929	3.6	1805	HDW
Fogera	346623	1315362	4.3	2069	HDW	Fogera	349821	1311202	3.8	1809	HDW
Fogera	346039	1315660	5.0	1804	HDW	Fogera	354312	1313654	1.2	1815	HDW
Fogera	345552	1315939	4.0	1805	HDW	Fogera	352645	1314492	4.6	1800	HDW
Fogera	342862	1316552	4.7	1803	HDW	Fogera	351749	1315600	3.8	1798	HDW
Fogera	351540	1315629	4.3	1800	HDW	Fogera	351844	1315876	4.5	1806	HDW
Fogera	351563	1315840	4.0	1794	HDW	Dera	348063	1307052	5.2	1800	BH
Fogera	351662	1315879	4.0	1798	HDW	Dera	350882	1308451	8	1802	BH
Dera	350614	1289545	25	2180	BH	Dera	355505	1303185	0.5	1814	BH
Dera	342189	1301216	5.2	1955	BH	Dera	363789	1285991	59	2220	BH
Dera	350355	1292665	2.28	2079	BH	Dera	373206	1286508	40	2336	BH
Fogera	377797	1316518	6	2065	BH	Dera	372073	1288388	36	2297	BH
Este	386200	1283171	12	2433	BH	Dera	372070	1287156	25	2308	BH

Annex 3b: Springs

Wereda	Village/ Scheme	Easting	Northing	Elevation	Yield (L/s)
DERA	Wanzaye	355505	1303185	1814	0.25
DERA	Gomengie	357037	1296661	2111	0.5
DERA	Aba solomon	369975	1286019	2426	0.1
DERA	Gibtsawit	348963	1301585	1871	2
DERA	Betekilan	371566	1289547	2248	0.5
ESTE	Recha Kuskuam	384974	1292336	2212	0.4
ESTE	Aroge Mesk M	384856	1286072	2404	0.3
ESTE	Aroge Mesk M	387477	1287409	2480	0.24
ESTE	Gindatemem	379775	1291860	2230	0.30
ESTE	Gindatemem	380043	1289223	2302	0.30
ESTE	Gindatemem	380856	1286769	2370	0.3
ESTE	Gindatemem	383385	1288933	2344	0.30
ESTE	Wulgede(Dafko	400153	1292426	2784	0.22
ESTE	Lewaye Asham	400965	1294412	2742	0.36
ESTE	Lewaye Asham	400150	1292421	2776	0.2
FOGERA	Tankua Gebriel	355074	1309388	1805	28
FOGERA	Mariam	354299	1304392	1808	1045
FARTA	Teliba Midir	405200	1297185	2967	0.2
FARTA	Teliba Midir	405108	1298402	3021	0.1
FARTA	Senbet Dar	388524	1310709	2658	0.07
FARTA	Achoka	387645	1303757	2278	0.1
FARTA	Hamus Gebia	388444	1301792	2057	0.4
FARTA	Hamus Gebia	386106	1302910	2186	0.7
FARTA	Hamus Gebia	385457	1302255	2072	1
FARTA	Amagaw	403734	1300666	2910	0.1
FARTA	Midirgua	403821	1300869	2896	0.04
FARTA	Midirgua	403688	1301788	2904	0.02
FARTA	Amba Meda	391104	1307711	2532	0.8
FARTA	Janmeda	397542	1308887	2625	0.5
FARTA	Boda	388549	1308304	2357	0.04
FARTA	Boda	389048	1310283	2440	0.1
FARTA	Boda	385789	1308196	2335	1.2
FARTA	Abo Denje	385288	1313484	2551	0.8
FARTA	Abo Denje	384847	1311360	2450	1.1

Annex 4: Hydrochemical Data

Source	Easting	Northing	Alt	pH	EC	TDS	Na	K	Mg	Ca	Cl	SO4	HCO3	CO3	NO3	F
R	368325	1297896	1918	6.1	49	36	1.7	1.6	2.2	4.5	1	16.3	9.13	T	0.4	0.14
SP	367449	1296565	1940	9.16	187	126	44.5	0.5	T	T	3.8	7.55	39.2	39	0.1	1.12
HD	367264	1298770	1930	6.53	244	162	7.7	1.1	8.1	35	8.6	13.6	100	T	20	0.41
BH	355516	1303185	1827	9.14	198	124	46	0.5	T	T	1.9	1.75	62.7	26	0.1	0.53
SP	355783	1303278	1838	9.15	194	130	48.5	0.4	T	T	2.8	3.3	60.1	29	0.1	0.18
HD	355129	1302836	1828	6.62	158	94	5.6	0.6	5.4	22	2.8	11.55	86.7	T	2	0.09
SP	354299	1304392	1808	6.67	249	164	6.5	0.7	11	33	2.8	3.3	139	T	12	0.48
SP	353967	1306286	1802	6.4	222	150	6.3	0.6	10	28	1.9	2.75	123	T	16	0.23
SP	355074	1309388	1805	6.68	206	136	6.3	0.7	8.1	28	2.8	3.85	116	T	8.4	0.09
HD	349036	1310444	1831	7.61	803	540	92	1.3	22	76	3.8	29.7	525	T	4.3	0.32
R	351267	1308819	1807	6.38	84	55	3.3	2	2.7	8.9	1	15.95	29.7	T	0.6	0.32
HD	347109	1306534	1822	7.15	344	230	5.8	1.4	8.6	60	4.8	12.1	194	T	6.5	T
HD	403424	1301214	2924	7.76	231	139	3.72	1.5	8.8	34	2.5	0.35	143	T	6.6	0.17
SP	403734	1300666	2910	7.84	93.5	56	1.99	0.9	2.6	20	1	0.32	65.9	T	7.7	0.1
SP	397542	1308887	2625	7.82	77.5	46	2.36	0.3	2.1	16	0.8	0.21	50	T	5.5	0.02
HD	397071	1309085	2631	7.86	216	130	8.01	1.3	2.7	38	2.7	2.53	128	T	9	0.15
R	354642	1303771	1796	7.66	247	149	11.7	6.1	8.7	18	6.2	0.84	173	T	T	0.19
HD	381085	1288870	2377	7.61	228	137	4.41	1.7	7.7	33.4	0.8	2.08	151	T	6.8	0.15
BH	373206	1286508	2336	7.62	270	163	6.02	1.8	14	33	3.2	0.14	166	T	15	0.08
BH	372073	1288388	2297	7.63	276	165	6.32	1.5	13	29	2.3	0.25	174	T	11	0.15
BH	363789	1285991	2220	7.62	274	164	6.81	2	9.4	30	0.6	0.1	198	T	2.8	0.1
R	401749	1295986	2853	6.7	118	88	9	5.2	5.4	11	1.9	6.6	53	T	0.9	0.24
R	375239	1287122	2345	8.13	206	134	6.7	1.9	5.9	33	T	2.2	138	T	0.7	0.14
R	351414	1309680	1794	7.46	373	240	14.1	4	13	54	2.9	3.9	244	T	1.6	T
R	371605	1299548	1905	7.66	209	138	7.5	2	7.7	32	1	2.2	143	T	0.7	0.04

*R-Rivers SP-Spring, HD-Hand Dug Wells and BH-Boreholes