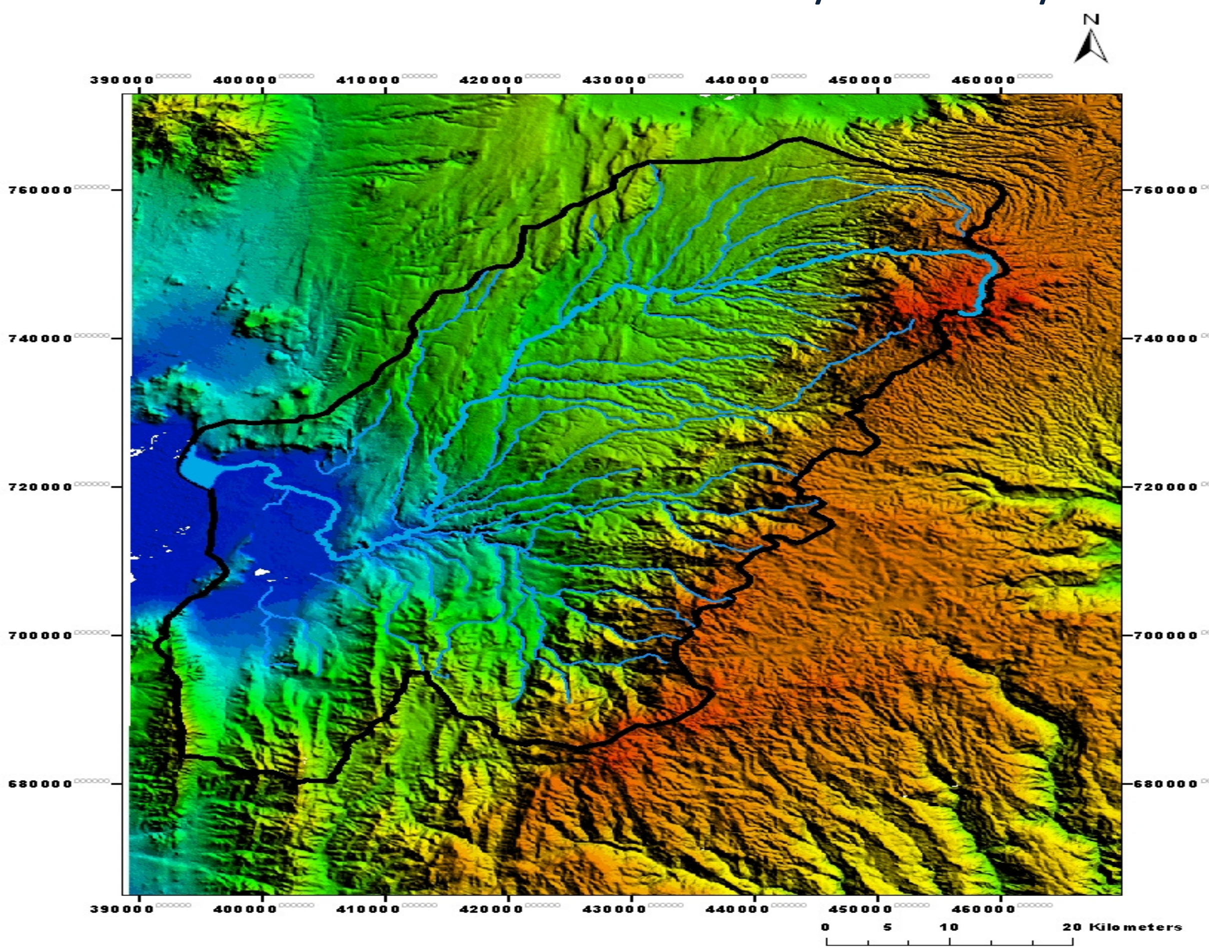
Department of earth sciences

GROUNDWATER RESOURCE ASSESSMENT IN THE GIDABO RIVER CATCHMENT.

IN THE SOUTHERN MAIN ETHIOPIAN RIFT PROVINCE./YIRGALEM-WONAGO/



A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for Degree of Master of Science in Hydrogeology.

By
Birhanu Debisso

October, 2009

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF EARTH SCIENCES

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university.

All sources of materials used for the thesis have duly acknowledged.

Birhanu Debisso

Signature_________________

Place and date of submission: School of Graduate Studies, Addis Ababa University, October, 2009

DEDICATION

This thesis is dedicated to my beloved brother in Christ Bereket Takele, my brother Melese Debisso, my father Debisso Dingama, My mother Kabushe Ararso and my fiancée Asegedech Kiflu; for all their help and encouragements.

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ABSTRACT

The Gidabo River Catchment area is found within southern Main Ethiopian rift, North-east of Lake Abaya; or more specifically lies in Sidama and Gedio Zones of Southern region and Borena Zone of Oromia region. The Catchment area coverage and the perimeter of the Gidabo River are 3342.37 square kilometers and 305.25 kilometers respectively. Assessment of groundwater resource potential of the catchment is studied based on conventional hydrogeological techniques, by gathering and interpreting geological, hydrometeorological, hydrogeological and hydrochemical data.

The Gidabo River Catchment area is dominantly covered by pyroclastic fall (flow) deposits and Trap-Series basalts with Trachytic compositions; alluvial and lacustrine deposits also cover considerable area of the Catchment.

Using analysis of the available meteorological data, potential evapotranspiration (PET) was calculated by two methods; (i.e. Thornthwaite (1948) and Penman). PET values obtained by Thornthwaite method for Highland, Escarpment and rift floor are estimated to be 689.85mm 786.8mm and 1307mm respectively. Modified Penman approach is used only for calculating PET of the rift floor and gave the value of 1301mm. Actual Evapotranspiration (AET) was calculated using Turc and Soil water balance method. The AET values obtained by Turc method for Highland, Escarpment and Rift floor is 665mm, 950mm, 1456mm respectively. AET values obtained by soil-water balance method for the Highland, the Escarpment and the Rift floor are estimated to be 688.9mm, 803.9mm, 1063.6mm respectively. Conventional water balance method has been used to compute the total groundwater recharge of the basin and recharge value of 353mm/year is obtained.

Ground water potential of the Gidabo Rive Catchment is seen to be under the control of fractures (faults) and weathering. Higher hydraulic conductivity zones are mapped at or near fractured regions and their values are decreasing away from the fractures (faults).

Graphical presentation (i.e. Piper (1944)) is used in order to facilitate the interpretation and analyses of the chemical data. The piper plot shows that most boreholes and spring water samples are Ca-Mg-HCO_3 type in the discharge area and Na-HCO_3 type towards the recharge areas.

The surface and shallow groundwater systems are characterized by high iron concentrations. The source is believed to be the red soils that cover the study area. According to Kedir Yasin (2002), the concentration of iron in the water is greater in the wet season than the dry season due to leaching effect.

High concentration of fluoride within the study area is noticed in the western part (discharge area) in geothermal borehole and hot springs.

CHAPTER ONE

1. INTRODUCTION

1.1 Background

The area under examination is within southern Main Ethiopian rift, North-East of Lake Abaya. The Gidabo River Catchment lies in Borena, Sidama and Gedeo Zones. The very upper part of the Catchment is humid environment; the mountain chains mark the eastern border of the River and its tributaries. These mountainous scenarios play crucial role in controlling rainfall condition due to orographic effect.

Physiographical appearance of the Catchment is imparted by the tectonic activity took place in association with the rifting episodes (*Raunet, 1977*). The eastern part of the Catchment is topographically higher while the western is lower due to the altitude ranging from 3200 meters on the high plateau peak (Geremba Mountain) to 1170 meters at Abaya Lake level over a distance of about 50 kilometres as the crow flies.

Surface water is draining from the eastern escarpments toward Lake Abaya. Gidabo River has formed prominent delta that goes up to lake shore from the slope base. Some part of the deltaic area is marshy. Shrubs and bushes with savannas' grass land make fairly dense vegetation.

Acidic rocks such as rhyolites and trachytes, localized basic rocks, lacustrine and alluvial deposits make the geology of the area. The acidic rocks chiefly characterize all eastern plateau and North-Eastern shores of Lake Abaya. These lithologies are exposed in different parts of the Catchment. They are also highly affected by weathering and show fractures in which secondary fillings are growing.

Hydrogeology of the area is less known as no or little detailed study has been conducted in the area so far. However, from field survey and few previous works in the area, it has been realized that the Catchment's hydrogeology is governed mainly by:-

- Adjacent plateau, escarpment and rift floor topography.
- Climatological condition.
- Land use land cover of the area.
- Geological formation of the area.
- Geological structures (*faults, fractures, fissures, etc*) effect.

These above points suggest that the water resources are ample; though threatening factors such as mismanagement, alarming deforestation, application of fertilizers, etc are there.

Several streams drain into Gidabo River from the surrounding east and South-East plateaus, The River carries huge water to Lake Abaya which is another surface water resource. The marshy delta of the River jammed in between shore of Lake Abaya and the eastern slopes literally indicates good groundwater potential near the marshy land (Abenezer Kefeni, 2007).

Hot springs also need detailed considerations in the area; they occur along tectonically affected weak zones, some in the Gidabo River Banks. These springs are rich in Total dissolved solids and Electrical conductivity as a function of higher temperature. For instance Waleme Hot Spring water near to Dilla town has EC Value of 3.12mS/cm and TDS Value of 1870mg/l where temperature reaching up to 68^0C.

In this thesis-research, it has been attempted to apply Land-Cover, Pedological, hydrometeorological, geological, hydrogeological, and hydrogeochemical methods to come up with the best outlook of groundwater resource potential in the Whole Gidabo River Catchment.

1.2 Previous works

A lot of regional scale works have been done within Main Ethiopian rift; concerning rift center geothermal resources, geochemical works, Groundwater study, Hydrogeology, Lake Hydrology and morpho-pedological studies.

The study area and its parts were studied separately by different researchers in different titles at different times. For instance, Gezahagn Yirgu, 1980, and WoldeGabriel *et al.,* 1999 studied geothermal resources around Lake Abaya and temporal variation in geochemical composition of south rift rocks.

Yetnayet Nigussie, 1990, conducted reconnaissance study of the groundwater resource of the Gidabo basin. Recently, AG consult, 2004, carried out hydrogeological mapping of Yirga Alem and Kilisa sheets, and Kedir Yassin, 2002, performed study of hydrogeology in upper Gidabo River Catchment, Southern Ethiopia.

Mesfin Gobena, 2005, conducted Pollution assessment in relation to wet coffee processing plants in surface and shallow groundwaters in Sidama and Gedeo zones.

Abraham Mechal, 2006, conducted Groundwater Resource Assessment in the Buna River Catchment: Dilla, Southern Ethiopia.

Mulugeta Musie, 2007, made study of Groundwater Circulation and Hydrochemistry of the Corridor (Upper Gidabo River and Lake Awassa Catchments), Sidama Zone, SNNPRS.

1.3 Present work

The present work is on the Groundwater Resource Assessment in the Gidabo River Catchment which covers an area of 3342.37 square kilometers.

1.3.1 Objectives of the study

1.3.1.1 General objective

To undertake Groundwater Resource Assessment and Potential Evaluation based on Land use-Land cover, Pedological, hydrometeorological, hydrogeological and hydrogeochemical methods.

1.3.1.2 Specific objectives

The specific objectives are to:

- Identify the existing geologic units and structures and map them at a scale of 1: 500,000
- Identify the different hydrogeological units and mapping them at a scale of 1: 500,000
- Zonation of hydraulic conductivity within the Catchment, thereby mapping groundwater potential zones.
- Determine each hydrologic input and output in the River Catchment by analyzing the available hydrometrological data.
- Show the flow systems of groundwater in the Catchment.
- Delineate recharge and discharge areas through analyses of various well completion reports of boreholes distributed within and around Gidabo River Catchment.
- Evaluate the cause for the enrichment of iron in the water samples of the Gidabo River Catchment.
- Know the controlling factor and the source for the heat that gives the hot springs.

1.4 Methodology

The methods employed to achieve the objectives of the research work are as follows:

- ★ Collection and revision of published and unpublished materials and reports such as water resources study reports; water points completion reports- boreholes, hand-dug wells, springs, and pumping test data.
- ★ Collecting the Pedological, Geological, Hydrological, Hydrogeological, hydrogeochemical and hydrogeophysical literatures either regarding the Catchment or the whole southern Ethiopian rift; paying great attention to the previous literatures of the Catchment and its surroundings.
- ★ Collecting the regional geologic map of the scale 1:500,000.
- ★ Collecting and scanning the topographical map of the scale 1:50,000.
- ★ Collecting the representative water samples from different water bodies to study the hydrochemistry of the Catchment.
- ★ Performing the in-situ test for the sensitive parameters like PH, TDS, EC, Temperature and Turbidity along with Chemical analysis of water samples in the Laboratory of the Southern Nations Nationalities and People's Water Resource Bureau.
- ★ Obtaining the Digital Elevation Models (*DEM*).
- ★ Collecting the river discharge data and meteorological records.
- ★ Obtaining and interpretation of the satellite imagery of the study area with appropriate resolution.
- ★ Collecting the primary data from the field. In this stage lithological description, inventory on water points and insitu tests of water chemistry has been done.
- ★ Organizing, Analyzing and interpreting the Primary and Secondary data collected; by using computer softwares such as Arc GIS, AQUACHEM, TIME PLOT, GLOBAL MAPPER and SURFER.

CHAPTER TWO

2. GENERAL OVERVIEW OF THE STUDY AREA

2.1 Location and Accessibility

The area under examination lies in Borena, Sidama, and Gedeo zones and covers the whole of the hydrographical system of the Gidabo River which rises in the highland area of the Aleta Wondo Escarpment, joining numerous large streams, draining an extensive catchment and flowing into the Lake Abaya as the Eastern tributary (Seleshi Bekele Awulachew, 2000).

The Region drained by the Gidabo River is bordered by the catchment of the: Lake Awassa to the North, River Bilate to the West, River Galana to the South and Genale-Dawa Rivers to the East.

The absolute geographical location of the area is between 6.09^0 and 6.60^0 N latitude and 38.0^0 and 38.38^0 E longitude with an area and perimeter of 3342.37 square kilometers and 305.25 kilometers respectively.

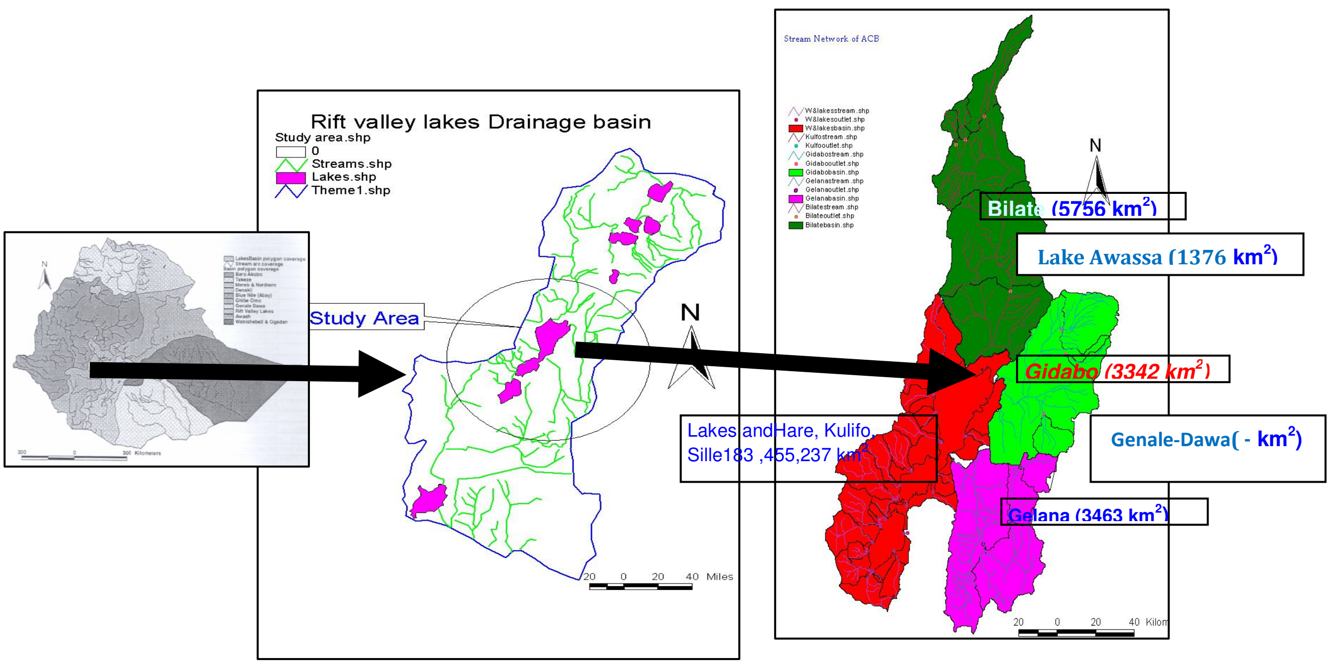


Figure 2.1 Location map of the Gidabo River Catchment (modified after study and design of Gelana, Gidabo and Bilate irrigation project; Gidabo hydrology study report.).

As far as the accessibility of the area is concerned, the main Asphalt Road from Addis Ababa to Ethio-Kenya Border town “Moyale” , passes through the whole length of the catchment.

Generally, the North-Eastern, central and South-Western parts of the area are well accessed through all weather gravel-packed and dry weather roads. The western, downstream part of the River is partially accessed through dry weather roads or not accessible completerly; upstream part of the Catchment including the eastern plateau and the escarpment are hardly accessible even in dry seasons due to very steep slopes and undulating topography (*See the map below*).

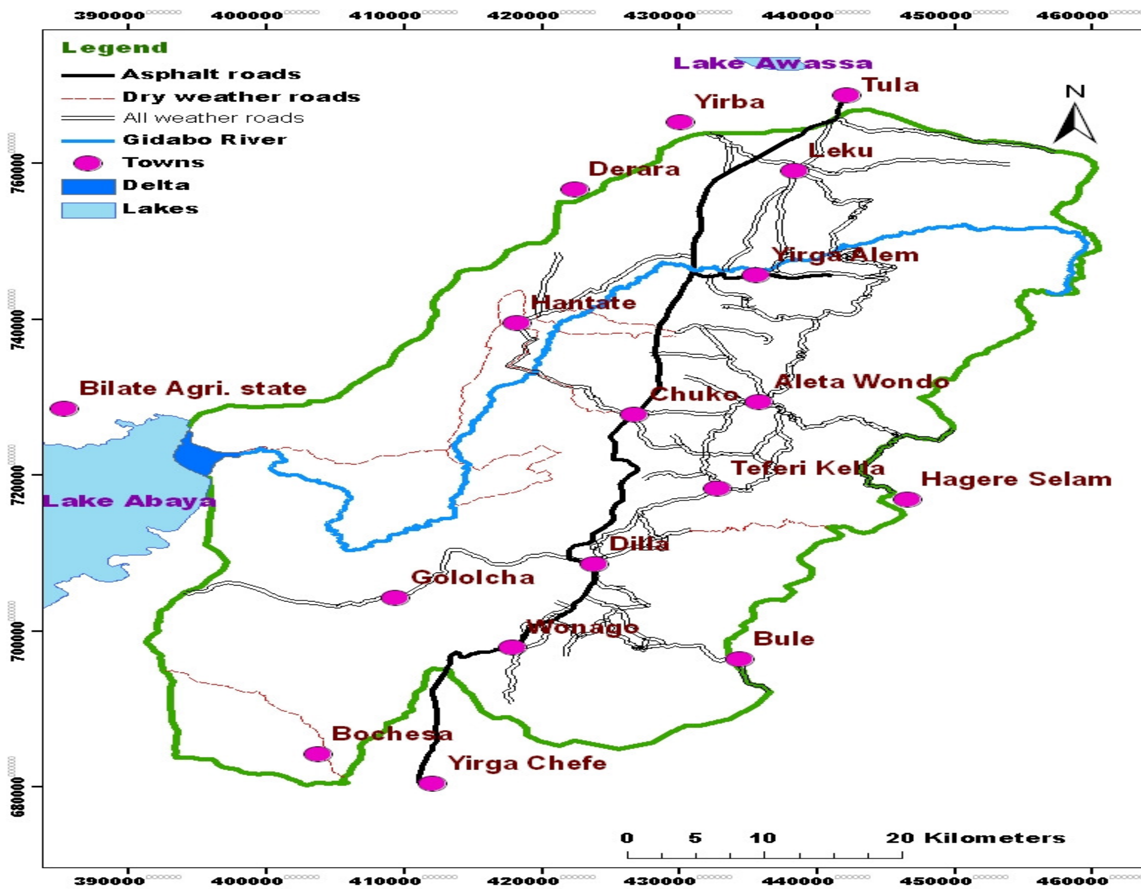


Fig.2.2 Accessibility map of the Gidabo River Basin.

2.2 Physiography and Drainage.

The overall phsiography and drainage network development within the Gidabo River Catchment is the result of the geologic history. The topographic elevation of the Gidabo Catchment mostly is an expression of pyroclastic volcanic rocks and NNE-SSW and NE-SW striking faults with East-West high angle downthrows. The topography in the area is characterized by moderately dissected to undulating local reliefs. The interfluves are convex upwards, and separated by narrow valleys with seasonally moderately drained alluviums (Abenezer Kefeni*,* 2007 Study and Design of Gidabo Irrigation project). Thus, main feature of the physiography of the Catchment is the very clear NNE-SSW orientation of all the components of the landscape.

The landscape of the Catchment can be broadly categorized into four large groups: The edge of Eastern high plateau, the large eastern escarpment of the Rift Valley, the Structural Basaltic reliefs and the floor of the Rift Valley. *(Source: M. Raunet, 1977.Gidabo Basin Morpho-Pedological Survey; Southern Rift Valley, Sidamo Province).*

The edge of the Eastern high plateau occupies a narrow strip in the Eastern and highest part of the Catchment; it represents the zone not affected by the tectonics and as yet not affected or only to a small extent. The Altitude ranges from 2,600 to 3,200meters and the Rainfall varies between 1,100mm in the North (*at Mt. Geremba area*) and 2200mm in the South (*in Bule town area*).

The large Eastern escarpment of the Rift Valley takes in the entire Eastern zone between the Altitude of 1,800 and 2,600meters. It is the zone of the Catchment receiving Rainfall between 1,100 and 1,900mm per year. This group forms mountainous landscape.

The Structural Basaltic reliefs covering the SSW part of the Catchment is the result of the incomplete collapse of the Rift Valley; the “ante-rift” basalts tilted and broke up, giving rise to dissymmetrical horsts dipping westwards. The landscape is clearly influenced by the tectonic structure. It takes the form of mountainous ridges, running roughly North-South, bordered by faults (*M. Raunet, 1977.Gidabo Basin Morpho-Pedological Survey; Southern Rift Valley, Sidamo Province).*

The floor of the Rift Valley is formed by ignimbrites which are poured out through cracks opened after the formation of the Rift Valley. The ignimbrite sheets originally formed sub-horizontal stretches; but this is not the case at present: the tectonics, the hydric dissection, and the subsequent and often imbricated geochemical processes have profoundly modified the original topography almost everywhere in the Rift floor. The Rainfall decreases rapidly from East to West until the centre of the Rift Valley is reached, where near the Lake Abaya, only 500mm fall. The Altitude decreases from 1,700 to 1,200 meters *at the shore of the Lake*.

A/ Rhyolitic lavas: To the North of Lake Abaya, separating the Catchements of Bilate and Gidabo Rivers with moderate or hilly reliefs, acidic lava slowly emerged in the form of domes or viscous flows (*M. Raunet,1977).*

B/ Lacustrine deposits: Recent lacustrine upbuilding, essentially form the Boky-Anole plain (about 100 square kilometers area) situated along the shores of the Lake Abaya (*M. Raunet, 1977).*

C/ Pluviatile and pluvio-lacustrine deposits: This sediment makes up the large upbuilding plain (about 120 square kilometers area) formed by alluvial deposits from the Gidabo Catchment area (*M. Raunet, 1977).*

In the Eastern high plateau and the escarpment the drainage of the Gidabo River and its tributaries give rise to a pattern which looks like the veins of a leaf (dendritic) indicating the presence of steeply sloped impermeable hard rocks beneath; but in the Rift floor and the Structural Basaltic reliefs the drainage takes parallel to nearly parallel and/or rectangular pattern indicating fault line controlled drainage of the catchment.

Buna from the South-East, Kolla from the North-East, Tiliku-Mencha from the North and Amalake from the South of the study area are some of the tributataries of the Gidabo River.

Tiliku-Mencha and Amalake join the Gidabo in parallel pattern, Kolla in nearly parallel and Buna in rectangular patterns. Except Kolla which joins at the middle part, all the other mentioned tributaries join Gidabo near to its mouth. Then the Main River Gidabo crosses the marshy land and flows into the Lake Abaya.

The drainage is much denser in the plateau and the escarpment, in contrast to less density in the Rift floor and the Structural Basaltic reliefs in the SSW of the study area (*See fig.2.3 and 2.4 below*).

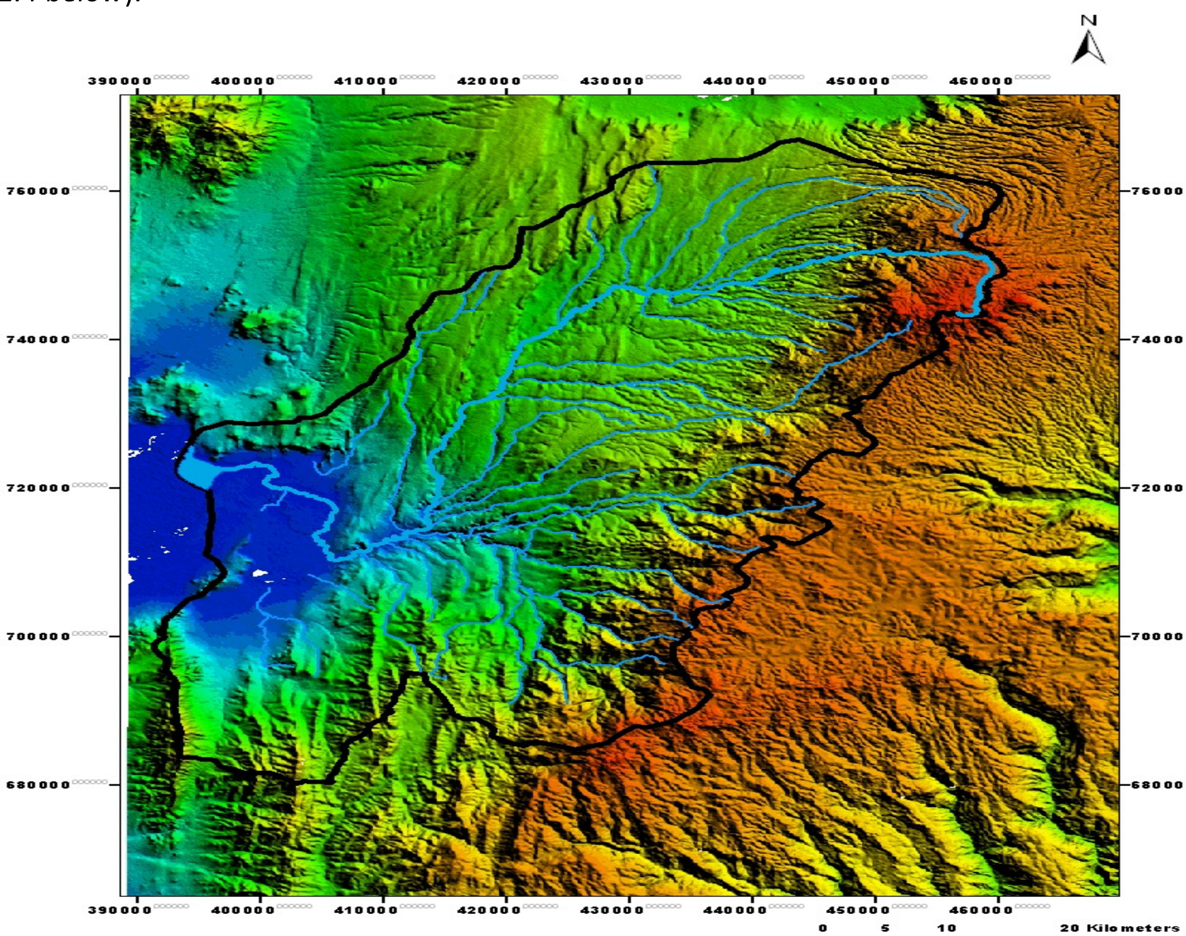


Fig.2.3.Physiographic map of the Gidabo River Basin.

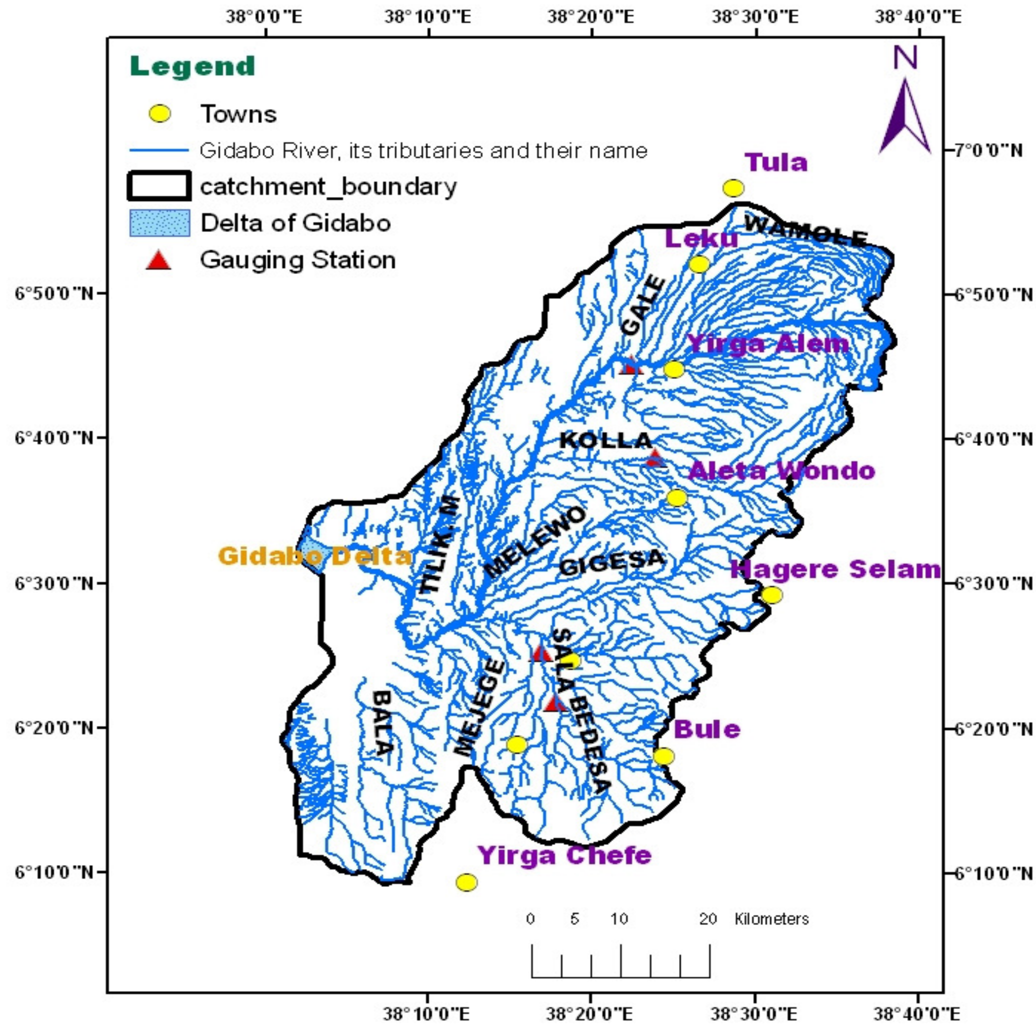


Fig 2.4 Drainage map of the Gidabo River Basin

2.3 Climate and Rainfall

Generally the climate of this region is determined by the displacement of equatorial low pressure, due to the convergence of dry north easterly winds, with moist winds from the South-East or South-West (*M. Raunet, 1977*).

From October to February-March, the North-East winds are responsible for the dry sunny season with low relative humidity.

From March on, the weather becomes more irregular with the prevailing influence of the South-East winds coming from the Indian Ocean, which bring precipitation.
The influence of this moist current is felt especially south of parallel $6^{0}30'$, after which the pattern of North Kenya is gradually reached.

The main rainy season in the Gidabo River Basin occurs between March and June with a second peak in September-October. These two peaks are separated by a relatively small rain season in July-August. The main dry season is between November and February, (*Raunet-1977*).

2.4 Land use-Land cover and human Settlement

The population density generally decreases as we go from East (i.e edge of Eastern high plateau) to West (i.e shore of Lake Abaya) across the Catchment. Based on their socio-economic systems the human settlement in the study area can be broadly categorized into two distinct groups: The Sidama-Gedeo and the Guji-Oromo, (*Raunet, 1977*).

The areas of land cover for these two distinct populations are fairly well defined: The Sidama-Gedeo who live in the same socio-economic system, constituted by far the greatest part of the population of the Gidabo Catchment. They are farmers who occupy the eastern rainy regions, with red soils and where the agricultural potential is greatest: The high plateau, the escarpment and the rift floor area. This region is densely populated with more than one hundred inhabitants per square kilometers, (*Raunet, 1977*).
The Guji-Oromo, on the other hand, are semi-nomadic breeders; they occupy the Eastern shore of Lake Abaya (i.e structural basaltic reliefs and part of the rift floor), but the population is highly scattered and not numerous.

Depending on the altitude and soil type the vegetation cover varies from east to west across the catchment.
In the high plateau (2,600-3,200 meters) of the study area the vegetation cover does not usually contain trees, except a few bamboo plants, and towards the North patches of open forest consisting of Juniper trees (*tsid*).
The upper humid mountainous part (2,400-2,600 meters) is characterized by a few bamboos. The bamboos seem to be common at higher altitudes. There are no more large bamboo forests on the Gidabo Catchment as the Sidama-Gedeo groups put them to intensive domestic use (*Raunet, 1977*).

Humans generally affected the natural vegetation with the exception of patches of open forests and shrubs in inaccessible areas. Thus, the highland part of the study area is commonly cultivated for Inset and cereals. The lower humid mountainous part, i.e the Escarpment (1,800-2,400 meters) is characterized by a few Juniper and conifer trees. In this zone of altitude Coffee Arabica plant is commonly cultivated (with the upper 2,200 meters limit of altitude, above which not cultivated) in association with false-banana trees, (*Raunet, 1977*).

The latter is cultivated in almost all altitudes and can be found over the whole escarpment.

The food crops (mainly maize and sorghum) on the slopes up to about 1,900 meters are replaced by barley, wheat, peas and beans above this altitude. Humid to semi-humid mountainous zone (1700-1800 meters) is rich Coffee growing region where cultivation is intense. In association with Coffee, plants like false-banana (Inset), maize and sorghum are cultivated in this zone. Due to anthropogenic activities the natural vegetation cover has been greatly disturbed and often commonly eliminated in this zone of altitude (*Raunet, 1977*).

Semi-humid savannah (1,500-1,700 meters) is characterized by plants such as shrubs, acacia albida, acacia seyal and herbaceous savannah owing to grey vertic soils with poor internal drainage and high water holding (logging) capacity. The water holding nature of the soil made this zone unfavorable for cultivation, (*Raunet, 1977*).

Semi-humid to semi-arid region which covers 1,300-1,500 m.a.s.l contains many acacia species occupying wide areas with some shrubs and succulent plants. The shore of Lake Abaya which has Semi-arid to semi-aquatic vegetation (*below. 1,300 m.a.s.l*) is characterized by shrubs, acacia, typha, phreatophytes, halophytes and large number of succulent plant species.

The recent lacustrine deposits of the Boky-Anole plain (1,200 m.a.s.l) are impregnated with sodium and potassium (lithologic origin).The soils are alkalized sodic and salted in places (sodium carbonate). Part of the plain is flooded during the rainy season, and the vegetation is then non-existent. Once the water evaporates during dry season it leaves a smooth, whitish, flat area with no cracks, due to saline efflorescences. The sodic plain is used only as grazing-land. The Sidama-Gedeo group's horsemen come from a great distance to collect salt for their livestock by scratching the surface, (*Raunet, 1977*).

Land use-land cover has an effect on the available moisture content of the soil. Because of this a detailed land use-land cover map for estimating the rooting depth is produced from field survey and previous works (*See fig.2.6 below*).

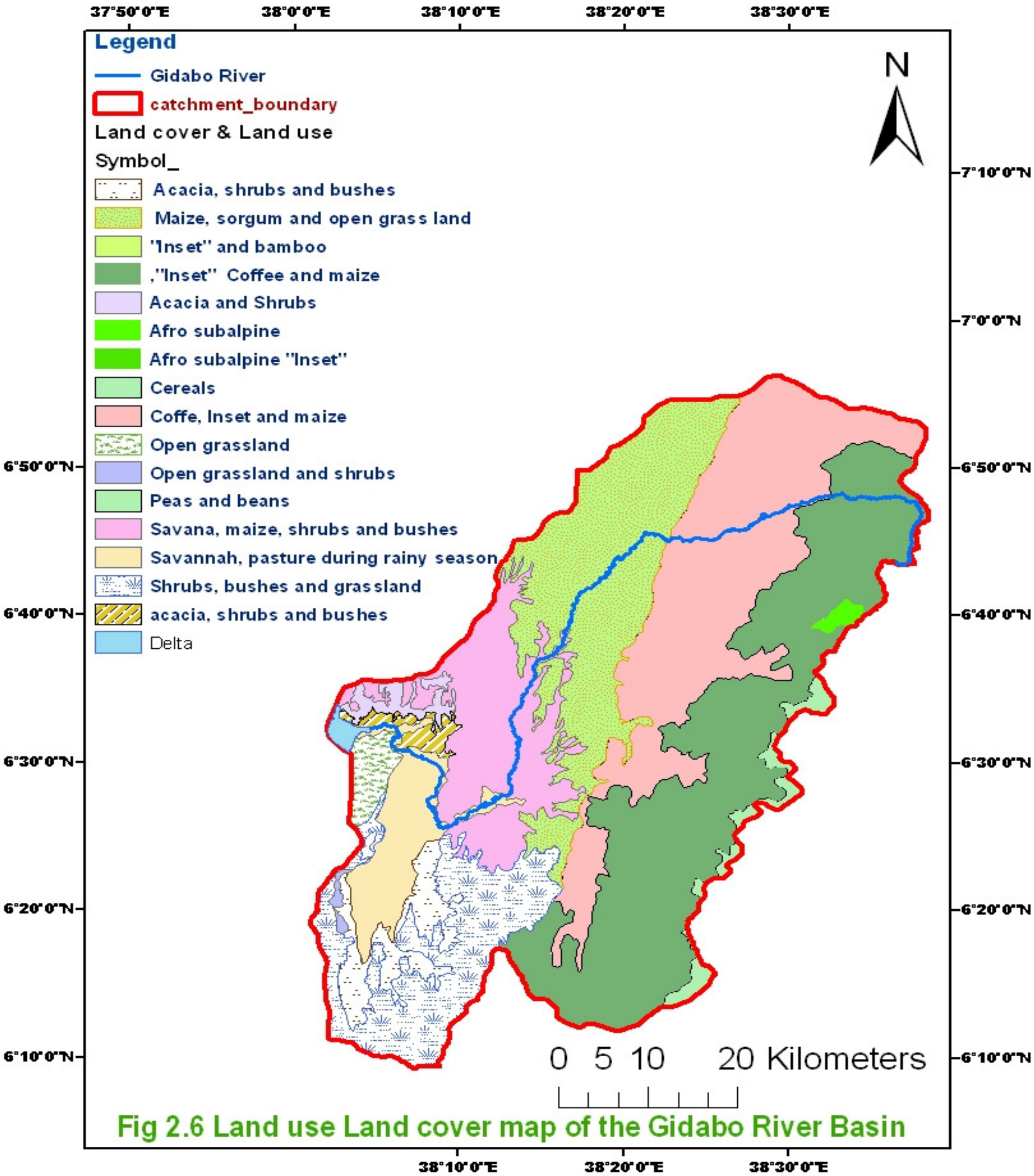


Fig 2.6 Land use Land cover map of the Gidabo River Basin

2.5 Soil

Raunet (1977) gave an account of the soils of Gidabo River Catchment. The most governing factor affecting the water holding capacity, infiltration and runoff characteristics of soils is texture. Since the study of (Raunet, 1977) didn't give a detailed account of soil texture, a soil map based on texture is produced from previous works (Kedir Yasin, 2004), well log data and field observations plus to Raunet's Morpho-Pedological map.

According to their texture, Soils in the Gidabo Catchment mainly range between the sandy alluvial deposits (transported soils) of the river flood plains and the in-situ clayey loam soils which have developed on their parental bed rocks (i.e *on volcanic terrain*).

The Eastern high plateau and the escarpment area have mainly reddish-brown silty loam soil derived from weathering of trap-series basalts and post-rift ignimbrites.

The foot part of the escarpment is mainly covered with red to reddish sandy loam soil which supports the dense vegetation cover for the densely populated human settlement. This soil is developed from weathering of underlying ignimbrites.

The Rift floor is mainly occupied by greyish gravelly to sandy loam soils (*See.fig.2.7 and 2.8 below*).

Fig.2.7. Red clay loam soil developed on top of ignimbritic parent rock with dense vegetation at the top, in Dara Woreda Odolla kebele quarry area, very near to Dilla town (2009).

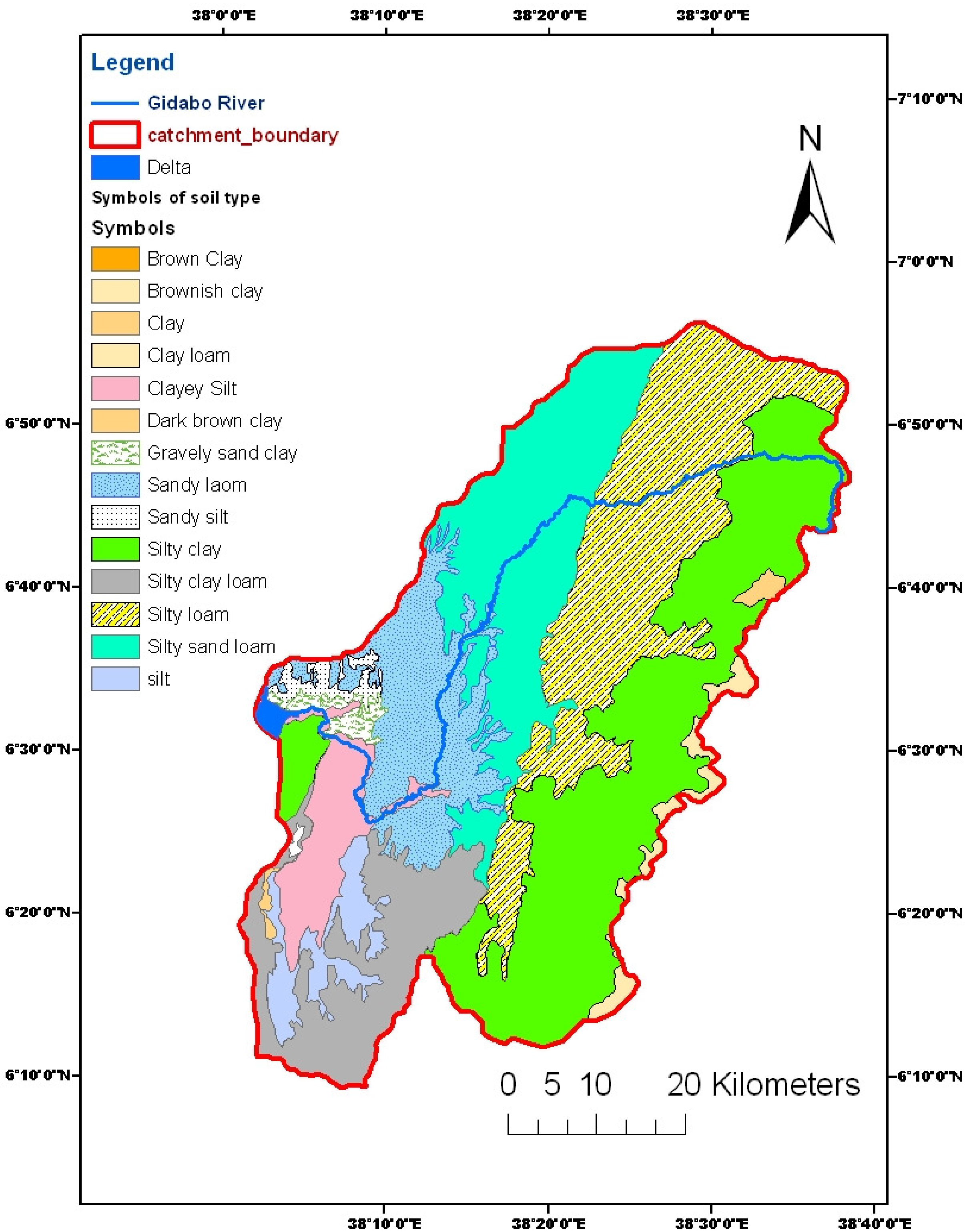


Fig.2.8 Soil map of the Gidabo River Catchment Basin.

CHAPTER THREE

3. GEOLOGY

3.1 Regional Geology

Following the regression of the Mesozoic Sea and convection movements within the mantle which gives internal thrust to overlying thin lithosphere the major uplifting occurred, which is known as the Afirica-Arabian Swell resulting in up-raised and up-arched land mass fissuring of which under tension permitted the ascension of voluminous basaltic magma to form the Ethiopian flood basalt and pre-rift ignimbrites (Trap-Series) province (Mengesha Tefera et al., 1996).

The earliest flood basalts (Trap-Series basalts) are known by the name as Ashangi Basalts (54 to 36 Ma), Jima Volcanics (42.7 to 30.5 Ma), Aiba Basalts (34 to 28 Ma), Arsi and Bale Basalts (Oligocene to Miocene), Mekonen Basalts (34.8 to 23.1), Alajae Formation (36 to 13 Ma), Tarmaber Gussa and Tarmaber-Megezez Formations (26 to 9 Ma) (Mengesha Tefera et al., 1996). This flood basalt volcanism culminated by the formation of alkaline basaltic shield volcanoes such as Tarmaber Formation (Mengesha Tefera et al., 1996).

Jima volcanics are the earliest volcanics, which cover most part of the southern Ethiopia, which are considered analogous with the main flood basalts volcanic sequences. It covers major part in the south and Southwest Ethiopia in the areas extending between Hagre Selam and Mizan Teferi in the east to west direction being dissected by the rift and covered by silicic volcanics in the rift proper and in the north to south direction extends between Bedele and Jinka. This volcanics form a thick succession of basalt and felsic rocks with basalt dominating in its lower part. Jima volcanics almost always rest on the Precambrian basement and Davidson, 1983, in Mengesha Tefera et al., 1996 has reported an age of 42.7 to 30.5Ma and 29.7 Ma by G.Woldegebriel et al (1990).

The geological development of the whole Main Ethiopian Rift Valley is the result of the geologic events that took place in the Eastern Africa. In the end of tertiary and early Pleistocene, as a result of the liberation of large amount of magma and the gradual widening of the fractures a continental scale collapse takes place, giving rise to the Rift Valley.

In the Pleistocene, most of the graben is filled in by deposits of volcanic clouds pouring from the cracks and giving rise to post-rift ignimbrites, ashes and blocks transported by the gases after a violent explosion. In the quaternary alternation of basic outpouring (alkaline basalts) and acidic outpouring (rhyolites, ignimbrites, obsidians, pumices and ashes) are common.

The post-rift volcanic activity has often taken place in a lacustrine environment and given rise to rocks with a volcano-lacustrine facies (ignimbrites and rhyolites, hyaloclastites, cinerites, diatomites, pumiceous tuffs, ashes, (M. Raunet, 1977).

The Main Ethiopian Rift is a part of a series of fractures in the earth's crust, extending from the Dead Sea to Mozambique, Via the Red Sea and the Rifts of East and Central Africa (the region of the great lakes, M. Raunet, 1977.

Main Ethiopian Rift system is divided into three geographical features represented by northern (Fentale to Nazareth), central (Nazareth to Awassa), and southern (Awassa to Konso) sectors (G. WoldeGabriel et al, 1999). North-eastern part of Lake Abaya basin is within the southern part of the Main Ethiopian Rift where the study area is located.

Distribution of volcanic rocks along the Main Ethiopian Rift shows a discontinuous sequence ranging in age from the Late Eocene up to the Plio-Quaternary, Mohr, 1970; WoldeGabriel et al., 1990, 1991; Ebinger et al., 1993.

Late Pliocene-Quaternary volcanism is mainly localized in the rift floor (Morton et al., 1979). The whole volcanic succession exposed along the border faults of both margins indicates a bimodal magma system of acidic and basic associations (WoldeGabriel et al., 1990; Boccaletti et al., 1995).

The name Nazareth Series was given to a thick succession of welded ignimbrites with fiamme, pumice, ash and rhyolite flows and domes with rare intercalations of basalt which occur in the Main Ethiopian Rift, rift margins and adjacent plateaus (Meyer et al., 1978 in Mengesha Tefera et al., 1996). These volcanics are considered to be products of eruptions mainly from rift centres and an age range of 9 to 3 Ma has been given on the basis of Mio-Pliestocene lacustrine sediments of the Chorora Formation and some Absolute K/Ar age determinations (Morbedelli et al., 1973, Tiercelin et al., 1980; Kazmin and Seifemichael Berhe, 1978 in Mengesha Tefera et al., 1996).

Dino Formation belong to a rocks made up of green and grey ignimbrites with well developed fiamme and unwelded pyroclastics and water lain pyroclastics with occasional intercalated lacustrine beds and aphyric basalts which overlies the Nazareth series in the rift valley.

According to Mengesha Tefera et al., (1996), this rock covers an extensive area within the Main Ethiopian Rift in the area between Lake Abaya and Awash town where the Gidabo Catchment is also situated. In the Awash Gorge an ignimbrite member of Dino Formation was isotopically dated to be 1.5 Ma old (Kazmin and Seifemichael Berhe , 1978 in Mengesha Tefera et al., 1996).

Rhyolitic rocks complexes belong to Quaternary volcanics, which are mainly developed along the axial zone (*Wonji Fault Belt*) of the Main Ethiopian Rift. These volcanoes have erupted forming peralkaline pyroclastics and smaller amount of obsidians into the Holocene and now host active fumaroles.

Most of the volcanoes of recent stages of activity are marked by obsidian flows, pumices, ignimbrites, tuffs and scoriaceuos basalt eruptions (Mengesha Tefera et al., 1996).

The Main Ethiopian Rift is characterized by active extensional tectonics. There are two distinct fault systems occurring in the Main Ethiopian Rift; they are: 1) the older includes Miocene, NNE–SSW and NE-SW-trending, steep, segmented, rift bounding fault systems (Kazmin, 1980; WoldeGabriel et al., 1990; Ebinger et al., 1993). 2) The younger includes Quaternary, NNE-SSW-trending faults and aligned eruptive centers affecting the rift floor (Fig. 5.1) (Meyer et al., 1975; Mohr and Woods, 1976; Boccaletti et al., 1998, 1999). The latter is referred to as the Wonji fault belt (WFB).

The Wonji fault belt, which began to develop at ca. 1.6 Ma (Meyer et al., 1975; Boccaletti et al., 1998), has an overall NNE-SSW orientation. Recent tectonic and magmatic activity along the Main Ethiopian Rift and Southern Afar is primarily located on the WFB (Mohr, 1967; Mohr and Woods, 1976). Extension along the WFB is marked by normal faulting, open fissures, and fissure-fed basalt flows (Mohr, 1967; Kazmin et al., 1980). Regularly spaced silicic volcanoes and calderas from which both lavas and ignimbrites were extruded also mark the axis of the WFB.

The average width of the WFB is 5–12 km (Mohr and Woods, 1976). It is segmented (Mohr and Woods, 1976; Kazmin, 1980). Collectively, the individual segments in the fault display an en-echelon, right-stepping array. The steps between adjacent segments range from a few kilometers up to 40 km (Mohr, 1967; Mohr and Woods, 1976; Kazmin, 1980).

South of Nazareth (Adama), the Ethiopian Rift Valley takes the form of a corridor demarcated by faults, between 35 and 80 kilometres wide, while in the North of Nazareth (Adama) this corridor opens into a triangle on the Afar which is the junction of three tectonic directions: The Red Sea, The Gulf of Aden and The Ethiopian Rift. The Afar depression is the meeting point of the disjunction lines of three plates of the earth's crust under the effect of tension beneath the earth's crust. *See fig 3.1 below.*

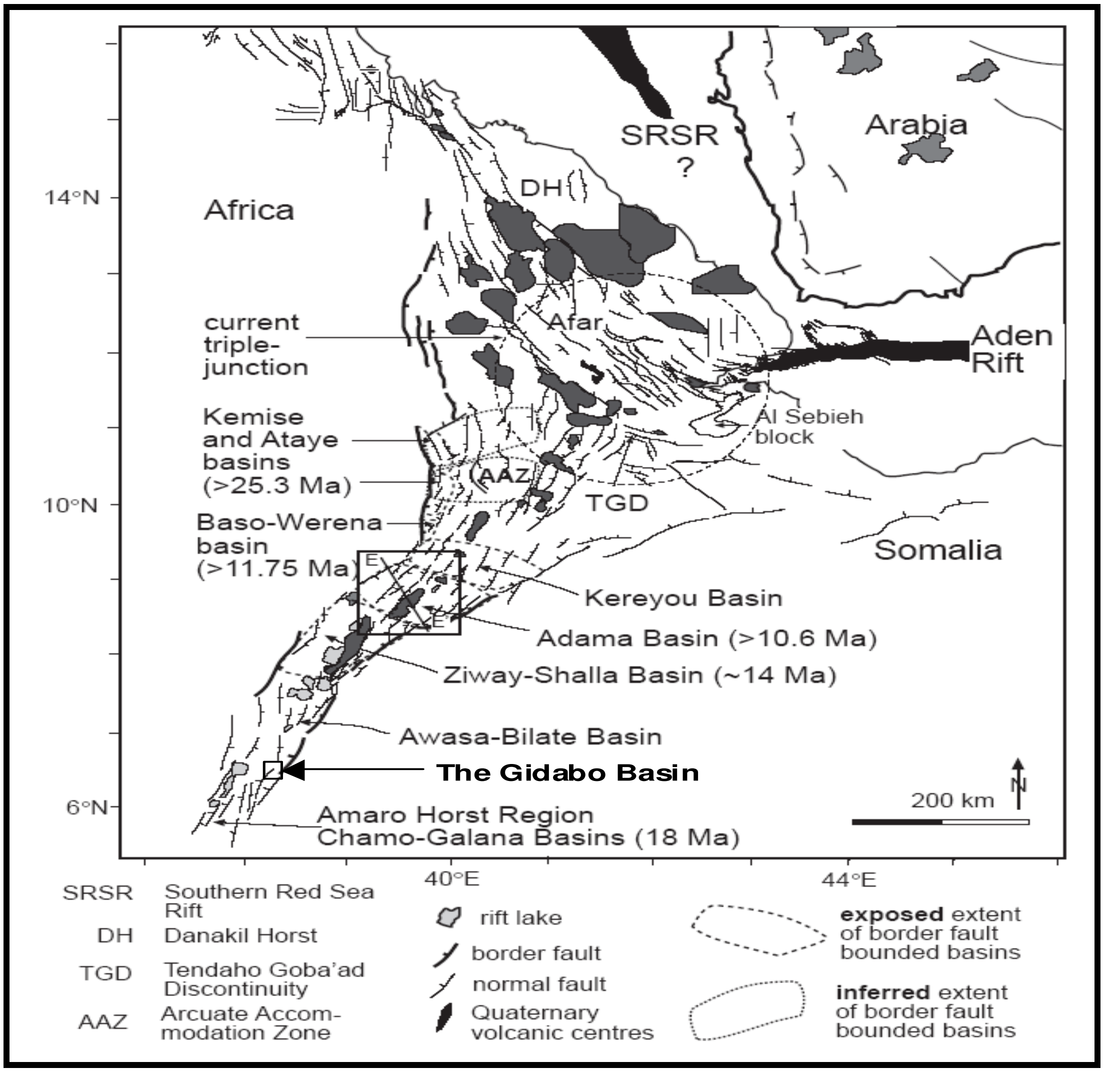


Fig.3.1. Basins and patterns of faults of the Main Ethiopian Rift valley (Source: Abenezer Kefeni, 2007 Study and Design of Gidabo Irrigation project).

3.2 Local Geology

Generally, understanding the lithological and structural view points of the Gidabo River Catchment is essential. In the lithological view point, basic distinction must be made between the pre-rift formations (basalts and ignimbrites of the Trap-Series) and the post-rift formations (ignimbrites, rhyolites, alluvial, lacustrine, and alluvio-lacustrine deposits). In the structural view point, earlier faults linked to the collapse of the Rift Valley (major faults) must be distinguished from the recent faults (minor faults) which recently affecting the rift floor ("Wonji Fault Belt"). Brief descriptions of this two view points are as follows:

3.2.1 The Lithological view point

3.2.1.1 Pre-rift formations

These formations are old basalts and old rhyolitic ignimbrites (*i.e old pyroclastic flow*) with age range of 42.7 Ma to 29.7 Ma by G. Woldegebriel et al (1990). The formation may belong to Jima volcanics (Meyer et al., 1978 in Mengesha Tefera et al., 1996). These volcanics abundantly found in the eastern rift escarpment of the Catchment Basin with the highest part corresponding to the edge of the Eastern plateau (Hagere-Selam town area) and in the structural old basaltic reliefs to the West of Yirga Chefe-Wonago asphalt road.

Forming the older unit in the area the basalt is aphanitic and shows spheroidal (onion-sheet like weathering) with general 45^0 dip to the West. Fresh old rhyolitic ignimbrite (old pyroclastic flow) overlying old basalt is highly welded, gray in color and phorphyritic texture with phenocrysts of feldspars and quartz. There are many pockets of trachytic plugs exposed in the areas between Dilla-Wonago and Bule.

Fig. 3.2 Dome-shaped trachytic plug, to the east of Kebado town, on the escarpment (Source: Abriham Mechal Msc Thesis, 2007).

3.2.1.2 Post-rift formations

These formations are young basalts and rhyolites or ignimbrites (*i.e young pryroclastic flow or fall deposits*) with age range of 9 to 3 Ma (Morbedelli et al., 1973, Tiercelin et al., 1980; Kazmin and Seifemichael Berhe, 1978 in Mengesha Tefera et al., 1996).

The formation may belong to Nazareth Series (Meyer et al., 1978 in Mengesha Tefera et al., 1996). This formation is commonly found in the rift floor of the study area.

The young basalts are vesicular, black in colour, with quartz and sometimes with calcite mineralization. Young rhyolites or ignimbrites are observed to overlay the young basalts.

Rhyolites and ignimbrites are compositionally the same; but they differ in state of viscousity of lava. The materials are rhyolites when they are formed in the form of slowly rising viscous lava with no or little side flow, in which case they are rhyolites, pumices or obsidians (if there is rapid cooling of lava usually when the lave interacts with water) and ignimbrites when they are formed from volcanic clouds, in which case they are ignimbrites or tuffs (*ashes*).

Young rhyolites cover a small area in the Western part of the Gidabo Catchment, North of Lake Abaya, where they form fairly low reliefs. They separate the Gidabo Catchment from the adjacent Lower Bilate Catchement serving as surface water divide. In the NNE of Lake Abaya, rhyolitic rocks exposures are observed as domes, viscous lava, pumiceous pyroclastics, calderas and volcanic glasses (obsidians). The pumiceous pyroclstics are presumed to deposit as the result of fractures developed due to the collapse of the Awassa Caldera (Paulos et al, 1979) and occupy considerable area around Yirga Alem.

Young ignimbrites are by far the most representative rocks in the Catchment area of Gidabo.These ignimbrites are bounded by the eastern escarpment and the structural basaltic reliefs in the SSW of the Catchment area and distributed into the existing depressions and valleys which they filled up, (M. Raunet, 1977). Ignimbritic rocks exposures in the study area usually observed in the stream valleys; which is due to down-cutting of underlying ignimbrites by the streams. The facies of ignimbrite varies in the Catchment; it may be light gray in colour, massive, fine grained and very hard in which case it resembles a real rhyolite, or it may also resembles tuff (ash) when it is soft, erodable and gray in colour. The latter case is quite common in the western part of the Gidabo Catchment, which is along the rift axis linking lakes Awassa and Abaya.

3.2.1.3 Alluvial deposits

These are deposits transported by the Rivers and their tributaries. They commonly consist of boulders, pebbles, cobbles, gravels and sands. Fine silt and clay commonly deposit on thin horizontal layers during flooding for meandering streams. These deposits occupy the major downstream courses and flood plains of the Gidabo River and its tributaries, having very small coverage area. In the flood plains of the River they overlie the pyroclastic flow or fall deposits. These are mainly observed on the flat right and left banks or flood plains of the River. Clayey silt or Clay soil is commonly seen on marshy area, at the “interior delta of Gidabo” where the River inundates the plain area, (M. Raunet, 1977).

3.2.1.4 Lacustrine deposits

Generally, lacustrine deposits have variable lithology which is related with their mode of origin such as ancient lake deposits, water deposited volcanic ejecta, or coarse sediments intruded into the lake by flooding, (Tenalem Ayenew, 1998).

These deposits in the the Gidabo River Catchment area are commonly exposed as lacustrine environment deposits adjacent to the Lake Abaya with soft, powdery, easily erodible, whitish in colour and light in weight characteristics. They are hyaloclastic ignimbriites, pumiceous tuffs, diatomites, obsidians ...etc. They can be either ancient (older) or recent (younger) lacustrine deposits.

Older lacustrine deposits of paleo lake "Abaya" are situated at an altitude of about 1,400 meters, where the present altitude of shore of the lake is at about 1,175 meters. These ancient lacustrine remnants, which erosion has largely caused to disappear, indicate that the level of the paleo lake "Abaya" used to be much higher than at present. At present older deposits of the paleo lake are found in very discontinuous strips, perched (intercalated) in basaltic and ignimbritic slopes surrounding the recent lacustrine deposits.

The recent lacustrine deposits constitute the Bokye-Anole plain which is situated on the edge of the Lake Abaya and the large plain situated to the East of the Bokye-Anole plain. This large plain is separated from the Bokye-Anole plain by the structural basaltic ridge, running NNE-SSW. To the South and South-East this large plain is locked in and can be over looked standing on top of the structural basaltic reliefs, as it has been done in the field survey, the water occupied a tectonic depression in it, formed by the tilting of the basalts during the collapse of the Rift Valley. The plain is occupied by a swampy zone, a sort of "interior delta of Gidabo" through which the Gidabo River follow a sinuous course before flowing into the Lake Abaya at its Delta, which is the "exterior delta of Gidabo" (M. Raunet, 1977).

3.2.1.5 Alluvio-Lacustrine deposits

Alluvio-Lacustrine deposits are deposits of both the River and the Lake.

Deltas are alluvial deposits usually triangular in shape, which are formed at the mouth of a river. It is normally built up only when there exists no current action (wave) from the water bodies (the lake) which is capable of removing the sediment as fast as it gets deposited, and hence the delta builds up forward from the shorelines.

This process of building up deltas is complex, and results in the formation of a number of separate channels, isolated lagoons, levees and marshy areas. Levees are raised banks which are formed by alluvial deposits, allowing the level of the river to rise above its flood plain.

Gidabo Delta is the best example and cause of alluvio-lacustrine deposits in the Catchment Basin.

These deposits occupy the "interior delta of Gidabo" and "exterior delta of Gidabo" which are situated in the large plain area of the ancient lacustrine deposits and Bokye-Anole plain area of the recent lacustrine deposits at the mouth of the River respectively. Area coverage of these deposit is estimated to be 4/5 area of the Catchment Basin of the River, M. Raunet, 1977. The River after meandering through this area, which is characterized by levees, deltas resulting from broken levees and swampy depressions, deposits clayey silt or Clay alluvio-lacustrine deposits (*See fig.3.5 below*).

3.2.2 The Structural view point

The Gidabo River seems to follow fault lineaments in its Catchment Basin. The Gidabo Catchment basin is a zone of faults and pyroclastic deposit filled basins extending along its length. The structures observed in the Gidabo River Catchment Basin are generally extensional and can be four types, NNE-SSW, N-S, NE-SW and E-W running faults/fracture zones.

All these faults are either related to older faults of the collapse of the Main Ethiopian Rift or younger faults of "Wonji Fault Belt"

3.2.2.1 The older faults

These are major fault systems of the tertiary age and they affected older basaltic and ignimbritic rocks of Trap-Series (pre-rift formations).

The eastern fault escarpment dipping towards the West is the result of the pronounced dissection of NNE-SSW running collapse occurred during the formation of the Rift Valley.

The fault escarpment is clearly observed in the East of the towns of Dilla and Aleta Wondo and ten kilometres east of Yirga Alem; The escarpment seems to be either interrupted or lessened in North of the Gidabo Catchment Basin where the young ignimbrites cover the whole escarpment at an angle which is much less steep, giving low relief to the area, which strictly seems to be the effect of collapse of Awassa Caldera which intrudes tectonic movement to the escarpment and the present relief to the area .

The fault escarpment is highly affected by erosional processes; as a result there exist mountainous reliefs.

The Southern structural basaltic reliefs in the SSW of the Catchment Basin, West of Yirga Chefe-Wonago asphalt road, formed a series of more or less parallel structural horsts and grabens. These are old basalts of Trap-Series and generally tilt towards the west and considered as it broke during the collapse of the Rift Valley (*M. Raunet, 1977).*

To the South and West of Dilla the post rift ignimbrite sheets deposited by pyroclastic fall have partially covered the deepest collapsed zones of the structural basaltic reliefs (M. Raunet, 1977).

3.2.2.2 The younger faults

These are minor fault systems of quaternary age, which presently coincides with "Wonji Fault Belt", (Mohr, 1967, 1987) and affected ignimbritic and rhyolitic lavas, domes and cones by a network of narrow faults running NNE-SSW strike directions.

The "Wonji Fault Belt" is characterized by NNE-SSW trending active extension fractures and normal faults, which in many places are associated with fissural or central volcanic activity (Gibson, 19; Mohr, 1987; Chorowicz et al., 1994). The faults are probably of recent Holocene (M. Raunet, 1977). Facts confirming the very recent age of these fault systems are on one hand the freshness of the escarpments and the absence of organized drainage system. In the West of the Asphalt road between Morocho and Aposto, the new drainage system has not yet established itself; the grabens are often swampy zones without a clear outlet. The young ignimbrites sheets are affected by the NNE trending faults suggesting that the deposits are earlier than the faulting.

These fault systems are clearly observed in the field, being situated to the West of the Asphalt road between Morocho and Aposto. It is characterized by a succession of more or less parallel horsts and grabens with clear fault escarpments formed by extensional normal faults of a high angle downthrow having a height approximately between 5 and 100 meters.

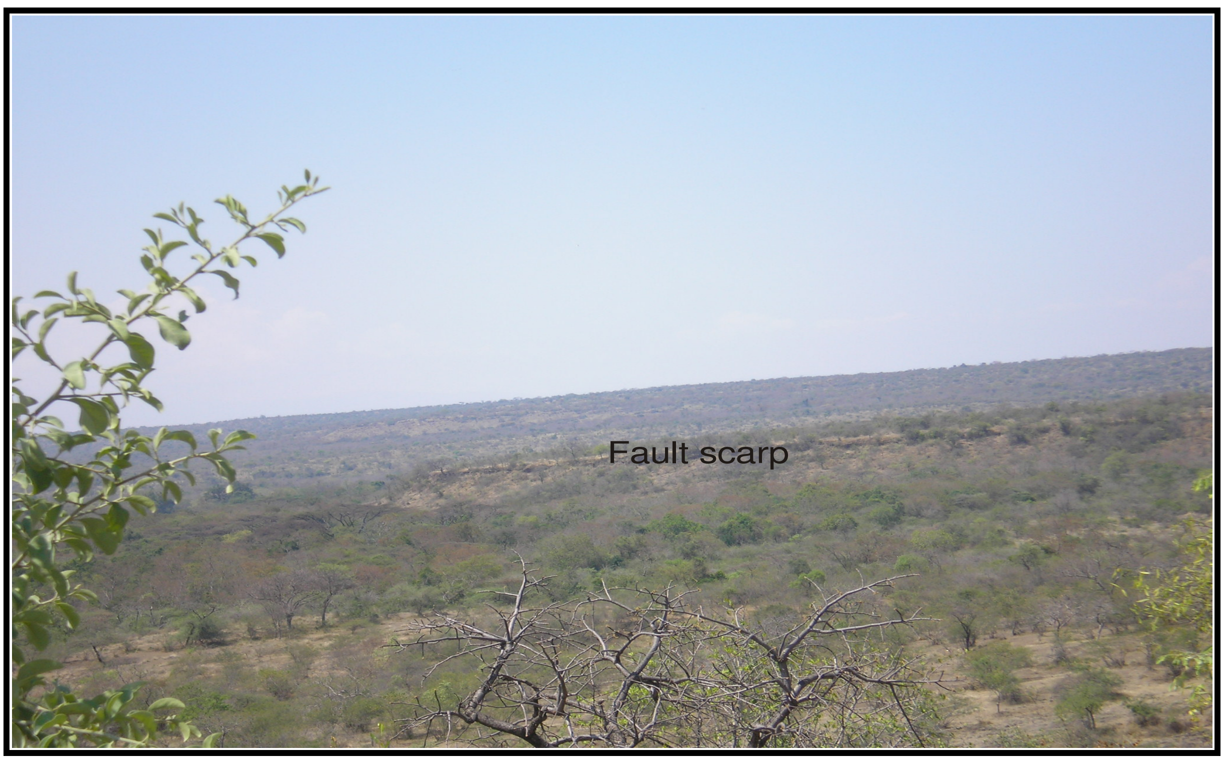


Fig 3.3: Fault escarp in the southern part of "Wonji Fault Belt" near the feasible site of the Gidabo Reservoir (source: Abenezer Kefeni, 2007 evaluation of the geomorphology, geology and structures of Gidabo dam site and reservoir area, in the Gidabo irrigation project).

On the other hand, in the southern part of "Wonji Fault Belt", which is North-East of Lake Abaya, the faults seem to have accelerated the development of the streams which are deep gorged.

The Bokye-Anole and the large plain of the "interior delta of Gidabo" are separated by a ridge, an elongated horst composed of basalts probably of Trap-Series and running in the same strike direction as the recent faults which sheared the ignimbrite sheets, farther to the North. These demonstrate the recent recession of the Paleo Lake "Abaya" due to the recent occurrence of the fault.

The existence of numerous hot springs in the Southern part of the "Wonji Fault Belt", North-East of Lake Abaya, in the Gidabo Catchment Basin is an indication for the seepage of water in the up-stream areas of the streams through the major fault system and emerging at the minor fault area because these minor faults act as barrier and exit for deep circulating water. For example, Hot springs of Odomike Waleme and Mechisho (Rift Valley Resort) localities, near to Dilla (*See fig.3.4 and 3.5 below*).

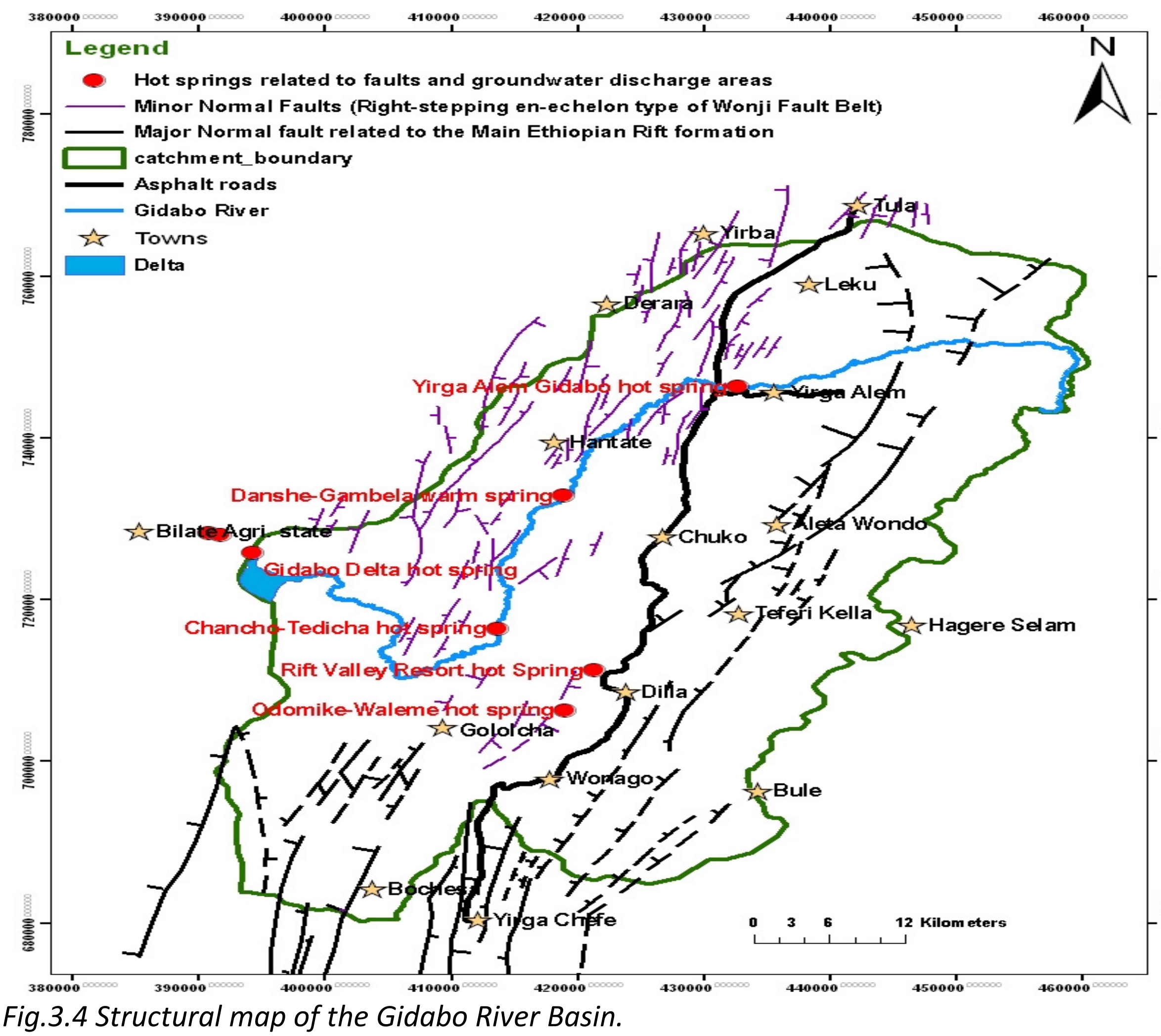


Fig.3.4 Structural map of the Gidabo River Basin.

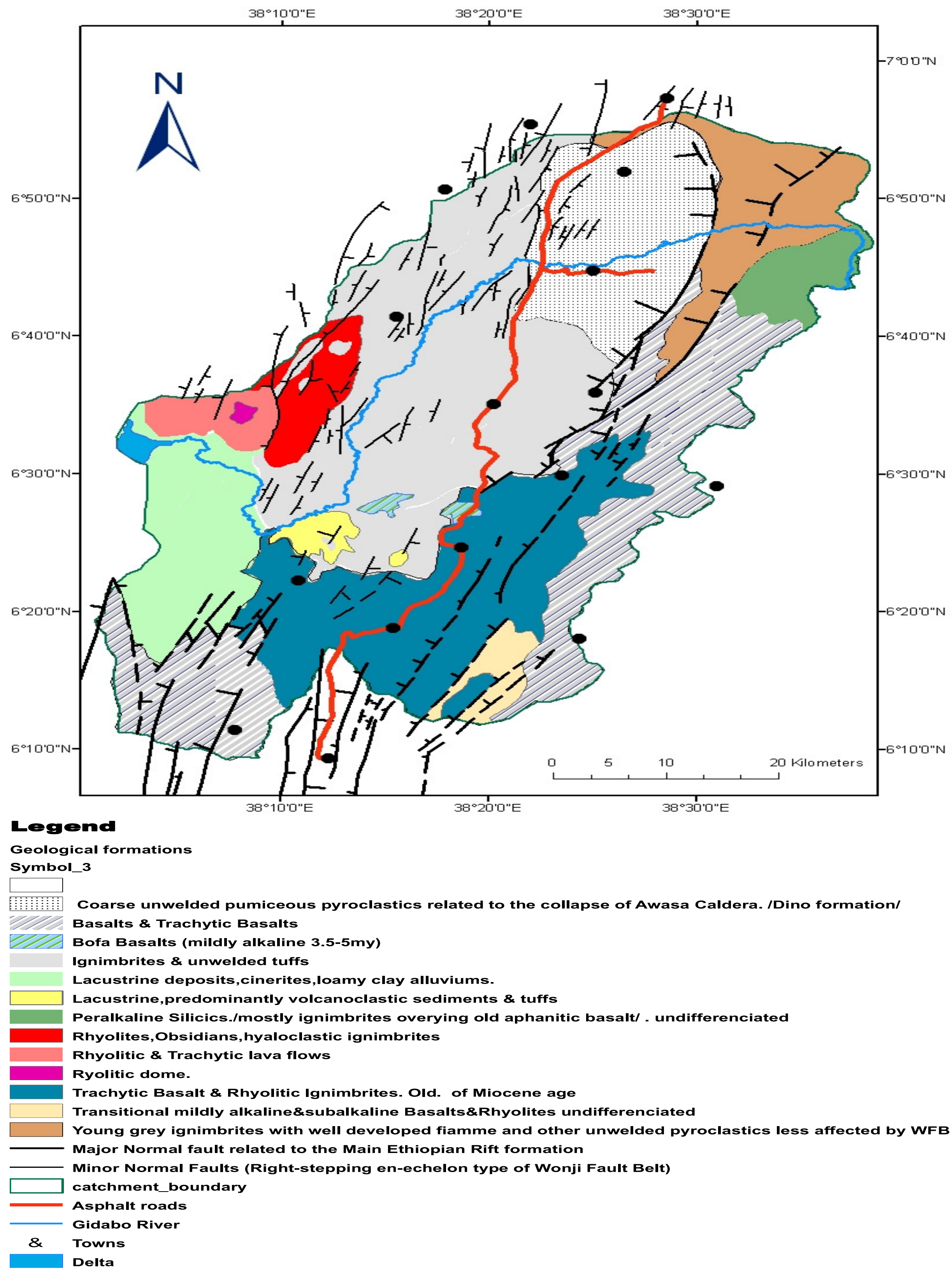


Fig.3.5 Geological map of the Gidabo River Catchment Basin.

CHAPTER FOUR

4. HYDROMETEOROLGY

4.1 General

Meteorology is the science dealing with the atmosphere and the movement of water both as vapor and as liquid in the air.
Hydrology is an earth science concerned with the distribution and occurrence of water on and under the earth's surface.
Both sciences are concerned with the hydrologic cycle.

Hydrometeorology is the field dealing with the borderline problems between meteorology and hydrology. It assists in giving solutions of surface water and groundwater problems for efficient control and management of water resources (Bruce and Clark, 1966).

Any water resource study and planning without consideration of hydrometeorological data analysis will be futile; as these data are the major sources of information to tell the total amount of water in each of the parts of the hydrologic cycle.

The most useful hydrometrological variations are precipitation, evaporation, evapotranspiration, solar radiation (sunshine hours), air temperature, relative humidity, soil moisture, stream discharge and water quality (Raghunth, 1987).

In this chapter, the main objective is to provide hydrometrological information by analyizing each variables so that the computation of evaporation, evapotranspiration and soil moisture being effective. The result of the analysis further will be used in the calculation of the water balance of the catchment.

4.2. Measurement of precipitation (ppt) at a point

Precipitation at a point is measured with rain gauges. There are three types of rainfall gauges: telemetric, recording, and non-recording types. In the latter case measurement are taken at a regular interval by emptying the total amount of precipitation falling and collected by the catch into a known graduated tube (*Dune and Leopold, 1978*). Accordingly there are eighteen metrological stations installed with non-recording type of rainfall gauge in and around the studied Catchment and adopted to estimate aerial depth of precipitation by Arithmetic mean method (*See table 4.1*).

4.3. Estimation of Areal depth of precipitation (ppt)

Since the Catchment and its surroundings seem to have a significant variation of precipitation due to orographic effect, it is necessary to obtain the effective uniform depth of precipitation for the catchment to have a more reliable and representative result. For this decadal rainfall data twenty eight meteorological stations record have been collected from the National Meteorological Service Agency (NMSA), among which eighteen representative stations are used. Accordingly the uniform depth of aerial precipitation over the Gidabo River Catchment was estimated using Arithmetic, Thiessen polygon and Isohyetal methods. The computed value is used in the evaluation of water balance of the studied Catchment.

4.3.1. Arithmetic mean method.

The arithmetic mean method is the simplest method of determining areal average rainfall. It involves averaging the rainfall depths recorded at a number of gauges. Here, the rainfall stations considered in the computation of areal depth of rainfall are those stations in and adjacent to the River Catchment of interest if the measurement is representative of the nearby parts of the catchment (Chow, 1988).

According to Chow, 1988, this method gives a very satisfactory measure if the area is sampled by many uniformly spaced rain gauges and has no marked diversity in topography. Hence, for such high altitude as 1500m.a.s.l elevation difference, where precipitation gradient are strong, the result obtained from these method is not satisfactory.

The Gidabo Catchment Basin is between the highest peak at the Mt. Geremba to the North-east which has 3200m.a.s.l and the Gidabo Delta at the mouth of the River which has 1170m.a.s.l. So the topographic difference would be 2030meters and the the phsiography of the Catchment Basin is highly undulating which is not suitable to use this method for estimation of the rainfall depth. However, for the sake of comparison with the other methods value, it is seen in this paper.

Table 4.1, in the next page, shows the mean monthly uniform aerial depth of precipitation calculated using the arithmetic mean method.

Station	Jan.	Fub.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
A/ wondo	41.8	51.7	108	236.7	235.7	145.4	155	166	206	167	57	30.5	1601.6
Billate Agri.	28.2	35.4	58.2	105.6	95.2	86.2	103	82.5	80.9	79.6	33.8	29.1	817.9
Bilate Tena	34.4	33.5	94.1	133	108.1	90.9	109	91	92.3	91.1	32.3	19.4	929.3
Bule	91	80.3	91.4	292.9	287	367.5	183	200.2	173	230	103.1	107.8	2206.7
Dilla	32.4	39.4	107	206	215.3	109.9	100	107.6	154	155	65.4	35.1	1327.2
HagerSelam	58.7	59.2	84.4	153.8	160	122.4	126	146.4	144	149	55.6	35.8	1295.1
Kebado	39.8	46.2	113	223	222.1	120.4	87.7	103.1	164	175	52.4	47.1	1394.4
Leku	57.9	32.3	75.5	181.9	94.6	70.5	94.1	126.5	146	65.9	23.9	26.4	995.9
Teferi Kella	28	37.2	108	236.7	249.8	121.7	127	167	222	187	46.6	32.4	1563.6
Wonago	49.8	36.6	118	259.2	246.9	128.7	103	108.5	174	218	71.1	35.3	1549.3
Abosto	35	47.6	99	172	145.8	118.6	103	100.5	170	121	40.1	27	1179.8
Yirba Muda	31.9	57.3	107	189.4	294.4	242.6	255	230.7	244	275	84.8	19	2030.8
Yirga Chefe	25.9	49.5	106	259	276.8	117.7	90.5	110.5	184	241	88.8	24.9	1575
Yirga Alem	27.2	49.8	108	160.7	157.2	112.3	109	119	143	162	39	32.2	1218.8
Bore	35.1	43.7	90.9	193.4	242.5	181.3	121	196	157	211	71.8	34.7	1578.5
Arbegona	39.5	39.6	81.2	133.5	86.3	83.9	89.6	79	86.3	96.8	40.6	51.4	907.7
Telamo.K	32.9	40.4	120	180.7	169	112.5	137	130.6	178	146	35.1	26.6	1309.2
Wajifo	27.9	16.1	54.1	131.9	157.9	84.8	114	147.3	62.9	91	57.2	45.9	991.2
Mean	40	44	96	192	191	134	123	134	155	159	56	37	**1360**

Table.4.1. Mean annual areal depth of precipitation obtained from arithmetic mean of eighteen different rainfall stations in and around the Gidabo River Catchment Basin.

4.3.2 Thiessen polygon method

The Theissen Polygon method of determining areal depth of precipitation assumes that at any point in the area under consideration the rainfall is the same as that as the nearest gauge so the depth recorded at a given gauge is applied out to a distance halfway to the next station in any direction.

The relative weights for each gauge are determined from the corresponding areas created in a Theissen Polygon network; the boundaries of the Polygons are formed by the perpendicular bisectors of the lines joining adjacent gauges (Chow, 1988). If there is i gauge, and the area within the Catchment assigned to each is a_i, and P_i is the rainfall recorded at the i^{th} gauge, the areal average precipitation for the Catchment under examination is given as:

Avg. Precipitation (P) = $\sum (a_i/A) P_i$, I = 1-n

Where:

P_i is the precipitation of the i^{th} gauge,

a_i is the area of the specific polygon created by using the Thiessen method corresponding to the precipitation P_i (*See fig.4.1.*).

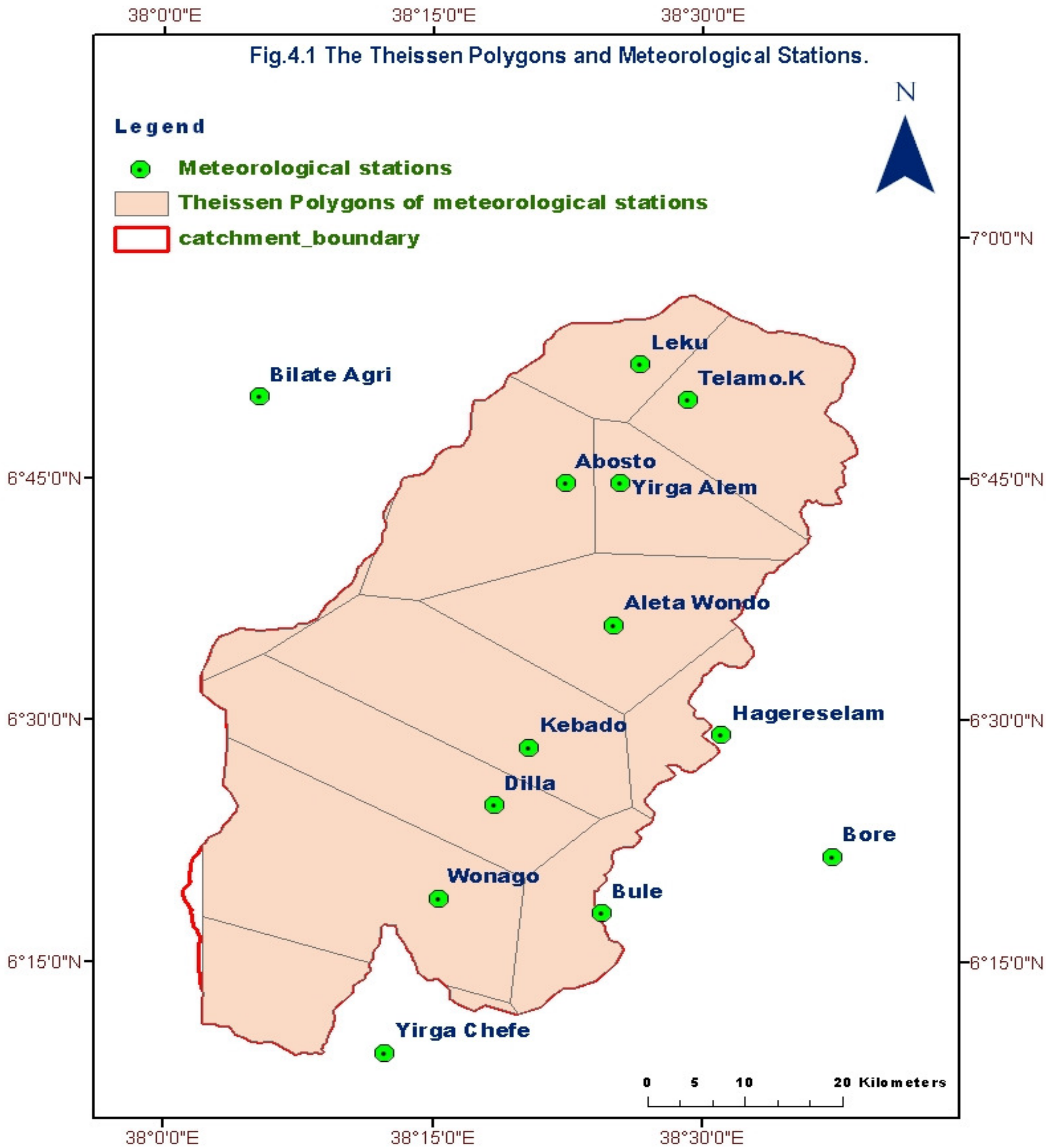
A is the total area of the catchment, i refers to the i^{th} precipitation gauge and n is the number of the Thiessen polygons.

The Theissen Polygon method is generally more accurate than the arithmetic mean method, but it is not flexible, because a new Theissen network must be constructed each time there is a change in the gauge network, such as when data is missing from one of the gauges. Also, the Thiessen method does not directly account for orographic influence on rainfall.

The areal depth of precipitation of the catchment is calculated and resulting values are presented in the table below.

S.No.	Stations	Area (a_i)(Km2)	Catchment area(A)(Km2)	Weighted area (a_i/A)	Annual ppt.(p_i)	(ai/A)*(pi)
1	Yirga Alem	190.0159304	3342.365779	0.056850729	1218.0	69.24418764
2	HagereSelam	102.0446421	3342.365779	0.030530663	1295.0	39.53720815
3	Kebado	448.6525617	3342.365779	0.134232035	1394.0	187.1194574
4	Bilate Agri	40.07988134	3342.365779	0.011991471	818.0	9.809023041
5	Leku	159.7844386	3342.365779	0.047805791	996.0	47.61456745
6	Aleta Wondo	370.669956	3342.365779	0.110900476	1601.0	177.5516621
7	Wenago	554.3507289	3342.365779	0.165855794	1549.0	256.9106243
8	Bule	164.7216182	3342.365779	0.049282942	2207.0	108.7674526
9	Arbegona	47.3468119	3342.365779	0.014165658	908.0	12.86241783
10	Telamo.K	312.536986	3342.365779	0.093507715	1310.0	122.4951064
11	Abosto	387.6756178	3342.365779	0.115988388	1180.0	136.8662975
12	Yirga Chefe	186.7757774	3342.365779	0.05588131	1575.0	88.01306285
13	Dilla	377.710829	3342.365779	0.11300703	1327.0	149.9603284
	Total	3342.365779	3342.365779	1	17378.0	**1407**

Table.4.2. Mean annual depth of precipitation obtained from Thiessen-Polygon method.



4.3.3 Isohytal method

The isohyetal method overcomes some of the difficulties faced in arithmetic mean and Theissen Polygon methods by constructing isohyets, using observed depths at rain gauges and interpolation between adjacent gauges. Where there is a dense network of rain gauges, isohytal maps can be produced by using computer programs for automated contouring.

Once the isohytal map is produced, the area (a_i) between each pair of isohyets, within the Catchment under consideration, is measured and multiplied by the average of (p_i) of the rainfall depths of the two boundary isohyets to compute the areal average precipitation by the following formula:

$$\text{Avg. Precipitation (P)} = \sum (a_i/A)\, P_i\ ,\ i = 1\text{-}n$$

This method is flexible, and knowledge of the storm pattern can influence the drawing of the isohyets, but a fairly dense network of gauges is needed to correctly construct the isohytal map from a complex storm, (Chow, 1988). The Isohyetal method not only gives us the areal average of precipitation but also the areal variability of precipitation in the catchment under examination (*See the table 4.3 and fig.4.2*).

S.No	B/n contours(mm)	ppt. avg. of two	a_i	A	a_i /A	p_i	$(a_i/A)*(p_i)$
1	1050 - 1100	1075	8	3342	0.002	1075	2.573309396
2	1100 - 1150	1125	326	3342	0.098	1125	109.7396768
3	1050 - 1100	1075	153	3342	0.046	1075	49.21454219
4	1000 - 1050	1025	76	3342	0.023	1025	23.30939557
5	950 - 1000	975	46	3342	0.014	975	13.42010772
6	1150 - 1200	1175	380	3342	0.114	1175	133.6026332
7	1200 - 1250	1225	417	3342	0.125	1225	152.8500898
8	1250 - 1300	1275	430	3342	0.129	1275	164.048474
9	1300 - 1350	1325	294	3342	0.088	1325	116.561939
10	1350 - 1400	1375	238	3342	0.071	1375	97.92040694
11	1400 - 1450	1425	198	3342	0.059	1425	84.42549372
12	1450 - 1500	1475	160	3342	0.048	1475	70.61639737
13	1500 - 1550	1525	172	3342	0.051	1525	78.48593656
14	>1550	1575	26	3342	0.008	1575	12.25314183
15	1550 - 1600	1575	72	3342	0.022	1575	33.93177738
16	1600 - 1650	1625	50	3342	0.015	1625	24.31178935
17	1650 - 1700	1675	42	3342	0.013	1675	21.0502693
18	1700 - 1750	1725	42	3342	0.013	1725	21.67863555
19	1750 - 1800	1775	40	3342	0.012	1775	21.24476361
20	1800 - 1850	1825	32	3342	0.010	1825	17.47456613
21	1850 - 1900	1875	31	3342	0.009	1875	17.39228007
22	1900 - 1950	1925	27	3342	0.008	1925	15.55206463
23	1950 - 2000	1975	22	3342	0.007	1975	13.00119689
24	2000 - 2050	2025	21	3342	0.006	2025	12.72441652
25	2050 - 3000	2525	18	3342	0.005	2525	13.59964093
26	3000 - 3050	3025	18	3342	0.005	3025	16.29263914
27	>3000	3025	5	3342	0.001	3025	4.525733094
	Total						**1341.801**

Table.4.3.Mean Annual depth of precipitation obtained from Isohytal method.

‘

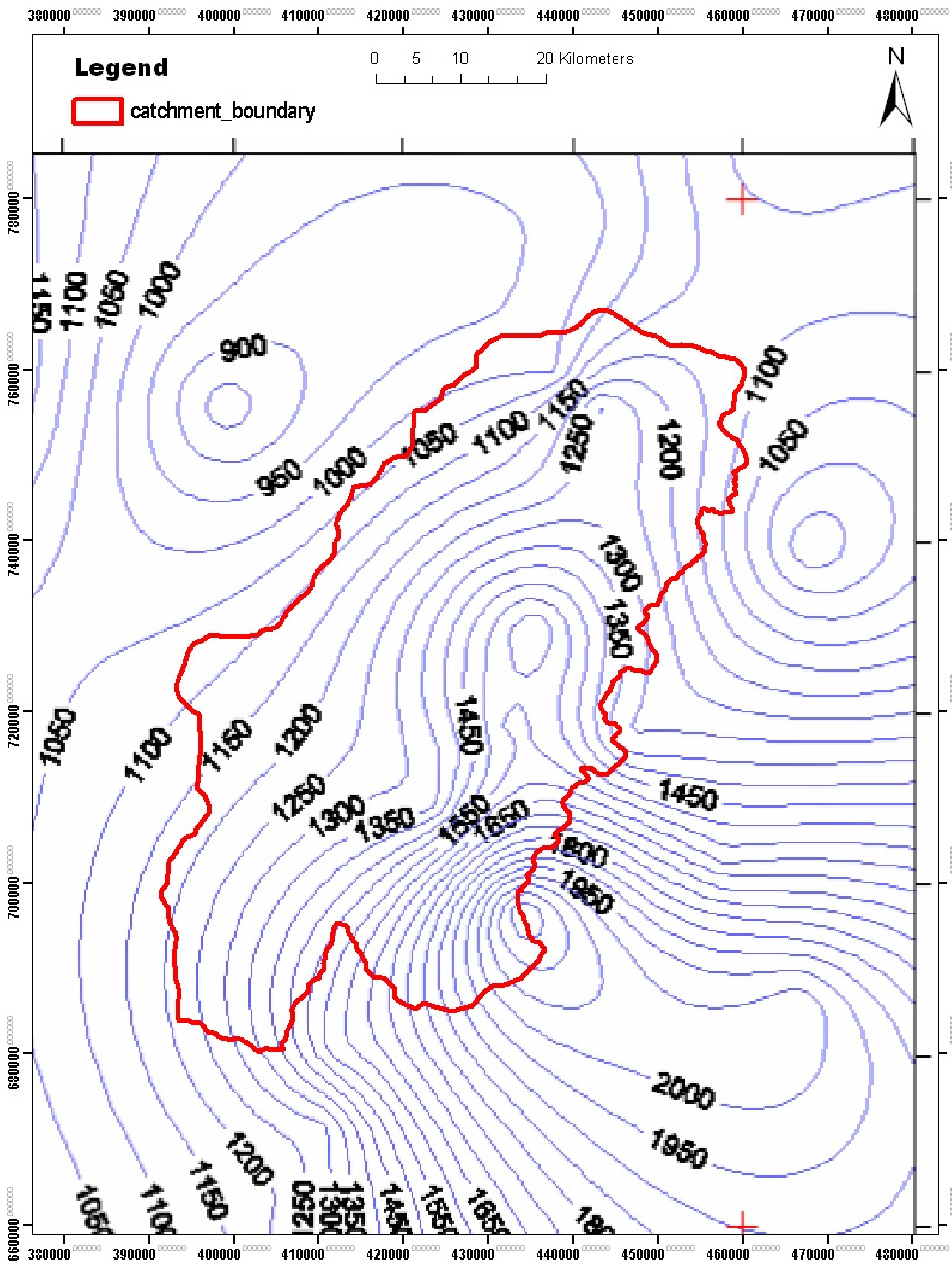


Fig.4.2 Isohytal Rainfall depth map of the Gidabo River Catchment Basin.

As we can see on the isohytal map the rainfall in the Gidabo River Catcment area decreases from North to the South and the highlands get high rainfall as compared to the lowlands, indicating the presence of orographic influence in the Catchment Basin.

By Considering topographic variations and non uniform distribution of meteorological stations in the Catchment under examination, it is logical to take the precipitation value obtained by averaging the Theissen Polygon and Isoheytal methods values.

Therefore, 1375mm of rainfall is taken by averaging precipitation of that of Theissen Polygon and Isohytal methods' in this thesis-research, as the mean annual precipitation of the Gidabo River Catchment Basin.

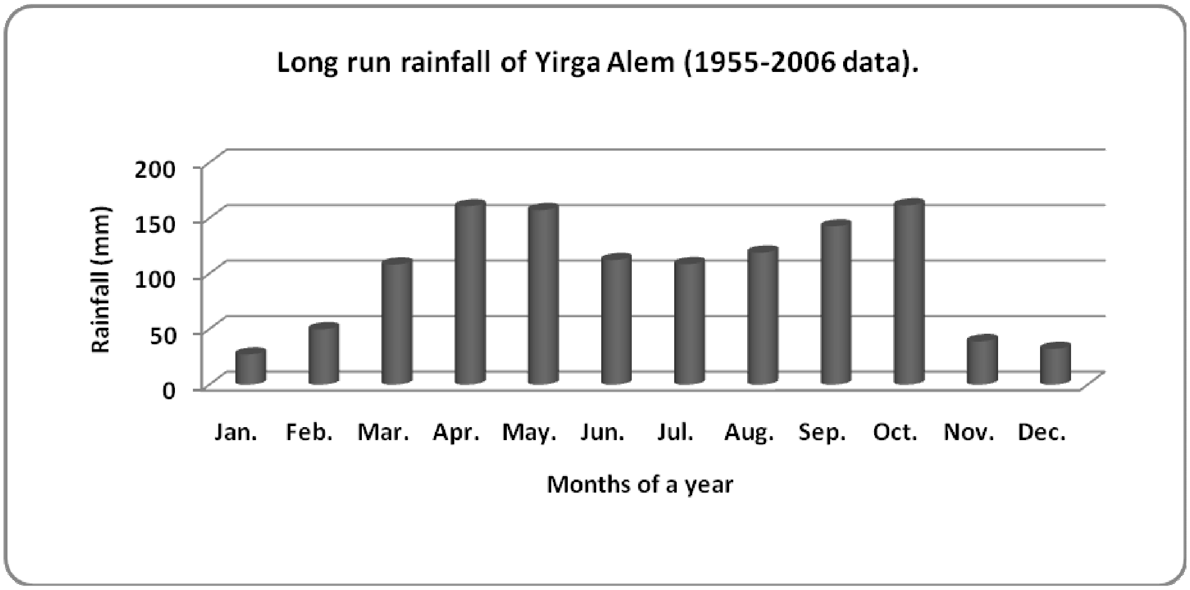
4.4 Rainfall distribution pattern, rainy and dry season months

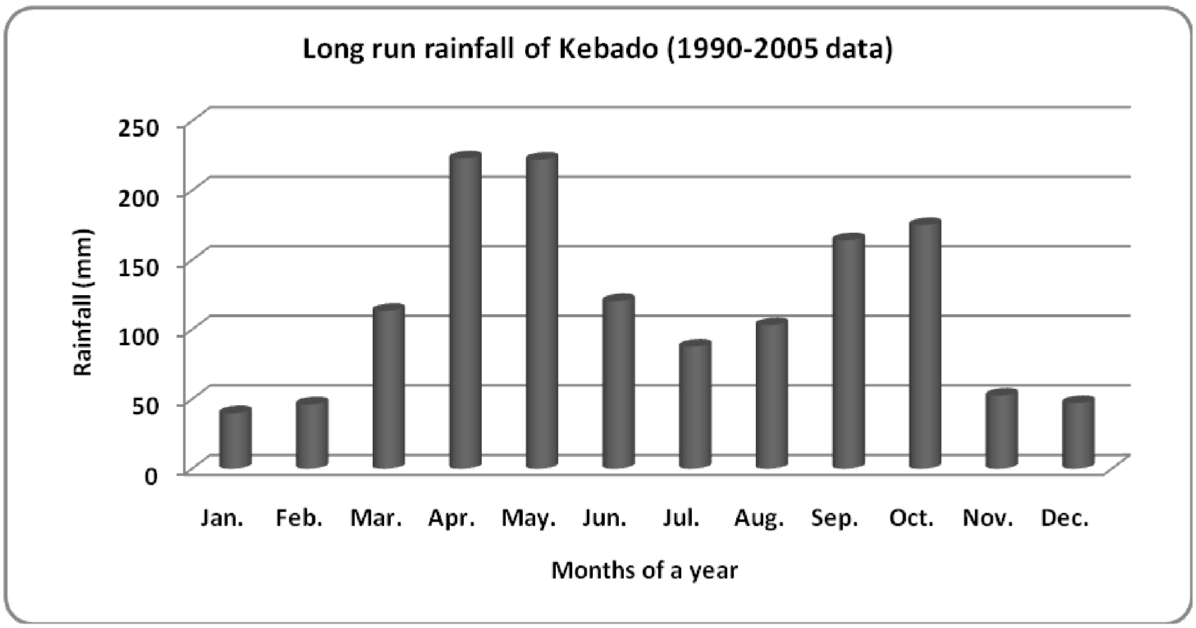
Based on the annual rainfall distribution patterns two broad rainfall regimes are recognized in Ethiopia. These are mono-modal and Bi-modal rainfall patterns.

i) Mono-modal (single peak) rainfall pattern.
This pattern is characterized by one rainy season, i.e., the rainy months are contiguously distributed. This also means that there is only one dry season. These pattern regimes are found in the western half of the country as well as in the south-western highlands.

ii) Bi-modal (two peak) rainfall pattern.
This pattern is characterized by two rainy seasons in which the contiguous rainy months are separated by two distinct seasons. It is found mainly in the eastern half of the country including the Southern and Southeastern areas and the Northern half of the escarpment of the Ethiopian rift systems.

The Gidabo River Catchment is characterized by Bi-modal pattern of rainfall with two big rain seasons separated by a dry season and relatively small rain months, November – February and June – August respectively.


Long run rainfall of Yirga Alem (1955-2006 data).
Rainfall (mm)
200
150
100
50
0
Jan.
Feb.
Mar.
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Months of a year


Long run rainfall of Kebado (1990-2005 data)
Rainfall (mm)
250
200
150
100
50
0
Jan.
Feb.
Mar.
Apr.
May.
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Months of a year

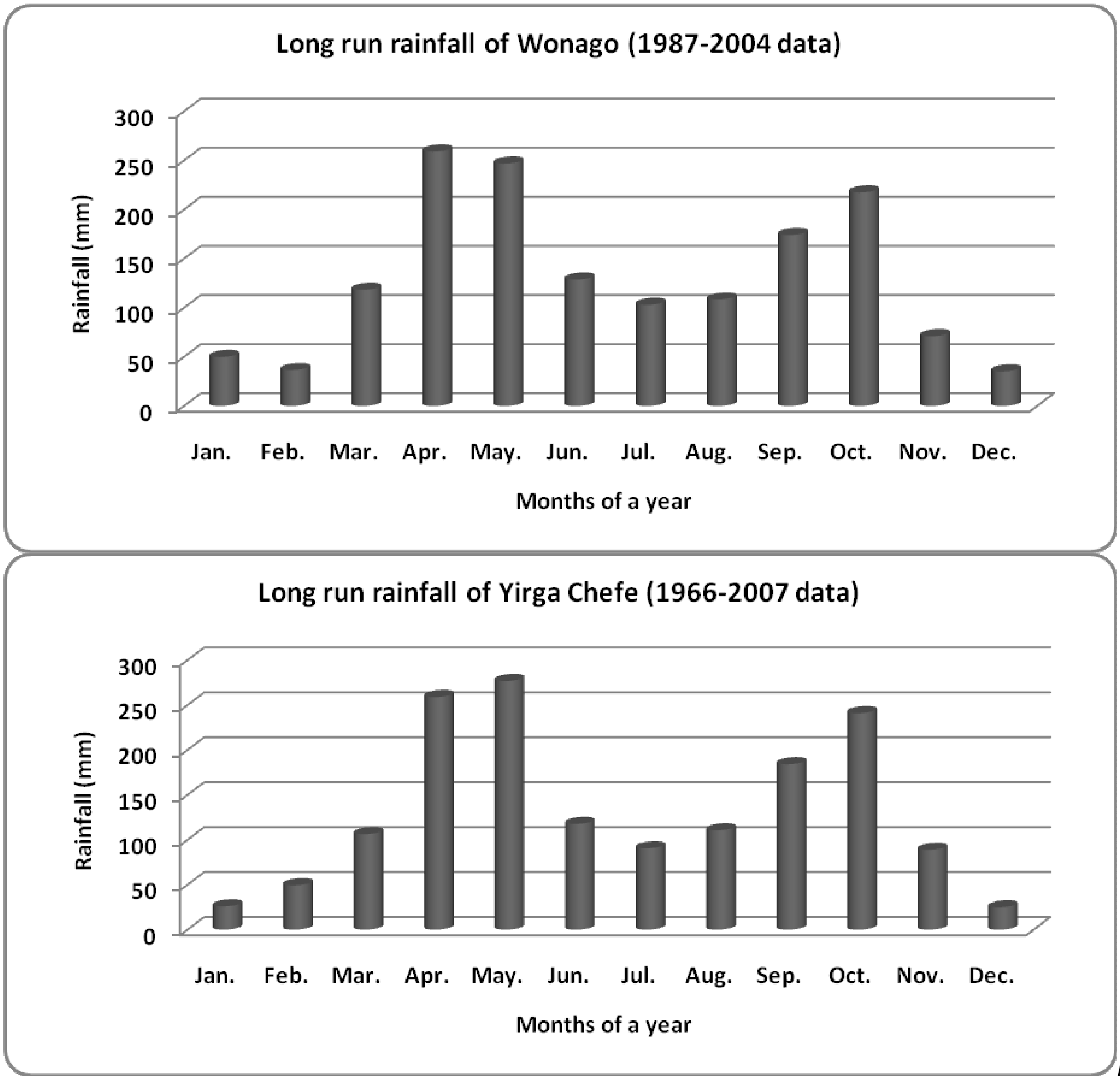


Fig.4.3 Mean monthly rainfall distribution in some of the selected meteorological stations in the Gidabo River Catchment Basin, Showing Bi-modal pattern of rainfall. Note that; except Yirga Chefe, all the selected areas are within the Catchment.

In the given hydrological year months can be grouped into dry and rainy season months based on Rainfall Index (RI). By definition, Rainfall Index is the ratio of mean monthly rainfall to the one twelve of the annual rainfall.

It is given as:

$RI = P_m/(P_Y/12)$ Where:

RI = Rain fall Index,

P_m = Mean monthly rainfall depth

P_Y = mean yearly rainfall depth

A month is said to be of dry season when the Rainfall Index is less than 0.6 and of small rain month when the Rainfall Index is between 0.6 and 0.8 and big rain month when the Rainfall Index is greater than or equal to 1 ((Daniel Gemechu, 1977).

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov	Dec
p_m	40	44	96	192	191	134	123	134	155	159	56	37
p_y	1351	1351	1351	1351	1351	1351	1351	1351	1351	1351	1351	1351
$p_y/12$	112.7	112.7	112.7	112.7	112.7	112.7	112.7	112.7	112.7	112.7	112.7	112.7
RI	0.36	0.39	0.85	1.7	1.7	1.19	1.09	1.19	1.38	1.41	0.5	0.33

Table.4.4.Classification of months based on Rainfall Index (After Daniel Gemechu, 1977)

Based on the Rainfall Index (RI) values shown in the table above, months in the given hydrologic year are classified as the following:

a) Dry months are November, December, January and February.

b) Small rain month is only March; relatively small rain months June, July and Augest.

c) Big rain months are April, May, September and October.

The dry months contribute only about 13.1% of the total mean annual rainfall of the area where as the remaining 86.9% of the total mean annual rainfall is contributed by the rainy months.

4.5 Temperature (T)

Like in most parts of Ethiopia, the diurnal variation of temperature in the Gidabo River Catchment Basin is more visible than its seasonal variation. Table.4.5 shows both the diurnal and seasonal variation of temperature at Teferi-Kella meteorological station, in the form of the mean monthly temperature for seasonal variation and mean minimum & mean maximum for diurnal temperature variation.

	Temperature Differences within the same month		Temperature Differences between different months
	Diurnal temperature Variations		Seasonal temperature Variations
Months	Maximum Temperature	Minimum Temperature	Mean monthly Temperature
Jan.	27.98	8.24	18.11
Feb.	27.87	8.41	18.14
Mar.	27.71	9.23	18.47
Apr.	26.28	8.7	17.49
May.	25.53	8.09	16.81
Jun.	25	8.01	16.51
Jul.	24.21	7.55	15.88
Aug.	24.57	7.29	15.93
Sep.	24.8	7.63	16.22
Oct.	25.38	7.87	16.63
Nov.	26.61	8.42	17.52
Dec.	27.47	8.91	18.19

Table.4.5 Diurnal and Seasonal temperature variations at Teferi-Kella meteorological station.

As we see on the table 4.5 in the previous page, there is a clear diurnal temperature difference of 19.74^{0}C between the mean maximum and mean minimum temperatures in the month of February; whereas the long-term Seasonal temperature varies between 15.88^{0}C in July and 18.47^{0}C in March respectively.

The following graph and table are constructed based on average of the mean minimum and mean maximum temperatures of each of the available meteorological stations separately.

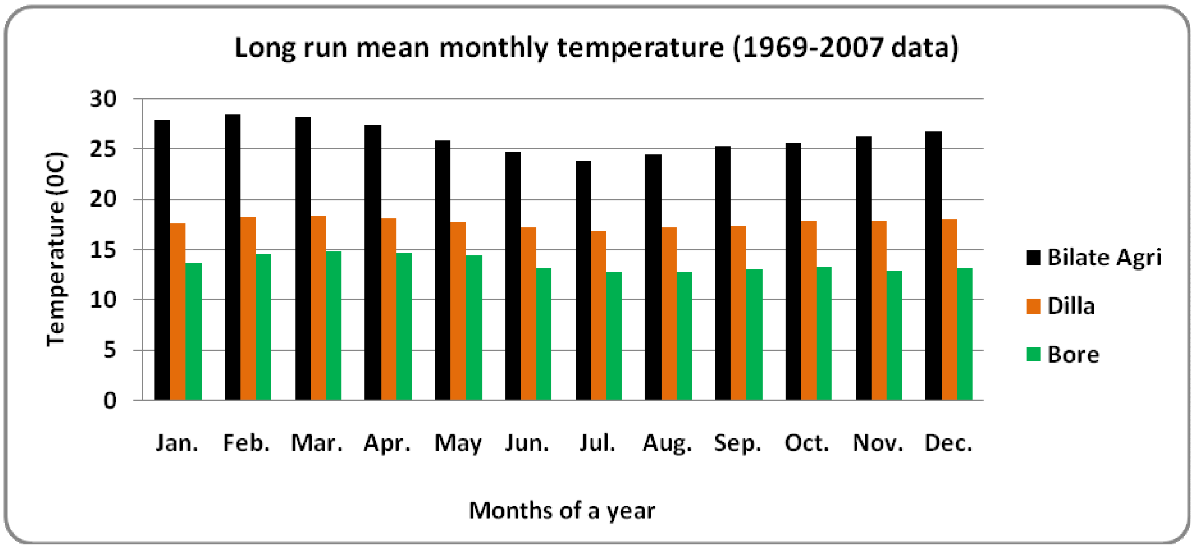


Fig.4.4 Seasonal mean monthly temperatures graph of the three meteorological stations; in and around the Gidabo River Catchment Basin.

Stations	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual.T
Bilate Agri	27.8	28.4	28.1	27.3	25.8	24.7	23.8	24.4	25.2	25.6	26.2	26.7	26.2
Wajifo	23.3	24.1	24.3	22.8	22.5	22.5	22	21.8	23.1	22.9	23.2	22.9	23
Yirga Chefe	17.4	18.2	18.8	18.5	18	17.7	17.6	17.6	17.6	17.5	17	17	17.7
Dilla	17.6	18.2	18.3	18.1	17.7	17.1	16.8	17.1	17.3	17.8	17.8	17.9	17.6
Wonago	18.8	19.3	18.3	17.3	16.8	16.5	16.3	16.5	16.5	16.6	18.1	18.8	17.5
Teferi-Kella	18.1	18.1	18.5	17.5	16.8	16.5	15.9	15.9	16.2	16.6	17.5	18.2	17.2
Hagere Selam	16.4	16.9	16.8	16.1	15.8	14.7	13.6	13.7	14.7	15	15.5	15.9	15.4
Arbegona	14	13.8	13.9	14.4	14.2	14.4	14.3	14.3	14.4	14.3	14.1	13.8	14.2
Bore	13.6	14.5	14.8	14.6	14.4	13.1	12.7	12.7	13	13.2	12.8	13.1	13.5

Table.4.6.Monthly mean temperatures of the available meteorological stations in varying altitudes.

As we can see on the graph 4.4 and table 4.6 in the previous page, the maximum average temperature for each of the meteorological stations mentioned is noted during the months of February and March, in July the minimum average temperature is observed. Normally, temperature at different station is variable because of altitudinal variations.

4.6 Relative humidity (RH)

Relative humidity is the relative measure of the amount of moisture in the air to the amount needed to saturate the air at the same temperature. It is dimensionless and commonly given as a percentage (%) as:

$$RH = \frac{e_d}{e_a} \times 100$$

Where: e_a = Saturation vapor pressure at air temperature, T_a.

e_d = Saturation vapor pressure of the water source, T_d.

As the air humidity increases, its ability to absorb water decreases and the evaporation rate slows down. For evaporation to take place, the saturated air must be replaced by drier air continuously (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Relative humidity has been measured three times a day; at the meteorological stations of Dilla, Bilate Agricultural state, Awassa and Woliata Sodo (*i.e from the data of National Meteorological Agency*). It is used in the calculation of Potential evapotranspiration in the Penman method for Rift floor sub-catchment of the Gidabo Basin.

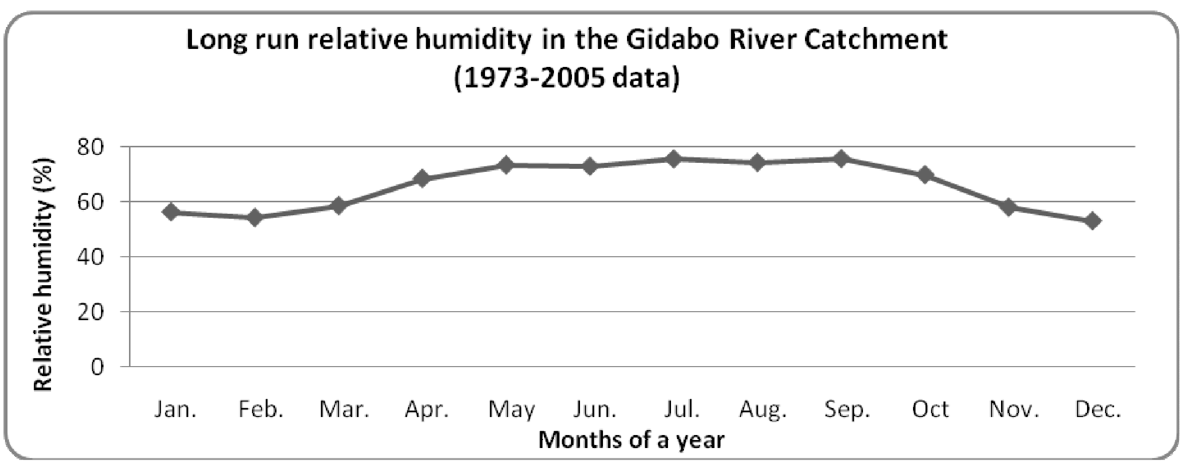


Fig.4.5.Long run relative humidity graph of the Gidabo River Catchment Basin.

			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct	Nov.	Dec.	Annual
1971-2005	W. Sodo	6:00	72	66.9	77.8	87.9	93.8	93.4	94.3	93.3	92.1	85.5	65.1	66.4	82.4
		12:00	52	48.6	53.6	62.4	69.5	74	80.1	77	70.7	62	49.8	46.5	62.2
		18:00	49	44.4	53.2	65.4	72	73.1	78.2	75.6	72.7	67.5	53.5	48.3	62.8
		Mean monthly RH (%)	58	53.3	61.5	71.9	78.4	80.2	84.2	82	78.5	71.7	56.1	53.7	69.1
1972-2005	Awassa town	6:00	83	80.6	86.5	91.7	93.9	92.1	92.8	92.9	95	94	88.9	85.8	89.8
		12:00	43	41.9	45.2	51.9	59.9	62.6	68.3	66.5	62.2	52.8	43.2	42	53.3
		18:00	38	37.7	49.7	59.5	65.6	63.1	66.9	67.3	74.3	63.8	45	38.4	55.8
		Mean monthly RH (%)	55	53.4	49.7	59.5	65.6	63.1	66.9	67.3	74.3	63.8	45	38.4	55.8
1973 - 2005	Bilate Agri.State	6:00	71	74.3	84.5	91.4	93.5	92.3	92.1	91.3	93.1	89.2	72.8	68.5	84.5
		12:00	41	42.8	48.3	56.1	60.7	92.3	64.5	59.9	55.5	50.8	47.9	43	52.8
		18:00	39	41.1	50.1	60.8	62.5	92.3	63.8	60.4	64.3	61.7	52.2	45.3	55.3
		Mean monthly RH (%)	51	52.7	60.9	69.4	72.3	72.4	73.5	70.5	71	67.2	57.6	52.2	64.2
1989 - 2005	Dilla town	6:00	83	80	83.3	89.7	90.6	90.7	91.2	93.5	93	92.3	90.5	88.3	88.9
		12:00	47	42.3	48.3	59.1	65.8	66.3	68.8	66.6	66.8	62.1	59.5	51.5	58.7
		18:00	57	50.5	56.8	72.9	78.6	73.9	76.6	74.9	80.1	78.9	70.6	64.6	69.6
		Mean monthly RH	63	57.6	62.8	73.9	78.3	76.9	78.8	78.4	80	77.8	73.5	68.1	72.4
	Mean of the Four stations (%)		56	54.3	58.7	68.7	73.7	73.2	75.9	74.6	76	70.1	58	53.1	65.4

Table.4.7 Mean monthly relative humidity at the Stations of Dilla, Woliata Sodo, Bilate Agricultural State and Awassa town.

As we see on the table 4.7 and the graph 4.5, the relative humidity of the Gidabo River Catchment is generally greater than 50%. Maximum humidity value is obtained in the month of July and September whereas minimum relative humidity is in February and December.

4.7 Wind Speed (U_2)

The horizontal component of the air movement parallel to the earth's surface is generally referred to as wind while the vertical components are referred to as the air current or turbulence (Jayarami, 1996). This parameter is also used from the four meteorological stations mentioned in the relative humidity sub-topic. The stations at Bilate agricultural state, Wolaita Sodo, Dilla and Awassa town have been measuring wind speed with Anemometer; all are at two meters above the ground and measuring the speed in meter per second (*i.e from the data of National Meteorological Service Agency (NMSA)*). Aerodynamic evaporation depends on wind speed. Decrease in wind speed results in decrease of evaporation rate, as the vapor-saturated air is not removed instantaneously. Hence, evaporation rate should always be considered together with wind speed.

Station	Duration	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Awassa	1973-2005	1.06	1.08	1.05	0.99	1.03	1.19	1.08	0.95	0.91	0.73	0.84	0.96	1
Dilla	1989-2007	0.55	0.68	0.7	0.59	0.5	0.45	0.39	0.4	0.39	0.42	0.43	0.48	0.5
W.Sodo	1971-2005	2.4	2.34	2.03	1.72	1.47	1.42	1.69	1.37	1.37	1.71	2.6	2.6	1.9
Bilate Agri.	1981-2005	1.38	1.49	1.2	0.93	1	1.07	0.93	0.85	0.76	0.65	0.87	1.26	1
Mean(all)		1.35	1.4	1.25	1.06	1	1.03	1.02	0.89	0.86	0.88	1.19	1.33	1.1

Table.4.8 Mean annual wind speed.

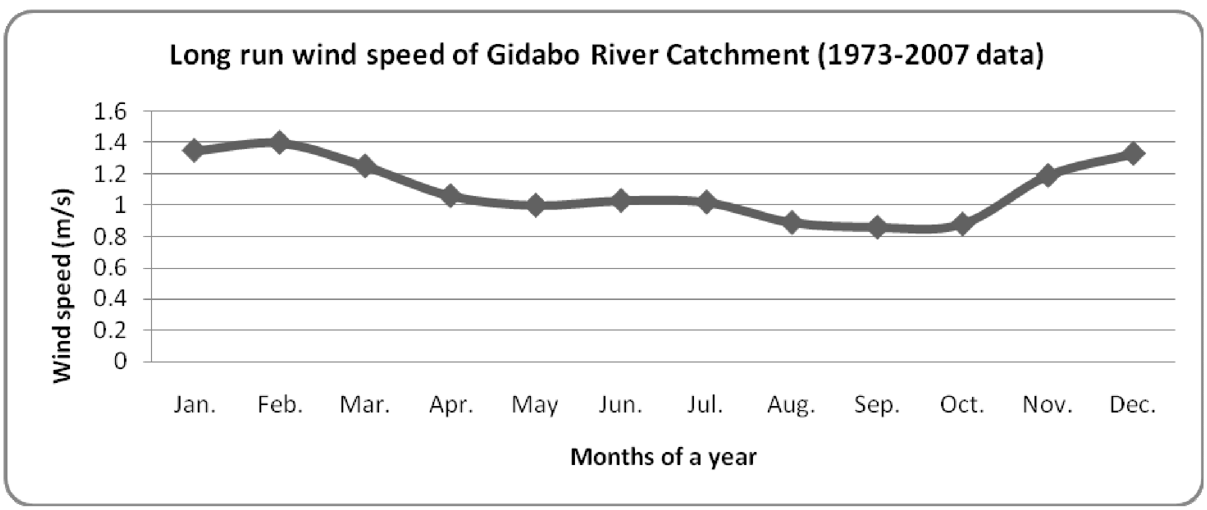


Fig.4.6 Long run wind speed graph of the Gidabo River Catchment Basin.

As we see on the graph 4.6 above, the wind speed is generally higher in dry seasons than the rainy seasons; indicating that evaporation by wind is higher in dry seasons than the rainy seasons.

4.8 Sunshine hours (n)

The sunshine hours or index of cloudiness has a significant effect on the total amount of evapotranspiration.

It is also taken from the Awassa, Dilla, Bilate and Sodo meteorological stations. As we see on the graph below the sunshine hours increase from the minimum in July to the maximum in December and then gradually decreases back to July.

Station	Duration	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
W.Sodo	1971-2005	12.9	12.3	11.3	10.2	9.4	7.6	5.5	6.4	8.3	10.5	11.7	13.4	10
Awassa	1975-2007	8.78	8.5	7.8	6.6	7.3	6.5	4.8	5.3	5.6	7	8.9	9.2	7.2
Bilate	1971-2004	8.6	7.6	7.5	6.1	7.5	6	5	5.1	6.1	6.6	7.6	7.5	6.8
Dilla	1988-2007	7.8	7.6	6.7	5.8	6.2	4.9	3.5	4.8	4.8	5.3	7.3	7.7	6
Mean		9.5	9	8.3	7.2	7.6	6.3	4.7	5.4	6.2	7.4	8.9	9.5	7.5

Table.4.9 Monthly and annual mean sunshine hours of the four meteorological stations.

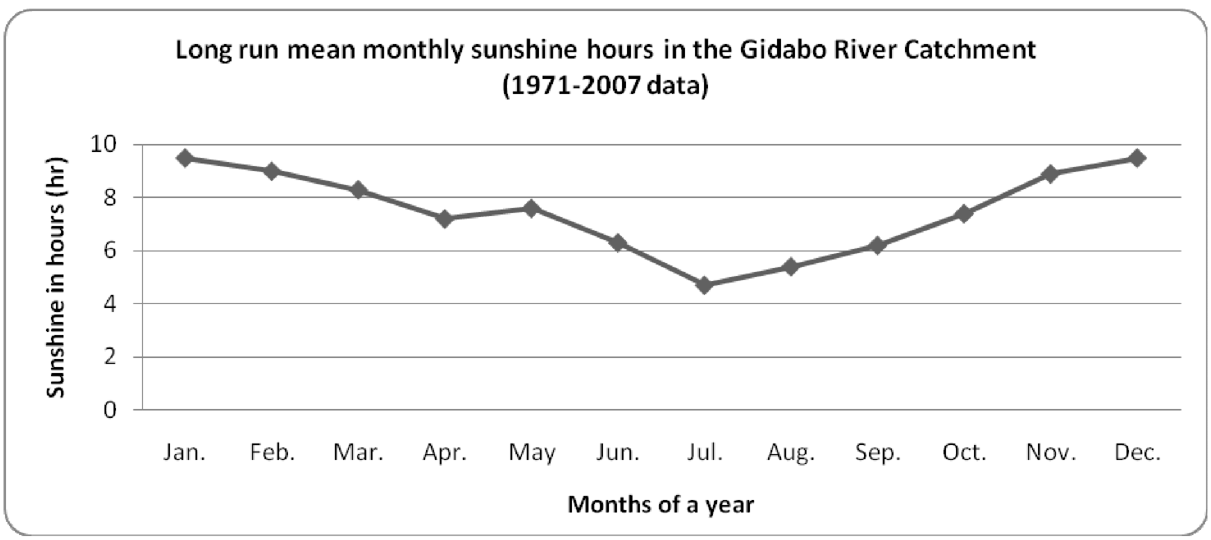


Fig.4.7 Mean monthly sunshine hours graph in the Gidabo River Catchment Basin.

As we see on the graph 4.7 above, the Sunshine hour is Maximum in the months of December and January, whereas minimum in the months of June, July and August.

4.9 Evapotranspiration (ET)

Evapotranspiration is the combination of evaporation from open water bodies, a bare soil or interception on a vegetal cover and transpiration from vegetation through stomatal opening. Of the water that is precipitated on the earth, a large amount is returned to the atmosphere as vapor, through the combined effect of these two parameters (Davis & DeWiest, 1966). Under field conditions it is not possible to separate the two processes. Thus, both in combination are said to be evapotranspiration.

There are two types of evapotranspiration; potential and actual evapotranspiration. Potential evapotranspiration is the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation. Actual evapotranspiration is the amount of evapotranspiration that occur under field condition; it is the proportion of potential evapotranspiration that is actually evaporated under the existing soil condition (Freeze & Cherry, 1979). Thus actual evapotranspiration is controlled by weather, vegetation and soil (Leopold & Dune, 1978); where as potential evapotranspiration is controlled only by climate (Tamiru Alemayehu, 1992).

As a major loss of water from a drainage basin, evapotranspiration dominates the water balance and controls such hydrologic phenomena as soil moisture content, groundwater recharge and stream flow. Because of its effect in decreasing recharge of Groundwater and stream flow in a drainage basin, evapotranspiration have to be quantitatively estimated in practical water resource study.

Evapotranspiration from Gidabo River Catchment can be viewed from the adjacent Gelana, Bilate Rivers' and Awassa Lake Catchments, which are in most circumstances identical to Gidabo River Catchment. Normally, they experience identical climatic conditions and other physical parameters; as they are located in the southern part of the Main Ethiopian Rift valley.

Thus, for estimation of evapotranspiration , Class A meteorological station located at Dilla town is taken together with Class A meteorological stations located at the adjacent Catchments; Woliata Sodo, Bilate Agricultural state and Awassa.

Class A stations are stations measuring; wind speed, relative humidity, sunshine hours, temperature and rainfall (*i.e from National Meteorological Service Agency*).

The study area has variable climatic conditions due to different character of climatic elements, such as rainfall, temperature, wind speed, relative humidity and sunshine hours. Thus, the Catchment Basin is sub-divided independently into three: the highland, the escarpment and the rift floor sub-catchments. For each sub-catchment evapotranspiration is estimated one independent of the other. After all the annual groundwater recharge of the sub-catchment is treated.

A number of methods have been formulated and are currently in use for the estimation of potential evapotranspiration; but their applicability is limited by availability of different required parameters, and some methods are site specific, i.e. they are best valid only under a given climatic zone.

For this study, Thornthwaite and Modified Penman methods have been adopted.

4.9.1 Potential Evapotranspiration (PET)

4.9.1.1 Thornthwaite method.

Thornthwaite method uses air temperature as an index of the energy available for evapotranspiration. However, because it is based on a single climatic element, its applicability outside the climatic regime where it was developed may result in errors (Leopold & Dune, 1978).

Thornthwaite (1948) used data for the summer months in the arid parts of the USA to establish the formula (M.Shaw, 1988). Compared with the estimates from the Penman formula, Thornthwaite formula tends to exaggerate the potential evapotranspiration, as will be seen here after. But for a rough estimate of evapotranspiration in the months of the growing season in moderate climates, the Thornthwaite formula may be useful when only precipitation and temperature data are available (M.Shaw, 1988). As a result, the value of evapotranspiratin obtained from this method can be used for the highland and escarpment sub-catchments of the study area.

An estimate of the potential evapotranspiration, PET, calculated on a monthly basis, is given as:

$$P_{ET\,(m)} = 16N_m\,[10T_m/I]^{a}\,\text{mm}$$

Where: P_{ET} = Monthly total potential evapotranspiration (in mm/month).

N_m = Monthly adjustment factor depending on altitude and season.

T_m = Monthly mean air temperature (in ^{O}C).

I = Heat index for the year, which is the summation of monthly heat index,i.e

$[i_m = [T/5]^{1.5}]$ and given by:

$$I = \sum i_m = \sum[T_m/5]^{1.5} \text{ for } m = 1\ldots 12$$

And:

$$a = 0.49 + 1.8 \times 10^{-2}I - 7.7 \times 10^{-5}I^2 + 6.7 \times 10^{-7}I^3$$

Which can be rewritten as: $0.49+0.018I-0.000077I^2+0.00000067I^3$.

The Thornthwaite formula above gives PET for standardized month of 30 days and 12 hours of sunlight. And monthly adjustment factor, N_m is obtained by dividing the mean daily duration of maximum possible sunshine hours (N) for the appropriate latitude (below 53^0N) by 12.

See annex.10, which is taken from book of M.Shaw, 1989. The latitude of the study area is between 6.09^0 and 6.60^0 N, which is very near to 5^0N; thus the adjustment factor is taken based on 5^0N.

The potential evapotranspiration is individually calculated for the three sub catchments, which are under varying temperatures and altitudes (*See annex 19, 20 and 21*). The mean monthly temperatures for each of the sub-catcments are estimated by taking average mean monthly temperatures of Hagere Selam, Arbegona and Bore for the Highland; Yirga chefe, Wonago and Teferi-Kella stations for the Escarptment; Bilate Wajifo, Dilla stations for the Rift floor sub-catchments (*data is from National Meteorological Service Agency*).

Thus, in this thesis-research work the PET values obtained by Thornthwaite method for the Highland, the Escarpment and the Rift floor are estimated to be 689.85mm, 786.8mm, 1307mm respectively (*See annex.19, annex.20 and annex.21*).

The PET of the Rift floor is calculated also by using Modified Penman method, because Thornthwaite Method considers only a single climatic variable i.e Temperature. In addition the method underestimates the PET values in the Rift valley case due to influence of other climatic variables such as wind speed, relative humidity, and sunshine hours which play a major role for the potential evapotranspiration are not considered .

Thus, for further work PET values obtained from Thornthwaite method are used in the Highland and the Escarpment sub-catchments of the Gidabo Basin.

But for the Rift floor PET obtained from Penman method is used, because penman considers other variables in addition to temperature.

The PET value of the whole Catchment estimated by this method could be obtained by averaging the PET values of the three sub-catchments together and is 927.87mm.

4.9.1.2 Modified Penman method

Class A stations located at Awassa, Dilla, Bilate and Woliata Sodo, where records of temperature, sunshine hours, wind speed, and relative humidity all available are used to estimate potential evapotranspiration of the rift floor sub-catchment of the Gidabo River Basin by using modified Penman method. The open water evaporation (Eo) formula modified by (MAFF, 1967) to allow for the condition under which evaporation plus transpiration takes place (Shaw, 1996), was used to directly calculate PET as the following formula:

$$P_{ET} = \frac{[(\Delta/\gamma)H_T + E_{at}]}{(\Delta/\gamma) + 1}$$

Where: P_{ET} = Potential evapotranspiration.

Δ = The slope of the curve of saturated vapor pressure plotted against temperature.

γ = Hygrometric constant (0.27mmHg/^{0}F).

$H_T = R_1(1-\gamma) - R_0$

RI $(1-\gamma) = 0.75Ra*fa\ (n/N)$, where γ= 2, R_1 is incoming radiation and R_0 is Outgoing radiation determined from Sunshine records, temperature and humidity.

R_a = the solar radiation fixed by latitude and season

$f_a\ (n/N) = 0.16 + 0.62n/N$, for latitudes South of 54(1/2)0N, which can also be Ethiopian case.

n/N is the cloudiness of the air

n = Bright sunshine hours, in hour per day.

N = Mean daily duration of maximum possible sunshine hours.

R_a and N are taken from the table in the Annex.10

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

σT_a^4 = the theoretical black body radiation at T_a

T_a = Mean air temperature for a week, 10 days or a month in ^{0}F or in ^{0}C. In this work mean air temperature of a month in ^{0}C is taken.

σ = The Stephan Boltzman Constant, = 5.67 * 10-8Wm-2/K4, which is 2.01*10^9 mm/day).

$\mathbf{E_{at}} = 0.35(1 + u_2/100)(e_a - e_d) = f(u_2)(e_a-e_d)$, where:

u_2 = mean wind speed at 2 meters above the surface, miles per day.

e_a = the saturated vapor pressure at air temperature, T_a

e_d = The saturated vapor pressure at the dew point, T_d

(e_a-e_d) = The saturation deficit.

Extra subscript t in E_{at} signifies inclusion of transpiration effects.

Unlike Thornthwaite considers only single climatic variable i.e temperature, all climatic variables mentioned above are considered in the Penman method. Because, these variables are considered, Penman method tends to give reasonable estimation of potential evapotranspiration for the Rift floor.

Mean annual PET of the Rift floor calculated by using Modified Penman method is present in the annex.16 And the value obtained by the method is 1301mm/year. However, the value of PET obtained by Thornthwaite method is more or less the same (*i.e 1307mm/year*) as this value.

In this research work PET obtained from Thornthwaite formula is used for the Highland and Escarpment sub-catchments, whereas the Value of PET obtained from Penman method is used for the Rift floor to estimate the water balance of the whole Gidabo River Basin.

4.9.2 Actual evapotranspiration (AET)

Potential evapotranspiration assumes continues supply of water with no deficit to the soil, which is difficult assumption for the Rift valley case where there is very high evaporation and water deficit. Actual evapotranspiration is the amount of evapotranspiration that occur under the existing field conditions; it is the proportion of potential evapotranspiration that is actually evaporated under the existing soil condition (Freeze & Cherry, 1979).

The most popular method of computing actual evapotranspiration is through calculation of potential evapotranspiration. When moisture conditions are suitable, the actual rate of evapotranspiration is equal to the potential rate.

4.9.2.1 Turc method

The formula estimates the mean actual evapotranspiration of the River Basins based on annual precipitation and temperature records.

It is given by:

$AET = P/ [0.9+ (P/L)^2]^{½}$ mm per year.

Where, AET is the annual actual evapotranspiration in mm.

P= mean annual precipitation (mm)

$L= 300 + 25T +0.05T^3$

T= mean annual Temperature in ^{0}C

Based on the above empirical formula, the values of AET of the Gidabo River Catchment are obtained by averaging the values of AET of Highland, Escarpment and Rift floor sub-catchments.

AET of each of the sub-catchments is estimated separately by taking average of mean annual precipitation of Hagereselam, Bore, Yirba Muda, Arbegona and Bule stations for the Highland sub-catchment; Yirga chefe, Wonago, Kebado, Teferi-Kella and Aleta Wondo stations for the Escarpment sub-catchment and Yirga Alem, Dilla, Abosto, Leku, Wajifo and Bilate Agricultural state stations for the Rift floor sub-catchment.

Similar to precipitation the mean annual temperatures for each of the sub-catcments are estimated by taking average mean annual temperatures of Hagere Selam, Arbegona and Bore for the Highland; Yirga chefe, Wonago and Teferi-Kella stations for the Escarptment; Bilate Wajifo, Dilla stations for the Rift floor sub-catchments (*data is from National Meteorological Service Agency*).

Thus, the AET values obtained by Turc method using the formaula in the previous page; for the Highland, Escarpment and Rift floor is 665mm, 950mm, 1456mm respectively. In the latter Rift floor case AET is greater than precipitation (1375mm) of the Catchment which shows the evaporating water also comes from the Groundwater.
Actually the downstream of the Catchment is under high evapotranspiration.

The AET value of the whole Catchment estimated by this method could be obtained by averaging the AET values of the three sub-catchments together and is 1024mm.

4.9.2.2 Soil Water balance method

The most popular method of computing actual evapotranspiration is through the calculation of potential evapotransipiration. If there is abundant moisture in the soil, the two rates are equal. But when moisture supply becomes limiting, the computed potential rate is modulated by a factor that depends upon the amount of water in the soil (Leopold and Dune, 1978). The relationship expressed by Leopold and Dune, 1978 is as follows:

$AET = PET \times f(AW/AWC)$

Where *AET* and *PET* = the actual and potential rates of evapotranspiration.

$f(\;)$ = Some function of the term inside the parenthesis.

AW = the available soil moisture = (soil moisture content –Permanent wilting Point) x rooting depth of vegetation (cm).

AWC = The available water capacity of the soil = (field capacity – Permanent Wilting point) x rooting depth of vegetation (cm).

Actual evapotranspiration for each of the sub-catchments is calculated strictly following the one outlined by Thornthwaite and Mather, 1957.

The way of calculation of AET by soil water balance method is presented as follows (*and the table is annexed in the annex.13, annex.14 and annex.15)*:

The mean monthly precipitation (ppt) value obtained by using arithmetic method for the Highland, the escarpment and the Rift floor sub-catchments separately is entered in raw 1 of each table.

The mean monthly potential evapotranspiration calculated by using Penman method for the Rift floor and by Thornthwaite formula for the escarpment and high land is entered in raw 2.

Changes in the balance of the precipitation and meteorological demand of each month is entered in raw 3, following the computation, the accumulated potential water loss (which is obtained by adding-up the negative values of P-PET for the consecutive dry months and adding the excess precipitation from row 3 to the soil moisture level at the end of the dry month for the wet months) is entered in raw 4.

The available water capacity of the soil is estimated by overlapping the land use-land cover map with the soil map; accordingly the available water at rooting depth for the Highland, the Escarpment and the Rift floor is estimated to be 240, 216, 171mm respectively (See the annex.1, annex.2 and annex.3.

The soil moisture value for the dry season is obtained by using the following formula and entered in raw 5. The formula is a substitute for published tables (Thornthwaite and Mather, 1957) and curves (Leopold and Dune, 1978) to obtain the soil moisture status from accumulated potential water loss.

$$SM_m = AWCRZ * In^{-1}[-acc\ pot\ WL / AWCRZ]$$

Where:

SM_m = soil moisture during month m (mm).

acc pot WL = accumulated potential water loss at month (mm).

AWCRZ = available water capacity of the root zone (mm).

The change in the soil moisture during the month is obtained by subtracting the soil moisture of the preceding month from the soil moisture of the month under consideration. These values are entered in raw 6.

The actual evapotranspiration equals the potential rate during the months when the precipitation exceeds potential evapotranspiration this is because the rain water is considered to be easily available to the plant even if the soil moisture of the whole root zone is not raised to the available water capacity. At times when the potential evapotranspiration exceeds the precipitation amount the actual evapotranspiration will be equal to the sum of precipitation and the amount of soil moisture withdrawn from storage (i.e ppt + ΔSM).

The soil moisture deficit is easily obtained by subtracting the actual evapotranspiration from the potential. The moisture surplus (amount of water that cannot be stored), which is attained after the soil moisture reaches its field capacity and it drains into the groundwater, is obtained by subtracting the change in soil moisture (ΔSM) from values of (P-PET).

Thus, in this thesis-research work the AET values obtained by soil-water balance method for the Highland, the Escarpment and the Rift floor are estimated to be 688.9mm, 803.9mm, 1063.6mm respectively.

The AET value of the whole Catchment estimated by this method could be obtained by averaging the AET values of the three sub-catchments together and is 852.1mm.

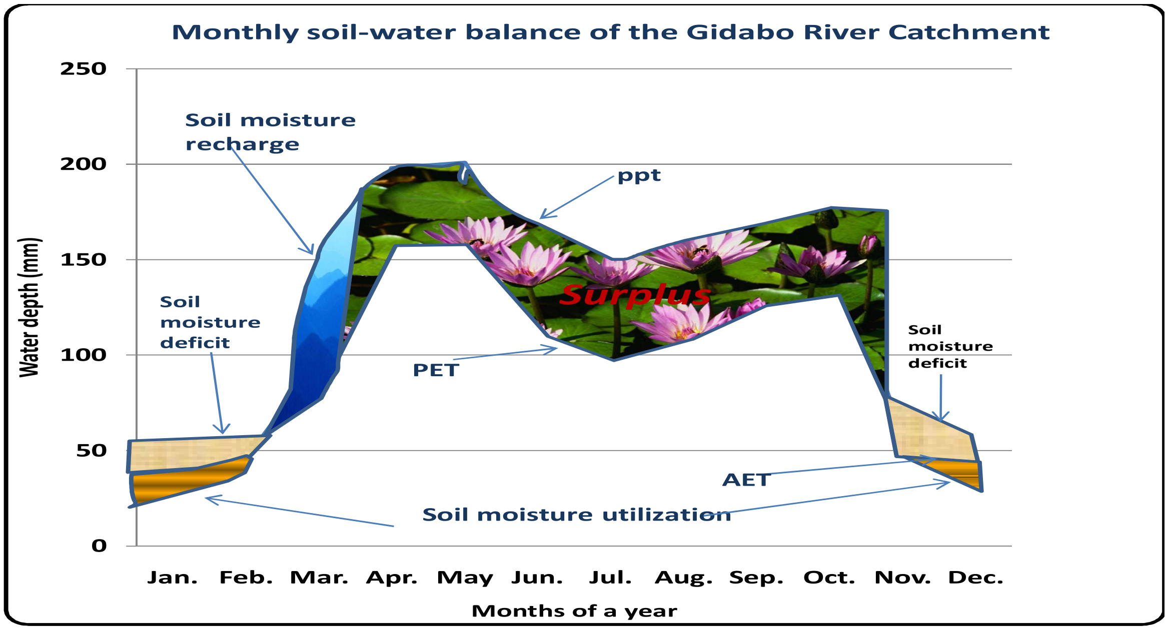


Fig. 4.8 Monthly soil water balance graph of the Gidabo River Catchment Basin.

Based on the previous study (*i.e Groundwater Resource Assessment in the Buna River Catchment, Abriham Mechal, 2007, which is the largest tributary of Gidabo River*) and the present study of soil water balance estimation, it can be suggested that most of the moths in highland area are under soil moisture surplus.

The highest soil moisture surplus occurs in the rainy months from April to October. This surplus is also apparent from the existence of many perennial streams and springs in the highland area.

Many areas of the rift are characterized by high potential evapotranspiration and low actual evapotranspiration due to the higher temperature and soil moisture conditions. It also remains without surface runoff and moisture surplus throughout the year.

4.10 Runoff

Runoff is the portion of precipitation that appears in the surface as streams of either perennial or seasonal nature. It is the flow which is collected from the catchments and appearing at the outlet (mouth) gauge station including surface runoff, interflow, base flow and direct precipitation on the channel of the streams or rivers; the major parts being surface runoff and base flow. In general sense, it is the excess precipitation after meeting the demands of evapotranspiration and soil moisture storage.

Gidabo Catchment (3342 sq.km) is measured at the main stream of Gidabo River at Abosto (646 sq.km) and two other locations on the upstream tributary rivers - Kolla (206 sq.km) and Bedessa (80 sq.km); which are gauged close to Aleta Wondo and Dilla respectively.

These three stations constitute slightly higher than one third (37%) of the total catchment area of Gidabo River but contribute about 75 % of the flows. Gidabo at Abosto (upper Gidabo River) alone contributes more than 45% of the flow while its area is only one fourth.

4.10.1 Drainage area ratio method of estimating discharge, at the mouth of the River.

Scaling up is made by calculating the proportionality (Drainage-Area Ratio) between the project site drainage area and the drainage area of the gauged sub-catchments.

The estimation is made on considering the following conditions: similarity in topography, climate patterns, soil characteristics, land-use and land cover.

The discharge data at the mouth of Gidabo River is extrapolated from the above mentioned gauging stations on the basis of drainage area ratio:

$A_G/Q_G = A_U/Q_U$

Where, A_G is the total drainage area above the gauging stations

A_U is total drainage area of the Gidabo River Catchment

Q_G is the total steam flow in m^3/sec of the gauged streams

Q_U is the discharge in m^3/s at the mouth of Gidabo River

Based on the above ratio the monthly statistics of extrapolated flows is as given in the Table below.

	Jan.	Feb.	Mar.	Apr.	May.	Jun	Jul.	Aug	Sep	Oct	Nov	Dec	Annual
Q (m^3/s)	12.1	10.5	12.2	26.4	48.6	46.1	42.9	61.6	71.7	83	39.1	20.4	39.55

Table 4.10 Monthly statitistcs of extrapolated flows of Gidabo River Discharge.

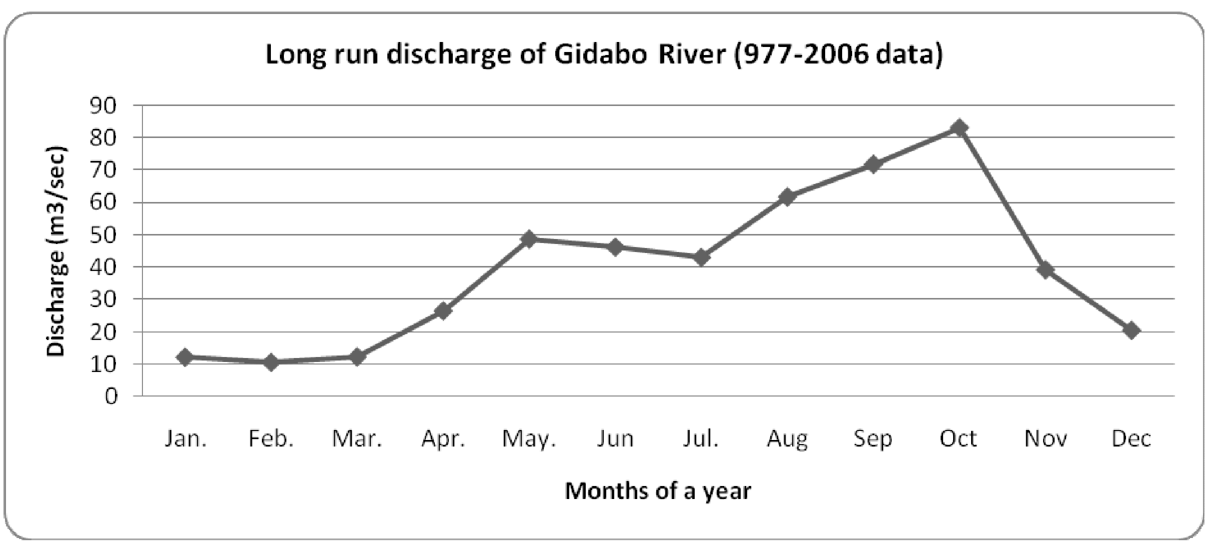


Fig. 4.9 Long run Gidabo River Discharge graph.

As we can see on the graph.4.9 and the table.4.10; the Gidabo River Discharge by itself shows us the Bi-modal flow pattern, just like the rainfall of the area. The highest peak flows are observed on May and October, while the lowest on January and February.

4.10.2 Hydrograph analysis of Gidabo River

A stream or a river hydrograph is the graph of discharge measured in m^3/sec (cumecs) versus time in month. The overall total extrapolated flow (discharge) of the river can be broadly broken down into groundwater run- off (base flow) and surface runoff, from which the surface runoff values are used to evaluate the annual water balance of the Catchment, and the hydrograph is further analyzed to obtain the annual groundwater recharge of the area.

4.10.2.1 Base flow separation methods

The method uses the time-series record of a river discharge to separate the base flow and surface runoff of the river. The common separation methods are graphical and spreadsheet software (i.e TIME-PLOT).

i) The graphical base flow Separation Method

The graphical methods are commonly used to plot the base flow component of a flood hydrograph event, including the point where the base flow intersects the falling limb. Stream flow subsequent to this point is assumed to be entirely base flow, until the start of the hydrographic response to the next significant rainfall event. These graphical approaches to partitioning base flow vary in complexity and include: constant discharge method, constant slope method and concave method.

ii) The Time-plot base flow separation method

Time-Plot software developed by Gabriel Parodi, which uses daily flow values and an attenuation coefficient that is controlled by the slope, land-use land cover conditions of a watershed possessing a value in the range of 0.9-0.995. A slight difference between the resultant values has been observed and mean values are adapted for further computations.

The conventional graphic base flow separation methods may either underestimate or over estimate the component of the river discharge. Because of this, the result obtained from the spread sheet program (*Time plot*) which considers the topographic characteristics of the basin and then estimates the base flow is used in this paper.

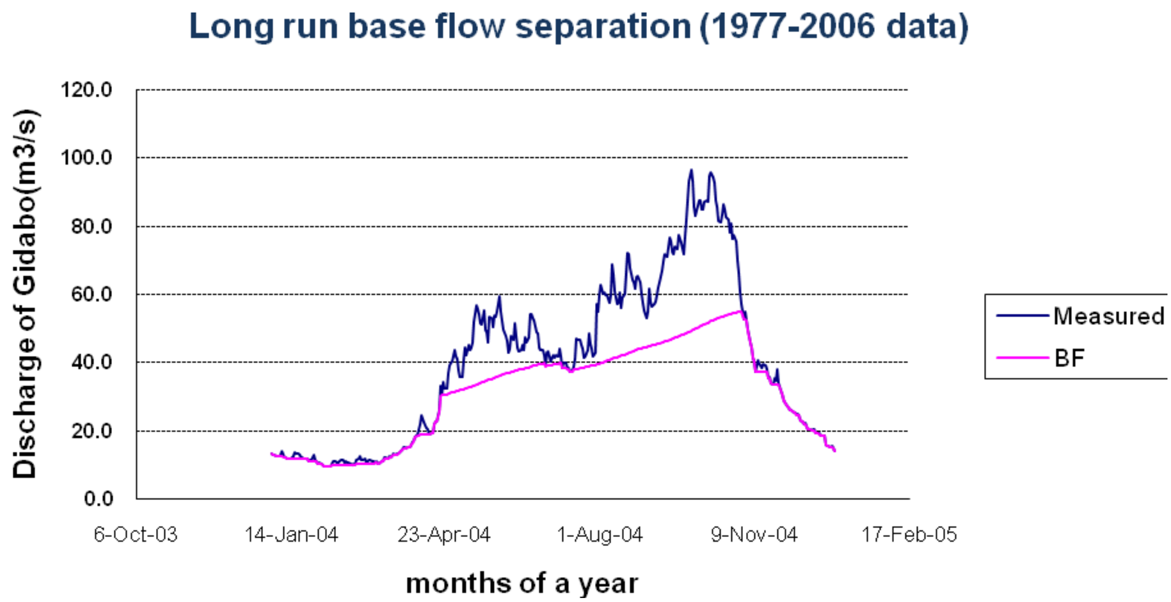


Fig.4.10 Base flow and surface runoff separation graph plotted by using Time-plot.

As estimated by using Time-Plot spread sheet software, the annual direct runoff and the base flow components of the total Gidabo River flow (39.32m^3/sec) are 8.89m^3/sec and 30.73m^3/sec respectively. To convert the runoff and the base flow into mm/year we divide the values of each component to the total area of the Catchment, accordingly the converted values of runoff and base flow are 84.11mm/year and 290.74mm/year respectively.

From base flow separation graph it can be suggested that the Gidabo River Catchment generally has high groundwater potential, because the base flow component (78%) is much larger than the direct runoff component (22%) of the total Annual flow.

4.11. The Water Balance.

An important objective of most groundwater studies is to make a quantitative assessment of the groundwater resource. In order to bring these objectives in to effect, two water balance approaches, which have generally the same ground but presented in different forms, have been applied.

The first approach is the one developed by Thornthwaite and Mather, 1957, known as soil water balance, and this method helps to quantify the annual actual evapotranspiration of the area on the basis of the potential evapotranspiration already computed by using empirical and physical formulae (*see soil water balance sub-topic*).

The second approach is based on the general water balance equation. This equation follows basic assumptions such as: Surface water divide coincides with groundwater divide and hence with no external inflows or outflows of groundwater across the watershed boundary and abstraction by human is insignificant.

The general form of the water balance equation is given as: -

$$\text{Inflow} = \text{Outflow} \pm \text{Change in storage}$$

The inflow component of a system includes precipitation, groundwater inflow, irrigation and artificial water transport to the system and the out flow components include abstraction, groundwater out flow, direct runoff, evapotranspiration, recharge and water transfer to another systems. This water balance approach involves identifying which components of inflow and out flow can take place within the area of consideration and quantifying each one individually.

On annual basis the change in storage is assumed to be zero; thus under a natural condition (i.e., no pumping) a long term average annual water balance for a catchment defined by a coinciding groundwater and surface water divide can be given as:-

$$PPT = AET + SRO + GWR$$

Where,

PPT = mean annual precipitation in mm
AET = mean annual actual evapotranspiration in mm
SRO = Mean annual surface runoff in mm
GWR = mean annual ground water recharge in mm

Water balance can be employed for different purposes: computation of ground water recharge, continuous record of soil moisture, and stream flow from meteorological records and a few observations on the soil and vegetation, seasonal and geographic patterns of irrigation demand, the flux of water to lakes, and prediction of human effect on hydrologic cycle (Leopold and Dune, 1978). Among these, its purpose in this paper is aimed at ground water recharge estimation.

Thus, by using the above relation of the conventional water balance equation, the mean annual groundwater recharge of the Gidabo River Catchment is estimated as follows:

AET is taken from Turc method and Soil water balance methods by averaging the values of both.

Recharge (GWR) = PPT- (AET+RO)
= 1375-(937.9 + 84.11)
= 353mm/year.

4.12. The optimum and reasonable amount of ground water recharge

The water balance result obtained by the conventional water balance approach above is thought to represent the optimum and reasonable amount of groundwater recharge of the study area; because of many reasons such as, it considers effects of hydrometeorology, pedology and land-use land cover. On the other hand, other methods that are not seen in this paper such as Chloride Mass Balance (CMB) approach is developed for specific climatic regions (i.e. deserts, which may not work in other areas other than deserts); whereas, mean long-term base flow and seasonal recession methods both use only a single variable (i.e. the river discharge), to estimate the groundwater recharge of the area.

Thus, in this paper, conventional water balance approach is used to evaluate the sustainable groundwater recharge of the Gidabo River Catchment.

CHAPTER FIVE

5. HYDROGEOLOGY

5.1 Introduction.

The dominant volcanic rocks in the earth's crust are basalts, andesites, trachytes, dacites, rhyolites and volcanic pyroclastic rocks such as welded tuffs (ignimbrites), unwelded tuffs, surge deposits, pumice and scoria fall deposits. Groundwater in these rocks is the major source of water for large parts of the world's population. They have extremely variable hydrogeological characteristics. Since they differ in their mineralogy, texture and structure their water bearing potential vary accordingly (Tenalem Ayenew and Tamiru Alemayehu, 2001).

The groundwater circulation and storage capacity of volcanic rocks depend on the nature of the porosity and permeability of the aquifers (Permeable geological formation which contains saturated pores and fractured media to store and transmit significant amount of groundwater).
In these rocks the occurrence of water bearing structures is conditioned by the primary and secondary porosity and permeability of the lithological units (Tenalem Ayenew and Tamiru Alemayehu, 2001).

All rock structures possessing primary porosity may not have necessarily a primary permeability; i.e. non connected vesicles possess a large primary porosity, but no or little primary permeability. Their later connections, due to weathering or fracturing, may give rise to secondary permeability. Primary porosities are peculiar characteristics of the volcanic textures and structures such as vesicles, flow contacts or interflow spaces, lava tubes or tunnels, clinker or rubble layers in the aa lavas, tree molds and shrinkage cracks. Whereas, secondary porosities are due to tectonic fractures, inter trappean beds, weathering zones and buried paleosols (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Welded tuffs (ignimbrites) generally have medium to low porosity and very low permeability. Although not significantly permeable the welded tuffs can transmit the most water because of its tendency to develop joints and other fractures that will remain open at considerable depth (Davis & DeWiest, 1966).

Both porosity and permeability of volcanic rocks tend to decrease slowly with time. Some of this decrease is owing to compaction, but the filling of the pores with secondary minerals is the most important cause of the decrease. On the other hand faulting and fracturing will increase the permeability of the volcanic rocks.

5.2. Hydrogeological units of the study area

Gidabo River Catchment is generally comprised of volcanic rocks. Detailed classification of hydrogeological units within the Catchment was done based on the information of surface geology, borehole lithologic log data, and pumping test data. The rocks in the Catchment are qualitatively classified into three permeability groups: low, medium and high. Thus, rock formations with similar hydrogeological character are grouped into one hydrogeological unit.

These hydrogeological units have significant role in determining groundwater availability and quality, because they control water passage through them. Major ones recognized in the field are briefly discussed as follows.

5.2.1 Trap-series (Old) aphanitic basalts and ignimbrites

These volcanics abundantly found in the rift escarpment of the Catchment Basin with the highest part corresponding to the edge of the Somalian plateau (Hagere-Selam town area) and in the structural old basaltic reliefs to the West of Yirga Chefe-Wonago Asphalt road. Forming the older unit in the area the basalt is aphanitic and shows spheroidal (onion-sheet like weathering) with general 45^0 dip to the West. Fresh old rhyolitic ignimbrite (old pyroclastic flow) overlying old basalt is highly welded, gray in color and phorphyritic texture with phenocrysts of feldspars and quartz.

The drainage pattern of streams over these rocks is dendritic with high drainage density owing to the low permeability of the underlying rocks.

The springs in these areas are of low discharge and with low EC value indicating shallow circulation of groundwater and they are contact springs emanating from the overlying silty loam soil showing the low permeability of the underlying unit. Thus these rocks are classified under the low permeability group.

5.2.2 Young basalts, rhyolites and pumice deposits

These formations are young basalts and rhyolites. The formation may belong to Nazareth Series (Meyer et al., 1978 in Mengesha Tefera et al., 1996). These formations are commonly found in the rift floor of the study area. The young basalts (Bofa basalts) are vesicular, black in colour, with quartz and sometimes with calcite mineralization in their vesicles; so, due to its vesicular nature the young basalt is grouped under high groundwater permeability unit. Young rhyolites, overlaying young basalts are observed in the field.

Young rhyolites cover a small area in the western part of the Gidabo Catchment, North of Lake Abaya, where they form fairly low reliefs. They separate the Gidabo Catchment from the adjacent Lower Bilate Catchment serving as surface water divide. In the NNE of Lake Abaya, rhyolitic rocks exposures are observed as domes, viscous lava, pumiceous pyroclastics, calderas and volcanic glasses (obsidians).

The pumiceous pyroclstics (with very high porosity, about 85%, Kedir Yasin, 2002), are presumed to deposit as the result of fractures developed due to the collapse of the Awassa Caldera (Paulos et al, 1979) and occupy considerable area around Yirga Alem, These rocks are generally highly affected by extensional fractures, faults and joints that are arising mainly from tectonic activities of "Wonji Fault Belt". The fractures are open and highly inter-connected improving the capacity of these rocks unit for the storage and transmission of groundwater.

The springs emanating from this formation are generally of high discharge and structure-controlled and many of the boreholes in this area are very deep up to 307meters depth (Derara Bore hole). Hence, this rock unit is classified under high permeability group.

5.2.3 Young ignimbrites

These are by far the most representative rocks in the Catchment area of Gidabo River. This unit is bounded by the eastern escarpment and the structural basaltic reliefs in the SSW of the Catchment area and distributed into the existing depressions and valleys which they filled up. Ignimbritic rocks exposures in the study area usually observed in the stream valleys; which is due to down-cutting deep valley outcrop of underlying ignimbrites by the streams.

In young ignimbrites secondary porosity is more preferable than primary pores. Primary permeability of these rocks is generally low except for some coarse grained and unconsolidated ignimbritic rocks. Secondary permeability in young ignimbrites is generally good but the Rift fracturing is usually in blocks form, hence fluid circulation is only limited to these joints (BGS, 2001).

Young ignimbrites in the field are observed as two types, welded ash tuffs with lithic fragments of pumice and quartz and crystallized ignimbrites with elongated lithic fragments. The welded ash tuffs are frequently fractured and show local normal faults within the rock but the fractures were filled with secondary fillings, affecting the overall permeability of the unit and thus this unit is classified under moderate permeability group.

Fig.5.1: Ignimbrite rocks in the Amalake stream, on the way from Dilla to Gololcha, showing fractures and inclusions (Source: Abenezer Kefeni, 2007 Study and Design of Gidabo Irrigation project).

5.2.4 Alluvial deposits

These are deposits transported by the Rivers and their tributaries. They commonly consist of boulders, pebbles, cobbles, gravels and sands. Fine silt and clay commonly deposit on thin horizontal layers during flooding for meandering streams. These deposits occupy the major downstream courses and flood plains of the Gidabo River and its tributaries, having very small coverage area. In the flood plains of the River they overlie the pyroclastic flow or fall deposits.

These are mainly observed on the flat right and left banks of the downstream courses of the River.

Their hydraulic characteristics have to do with their grain sizes; it is obvious that, in the coarser deposits water moves easily along the gap created in between the materials due their irregularities. So, this unit is classified under high permeability group.

Fig.5.2. Sandy alluvial deposits on the left and right banks of the Gidabo River (Source: Abenezer Kefeni, 2007 Study and Design of Gidabo Irrigation project).

5.2.5 Lacustrine deposits

Generally, lacustrine deposits have variable lithology which is related with their mode of origin such as ancient lake deposits, water deposited volcanic ejecta, or coarse sediments intruded into the lake by flooding, (Tenalem Ayenew, 1998).

These deposits in the the Gidabo River Catchment area are commonly exposed as lacustrine environment deposits adjacent to the Lake Abaya with soft, powdery, silty-clay, easily erodible, whitish in colour and light in weight characteristics. They are hyaloclastic ignimbriites, pumiceous tuffs, diatomites, obsidians ...etc.

Some parts of areas covered by these deposits are swampy. Stagnant water on the deposits, sustains throughout the whole year even if there exists high evaporation rate, this may refers to poor permeability of the formation, besides the formation is fine and compacted so as to allow infiltration owing to which the water stays in the whole year. The deposits thickness increases toward the lake which estimated to be 100m (Abenezer Kefeni, 2007).

Based on the above mentioned characteristics this unit is classified under low permeability group.

5.3. Groundwater flow directions and equipotential surfaces in the study area.

By means of field measurements of the water table or piezometric surface, representative contour maps can be drawn for the various types of aquifers within the hydrogeological basins (Tenalem Ayenew and Tamiru Alemayehu, 2001).

The groundwater flow lines, sketched perpendicular to the groundwater level contour lines (equipotential surfaces), show the direction of groundwater flow. Equipotential surfaces are groundwater level contour lines of equal head.

Contour maps of groundwater levels (i.e. groundwater elevation levels) and flow lines provide very useful data for locating new productive wells in a given area.
Diverging contour lines indicate regions of groundwater recharge, while converging contour lines are associated with groundwater discharge areas (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Furthermore, areas of favorable hydraulic conductivity can be ascertained from the spacing of the contour lines. In fact for areas with uniform groundwater flow, the portions having wide water table contour spacing and consequently flat gradients are characterized by higher hydraulic conductivity or permeability (Tenalem Ayenew and Tamiru Alemayehu, 2001). In other words, dense contour map does not tell us high productivity of the aquifer; the closer (denser) the groundwater contour lines, the lower the hydraulic conductivity and the farther the groundwater contour lines the higher will be hydraulic conductivity.

Accordingly, in the Gidabo River Catchment, there exist clear groundwater discharge (converging flow) zones associated with contour lines which are far apart each other. These discharge zones are because of relatively higher hydraulic conductivity. The zones are clearly observed in areas very near to Yirga Alem and Dilla (see the groundwater contour map in the figure below).

In fact favorable hydraulic conductivity in the areas very near to Yirga Alem is due to saturated coarse grained pumiceous pyroclastics, highly weathered and fractured ignimbrites and sands, which most of the time bring collapse of the hydogeologicac unit during water well drilling in the area. For instance, Yirba well collapse during 1998, as reported by well completion reports.

Similarly, areas very near to Dilla possess favorable hydraulic conductivity because of saturated and highly weathered, faulted and fractured ignimbrites which are also associated with numerous hot springs in the vicinity. In addition, the area is closer to the mouth of the Gidabo River and its large tributaries which mostly deposit coarse grained alluvial sediments but with relatively small areal extent.

Finally, eventhuogh the flow lines converge and diverge within the Catchment area of the Gidabo River as we will see in the next fig.5.3; there is groundwater outflow to the adjacent catchments of Lake Awassa, Rivers Gelana and Bilate. These is because of that, the rift valley is open and susceptible to groundwater outflow and circulation in its Southeastern and Northwestern or middle parts.

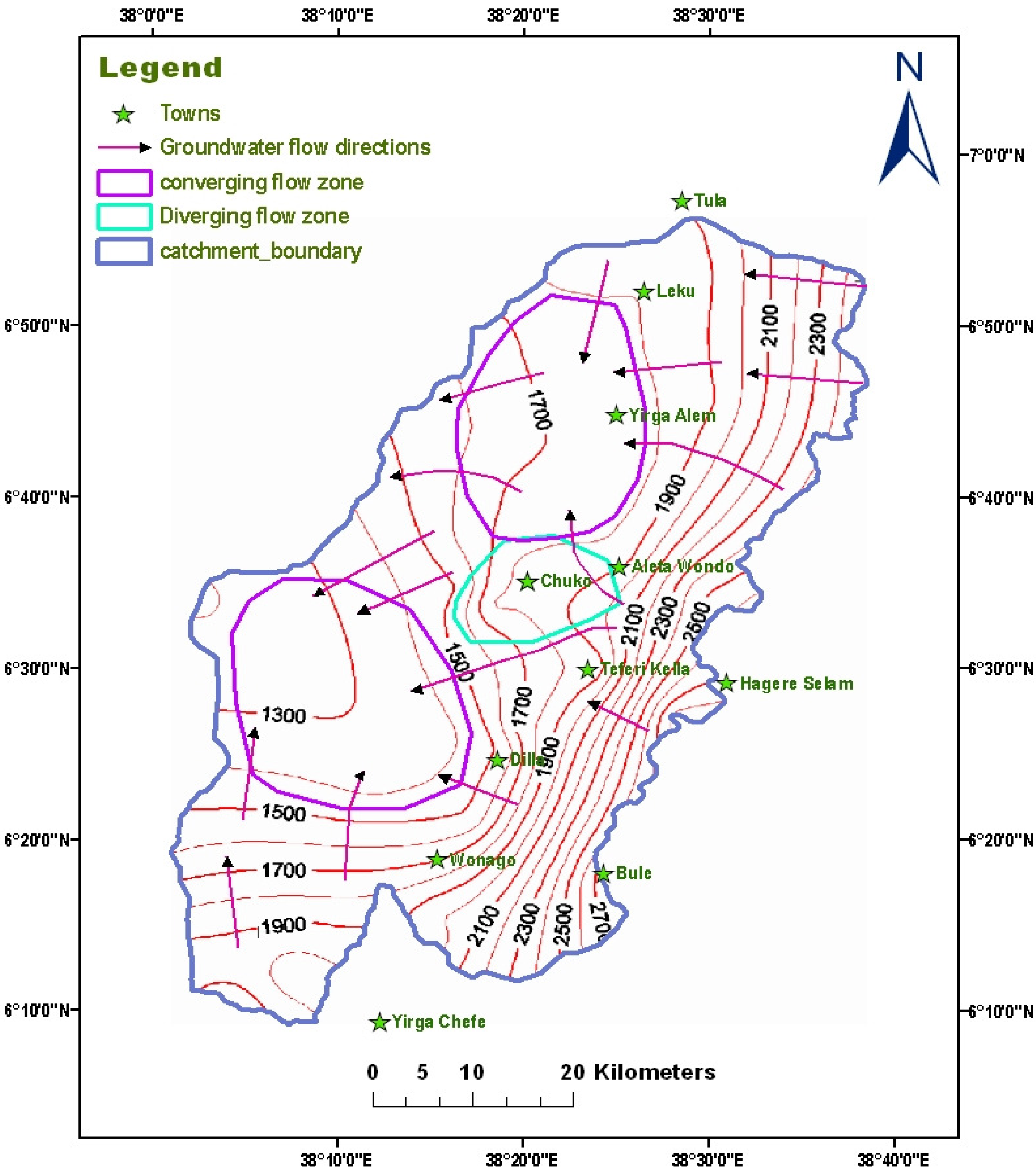


Fig. 5.3 Converging and diverging flow zones, associated with discharge and recharge areas respectively and drawn on groundwater level contour lines (equipotential lines). Note that, the groundwater flow directions are drawn perpendicular to the groundwater level contour lines.

Topographic elevation is the highest 3200m.a.s.l at the Mt. Geremba peak where a little Gidabo starts to originate; but when we see the groundwater level contour lines on the figure.5.3 in the previous page the water level decreases towards North (Geremba area) and increases toward South, Bule town area (i.e. 2700m.a.s.l), What is the reason behind? The reason is due to relatively low annual rainfall intake in the Geremba area and an excellent annual rainfall receiving nature of Bule town area in the SSE of the basin, in turn the best groundwater recharge in the South-Eastern highland area of the Basin. To have hint about the altitude of ground surface see, the figures 5.4 and 5.5 in the coming pages.

5.4 Groundwater recharge and discharge areas.

Groundwater recharge is a downward flow of water reaching to the water table and forming an addition to the groundwater reservoir (i.e an aquifer)

Eventhough, the magnitude may differ, every catchment posses the following identifiable three different types of groundwater recharges (Tenalem Ayenew and Tamiru Alemayehu, 2001).

The first one is direct groundwater recharge which comes from the rainfall. It is the ultimate groundwater recharge that we worry and should worry about.

The second is Localized groundwater recharge which is associated with very local lateral flows of infiltrated water, ultimately joining the groundwater level (table) at some distance from the point of infiltration.

The third is indirect recharge which is obtained from surface water bodies. This type of recharge can be originated either from natural (eg.Rivers, streams, ponds, lakes, etc.) or man-made structures (eg.Dams, irrigations, reservoirs, canals, etc). The indirect recharge is common in arid and semi-arid areas (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Groundwater recharge area can be defined as that portion of the drainage basin in which the net saturated flow of ground water is directed away from the ground surface and the water table usually lies at some depth; whereas, discharge areas can be defined as the movement of the net saturated flow of groundwater is directed toward the ground surface and the water table usually lies at or very close to the surface (Freeze and Cherry, 1979).

Toth (1963) cited in Fetter (1994) showed the possibility of mapping recharge and discharge areas on the basis of field observation using the basic indicators such as topography, peizometric patterns, hydro chemical trends, environmental isotopes, and soil and land surface feature. Among these indicators, topographic elevation is the simplest (Freeze and Cherry, 1979) and peizometric measurements are the most direct.

Below is the topographic map and groundwater level contour map based identification of recharge and discharge zones is used in this paper work.

According to topographic elevation view point of delineating recharge areas, the main recharge area for the Gidabo River Catchment is the eastern high plateau lineament including mountain Geremba, town Hagere selam and town Bule areas. Mountain Geremba is the highest peak mountain reaching up to 3200m.a.s.l and acting as the ground and surface water divide of Genale and Gidabo basins. This mountain Geremba is also the area where the little Gidabo River starts to originate.

As far as the annual rainfall depth of the plateau lineament is concerned, it relatively decreases from North-East to South-West of the lineament. For instance, the annual rainfalls at Mt. Geremba, Hagere Selam and Bule are estimated to be 1063mm/year, 1295mm/year and 2230mm/year respectively. As a result, town Bule area and its surroundings receive the highest annual rainfall in

the Catchment Basin of Gidabo and is the wettest (humid) region, possessing highly weathered and fractured volcanic rocks, clay loam soil regolith, dense vegetal cover and high human population density. These behaviors made the Bule area and its surroundings, excellent region for the groundwater recharge in the Gidabo River Catchment Basin.

In addition to the plateau area, the escarpment and parts of the rift floor are also the prominent areas of groundwater recharge.

The escarpment areas are characterized by essential rainfall depths of 1602mm/year, 1564mm/year, 1394mm/year and 1549mm/year for the town areas of Aleta Wondo, Teferi-Kella, Kebado and Wonago respectively. Based on the mentioned rainfall depths the escarpment areas are relatively semi-humid region possessing slightly to highly weathered and fractured volcanic rocks, silty clay to clay loam soil regolith, good vegetal cover and high human population density. Thus, the rift escarpment areas are very good groundwater recharge regions of the Gidabo River Basin.

A few Rift floor town areas such as Leku and Dilla, having annual rainfall depths of 996mm/year and 1327mm/year respectively and including town areas of Chuko and Morocho are relatively semi-humid to semi- arid region possessing slightly to highly weathered and fractured volcanic rocks, pyroclastic fall deposits, sandy-silt-clay loam to silty clay loam soil regolith, an important vegetal cover and high human population density. As a result, the mentioned parts of the rift floor areas are good groundwater recharge zones in the study area.

Finally, groundwater discharge areas, which we should worry and worry about for the sustainable development and utilization of groundwater have small areal coverage relative to recharge areas and identified in areas near to Yirga Alem and Dilla towns by using groundwater level contour lines and groundwater flow vectors drawn perpendicular to the contour lines (*see fig.5.5 or 5.6 in this and the next page*).

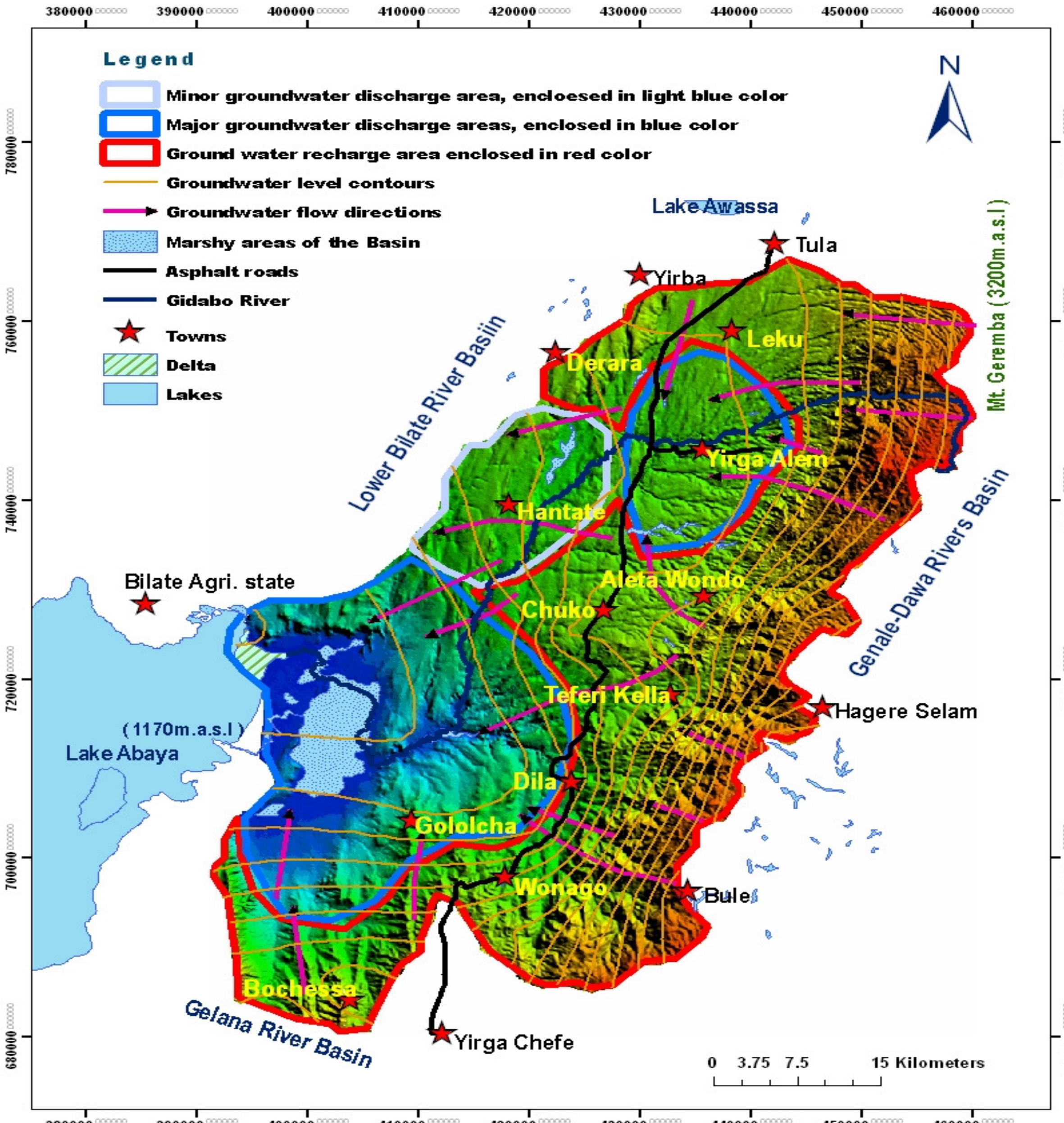


Fig. 5.4 Groundwater recharge and discharge area map produced by overlapping Digital image modeling map and groundwater level contour map. Note that, the groundwater flow vectors converge toward discharge areas and diverge away from recharge areas and drawn perpendicular to the groundwater level contour lines.

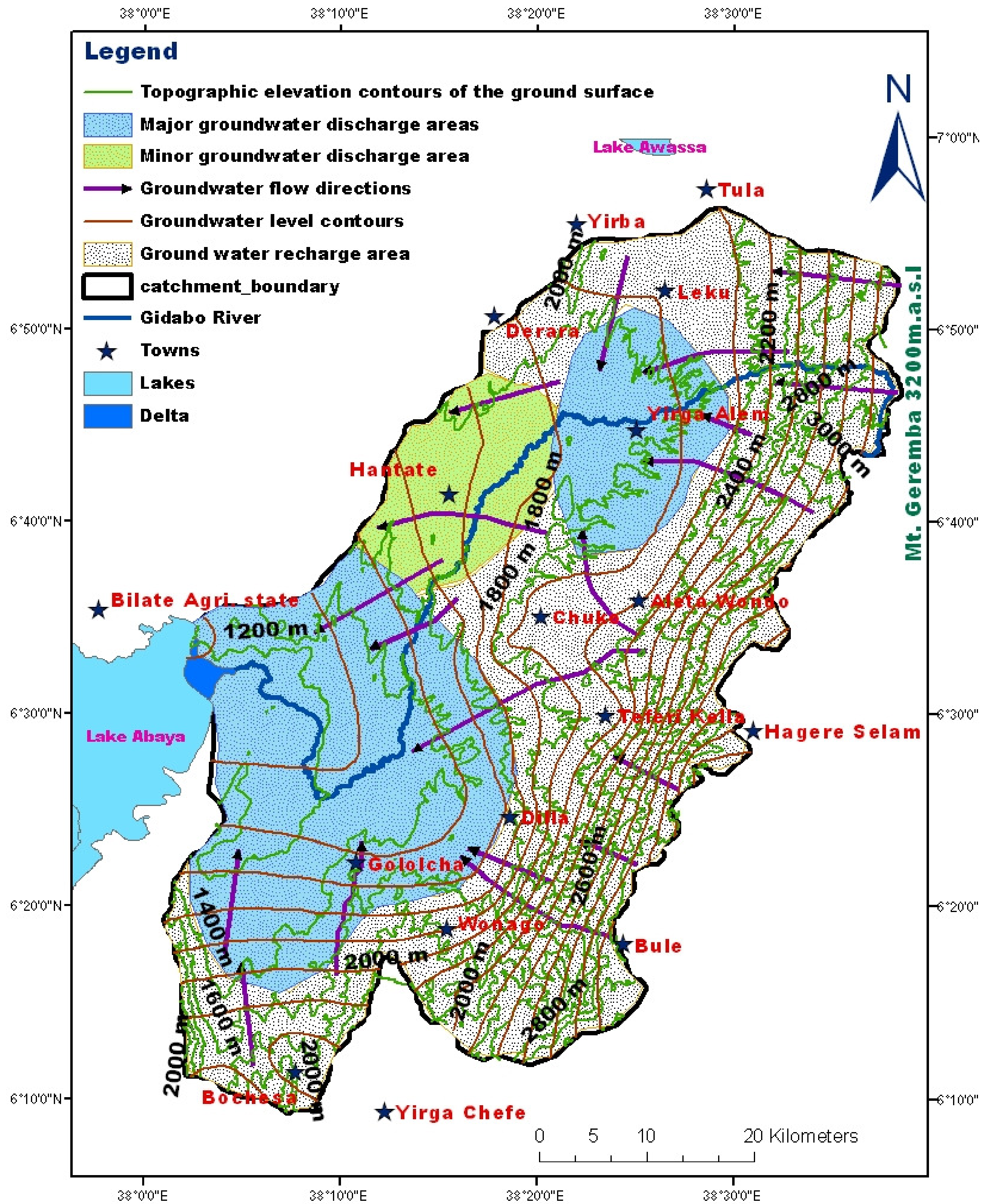


Fig. 5.5 Groundwater recharge and discharge area map produced by overlapping topographic map contours and groundwater level contours. And contour label numbers on the map are that of topographic map.

5.5 Groundwater divides

Groundwater divides are imaginary and vertical impermeable boundaries across which there is no flow (Freeze and Cherry, 1979) or the groundwater flow is away from this ideal line.

The regional groundwater divide is the divide that separates one catchment basin from the other (e.g mountain Geremba-Hagere Selam-Bule lineament of the Somalian high plateau, in the study area acts as the groundwater divide between Gidabo River Catchment basin and Genale-Dawa basin.

Surface water divides between Lake Awassa, Rivers Bilate and Gelana do not coincide with the Groundwater divides of the area; this is due to influence of the fault in the region, which also acts as conduit of water to flow out to the adjacent catchments.

The local groundwater divide is the divide localized within the Catchment basin under investigation.

The divide can be identified by using groundwater flow directions generated from groundwater level contours and groundwater flow vectors drawn perpendicular to the groundwater level contours.

Accordingly, in the Gidabo River Catchment there exists local groundwater divide, in the town area of Chuko. This identified groundwater divide also acts as surface water divide between upper Gidabo River in the North and Buna River in the South. In this divide area the groundwater flows to the North to interact with the largest tributary of upper Gidabo that is Kolla River and to the South to interact with the largest tributary of Gidabo that is Buna River.

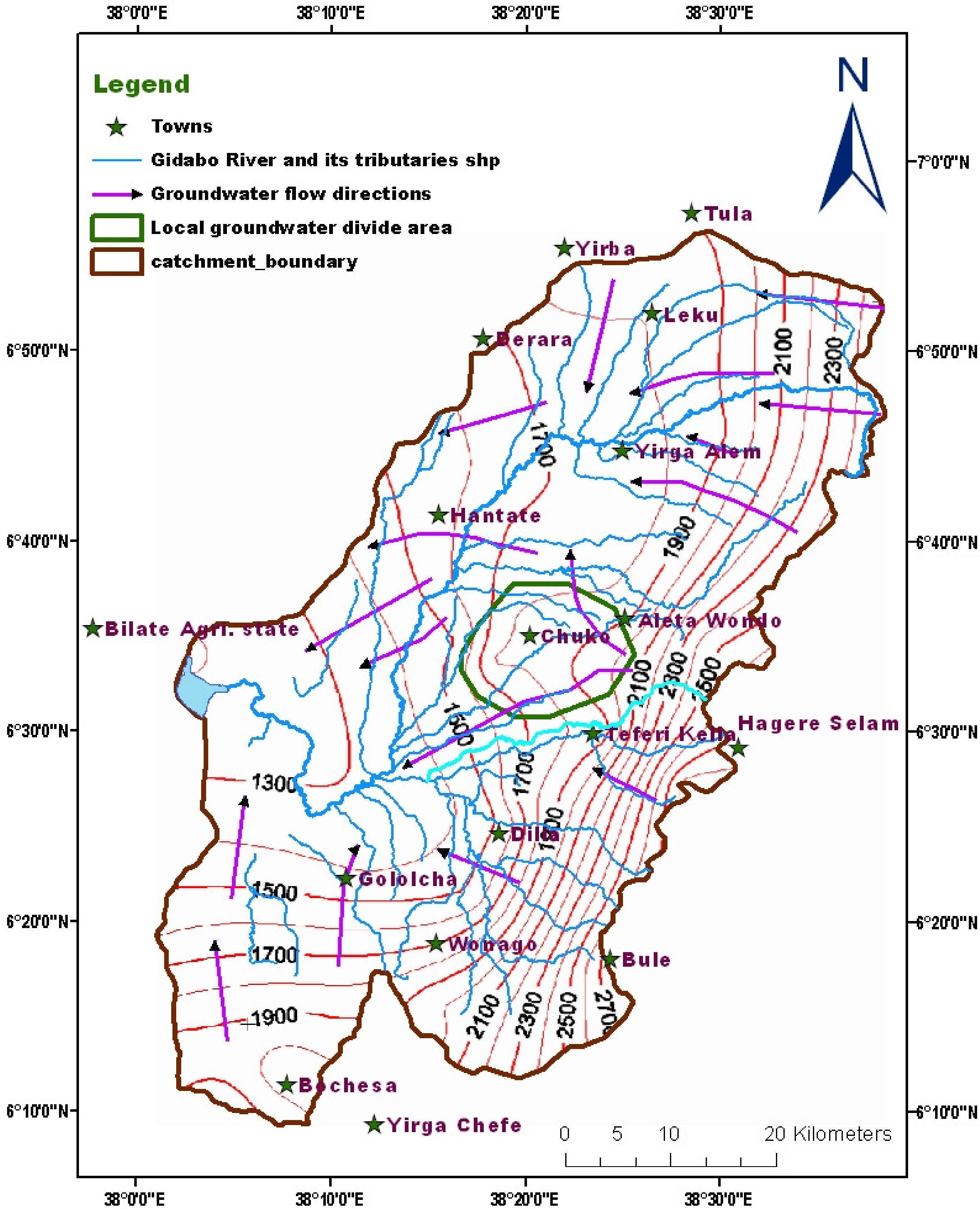


Fig.5.6. Local groundwater divide between upper Gidabo and Buna River (the largest tributary of Gidabo).

5.6. Groundwater and surface water interactions.

Groundwater and surface water are not isolated components of the hydrologic system, but instead interact in a variety of physiographic and climatic landscapes (Sophocleous, 2002).

In many regions ground water and surface water resources are connected, and most surface water features (rivers, lakes, dams, wetlands) generally interact with groundwater. The exploitation of, or quality of one resource, can therefore affect the other.

Groundwater and surface water bodies such as rivers most of the time interact in such a way that they are gaining, losing or acting as both (Winter et.al., 1998).

Interactions of the groundwater and streams can be evidenced by observations of groundwater flow directions (vectors) drawn perpendicular to the ground water table contours and overlapped with the drainage networks (*see fig.5.7. below.*).

A typical stream or river of humid region receives groundwater discharge: therefore as one goes downstream the base flow increases, even if no tributaries join the river. This is a gaining or effluent stream type. In such a case, the water table slopes toward the stream, so that the hydraulic head (groundwater flow direction) of the aquifer is towards the stream (Tenalem Ayenew and Tamiru Alemayehu, 2001).

In arid regions, many rivers are fed by overland flow, interflow and base flow at high altitudes. As they wind their way to a lower elevation, the local rainfall amount decreases, consequently, there is less infiltration and a lower (deeper) water table elevation. There may also be a dramatic change in the depth of groundwater when a stream draining a high altitude basin of lower permeability flows out onto coarse alluvial materials. For whatever reasons, if the bottom the stream channel is higher than the local water table, water may drain from the stream into the groundwater at depth. As one goes downstream of a given river of such a type, less and less water will be found in the channel. This is a losing or influent stream. The rate of water loss is a function of the depth of the flowing water and the permeability of the underlying alluvium. Fine grained alluvial deposits on the channel will retard the rate of loss into the groundwater (Tenalem Ayenew and Tamiru Alemayehu, 2001).

A stream that is normally a gaining stream in the flood period, may temporarily become a losing stream during base flow recession.

Gidabo River and its large tributaries have the behavior of gaining on ones side and losing on the other side; However a few streams in the Gidabo River Catchment such as, Tilikum Mencha, Ula-Ula, Amalake and the like are losing stream types draining a high altitude basin of lower peremeability at their upstream; and they fed the aquifer at their downstream.

This has also been confirmed by comparing the ground water table elevation and the elevation of the stream bed of Amalake stream on the way from Dilla to Gololcha. In the area, borehole drilled for the purpose of Gololcha community domestic water supply is very near to Amalake River and has a groundwater depth elevation of 1350m.a.s.l, but the Amalake river bed elevation nearer to the borehole is 1384m.a.s.l which is a bit elevated indicating that the stream is losing type and feeds the aquifer**.**

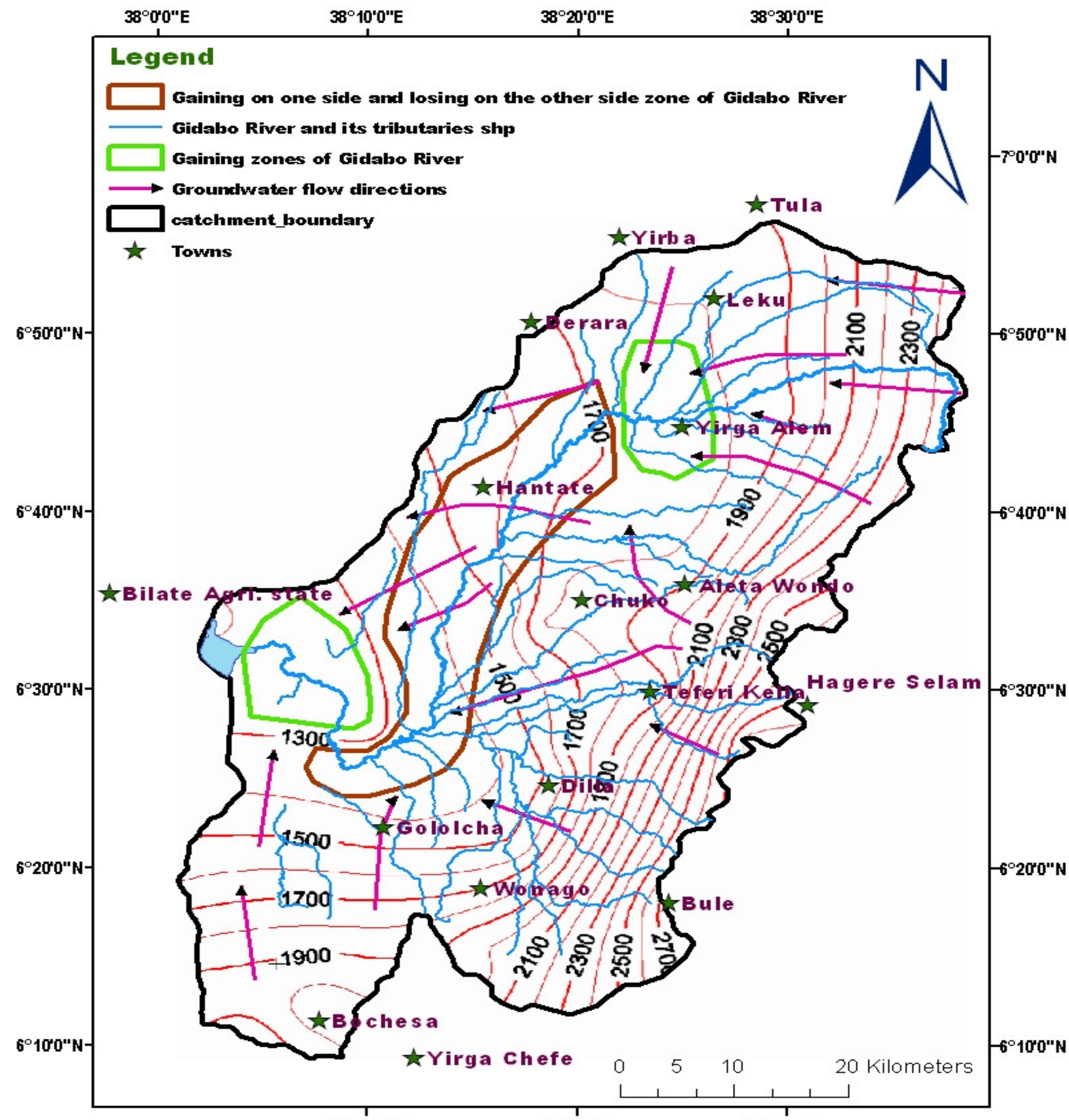


Fig.5.7. Gaining and losing zone map of Gidabo River, indicating groundwater and surface water interactions.

5.7. Inventory of groundwater sources

Natural groundwater discharge areas can be manifested on the ground surface as springs, swampy or marshy lands and seepage zones.

To be distinguished from springs are seepage zones which indicate a slower movement of groundwater to the ground surface. Water in seepage areas may pond and evaporates or flows, depending up on the magnitude of the seepage, the climate and the topography (Todd, 1959).

Groundwater can also be artificially drawn to the ground surface through shallow hand dug wells and deep boreholes for the purpose of domestic, irrigation, soft and beverage drinks, canned and bottled food manufacturing, livestock production, and etc. use.

In this section of the paper it is tried to give an account on the distribution and nature of these groundwater sources and schemes.

5.7.1 Springs

A spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water (Todd, 1959).

Springs occur in many forms and can be classified by means of their origin, rock structure, discharge, temperature and variability (Todd, 1959).

Other than the above classification scheme of the springs, Bryan cited in Todd (1959) classified all springs into two: (a) those resulting from gravitational forces and (b) those resulting from non gravitational forces.

Of the gravity springs, which result from water flowing under hydrostatic pressure, the following types are recognized: Depression springs- formed where the land surface intersects the water table; Contact springs- Created by a permeable water-bearing formation overlying a less permeable formation which intersects the ground surface; Artesian springs- resulting from releases of water under pressure from confined aquifers either at an outcop of the aquifer or through an opening in the confined bed; And Tabular or Fracture springs- issuing from rounded channels such as lava tubes or solution channels, or fracture in impermeable rock connecting with a groundwater supply (Todd, 1959).

Non gravity (thermal) springs are mainly originated by hydrothermal phenomena which involve the release of water and steam. These springs are always associated with volcanic rocks and tend to be concentrated in regions where large geothermal gradient occur. The natural condition for thermal springs to be originated is the occurrence of deep aquifers that permit the groundwater to percolate to a great depth through fractures or faults of the earth's crust, often 1,500 to 3,000m.

This water, heated from below, form a large convective current that rise up to supply hydrothermal areas. Thermal springs of various kinds are found throughout the world (Tenalem Ayenew and Tamiru Alemayehu, 2001).

In the Main Ethiopian Rift system, more than 500 hydrothermal features were indicated by UNDP (1973). Thermal springs occur in all topographic range from the Rift floor up to 2200m.a.s.l.

The distribution of thermal springs in Ethiopia was first presented by Kundo (1967) where the springs are largely clustered in the Rift due to its peculiar characteristics of thermal anomaly. The concentration of major ions and trace elements is high in thermal springs than in the cold springs. Thermal springs that are associated with magmatic activity are loaded with Na, HCO_3, and Cl (Tamiru Alemayehu, 2006).

Non-magmatic thermal springs get their temperature from deep circulation of groundwater, where the temperature of the rocks is high because of the normal temperature gradient with depth of the earth (i.e. geothermal gradient).

The magmatic thermal springs attain their temperature from underlying hot acidic magma chamber that is located at shallow depth.

Thermal springs, both magmatic and non-magmatic origin are part of deep-seated aquifer (groundwater).

The groundwater that rises up from deep thermal sources may consist of juvenile water (new waters of magmatic or cosmic origin which have not previously been part of the hydrosphere, hydrologic cycle) or a mixture of meteoric and juvenile water (Todd, 1959).

According to Tenalem Ayenew (1998) the stable isotope ($^{2}H/^{18}O$) composition of most thermal springs in the lakes region fall close to the local meteoric water line, indicating the recharge from precipitation (i.e. meteoric water , not the magmatic).

In the Gidabo River Catchment Basin there are numerous gravity springs (cold springs) and relatively a few warm or hot springs observed in the field.

5.7.1.1 Cold springs

These types of springs are observed in the eastern part of the Gidabo Basin, on the plateau and the escarpment. They possess low Electrical conductivity, low temperature, low PH, low TDS and high Eh values, indicating shallow groundwater circulation in the mentioned areas of the Gidabo. For instance, a spring situated at Abera Doda town, near to Hagere Selam and at elevation of 2775m.a.s.l (0441367E, 0713154N) has EC, TDS, PH, Eh, Temperature and discharge of 64µs/cm, 38mg/l, 6.45, +46mv, 15.10C and 0.1l/sec respectively.

These springs are commonly Contact, depression and fracture types.

The inventory data on springs conducted by Sidama and Gedeo Zones in year 2001 and the present field work generally indicates the presence of enormous cold springs in the Gidabo Basin. According to inventory data almost all cold springs discharge their water throughout the year, even during dry seasons; however, many of the springs are of low and fluctuating yields. But, some springs of fracture types in the southern and south-eastern part of the catchment near to Dilla-Bule road have discharge ranging from 3 to 5l/sec (Abriham Mechal, 2007). Lists of some of them are annexed. As a result fracture type cold springs with the good rainfall amount have dependable yield than contact and depression types.

5.7.1.2 Hot springs

As have been confirmed by water chemistry test of Odomike-Waleme, Rift valley resort and Yirga Alem Gidabo hot springs, all waters of the springs are of $NaHCO_3$ type, which are similar to shallow groundwater chemistry of the area. Findings by Tenalem Ayenew,(1998) and Tamiru Alemayehu, (2006), mentioned above lead to the conclusion that these hot springs receive the recharge from highland and rift escarpment.

As field observation of in-situ water quality parameters in the study area, non-gravity (hot) springs possess relatively high Electrical conductivity, high temperature, high TDS and low Eh values. For example, a spring situated at Odomike-Waleme, near to Dilla town and at elevation of 1427m.a.s.l (0419097E, 0706697N) has EC, TDS, Eh and Temperature of 3120µs/cm, 1870mg/l, +32mv and 680C respectively.

According to the water chemistry, Tenalem Ayenew and Tamiru Alemayehu findings and field observation of in-situ water quality parameters, hot springs within the study area are the result of deep circulation of highland and escarpment recharged water, through the major faults of the Main Ethiopian Rift formation, emerging at the foot of the escarpment and the rift floor (i.e their temperature is geothermal gradient origin, with 1^{0}C for every 6meters depth), (Tamiru Alemayehu and Vernier, 1997)

Hot springs in the Gidabo River Basin are clearly observed being situated in the major groundwater discharge zones, very near to Dilla and Yirga Alem towns (see fig.5.9 below). As a result we can have many unknown and undeveloped hot springs in the indicated major groundwater discharge areas of Gidabo River Basin.

There are also three hot springs located at the North-eastern shore of Lake Abaya. Gidabo-Delta hot spring is among these springs and is situated at the foot of rhyolitic dome and in the major groundwater discharge zone of Gidabo.

Minor groundwater discharge zones such as areas very near to town of Hantate possess hot springs of relatively warm temperature (Danshe-Gambela warm spring, 33.4^{0}C), as compared to the hot temperatures of Yirga Alem Gidabo (44^{0}C), Rift valley resort near Dila (53^{0}C) and Odomike-Waleme near Dila (68^{0}C) hot springs.

Thus, hot springs of relatively higher temperature can be used as indicator of potentially high groundwater discharge areas with deep circulation, because they does not logically emerge in the groundwater recharge areas.

A) Odomike waleme hotspring at the foot of Rhyolitic dome to the west of the spring.

B) The water is boiling at 68^{0}C because of high atmospheric pressure at an altitude of 1427m

Fig.5.8. Odomike-Waleme hot spring water photo, near to Dilla town.

5.7.2 Marshy and swampy areas

There are several swampy areas exposed as groundwater body on the surface in the Gidabo Basin.

The biggest one is the "Gola" marsh at the major groundwater discharge area near to Dila-Gololcha (see fig.5.9). The "Gola" marsh is due to very shallow circulation of groundwater, closer to the ground surface. This behavior of shallow circulation of groundwater is clearly manifested on the surface during rainy seasons.

The second one is "Cheleleka" swamp, observed in the minor groundwater discharge area very near to Hantete town. It is situated to the North of gravel packed road between Abosto and Hantete.

The third and the smaller "Raro" swamp is identified in the major groundwater discharge area, to the South of the gravel packed road between Aleta Wondo and Abosto towns.

These all swamps, mentioned above are situated in the rift floor areas where in a general sense there is groundwater discharge. However, there are also pockets of swamps in areas situated at the foot of the main Ethiopian rift escarpment. For instance, swampy area very near to Aleta Wondo town to the West of gravel packed road between Teferi Kell and Aleta Wondo.

Highland areas of Genale-Dawa basin have numerous swampy zones. For example, areas between Hagere Selam and Bule towns which have the highest annual rainfall possess numerous swamps.

Therefore, swampy zones can be used as indications of shallow groundwater discharge areas.

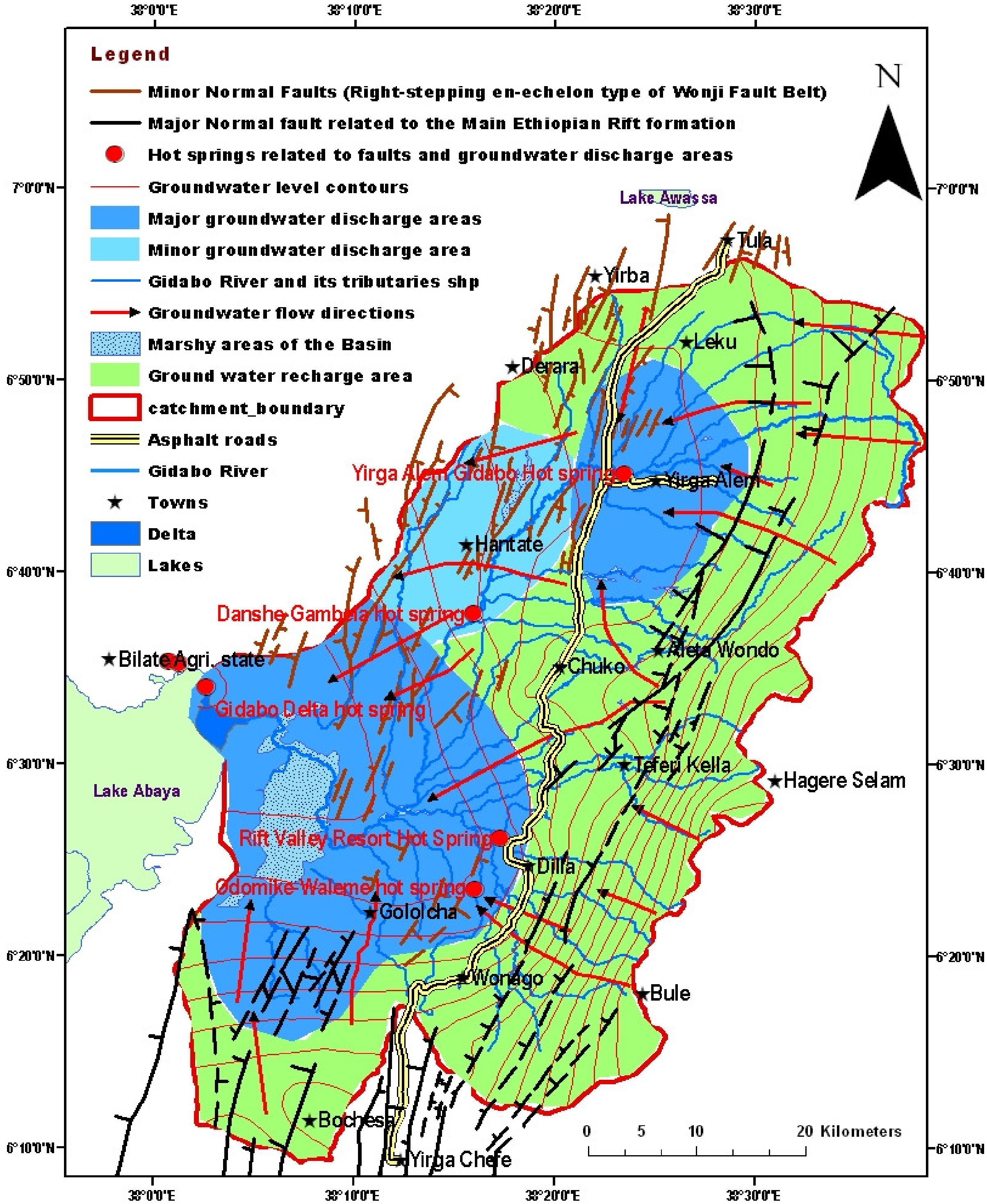


Fig.5.9 Hot springs situated at major groundwater discharge areas in the Gidabo River Catchment basin.

5.7.3 Water wells

Water well is a hole or shaft, usually vertical, artificially excavated in the earth for bringing groundwater to the surface. Many methods exist for constructing wells; selection of a particular method depends upon the purpose of the water supply, the quantity of water required, depth to groundwater, geologic conditions and economic factors (Todd, 1959).

Shallow wells are dug, bored, driven, or jetted wells of generally less than 25meters depth (Todd, 1959).

Deep and high capacity wells (boreholes) are constructed by drilling. Three basic methods of drilling are employed: Cable tool (also known as percussion or standard), hydraulic rotary and reverse rotary methods (Todd, 1959).

5.7.3.1 Shallow wells (Hand-Dug wells)

Based on the definition of Todd, shallow wells in the study area are traditionally hand-dug unprotected private open wells and hand-dug and protected hand-pump fitted wells.

However, depths of the hand-dug wells vary from 2 - 30meters, and have a diameter of 1 to 1.5meters. But the majority of the wells in the study area are up to 24meters depth with variable static water levels ranging from 1.5 to 15meters.

Hand–dug wells in the study area are enormous in number and distributed almost in recharge areas of the Gidabo River Basin, indicating that they tap shallow circulating groundwater.

The seasonal fluctuation of the static water levels in most of the hand-dug wells is highly attributed to the direct recharge condition from precipitation in to the well which intern indicates the unconfined nature of the aquifers.

Water of these wells are not dependable, for the reason that they commonly dry out during dry seasons and an aquifer is vulnerable to pollution.

The inventory of hand-dug wells in the Gidabo River Basin is given in the annex.6.

5.7.3.2 Boreholes

Deep and shallow boreholes are distributed in and around the study area. They are commonly drilled by governmental and non-governmental organizations, for the purpose of water supply to urban and rural communities.

There are about 59 deep boreholes, with their depths between 70 to 307meters, and 17 shallow boreholes with their depths ranging from 31 to 68 meters.

The main aquifer formations of the boreholes are volcanics which are pyroclastic deposits, weathered and fractured basalts, ignimbrites (welded tuffs), unwelded tuffs, rhyolites and trachytes. Alluvial and lacustrine formations are also recognized.

The static water levels of the boreholes in the study area lie at 0meter (*i.e. ground surface*), with yield of 6 liters per second for flowing artesian well of recently drilled borehole (in 2009) which is located in Dara-woreda, Mechisho-Anno locality, having 56meters depth (*see the figure below*).

Fig.5.10. Flowing artesian well located in Mechisho-Anno locality; Near to Dilla town, 2009. Before water distribution work rural communities are using the flowing water for their domestic use.

On the other hand, the SWL for the deepest Derara locality borehole of Boricha woreda is 244meters with yield of 5 liters per second.

Most of the deep boreholes are fitted with submersible electrical pumps and others are equipped with Indian mark II hand-pumps.

Inventory data of the boreholes is in the annex.4.

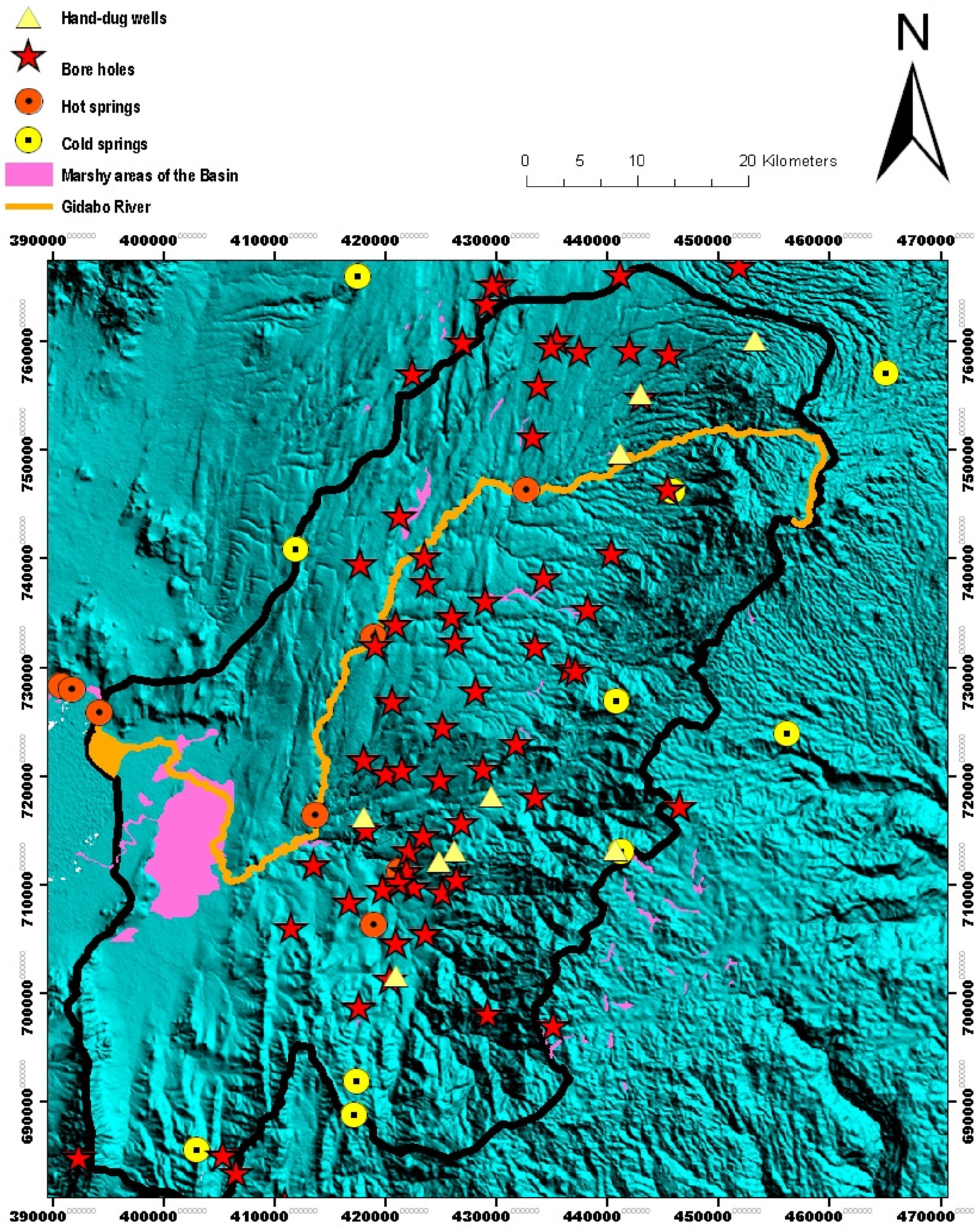


Fig.5.11. Distributions of boreholes, hot springs, marshy areas and cold springs, in and around Gidabo River Basin.

5.8 Types of aquifers, their thickness and lateral extent.

An aquifer is defined as a saturated a permeable geological unit that stores and transmits economic quantities of water to wells. The excellent aquifers are unconsolidated sands and gravels of alluvial deposits, but permeable sedimentary rocks such as sandstone and limestone, and highly fractured and/or weathered volcanic and crystalline rocks can also be classified as aquifers.

An aquitard is a semi-permeable geological unit that store but transmit very small amount of water. When viewed over large areas and long periods, its permeability is not sufficient to justify production wells being placed in it. Clays, loams, and shales are typical examples of aquitards.

An aquifuge is an impermeable geological unit that neither store nor transmit water at all. Dense unfractured igneous or metamorphic rocks are typical examples of aqufuges. However, in nature truly impermeable geological units seldom occur. All of them leak to some extent, and must therefore be classified as aquitards. In practice, however, geological units can be classified as aquifuges when their permeability is several orders of magnitude lower than that of an overlying or underlying aquifer.

The above definitions are qualitative, i.e. they are purposely imprecise with respect to permeability.

There are three types of aquifers: confined, unconfined and leaky.

A confined aquifer is an aquifer bounded above and below by an aquifuge; whereas an unconfined aquifer is a water table aquifer, and is bounded below by an aquifuge, but it is not restricted by any confining layer above. A leaky aquifer is also known as a semi-confined aquifer, whose upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquifuge.

Based on the existing hydrogeological unts, the distribution and discharge of cold and hot springs, hand-dug wells and lithological logs of boreholes in and around the area, all aquifer types defined above are recognized in the Gidabo River Basin. The types are recognized based on the approaches described below.

The first approach relies on analysis of lithological logs of each boreholes distributed within and around the study area. Based on this analysis of each borehole logs; many of boreholes have seen to possess aquitards as a confining layers. As a result, the common type of aquifer in the area is leaky. For example, from lithological log information of Dara-Mechisho 173meters deep borehole of 36meters aquifer thickness, 30meters static water level and discharge of 4.3*l/sec*, there is leaky layer of slightly weathered ignimbrite with clay inclusion at 34-40meters depth ranges which makes the aquifer leaky. However, some deep boreholes tapping unconfined aquifer water are also recognized in the study area.

For instance, unconfined aquifer type in Wonsho-Bokaso deep borehole of 132meters depth, 62.1meters static water level, with variable aquifer thickness and 1*l/sec* discharge of the well.

The second approach which is recognized based on the first approach is observation of seasonal groundwater level fluctuations of hand-dug wells, and shallow boreholes. The fluctuation is thought to arise in response to direct recharge from precipitation. This is clearly observed by looking at dramatic seasonal groundwater level variations i.e. high and low water levels in wet and dry seasons respectively. In addition to water level fluctuation in wells, turbid waters in cold springs, hand-dug wells and shallow boreholes is confirmation to percolation of rainfall water to the underlying aquifer (eg.Turbid water of Dara-Gelowacho shallow borehole of 48meters depth and 20meters static water level). Therefore, based on this approach an aquifer of this borehole is unconfined aquifer.

In some of the areas by comparing the first depth of the main aqufer struck when drilling is in progress and the final level that the water rests (i.e. static water level (SWL)) which is achieved after completion of the drilling process, gave a clue of the aquifer type. For instance, confined aquifer of Chuko-Gambella newly drilled deep borehole (2009) of 162meters depth, 41meters SWL, 30meters aquifer thickness and 5.5*l/sec* discharge has confining layers of tuff at 46-56meters depth ranges above and tuffaceous basalt at 148-154meters depth ranges below.

The third approach is based on the type of curves obtained by using pumping test records and plotting of the draw-dawn in meter (linear scale) versus time in minute (logarithmic scale); or draw-dawn in meter (logarithmic scale) versus time in minute (logarithmic scale). The plots help in identifying aqufer types that strictly rely on theoretical models (curves), i.e. identification of aquifer types is made by comparing its draw-dawn versus time curve with that of the various theoretical model curves.

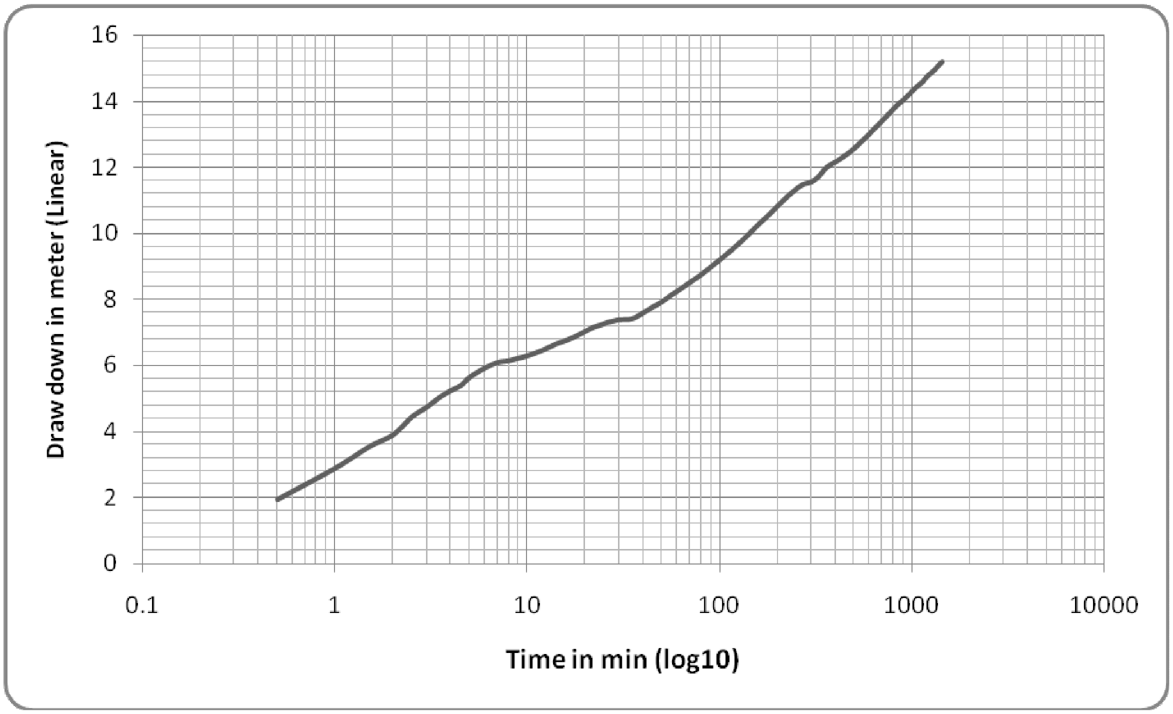


Fig.5.12. Linear-log plot of unconfined aquifer for Wonsho-Bokaso 132meters deep borehole.

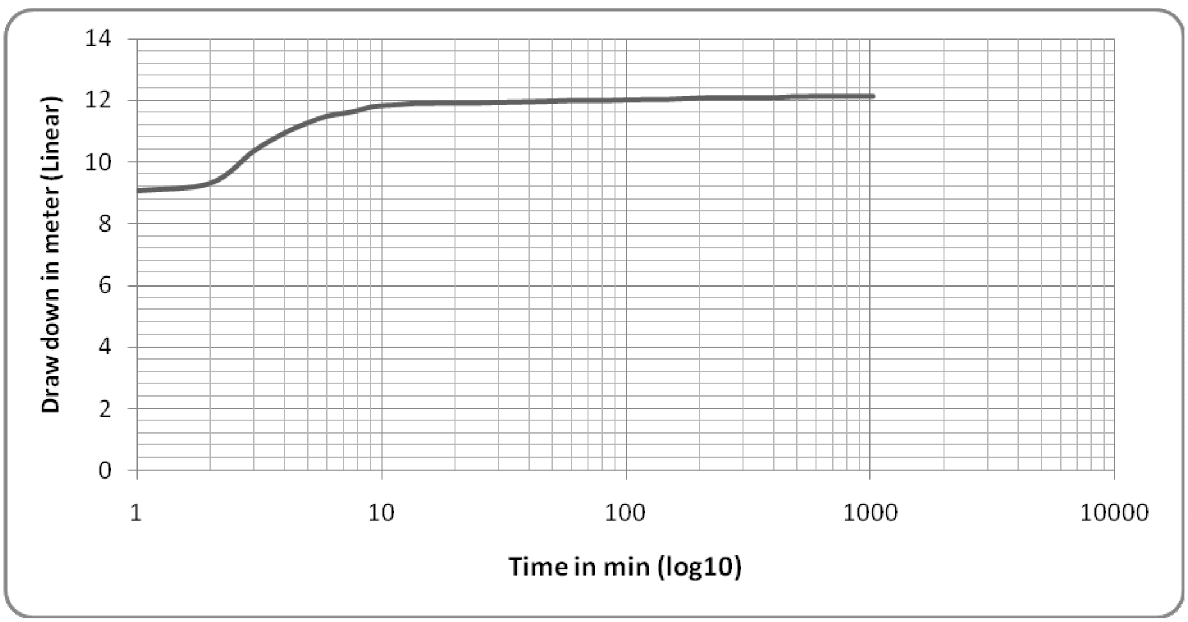


Fig.5.13. Linear-log plot of Leaky aquifer for AletaChuko-Miridicha 183meters deep borehole.

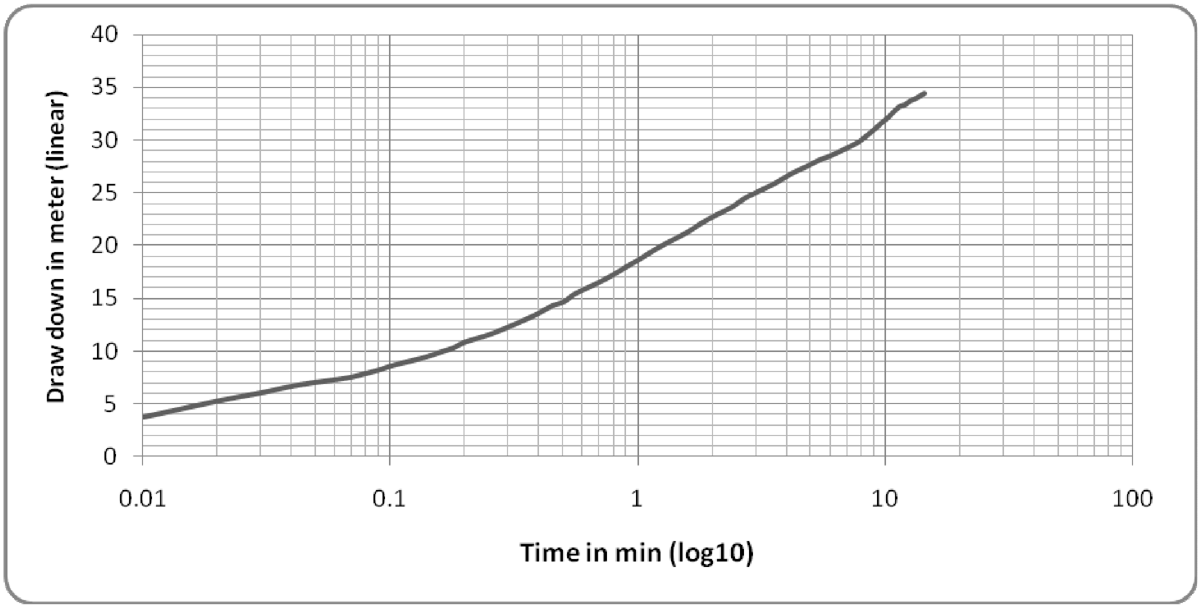


Fig.5.14. Linear-log plot of confined aquifer for Dara-Mechisho town 173meters deep borehole.

Based on the third approach, analysis and comparison of the plots with the theoretical models (curves), there is an existence of unconfined, semi-confined (leaky) and confned aquifers within the Gidabo River Basin (see the curves above by comparing with theoretical models).

Based on the analysis discussed above, all the aquifer types are recognized in the Gidabo River Catchment.

As far as the distribution of aquifers in the study area is concerned unconfined aquifer types are commonly situated in the eastern and south-eastern parts of the study area (i.e. highlands and escarpments) at a depth range of 5-30meters below a ground surface. This is probably due to high erosion processes as a result of slopping topography and low deposition that cause existence of thin layers and freshness of underlying geological units (aquifuges). Cold springs and very many hand-dug wells tap water of this shallow aquifer type in the escarpment and highland areas of Gidabo River Basin.

The above unconfined aquifers are underlain by slightly weathered and fractured ignimbrites, paleo-soils and tuffs in the area. Existence of these underlying geological units is the cause for the appearance of leaky aquifers below it at the depth ranges of about 30-40meters. Leaky aquifers are very common in the lower part (foot of) of the rift escarpment and the Rift floor.

This is probably due to relatively flat topography, high deposition in grabens of wonji fault belt that cause existence of thick layers. Hot springs and boreholes in the rift floor commonly tap water of this deep aquifer types.

Confined aquifer types are very common at relatively significant depths below depths of existence for unconfined and leaky aquifers (i.e. below 40meters depths). These aquifers exist in the rift floor of the study area.

Aquifer thickness and areal extent in the study area both vary significantly from borehole to borehole and place to place. This is because of that on a regional scale some aquifers slope, and none of them extend to infinity for the reason there is complex geological processes that cause inter-fingering of layers and pinch-outs of aquifers, aquitards and aquifuges. In some places, aquifers, aquitards and aquifuge are cut by deep stream channels or faults. In other words, aquifers, aquitards and aquifuges are latterly bounded in one way or another. The largest aquifer thickness recognized in the area from the lithological logs of wells is that of Gobo Hebisha and Gobo hobolso deep boreholes and is 59meters thick for both. The smallest thickness is that of Kebado newly drilled borehole (2009) and is 24meters thick. Thicknesses of unconfined aquifers are variable due to fluctuations of water tables.

5.9 Hydraulic Parameters

Hydraulic conductivity (K), Transmissivity (T) and Storativity(S) (specific yield for unconfined aquifers) are the hydraulic properties of aquifers and soil materials that determine how fast water moves into, through, and out of subsurface materials and how piezometeric surfaces or water tables are affected. Much of the success in predicting underground movement depends on how accurate the pertinent hydraulic parameters can be evaluated.

Hydraulic conductivity is a measure of the ability of a fluid to move through interconnected void spaces in the sediment or rock. It is a function of both the medium and the fluid (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Transmissivity is the rate at which water flows through a vertical strip of the aquifer. Or it can also be defined as the product of the average hydraulic conductivity and the saturated thickness of the aquifer (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Storativity is volume of water per volume of aquifer.

5.9.1 Hydraulic conductivity

This is the most important parameter, because the other parameter as Transmissivity is obtained as a function of hydraulic conductivity; i.e. by multiplying K with aquifer thickness.

Storativity is mostly the prominent character of unconfined aquifers and it ranges from 0.01 to 0.3, for confined ones storativitity is very negligible and ranges from 0.00005 to 0.005; because in confined aquifers, assuming the aquifer remains saturated change in pressure produce only small change in storage volume (Tenalem Ayenew and Tamiru Alemayehu, 2001); because the water is under pressure, and when it is removed, other pressurized water nearby replaces.

Thus, Hydraulic conductivity is the most important character of all aquifer types (i.e. confined, unconfined and leaky).

Hydraulic conductivity is governed by the size and shape of the pores, the effectiveness of the interconnection between pores, and the physical properties of the fluid. If the interconnecting pores are small in size, the volume of water passing from one pore to the other is restricted and the resulting hydraulic conductivity is quite low. Similarly, if the fluid is viscous due to dissolved materials, the hydraulic conductivity will be low.

The study area is constituted by deposits and lithologies such as aphanitic basalts, trachytes, ignimbrites, tuffs, rhyolites, pumices, obsidians, alluvial and lacustirne deposits. The result of these complex geological materials gives rise to different types of aquifers. Thus, these different geologic materials have different hydraulic conductivities.

Complex lithology and tectonic activities make the observed hydraulic conductivity of the area extremely varying from place to place within the basin; in consequence the large variation in yields, even within nearby area and wells very close to each other. For instance, as the pile foundation and water well drilling P.L.C , recently drilled neighbouring boreholes of “Dale shafina(Manche)” and “Aleta wondo Shiko” have 0.85m/day and 38.6m/day hydraulic conductivities respectively.

As shown in the map below, which is produced based on the information of pumping test data of different boreholes distributed within and around the study area. The area has different hydraulic conductivity zones. Slightly weathered and Aphanitic basalts of the highland; and volcanic ash and tuff deposits of the rift floor, both have low hydraulic conductivity values, which are in the order of about 0.06m/day to 0.3m/day.

The rift floor and areas closer to the escarpment are mainly covered by ignimbrites, which are highly affected by tectonic activities, according to the available data, relatively high hydraulic conductivity which ranges between 0.5m/day to 38.6m/day exists in Gidabo Basin. It then, could be said that, for such a hydrogeologic environment, secondary permeabilities due to faulting and fracturing play an important role than weathering. However, in a general sense, hydraulic conductivity of the study area is observed increasing from highland to the rift floor.

See the annex for a few boreholes' hydraulic parameters, collected from well completion reports.

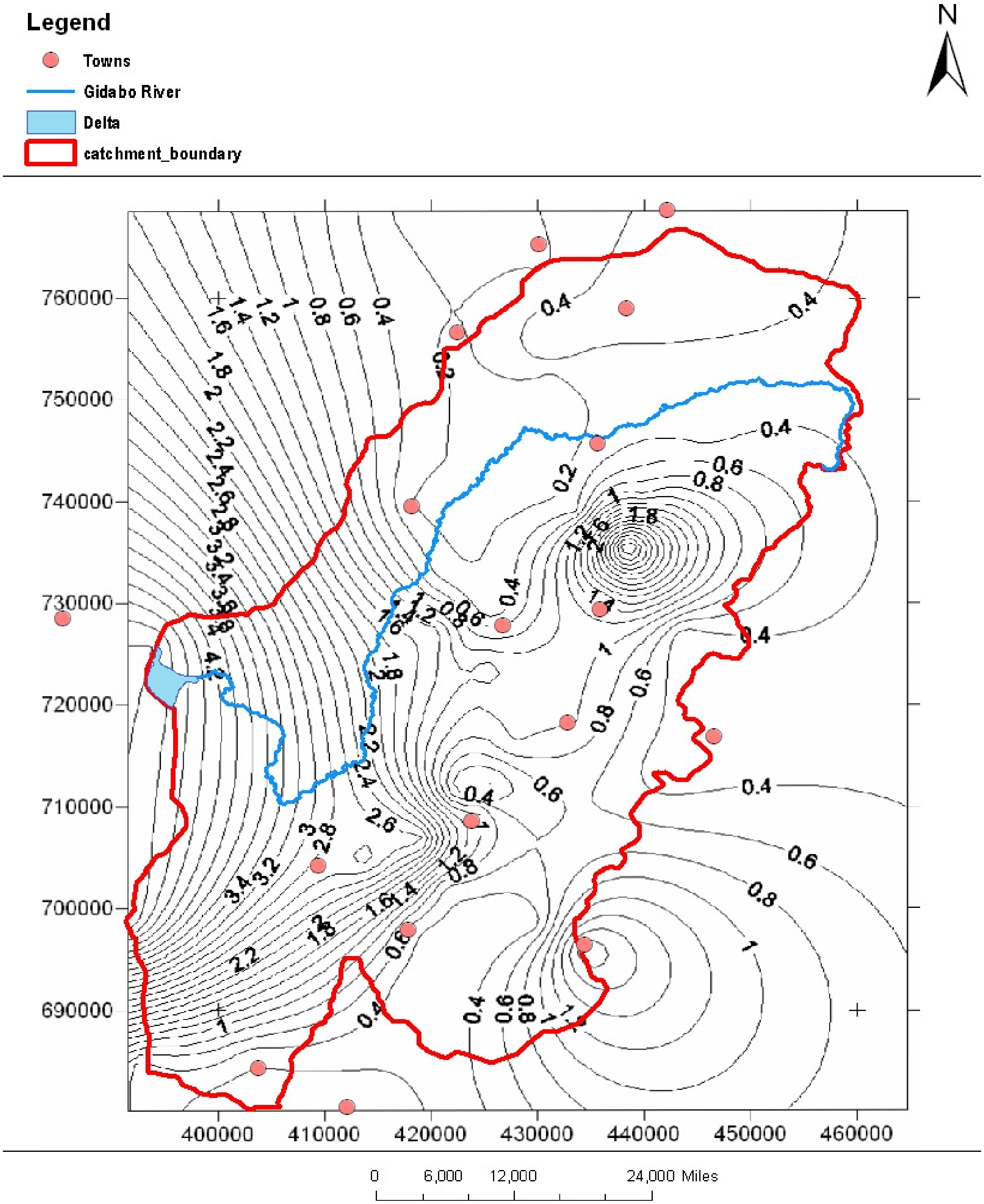


Fig.5.15 Hydraulic conductivity contour map. Note that hydraulic conductivity generally increases from highland area to the lowland area, near to the Gidabo Delta at the shore of Lake Abaya.

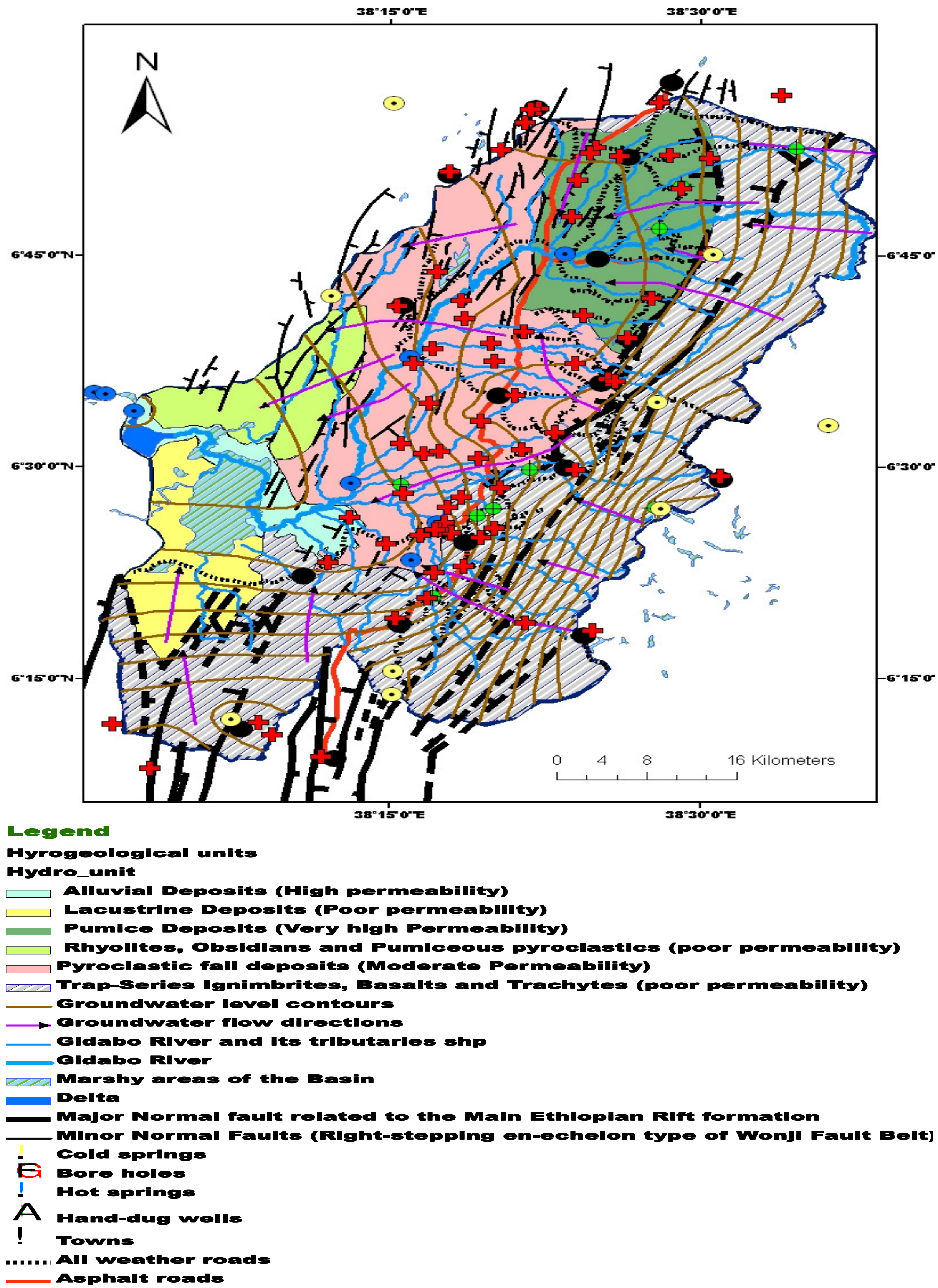


Fig.5.16. Hydrogeological map of the Gidabo River Catchment.

CHAPTER SIX

6. HYDROGEOCHEMISTRY

6.1 Introduction

Hydrochemical and isotopic data are useful in identifying sources of recharge to groundwater systems and in tracing groundwater flow. Differences in chemical and isotopic composition can be used to trace the infiltration of surface water, recognize leakage between aquifers, define areas of sea water intrusion, and investigate recharge rates through deep unsaturated zones. The composition of water held within groundwater reservoir reflects the composition of soil water percolating to the water table and further water-rock interactions occurring within the groundwater body. In more detail, we may define the primary controls on the solute content of groundwater as the original chemical composition of the water entering the zone of saturation; the distribution, solubility, exchange capacity, and exchange selectivity of the minerals in the strata; the porosity and permeability of the rocks; and the flow path of the groundwater. The thermodynamics and kinematic considerations are clearly also important, although the long residence times that are generally involved mean that groundwater has a greater opportunity to achieve equilibrium with the surrounding rock (John Wiley & Sons, 1980). Cation-anion association can also be used to identify solute origin and trace movement through groundwater systems.

Hydrochemistry can also assist in understanding the evolution of water quality, to examine natural base line conditions against which human impacts can be recognized and to take a look at some ways in which the protection and management of groundwater resources can be achieved. Some information on key minor and trace elements (Fe, Mn and F, for example) is also a requirement for understanding the geochemical environment of water, as well as, its potability.

6.2 Water sampling sites and methods.

Examination of the different sources of water in the field is an important part of hydrogeological studies. Certain properties of water such as pH, Eh, EC, TDS and T are so closely related to the environment of the water that they are likely to be altered by sampling and storage, and a meaning full value can be obtained only in the field.

Accordingly, totally 17 samples all from recharging, discharging areas of the Gidabo River and its adjacent catchments are collected. In addition to these primary samples other secondary data of 58 samples analyzed by regional water bureau laboratory have been also used in this work.

The method was involved the withdrawal of water from pumping boreholes sufficiently in order to insure that the sample represents the groundwater that feeds the well; accordingly, in-situ measurements of pH, Eh, EC, TDS and Temperature had been conducted (information obtained by consulting water samplers at regional water bureau).

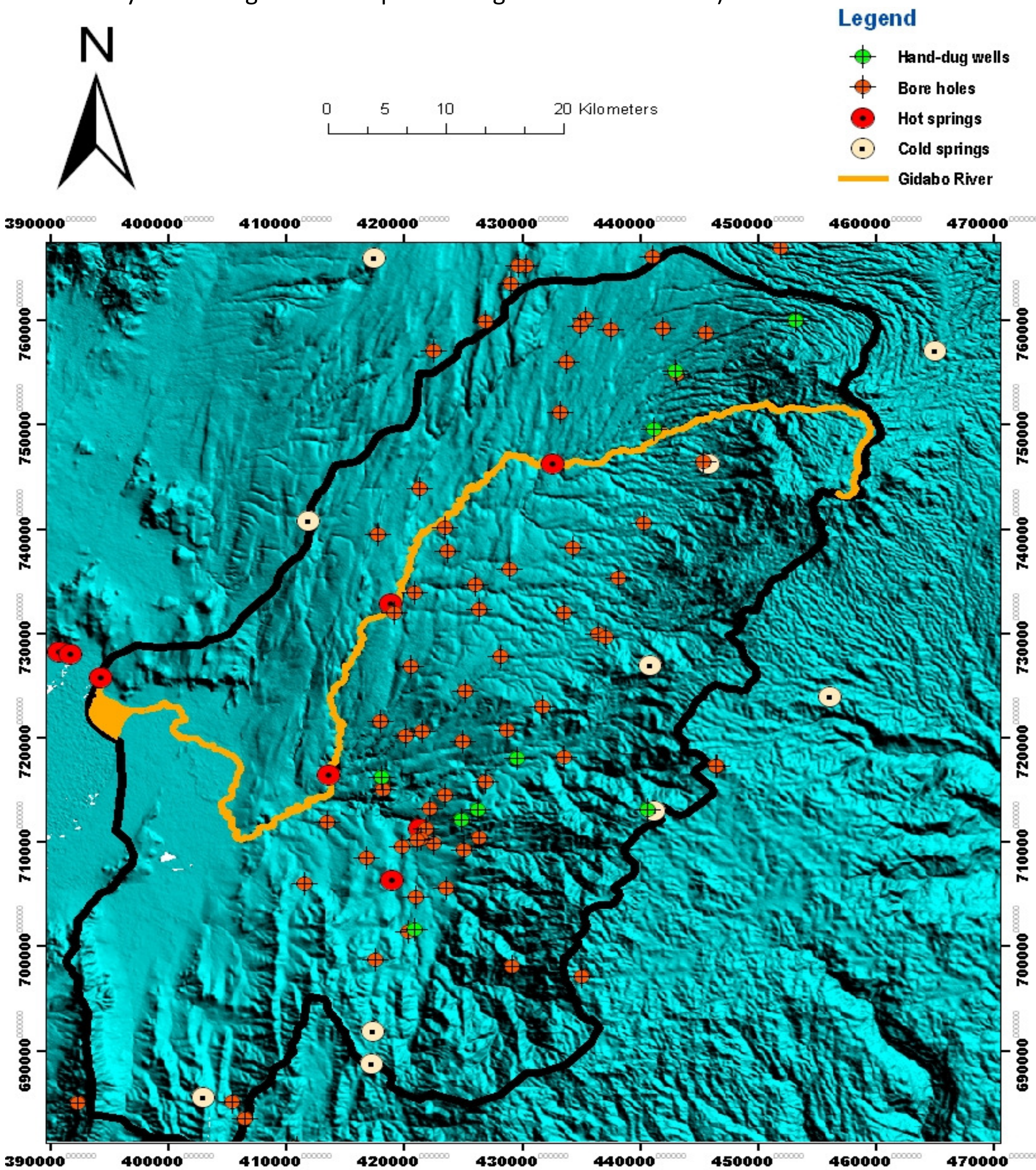


Fig.6.1. all water sources site distribution; which are taken for the purpose of Laboratory analysis.

6.3 Physical and chemical properties of the waters.

6.3. 1 In-situ measured properties of the waters.

In recent years it has been recognized that the quality of groundwater is of nearly equal importance to quantity (Todd 1959). Physical characteristics of water that can be altered after sampling due to the physical and chemical changes of water and storage conditions should be measured during the field survey. These physical (water quality) parameters measured in the field are Temperature, pH, EC, TDS and Eh.

6.3.1.1 Temperature

Temperature of groundwater is reported in ^{0}C and obviously must be measured immediately after collecting the sample (Todd, 1959).

Groundwater temperatures vary from a few degrees above freezing or boiling, and in geothermal wells steam it can reach up to 300^{0}C. This high range of temperatures is caused by a variety discharge mechanisms and, to a larger extent, by differences in the depth of circulation and local heat gradient values (Marcel Dekker.1997)

Groundwater colder than local annual surface temperature occurs at high altitudes and is caused mainly by snowmelt recharge. Groundwater with a temperature close to the local average annual surface temperature belongs to the shallow active water cycle, circulation being limited up to 100m, and rarely 200m depth. Groundwater that is more than 6^{0}C above local average annual surface temperature circulates to appreciable depths, deducible from the heat gradient (Marcel Dekker.1997). For instance, in Gidabo Basin, Danshe-Gambella warm (hot) spring has temperature of 33.4^{0}C; whereas average annual surface temperature in the locality is 20^{0}C. The difference is 13.4^{0}C which is greater than 6^{0}C, as a result the spring reports deep circulating groundwater.

Generally the temperature of groundwater, because they are more or less extensively circulates in the sub-surface, most of the time tends to assume a near constant value, which roughly corresponds to the mean yearly temperature of the same environment. But Seasonal temperature fluctuations are usually damped out below a depth of 10 to 20m (Bouwer, 1978).

Groundwater temperature increases with depth because of the hot interior of the earth. This increase is 1 to 5 ^{O}C (average about 2.9 ^{O}C) per 100-meter depth increase (Todd, 1980). There are also places where the temperature increases much faster with depth. These are called geothermal anomalies, and they are mostly associated with young mountain buildings, tectonic plate boundaries and volcanic activity. For the Ethiopian rift the increase of temperature with depth was found to be 1 ^{O}C per 6m-depth increase (Tamiru Alemayehu & Vernier, 1997).

In Gidabo River Catchment, the lowest temperature of groundwater attained is observed in Kosso spring near Hagere-Selam town and is 15.1^{0}C.

This temperature is very close to the ambient annual temperature of Hagere-Selam area which is 15.4^{0}C; whereas the highest groundwater temperature is observed in Odomike-Waleme hot spring near to Dilla town and is 68^{0}C. The water of Odomike-Waleme hot spring is boiling at 68^{0}C, this is probably because of latent heat of water and very high atmospheric pressure at the local altitude of the ground surface which is 1427m.a.s.l.

As we have seen above, temperature is the best and reliable tool to establish the depth of groundwater circulation. Groundwater is commonly temperature equilibrated with the aquifer rocks. Temperature measured in springs or wells reflects the temperature attained at depth, and therefore provides information on the depth of circulation. The calculation is straight foreword (Marcel Dekker.1997):

$$\text{Depth (m)} = \frac{T_{measured} - T_{surface}}{\Delta T/6m}$$

Where: $T_{measured}$ is the measured spring or well temperature, $T_{surface}$ is the local average annual surface temperature obtained from meteorological records and $\Delta T/6m$ is the local geothermal heat gradient in Ethiopian rift case.
Based on the above formula the depth of groundwater circulation for Odomike-Waleme hot spring which is situated near Dilla town can be calculated as follows:

$T_{surface}$ of spring area is that of Dilla town and is 17.6^{0}C.

$$\text{Depth (m)} = \frac{68^0C - 17.6^0C}{1^0C/6m}$$

Therefore, the depth of groundwater circulation for the emerged water of Odomike-Waleme is estimated to be 302.4meters from the ground surface.

Generally, in the Catchment under study, the temperature of groundwater increases as we move from Somalian high plateau area to the rift floor, the highest being situated at the Gidabo Delta hot spring area which is also the North-Eastern shore of Lake Abaya. Hot water boreholes are also existent in Dila area, (eg. Dila University Semera Campus BH #1 (2009) with GPS location of UTM= 0421388, 0710657 and Altitude of 1432m has reported water temperature of 70^{0}C). Relatively high temperature record of this borehole (60^{0}C), which is above local annual ambient temperature of Dilla area (17.6^{0}C), was due to encountering of the same fault line which was responsible for hot water of Odomike-Waleme and Rift valley resort hot springs in Dila town vicinity.

The high temperature in the geothermal field is observed to be responsible for the existence of very high TDS and EC of ground water systems in the area.

	Temperature in ^{0}C	
Water source	Minimum	Maximum
Cold springs	15.1	24
Hot springs	33.4	68
Hand-dug wells	15.2	19.5
Boreholes	15.4	60

Table.6.1.Minimum and maximum temperatures of groundwater in the Catchment.

6.3.1.2 Hydrogen ion activity (pH)

The pH of water indicates the effective concentration of hydrogen ions (H^+) in it (Marcel Dekker.1997)

Hydrogen ion activity (pH) is the measure of the water's alkalinity or acidity. It is the negative logarithm of the hydrogen ion concentration in moles per liter.

$pH = - \log[H^+]$

pH range is between 0 and 14. At room temperature (25^{0}C), pH=0 represents highly aggressive and acidic media, whereas pH=14 represents highly aggressive basic media. Both acidic and basic aggressive waters accelerate weathering process of rocks. On the other hand, pH= 7 value is for neutral water, pH below 7 is for acidic and pH above 7 for basic. Most groundwater has pH value ranging from around 6 to 8.5, but water having lower is not uncommon in thermal springs. River water whose pH in areas not influenced by pollution generally has a pH between 6.5 and 8.5.

The acidity of natural waters depends on the occurrence of several acidic compounds which may be dissolved and more or less dissociated in the water, as carbonic acid (H_2CO_3), sulphuric acid (H_2SO_4), nitric acid (HNO_3), Hydrochloric acid (HCl), etc. The alkalinity of natural waters depends on the total concentration of CO_3^{-2}, HCO_3^-, alkaline and alkaline earth hydrates, which are present in the water sample. Weak acids (CO_3, HCO_3, S) combined with the alkalies (Na and K) and alkali-earth metals (Ca and Mg) give primary and secondary alkalinity respectively. Alkalinity measurements are commonly performed by means of titration of the water sample with standard solutions using peculiar indicators.

Many chemical reactions are controlled by pH and biological activities usually restricted to a fairly narrow pH range of 5 - 8. Highly acidic or alkaline waters are undesirable because of corrosion problems and possible difficulties in treatment. The pH of natural waters is usually governed by the CO_2-HCO_3-CO_3 equilibria and lies between 6 and 8 (Tenalem Ayenew, 1998), which suggests that HCO_3 type water is very common in a natural environment.

Groundwater's pH values in the Gidabo River Basin, measured in the field, lies in the range of 6.15 to 8.4. The lowest pH=6.15, is for the hand-dug well situated near to Hagere-Selam (at Abera doda town) and the highest pH= 8.4, is observed at Teferi-Kella town Old bore hole, situated near to Bonkoka river bridge. Generally, the pH values of each of the groundwater sources is observed, increasing from the somalian high plateau area (Hagere Selam) in the East to rift floor area (Shore of Lake Abaya) in the west, i.e. slightly acidic in the highland area and slightly basic in the lowlands.

Near the shore of Lake Abaya the pH value of groundwater is very high i.e basic water; these is due to alkaline (sodic) plain at the North-Eastern shore of Lake Abaya which is comprised of recent lacustrine deposits.

	pH	
Water source	Minimum	Maximum
Cold springs	6.45	7.12
Hot springs	6.8	7.21
Hand-dug wells	6.15	7.5
Boreholes	7.4	8.4

Table.6.2. Minimum and maximum pH of groundwaters in the Catchment.

6.3.1.3 Electrical Conductivity (EC)

Electrical conductivity of water is its ability to conduct electric current at a specified temperature and it is usually measured in micromhos per centimeter or micro semens per centimeter (μS/cm) (Weast, 1968).

The values of EC increase with temperature, between 20^0C and 30^0C, in this range of temperature an increase in 1^0C, increases with the EC by two percent on the average (Hem, 1992).

The American Society for Testing and Material (1964, p 383) defined electrical conductivity of water as "the reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube of aqueous solutions at a specified temperature".

Pure liquid water has a very low electrical conductivity which is a few hundredths of μS/cm at 25^0C. This value has only theoretical significance, because it is very difficult to obtain pure natural water.

The presence of charged ionic species in water makes the water conductive. As ion concentration in water increases its electrical conductivity will also increase; therefore, the electrical conductivity measurement provides an indication of ion concentration.

However, generally speaking the EC value will be high if there is high residence time, when the permeability is low, in the flow direction of both surface and ground water; since the rock-water interaction will be high, the dissolution will be also high.

The highest field measured electrical conductivity of groundwater in Gidabo Basin is observed at Odomike-Waleme hot spring located near Dilla town and is 3120µs/cm and the lowest is observed at Kosso cold spring near Hagere Selam (Abera Doda town) which is 64µs/cm. Under the Sodic (alkaline) plain area, near the shore of Lake Abaya, groundwater electrical conductivity is expected to be much higher than that of Odomike-Waleme hot spring, due to high evaporation which leads to high concentration of ions both in surface and groundwaters.

Electrical conductivity values of groundwaters in Gidabo Basin considerably vary spatially, temporarily and with different sources of water. In the case of temporal variation we can see the difference by comparing the seasonal variation of EC values within different water bodies (see the table below), from these, it can be seen that generally the EC value increases in the dry season as compared to the wet season due to less and more dilution effects respectively.

	EC in µs/cm	
Water source	Wet season	Dry season
Cold springs	53.4	72
Hot springs	279.1	286
Hand-dug wells	173.5	191.2
Boreholes	347.2	359

Table.6.3. Seasonal variations of EC within different groundwater bodies, in the Catchment.

As we see, variation of electrical conductivity in hot springs and deep borehole waters, it is not that much considerable this is probably due to constant temperature of deep circulating groundwater.

	EC in µs/cm	
Water source	Minimum	Maximum
Cold springs	64	176
Hot springs	290	3120
Hand-dug wells	198	240
Boreholes	362	842

Table.6.4. Minimum and maximum EC of different groundwater bodies, in the Catchment.

Generally speaking, the EC values of each of the groundwater sources is observed, increasing gradually from the somalian high plateau area (Hagere Selam) in the East to rift floor area (Shore of Lake Abaya) in the west, i.e. The water is less conductive in the highland area and more conductive in the lowlands.

6.3.1.4 Total Dissolved Solids (TDS)

Total Dissolved Solids include all solid materials in solution, whether ionized or not. As it is related to the sum of the concentrations of all ions, it is directly related to the electrical conductivity.

All natural surface waters and some groundwaters carry both dissolved and suspended particles. The amount of the latter present in groundwater before it is brought to the land surface generally is small. But, in river water the concentration of suspended material may be large, and at high stage of flow in many streams it generally exceeds the Total Dissolved Solids concentration (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Total dissolved solids (TDS) can be determined by evaporating a known volume of the water sample and weighing the residue. TDS can be estimated by summing the concentrations of the individual ions. This method does not account for any dissolved substances, for example, dissolved silica, SiO_2, may not be reported but contributes to TDS. One basic measure of water quality is the TDS, which is the total amount of solids, in milligrams per liter that remain when a water sample is evaporated to dryness.

The natural quality of groundwater varies substantially from place to place. It can range from Total Dissolved Solids contents of 100mg/l or less for some fresh groundwater to more than 100,000mg/l for some brine groundwater found in deep aquifers (Fetter, 1994).The total concentration of dissolved solids can be used for simple classification of water.

Class	TDS (mg/l)
Fresh	0-1000
Brackish	1,000-10,000
Saline	10,000-100,000
Brine	> 100,000

Table.6.5. General Classification of groundwater bodies (After Davis and DeWiest, 1966).

Whenever chemistry of water is not modified by soluble minerals like evaporite and gypsum; TDS generally increases from regions of higher rainfall and lower evapotranspiration to regions of lower rainfall and higher evapotranspiration. Accordingly, TDS in Gidabo Basin generally increases as the water moves from the Eastern Somalian high plateau (recharge) area to low elevation North-Eastern shore of Lake Abaya (discharge) area. The increment has entirely the same trend with that of EC. Thus, it can be suggested that shallow circulating groundwaters which are situated mostly in recharge areas are lower in dissolved solids than the waters that are circulating in deeper aquifers which posses higher dissolved solids (Freeze and Cherry, 1979).

Similar to Electrical Conductivity value, the highest Total Dissolved Solids value observed in the Gidabo Basin is at Odomike-Waleme hot spring and is 1870mg/l, whereas the lowest is in Kosso cold spring situated near Hagere Selam (Abera doda town) which is 38mg/l.

According to general water classification table above, Odomike-Waleme, Gidabo-Delta (TDS>1870mg/l) and Rift valley resort (TDS=1675mg/l) hot springs waters are all saline, whereas, that of Yirga Alem-Gidabo (TDS=174.2mg/l), Danshe-Gambella (TDS=224mg/l) and Rufo-Chancho-Tedicha (≥ 224mg/l) hot springs waters are all fresh. The salinity of former one is due to deep circulation of water and high rock-water interaction at the course of long groundwater flow (i.e. long residence time). In addition this area is intensively affected by tectonic activity like fractures and faults, which acts as conduits for groundwater flow and accelerates rock-water interactions.

	TDS (mg/l)	
Water source	Minimum	Maximum
Cold springs	38	250
Hot springs	174	1870
Hand-dug wells	119	126.2
Boreholes	217	422

Table.6.6. Minimum and maximum TDS of different groundwater bodies, in the Catchment.

6.3.1.5 Redox potentials (Rh)

Hem, (1989) defines redox potentials (Eh) as a numerical index of the intensity of oxidizing and reducing condition within the system, it can be positive or negative, where positive redox potential indicates that the system is oxidizing where as negative Eh indicate that the system is reducing. High Eh is generally the direct result of dissolved oxygen in the water.

The redox potential of groundwater decreases (negative) as the water moves along its flow paths. This tendency was first recognized by Germanov et al, (1958). As water from rain and snow enters the subsurface flow system, it initially has a high redox potential as a result of its exposure to atmospheric oxygen. The initial redox conditions reflect high concentrations of dissolved oxygen, with pE values close to 13, or, expressed as Eh, close to + 75mV (Freeze and Cherry, 1994), for aerobic (oxidizing) water; in the other extreme, there is anaerobic (anaerobic) water in which methane (CH_4) and CO_3 are produced by micro-organisms in expense of oxygen (Tamiru Alemayehu, 2004), for deep circulating water. Furthermore, as groundwater travels through the aquifer, its dissolved oxygen is chemically reduced due to its contact with reducing species which in turn brings low Eh to the water.

Therefore, the highest oxidation potentials are common in shallow circulating ground water of recharge areas and it is found to decrease with increasing groundwater flow length towards the discharge areas.

In the study area, the highest Known Eh value is measured at Gowadamo shallow borehole (Eh=+60mV), situated on the East of the gravel packed road between Aleta Wondo and Teferi-Kella; whereas the lowest is observed at Teferi-Kella old borehole (-60mV).

Unlike to other field measured water properties, Eh of groundwater in Gidabo Basin generally decreases as the water moves from the Eastern Somalian high plateau (recharge) area to low elevation North-Eastern shore of Lake Abaya (discharge) area. The reason for the decrease in Eh probably is deep circulation of groundwater through highly dissected Wonji Fault Belt with numerous faults, fractures and joints which serve as conduits for groundwater to easily circulate through and deprive of oxygen.

	Eh (mV)	
Water source	Maximum	Minimum
Cold springs	+46	+13
Hot springs	+19	+7
Hand-dug wells	+63	-9.2
Boreholes	+60	-61

Table.6.7. Minimum and maximum Eh of different groundwater bodies, in the Catchment.

6.3.2 Laboratory analyzed properties of the waters.

6.3.2.1 Classification of the waters based on Hardness.

Hardness is usually expressed in terms of calcium carbonate ($CaCO_3$); hardness of water may be divided into two types: carbonate and non-carbonate.

Carbonate hardness includes that portion of the calcium and magnesium that combines with bicarbonates and the small amount of carbonate present.

Non-carbonate hardness is the difference between total hardness and carbonate hardness. It is caused by those amounts of calcium and magnesium that combine normally with sulfate, chloride and nitrate ions, plus the slight hardness contributed by minor constituents such as iron.

Carbonate hardness can be removed by boiling but non-carbonate hardness cannot be removed. The way of removal of Carbonate hardness is by boiling is as the following chemical equation.

$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3(s) + CO2\ (g) + H_2O$

Increased temperature may force this reaction to the right by evolving CO_2 gas, and a white precipitate of calcium carbonate may form in boiling water having temporary hardness.

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

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

Where $[Ca^{2+}]$ and $[Mg^{2+}]$ are concentrations in mg/l.

Table.6.8. Classification of water based on hardness (After Hem, 1985).

Total hardness (in mg/l as $CaCO_3$)	Description
0-60	Soft
61-120	Moderately hard
121-180	Hard
> 180	Very hard

Water source	Hardness range in mg/l as $CaCo_3$	
	Minimum	Maximum
Cold springs	28	216
Hot springs	80	190
Hand-dug wells	50	80
Boreholes	70	210

Table.6.9. Maximum and Minimum total hardness as $CaCO_3$ of different groundwater bodies in Gidabo River basin.

In the study area, the highest Known groundwater hardness value is analyzed at Bocessa cold spring (Hardness as $CaCO_3$=216mg/l), situated on the West of the Asphalt road between Wonago and Yirga Chefe; whereas the lowest is observed at Garbicho Kila cold springs (Hardness as $CaCO_3$ = 28mg/l) located in the North side of the gravel packed road between Aleta Wondo and Hagere Selam. Therefore, Bocessa-Matarba cold spring water falls in the range of very hard water; whereas, Garbicho-Kila cold spring water is in soft water range. The reason for Bocessa cold spring water to be very hard may be due to dissolution of high Calcium (=144mg/l) and Magnesium (=72mg/l) from Trachy-Basalt and Basaltic rocks undifferentiated, in the SSW structural basaltic reliefs of the study area. Boreholes (Golocha-borehole) located nearly at the foot of these basaltic reliefs also reported high Calcium (=140mg/l) and Magnesium (=70mg/l) concentration in the groundwater.

Generally speaking, as the water flows from Somalian high plateau area to the rift floor, mainly to the North-Eastern shore of Lake Abaya, its hardness increases.

6.3.2.2 Presentation of laboratory analyzed water chemistry results

Tables of data are the most common forms in which the results of analysis of water chemistry are reported. The data may also be presented in graphical form. Over the years, a considerable number of techniques for graphical representation of analysis results have been proposed; some of these are useful principally for display purposes, i.e. to illustrate oral or written reports on water quality, to provide means for comparing the analysis with each other, or to emphasize differences and similarities. Graphical procedures do this much more effectively than numbers presented in tables (Hem, 1989).

Most of the graphical methods are designed to simultaneously represent the total dissolved solid concentration and the relative proportions of certain major ionic species (Hem, 989) and all the graphical methods use a limited number of parameters, usually the available data, unlike the statistical methods that can utilize all the parameters. Unlike tabular presentation of chemical data, graphs facilitate easy understanding, interpretation, comparison and classification of water samples.

Piper diagrams and water types

A trilinear diagrams developed from the work of Piper (1944) are frequently used to characterize the chemical composition of groundwater. The Piper diagrams assume that the water composition and may be designed by three Cation constituents, i.e. Ca^{+2} , Na^{+} + K^{+}, and Mg^{+2} , and three anion constituents, i.e. HCO_3^{-} , SO_4^{-2} , and Cl^{-}. The proportion of each cation constituent, expressed as a percentage of the total equivalents per million (epm) is plotted as a single point in the left hand triangular field and that of each anion in the right-hand triangular field. The central diamond field is used to show the overall chemical character of the groundwater by a third single point which lies at the intersection of the rays projected from the cation and anion plotting positions. Areas very near to the apex of triangles show the dominant water types, which are commonly referred to as hydrochemical facies (John Wiley and Sons Ltd, 1980).

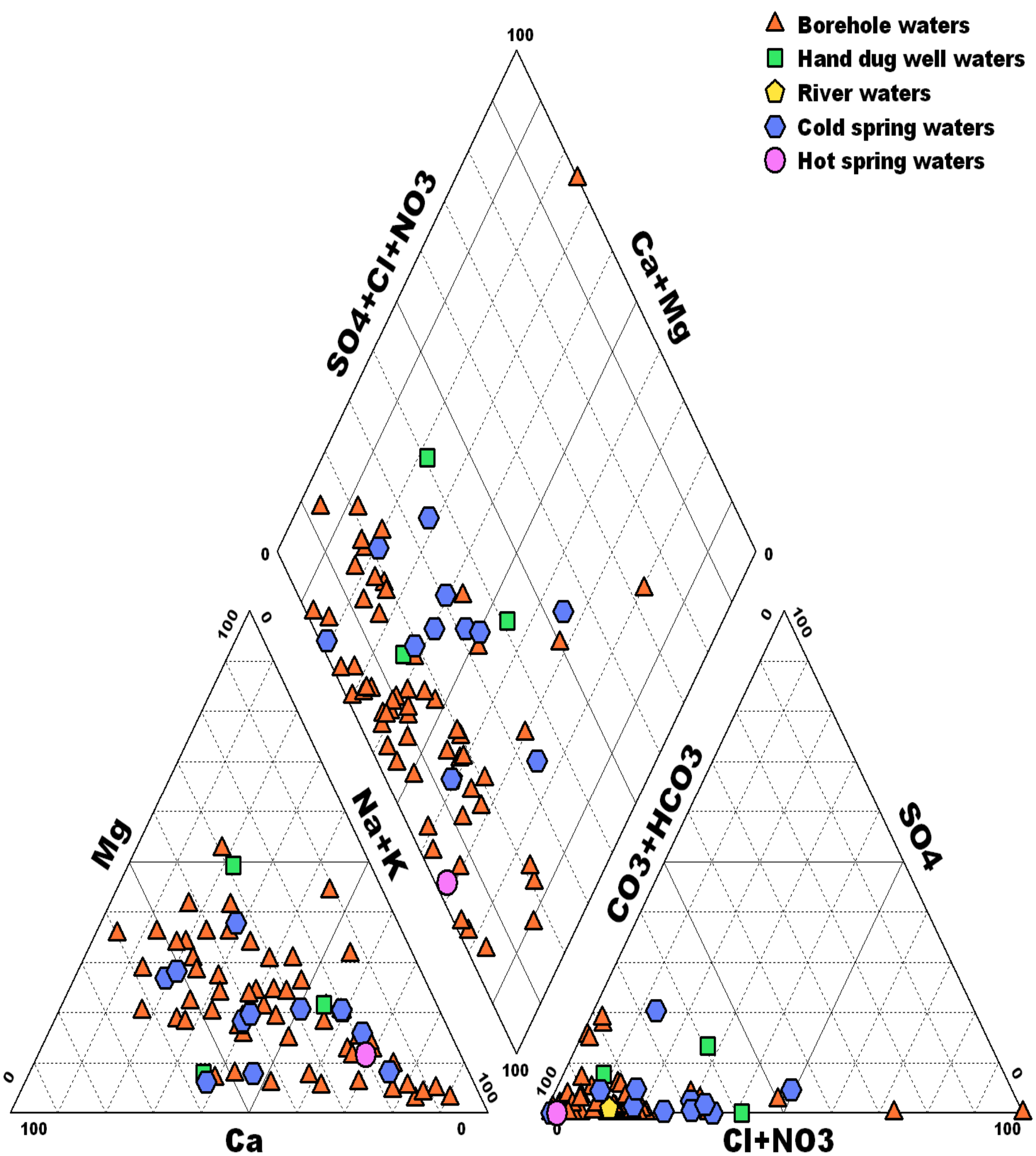


Fig.6.2. Piper plot of all water sources, in the Gidabo River Catchment.

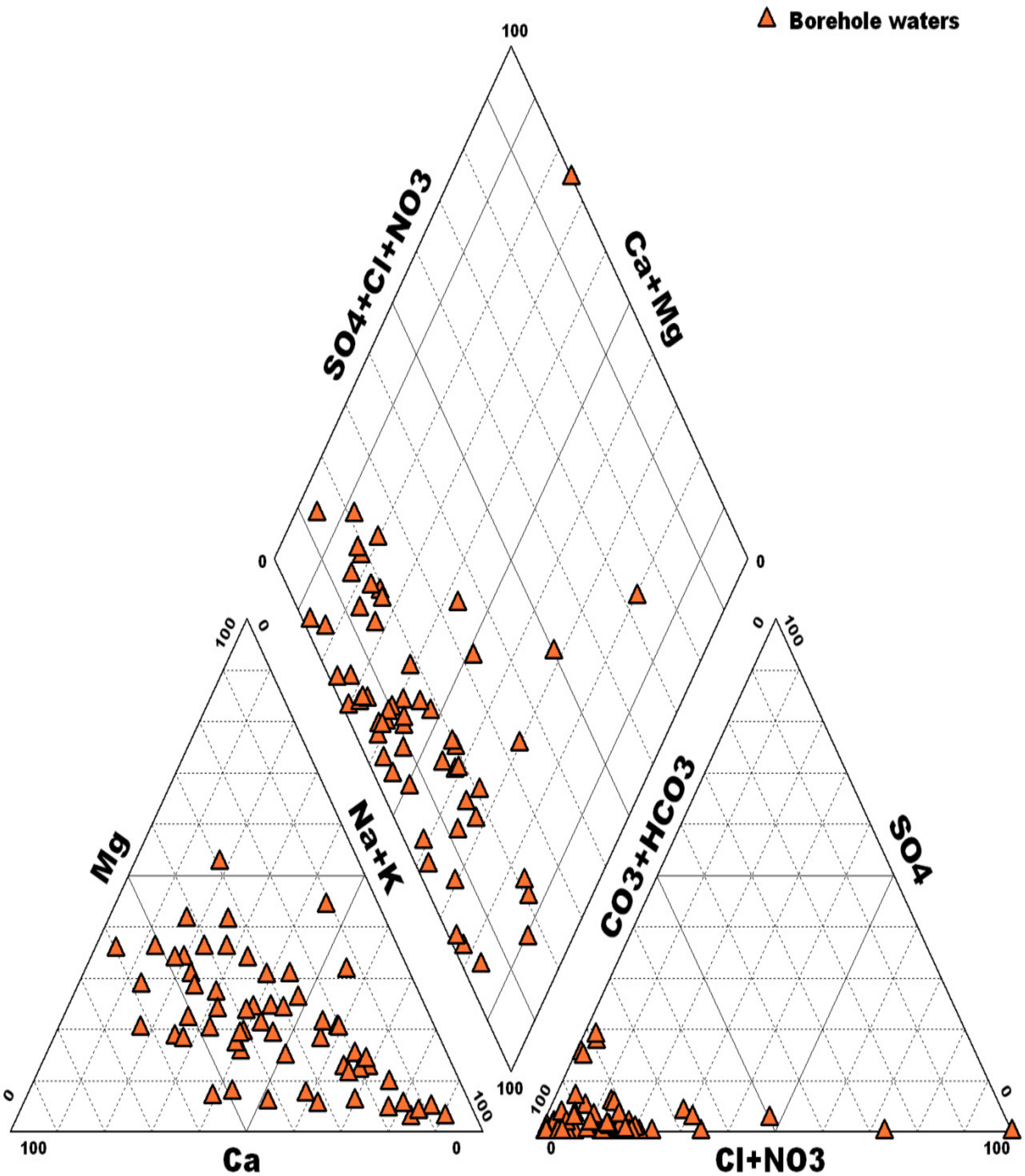


Fig.6.3. Piper plot of borehole waters, in the Gidabo River Catchment.

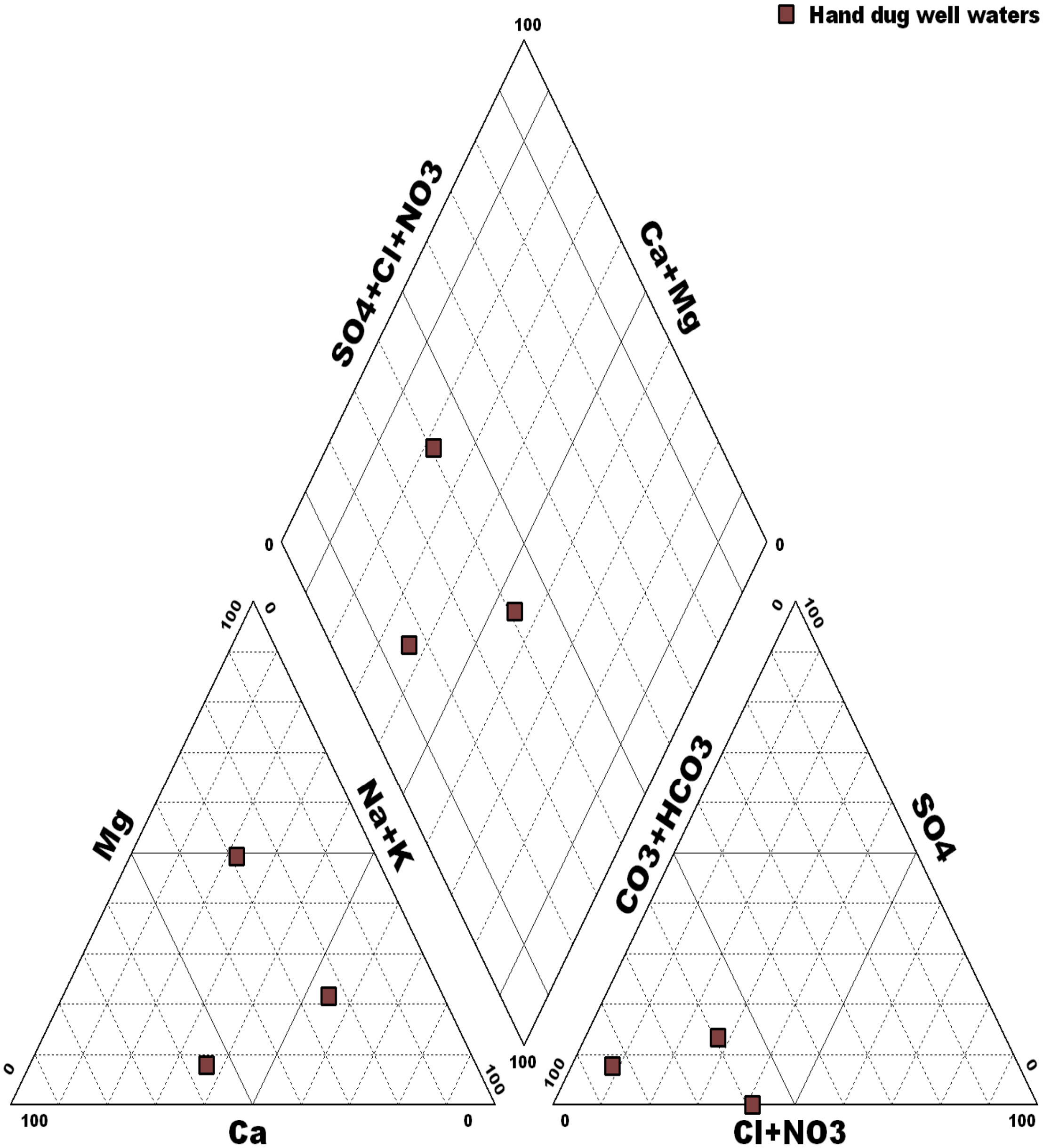


Fig.6.4. Piper plot of hand dug well waters, in the Gidabo River Catchment.

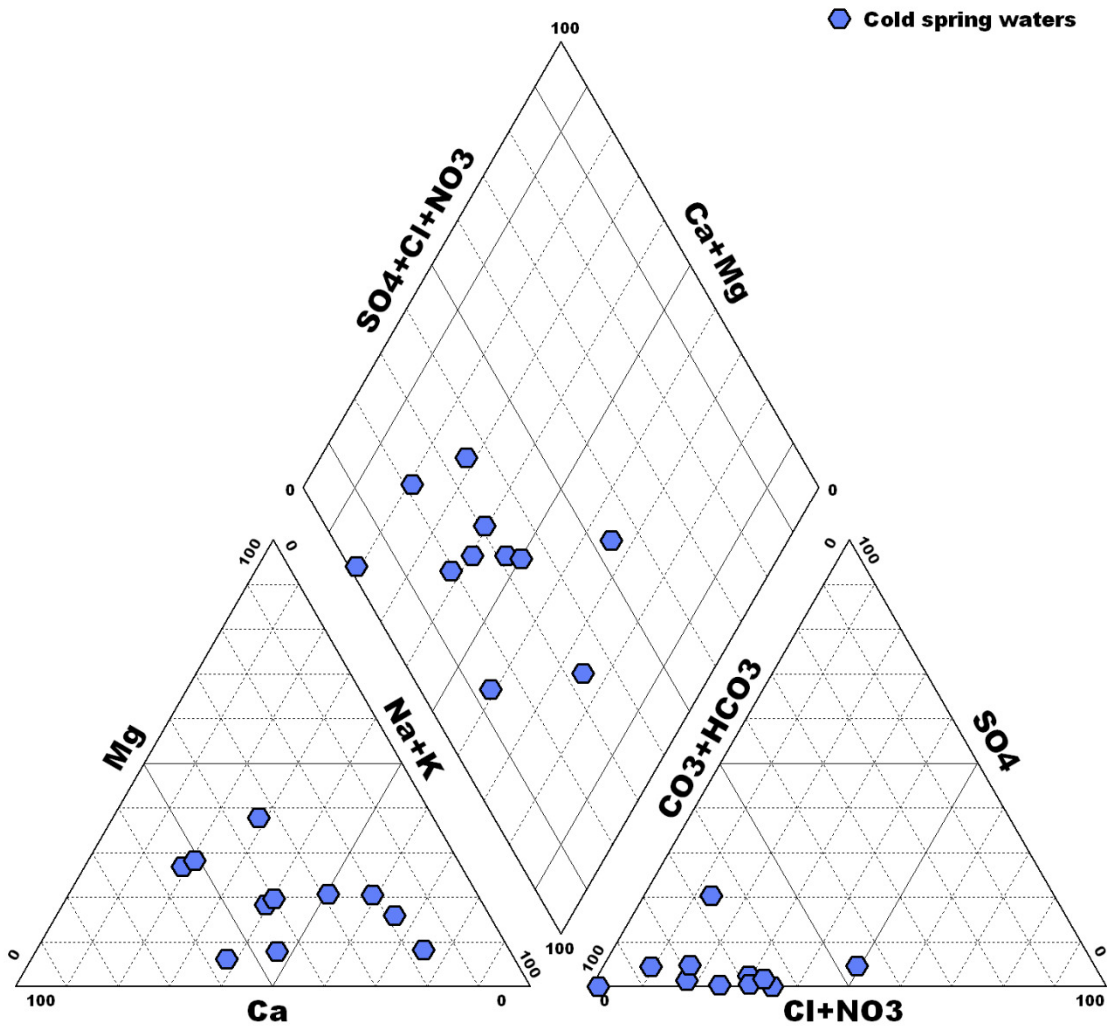


Fig.6.5. Piper plot of cold spring waters, in the Gidabo River Catchment.

As we see on the Piper plot of all waters above, all cations are concentrated very near to calcium and sodium bar lines and slightly go to the centre of the triangle. On the other hand, all anions are concentrated very near to bicarbonate bar line and slightly go to the centre of the triangle. In addition, a large number of samples have very high concentration of sodium followed by moderate concentration of that of calcium and magnesium; whereas, in the case of anions the principal ion is bicarbonate with lesser concentration of chloride, nitrate and sulphate. Accordingly, the waters are Na-HCO_3 and Ca-Mg-HCO_3 types.

From close examination of samples from highland, escarpment and rift floor areas, it has been recognized that in the rift floor wells sodium is the dominant cation; while, in highland wells calcium and magnesium are also important in addition to sodium.

The hydrochemical signature of cold springs is similar to that of many boreholes and hand dug wells, and different from that of the hot springs. In general, most of boreholes and cold spring water samples are Ca-Mg-HCO_3 type in the groundwater discharge areas and Na-HCO_3 type in the recharge areas.

6.3.3 Water quality problems in the study area.

6.3.3.1 Fluorides.

In nature fluoride ions come from chemical weathering product of igneous rocks, magmatic emissions, atmospheric dusts from continental sources and industrial pollution (Hem, 1970).

Artificially high concentration of fluoride is contained in waste water from the manufacturing of glass and steel, as well as from foundry operations. Organic fluorine is present in vegetables, fruits, and nuts (Tamiru Alemayehu, 2004).

There is no agreement among researchers as to how the high fluoride is introduced into the groundwater. According to Gerasimovskiy and Savinova (1969) the volcanic rocks of East Africa are richer in fluoride than similar rocks in other parts of the world. The most important sources are acidic volcanic rocks such as tuff, pumice and obsidians, along with emanation from geothermal systems (Tesfaye Chernet, 1982; Tesfaye Chernet et al., 2001).

The interaction of water with glassy rock is responsible for weathering of rock and leaching of F and Na in to the groundwater system. The high permeability of rocks due to weathering and tectonic activity resulting large water rock interaction makes the leaching process more effective in glassy rocks.

High fluoride groundwaters have sodium and bicarbonate as the dominant dissolved constituents, with relatively low calcium and magnesium concentration. Accordingly, it believed that the high concentrations of these ions are inter-related.

$CaCO_3\ (s) + CO_{2(aq)} + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$

High bicarbonate ion concentration in the above chemical equation, will favor backward reaction speed to be greater than the forward.

High bicarbonate ion concentration will decrease the calcium ion (Ca^{2+}) concentration due to accelerating calcite precipitation; the resulting low calcium ion concentration will make the more fluorite to dissolve and thus increasing the fluoride concentration in the water.
High concentration of fluoride in water causes problems of teeth motility (i.e. detrimental effects on teeth structure) and abnormalities in human skeleton.

Groundwater of 1mg/l and more is very common in the Gidabo River Basin. High fluoride concentration in the study area is recognized by its relatively higher concentration in the rift floor boreholes than the escarpment and the highland boreholes; in addition fluoride effects, such as teeth motility is recognized in the rift floor inhabitants than the highland ones.

Generally, fluoride concentration in groundwater of Gidabo River Basin is higher as the water moves from highland (recharge) area to the rift-floor (discharge) area.

Location (UTM)		Water sources	F^- (fluoride)=mg/l
X	Y		
425822	711671	Dila chichu Borehole No.2	1.05
425364	738069	Aleta sodo Borehole	1.3
418850	732980	Danshe-Gambela hot spring	1.21
433803	718366	Teferi-Kella Borehole	1.96?
429409	763401	Boricha Arke Well #1	2.38
424597	709592	Dila town Borehole	2.5
421663	710637	Dila university (Semera campaus Borehole#1	1.2
421117	709073	Dila Agri.Chol Borehole	1.3
		Loka Abaya Teme Borehole	1.3
421388	710657	Dila university (Semera campus)Borehole#3	7.2
422314	737052	Aleta Sodo BaltasuraBorehole	1.37
425277	737875	Aleta Sodo Jissa Borehole	1.25
423990	742131	Loka Abaya Benka Borehole	1.48
425364	738069	Jirmancho Borehole	1.5
422669	745541	Sala Kebado Dansanto Borehole	1.39
422647	745610	Sala Kebado Worku Borehole	1.2
		Dale Tula Borehole	1.75
		Kaliti Simita Borehole	1.17
423533	744647	Loka Abaya Chancho	1.01
419097	706697	Odomike Waleme hot spring	1.01
421535	711456	Rift valley resort (Chombe) hot spring	1.12
432371	746688	Yirga Alem Gidabo hot spring	1.43

Table.6.10. Groundwater sources possessing 1mg/l and greater fluoride concentration in the Gidabo River Basin.

Recommended fluoride concentration in domestic water supplies at a temperature range of 17^0C- 21^0C (temperature range of Dilla town area and its surrounding) is 1.8 mg/l, (Hem, 1985).

According to fluoride concentration range given above Boricha Arke Well #1 and Dillauniversity Semera Campus borehole #3 have excess fluoride concentration of 2.38mg/l and 7.2mg/l respectively; which shows unsuitable water for drinking purpose.

Fluoride can be removed from water by anion exchange, adsorption by calcium phosphate and magnesium hydroxide. Activated carbon will also reduce the fluoride content of drinking water. In addition reverse osmosis will remove 93%-95% of the fluoride (Tamiru Alemayehu, 2004).

6.3.3.2 Salinity.

Marshy area groundwater chemistry in the Gidabo River Basin is less known as there is no boreholes in the vicinity ; However, two shallow wells (hand pump fitted) situated in marshy (Ficha peasant association) area are used.

Sample taken from one of shallow wells is salty; its Electrical conductivity (EC) is very high which is about 3790µS/cm, likewise other parameters also show considerable excessive character compared to the normal ones, these are total dissolved solids (TDS=2723mg/l), total solids (TS=2786mg/l), turbidity, etc. Besides, groundwater is rich in Sodium (Na+=580mg/l), Bicarbonate (HCO3- =948.67), Sulphate (SO42- = 792.06mg/l), chloride (Cl-= 516.36mg/l) and it is Na-Ca-HCO3-SO4-Cl type water (*source: Gidabo irrigation project, Abenezer Kefeni, 2007).*

Boky-Anole plain area (Marshy area), which approximately covers 65km^2 (Raunet, 1977), located very near to the North-Eastern shore of Lake Abaya (Gidabo Delta area), is impregneated with sodium (Na) and potassium (K) which come from weathering of acidic silicic rocks (eg. ignimbrites) and evaporation. In the plain, the soils are alkalized sodic and salted in places (Na_2CO_3). Part of the plain is flooded during the rainy season, and the vegetation is then inexistent; once the water evaporates during dry season it leaves a smooth, flat area (no cracks) with whitish areas due to saline efflorescences. Local people collect the sodic deposits (“Amole chew”) of the plain for their livestock by scratching the surface *(*M. Raunet, 1977). In this plain area groundwater table is very close to the surface and liable to evaporation which accelerates additional deposition of alkaline materials. During rainy season, saline deposits will be dissolved by fresh water and easily percolates to the groundwater in turn making the water alkaline.

According to Abenezer Kefeni (2007), salinity of marshy area of Gidabo Basin is under sensitive range of SAR (Sodium Adsorption Ratio) which is 10.3 for irrigation of different types of crops; But within tolerance limits based on the types of crops.

6.3.3.3 Iron.

Iron is essential element in the metabolism of animals and plants. If present in water in excessive amounts, however, it forms red hydroxides precipitates that stain laundry and plumbing fixtures and, therefore, is an objectionable impurity in domestic and industrial water supplies. Recommended upper limit for iron in public water supplies is 0.3 mg/l (Hem, 1985).

Iron occurs naturally in groundwaters in three forms, Ferrous (II) Iron (clear water iron), Ferric (III) Iron (red water iron), and Heme Iron (organic iron).

Each can exist alone or in combination with one another. Ferrous iron, or clear water iron as it is sometimes called, is ferrous bicarbonate ($Fe_2 (HCO_3)$. The water is clear when drawn but it turns cloudy when it comes in contact with air (Tamiru Alemayehu, 2004).

The air oxidized the ferrous iron and converts it to ferric iron. Ferric iron, or ferric hydroxide ($Fe_3 (HCO_3)$, is visible in the water when drawn; hence the name "red water iron".

Heme iron is organically bound iron complexed with decomposed vegetation. These organics cause the water to have a weak tea or coffee color.

Certain types of bacteria use iron as an energy source. They oxidize iron from its ferrous state to its ferric state and deposit it in the slimy gelatinous material which surrounds them. These bacteria grow in stringy clumps and are found in most iron bearing formation waters.

In order to investigate the mineral composition of the red soil in upper Gidabo River Basin, Kedir yasin, (2002) collected three soil samples around Aleta Wondo town and analyzed in the SGS mineral service laboratory, Italy. The result shows the soil is enriched with Fe, according to Kedir, this may be due to the solubility of this element and downward percolation and deposition in the B-horizon of soil profiles. Thus acidic water coming in contact with these soils can dissolve the iron and enriches it in the water.

From the field measured parameters it can be seen that waters containing high iron concentrations are characterized by low pH and low Eh, which are conditions triggering the solubility of iron.

Based on the available secondary data of borehole water chemical analysis results and primary data of field investigation for this thesis work, iron concentration in the Gidabo River Catchment reaches its maximum in red soil covered areas (eg. Gajamo borehole in Yirga Alem woreda 2.87 mg/l); and its minimum at rift floor areas (eg. 0mg/l at Sala kebado borehole in Loka Abaya woreda).

Generally speaking, iron concentration in the Somalian high plateau area which is covered by dark brown clay loam soil is lower as compared to the rift escarpment area which is covered by red soil (Lateritic soil, the main source soil of Iron and Almunimum). The rift floor area which is in turn covered by grey silty clay loam soil also has very low Iron concentration.

Ferrous Iron must be converted into ferric iron through aeration process with oxidizing agent such as chlorine, before it can be removed by mechanical filtration. Ferric Iron (red water iron) can easily be removed by mechanical filtration process. Heme Iron can be also removed by oxidizing the water with chlorine followed by mechanical filtration process. Oxidizing agents such as chlorine will also kill iron bacteria if it exists (Tamiru Alemayehu, 2004).

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion.

In this paper it is attempted to analyze and give recommendations on groundwater resource potential zones of Gidabo River Catchment; based on geological, hydrometeorological, hydrogeological and hydrochmical data.

Data from National meteorological Agency, Water Resources Ministry, Primary field (in-situ) measurements associated with chemical analysis results of different groundwater sources from the Catchment and Secondary water chemistry data from Southern Nations, Nationalities and Peoples Regional State (SNNPRS) are inputs in the evaluation of different hydrogeological and hydrochemical behaviors of the Basin.

Gidabo River Catchment is mainly composed of volcanic rocks of Tertiary and Quaternary age. Five lithological units are identified and mapped. These include old aphanitic basalts and ignimbrites of the Somalian high plateau, highly fractured young basalts, rhyolites and pumice deposits of the rift floor, slightly to highly fractured young ignimbrites of the rift escarpment and rift floor, alluvial and lacustrine deposits.

The geological structures in the study area are extensional and include the normal faults oriented in the NNE-SSW direction (i.e. right stepping en-echelon type of the fault systems "Wonji Fault Belt"). The structures are frequent in the central and western part of the Gidabo River Catchment than the eastern part.

Climate of the study area ranges from semi arid in the rift floor to humid in the mountains of the escarpment and the Somalian high plateau. Average long-term aerial rainfall depth of the study area is estimated to be 1375mm/year; by using Theissen Polygon and Isohytal methods.

An attempt was made to evaluate the most important component of hydrologic cycle (i.e. evapotranspiration). Potential evapotranspiration was calculated using two methods; (i.e. Thornthwaite (1948) and Penman). To evaluate the PET for the Catchment, the basin has been divided into three sub-catchments; Highland, Escarpment and Rift floor. The sub-division is based on climatic differences among the sub-catchments.

In this thesis-research work the PET values obtained by Thornthwaite method for the Highland, the Escarpment and the Rift floor are estimated to be 689.85mm, 786.8mm, 1307mm respectively.

The PET value of the whole Catchment estimated by Thornthwaite method could be obtained by averaging the PET values of the three sub-catchments together and is

927.87mm. Mean annual PET of the Rift floor calculated by using Modified Penman method is 1301mm.

For the estimation of water balance within the basin, AET was calculated using Turc and Soil water balance method. The AET values obtained by Turc method for Highland, Escarpment and Rift floor is 665mm, 950mm, 1456mm respectively. The AET value of the whole Catchment estimated by Turc method is obtained by averaging the AET values of the three sub-catchments together and is 1024mm.

Soil water balance method has been used to estimate the AET based on various soil textures and land use-land cover of the study area. Accordingly, in this work the AET values obtained by soil-water balance method for the Highland, the Escarpment and the Rift floor are estimated to be 688.9mm, 803.9mm, 1063.6mm respectively. The AET value of the whole Catchment estimated by this method is obtained by averaging the AET values of the three sub-catchments together and is 852.1mm.

Actual evapotranspiration computed from the two methods is averaged to estimate annual groundwater recharge.

The surface water and groundwater runoff has been computed by base flow separation of 27 years long run annual Gidabo River discharge. The total runoff of the catchment is extrapolated from flow values measured at three gauging sites located within the Gidabo River Catchment. These gauging sites are near Abosto, Aleta-Wondo and Dilla for Upper Gidabo, Kolla and Bedessa rivers respectively. The extrapolation involves scaling up of flows of the Catchment on the basis of area-ratios ($A_G/Q_G = A_U/Q_U$).

Separating the surface runoff and base flow has been made with the aid of Time-Plot spread sheet computer software.The result obtained from the spread sheet program (Time plot) reasonably separates the surface runoff and base flow by considering the topographic characteristics of the basin.

Conventional water balance method has been used to compute the total groundwater recharge of the basin and recharge value of 353mm/year is obtained. The value estimated by this method is taken as optimum and reasonable values of groundwater recharge of the Catchment, because the method considers many variables as Precipitation, Surface Run off and AET; AET in turn considers many variables to be calculated as has been seen in Soil water balance.

Hydrogeological mapping was done by classifying the volcanic rocks in the area based on surface geology, borehole lithologic log and pumping test data. Accordingly five hydrogeological units are identified and mapped. These include old basalts and ignimbrites of the Somalian high plateau, highly fractured young basalts, rhyolites and pumice deposits of the rift floor, slightly to highly fractured young ignimbrites of the rift escarpment and rift floor, alluvial deposits and lacustrine deposits.

The study area is classified into different hydraulic conductivity zones. The basalts of the mountain have low hydraulic conductivity values which are in the order of 0.06m/day to 0.3m/day. The rift proper and areas closer to the escarpment are principally covered by pyroclastic rocks (mostly ignimbrites) which is highly affected by tectonic activity has relatively high hydraulic conductivity ranging between 0.5m/day to 38m/day. In general, the hydraulic conductivity increases from highland to the rift proper (i.e. east to west of the Gidabo River Catchment).

The regional flow direction of the groundwater system is generally westward and local flow systems are observed in the recharging and central zones of the basin; based on groundwater level contour generation and then constructing groundwater flow lines perpendicular to the contours generated. However both the groundwater and surface water systems are highly controlled by NNE-SSW trending right stepping en-echelon fault of “Wonji Fault Belt”.

A plot of contours of the hydraulic heads and the stream networks reveal that Gidabo River and its major tributaries gain water from their eastern part and loose in their western.

The springs in the study area are generally of two types: gravity and non-gravity. The gravity springs are of contact or depression type. Whereas the non-gravity (hot) springs are located along fault zones and concentrated in the western part (discharge zone) of the Gidabo River Catchment.

The heat source for the thermal springs (non gravity) is suggested to be the result of deep circulation of ground water (geothermal gradient) from the escarpment towards to the rift proper with high geothermal gradient.

The high value of TDS for hot springs while others are low at the same elevation can be partly attributed to the influence of geothermal heating, deep circulation and to rock water interactions due to long residence time.

Graphical presentation (i.e. Piper (1944)) is used in order to facilitate the interpretation and analyses of the chemical data. The piper plot shows that most boreholes and spring water samples are Ca-Mg-HCO_3 type in the discharge area and Na-HCO_3 type towards the recharge areas.

The surface and shallow groundwater systems in the Gidabo River Catchment are characterized by high iron concentrations. The source is suggested to be the red soils that cover the area. According to Kedir Yasin (2002), the concentration of iron in the water is greater in the wet season than the dry season due to leaching effect.
High concentration of fluorine within the study area is noticed in the western part (discharge area) in geothermal borehole and hot springs.

7.2 Recommendations.

Based on some of the findings of the study, the following recommendations are forwarded for future consideration.

- ✓ To calculate the water balance components more efficiently meteorological stations have to be installed in the highlands and upgrading of the existing stations has to be done.
- ✓ Streams gauging instruments should be installed at the mouth of the Gidabo River that greatly help reduce the uncertainties arising from projection of flow rates from analogue catchments.
- ✓ Even if, there are many boreholes drilled in the area most of them lack lithological and drilling logs and proper pumping test results. Thus the Southern Region Water, Mines and Energy Resource Development Bureau has to make a close follow up to have a complete well drilling and pumping test reports for the further schemes.
- ✓ The source of iron in some part of the study area requires detail investigation.
- ✓ To determine the depth and thickness of the water bearing formation and to quantify the ground water resource of the area, geophysical investigation especially Vertical Electrical Sounding (VSE) is recommended at selected sites.
- ✓ Isotopic survey of hot spring should be carried out to determine the origin of deep waters to enhance the degree of uncertainty.
- ✓ The area near to Yirga Alem town is high groundwater potential area with fresh water which has exploitable groundwater source for irrigation of downstream part of Gidabo River.
- ✓ Hot springs of Chancho-Tedicha in Chuko Woreda and Odomike Waleme in Abaya Woreda are not developed, hence should be developed by investors.

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ANNEXES.

Annex.1 Estimation of available water in the rooting depth for the Highland area of the Catchment.

S.No	Soil Type	Areal Prop. Of the soil (%)	Available Water in the soil in 1m column (mm/m)	Land Use - Land Cover Type	Land Use - Land Cover Percentage	Rooting Depth (m)	Available Water at rooting depth (mm)	Available water w.r.t land use in (mm)	Available water in the root zone for the soil (mm)	Available water for the soil w.r.t areal proportion	Total available water at rooting depth for the highland sub-catchment (mm)
1	2	3	4	5	6	7	8 = 4 * 7	9 = 8 * 6	10 = ∑ 9	11 = 10 * 3	12 = ∑ 11
i	Clay loam	100%	300	Cultivated for cereals maize, barley, wheat, peas, beans sorgum and the like.	40	0.5	150	60	240	240	240
				Cultivated for *enset*	60	1	300	180			

Annex.2 Estimation of available water in the rooting depth for escarpment

No.	Soil Type	Areal Prop. Of the soil (%)	Available Water (mm/m)	Land Use - Land Cover Type	Land Use - Land Cover Percentage	Rooting Depth (m)	Available Water at rooting depth (mm)	Available water w.r.t land use (mm)	Available water in the root zone for the soil (mm)	Available water for the soil w.r.t areal proportion (mm)	Total available water at rooting depth for the escarpment sub-catchment (mm)
1	2	3	4	5	6	7	8 = 4 * 7	9 = 8 * 6	10 = ∑ 9	11 = 10 * 3	12 = ∑ 11
i	Clay loam	62	300	Cultivated for coffee and *enset*	60	1	300	180	240	149	216
				Maize, sorghum	40	0.5	150	60			
ii	Silty loam	38	200	Cultivated for coffee and *enset*	75	1	200	150	175	67	
				Maize and sorghum	25	0.5	100	25			

Annex.3 Estimation of available water in the rooting depth for the Rift floor.

No.	Soil Type	Areal Prop. (%)	Available Water (mm/m)	Land Use - Land Cover: Type	Land Use - Land Cover: Percentage	Rooting Depth (m)	Available Water at rooting depth (mm)	Available water w.r.t land use in (mm)	Available water in the root zone for the soil (mm)	Available water for the soil w.r.t areal proportion (mm)	Total available water at rooting depth for the Rift floor sub-catchment (mm)
1	2	3	4	5	6	7	8 = 4 * 7	9 = 8 * 6	10 = ∑ 9	11 = 10 * 3	12 = ∑ 11
i	Clay loam	41%	300	Coffee and Inset(false banana)	60	1	300	180	240	98.4	170.5
				Open (savanna grassland) and maize	40	0.5	150	60			
ii	Sandy loam	44%	150	Coffee and "Inset"	25	1	150	37.5	127.5	56.1	
				Grassland(Savannah)	30	0.5	75	22.5			
				Shrubs and bushes	45	1	150	67.5			
iii	Rock surface (Gravely sand)	16%	100	Shrubs and bushes	100	1	100	100	100	16	

Annex.4

A)Boreholes

	Zone	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Elevation a.s.l. (m)	Depth(m)	S.W.L.(m)	G.W.L(m)
1	Sidama	AletaChuko	Rufo Debeka	420400	723500	1640	85.5	55.4	1585
2	Sidama	AletaChuko	Rufo Chancho	423164	725273	1858	84	41.65	1816
3	Gedeo	wonago	Dako	411694	693793	1957	75	55	1902
4	Gedeo	wonago	Tumticha chirecha#1	420365	699739	1616	72	31	1585
5	Sidama	AletaChuko	Synteria	432145	723778	1962	151	11.7	1950.3
6	Sidama	AletaChuko	Futahe	429832	721112	1940	111	40	1900
7	Sidama	AletaChuko	Gembela Gurara	423232	720691	1673	80	20	1653
8	Sidama	AletaChuko	Tesso Village	424000	72000	1685	70	30.6	1654
9	Sidama	AletaChuko	Rufo Waeno	424176	726407	1870	93	46.1	1824
10	Sidama	AletaChuko	Rufo Chancho	423164	725273	1858	84	41.65	1816
11	Sidama	AletaChuko	Gambela-Kilto Lamala	422104	719204	1600	91	80	1520
12	Sidama	Dara	Teferi-Kella	433803	718366	1858	91	10	1848
13	Sidama	Hgereselam	Hagere Selam	446574	716715	2759	150	29.06	2730
14	Sidama	Aletawondo	A/Wondo town high school	436215	730654	1904	154	72	1841
15	Sidama	Aletawondo	A/Wondo town Gidibo BH	436047	73200	1886	145.5	57.3	1828.7
16	Sidama	Aletawondo	A/Wondo Chenese old No.5	433220	727800	1880	79.89	15.81	1864
17	Sidama	Loka Abaya	Aleta Sodo	425364	738069	1764	70	50	1714
18	Gedeo	wonago	Wonago town	418196	698026	1739	100	47	1692
19	Gedeo	Bule	Bule town	434316	695956	2801	70	23.6	2777.4
20	Gedeo	Dilla Zuria	Chichu Well #2	425822	711671	1741	115	14	1727
21	Gedeo	Dilla Zuria	Chichu Well #1	425821	711672	1741	103	5	1736
22	Gedeo	Dilla	Dilla TW-1 Near Lega Dara	424597	709592	1549	74	5	1544
23	Gedeo	Dilla	Dilla Donbsco Salesian Frs	422600	709500	1520	125	64	1456
24	Gedeo	Dilla	Dilla Donbsco Salesian Srs	422600	709500	1518	125	64.65	1453.35
25	Borena	Abaya	Guangua	421303	702296	1560	160	31.45	1528.55
26	Borena	Abaya	Michicha Gelo	392581	684598	2053	100	42	2008
27	Borena	Abaya	Semero-Gambela	413630	704835	1450	138	38	1412
28	Borena	Abaya	Gololcha	411743	706449	1388	120	38	1350

G.W.L. = ground water level below ground surface S.W.L. Static water level

Boreholes Continued

				(UTM)		Elevation			
	Zone	Woreda	Site Name/Locality	X	Y	a.s.l(metres)	Depth(m)	S.W.L(m)	G.W.L(m)
29	Sidama	Dale	Shafina(Manche)	439985	740659	1840	175	30.52	1809.5
30	Sidama	Dara	Mechisho town BH	422257	711782	1488	172.5	30	1458
31	Sidama	Dara	Kebado new BH,2009	427622	716074	1778	72	35.2	1742.8
32	Sidama	Dara	Kumato new BH,2009	423987	715920	1612	92	21	1591
33	Sidama	Dara	Odolla new BH,2009	424470	710141	1565	72	22	1543
34	Sidama	AletaChuko	Chuko #2 *	425635	729575	1840	108	30	1810
35	Sidama	AletaChuko	Chuko Gambella new,2009	425209	723579	1799	162	41.03	1757.97
36	Sidama	AletaChuko	Loko Haytale	422391	731463	1718	84	49.7	1668.3
37	Sidama	AletaChuko	Miridicha	420422	727153	1662	183	148.8	1513.2
38	Sidama	AletaChuko	Gunde	420635	732564	1679	93	35	1644
39	Sidama	AletaWondo	Shiko	438425	735391	1900	122	66.97	1833.03
40	Sidama	AletaWondo	Aleta Wondo #1*	434769	729514	1890	90	48	1842
41	Sidama	Dale	Mesenkela	431250	752170	1800	121	10	1790
42	Sidama	Dale	Wicho	433643	739043	1846	214	114	1732
43	Sidama	LokaAbaya	Jirmancho	421587	744105	1622	165	17	1605
44	Sidama	LokaAbaya	Sodo Simita	424407	738825	1723	153	43	1680
45	Sidama	Shebedino	Gobo Hebisha	445875	760540	2014	177	93	1921
46	Sidama	Shebedino	Gobo Hobolso	441586	758626	1886	147	23	1863
47	Sidama	Shebedino	Morocho	436649	763919	1864	170	43	1821
48	Sidama	Shebedino	Abela Lida	442014	765157	1912	165	63	1849
49	Sidama	Shebedino	Leku new	440280	760414	1864	152	60	1804
50	Sidama	Shebedino	Diramo Aferara	430871	755256	1782	78	19	1763
51	Sidama	Shebedino	Midre Genet	434540	759693	1840	224	43	1797
52	Sidama	Boricha	Yirba #1	429989	763353	1957	150	83	1875
53	Sidama	Boricha	Yirba #2*	430000	765500	2010	200	143	1867
54	Sidama	Boricha	Derara Gort	421535	755179	1883	307	244	1639
55	Sidama	Boricha	Alawo Arke	429256	761374	1960	220	64	1896
56	Sidama	Boricha	Konsore Arke	429409	763401	1954	204	95	1859
57	Sidama	Melga	Wijigra	451697	766560	2170	110	41	2129
58	Sidama	Wonsho	Bokaso	445709	747119	1970	132	62.1	1907.9
59	Sidama	Dale	Telamo.K	444010	756200	1960	80	60.1	1900

Annex.5 Shallow wells (shallow boreholes)

	Zone	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Elevation a.s.l. (m)	Depth(m)	S.W.L.(m)	G.W.L(m)
1	Sidama	Dara	Kumato primary school	423834	715015	1607	60	20	1587
2	Sidama	Dara	Mechisho anno	422876	712114	1525	56	0	1523
3	Gedeo	Bule	Basura #1	429821	698499	2332	31	14	2318
4	Gedeo	Bule	Basura #2	430045	698443	2333	31	15	2318
5	Gedeo	wonago	Tototiy	411171	692959	1926	55	35	1891
6	Sidama	Aletawondo	Gambela	424945	722930	1650	33	30	1620
7	Sidama	Dara	Gelowacho	426837	713901	1852	48	20	1832
8	Sidama	Aletawondo	Gowadamo	434872	724902	2083	48	15	2068
9	Gedeo	wonago	Sokicha#1	417521	691660	2000	62	29.2	1970.8
10	Gedeo	wonago	Sokicha#2	418142	692003	2009	52	17.4	1991.6
11	Gedeo	wonago	Sokicha#3	418140	690878	1999	59.5	28.6	1970.4
12	Gedeo	wonago	Sugale	418193	695915	1803	46	6	1797
13	Gedeo	wonago	Kara Soditi	413900	696259	1929	60	14	1915
14	Borena	Abaya	Biyo	394765	680213	1600	62	26	1574
15	Borena	Abaya	Oddomike(Arerebi)	420649	704835	1727	34	22	1705
16	Borena	Abaya	Semero Gambella(Kuka)	413630	704835	1450	52	34	1416
17	Sidama	Boricha	Sedamo Dikicha	430980	764085	2035	61	56	1979

Annex.6 Hand dug wells

	Zone	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Elevation a.s.l. (m)	Depth(m)	S.W.L.(m)	G.W.L(m)
1	Sidama	Dara	Abera doda	440814	713337	2792	15	10	2782
2	Sidama	Dara	Shoicho near school	430189	718446	1832	18	10	1872
3	Sidama	Dara	Ato Mulatu	434572	729532	1880	7	1.5	1878
4	Sidama	Dara	Ato Beyene	435039	729322	1876	12	5	1871
5	Sidama	Dara	Ato Areda	435631	729776	1882	10	8.5	1874
6	Sidama	Dara	Gura	428204	728062	1796	20	7.5	1788
7	Sidama	Dara	Ato Fikadu	435648	722865	1789	18	15	1774
8	Sidama	Dara	Dibicha	424260	720080	1655	27	11	1644
9	Sidama	Dara	Dibicha#3	423843	719540	1616	28	10	1606
10	Sidama	Dara	Mechisso#3	424955	712875	1755	11	5	1750
11	Borena	Abaya	Gaungua#1	421303	702298	1561	15	11	1550
12	Borena	Abaya	Gaungua21	421250	702715	1562	17	10	1552
13	Borena	Abaya	Gaungua#3	421278	703084	1555	16	10	1545
14	Borena	Abaya	Bunata bikitu#1	417102	703432	1558	18	13	1545
15	Borena	Abaya	Bunata bikitu#2	417443	701323	1562	24	14	1548
16	Borena	Abaya	Bunata bikitu#3	417232	704331	1595	16	11	1584

Annex.7 Hot and Cold Springs.

	Zone	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Ground Alt	Q (L/s)	Type
1	Borena	Abaya	Odomike(Hot spring)	419097	706697	1427	dispersed	fracture
2	Sidama	Dara	Mechisho(Hot spring)	421535	711456	1409	dispersed	fracture
3	Sidama	Dale	Yirgalem Hospital(Hot spring)	432371	746688	1682	dispersed	fracture
4	Sidama	Loka Abaya	DansheGambela(Hotspring)	418850	732980	1601	0.04	Fracure
5	Sidama	Loka Abaya	Oito (Hot spring)	394183	725926	1185		Fault
6	Gedeo	Wonago	Kidane mihiret(Hot spring)	420913	710373	1385		fracture
7	Gedeo	Wonago	Bersiso(Hot spring)	421667	711371	1378		fracture
8	Borena	Abaya	Bochessa	403178	685592	2067	0.13	Contact
9	Gedeo	Wonago	Sokicha	417755	692044	1994	0.1	Depression
10	Sidama	Dara	Abera town spring	441367	713154	2775	0.11	Depression
11	Sidama	Aletawondo	Garbicho kila	443551	726883	2466	0.05	Depression
12	Sidama	Wonsho	Bokaso	445708	747120	1970	0.33	Depression
13	Gedeo	Dila Zuria	Andida	708885	427777	1860	0.67	depression
14	Gedeo	Wonago	Gorso salo	416936	696439	1800	1.2	contact
15	Gedeo	Wonago	Heleya ridge	417992	95301	1762	1	contact
16	Gedeo	Wonago	Heleya	418895	694559	1744	0.8	fracture
17	Gedeo	Wonago	Dobota	419479	693398	1943	0.23	fracture
18	Gedeo	Wonago	Lekicha	417563	689034	1947	1.1	contact
19	Borna	Abaya	Guangua	420599	703805	1508	2.5	fracture
20	Gedeo	Wonago	Tnticha	425457	702999	1751	1	depression
21	Gedeo	Wonago	Tnticha	425257	700920	1799	1	depression
22	Gedeo	Wonago	Daro	425546	700265	1963	0.83	depression
23	Gedeo	Wonago	Bsura	425635	699845	1954	0.21	depression
24	Gedeo	Bule	Oslo mejo	432985	696534	2718	0.56	depression
25	Sidama	Dara	Shoicho	429538	717299	1774	1	depression
26	Sidama	Dara	Shoicho	430264	717292	1764	0.43	depression
27	Sidama	Dara	Setamo	431090	716928	1764	1.33	depression
28	Sidama	Dara	Loya	435411	718195	1891	Dispersed	depression

Hot and cold springs Continued

	Zone	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Ground Alt	Q (L/s)	Type
29	Sidama	Dara	Korate bute	428013	712213	1861	0.56	contact
30	Sidama	Dara	Chancho#2	430965	713349	2045	1	depression
31	Sidama	Dara	Chancho	433575	712900	2341	1.67	depression
32	Sidama	Dara	Banko Markos	433975	711701	2533	1.67	depression
33	Sidama	Dara	Banko Markos	441391	712394	2845	1.5	depression
34	Sidama	Dara	Kumato(Kisho)	426120	715720	1729	0.07	depression
35	Sidama	Dara	Abera	441341	713176	2844	1.5	fracture
36	Gedeo	Wonago	Dodoro	415287	694460	1927	1	depression
37	Gedeo	Wonago	Dodoro	410457	713866	1927	1	contact
38	Gedeo	Wonago	Yederyu	415873	693120	1830	0.75	fracture
39	Sidama	Dara	Safa	425739	716918	1622	0.38	contact
40	Sidama	Dara	Adame	425200	718300	1676	1.4	depression
41	Sidama	Dara	Adame	424504	715327	1653	0.75	contact
42	Gedeo	Wonago	Kelecha	422219	697632	1586	0.97	contact
43	Gedeo	Wonago	Hase haro	420834	692752	1586	1.2	contact
44	Gedeo	Wonago	Hase haro	418264	692545	1600	1.35	depression
45	Gedeo	Wonago	Uraga	417876	695433	1643	1.26	contact
46	Sidama	Dara	Lela Honcho(Dondie)	430726	719813	1836	0.5	
47	Sidama	Dara	Hallo(Della)	431702	722595	1937	0.5	
48	Sidama	Dara	Lela Honcho	432705	720198	1865	0.25	
49	Sidama	Dara	Mekala(Bonha)	428006	719563	1816	0.3	

Annex.8 Runoff estimation for month of January (by using Gidabo near Abosto, Kola near Aleta Wondo and Bedessa near Dila gauging stations).

Jan.	Gidabo	Kola	Bedesa	$Q_g(m^3/s)$ = QGidabo + QBedesa + QKola	$Q_u = (Q_g*A_u)/(A_g)$	$Q_u = (Q_g*A_u)/(A_g)$
1	2.3356071	0.77904	0.6199167	3.7345638	13.37436413	13.1116534
2	2.3151071	0.75988	0.6022917	3.6772788	13.16921287	12.91053191
3	2.2809286	0.7556	0.5968333	3.6333619	13.01193596	12.75634436
4	2.2277241	0.75068	0.57375	3.5521541	12.72111157	12.47123259
5	2.2268276	0.72072	0.56775	3.5152976	12.58911946	12.34183319
6	2.2302069	0.71768	0.5562083	3.5040952	12.54900115	12.30250291
7	2.2102414	0.70936	0.7266667	3.6462680	13.05815593	12.80165644
8	2.6760345	0.69532	0.54175	3.9131045	14.01376088	13.73849058
9	2.2193103	0.6822	0.546	3.4475103	12.34635717	12.10383944
10	2.135069	0.69136	0.5489583	3.3753873	12.08806734	11.85062316
11	2.1000345	0.72016	0.5249167	3.3451111	11.97964122	11.74432684
12	2.0824483	0.7332	0.5267917	3.3424399	11.97007499	11.73494852
13	2.0500345	0.69212	0.5591667	3.3013211	11.82281878	11.59058484
14	2.1715172	0.70256	0.534125	3.4082022	12.20558548	11.9658329
15	2.081069	0.69124	0.7149583	3.4872673	12.48873631	12.24342185
16	2.1751724	0.76412	0.8746667	3.8139591	13.65869754	13.39040169
17	2.2795172	0.72808	0.7306667	3.7382639	13.38761506	13.12464405
18	2.342	0.72548	0.6345	3.7019800	13.25767373	12.99725514
19	2.3181724	0.71648	0.60875	3.6434024	13.04789342	12.79159551
20	2.1782759	0.6878	0.5689583	3.4350342	12.30167711	12.06003702
21	2.1717241	0.68216	0.5511667	3.4050508	12.19429943	11.95476855
22	2.1536897	0.63216	0.546625	3.3324747	11.93438692	11.69996146
23	2.1828276	0.63784	0.51875	3.3394176	11.95925121	11.72433735
24	2.0861429	0.69452	0.494125	3.2747879	11.72779673	11.4974293
25	2.0434643	0.63156	0.471	3.1460243	11.26666366	11.04535419
26	2.0462857	0.67144	0.46625	3.1839757	11.40257678	11.17859759
27	2.0598929	0.63852	0.46825	3.1666629	11.34057531	11.11781401
28	2.4912857	0.683	0.4782917	3.6525774	13.08075116	12.82380784
29	2.1645714	0.56668	0.4326667	3.1639181	11.33074566	11.10817744
30	2.04125	0.58664	0.4549167	3.0828067	11.04026628	10.82340391
31	1.9535357	0.54936	0.4245	2.9273957	10.48370258	10.2777727

Annex.9 Runoff estimation for month of February (by using Gidabo near Abosto, Kola near Aleta Wondo and Bedessa near Dila).

Feb. 1	1.9786207	0.56212	0.412	2.9527407	10.57446898	10.3667562
2	1.8887931	0.53624	0.4439167	2.8689498	10.2743937	10.07257526
3	1.8296897	0.52452	0.3825417	2.7367513	9.800959515	9.608440668
4	1.8180345	0.5338	0.36725	2.7190845	9.737690349	9.546414288
5	1.8198276	0.51072	0.3484583	2.6790059	9.594159451	9.405702747
6	1.8498966	0.4976	0.349125	2.6966216	9.657245233	9.467549344
7	1.8593448	0.50324	0.3389167	2.7015015	9.674721471	9.4846823
8	1.8492069	0.51088	0.3402083	2.7002952	9.670401551	9.480447235
9	1.9398276	0.6006	0.3302083	2.8706359	10.28043221	10.07849515
10	2.2025172	0.55096	0.328125	3.0816022	11.03595294	10.8191753
11	2.2088276	0.56848	0.3337083	3.1110159	11.14129035	10.92244357
12	2.1404483	0.56828	0.3295833	3.0383116	10.88091886	10.66718653
13	2.1836207	0.551	0.3030833	3.0377040	10.87874295	10.66505336
14	2.1938276	0.552	0.3202917	3.0661193	10.98050467	10.76481618
15	2.224931	0.52036	0.4430833	3.1883744	11.41832941	11.19404079
16	2.1727586	0.63324	0.3976667	3.2036653	11.47308984	11.24772557
17	2.0688966	0.58352	0.3624583	3.0148749	10.79698636	10.5849027
18	2.0754828	0.62848	0.3571667	3.0611294	10.96263491	10.74729743
19	2.0647931	0.58844	0.3645833	3.0178164	10.80752076	10.59523017
20	2.044	0.55832	0.3925417	2.9948617	10.72531425	10.51463843
21	1.9995172	0.51624	0.364875	2.8806322	10.31623142	10.11359116
22	1.9760345	0.49596	0.3308333	2.8028278	10.03759521	9.840428159
23	2.0264483	0.5412	0.3455	2.9131483	10.4326791	10.22775147
24	1.92875	0.527	0.345375	2.8011250	10.03149702	9.834449754
25	2.2716071	0.56152	0.338125	3.1712521	11.35701063	11.1339265
26	2.3614286	0.6452	0.355125	3.3617536	12.03924171	11.8027566
27	2.5834643	0.64052	0.3392917	3.5632760	12.76094144	12.51028009
28	2.2741429	0.59316	0.3405	3.2078029	11.48790746	11.26225214

Annex.10 Mean Monthly duration of Maximum possible sunshine hours (N). After M.Shaw,1989.

NorthLats	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
SouthLats	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.
60	6.7	9	11.7	14.5	17.1	18.6	17.9	15.5	12.9	10.1	7.5	5.9
58	7.2	9.3	11.7	14.3	16.6	17.9	17.3	15.3	12.8	10.3	7.9	6.5
56	7.6	9.5	11.7	14.1	16.2	17.4	16.9	15	12.7	10.4	8.3	7
54	7.9	9.7	11.7	13.9	15.9	16.9	16.5	14.8	12.7	10.5	8.5	7.4
52	8.3	9.9	11.8	13.8	15.6	16.5	16.1	14.6	12.7	10.6	8.8	7.8
50	8.5	10	11.8	13.7	15.3	16.3	15.9	14.4	12.6	10.7	9	8.1
48	8.8	10.2	11.8	13.6	15.2	16	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14	12.6	11	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15	14.7	13.7	12.5	11.2	10	9.3
35	10.1	11	11.9	13.1	14	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12	12.9	13.6	14	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12	12.7	13.3	13.7	13.5	13	12.3	11.6	10.9	10.6
20	11	11.5	12	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12	12.5	12.8	13	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12	12.2	12.3	12.4	12.3	12.3	12.1	12	11.9	11.8
Equator 0	12	12	12	12	12	12	12	12	12	12	12	12

Annex.11 Data used to construct draw dawn versus time curve for Dara-Mechisho borehole.

Dara-Mechisho borehole				
Time	Drawdown		Time	Drawdown
1	3.77		120	19.77
2	5.3		140	20.61
3	6.08		160	21.33
4	6.71		180	22.11
5	7.08		210	22.98
6	7.32		240	23.65
7	7.58		270	24.48
8	7.93		300	25.02
9	8.24		360	25.93
10	8.61		420	26.86
12	9.08		480	27.49
14	9.49		540	28.1
16	9.95		600	28.5
18	10.34		660	28.95
20	10.88		720	29.38
25	11.58		780	29.81
30	12.32		840	30.4
35	13		900	30.98
40	13.65		960	31.57
45	14.31		1020	32.08
50	14.68		1080	32.64
55	15.37		1140	33.16
60	15.82		1200	33.33
70	16.56		1260	33.7
80	17.29		1320	33.89
90	18.02		1380	34.16
100	18.63		1440	34.41

Annex.12 Water points used to construct groundwater level contours

S.No	Water point at	X	Y	Groundwater level (G.W.L)
1	Hagereselam BH	446574	716715	2730
2	Gololcha BH	411743	706449	1350
3	Dila lagadara BH	424597	709592	1544
4	Wonago BH	418196	698026	1692
5	Bule basura BH	429821	698499	2318
6	Michicha gelo BH	392581	684598	2008
7	A/wondo highscool BH	436215	730654	1841
8	Loko Haytale BH	422391	731463	1668.3
9	Mesenkala BH	431250	752170	1790
10	Gobo hebisha BH	445875	760540	1921
11	Bokaso BH	445709	747119	1907.9
12	Dibicha BH	424260	720080	1644
13	Yirba #1 BH	429989	763353	1875
14	Wijigra BH	451697	766560	2129
15	Biyo BH	394765	680213	1574
16	Iyeye CSP	391576	698585	1600
17	Balala CSP	417263	768491	1860
18	Hogiso CSP	464770	757568	2696
19	Teticha CSP	448711	724825	2630
20	Gidabo delta Hsp	394183	725926	1185
21	Rufo Chancho BH	423164	725273	1816
22	Garbicho kila CSP	443551	726883	2466
23	Sokicha CSP	417755	692044	1994
24	Lekicha CSP	417563	689034	1947
25	Abera HDW	441341	713176	2844
26	Odomike(Hot spring)	419097	706697	1427
27	Bochessa CSP	403178	685592	2067
28	Derara Gort BH	421535	755179	1639
29	Konsore Arke BH	429409	763401	1859
30	Abela Lida BH	442014	765157	1849
31	Diramo Aferara BH	430871	755256	1763
32	Jirmancho BH	421587	744105	1605
33	Miridicha BH	420422	727153	1513.2
34	Chuko #2 *BH	425635	729575	1810
35	Shafina(Manche) BH	439985	740659	1809.5
36	Kebado new BH,2009	427622	716074	1742.8
37	Semero-Gambela BH	413630	704835	1412
38	Guangua BH	421303	702296	1528.55
39	Synteria BH	432145	723778	1950.3
40	Aleta Sodo BH	425364	738069	1714
41	Chichu Well #2 BH	425822	711671	1727
42	Teferi-Kella BH	433803	718366	1848
43	Mechisho anno BH	422876	712114	1523
44	Chuko Gambella BH,2009	425209	723579	1757.97
45	Mechisho town BH	422257	711782	1458
46	Bule town BH	434316	695956	2777.4
47	Wicho BH	433643	739043	1732
48	Gunde BH	420635	732564	1644
49	Shiko BH	438425	735391	1833.03
50	Leku new BH	440280	760414	1804

Annex.13 Soil-Water balance method of estimating AET, (Thornthwaite & Mather. 1957) for the Highland.

Componens (mm)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Precipitation	51.24	56.02	90.98	192.6	214.04	199.54	154.92	170.46	160.86	192.36	71.18	49.74	1603.94
PET	57.42	60.26	61.49	62.4	61.28	57.49	54	54	55.56	55.61	54.82	55.08	689.41
Precipita - PET	-6.18	-4.24	29.49	130.2	152.76	142.05	100.92	116.46	105.3	136.75	16.36	-5.34	
ACC. POT.WL	-11.52	-15.76										-5.34	
SM	228.75	224.75	240	240	240	240	240	240	240	240	240	234.72	
ΔSM	-5.97	-4	15.25	0	0	0	0	0	0	0	0	-5.28	
AET	57.21	60.02	61.49	62.4	61.28	57.49	54	54	55.56	55.61	54.82	55.02	688.9
SMD	0.21	0.24	0	0	0	0	0	0	0	0	0	0.06	
Surplus	0	0	14.24	130.2	152.76	142.05	100.92	116.46	105.3	136.75	16.36	0	

Annex.14 Soil-Water balance method of estimating AET, (Thornthwaite & Mather. 1957) for the Escarpment.

Componens (mm)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Precipitation	37.06	44.24	110.6	242.9	246.26	126.78	112.64	131.02	190	197.6	63.18	34.04	1536.34
PET	67.83	71.42	72.21	68.9	65.37	63.9	61.43	61.61	61.1	61.18	64.54	67.01	786.5
Precipitation - PET	-30.77	-27.18	38.39	174	180.89	62.88	51.21	69.41	128.9	136.42	-1.36	-32.97	
ACC. POT.WL	-65.1	-92.28									-1.36	-34.33	
SM	159.8	140.9	179.19	216	216	216	216	216	216	216	214.6	184.3	
ΔSM	-24.46	-18.9	38.29	36.81	0	0	0	0	0	0	-1.36	-30.38	
AET	61.52	63.14	72.21	68.9	65.37	63.9	61.43	61.61	61.1	61.18	65.9	97.39	803.65
SMD	6.31	8.28	0	0	0	0	0	0	0	0	-1.36	-30.38	
Surplus	0	0	0.1	137.2	180.89	62.88	51.21	69.41	128.9	136.42	0	0	

Annex.15 Soil-Water balance method of estimating AET, (Thornthwaite & Mather. 1957) for the Rift floor.

Components(mm)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Precipitation	34.49	36.81	89.49	159	142.89	98.21	108.64	113.13	128.39	113.95	40.85	30.21	1096.03
PET	123.3	132.78	130.72	113.5	104.15	92.67	75.53	88.73	97.42	106.17	115.4	120.7	1300.95
Precipitation - PET	-88.77	-95.97	-41.23	45.48	38.74	5.54	33.11	24.4	30.97	7.78	-74.51	-90.45	
ACC. POT.WL	-253.7	-349.7	-390.9								-74.51	-165	
SM	38.78	22.12	17.38	62.86	101.6	107.14	140.25	164.65	171	171	110.6	65.17	
ΔSM	-26.39	-16.66	-4.74	45.48	38.74	5.54	33.11	24.4	6.35	0	-60.4	-45.43	
AET	60.88	53.47	94.23	113.5	104.15	92.67	75.53	88.73	97.42	106.17	101.3	75.64	1063.64
SMD	62.38	79.31	36.49	0	0	0	0	0	0	0	14.11	45.02	
S	0	0	0	0	0	0	0	0	24.62	7.78	0	0	

Annex.16 Modified Penman Method.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	*Total*
T (^{0}C)	23	24	24	23	22	21	20	21	22	22	22	23	
T (^{0}F)	73.4	75.2	75.2	73.4	71.6	69.8	68	69.8	71.6	71.6	71.6	73.4	
T (^{0}K)	296	297	297	296	295	294	293	294	295	295	295	296	
e_a (mm/d)	21.04	22.1	22.1	21.04	19.74	18.75	17.53	18.75	19.74	19.74	19.74	21.04	
e_d (mm/d)	11.86656	12.0003	12.9727	14.45448	14.54838	13.725	13.30527	13.9875	15.0024	13.83774	11.4492	11.17224	
e_a-e_d	9.17344	10.0997	9.1273	6.58552	5.19162	5.025	4.22473	4.7625	4.7376	5.90226	8.2908	9.86776	
RH (%)	56.4	54.3	58.7	68.7	73.7	73.2	75.9	74.6	76	70.1	58	53.1	
	100	100	100	100	100	100	100	100	100	100	100	100	
RH (%) /100	0.564	0.543	0.587	0.687	0.737	0.732	0.759	0.746	0.76	0.701	0.58	0.531	
U_1 (m/s)	1.35	1.4	1.25	1.06	1	1.03	1.02	0.89	0.86	0.88	1.19	1.33	
	54	54	54	54	54	54	54	54	54	54	54	54	
U_2 (miles/day)	72.9	75.6	67.5	57.24	54	55.62	55.08	48.06	46.44	47.52	64.26	71.82	
	100	100	100	100	100	100	100	100	100	100	100	100	
U_2/100 (miles/day)	0.729	0.756	0.675	0.5724	0.54	0.5562	0.5508	0.4806	0.4644	0.4752	0.6426	0.7182	
1	1	1	1	1	1	1	1	1	1	1	1	1	
1+U_2/100	1.729	1.756	1.675	1.5724	1.54	1.5562	1.5508	1.4806	1.4644	1.4752	1.6426	1.7182	
	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
0.35(1+U_2/100)	0.60515	0.6146	0.58625	0.55034	0.539	0.54467	0.54278	0.51821	0.51254	0.51632	0.57491	0.60137	
n(hr/d)	9.5	9	8.3	7.2	7.6	6.3	4.7	5.4	6.2	7.4	8.9	9.5	
N (hr/d)	11.75	11.87	12	12.33	12.38	12.48	12.38	12.33	12.1	11.95	11.82	11.72	
n/N (hr/d)	0.8085106	0.758214	0.6916667	0.5839416	0.6138934	0.5048077	0.3796446	0.4379562	0.5123967	0.6192469	0.7529611	0.8105802	
R_a (mm/d)	13.47	14.31	14.95	15.02	14.59	14.28	13.79	14.74	14.84	14.5	13.66	13.17	
	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	
	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	
0.62 (n/N)	0.5012766	0.4700927	0.4288333	0.3620438	0.3806139	0.3129808	0.2353796	0.2715328	0.317686	0.3839331	0.4668359	0.5025597	

Continued Modified Penman method.

	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	
$R_a f_a$ (n/N)	8.907395745	9.016626116	8.80305833	7.84109781	7.887556704	6.75416538	5.452285299	6.360794161	7.088859504	7.887029289	8.562578003	8.725911604	
R_I (1-r)(mm/d)	6.680546809	6.762469587	6.60229375	5.880823358	5.915667528	5.06562404	4.089213974	4.77059562	5.316644628	5.915271967	6.421933503	6.544433703	
σTa^4(mm/d)	14.96741215	15.17070176	15.1707018	14.96741215	14.76617249	14.566969	14.3697878	14.56696897	14.76617249	14.76617249	14.76617249	14.96741215	
R_0 (mm/d)	3.096598164	2.946316118	2.58501675	2.039491086	2.18304333	1.82955884	1.470644377	1.608136112	1.751720247	2.185898562	2.933596555	3.217876147	
$e_d^{1/2}$	3.444787366	3.464144916	3.60176346	3.801904786	3.704726711	3.70472671	3.647638962	3.739986631	3.873293172	3.719911289	3.38366665	3.34249009	
0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	
$0.09e_d^{1/2}$	0.310030863	0.311773042	0.32415871	0.342171431	0.333425404	0.3334254	0.328287507	0.336598797	0.348596386	0.334792016	0.304529999	0.300824108	
0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	
0.56-0.09ed1/2	0.249969137	0.248226958	0.23584129	0.217828569	0.226574596	0.2265746	0.231712493	0.223401203	0.211403614	0.225207984	0.255470001	0.259175892	
0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	
0.9n/N	0.727659574	0.682392586	0.6225	0.525547445	0.552504039	0.45432692	0.341680129	0.394160584	0.461157025	0.557322176	0.677664975	0.729522184	
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
0.1+0.9n/N	0.827659574	0.782392586	0.7225	0.625547445	0.652504039	0.55432692	0.441680129	0.494160584	0.561157025	0.657322176	0.777664975	0.829522184	
E_{at} (mm/d)	5.551307216	6.20727562	5.35087963	3.624275077	2.79828318	2.73696675	2.293098949	2.467975125	2.428209504	3.047454883	4.766463828	5.934174831	
Δ/γ	2.75	2.92	2.92	2.75	2.58	2.39	2.23	2.39	2.58	2.58	2.58	2.75	
1	1	1	1	1	1	1	1	1	1	1	1	1	
$1+\Delta/\gamma$	3.75	3.92	3.92	3.75	3.58	3.39	3.23	3.39	3.58	3.58	3.58	3.75	
Δ/γ	2.75	2.92	2.92	2.75	2.58	2.39	2.23	2.39	2.58	2.58	2.58	2.75	
H_T	3.583948645	3.816153469	4.017277	3.841332272	3.732624198	3.2360652	2.618569598	3.162459508	3.564924381	3.729373405	3.488336947	3.326557556	
$(\Delta/\gamma)H_T$	9.855858773	11.14316813	11.7304488	10.56366375	9.630170431	7.73419582	5.839410203	7.558278225	9.197504903	9.621783385	8.999909324	9.148033279	
E_{at} (mm/d)	5.551307216	6.20727562	5.35087963	3.624275077	2.79828318	2.73696675	2.293098949	2.467975125	2.428209504	3.047454883	4.766463828	5.934174831	
$(\Delta/\gamma)HT+E_{at}$	15.40716599	17.35044375	17.0813285	14.18793882	12.42845361	10.4711626	8.132509152	10.02625335	11.62571441	12.66923827	13.76637315	15.08220811	
PET(mm/d)	4.108577597	4.42613361	4.35748175	3.783450353	3.471635087	3.08883852	2.517804691	2.957596858	3.247406259	3.538893371	3.845355629	4.021922163	43.4
PET(mm/month)	123.2573279	132.7840083	130.724453	113.5035106	104.1490526	92.6651555	75.53414073	88.72790575	97.42218777	106.1668011	115.3606689	120.6576649	1301
Annual PET(mm/year)													

Annex.17 Few boreholes' hydraulic parameters obtained from well completion reports.

	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Depth (m)	S.W.L (m)	Yield (l/s)	K (m/d)	T (m2/day)	Aquifer thickness(m)	Storativity	Aquifer type	confyning layer
1	Dara	Mechisho town BH	422257	711782	173	30	4.3	0.17	6.15	36	0.935	confined	Slightely weathered ignimbrite at 32-40m depth
2	Dara	Kebado new BH,2009	427622	716074	72	35	10	1.04	25	24	0.448	leaky	Clay wih gravel at 19-38m depth
3	Aletawondo	Shiko	438425	735391	122	67	5.5	38.6	1158	30	0.0119	leaky	Tuff at 68-70m depth
4	AletaChuko	Chuko Gambella new,2009	425209	723579	162	41	5.5	0.203	6.09	30	1.85	confined	welded tuff at40-56m depth
5	Dale	Shafina(Manche)	439985	740659	175	30.52	5.4	0.85	35.71	42	0.000000139	leaky	Blach-cotton soil wit clat at 34-46m depth
6	Dale	Wicho	433643	739043	214	114	3.9			60		confined	Fresh ignimbrite at 125m depth
7	LokaAbaya	Jirmancho	421587	744105	165	17							
8	LokaAbaya	Sodo Simita	424407	738825	153	43	3.35			28		leaky	slightly weathered to fresh ignimbrite at 90m depth
9	Shebedino	Gobo Hebisha	445875	760540	177	93	6.4	0.5	29.7	59	0.00367	unconfined	
10	Shebedino	Gobo Hobolso	441586	758626	147	23	7	3.1968	188.64	59	0.0000133	leaky	slightly weathered ignimbrite & tuff at 26m depth
11	Shebedino	Leku new	440280	760414	152	60	5.5		10.2	30		confined	Fresh ignimbrite at 94m depth
12	Boricha	Konsore Arke	429409	763401	204	95							
13	Dale	Mesenkela	431250	752170	120	10	6.6	0.113	2.71	66		leaky	slightly weathered ignimbrite & tuff at 25m depth
14	AletaChuko	Loko Haytale	422391	731463	84	49.7	2.2	0.386	5.6	variable		unconfined	
15	AletaChuko	Miridicha	420422	727153	183	148.8	7	39	582			leaky	
16	Shebedino	Diramo Aferara	430871	755256	78	19	2.5	0.18	2.9	36		leaky	
17	Dila Zuria	Chichu well #2	423500	708500	115	14	8	2	14.4		0.0262		
18	Boricha	Yirba #1	429989	763353	150	83	4			variable		unconfined	
19	Wonsho	Bokaso	445709	747119	132	62.1	1	0.19	5.82	30		unconfined	
20	Dara	Tefri kela	432752	718123	80	10	5	1.52	30.93	30	0.0179	leaky	sligtely weatherd ignimbrite
21	Aletachuko	Synteria	432149	718123	151	12	5	1.42	6	Variable	0.0296	leaky	Tuff at 15 m depth
22	Aletawondo	Aletawondo Gidibo BH	436047	73200	146	57.3	7.2	2.5	68.5	Variable		unconened	
23	Aletawondo	Rufo Chancho	423164	725273	84	42	1.5	0.62	9.5	74-90	0.00577	leaky	

E)Continued of Annex.17

	Wereda	Site name/ Locality	Coordinates (UTM) X	Y	Depth (m)	S.W.L .(m)	Yield (l/s)	K (m/day)	T (m2/day)	Aquifer thickness(m)	Storativity
24	Dila Zuria	Chichu well #1	423200	704000	103	5	6	3.6	8.53		0.0221
25	Dilla	Dilla TW-1 near Laga Dara	423500	705450	74	5	6	0.76	21.5	30	0.0318
26	Dila	Dilla TW-2	423500	706000	105	14	8	4.032	54	21	
27	Dila	Dilla Donmbosco Salesian Frs	422600	709500	125	64	3.5	3.14	54		
28	Dila	Dilla Donmbosco Salesian Srs	422600	709500	125	64.65	2.5	1.4	31	variable	
29	Abaya	Semero Gembela	413630	704835	138	38	14.22	2.54	28		0.019
30	Hgereselam	Hgereselam	446574	716715	150	29.06	5	0.3	10	variable	0.0052
31	Abaya	Guanguaa	421303	702296	160	31.45	8	0.47	15.04	32	
32	Bule	Bule town#1	434316	695956	70	23.6	4	0.28	6.14	42-48,54-70	
33	Aletawondo	Aletawondo Town High School	436309	730865	154	72	1.7	0.78	79		0.0108
34	Aletawondo	Aletawondo Chinese old NO. 5	433220	727800	79.89	15.81	1.4	0.44			0.005
35	Aletawondo	Rufo Debeka	420400	723500	85.5	55.4	5	14.19	314	Variable	0.1724
36	Aletawondo	Rufo Waeno	424176	726407	93	46.1	0.5	0.06	9.7	60-89	0.00097

Annex.18 Hydrochemistry data used for Piper plot to identify the water types.

	UTM				mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Type	x	y	z	Location	Na^+	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	Cu^{2+}	Mn^{2+}	Cr^{6+}	Cl^-	F^-	HCO_3^-	NO_3^-	NO_2^-	Br^-	SO_4^{2-}	PO_4^{3-}
BH-1	411743	706449	1388	Gololcha BH	10.88	0.05	7	56	16.8	0.1	0.14	0.02	0	3.5	0.6	390.4	0.04	0.02	0.01	0	9.7
BH-2	422876	712114	1525	Mechisho BH	33.1	0.04	4	44	16.8	0.2	0	0	0.01	2	0.28	280.6	0.06	0.01	0.2	0	14.3
BH-3	426837	713901	1852	Gelowacho BH	31.77	0.04	6	23	7.68	0	0	0.01	0.01	3	0.2	161.04	1.32	0.03	0	0	18
BH-4	427765	715980	1773	Kebado BH	188.28	0.04	6	28	3.36	0.3	0.06	0.01	0.04	2.5	0.16	202.52	0.33	0.01	0.07	3	17.6
BH-5	434872	724902	2083	Gowadamo. A BH	16	0.06	1	8	4.8	0.3	0.12	0.03	0	2.6	0.12	53.68	3.59	0	0.13	3	4.6
BH-6	436215	730654	1904	A/wondo.H.sc BH	50.37	0.01	5	24	2.4	0.15	0	0.01	0.02	2.5	0.46	190.32	0.65	0.02	0.15	0	15.7
BH-7	427350	727216	1872	Chuko Lamala BH	39.25	0.03	6	11	5.28	0.3	0.1	0	0.01	5.5	0.47	114.68	0.15	0	0.14	5	22.5
BH-8	426100	710427	1680	Odolla BH 2009(new)	22.67	0.03	4	48	9.6	0.2	0.08	0.03	0	2.5	0.35	256	0.01	0.07	0	0	0
BH-9	425822	711671	1741	Chichu BH#2	77.64	0.01	4	16	2.4	0.25	0.06	0.02	0	1.3	1.05	231.8	0.39	0	0.08	2	17.3
BH-10	425364	738069	1764	Aleta Sodo BH	40.52	0.01	6	33	11.52	0.1	0.06	0.01	0	3	1.3	219.6	0.11	0.01	0.13	2	22.3
BH-11	433803	718366	1858	Teferi-Kela BH #1 old	76.56	0	3	14	5.28	0.2	0	0	0	2.5	1.96	256.2	0	0	0	0	4.9
BH-12	421117	709073	1461	Dila Agri.Chol BH	160.154	0.1032	11	14	4.8	0.25	0.08	0.012	0.06	8.8	1.3	378.2	0.1892	0.0231	0.14	66	15.5
BH-13	423533	744647	1615	Loka.A.Chancho.M.A BH	32.154	0.0129	6	35	3.36	0.7	0	0.004	0	38	1.01	124.44	0.2728	0.231	0	0	13.9
BH-14	421907	747046	1778	Sala Kebado.T BH	12.5281	0.1032	2	28	12.48	0	0.04	0.002	0.02	20	0.57	112.24	0.8492	0.132	0.03	0	18.5
BH-15	422647	745610	1623	Sala Kebado.W BH	6.3411	1.161	5	33	13.92	0.25	0	0.021	0.01	20	1.2	128.1	0.0396	0.033	0.02	0	16.8
BH-16	421873	744971	1612	Jirmancho BH	29.2445	0.0129	7	7.2	17.28	0	0.02	0.008	0.01	15	1.5	134.2	0.8448	0.0132	0.02	0	16.2
BH-17	422660	745541	1619	Sala Kebado.D BH	10.9365	0	4	24	9.6	1	0	0.004	0	10	1.39	114.68	0.0484	0.0165	0	0	11.9
BH-18	425636	747671	1660	Loka.A.Bilate BH	28.5131	0.0129	1	11	4.8	1.67	0.22	0.2	0.02	7.5	0.11	58.56	0.2728	0.0132	0.03	1	34.2
BH-19	421663	710637	1451	Dila Univ.BH#3	371.981	0.0258	20	24	6.72	0.25	0.18	0.008	0.001	7.5	7.2	878.4	0.1276	0.0198	0.15	128	24.6
BH-20	422377	741059	1840	Loka.SalaSire G.BH	105.598	0.0387	6	17	3.84	0.5	0.04	0.01	0.12	105	0.34	67.1	0.7392	0.0231	0.04	0	58.2
BH-21	430233	698345		Bulebasura.BH	15.824	0	2	40	16.8	0	0.38	0	0	10	0	214.72	19.8	0	0.33	0	0.165
BH-22	421388	710657	1432	Dila Univ.BH#1 semera	133.218	0.0129	12	44	14.4	0.4	0.04	0.016	0.02	6.3	1.2	457.5	0.0088	0.0165	0.02	63	13.8
BH-23	420446	709514	1432	DilaUnBH#2Old campus	165.112	0.0516	11	21	4.32	0.25	0.12	0.017	0.04	7.5	1.33	397.72	0.0176	0.0231	0.55	75	16
BH-24	424562	709368	1543	Dila town BH	68.4457	0	5	16	6.72	0.2	0.06	0.006	0.08	2.5	2.65	133.02	0	0.0066	0.33	4	10.9
BH-25	422317	743037	1631	Loka.A.Benka BH	23.3818	0.0129	5	22	8.64	0.8	0.06	0.01	0.04	15	0.46	119.56	0.506	0	0.08	0.08	17.8
BH-26	425386	747188	1640	Loka.A.Kura BH	15.7941	0	2	19	14.4	0.03	0.04	0.027	0	15	0.14	109.8	0.0836	0	0	0	20.6
BH-27	428671	736996	1790	Dale Megera BH	32.8624	0.129	6	44	14.4	0.47	0.26	0.5	0.003	0.5	0.05	292.8	11	0.0063	0.04	0	0.779
BH-28	424488	710149		Dara Odolla BH(old)	27.3608	0	1	48	9.6	1.55	0.22	0	0.046	5	0.37	229.36	3.08	0.0195	0.01	0	0.74
BH-29				Dale-Gajamo Woybo	28.0485	0.0774	1	14	1.92	0.02	0.12	0	0.013	6	0	107.36	11.88	0.1175	0.03	0.5	0.114
BH-30				Dale-Gajamo Gidiwo	30.245	0.0645	1	8	2.88	2.88	0.2	1	0.005	6.5	0	112.24	11.44	0.0884	0.07	0.5	0.08
BH-31	422677	751963	1847	Salasire BH	9.9728	0	6	21	11.04	0	0.1	0.007	0.07	9	0.1	91.5	2.92	0.1716	0.07	1	22.6
BH-32				Haru BH	2.8037	0.128	1	40	14.4	0.73	0.2	0	0	7.5	0.55	175.68	14.52	0.0924	0.17	0	0.36
BH-33	418196	698026		Wonago town BH	18.814	0	1	28	30.24	0	0.08	0	0.019	5	0.34	195.2	45.76	0.0145	0.05	0	0.235
BH-34				Dale Mesenkela BH	15.18	0.516	16	18	1.458	0.2	0.03	0.3	0.03	8.5	0.4	86.4	22	0.012	0.03	4	0.3
BH-35				Boricha Arke well #1	52.2744	0.516	1	16	9.6	0.5	0.01	0.6	0.008	1.5	2.38	224.48	6.6	0.0168	0	0	0.432
BH-36				wonago Machaly	57.5943	0.1935	3	52	19.2	0	0.22	0.012	0	13	0.51	355.26	0.044	0.066	0	0	18

Continued of Annex.18

BH-37				Wonago Dobota	51.8742	0.0387	2	27	19.68	0.15	0.14	0.018	0	6.3	0.32	233.26	0.3212	0.0429	0.08	14	31.3
BH-38				Dale Hondowa	86.7928	0.0426	2	20	9.6	0.03	0.15	0.1	0.011	88	0.23	170.8	11.88	0.0092	0.05	6.7	0.286
BH-39				Dale Goyda	46.6141	0.1355	2	44	9.6	0.07	0.22	0	0.001	10	0.2	268.4	14.08	0.1003	0.04	7.6	0.198
BH-40				Dale-wara	25.9509	0.0839	1	8	2.4	0.09	0.14	0.1	0.013	5	0	85.4	13.2	0	0.11	0.6	0.103
BH-41				Dale-Tula	39.04	0.2748	3	24	6.24	0.2	0.23	0	0.11	2.5	0	201.3	8.8	0.0297	0	0.2	0.278
BH-42				Dale-Wenanata	37.7131	0.7224	2	35	10.08	0.1	0.77	0.1	0.001	2.5	0	244	15.84	0.0053	0	0.1	0.163
BH-43				Dale-Gadelo	14.1496	1.7028	2	26	6.72	0.04	0.25	0	0	2.5	0	128.1	16.72	0.5082	0.09	6.7	0.291
BH-44				Dale-Daguwa	19.8099	0.5844	2	25	1.92	0.02	0.15	0.1	0.007	3	0	128.1	9.24	0.0112	0.11	0.3	0.215
BH-45				Dale Kaliti Simita	28.5798	0.0284	2	26	15.84	0.13	0.17	0.1	0	3	0.82	219.6	8.8	0.0135	0.04	0	0.564
BH-46				Dila zuria Gola #2	37.6694	0.0387	6	28	16.8	0.65	0	0.031	0	6.3	0.3	234.24	0.0132	0	0.25	0	17.5
BH-47				Dila zuria Mechlesisota	53.7602	0.0645	3	54	12.96	0.7	0.28	0.016	0	11	0.66	308.66	0.0044	0.0033	0.09	9	20.4
BH-48				Dila zuria Tumticha	25.3874	0.0516	3	45	16.32	0.3	0.02	0.003	0.01	2.5	0.2	276.45	0	0.0033	0.17	0	12
BH-49				Loka Abaya Teme	69.4439	0.0129	9	22	3.36	0.85	0	0.019	0.07	43	1.3	158.6	1.3068	0.0297	0.02	5	21.6
BH-50				Teferi-Kela BH #2 new	22.6251	0.1935	2	8.8	4.8	0.3	0.06	0.1	0.007	3	0	97.6	11.44	0	0.05	1	0.061
BH-51				Wonago Tumata Chercha	38.7964	0.0516	4	38	10.56	0.3	0.1	0.031	0	6.2	0.38	207.4	0.154	0.0132	0.14	3	29.6
BH-52				Yirga Alem town BH #2	5.8949	0.0387	6	20	12	0.43	0.09	1	0	7.5	0.18	119.56	9.68	0.0106	0.04	3.7	0.774
BH-53				Chuko Lela womerera	12.4591	0.1754	3	44	8.64	0.3	0.29	0.2	0.002	3	0	207.4	3.52	0	0.35	0	0.95
BH-54				Chuko Kosoricha Health	8.6595	0	3	12	6.96	0.24	0.13	0	0.04	1.5	0	82.96	11	0.0264	0	1	0.527
BH-55				Wonago Karasodet	33.6697	0.0516	5	47	12	0.75	0.3	0.16	0	7.5	0.1	258.64	0.4664	0	0.26	0	16
BH-56				Dale Mesincho Bute	25.6749	0.1187	3	5.6	8.16	0.09	0.1	0.1	0.008	4.5	0	104.92	18.04	0.0792	0.06	0	0.27
BH-57				Dale Mesincho Agudo	22.8942	0.4592	2	16	7.2	0.54	0.18	0.3	0.013	2.5	0.05	134.2	11	0.1323	0.09	2	0.22
BH-58				Dale Goyda #2	33.5064	2.3994	2	20	9.6	2.26	0.56	0.4	0.115	7.5	0	195.2	0	0.6475	1.45	4.4	0.329
BH-59				Dale Dagia Kebado	38.7642	0.1084	2	12	7.2	0.01	0.16	0.1	0.007	10	0	146.4	15.4	0.0145	0.06	0.4	0.231
HDW-60	441367	713154	2775	AberaDoda HDW	25.04	0.06	5	10	5.76	0.15	0.06	0	0	17	0.02	68.32	19.8	0	0.05	0	9.8
HDW-61	430189	718446	1832	Shoicho HDW	18.48	0	5	28	2.4	0.28	0.04	0.01	0	4	0.03	111.02	4.36	0	0.05	8	11.2
HDW-62				Boricha wome	8.6158	5.5148	10	16	16.8	2.61	0.02	0	0	33	0	141.52	9.68	0.1353	0.22	25	0.75
RIV-63				Gidabo-Abosto RV	24.0281	0.2813	5	8	4.8	0.7	0.07	0.3	0.001	3.5	0.1	104.92	10.12	0.0099	0.11	0.9	0.189
CSP-64	403178	685592	2067	Bochesa CSP	23.25	0	0	58	17.28	0.3	0	0	0	2	0.25	292.8	0.47	0	0	0	14
CSP-65	443551	726883	2466	Garbicho.K CSP	17.07	0.48	2	5.6	3.36	0.3	0.02	0.01	0.01	2.5	0.35	48.8	1.01	0	0.08	2	14.2
CSP-66	441341	713176		Dara Abera Doko CSP	5.727	0.3715	1	6.4	4.32	0	0.47	0	0.26	2.5	0.11	39.04	17.16	0.0142	0	0	0.443
CSP-67	433975	711701		Banko Markos CSP	25.8635	0.3354	1	6.4	3.36	0.26	0	0	0	3.5	0.45	48.8	46.64	0.0531	0	3.8	0.285
CSP-68	417755	692044	1994	Sokicha CSP	48.93	0	1	9.6	2.88	0.1	0.02	0	0	6.3	0.31	58.56	0.85	0	0.02	14	45
CSP-69				Wonsho Gewado	15.9436	0.3521	1	14	1.44	0.15	0.06	0.3	0.016	2.5	0.22	63.44	23.32	0.025	0.25	1.7	0.267
CSP-70				Wonsho Naniga	19.4419	0.1457	0	18	4.8	0.05	0.19	0.1	0.018	3	0.13	91.5	35.64	0.0181	0.08	0.4	0.671
CSP-71				Wonsho Bokaso	27.7771	0.3779	1	36	2.4	0.02	0.05	0.2	0.009	1	0.2	158.6	33.88	0.0174	0.24	2.1	0.871
CSP-72				Wonsho Tehamo	6.5044	0.3715	0	14	4.8	0.08	0.4	0.2	0	3.5	0.13	61	7.16	0.0171	0.07	2.9	0.308
CSP-73				Wonsho Mayke	17.1143	0.2399	1	8.8	3.84	0.05	0.06	0.1	0.014	3	0.2	61	25.52	0.0217	0.12	1.3	0.347
CSP-74				Wonsho Wodincho	18.3793	0.2076	0	16	4.8	0.07	0	0.1	0.013	2.5	0.1	91.5	26.4	0.03	0.2	0.3	0.559
HSP-75	418850	732980	1601	DansheGamb HSP	74.45	0.05	8	20	7.2	0.3	0.8	0	0.02	3.5	1.21	256.2	0.47	0	0.1	0	22.3

Annex.19

Rift floor = $P_{ET\ m} = [16N_m[10T_m(^0C)]^a$

Rift floor PET	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
T_m (^{0}C)	22.9	23.56666667	23.56666667	22.73333333	22	21.433333	20.866667	21.1	21.866667	22.1	22.4	22.5
T_m (^{0}C) /5	4.58	4.713333333	4.713333333	4.546666667	4.4	4.2866667	4.1733333	4.22	4.3733333	4.42	4.48	4.5
$i_m = [T_m (^0C) /5]^{1.5}$	9.801628028	10.2327469	10.2327469	9.694818288	9.229517864	8.8752291	8.5255933	8.668993	9.1457404	9.2925179	9.482373	9.5459415
$I = \sum i_m$ = 112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73	112.73
N	11.75	11.87	12	12.33	12.38	12.48	12.38	12.33	12.1	11.95	11.82	11.72
N_m *(N/12)*	0.979166667	0.989166667	1	1.0275	1.031666667	1.04	1.0316667	1.0275	1.0083333	0.9958333	0.985	0.9766667
T_m (^{0}C)/I	0.203140247	0.209054082	0.209054082	0.201661788	0.195156569	0.1901298	0.185103	0.187173	0.1939738	0.1960436	0.198705	0.1995919
a = 2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
$10T_m$ (^{0}C)/I	2.031402466	2.09054082	2.09054082	2.016617878	1.951565688	1.9012981	1.8510305	1.871729	1.939738	1.9604364	1.987049	1.9959195
$[10T_m (^0C)/I]^a$	5.881524878	6.318974899	6.318974899	5.775093665	5.320567221	4.9845451	4.6615884	4.792999	5.2403186	5.3812345	5.565719	5.6280446
$16N_m$	15.66666667	15.82666667	16	16.44	16.50666667	16.64	16.506667	16.44	16.133333	15.933333	15.76	15.626667
$16N_m[(10T_m(^0C)/I]^a$	92.14388975	100.0083094	101.1035984	94.94253985	87.8248296	82.94283	76.947287	78.79691	84.543807	85.741003	87.71573	87.947576
$P_{ET\ m} = [16N_m[10T_m(^0C)]^a$	=1060											

Annex. 20

Escarpment=PET $P_{ET\ m} = [16N_m[10T_m(^0C)]^a$

Escarpment PET	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
T_m (^{0}C)	18.1	18.53333333	18.53333333	17.76666667	17.2	16.9	16.6	16.66667	16.766667	16.9	17.53333	18
T_m (^{0}C) /5	3.62	3.706666667	3.706666667	3.553333333	3.44	3.38	3.32	3.333333	3.3533333	3.38	3.506667	3.6
$i_m = [T_m (^0C) /5]^{1.5}$	6.887519728	7.136336149	7.136336149	6.69813544	6.380249525	6.2140544	6.0493279	6.085806	6.1406605	6.2140544	6.566618	6.8305197
$I = \sum i_m$ = 78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34	78.34
N	11.75	11.87	12	12.33	12.38	12.48	12.38	12.33	12.1	11.95	11.82	11.72
N_m (N/12)	0.979166667	0.989166667	1	1.0275	1.031666667	1.04	1.0316667	1.0275	1.0083333	0.9958333	0.985	0.9766667
T_m (^{0}C)/I	0.231044166	0.236575611	0.236575611	0.226789209	0.219555782	0.2157263	0.2118969	0.212748	0.2140243	0.2157263	0.223811	0.2297677
a = 1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
$10T_m$ (^{0}C)/I	2.310441665	2.365756106	2.365756106	2.267892094	2.195557825	2.1572632	2.1189686	2.127479	2.1402434	2.1572632	2.238107	2.2976768
$[10T_m (^0C)/I]^a$	4.329784321	4.512814134	4.512814134	4.191207643	3.96007617	3.8399935	3.721499	3.747694	3.7871328	3.8399935	4.095356	4.2880085
$16N_m$	15.66666667	15.82666667	16	16.44	16.50666667	16.64	16.506667	16.44	16.133333	15.933333	15.76	15.626667
$16N_m[(10T_m(^0C)/I]^a$	67.83328769	71.42280502	72.20502614	68.90345365	65.36765732	63.897492	61.429544	61.61208	61.099076	61.183897	64.5428	67.00728
$P_{ET\ m} = [16N_m[10T_m(^0C)]^a$	=786.504											

Annex.21Highland

PET= $P_{ET\ m} = [16N_m[10T_m(^0C)]^a$

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
T_m (^{0}C)	14.66666667	15.06666667	15.16666667	15.03333333	14.8	14.066667	13.533333	13.56667	14.033333	14.166667	14.13333	14.266667
T_m (^{0}C) /5	2.933333333	3.013333333	3.033333333	3.006666667	2.96	2.8133333	2.7066667	2.713333	2.8066667	2.8333333	2.826667	2.8533333
$i_m = [T_m (^0C) /5]^{1.5}$	5.023913186	5.2308319	5.282995082	5.21348255	5.092576558	4.7188024	4.4529945	4.469457	4.7020393	4.7692107	4.752388	4.8197972
$I = \sum i_m$ = 58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53	58.53
N	11.75	11.87	12	12.33	12.38	12.48	12.38	12.33	12.1	11.95	11.82	11.72
N_m (N/12)	0.979166667	0.989166667	1	1.0275	1.031666667	1.04	1.0316667	1.0275	1.0083333	0.9958333	0.985	0.9766667
T_m (^{0}C)/I	0.250583746	0.257417848	0.259126374	0.25684834	0.25286178	0.2403326	0.2312205	0.23179	0.2397631	0.2420411	0.241472	0.2437496
a = 1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414	1.414
$10T_m$ (^{0}C)/I	2.505837462	2.574178484	2.591263739	2.568483399	2.528617803	2.4033259	2.3122046	2.3179	2.3976308	2.4204112	2.414716	2.4374964
$[10T_m (^0C)/I]^a$	3.665383304	3.807527595	3.843310103	3.795621893	3.712588649	3.4551676	3.271396	3.282795	3.443596	3.4899504	3.478345	3.5248351
$16N_m$	15.66666667	15.82666667	16	16.44	16.50666667	16.64	16.506667	16.44	16.133333	15.933333	15.76	15.626667
$16N_m[(10T_m(^0C)/I]^a$	57.42433843	60.26047007	61.49296166	62.40002392	61.28246329	57.493989	53.999844	53.96916	55.556682	55.606544	54.81871	55.081423
$P_{ET\ m} = [16N_m[10T_m(^0C)]^a$	=689.38											