HYDROGEOLOGICAL INVESTIGATION OF THE UPPER AND MIDDLE BORKENA RIVER CATCHMENT, NORTHERN ETHIOPIA, WOLLO

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By
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ABSTRACT

The geology, hydrology, hydrogeology and hydrochemistry of the Borkena catchment which is located on the western edge of the Afar rift was studied based on conventional geologic and hydrogeological mapping, river discharge measurements, water sample analysis and assessment and interpretation of hydrometeorological data. The main objective of this work is to understand the different lithologic unit and to characterize and group them into hydrostratigraphic unit and map them, to analyze the water balance and to study the water quality.

Four hydrostratigraphic units were recognized and mapped. These are: colluvial and river channel deposits, alluvial deposits, scoraceous and basaltic lava flow and fractured massive basalt, welded tuff and rhyolite. Generally the volcanic rocks lie with in the recharge zone while the Quaternary sediments lie in the discharge zone. Accordingly the hydrostratigraphic unit located on the Quaternary sediments are characterized by many springs and hand dug well where as low or rare in the volcanic regions.

From storage, utilization and abstraction point of view, the colluvial and river channel deposits are the most promising units than other units as a result most of the springs, hand dug wells and boreholes are located in this hydrostratigraphic units.

Generally seven rock units and three set of faults are identified and mapped at the scale of 1:50,000. Among the rock units, scoraceous and basaltic lava flow and alluvial deposits cover more than 70 percent of the catchment.

From hydrochemical analysis, measurement of TDS, EC and other variables, the water bodies are characterized by low total dissolved solids (TDS) and low electrical conductivity (EC) values as a result they are classified as fresh water and their utilization for various purposes scarcely bring danger.

CHAPTER 1

Introduction

1.1 Background

In any country specially drought prone like Ethiopia, intensive water resource planning, development and management can have a deceive role in the economic and social growth of the country and in reducing the recurrent drought problems.

In Ethiopia, there is a large variation in altitude ranging from 120m below sea level to 4620m above sea level. The large topographic, geologic and climatic variation results in variable hydrogeologic properties which is reflected by the variations in the aquifers' permeability, storage capacity and productivity. In addition, there are differences in the depth to the groundwater level (Tesfaye Chernet, 1993).

The surface and groundwater resource of the highland are wide spread and low to large quantities with good to fair chemical quality but a few cases of poor chemical quality. Mostly the streams are seasonal and have intermittent flow except for few perennial ones and the depth to the groundwater is generally less than 100m which is exploitable in low relief areas (Tesfaye Chernet, 1993). Accordingly shallow groundwaters are tapped and many water wells drilled in Kombolcha area are characterized by flowing well in nature (artesian).

The project area, the Borkena river catchment is located in south Wollo Administrative Zone, Northern Ethiopia. It is located between $10^0 59'$ and $11^0 18'$ north latitude and between $39^0 32'$ and $39^0 46'$ east longitude (Fig. 1.1a). The average elevation in the catchment ranges from 1680m to 3360m a.s.l southern Kombolcha and Kutaber area respectively. The total area of the catchment is 326 km^2 and it is crossed by the main road from Addis Ababa to Mekele via Dessie (Fig. 1.1b).

In the study catchment, there is a large area of alluvial deposit (35.4%, Fig. 3.3 and Table 3.1) which is potential area for farming, except for the lack of sufficient amount of surface water in the dry seasons. Hence it is imperative to investigate the water resource potential of the area for various purposes specifically to see whether it satisfies the needs of the rapidly growing population and industries in the area and to assess the general surface and groundwater resources.

Most streams in the catchment are intermittent with the exception of Borkena and this river emanates from a contact spring found in the locality called Aremenae located some 3 to 3.5 km northeast of the town of Kutaber (Fig. 1.1b).

Regional and local hydrogeological studies were conducted in the area of interest some to mention are: Mezmur Hailemeskele, (1977); Ketema Tadesse, (1980); and Molla Demlie, (2000). Long years have passed since Ketema Tadesse had been studying the area, hence the hydrogeological, hydrochemical and hydrological data need a thorough updating in accordance with the currently available data, so that it will be utilized for future water resource planning, development, utilization and management.

Fig. 1.1a LOCATION MAP OF THE BORKENA RIVER CATCHMENT

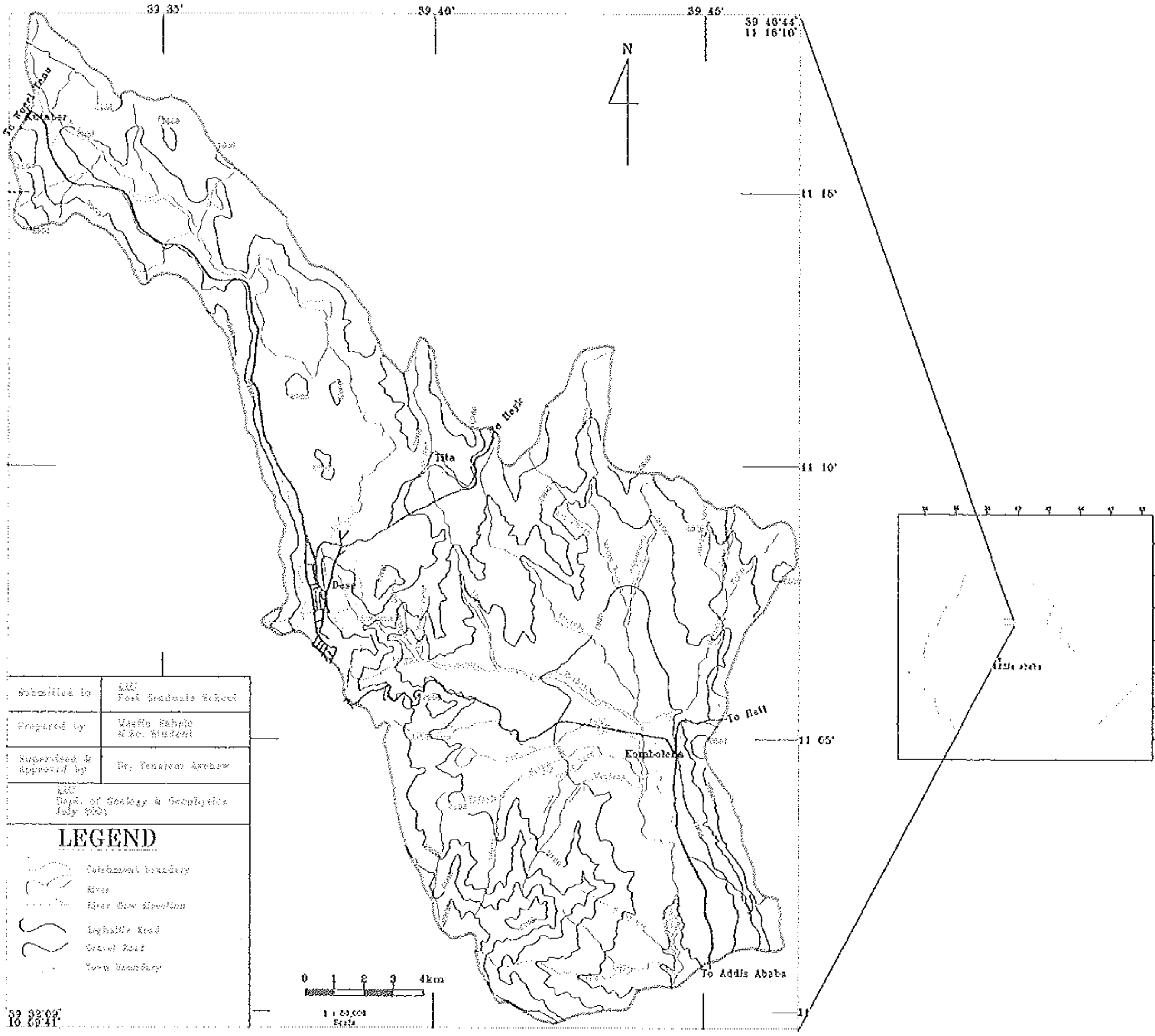
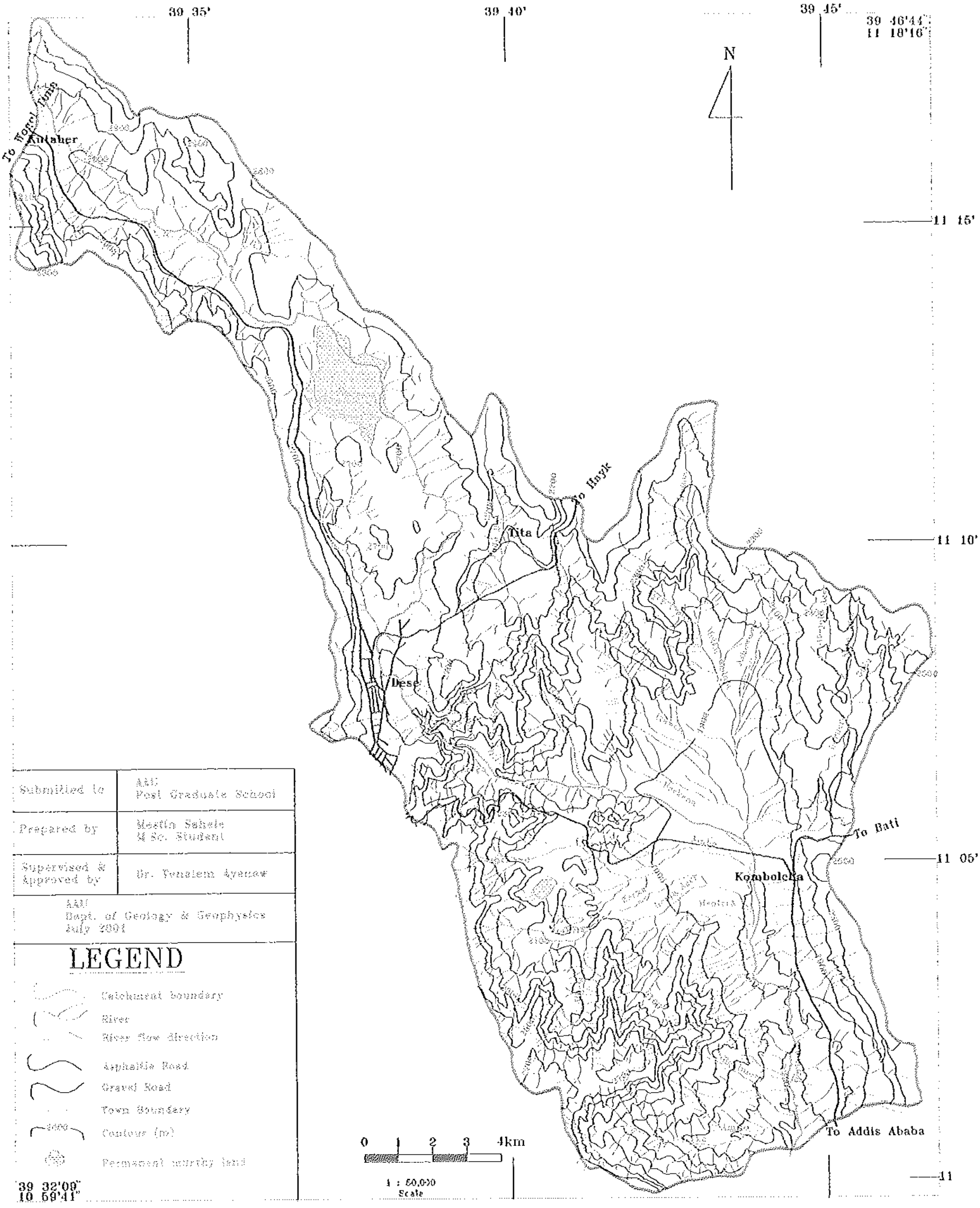


Fig. 1.1b SIMPLIFIED TOPOGRAPHIC MAP OF THE STUDY AREA



1.2 Objective and Scope of the study

The general objectives of this research work are:

- To study the general hydrology and hydrogeology.
- To assess the water balance of the area.
- To produce the hydrogeological map of the catchment at the scale of 1:50,000
- To study the surface and groundwater interaction through conventional hydrogeological mapping and water quality studies.
- To study the water quality.

The specific objectives of the research work are:

- To determine each hydrologic input and output in the catchment by analyzing the available hydrometeorological data.
- To evaluate and assess the groundwater and surface water resource potential.
- To identify the possible discharge and recharge areas.
- To suggest possible future sustainable development site from the stand point of water quality and availability in the catchment.

1.3 Methodology

To meet the objectives mentioned above, different materials and methods were used. These are:

1. Air photos produced in 1986 by the Ethiopian Mapping Agency at the scale of 1:50,000.
2. Topographic maps of Dessie, Haik, Degan, Harbu and Degega published in 1993 were used.
3. GPS was used to locate water sampling sites such as springs, boreholes, hand dug well and rivers
4. EC of water samples was measured in the field
5. Water samples were collected carefully and kept in a new plastic bottle
6. Field conventional hydrogeological mapping was done
7. River discharge measurements

The methods that were used include desk top studies of topographic map and air photos with preparation of the Base map including literature review with particular emphasis on the hydrology, hydrogeology, hydrochemistry and geology. During the fieldwork from February 19, to March 10, 2001, systematic sampling and locating of water points such as springs, hand dug wells, boreholes and rivers together with conductivity and discharge measurements were done. In addition preliminary geologic map was also prepared by conventional mapping. Just after the fieldwork, detailed geologic, land use-land cover, soil, slope, drainage, isohyetal and thiessen polygon map, together with hydrogeological map were prepared.

For the purpose of hydrometeorological data analysis, data collected from the Ethiopian Meteorological Services Agency and from the Ministry of Water Resource were used. Concerning the hydrochemical data analysis, fourteen water samples were analyzed in the Ethiopian Geological Survey's Central Laboratory. Atomic Absorption Spectrometry was used for the major cations (Na^+, K^+, Ca^{+2}, Mg^{+2} Titrimetric method for CO_3^{2-}, HCO_3^-, Titrimetric (Mohr Method) for Cl^-. Ion selective method for F^-.

UV-visible Spectrometric method for NO_3^-, SiO^2 and SO_4^{2-}.

CHAPTER 2

General Overview of the Study Area

2.1 Location and Accessibility

The studied area is located on the western margin Afar rift and is found some 400 kilometer northeast of Addis Ababa and lies between the town of Kutaber and Kombolcha (Fig. 1.1a). The average elevation varies between 1680 and 3360 meter above mean sea level (a.s.l). A large proportion of the catchment is part of the floor of a graben (Fig. 1.1b).

Most parts of the area are not accessible to vehicles and the main access roads are: Kombolcha-Dessie, Kombolcha-Bati, Dessie-Kutaber, and Dessie-Haik.

2.2 Climate

The climate of the study area varies between subhumid and subtropical traditionally called 'Dega" and Weigna Dega" and such classification is possible considering altitude as the major factor in determining the climate of the region. The mean annual rainfall over the studied catchment is 1028mm and most of which are concentrated in the big rainy months that last from July-September and contribute about 84 percent of the annual rainfall. The mean monthly temperature considering the Kombolcha station is varying between 16.1°C and 22.1°C which corresponds to December and June respectively. Monthly mean sunshine hour and relative humidity varies between 5.0 to 8.5 and 40.1% to 64.3% with rainy seasons being the most humid and have lowest sunshine hour. The aerial coverage of subhumid and subtropical climates are approximately equal, contributing 50.3% and 49.7% of the area of the studied catchment.

2.3 Physiography and Drainage

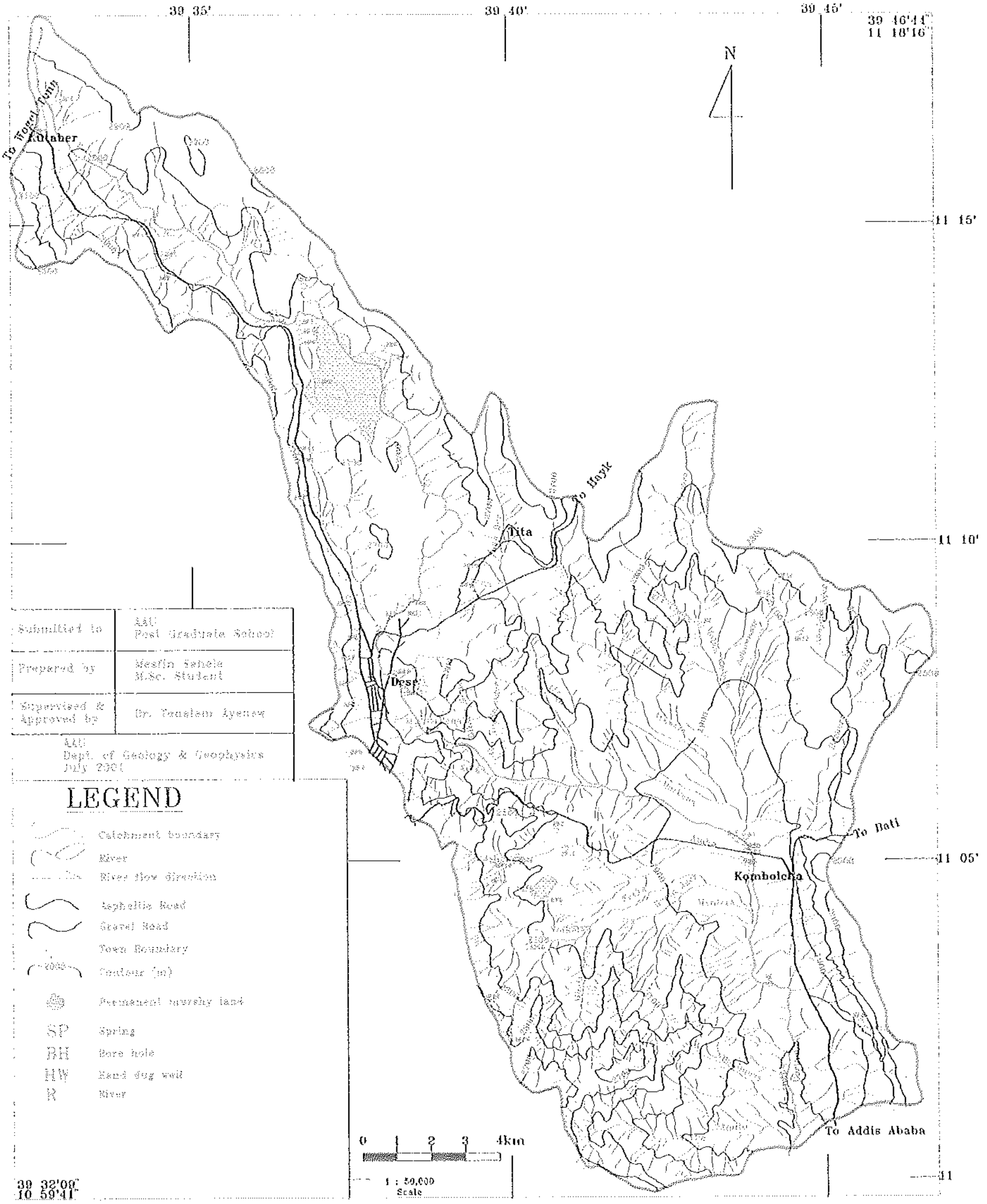
The different landscapes that are present in the catchment are the results of volcano-tectonic and erosional processes. The graben is mainly bordered by fault escarps that have N-S and E-W orientation (Fig. 3.3). There large topographic differences between the floor of the graben and the top of the ridge. Accordingly the minimum and maximum elevation in the catchment ranges from 1680m and a little over 3360m a.s.l south of Kombolcha and northwest of the water divide of Kutaber. Both the towns of Dessie and Kombolcha are located on the floor of the graben at an elevation at 1903m and 2660m a.s.l respectively. This fault bounded graben form large plain areas such as the Boru plain, Alensha plain, Mariam Wiha plain and large flat lands in Kombolcha and it's surrounding. These plains are seasonally flooded by the Borkena river, specially small parts of the Boru plain permanently stay as marshy area (Fig. 2.1).

From geomorphological point of view, the catchment lies between very steep fault bounded grabens. To the west it is bounded by the Tosa, Wefkele and Walet Ridges and to the east it is bounded by Dosheny, Kundi Ameraro and Irfo Ridge. The topography and slope of the catchment get lower from the ridge towards the floor of the graben and from the Dessie towards Kombolcha (Fig. 1.1b & 2.4).

Most of the streams originate from the surrounding ridge, hills and fault escarp regions and the associated drainage patterns are mainly dendritic with some radial and trellies patterns (Fig. 2.1). The drainage patterns are dense in the topographically highs and low in the topographically lows, this shows that the topographically high areas are covered relatively with impervious geologic materials. From the dense drainage patterns predominated by first and second order, it is possible to deduce that there is high runoff with little infiltration recharging the subsurface water.

The main streams in the catchment that have separate drainage system and joining the Borkena river are: Ambo, Berber, Tedo, Guto Beriho, Ager Chore, Amito and Wefkele. During the field work investigation from February through March, all rivers were dry with the exception of Berber, Ager Chore and Wefkele. There are no rivers entering into the catchment however the Borkena river flows out of the catchment, so it is not a closed catchment.

Fig 2.1 DRAINAGE & WATER SAMPLE LOCATION MAP OF THE BORKENA RIVER CATCHMENT



2.4 Land use-land cover

Generally six land use-land cover units are identified and mapped in the catchment (Table 2.1 and Fig. 2.2). These are:

- Bushes, shrubs with scattered trees
- Large settlement area
- Woodland
- Large cultivation and small irrigated land
- Inundated/marshy and large grazing land
- Bare ground with occasional bushes and shrubs.

Table 2.1 Aerial and percentage distribution of the land use-land cover units.

No.	Land use-land cover units	Aerial coverage (in km^2)	Aerial proportion in percent
1	Bushes, shrubs with scattered trees	96.0	29.5
2	Large settlement area	11.8	3.6
3	Woodland	19.4	6.0
4	Inundated/Marshy and Large grazing land	10.6	3.3
5	Large cultivation and small irrigated land	140.7	43.2
6	Bare ground with occasional bushes and shrubs.	47.4	14.5

The rapid population growth which forces people to use lands even in steeply sloping area in addition to the gentle and flat lands makes large area to be cultivated and enhances the subsequent clearing of forests with the aim of seeking additional plough area, satisfaction of energy consumption and construction material forces to change the pattern of land use-land cover of the area. Accordingly the proportion of vegetated land is diminishing with increasing of plough and bare lands (Table 2.1 and Fig. 2.2).

There is a large flat land starting from some 8 km north east of Dessie, however it is seasonally flooded by the Borkena river. Hence, left for community grazing land and accounts about 3.3 percent of the catchment (Table 2.1 and Fig. 2.2).

The major crops grown in the area are: wheat, maize, beans, teff, sorghum, millet and peas. Concerning the vegetation, Eucalyptus, Acacia and Juniper trees cover small proportion followed by large coverage of related bushes and shrubs. Both large and scattered settlements are identified in the major towns (Dessie, Kombolcha, Kutaber and Tita) and rural areas.

Along with the land use-land cover units, a broad classification and mapping of the soil types and slope classes was done in view of better understanding of the infiltration, runoff and evapotranspiration processes. Therefore, the major soil types in the catchment are clay loam soil, residual clay soil rich in organic material, gravely sand soil and fractured rock with big boulders and cobbles. These different soils occupy the flat, gentle-moderate and moderate-steep slopes and account 32.2%, 1.5%, 13.1% and 52.2% of the catchment's area respectively (Table 2.2 and Fig. 2.2). On the other hand the slope classification which was made on the basis of the Ministry of Agriculture land use and Regulatory Department shows that five slope classes were identified and mapped. Slope class 12-35% predominate and cover 40.7%.

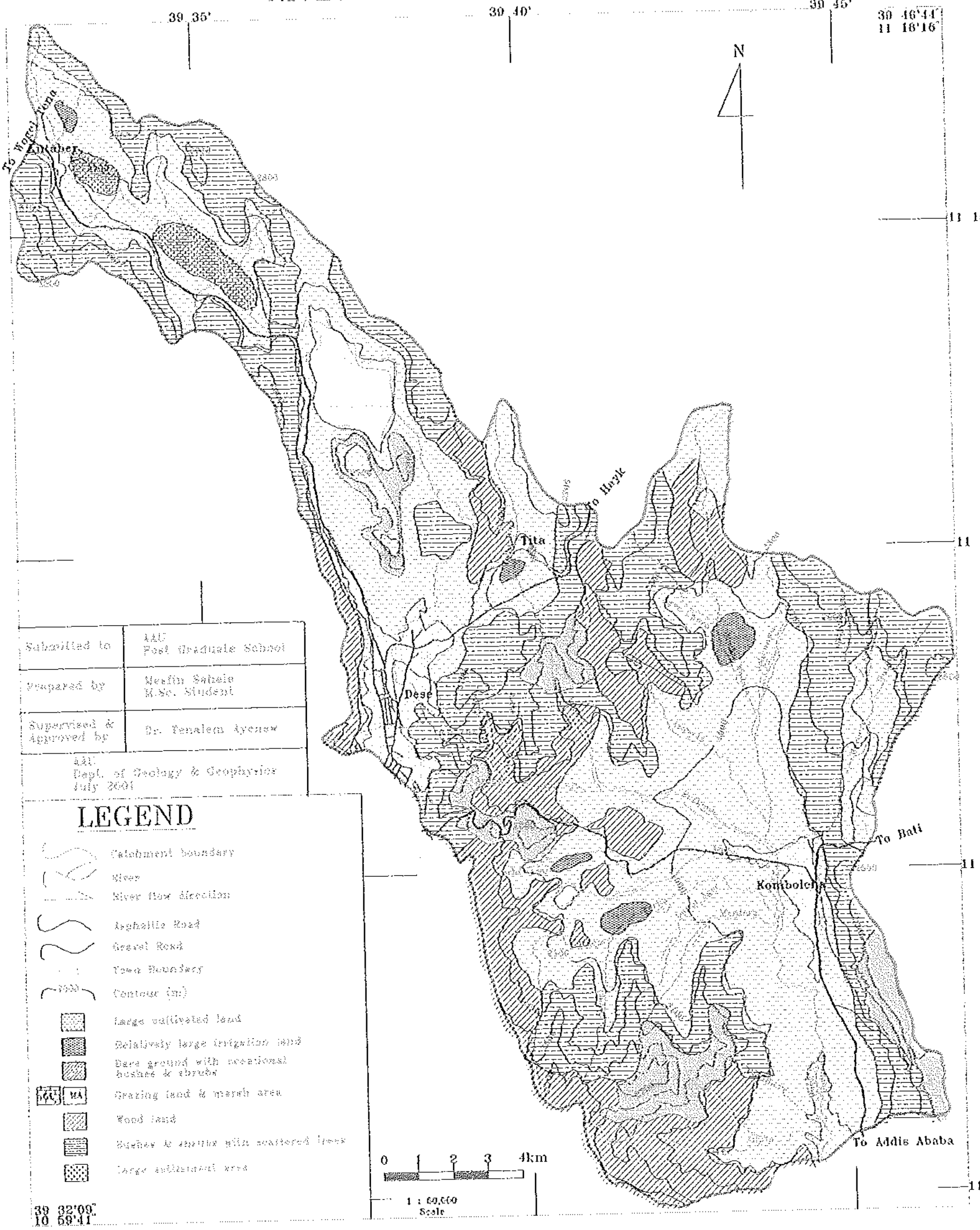
Table 2.2 Soil unit of the catchment

No.	Soil Types	Aerial Coverage (in km^2)	Aerial proportion in percent
1	Clay loam soil	108.0	33.2
2	Residual clay soil rich in organic material	5.0	1.5
3	Gravely sand soil	42.5	13.1
4	Fractured rock with big boulder and cobble	169.8	52.2

Table 2.3 Slope classification of the catchment

No.	Slope class	Area proportion (in km^2)	Area proportion in percent
1	< 5%	56.8	17.4
2	5-12%	110.5	33.9
3	12-35%	132.8	40.7
4	35-60%	21.8	6.7
5	>60%	3.9	1.2

Fig. 2.2 LANDUSE–LANDCOVER MAP OF THE BORKRNA RIVER CATCHMENT



2.3 SOIL MAP OF THE BORKENA RIVER CATCHMENT

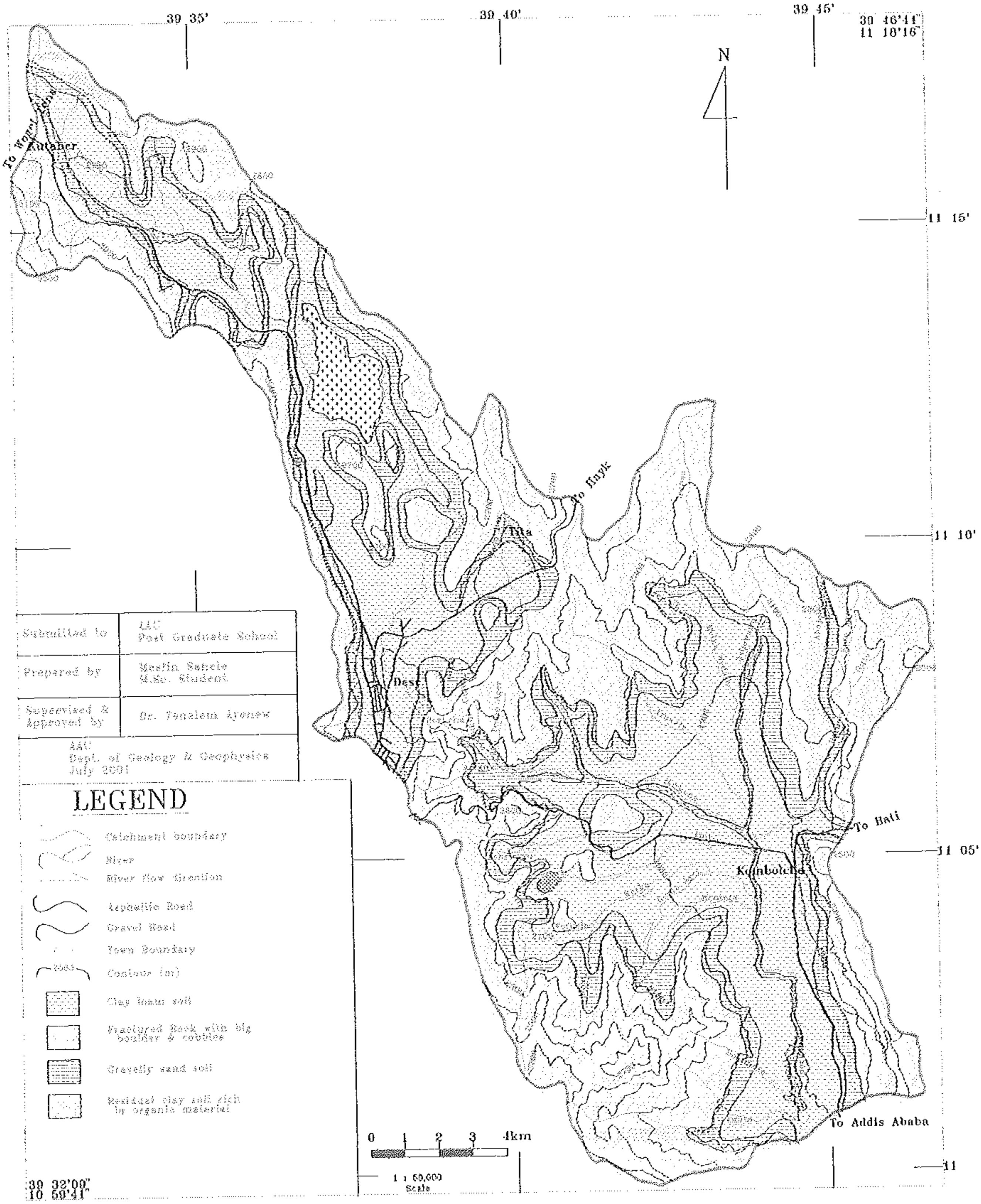
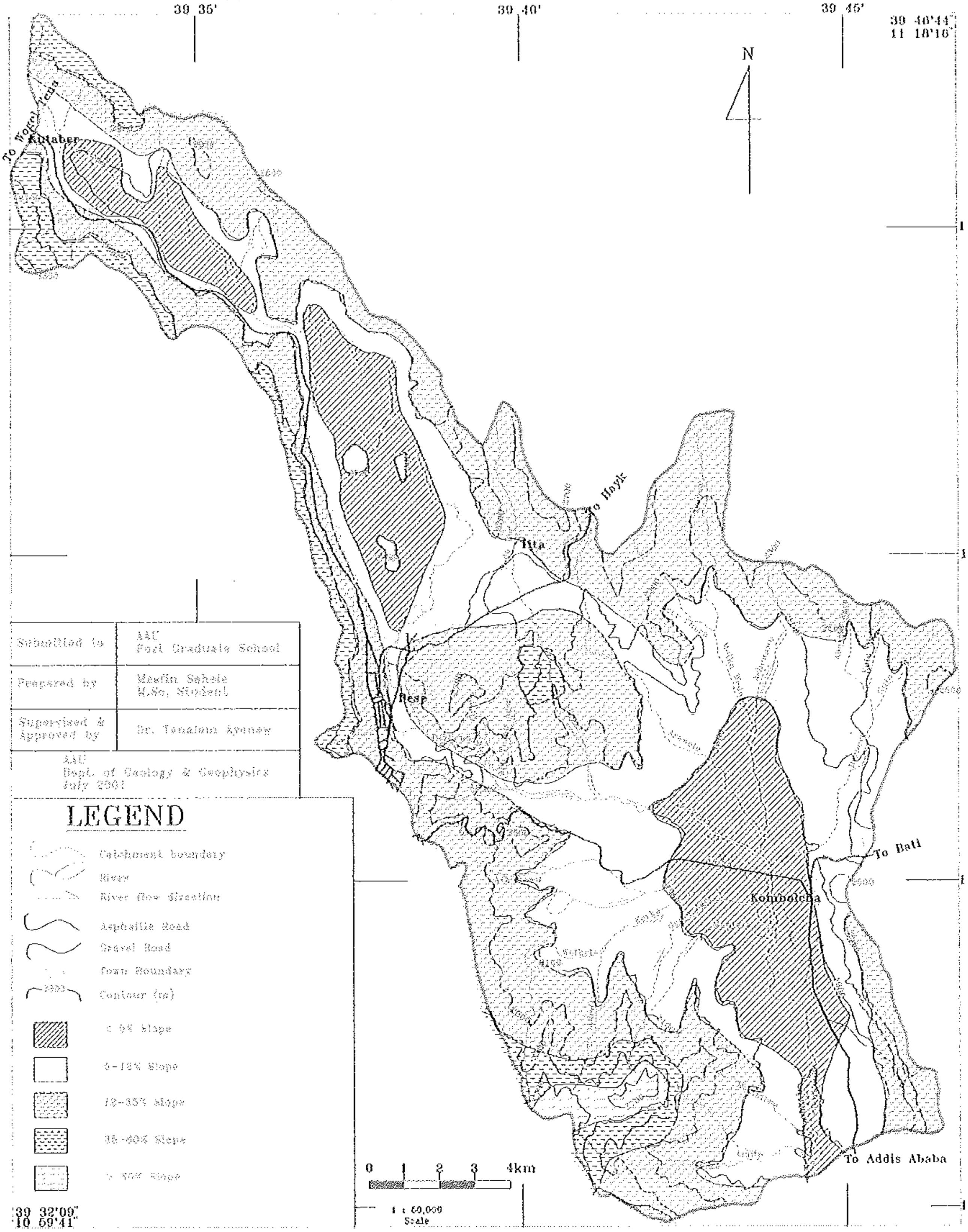


Fig. 2.4 SLOPE MAP OF THE BORKENA RIVER CATCHMENT



CHAPTER 3

Geology

3.1 Regional Geology

The Cenozoic Ethiopian continental flood basalt province is located at the junction of three rifts: two oceanic rifts, Red Sea and Gulf of Aden and the East African Rift. In Ethiopia this huge volume of lava was erupted 30 million years (Ma) prior to the significant extension (Courtillot et al., 1987; Jestin and Huchan, 1992 cited in Pik et al., 1998) and forms a pile of 2000 meters and cover an area of about 600,000 km^2 (Mohr and Zanettin, 1988 cited in Pik et al., 1998). On the northwestern plateau, this Oligocene basalts are overlain by less voluminous Niocene lava erupted from large central vent volcanoes. In contrast in southern Ethiopia, Eocene-Oligocene basalts are rare and the volcanic sequence is dominated by this Eocene-Miocene acidic lavas and ignimbrite. In this area the youngest volcanic activity is represented by Miocene basalts and ignimbrites. In Afar and the Main Ethiopian rift (MER), Miocene and Plio-Quaternary volcanism is located along the rift axis and is related either to fissural activity (the Afar stratoid formation), or more frequently to central vent type (Pik et al., 1998).

Following the physiographic subdivision of the country, the volcanics show an asymmetric distribution about Afar and the Rift valley being voluminous in the western Ethiopia plateau (Mohr, 1983).

3.2 Regional Stratigraphy

Until recently, the Ethiopian volcanics were divided into two main series: 1) Trap (=Plateau) series; 2) Rift series. It is now generally accepted that the Trap Series in the north western Ethiopian plateau was formed by two stage or cycle of volcanism: the Ashangi cycle (50-35Ma) and the post Ashangi cycle (32-15Ma). The rift series is younger than 15-13Ma, Fig. 3.1a (Zanettin et al., 1978 cited in Zanettin, 1993).

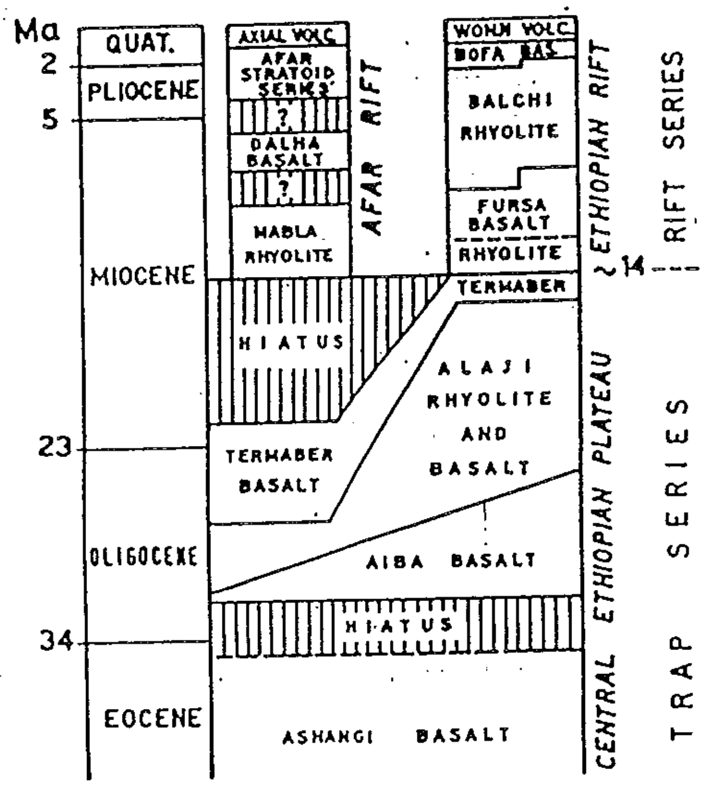
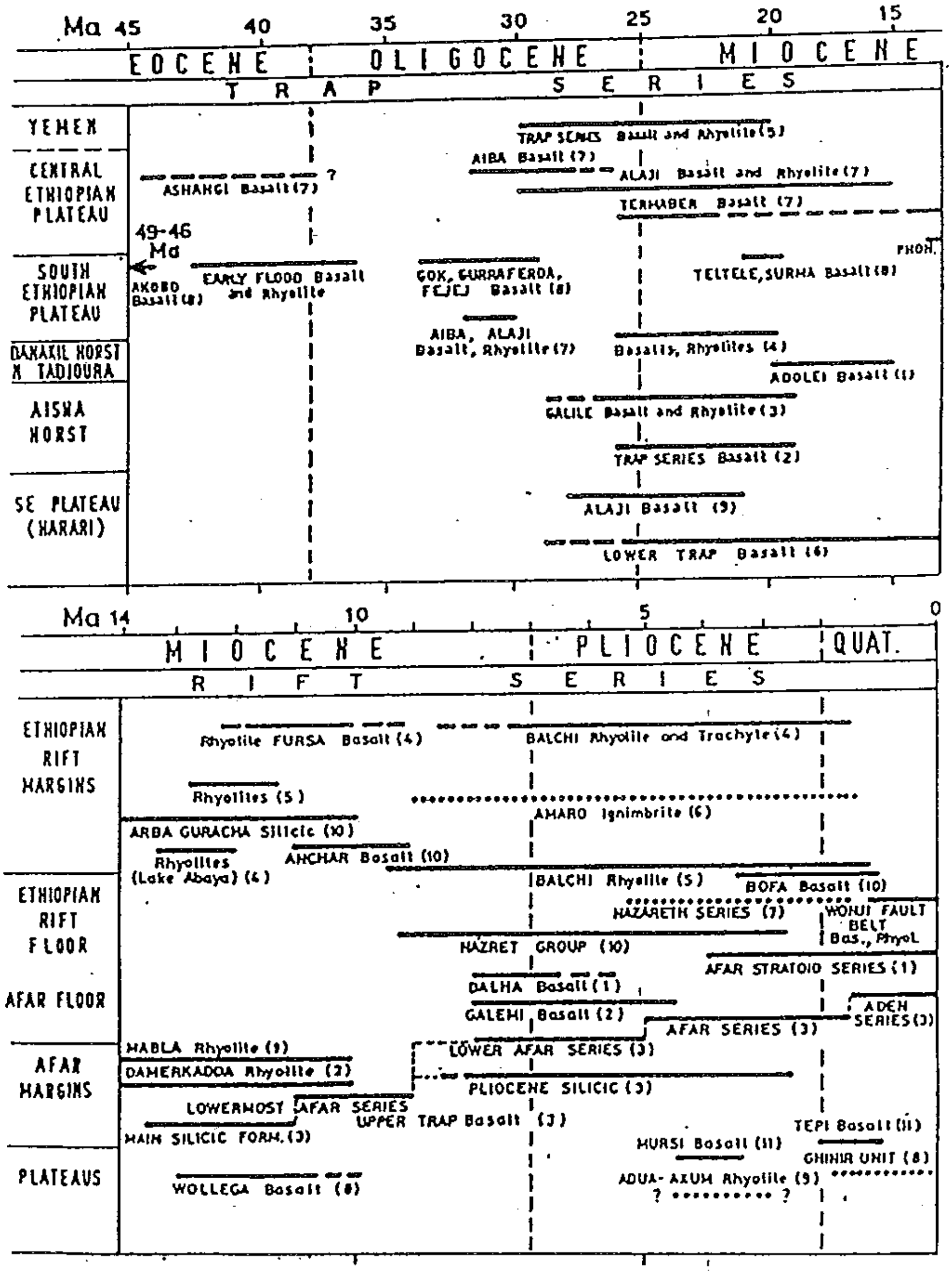


Fig. 3.1a Schematic stratigraphic sequence of volcanics from north western Ethiopia and Afar rift (after Zanettin et al., 1978 cited in Zanettin, 1993)

The Chronological correspondence with the volcanic sequence recognized by other authors in the north western Ethiopia is summarized and shown in Fig. 3.1b



.... No radiometric dating

Fig. 3.1b Chronological correspondence among volcanic formations of North western Ethiopia and those described by other authors in different sectors of Ethiopia (after Zanettin et al., 1980 cited in Zanettin, 1993).

3.3 Volcanism of the Trap (Plateau) Series

3.3.1 Ashangi Cycle (35-50Ma)

The Ashangi cycle occurs in Wollega (Merla et al., 1973; Seifemichael Berhe et al., 1987 cited in Zanettin, 1993) and the south eastern Ethiopian plateau (Davidson et al., 1980 cited in Zanettin, 1993) as well as in the north western Ethiopian plateau. Its northern branch trends E-W, i.e. almost perpendicular to the present western Afar escarpment (Zanettin et al., 1980 cited in Zanettin, 1993). The "fissural" basalts of the north western plateau are represented by transitional basalt with tholeiitic affinity while the "moderately fissural" basalts are still transitional but alkaline affinity and are characterized by low Na_2O/K_2O and lower content of Al_2O_3 (Zanettin, 1993)

3.3.2 Post-Ashangi Cycle

Plateau Sequences: Aiba and Alaji Fissural Volcanism (15-32Ma)

This cycle began at the end of the Ashangi cycle with immense outpouring of Aiba flood basalt covering the peneplain and dated back 25-32 Ma are typical of transitional basalt. It is followed by the Alaji rhyolite exposed on the eastern edge of the northwestern plateau basalt and in the underlying escarpment: the occurrence of Alaji volcanism is controlled by tectonics and in the course of time, it died out in the north and was progressively confined to the south. The Alaji volcanics are generally represented by interlayered silicic rocks and transitional basalts, but sometimes only by silicic rocks mostly slightly peralkaline rhyolite. The Alaji rhyolite began to form 25-30 Ma ago in the Afar escarpment and then progressed to the south upto Addis Ababa and paralleling it 15 Ma (Zanettin, 1993).

3.3.3 Tarmaber Central Volcanism

The Alaji volcanism ended up with the initiation of a central type of volcanism which built up large shield volcanoes decreasing in age from north to south. In this regard, the composition of the lava changed to alkali basalt and basanites. This stage was completed and followed by a strong uplift which caused the appearance of a proto-Ethiopian rift (Zanettin, 1993).

3.4 The Rift Series

The series was confined in the rift and formed after the escarpment fissural volcanism completed. This new volcanic stage began with the emission of Mabla rhyolitic ignimbrites (11-14Ma) followed by the voluminous Fursa basalt (9-12Ma). The Fursa basalt which was exposed at the base of the Ethiopian and Harar escarpment show a transitional and alkaline composition and corresponds to the Aiba and Anchar basalts in cases of Ethiopian and Harar escarpment respectively Zanettin, 1993.

Volcanism has of different composition in the Afar and Ethiopian rift. In the last 8Ma, lavas of basic character largely prevailed in the Afar while silicic products in the Ethiopian rift (Zanettin, 1993).

Mainly transitional basalts with varying affinity from tholeiitic to alkaline were emitted in Afar. The formation of the Dalha basalts (6-8Ma), the Afar stratoid series (1-4Ma) and the younger volcanoes built up on the axial fissural system of Afar (Barberi et al.,1975 cited in Zanettin, 1993). Instead the volcanoes placed on the tectonic lines transversal to the axial fissures have a clearly alkaline composition (De Fino et al., 1973; Zanettin, 1978 cited in Zanettin, 1993).

Voluminous ignimbrite mainly peralkaline rhyolites (Balchi Formation), locally interlayered with basalts were emitted in the Ethiopian rift and in southern Afar from 2 to 8 Ma. The Balchi rhyolite are covered by Bofa transitional alkaline basalts (Kazmine et al., 1980; Brotzu et al., 1980b cited in Zanettin, 1993), and still younger basalts and peralkaline silicics built up volcanics in the axial zone of the Ethiopian rift (Wonji Group) (Zanettin, 1993). During this same time, the rift has been strongly downfaulted relative to either side of the plateau. Interesting but volumetrically minor basaltic eruption have occurred on both plateaus of Ethiopia during Quaternary time notably in the Tana basin and along fault zones west ward from Addis Ababa region (Mohr, 1983).

3.5 Structural Evolution of the Ethiopian Volcanic Province

Generally the structural evolution of the Ethiopian volcanics which was addressed by Merla et al., 1963; Azzoroli, 1968 and Baker et al., 1972 as cited in Zanettin, 1993 seems the following:

A) A flat low-lying territory was highly fractured and then covered by volcanics.

B) The uplift of the two opposite blocks separated by a long belt lying at a lower level caused the appearance of a very wide rift (proto-rift) to which volcanism was confined.

C) Further repeated rising of the peripheral strips of the rift floor caused narrowing of the rift itself. At the same time the rift floor thinned out until continental spreading was complete.

The Ethiopian plateau and Afar rift seems to have occurred through a sequence of distinct uplift (beginning from the north) of blocks bordered by major fault trending N-S and by a minor fault transversal to the present escarpment (Zanettin, 1993).

As regard to the relationship between tectonic and volcanic activity, it may be said that: 1) territorial uplift was preceded by emission of ignimbrite from fissures parallel to the future escarpment; 2) fissural volcanism, both acidic and basic (transitional basalts) died out in the uplifted territories while it continued elsewhere (i.e. to the east and south); 3) in the course of uplift, alkaline basic and intermediate lavas built up shield volcanoes mainly located at the border of the uplifted block.

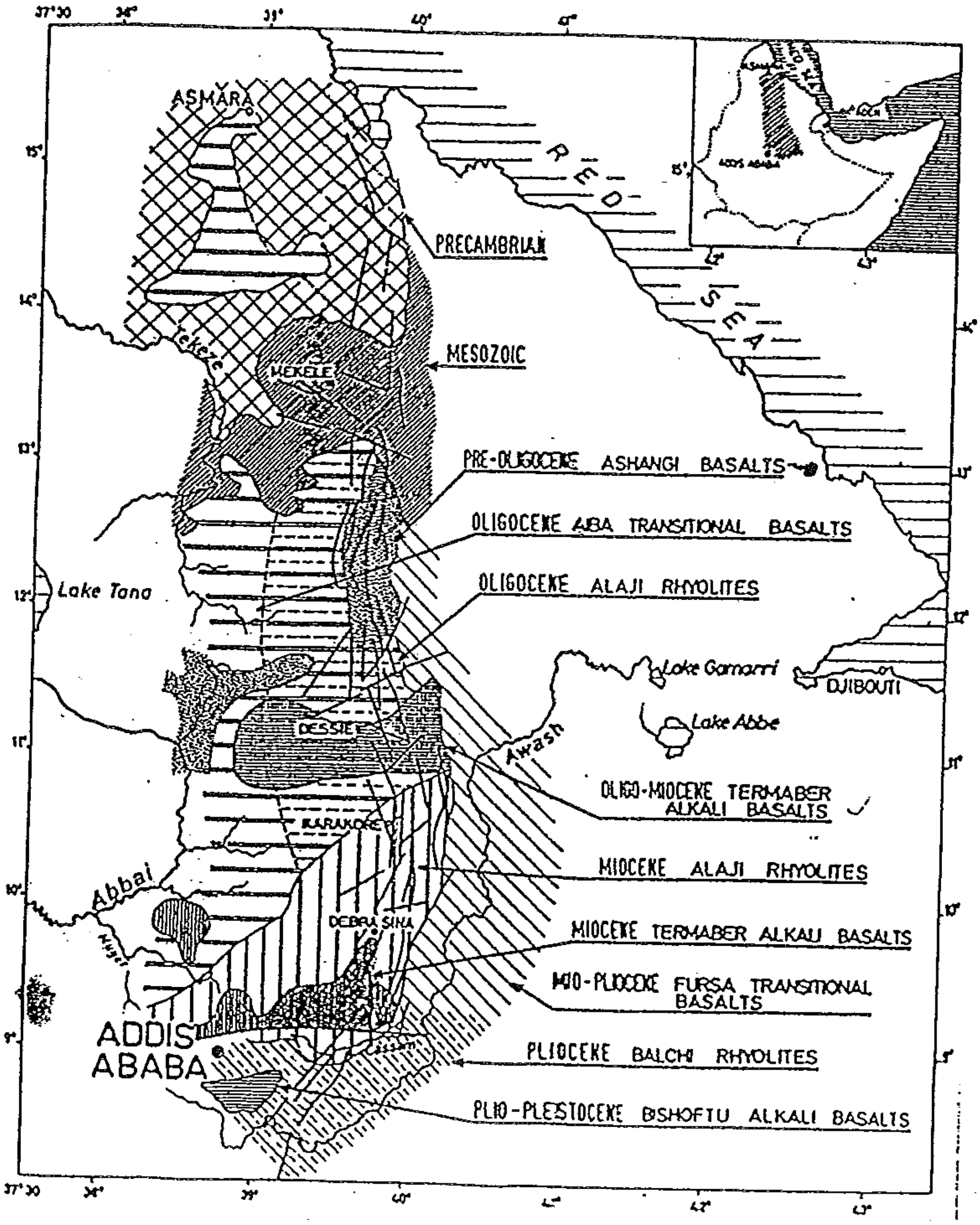


Fig. 3.2 Distribution of volcanics in central Ethiopia (after Zanettin, 1978)

3.6 Local Geology

3.6.1 General

Considering previous works, field mapping has been carried out. The rock units of the studied catchment is subdivided into seven units and mapped at the scale of 1:50000 (Table 3.1 & Fig. 3.3). These different rock units are correlated with the regional stratigraphy mainly considering their stratigraphic position and relative age as a comparison with the regional stratigraphy which is outlined by different authors put for the central and eastern Ethiopia plateau. Some to mention are Zanettin and Justin-Visenttin (1974a); Zanettin et al., (1974) and Zanettin et al., (1978) cited in Molla Demlie, (2000). The stratigraphic succession outlined by Zanettin et al., (1978) shows that rocks outcropping in the Kutaber-Dessie-Kombolcha area belongs to the Alaji Rhyolite, Tarmaber Basalt and recent Quaternary deposits.

Since the age of Oligocene and Miocene, volcanics become younger from north to south and southwest, Zanettin et al., (1974); Zanettin et al., (1974a); Zanettin and Justin-Visenttin, (1975); and Zanettin et al., (1978). The Alaji Rhyolite and the Tarmaber Basalt in the area belongs to the relatively older subunits of the northern sector of the "Alaji-Sirro" Formation which has an age range between 26-32 Ma.

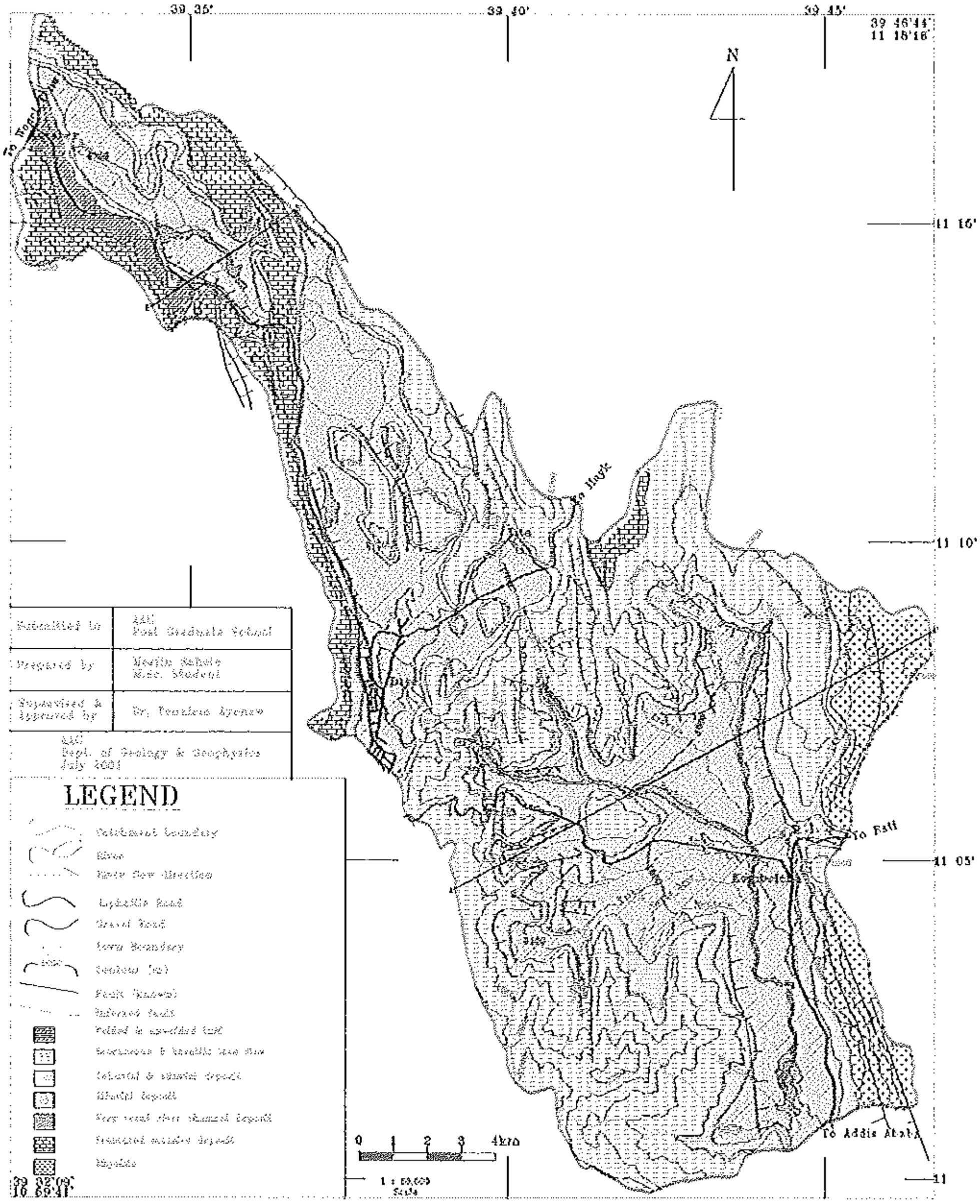
The second cycle of volcanism together with the N-S orientation of fissural system which were opened up since the age of Oligocene is responsible for the formation of the Alaji Rhyolite and the Tarmaber Basalt, Zanettin and Justin Visenttin, (1975) cited in Zanettin, (1993). As it was described by Zanettin et al., (1974) fissural silicic volcanism having an approximate N-S orientation of extensive tectonic crustal movement was responsible for the formation of these rocks.

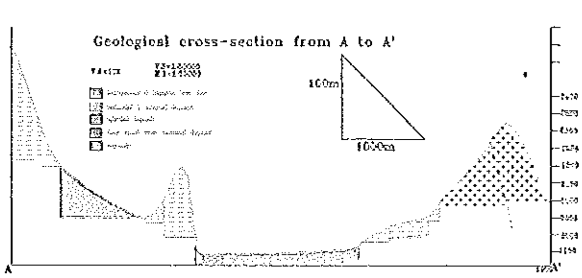
During field investigation which were conducted from February-March, 2001 and review of previous works, it is possible to identify four phases of eruption and seven lithologic units. These are:

1. Eruption related to fractured massive basalts
2. Eruption related to welded and unwelded tuff
3. Eruption related to scoraceous and basaltic lava flows
4. Eruption related to rhyolite
5. Weathering and gravity results in colluvial deposits
6. Weathering and erosion resulting in alluvial deposits
7. Weathering and channel erosion and transportation resulting river channel deposits

These different lithologic units are mapped separately based on their lithologic, and stratigraphic differences (Table 3.1).

Fig 3.3 GEOLOGICAL MAP OF THE BORKENA RIVER CATCHMENT





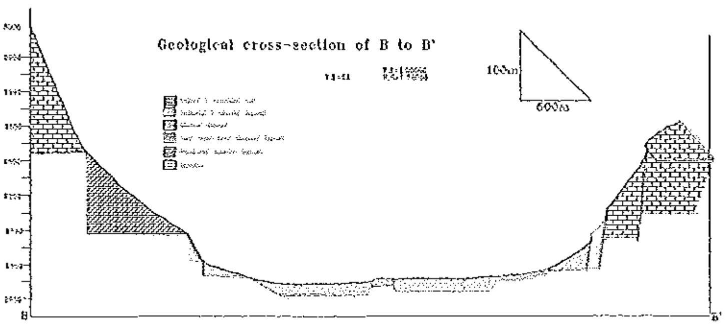


Table 3.1 Aerial coverage of lithologic unit

No.	Lithologic unit	Aerial coverage (in km^2)	Area proportion in percent
1	Rhyolite	19.4	6
2	Scoraceous and basaltic lava flow	120.2	36.9
3	Welded and unwelded tuff	5.2	1.6
4	Fractured massive basalt	24.2	7.4
5	Colluvial and Alluvial deposits	36.8	11.3
6	Alluvial deposits	115.2	35.3
7	River channel deposits	5.0	1.5

3.6.2 Rhyolite

This unit outcrops in southeast, east and northeast of Kombolcha along the road leading to Kombolcha-Ancharo and Kombolcha-Ardibo. The maximum thickness of the unit is observed ESE of Kombolcha and has about 400 m thick (Fig. 3.6). It is fine grained and reddish to gray in color. The unit is less weathered and relatively moderately fractured and as a result it favors moderate infiltration to recharge the aquifer. However its geomorphic and topographic position allows rapid drainage so there is little infiltration recharging the subsurface water.

3.6.3 Scoraceous and Basaltic Lava Flow

The scoraceous and basaltic lava flow unit outcrops in most parts of the area and cover 36.9% of the catchment. It is highly weathered and fractured due to the wide spread and frequent faulting. The unit contains high amount of agglomerate showing spheroidal weathering characteristics with lithic fragments contained as phenocrysts with in the ground mass and its color varies between reddish and dark gray. In some parts of the catchment, this unit is overlain by columnar jointing basalt and highly fractured and weathered flow basalt. Since it is located on the topographic high and relatively steep slope parts of the catchment, hence the corresponding infiltration would be lower as compared to the same unit located in relatively gentle and flat areas.

3.6.4 Welded and Unwelded Tuff

The Welded tuff unit outcrops in Kutaber area and covers 1.5% of the catchment. Its maximum thickness is about 100 m and is fine grained. The color varies between white and light gray. The unit contains phenocrysts of quartz with large vesicles uniformly scattered on its surfaces are common. It is moderately weathered and fractured however its geomorphic and topographic position favors rapid runoff. In some parts of the catchment, the unit is underlain by ash and alternating units of paleosoil layers with welded tuff.

3.6.5 Fractured Massive Basalt

The unit overlies the ignimbrite in Kutaber and the degraded basalt in other areas. It is one of the most intensively fractured unit among others and contains volcanic flow structure subparallel to other units. The fractures are ill defined with no systematic orientation but mostly it is dominated by vertical fractures as a result it favors infiltration of precipitated water. In some locality the unit overlies a very thin layer of paleosoil not more than 50 cm thick. It is fine grained and aphanitic basalt with large proportion of quartz grains are visible on the freshly cut samples. Geomorphologically it lies on top of all other rock units and on the face of the escarpment.

3.6.6 Colluvial and Alluvial Deposits

This unit outcrop in most part of the catchment and has not any unique composition, so the composition is depicted by one or more of the lithology overlying it. Mainly the unit is formed by gravity movement and deposition while weathering, fracturing and erosion facilitates for further deposition of the unit. The grain sizes contained in this unit shows large variation that ranges between gravel and cobble to large fragments of rock and it is found in the gentle and flat slope regions of the catchment.

3.6.7 Alluvail Deposits

The unit outcrop in the gentle and flat regions of the catchment and is mainly composed of clay loam soil with minor proportion of sands and gravels. This units is formed as a result of the end product of weathering of different rock unit in the area. The units occupy 35.4% of the catchment and the second largest in terms of aerial coverage and one of the most cultivated unit among the different units.

3.6.8 Very Recent River Channel Deposit

The outcrop of the unit is found along the Borkena river channel and in some of its tributaries and it is the most recent unit mapped in the catchment. The grain size shows a large variation which ranges from sand to boulder and cobble. The grain sizes tends to be large as one goes down stream of the catchment this is owing to the fact that more and more tributaries join the

Borkena River and hence, enhances the transporting capacity of the river. The deposits of this unit accounts 1.5% of the catchment and it overlies one or more of the volcanic unit.

3.7 Geologic Structures

It is clearly seen that elongated ridges in the area have generally N-S orientation which depicts the regional tectonics in the central and Afar rift margins.

At least two sets of faults are recognized and mapped having orientations of NNW-SSE and NNE-SSW and one minor set of E-W faults. These faults affect all rock unit and as it seen Fig. 3.3, the E-W trending fault are observed to cross the N-S running fault, hence it is younger. The Red sea rift parallels the NNW trending fault sets (Kroberg et al., 1975, cited in Molla Demlie, 2000) while the Ethiopian rift or probably the influence of interaction of the central and Afar rift parallels the NNE trending sets of faults. The E-W trending sets of faults are probably associated with the Gulf of Aden rift. As it is given in the interpretation in Zanettin et al., (1978) the fault sets are situated between $11^0 00'$N-$12^0 00'$N, parallel to the pre-Oligocene rift of "Ashangi" and are a rejuvenation of an older major tectonic lineament extending from the Gulf of Aden.

CHAPTER 4

Hydrometeorology

4.1 General

The term hydrometeorology include both hydrology and meteorology. Hydrometeorological data are required to determine the water balance of a basin for developing and managing its water resources. The most useful hydrometeorological variables are precipitation, evaporation, evapotranspiration, solar radiation (sunshine hour), air temperature and relative humidity, soil moisture, stream discharge and water quality (Raghunath, 1992).

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

4.2 Measurement of precipitation at a point

There are two types of gauges that are used in the measurement of precipitation. These are: the recording type and the non-recording type. In the latter case measurements are taken at regular interval by emptying the total amount of precipitation falling and collected by the catch into a known graduated tube (Dunne and Leopold, 1978). Accordingly there are five meteorological stations installed with non-recording type of rainfall gauge in and around the studied catchment (annex 1). The long term mean monthly and annual rainfall over the catchment was estimated by using thiessen polygon and Isohyetal methods which enables to change point rainfall data into aerial rainfall. Moreover these two methods takes into consideration the effect of orography and non-uniform distribution of meteorological station and the corresponding rainfall patterns associated with them. Hence the long-term calculated rainfall values are very well closes to the actual rainfall over the area and the annual rainfall calculated by using these two methods is 1086.6mm

4.3 Computation of Aerial Rainfall

Rainfall measurement of any station gives a point rainfall value, hence it is necessary to convert this point data into aerial rainfall. Accordingly the uniform depth of aerial rainfall over the Borkena catchment was estimated using the three methods of estimating aerial rainfall. These are: arithmetic mean, thiessen polygon and isohyetal methods. The computed value is used in the evaluation of water balance of the studied catchment.

The mean annual rainfall which is obtained through the calculation of arithmetic mean considering the recorded data in the five meteorological station (Cheffa, Kombolcha, Dessie, Kutaber and Haik) in and around the catchment is 996.8mm (Table 4.1a & d). Hence the average rainfall is given by:

$$\bar{p} = \frac{\sum_{i=1}^{n} \bar{p}_i}{n} \quad (4.1)$$

where $\overline{P}$: the mean annual rainfall over the catchment

$\overline{P_i}$: station mean annual rainfall

n: number of stations

Table 4.1a Meteorological stations and monthly Rainfall (in mm)

Year considered	1962-1999	1952-1999	1980-1999	1962-1988	1956-1999
Station	Dessie	Kombolcha	Haik	Cheffa	Kutaber
Monthly mean min.	21.5	11.8	15.2	8.6	4.4
Monthly mean max.	246.36	235.42	231.47	208.2	212.8
Annual Mean	1149.61	1050.0	1136.4	848.9	798.7
Altitude	2460	1903	1900	1400	2700
Latitude	$11^0 06'$	$11^0 07'$	$11^0 19'$	$10^0 59'$	$11^0 16'$
Longitude	$39^0 38'$	$39^0 44'$	$39^0 40'$	$39^0 46'$	$39^0 32'$

The Thiessen polygon method of computing weighted annual rainfall considering the five stations is 1024mm (Table 4.1b and Fig. 4.1). The Thiessen polygon method is expressed by the following equation:

$$\overline{P} = \frac{1}{A}\sum_{i=1}^{n} a_i \overline{p_i} \qquad (4.2)$$

where $\overline{P}$: weighted rainfall of the catchment

a_i: aerial influence of the i^{th} polygon

$\overline{p_i}$: the i^{th} station mean annual rainfall

A: total area of the catchment

Table 4.1b Thiessen polygon method of computing weighted annual rainfall

Station	Mean Annual Rainfall (in mm)	Acrial influence (in km^2)	Acrial Proportion in percent	Weighted rainfall (in mm)
Cheffa	849	32.9	0.10	84.9
Kombolcha	1050	129.5	0.40	420.2
Dessie	1150	106.5	0.33	379.5
Kutaber	799	53.3	0.16	127.8
Haik	1136	3.7	0.01	11.4
			Total	1023.6

The third method employed is Isohyetal. This method makes use of joining points of equal rainfall value and then measures inter-isohyetal area. Accordingly the catchments weighted rainfall is 1032mm (Table 4.1c and Fig. 4.1) and it is calculated from the formula given below:

$$\overline{P} = \frac{1}{A}\sum_{i=1}^{n} a_i \overline{p_i} \tag{4.3}$$

where $\overline{P}$: weighted rainfall of the catchment

a_i: inter-isohyetal aerial

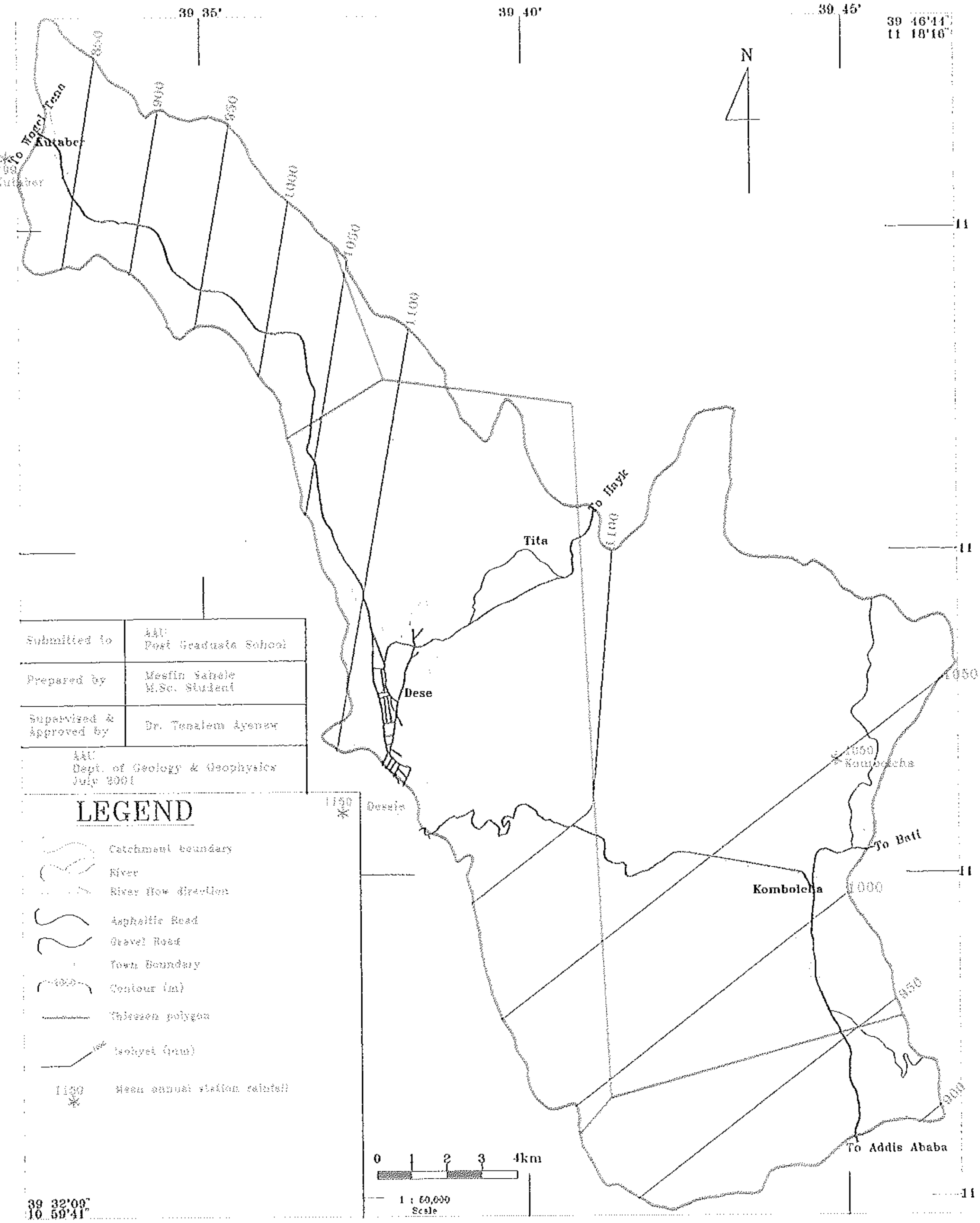
$\overline{p_i}$: mean rainfall between successive isohyets

A: total area of the catchment

Table 4.1c Isohyetal method of computing weighted annual rainfall

Isohyetal range	Mean Isohyet (in mm)	Interisohyetal Area (in km^2)	Aerial Proportion in percent	Weighted Rainfall (in mm)
800 - 850	825	9.2	0.03	23.3
850 - 900	875	10.5	0.03	28.2
900 - 950	925	30.9	0.09	87.7
950 - 1000	975	42.3	0.13	126.5
1000 - 1050	1025	53.6	0.16	168.5
1050 - 1100	1075	102.9	0.32	339.3
1100 - 1100	1100	76.6	0.23	258.5
Total		326		1032

Fig. 4.1 THIESSEN POLYGON AND ISOHYETAL MAP OF THE BORKENA RIVER ON ANNUAL BASIS



From the calculation of mean annual rainfall computed so far, the arithmetic mean method underestimate the value. This is due to the inherent drawback of the method which doesn't take into account the random distribution of station and rainfall over the catchment.

The mean annual rainfall over the stations varies between 799 mm and 1150 mm while the mean annual rainfall of the catchment obtain considering arithmetic, isohyetal and thiessen methods are 997mm 1032mm and 1024mm respectively.

Considering topographic variation, nonuniform distribution of meteorological station and rainfall patterns, it is logical to take the average value obtained through the combination of thiessen and isohyetal methods. Therefore, 1028mm of rainfall is considered in this work as the mean annual value of the studied catchment. The same procedure is followed to evaluate the mean monthly rainfall and is presented in Table 4.1d & e.

Table 4.1d Mean monthly station Rainfall

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Cheffa	32.5	49.0	77.7	98.0	75.2	26.0	195.3	247.5	102.1	38.7	25.6	14.6
Kombolcha	30.4	42.6	77.3	95.4	65.4	32.7	261.1	256.3	123.0	37.4	19.9	17.0
Dessie	27.5	38.2	80.3	95.7	75.5	40.4	282.3	291.6	149.9	53.2	24.2	20.3
Kutaber	12.6	25.2	51.5	57.9	70.0	40.2	272.5	309.4	119.1	35.0	13.2	6.6
Haik	34.0	64.7	120.1	118.9	75.1	25.4	254.1	249.3	134.2	40.1	19.1	17.1
Average	*27.4*	*43.9*	*81.4*	*93.2*	*72.2*	*32.9*	*253.1*	*270.8*	*125.7*	*40.9*	*20.4*	*15.1*

Table 4.1e Mean monthly rainfall using different methods

No	Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	Arithmetic	27.4	43.9	81.4	93.2	72.2	32.9	253.1	270.8	125.7	40.9	20.4	15.1
2	Thiessen	26.8	39.2	74.6	89.9	70.5	35.7	263.2	275.5	129.2	42.3	20.8	16.1
3	Isohyetal	28.51	41.4	79.6	94.8	71.5	34.00	258.8	271.8	129.7	43.0	21.1	15.1
4	*Average of 2&3*	*27.7*	*40.3*	*77.1*	*92.4*	*71*	*34.9*	*261*	*273.7*	*129.5*	*42.7*	*21.0*	*15.6*

The mean monthly rainfall obtained using the combination of thiessen and isohyetal methods ranges between 16 mm and 274 mm. The rainy months extends from March-May and July-September. The percentage contribution of rainfall is being obtained by diving the mean monthly rainfall to the mean annual rainfall. Accordingly the estimated commulative monthly percentage contribution of the rainy months shows the catchment obtain 83% of its mean annual rainfall only during the rainy months while 17% being received during the dry seasons. From the rainy months, the big rain account about 70% where as 14% with small rains in March and May (Table 4.1f). As it is shown in the Fig. 4.2a & b, the rainfall shows seasonal and annual variability over the whole catchment. From the figure 4.2a, it is evident that the area get its maximum and minimum mean monthly rainfall in August and December respectively while it gets its three maximum and minimum annual mean rainfall in 1998, 1988, 1963 and 1965, 1984, 1991 which corresponds to the wettest and dry periods prevailing throughout the region.

Table 4.1f Monthly percentage contribution of rainfall

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Combined Thiessen and Isohyetal	27.7	40.3	77.1	92.4	71	34.9	261	273.7	129.5	42.7	21	15.6
% Contribution	2.5	3.7	7.1	8.5	6.5	3.2	24.0	25.2	11.9	3.9	1.9	1.4

Table 4.1g Evaluation rainfall coefficient

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean Rainfall	26.7	40.3	77.1	92.4	71	34.9	260.9	273.4	129.3	42.5	20.9	15.6
Rainfall Coefficient	0.3	0.5	0.9	1.1	0.8	0.4	3.1	3.2	1.5	0.5	0.2	0.2
Designation	dry	dry	rainy	rainy	rainy	dry	rainy	rainy	rainy	dry	dry	dry

Table 4.1h Classification Scheme of monthly rainfall coefficient

Rainfall Coefficient	Designation	Corresponding Months
Less than 0.6	dry month	Jan-Feb, Jun, Oct-Dec
0.6 and over	rainy month	Mar-May, Jul-Sept
0.6 to 0.9	small rains	Mar, May
1.0 and over	big rains	Apr, Jul-Sept
1.0 to 1.9	moderate concentration	Apr, Sept
2.0 to 2.9	high concentration	
3.0 and over	V. high concentration	Jul, Aug

After Daniel Gemechu, 1977.

To compare the monthly distribution of rainfall and to identify dry and rainy seasons, "rainfall coefficient" was employed. The rainfall coefficient is being obtained by dividing mean monthly rainfall to one twelve of the annual mean rainfall (UNFAO, 1965 cited in Daniel Gemechu, 1977). If for instance 0.6 is obtained, it means, that particular month obtain 60 of percent one twelve of the annual mean.

On the basis of estimation (Table 4.1g & h), the dry and rainy seasons are identified. Hence, according to Daniel Gemechu, (1977) rainfall regime classification, the catchment is characterized by type - II rainfall with two rainy seasons lasting from March-May and July-September.

A) Type-I Rainfall Regime

These regimes are characterized by one rainy season, i.e., the rainy months are contiguously distributed. This also means that there is only one dry season. These regimes are found in the western half of the country as well as in the southwestern highlands.

B) Type-II Rainfall Regimes

These regimes are characterized by two rainy seasons in which the contiguous rainy months are separated by dry seasons. It is found mainly in the eastern half of the country including the northern half of the escarpment of the rift system.

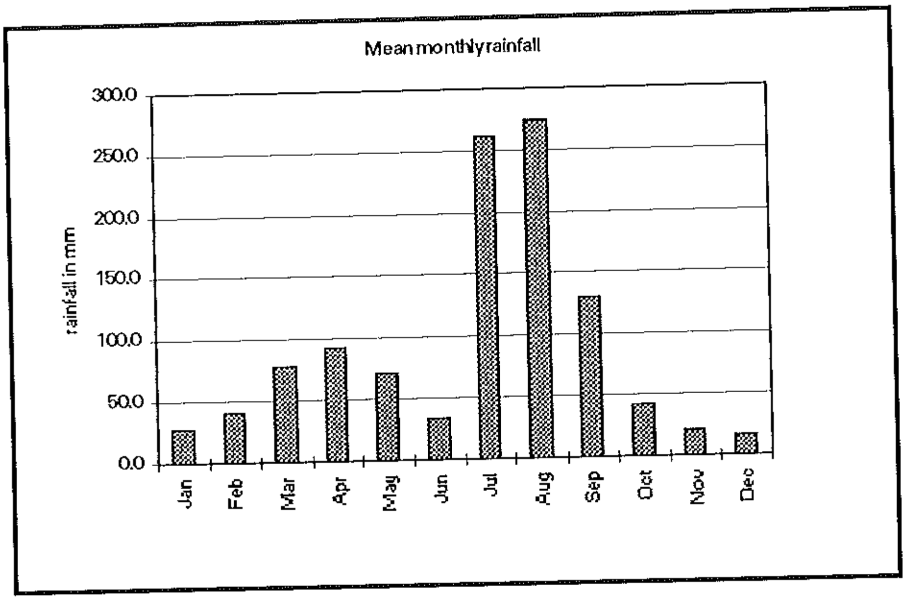


Fig. 4.2a Seasonal variability of rainfall

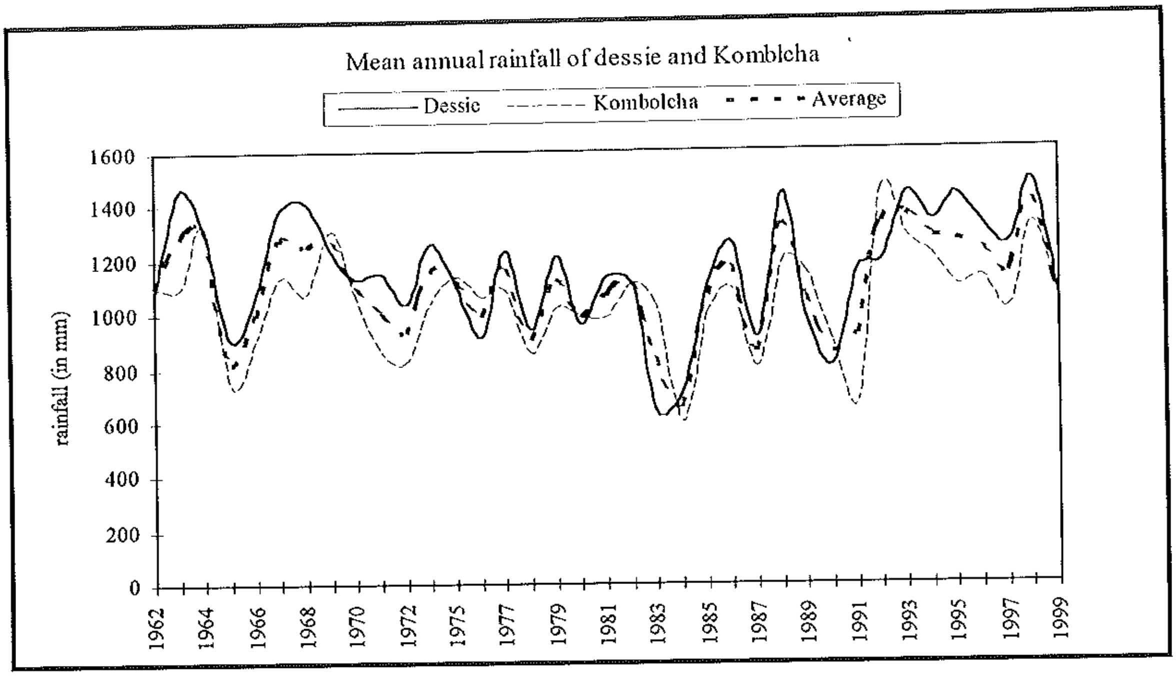


Fig. 4.2b long term annual variability of rainfall

4.4 Rainfall - Altitude Relationship

Altitude is considered to be one of the major factor in determining the climatic condition of a region (UN, 1965). Hence, it affects rainfall, temperature and evaporation. In many areas of the world, rainfall uniformly increase with altitude (Dunne and Leopold, 1978; Dingman, 1994). However, this increase of rainfall with altitude in the area under study is valid only for the station Cheffa, Kombolcha, Dessie and Haik (Table 4.2 and Fig. 4.3) where as the lowering of rainfall in Kutaber might be related to the movement and direction of moisture laden winds and topographic barriers beside these, local conditions such as gauge exposure, missed data and probably wind direction might be accountable for the reduction of rainfall for the station at Kutaber.

Table 4.2 Rainfall-altitude relationship

Station	Cheffe	Kombolcha	Dessie	Kutaber	Haik
Rainfall (mm)	849	1050	1150	799	1136
Altitude (m)	1400	1903	2460	2700	1900

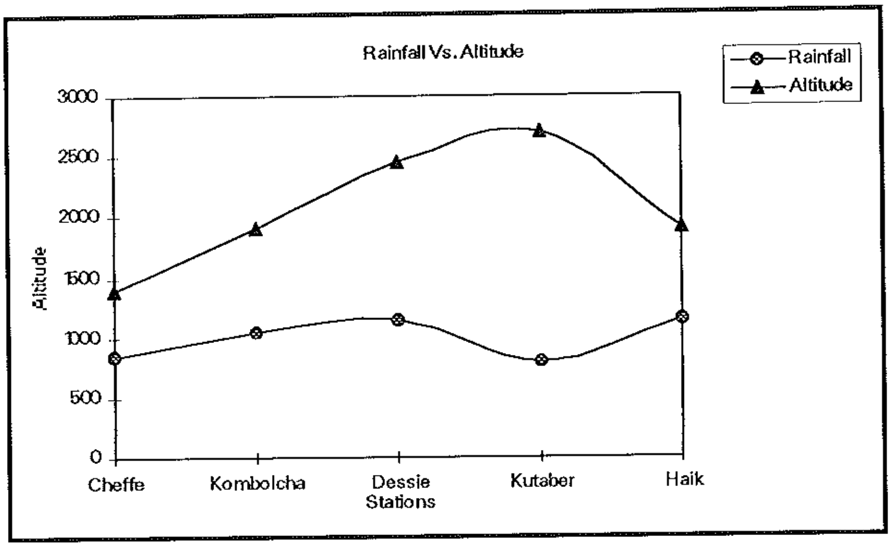


Fig. 4.3 Rainfall altitude relationship

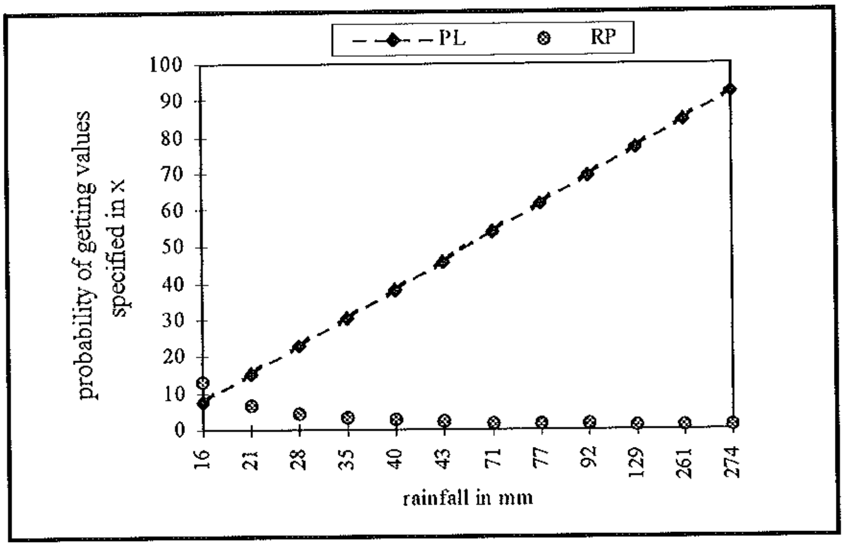
4.5 Rainfall Pattern

4.5.1 Temporal and Spatial Variability of Rainfall

Considering the combined method of Thiessen and Isohyetal conversion of point rainfall data into aerial rainfall, the catchment would get 1086 mm of rainfall per annum. The rainfall pattern in the area exhibit temporal and spatial variability. Generally the rainfall data of the five meteorological stations shows an increase of rainfall from southwest to northeast excluding the station rainfall in Kutaber. It is locally observed that the rainfall tends to increase with altitude and this increase in rainfall is most probably explained by the topography of the area. For instance Kombolcha at an altitude of 1903 m a.s.l in the south gets 1050 mm mean annual rainfall where as Haik located at an altitude of 1900 m a.s.l in the north gets a mean annual rainfall of 1136 mm, hence the pattern of rainfall shows a spatial variability which generally tends to increase from south to north .

4.6 Computation of Recurrence Interval on Monthly Rainfall Basis

As it is shown in the Fig. 4.4 the probability of getting less than or equal to 129 mm of monthly rainfall is 77% and there is a chance of 23% that it will exceed 129 mm rainfall value. The corresponding return period for getting such monthly rainfall is 1.3 months and such calculation of return period will have great significance in the design of water supply and related problems. If the upper and lower rainfall limits of crop tolerance are known, the probability of crop failure due to drought and water logging can be assessed (Dunne and Leopold, 1978).



Note: PL = Probability of getting rainfall specified in x
RP = Return period in months

$$PL = \frac{m}{n+1}$$

$$RP = \frac{n+1}{m}$$

n is number of months considered in which case is 12
m rank assigned to each rainfall beginning with 1 to the smallest rainfall then increasing by one onwards

Fig. 4.4 Recurrence interval graph

4.7 Temperature

Temperature date is available in Kombolcha station and it plays a vital role in the evapotranspiration process and in the evaluation of the water balance of the area in addition to other factors such as climate, latitude, altitude, soil moisture condition, vegetation type, land use and amount of rainfall. However, incorporating and using of this data for the catchment might overestimate the evapotranspiration value and reduce the amount of groundwater recharge. As it is shown in Table 4.3 and Fig. 4.5, the monthly minimum temperature varies from the lowest value 8.4 ^{0}C, 8.6 ^{0}C and 9.8 ^{0}C to a maximum about 30 ^{0}C in June then decreases following the same pattern. The highest monthly temperature are recorded in May, June and July with 20.9 ^{0}C, 22.1 ^{0}C and 20.7 ^{0}C respectively and then decreases to a minimum value in November-January (16.1 ^{0}C to 16.9^{0}C), which corresponds to the dry seasons in 'Bega". The mean monthly temperature value varies between 16.1 ^{0}C and 22.1 ^{0}C (Table 4.3, and annex 2). Fig. 4.5 shows the variability of the monthly mean maximum, mean minimum and mean temperature value for the station at Kombolcha.

Table 4.3 Monthly variability of temperature (in ^{0}C) at Kombolcha

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	16.9	17.9	19.3	19.9	20.9	22.1	20.7	19.9	19.2	17.5	16.3	16.1
Mean max	23.9	24.9	26.2	26.7	28.3	30	27.5	26.2	25.6	24.8	24.1	23.6
Mean min	9.8	11.0	12.4	13.1	13.5	14.3	13.9	13.6	12.9	10.2	8.40	8.6

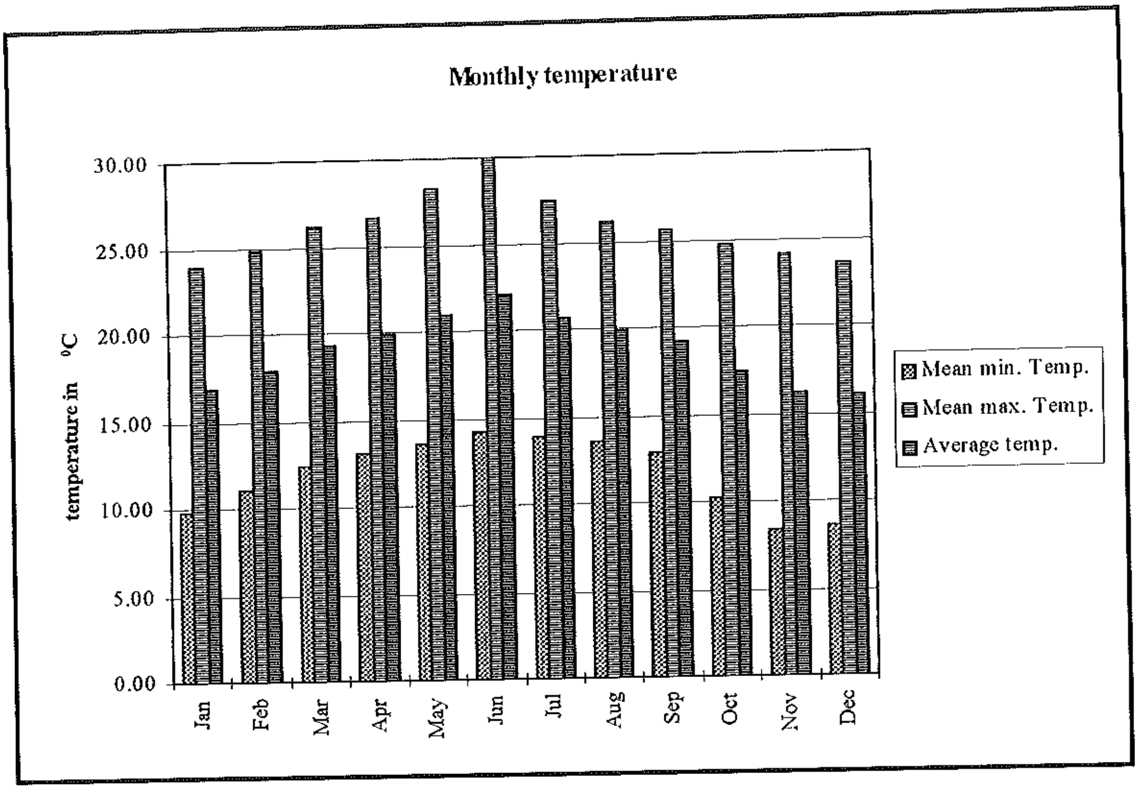


Fig. 4.5 Monthly temperature variability at Kombolcha

4.8 Relative Humidity

The moisture content of air is a significant factor in evaporation process and is expressed in weight per unit volume and is called Absolute humidity. Under most conditions of practical interest, the relative humidity is taken into consideration (Warren and Gary, 1996). Hence the relative humidity of an air mass is the percent ratio of an absolute humidity to the saturation humidity for the temperature of the air mass (Fetter, 1994).

From forty four years meteorological station recorded data (annex 3), the mean monthly relative humidity value which is computed through averaging the relative humidity values recorded at 6:00, 12:00 and 18:00 local time varies between 40.1% and 64.3%. The maximum and minimum relative humidity value corresponds to the big rainy months (July, August and September) and to the dry months in May, June, and November, (Table 4.4 and Fig. 4.6).

Table 4.4 Mean monthly relative humidity at Kombolcha

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	61.8	60.9	60.3	59.7	49.1	40.1	58.3	64.3	64.1	59.3	57.6	59.9
Min.	43	38.3	32.3	33	27.7	21.7	30.7	35.7	48	36.7	33.3	33.3
Max.	85.0	87.7	80.0	85.0	73.3	59.0	74.0	79.7	81.3	82.3	82.3	83.7

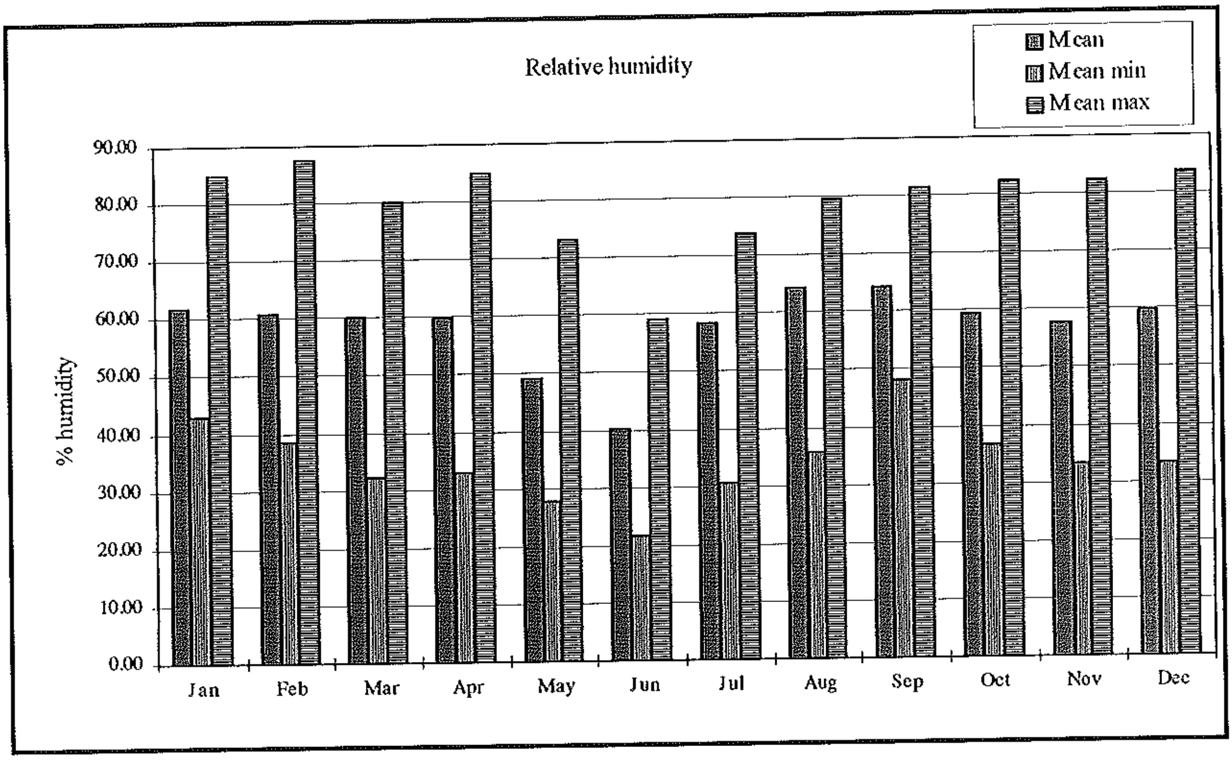


Fig. 4.6 Monthly variability of relative humidity

4.9 Wind speed

The daily measurement of wind speed at 2m above the land surface and the direction of ten minute at 12:00 (noon) local time at the various stations are grouped in accordance with the seasonal prevailing wind directions (NAE, 1988). Wind speed has a strong influence in the evapotranspiration process by removing moist air and leaving the air above dry and hence the evapotranspiration process continues to feed the air with moisture. The mean monthly wind speed computed considering the Kombolcha station ranges from 0.9 m/sec to 1.6 m/sec. The maximum and minimum monthly wind speed occurs in June and October corresponding to the dry seasons, (Table 4.5 and Fig. 4.7).

Table 4.5 Monthly wind speed in m/sec at Kombolcha

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	1.39	1.53	1.46	1.44	1.41	1.60	1.59	1.43	1.08	0.94	1.01	1.16
Min.	1	1.1	1	1	1	1.26	1.15	1.03	0.67	0.57	0.8	0.81
Max.	1.8	1.85	1.71	2.99	1.82	1.91	2.1	1.81	1.5	1.4	1.5	1.4

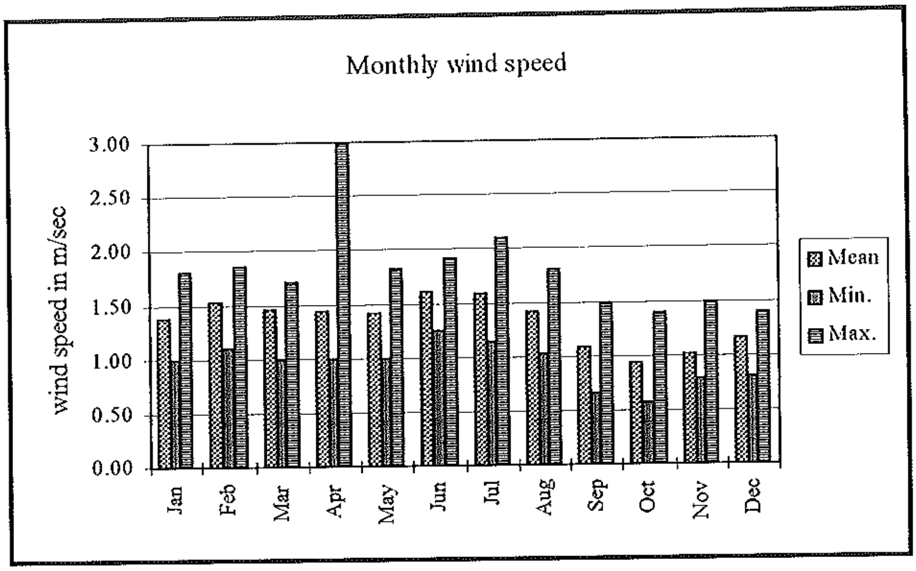


Fig. 4.7 Monthly variability of wind speed at Kombolcha

4.10 Sunshine Hour

Generally most parts of Ethiopia receive over 7 hours of bright sunshine daily and in the southeastern, north, and northwestern lowlands, it reaches 10 to 12 hours duration. In the study area the monthly sunshine hour ranges from 5 hr to 7.9 hr. The maximum sunshine hour corresponds to the minimum cloud cover in dry months of October, November and December, (Table 4.6 and Fig. 4.8).

Table 4.6 Mean monthly sun shine hour at Kombolcha

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	7.40	7.3	6.7	6.9	7.7	6.3	5.0	5.7	5.8	7.9	8.5	7.9
Min.	4.2	4.1	3.9	3.8	5.1	2.8	1.8	3.4	3.3	4.7	6	3.4
Max.	10	10.2	9.3	9.1	10.9	9.1	8.9	9.8	8.5	9.4	10.5	10.2

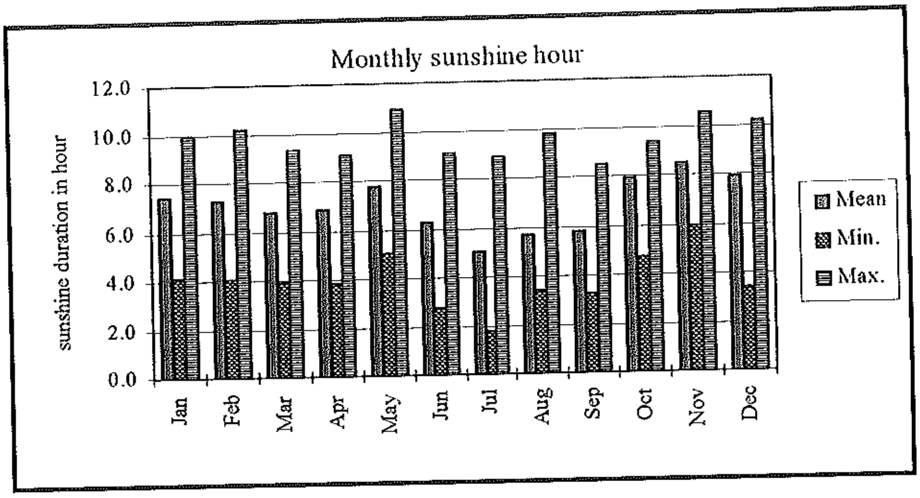


Fig. 4.8 Monthly sunshine hour at Kombolcha

4.11 Evaporation

In any water resource planning and management proper evaluation of evaporation in the area under investigation is crucial. Evaporation is the process by which water vapor is transferred from the land and water masses such as lakes, reservoirs, ponds, seas, rivers and oceans of the earth to the atmosphere. Evaporation rate depends up on temperature, vapor pressure, wind velocity and the nature of the evaporating surface. Evaporation is the net rate of vapor transfer to the atmosphere. Hence it is a function of solar radiation, differences in vapor pressure between a water surface and the overlying air, temperature, wind speed, atmospheric pressure and the nature of the evaporating surface (Warren and Gary, 1996). The different methods that help to estimate evaporation are: the water budget, energy budget and mass transfer technique and the use of pan evaporation data. Among others, the Penman method which combines mass transfer and energy budget theory is the most widely employed and generate more reliable data of evaporation, provided good relevant data is available..

From one year Piechie evaporation measurements taken at Kombolcha, the variation in the daily and monthly evaporation ranges between 3.29 mm/day to 8.03 mm/day and 102.1 mm/month to 240.8 mm/month while 1203.1 mm/year being the annual total, (Table 4.7, annex 5 and Fig. 4.9). The maximum and minimum daily or monthly evaporation record corresponds to the dry and big rainy months in June and August. The annual evaporation which is calculated on the basis of Penman combination and modified methods gives 1425.6 mm and 1488.1 mm (annex 8 & 8A) and accounts 131% and 137% of the annual rainfall. The evaporation value which is determined through piechie (1203.1mm) largely underestimate as compared to evaporation determined by the above two methods and for the near by lake Haik-Ardibo catchment (1465.1mm/year, Molla Demlie, 2000). Hence, the evaporation rate of 1488.1 mm per annum is used in this work.. As it is seen in the Fig. 4.9 evaporation is above average in the months of May to July which corresponds to the high temperature prevailing in these months. The very high rate of evaporation in the catchment would largely affect the surface and groundwater resource potential and the existing and planned water supply of the area.

Table 4.7 Monthly Evaporation (in mm) computed by Penman method

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
99.2	102.8	124.3	126.4	174.5	227.2	148.6	114.7	95.8	95.0	90.6	89.1

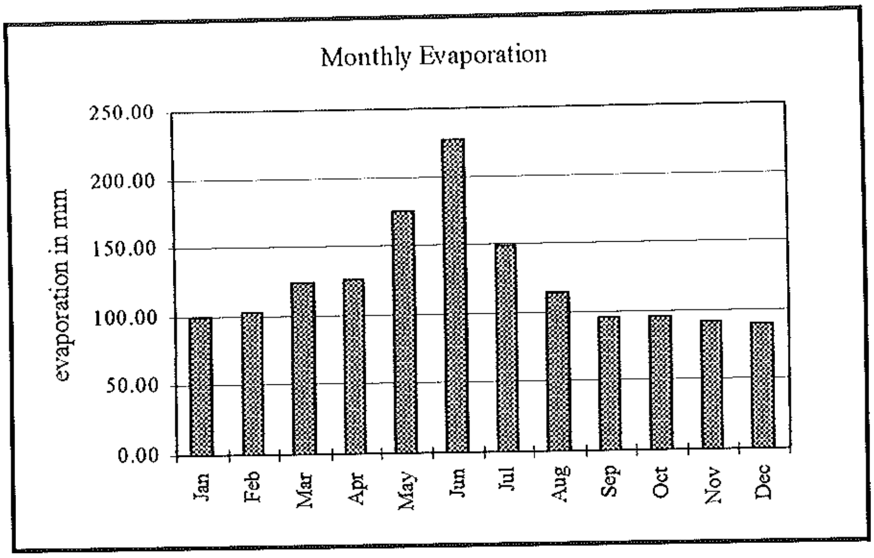


Fig. 4.9 Monthly evaporation of the catchment

4.11.1 Computation of Evaporation (Penman combination method)

This method combines the mass transfer and energy budget technique that are used to estimate open water evaporation. The basic energy balance equation in simplified form is given below (Shaw, 1988).

$$H = E_0 + Q \tag{4.4}$$

where H - is the available heat (W/m^{-2})

E_0 - is the energy for evaporation (mm/day)

Q - energy for heating the air (W/m^{-2})

The value of E_0 and Q can be given by the aerodynamic equation as

$$E_0 = f(u)\,(e_s - e_d) \tag{4.5}$$

$$Q = \gamma\, f_1(u)\,(T_s - T_d) \tag{4.6}$$

Where f(u) is a function of the wind speed

e_s saturation vapor pressure of the air at the water surface (mm of mercury)

e_d vapor pressure of air at dew point (mm of mercury)

γ hygrometric constant (0.27mm of Hg/ ^{0}F)

T_s temperature of the water surface (^{0}C)

T_d dew point temperature of the air (^{0}C)

The aerodynamic equation based on air humidity and air temperature T_a is given by

$$E_a = f(u)(e_a - e_d) \qquad (4.7)$$

where e_a - is the saturation vapor pressure at air temperature, T_a

T_a - air temperature at h meter above the surface

$$\Delta = \frac{de}{dT} \approx \frac{e_s - e_d}{T_s - T_d} \approx \frac{e_a - e_d}{T_a - T_d} \qquad (4.8)$$

where Δ - the slope of the saturation vapor pressure plotted against temperature and empirically it is given by: $\Delta = \frac{25083}{(T + 237.3)^2} \exp\left(\frac{17.3T}{T + 237.3}\right)$ where T is in ^{0}C

then from eq. (4.6)

$$Q = \gamma f(u) [(T_s - T_d) - (T_a - T_d)]$$

$$Q = \gamma f(u)\left[\left(\frac{e_s - e_d}{\Delta}\right) - \left(\frac{e_a - e_d}{\Delta}\right)\right] = \gamma \frac{f(u)}{\Delta}\left[\frac{E_o}{f(u)} - \frac{E_a}{f(u)}\right]$$

$$Q = \gamma\left[\frac{E_o - E_a}{\Delta}\right] \qquad (4.9)$$

substituting Eq. (4.9) in the energy balance equation (eq. (4.4))

$$E_o = H - Q$$

$$= H - \frac{\gamma E_o}{\Delta} + \frac{\gamma E_a}{\Delta}$$

$$E_0\Delta = \Delta H - \gamma E_o + \gamma E_a$$

$$E_o(\Delta + \gamma) = \Delta H + \gamma E_a$$

$$E_o = \frac{\Delta \mathrm{H} + \gamma E_a}{\Delta + \gamma}$$

$$E_o = \frac{\left(\frac{\Delta}{\gamma}\mathrm{H} + E_a\right)}{\left(1 + \frac{\Delta}{\gamma}\right)} \tag{4.10}$$

eq. (4.10) is the basic Penman formula for open water evaporation. It requires values of H and E_a as well as Δ for its application.

More often H and E_a determined empirically and are given by:

$$H = R_I(1-r) - R_o \tag{4.11}$$

where R_I - incoming solar radiation and is given by

$$R_I(1-r) = 0.95 R_a f_a(n/N) \tag{4.12}$$

r - albedo and is equal to 0.05 for water

R_a - solar radiation fixed by latitude and season. Available in standard meteorological table.

R_o - outgoing solar radiation and is given by

$$R_o = \sigma T_a^4 (0.56 - 0.09\sqrt{e_d})(0.1 + 0.9\, n/N) \tag{4.13}$$

$$f_a(n/N) = 0.18 + 0.55\, n/N \tag{4.14}$$

where N - is maximum possible sunshine hour fixed by latitude and season and are available in standard meteorological table

n - duration of sunshine hour

σ - Stefan - Boltzman constant

$\sigma = 5.67 * 10^{-8}$ Wm^{-2}

T_a - air temperature given in degree Kelvin

E_a in eq.(4.10) is obtained by

$$E_a = 0.35(0.5 + {}^{u_2}\!/_{100})(e_a - e_d) \qquad (4.15)$$

where u_2 - wind speed at 2m above the surface

Finally Δ is found from the curve of the saturation vapor pressure against temperature corresponding to the air temperature

4.11.2 Potential Evapotranspiration

Evaporation is a collective term that accounts the water loss that would occur from the land surface (bare soil and water bodies) while the loss of water from the vegetated surface is termed as transpiration. Evapotranspiration is equally affected by all factors that affect evaporation from open water bodies moreover it is influenced by the supply of moisture at the evaporating surface. "The water loss, which will occur if at no time there is a deficiency of water in the soil for the use of vegetation, " is termed as potential Evapotranspiration Thornthwaite, (1944) cited in Fetter, (1994). Since there is often no sufficient available water from the soil moisture, the term actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions. Under conditions of limited soil moisture storage, the actual evapotranspiration is much less than the potential rate.

The actual evapotranspiration over the catchment is then calculated from the potential evapotranspiration. The consideration of the potential evapotranspiration together with the actual soil moisture content enables us to calculate the actual evapotranspiration over the whole catchment. Hence the empirical relation developed by Penman are employed in the calculation of potential evapotranspiration.

4.11.3 Calculation of Potential Evaporation

The value of actual evapotranspiration (ET_m) over the catchment is more often obtained through the calculation of potential evapotranspiration assuming unlimited water supply and then modifying to account for the actual soil moisture content. Accordingly the Penman formula has been employed more widely to provide a numerical evaluation of the moisture content and in the computation of ET_m.

Penman (1)

In this method, Penman relates evaporation from an open water to the potential evapotranspiration of a vegetated land surface and proposed a formula (Shaw, 1988)

$$PE = f^* E_0 \tag{4.16}$$

Where f is a factor which account for the climate of the different seasons and an average value of 0.7 (Shaw, 1988) was taken in this work. Accordingly the evapotranspiration calculated for the catchment using this method generates 1019.53 mm (annex 8).

Penman (2)

In this second modified method, E_o (evaporation from open water bodies) is changed to account for the evaporation and transpiration from a vegetated surface. Hence the basic equation is used for PE directly (Shaw, 1988).

$$PE = \frac{(\Delta/\gamma)H_T + E_{at}}{(\Delta/\gamma) + 1} \qquad (4.17)$$

where $H_T = (1-\gamma)R_I - R_o$, where γ is the albedo of the vegetative cover of the catchment and is taken to be an average of 0.21(Dunne and Leopold, 1978; Subramaya, 1988) hence H_T would be

$$H_T = 0.79R_I - R_o \qquad (4.18)$$

E_{at} is very similar to E_a in eq.(4.10) while the coefficient of 0.5 is replaced by 1 to allow the extra roughness in the wind speed function.

$$E_{at} = 0.35(1 + {}^{u_2}/_{100})(e_s - e_d) \qquad (4.19)$$

$$R_I(1-\gamma) = 0.79R_a f_a({}^{n}/_{N}) \qquad (4.20)$$

$$f_a({}^{n}/_{N}) = 0.16 + 0.62\,{}^{n}/_{N} \quad \text{for latitude south of } 54\tfrac{1}{2}^0 \qquad (4.21)$$

$$R_o = \sigma T_a^4(0.47 - 0.075\sqrt{e_d})(0.17 + 0.83\,{}^{n}/_{N}) \qquad (4.22)$$

After inserting the appropriate variables into the above equation, the modified Penman gives annual potential evapotranspiration of 1339 (annex 8A) mm. As it is evident in the calculation, the Penman combination method underestimate the annual potential evapotranspiration this might be due multiplying open water evaporation by a factor lower than the region under investigation. Therefore, hereafter the Penman modified potential evapotranspiration value (1339 mm) is used in this work and for the computation water balance of the studied catchment.

4.11.4 Estimation of Actual Evapotranspiration

When water supply and moisture conditions are suitable, the actual rate of evapotranspiration is equal to the potential rate. If there is frequent wetting of the soil by rainfall or irrigation, evapotranspiration will continue to lower the soil moisture until the soil loss will no longer occur at the potential rate Dunne and Leopold, (1978).

The evaluation of actual evapotranspiration was done through the computation of potential evapotranspiration. If there is abundant moisture in the soil, the two rates are equal. When moisture supply is limiting, the potential exceeds the actual rate. Accordingly, the actual evapotranspiration of the Borkena catchment is computed from the potential evapotranspiration rate by considering land use-land cover and soil moisture condition, rooting depth and soil map of the catchment. For the sake of quantification of available water capacity, soil unit in the catchment is further refined into fine sand, sandy loam and clay loam to account for the corresponding units of fractured rock, gravely sand, clay loam and residual clay soil in the soil map.

The computation of actual evapotranspiration of the Borkena catchment is adopted from the estimation monthly water balance model as proposed by Thornthwaite and Mather, (1955) cited in Dingman, (1994). The method developed a simple "bookkeeping" procedure that uses monthly values of precipitation and potential evapotranspiration to estimate monthly actual evapotranspiration. As Alley, (1984) cited in Dingman, (1994) the computation of soil moisture and actual evapotranspiration will be as follows Dingman, (1994).

If for a given month $P_m > PE_m$, then the value of the soil moisture at the end of that month, S_m, is found as:

$$S_m = \min \{[(P_m - PE_m) + S_{m-1}], S_{max}\} \quad (4.23)$$

If $P_m < PE_m$, a soil moisture deficit develops or increases. The soil moisture for this case is given by:

$$S_m = S_{m-1} \exp\left[\frac{-(PE_m - P_m)}{S_{max}}\right] \quad (4.24)$$

The monthly actual evapotranspiration, ET_m is then found as

$$ET_m = PE_m, \text{ if } P_m > PE_m. \quad (4.25)$$

$$ET_m = P_m + S_{m-1} - S_m, \text{ if } P_m < PE_m. \quad (4.26)$$

Where S_m is soil moisture at the month m

S_{max} maximum soil moisture capacity of the soil (mm)

S_{m-1} soil moisture in the previous month (mm)

P_m precipitation of the m month (mm)

PE_m potential evapotranspiration of the m month (mm)

ET_m actual evapotranspiration of the m month (mm)

As it is computed for the three soil types and the corresponding land use-land cover units, the actual evapotranspiration loss from the catchment accounts about 84% (860 mm) of the mean annual rainfall. Accordingly the weighted average value is tabulated and presented in Table 4.8 and annex 9. The annual surplus water in the soil moisture is 226 mm per annum and occurs only during the big rainy months that last from July to September.

Table 4.8 Monthly actual Evapotranspiration (in mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	34.63	44.34	78.59	93.21	72.20	35.80	105.65	109.89	106.15	96.30	52.49	30.47

4.12 Runoff

The portion of the rainfall which drains into the lake, seas, oceans in channelized form either surface or subsurface flow is termed as runoff. Runoff in a catchment or basin occurs only after the rainfall exceeds the infiltration capacity of the soil and paddle storage, however in exceptional stormy rains, runoff might occur before rainfall exceeds the infiltration capacity of the soil. The pattern and volume of runoff in any catchment or basin is a function of duration, intensity and aerial distribution of rainfall and other factors such as size, shape, geology, topography, slope and land-use (Schwab, 1993).

In the study area, there is one gaging station. The data collected from the Ministry of Water Resource at the Department of Hydrology shows that 41.6 million cubic meter (mcm) of water per annum leaves from a catchment of 44.1 km^2, (Table 4.9 and annex 10) and as it is calculated from the weighted thiessen and isohyetal methods, the catchment as whole receive 1028 mm of mean annual rainfall. The estimation of runoff coefficient for the whole catchment is therefore taken from the ratio's obtained by dividing the surplus water determined in the Thornthwaite and Mather, (1955) cited in Dingman, (1994) to the mean annual precipitation (1028 mm) and is computed as 0.11. This runoff coefficient value is used in the determination of the annual runoff and in the computation of water balance of the studied catchment.

Table 4.9 Monthly discharge at the gaging site in millions m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Set	Oct	Nov	Dec
1989	0.421	0.356	0.691	0.774	0.462	0.357	1.097	4.007	1.666	0.359	0.282	0.443
1990	0.288	0.367	0.438	0.140	0.377	0.842	5.879	7.317				0.344
1991	0.298	0.429	0.502	0.495	0.369	0.335	7.510	10.448	2.090	0.515	0.408	0.318
1992	0.684	2.080	0.815	2.095	0.709	0.465	2.205	3.798				0.524
1993	0.511	0.292	0.138	1.608	1.092	0.420	2.190	4.449	1.663	1.511	0.578	0.428
1994	0.334	0.227	0.424	0.260	0.189	0.368	25.935	34.802	3.193	0.955	1.192	0.760
1995	0.558	4.960	10.296			0.150	2.140	49.739	1.640	1.081	0.663	0.672
1996	0.993	0.536	0.522	0.606	1.294	1.035	4.375	72.219	2.671	0.435	0.378	0.343
1997	0.342	0.258	0.343	0.255	0.225	0.274	4.243	9.254	0.853	0.984	2.311	0.516
1998	0.357	0.343	0.334	0.307	0.273	0.204	72.894	19.225	2.295	0.853	0.497	0.476
1999	0.458	0.335	0.347	0.315	0.321	0.315	10.408	12.376	4.581	3.748	0.584	0.513
mean	*0.477*	*0.926*	*1.350*	*0.686*	*0.531*	*0.433*	*12.625*	*20.694*	*2.294*	*1.160*	*0.766*	*0.485*
min	*0.288*	*0.227*	*0.138*	*0.140*	*0.189*	*0.150*	*1.097*	*3.798*	*0.853*	*0.359*	*0.282*	*0.318*
max	*0.993*	*4.960*	*10.296*	*2.095*	*1.294*	*1.035*	*72.894*	*72.219*	*4.581*	*3.748*	*2.311*	*0.760*

4.12.1 Rainfall-Runoff relationship

To compare between rainfall and runoff, it is a standard practice to express values in similar units. In areas having similar geology, land use, topography, slope and uniform distribution of rainfall, the two variables exhibit a direct relationship (Warren and Gary, 1996). Accordingly rainfall-runoff relationship is established for the Borkena River catchment on monthly basis, (Table 4.10 and Fig 4.10). As it is seen in Fig. 4.10, higher runoff corresponds to higher rainfall and vice versa . In addition to determining the peak runoff, it is also used to estimate the water yield of the catchment. The relationship established is given in Table 4.10.

Table 4.10 Rainfall-Runoff relationship

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall in mcm	1.23	1.79	3.43	4.11	3.16	1.55	11.61	12.17	5.75	1.89	0.93	0.69
Runoff in mcm	0.48	0.93	1.35	0.69	0.53	0.43	12.62	20.69	2.29	1.16	0.77	0.49

Note: mcm = million cubic meter

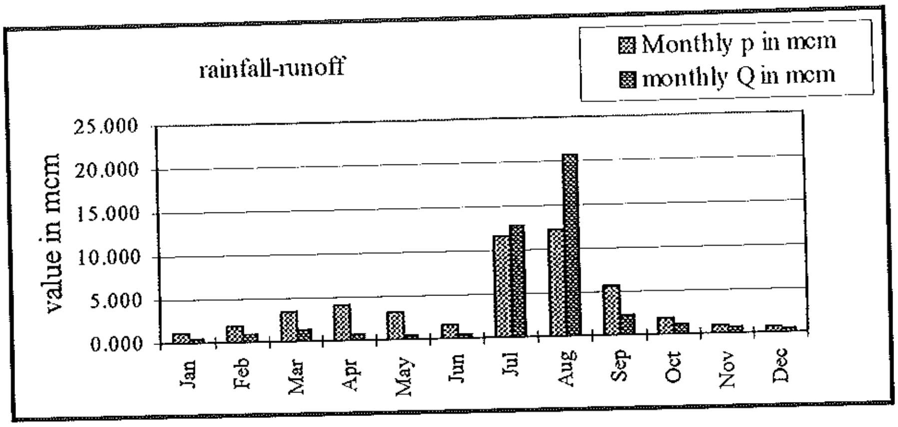


Fig. 4.10 Rainfall-runoff relationship

4.12.2 Area-Runoff Relationship

Assuming the same geology, structure land use, topography and distribution of aerial rainfall, the quantity of discharge leaving a certain catchment is a function of the aerial extent of the catchment Warren and Gary, (1996). Hence area-runoff relationship is done for the studied area, (Table 4.11 and Fig. 4.11) on daily discharge measurement basis determined by float method. As it is clearly seen on the figure, the discharge of a certain defined part of the Borkena catchment increases with corresponding increase in aerial extent of the catchment. From this observation, it is possible to say that, the groundwater table is shallow and recharges the stream since the stream is perennial.

Table 4.11 estimation of river discharge by float methods

Rivers	S6 (R_9)	S1 (R_4)	S2 (R_5)	S4 (R_7)	S7 (R_{10})	S8 (R_{11})	S3 (R_6)	S9 (R_{12})	S5 (R_8)
T. area (km^2)	12.4	19.325	43.825	59	76.45	88.85	100.125	148.125	270.45
T. 'discharge (m^3/sec)	0.016	0.010	0.044	0.032	0.005	0.057	0.155	0.106	0.247

Note: S6 = site 6; R_9 = 9th river discharge measurement; T = total

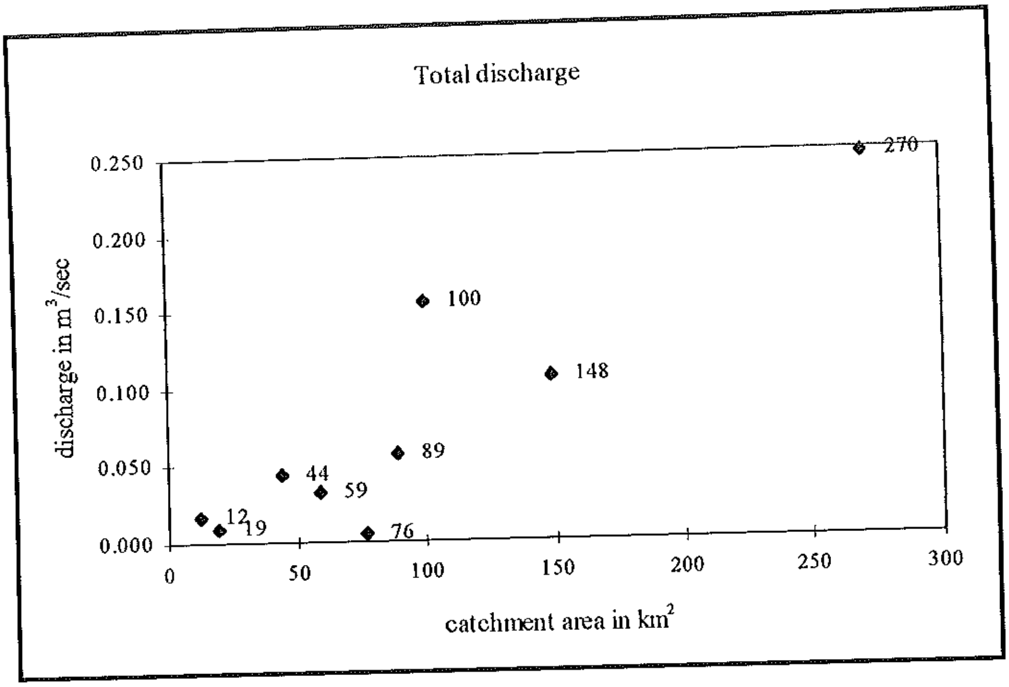


Fig. 4.11 Area-Runoff relationship

4.12.3 Computation of Field Measured Discharge

Efficient water management is founded on reliable stream flow information and the final reliability of the information depends on the initial field measurements. The measurement of stream flow will have advantage in water management such as water supply, pollution control, irrigation, flood control, energy generation and industrial water use (Herschy, 1995). Accordingly one time river flow measurements were taken at different sections along the Borkena River to get information on the water yield and characterization of the catchment. Accordingly float method was employed.

- **Float method**

The discharge determined by this method at different sites along the river channel during the dry month season tabulated and presented in Table 4.11 and Fig. 4.12. From the table it is seen that 0.25 m^3 of water leaves in a defined channel per unit second . As it shown in the Fig. 4.12, some parts of the river channel in north of Dessie and Kombolcha is characterized by an influent stream.

Table 4.12 Estimated net discharge of the subcatchment by float method

Rivers	S1 (R4)	S2 (R5)	S3 (R6)	S4 (R7)	S5 (R8)	S6 (R9)	S7 (R10)	S8 (R11)	S9 (R12)
Net Area (km^2)	19	25	13	59	63	12	33	11	48
Net discharge (m^3/sec)	0.010	0.035	0.098	0.032	0.141	0.016	-0.039	0.035	-0.049

Note: S6 = site 6; R_9 = 9th river discharge measurement

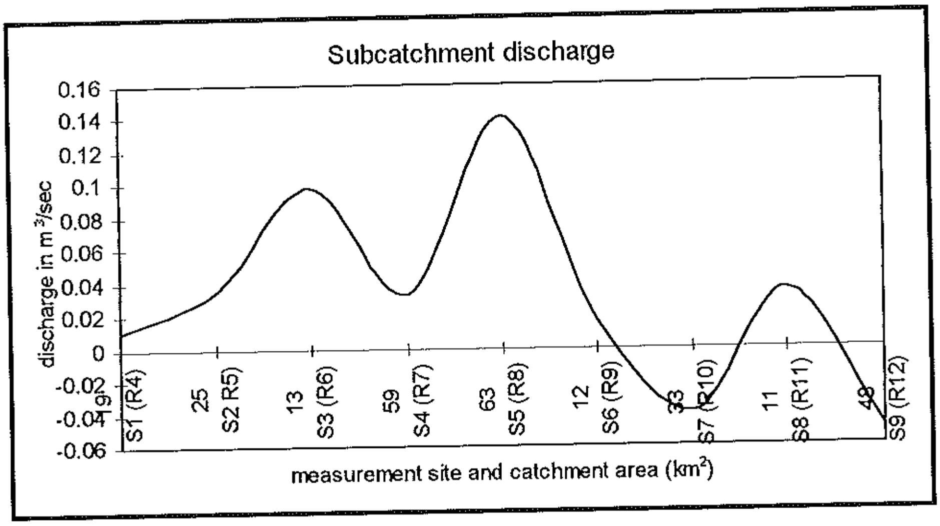


Fig. 4.12 Plot of discharge Vs catchment area

4.13 Area-Elevation Relationship

The aerial distribution of elevation between successive contours gives an insight into the drainage basin for the sake of comparison storage and flow characteristics (Warren and Gary, 1996). For such studies the area contained between any two successive level contour is small as compared to the size of the basin or catchment, the corresponding runoff will be high with subsequent low storage and vice versa. Hence the area elevation relationship is presented in Table 4.13 and Fig. 4.13. As it is seen on the figure the mean and median elevation of the catchment is 2318 m and 2400 m a.s.l. In the studied catchment, about 22% of the area lies between 2500 - 2700 m a.s.l and the associated slope is less than 5 percent implies that there is slow runoff with correspondingly high storage. Hence, this well explains the marshy area located some 8 km northeast of Dessie. In general the catchment is characterized by large elevation contrast and correspondingly rugged topography.

Table 4.13 Aerial distribution between successive contours

Contour interval	Area (Sq. Km)	% of total area	commulative area	commulative %	mean height
3100-3360	1.6	0.5	1.6	0.5	3230
2900-3100	7.5	2.3	9.1	2.8	3000
2700-2900	39.5	12.1	48.6	14.9	2800
2500-2700	71.1	21.8	119.7	36.7	2600
2300-2500	44.2	13.6	163.9	50.3	2400
2100-2300	54.3	16.6	218.2	66.9	2200
1900-2100	63.5	19.5	281.7	86.4	2000
1720-1900	42.5	13	324.2	99.4	1810
1680-1720	1.8	0.6	326	100	1700

The median height corresponds to 50% in the elevation distribution curve where as the mean height is calculated from the formula given below:

$$\overline{H} = \sum \frac{a_i H_i}{A} \qquad (4.27)$$

where a_i - area between successive level contours

H_i - mean height between two successive level contours

A - total area of the catchment

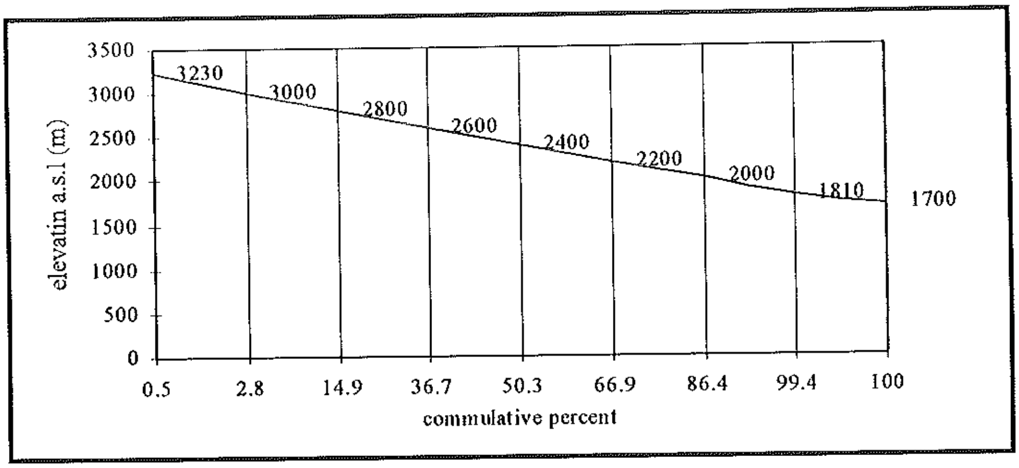


Fig. 4.13 Percentage distribution of elevation over the catchment

CHAPTER 5

Hydrogeology

5.1 Introduction

Hydrogeology in general encompasses the link between various geologic material with water. In its intent, it deals with the movement, chemistry, origin, storage and aquifer hydraulic characteristics of the subsurface materials.

Groundwater is continually being replenished mainly by direct precipitation .In addition surface and subsurface inflows into the catchment recharges the groundwater reservoir. The water bearing unit in the groundwater reservoir are called aquifers. Depending on the hydraulic nature of the overlying and underlying geologic material, the aquifer can be classified into unconfined (in which case the aquifer crops out and there is a direct recharge) and confined (in which case the aquifer is sandwiched between two relatively impermeable units). Confining layer can further be classified into two units as aquifuge and aquiclude on the basis of their storage capacity and hydraulic conductivity. The aquifer in a given geologic media is largely a function of the degree of weathering, fracturing and faulting, the nature of the geologic material, the sediment grain size, degree of sorting and packing. Accordingly considering all these facts together with the spring location and its corresponding discharge, topographic and geomorphic position, vegetation cover and settlement patterns were used to classify the different lithostratigraphic units into similar groups of hydrostratigraphic unit which show homogeneity in their hydrogeologic characteristics (Tenalem Ayenew, 1998).

In this work emphasis is mainly laid upon qualitative description of the different lithologic units given in section 3.4. The lack of pumping test data on most of the lithologic units forces to follow qualitative description and interpretation of the lithostratigraphic unit into groups having similar hydrostratigraphic units and exhibit homogeneity in their hydrogeological characteristics such as degree of weathering, fracturing and faulting, spring discharge and its location, vegetation cover and settlement pattern, geomorphic and topographic position. Based on field hydrogeological mapping, interpretations of the various lithologic units, discharge of springs, it is possible to classify and group rocks having similar hydrogeological characteristics into one unit. Accordingly four hydrostratigraphic units are identified, described and mapped (Fig. 5.1).

5.2 Hydrogeological Mapping

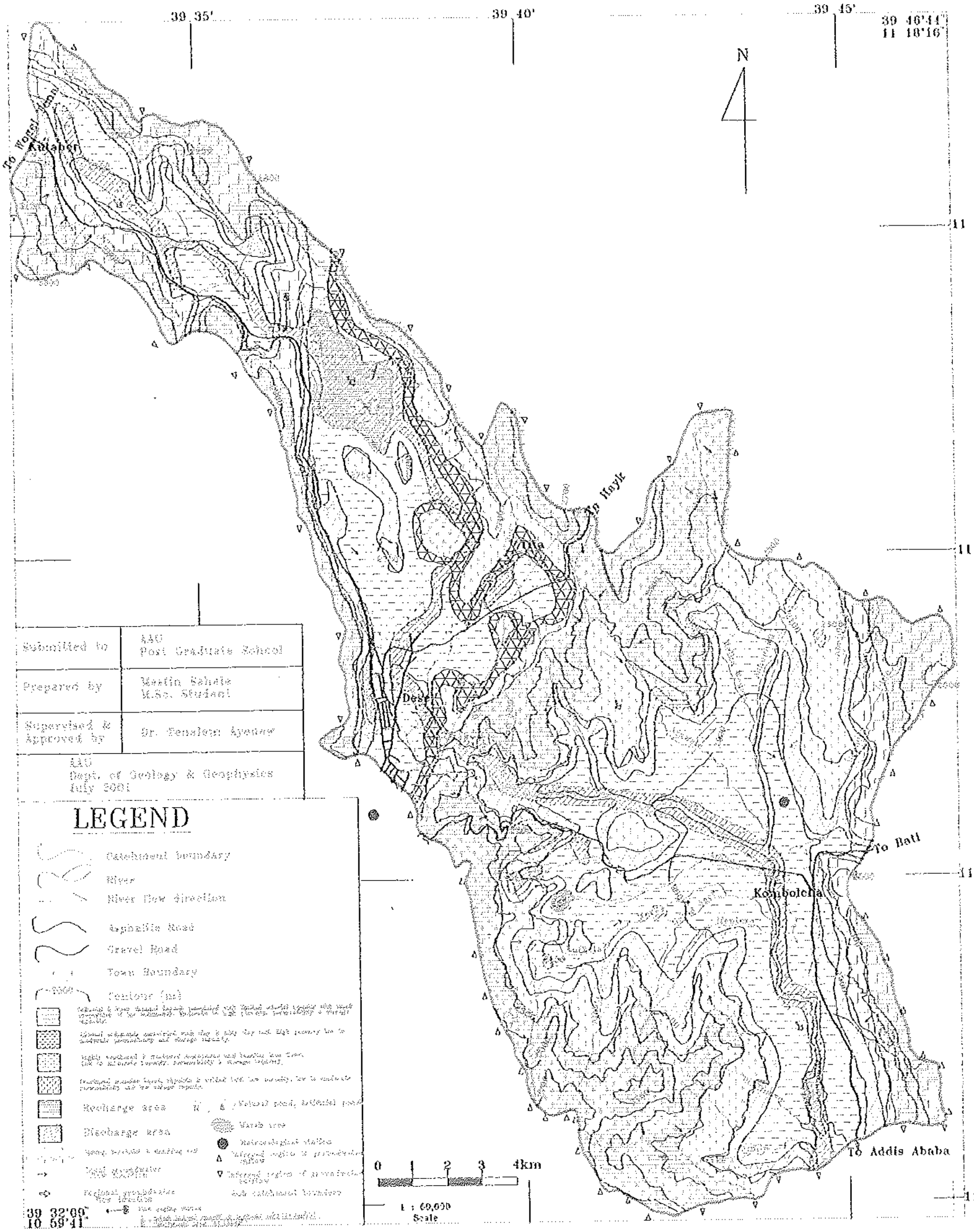
The purpose of hydrogeological mapping is to enable various areas to be distinguished according to their hydrological character in relation to the geology (UNESCO, 1983). Accordingly the hydrogeological map of the studied catchment is prepared at the scale of 1:50,000 after making a field survey and with the application of qualitative description and classification of the different lithologic units into similar groups of hydrostratigraphic unit. The main criteria that was used in the classifications of lithologic units into similar groups of hydrostratigraphic units are:

- Degree of weathering, fracturing and faulting
- Geomorphic and topographic position
- Lithologic make up of the rock

- Spring location and its corresponding discharge
- Thickness of the weathered layer
- Vegetation cover and type of settlement pattern

In general hydrogeological map of the studied catchment include such items as: water points (springs, hand dug wells, and borehole), marshy areas, ponds (both natural and artificial), meteorological stations, staff gage, recharge and discharge areas, possible regions of groundwater inflow and outflow sites. Even if there is a transmissivity and hydraulic conductivity data on some of the boreholes, their corresponding geographic locations are lacking as a result, they are not indicated on the hydrogeological map rather presented in tabulated form.

Fig. 6.1 HYDROGEOLOGICAL MAP OF THE BORKENA RIVER CATCHMENT



5.3 Hydrogeology of the study area

Generally the hydrogeological units described in the study area can be grouped into fractured aquifer (scoraceous and basaltic lava flow, fractured massive basalt, rhyolite and welded tuff) and intergranular aquifer (colluvial and river channel deposits and alluvial deposits). Both of which are dominated by processes resulting in secondary porosity and permeability. Specially the volcanic aquifers possess in most cases relatively few primary porosity and permeability, which is negligible from water resource and exploitation point of view. In contrast the colluvial and river channel deposits and alluvial deposits are more promising for locating water wells than the volcanic aquifer. Moreover most of the larger yield springs are located in these units (Fig. 5.1 and 5.2).

Table 5.1 Percentage distribution of hydrostratigraphic units

Type of hydrostratigraphic unit	Areal coverage (km^2)	percentage proportion
A	42.5	13
B	113.0	35
C	120.4	37
D	49.3	15

Note: A = colluvial and river channel deposits; B = alluvial deposits;
C = scoraceous and basaltic lava flow; D = fractured massive basalt, welded tuff and rhyolite

5.3.1 Colluvial and River channel Deposits

This hydrostratigraphic unit contains colluvial and river channel deposits and is exposed on the foot of hills, fault escarpments and along the Borkena river channel and accounts 13% of the studied catchment, (Table 5.1 and Fig. 5.1). Because the unit lies on the topographical low and flat to gentle region of the catchment together with the sediment particle size dominated by coarse sand and gravel would assist in relatively good infiltration to recharge the groundwater

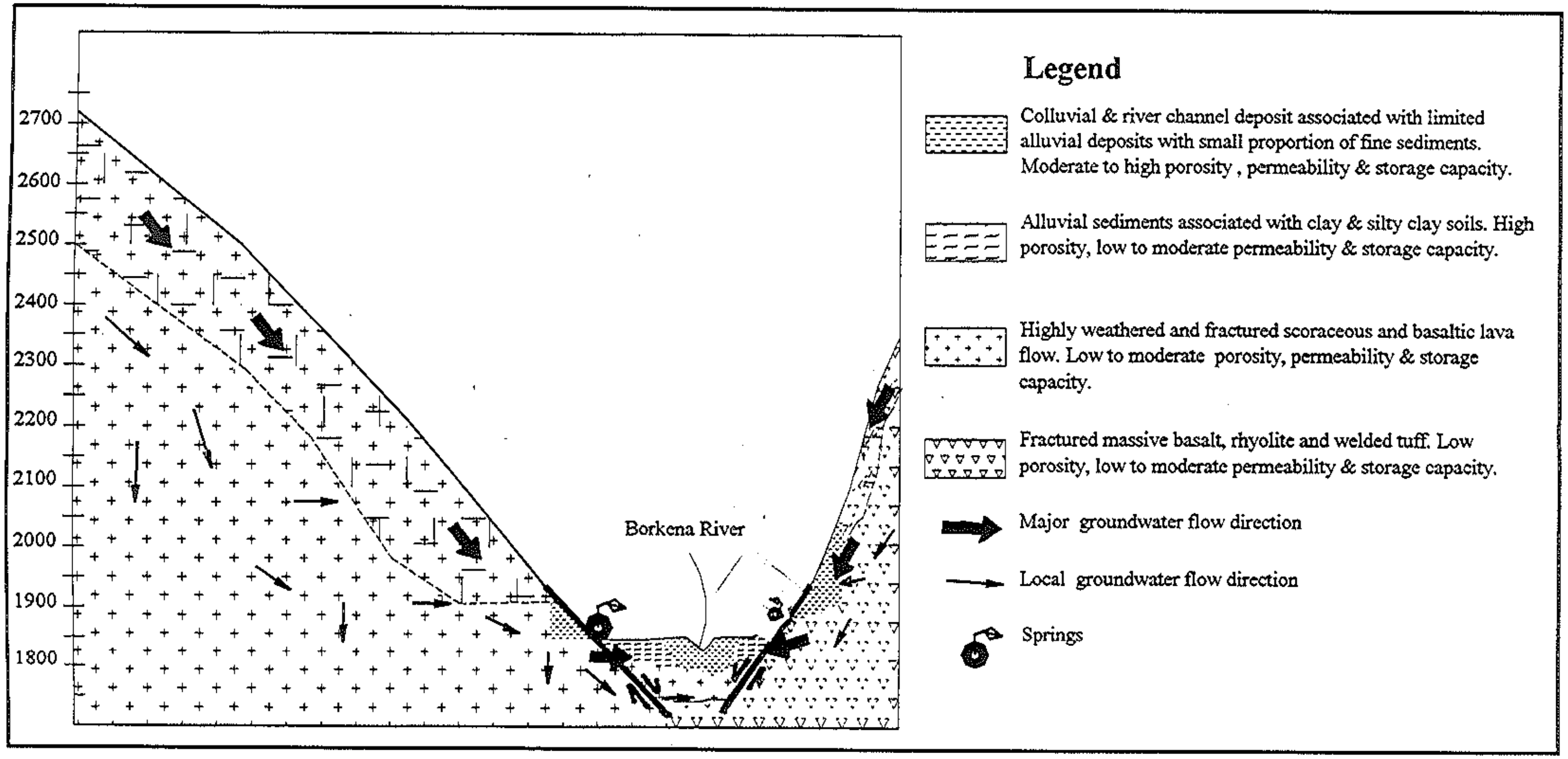


Fig. 5.2. Schematic Model of Borkena River Catchment South of Kombolcha

reservoir at the expense of low runoff. Mainly the unit is recharged through direct precipitation and indirectly through faults channelized water from the upland volcanic aquifers, as results most springs, hand dug well and borehole are located on this unit.

The discharge of springs located on this unit varies from 0.1 l/s to 9 l/s. Hence, it is one of the most productive aquifer in the limits of the catchment and relatively characterized by moderate to high porosity, permeability and storage capacity.

The colluvial and river channel deposits show similarity in their hydrogeological characteristics such as relative infiltration capacity, permeability, grain size and degree of weathering. If comparison is made between these two units, it is obvious that the river channel sediment would give higher permeability and infiltration capacity since the degree of sorting and grain size distribution is good in cases of river channel deposits than the colluvial deposits. Springs of larger yield are also controlled by E-W oriented faults.

In some areas, especially along the Borkena river channel, it was seen that the discharge of the river suddenly reduces in volume. From this observation it is inferred that the groundwater table is deep and as a result the river recharges the groundwater reservoir. Generally the majority of the unit lies with in the discharge zone and constitutes the extensive permeable unconfined layer of the catchment. The thickness of the unit varies from place to place however it generally does not exceed a few tens of meters being large in the Kombolcha subcatchment.

5.3.2 Alluvial Deposits

Geomorphologically the unit occupies the flat area of the floor of the graben in the catchment. The grain size varies between clay and silt. Small proportion of sand size particles are associated with them. In terms of infiltration, it is situated most favorably however the rate of infiltration is strongly influenced by its fine grain size proportions. Hence the amount of the corresponding recharge is lowered at the expense of high runoff. As compared to other units in the catchment, it is the second largest and covers an area of 35% of the catchment. From water resource and exploitation point of view it is moderately promising and as a result reasonable number of springs, hand dug well, and borehole are located on it. During field survey conducted at February, one artesian well with discharge of about 0.4 l/s to 0.6 l/s was identified. Hydrogeologically the unit is characterized by high porosity, low to moderate permeability and storage capacity.

Pumping test data conducted on the same unit in the Kombolcha subcatchment shows that the unit has a discharge of 8 l/s with hydraulic conductivity of 1.08 m/day (Ketema Tadesse, 1980). Most of the wells drilled in the Kombolcha subcatchment are of overflowing (artesian) type in nature however during field investigation conducted in February, 2001 and personal communication with experts at the Amhara Water Works Construction and Design Enterprise (AWWCE), the artesian well located in the compound of AWWCE office was no more artesian in effect of the high pumping rate of wells located in the Poultry Farm and Disaster Prevention and Preparedness Commission (DPPC) compounds.

5.3.3 Scoraceous and Basaltic Lava Flow

This unit outcrop in most parts of the catchment occupying the topographically elevated and relatively moderate to steep slope and accounts 37% of the catchment. The unit is highly weathered, fractured and topographically located on the recharge area facilitating good infiltration to take place however the expected infiltration and recharge is largely reduced due to rapid runoff and the development of thin soil cover which in most cases was eroded away owing to rapid runoff and even the small infiltrated water comes out as lines of seepage and springs following the dip direction of the fault plane and on contact with the paleosoil layer underlying it. Consequently few wells with relatively small yields are located on the unit. The minimum and maximum static water level in the unit varies between 5.4 m and 16.7 m at Kombolcha and Cheffa respectively while the mean static water level lies at 10.3 m (Ketema Tadesse, 1980).

Considering the hydrogeologic characteristics, it is the second promising unit however its groundwater potentiality for abstraction is largely discouraged owing to its topographic position with consequence of rapid runoff and very thin soil cover development. As a result only few wells have been drilled and located on it and correspondingly the yield is small, (Table 5.3). This unit contains highly weathered and fractured basalt with few beds of basaltic flows and columnar jointings. The aquifer is characterized by low to moderate porosity, permeability, and low storage.

5.3.4 Fractured Massive Basalt, Rhyolite and Welded Tuff

From field observations, the unit lacks primary porosity and permeability but relatively affected by sets of widely spaced faults than other units in the catchment and are considered poor aquifer. The unit is exposed in the most elevated topography and steep slope parts of the region and is almost all located in the recharge area. These lithologic units which are grouped in one hydrostratigraphic unit show homogeneity in their hydrogeological characteristics such as degree of weathering, fracturing, and faulting. Hence, as compared to other units in the catchment, they are low to moderately weathered, sparsely affected by joints and fractures and possesses a very thin soil cover with scattered bushes, shrubs and trees that grow in between fractures.

Though the unit is located on the recharge area, the corresponding infiltration is largely reduced by its low degree of fracturing, weathering and steep slope nature moreover the small infiltrated water is channelized along the dip direction of the sets of fault plane with consequent reduction of the storage capacity and limiting the yield of wells located on the unit. The N-S and E-W oriented faults largely control springs of low to moderate yield and lines of seepage. The unit is characterized by low porosity, low to moderate permeability and low storage capacity.

Table 5.2 Water wells in the studied catchment

No.	Location and owner of borehole	Elevation (m)	Casing dia. (mm)	Total depth (m)	Static water level (m)	Yield (l/s)	Lithology
1	Kurkur (Dessie Municipality)	2512	6″	?	20	5	Basalt
2	Hote meda	2465	6″	60	8.8	5.6	River gravel
3	Kidame Gebeya	2530	6″	91	3.5	-	Basalt
4	K. well #1 (K. Municipality)	1682	6″	80.3	Overflow	-	Alluvium
5	K. well #2 (K. Municipality	1679	6″	72.1	overflow	-	Alluvium
6	K. well #1 (Textile Factory)	1695	8″	94	overflow	-	Alluvium
7	K. well #2 (oil & soap factory)	1669	8″	45	overflow	-	Alluvium
8	K. well #1 (water resource)	1705	6″	25	?	-	Alluvium
9	K. well #2 (water resource)	1702	6″	-	3.7	-	Alluvium
10	K. Municipality well	1665	8″	48	-	-	Alluvium
11	K. Meat factory well	1700	8″	-	6	1.5	Basalt
12	K. Agip station well	1750	-	?	-	-	Alluvium
13	K. ERA well	1722	6″	-	92	-	Basalt
14	K. Ghion Hotel well	1748	6″	-	30.3	-	W. Basalt
15	Muti Kolo (K. Municipality)	1854	6″	-	5.4	-	-
16	K. High School	1930	8″	46	4.7	6	S. gravel

Source: After Ketema Tadesse, 1980 with some modification

Note: K = Kombolcha; W = weathered ; S = sandy

5.4 Recharge and Discharge Areas

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

Generally recharge areas are located on topographically high areas and the flow lines are diverging while discharge areas are located on topographical low and if flow lines are constructed, they are converging (Fetter, 1994). Accordingly the regions of recharge and discharge areas are identified and mapped. The recharge area in the studied catchment occupy the topographically elevated areas which is underlain by fractured volcanic rocks where as discharge areas are located on the topographical lows comprising the main Borkena river channel, lines of seepage, springs, marshy and inundated areas, sites of hand dug well and borehole, (Fig. 5.1). Most of the discharge areas are covered by riverbed and colluvial deposits.

In the studied catchment, the recharge areas cover relatively larger regions than the discharge area. As it is shown in the Fig. 5.1, it is possible to identify small patches of discharge area with the limits of recharge area.

Even if water sample data are lacking from the recharge areas, it is often possible to separate recharge and discharge on the basis of their electrical conductance (EC) and total dissolved solid (TDS) value. If comparison is made between recharge and discharge areas residence time and flow pattern, water in the discharge area would have higher residence time, longer and deeper circulation patterns than the recharge areas water as a result discharge areas water would have time to undergo geochemical evolution and leading to higher EC and TDS values than recharge areas' water.

5.5 Dessie Subcatchment

The Dessie subcatchment is mainly located north of the town of Kombolcha and is characterized by groundwater outflow, shallow water table low to moderate drainage density that is dominated by first order drainage pattern. The permanent marshy area accounts

1.5 km^2 however the area increases in response to seasonal flooding during the big rainy months which lasts from July to September. The maximum elevation difference between the floor of the graben and the top of the ridge is 800m.

The two major faults i.e. NNW-SSE and NNE-SSW delineate its eastern and western boundaries. The volcanic aquifer (fractured aquifer) and alluvial aquifer (intergranular aquifer) accounts 47.2% and 52.8% of the catchment. The NNW-SSE and NNE-SSW faults are more common and dissecting the different lithologic units with consequent channelization of recharges from the upland volcanic aquifer into the low-lying alluvium, colluvial and river channel aquifers and manifested there as lines of seepage (controlled by NNW-SSE fault) and larger yielding springs (controlled by E-W faults).

More than 75 % of the springs is located in this subcatchment and is characterized by very slight differences in their EC value and almost all EC values are less than 400 μS/cm. Wells located in this subcatchment yield 5 to 5.6 l/s (Ketema Tadesse, 1980) which is more productive than wells located in the Kombolcha subcatchment, even some of the springs are used to supply water for small towns like Kutaber and Boru Hospital and its surrounding residence. The static water level in this unit generally less than 20m.

The sparse distribution of drainage indicates that, there is relatively more infiltration and than runoff while the reverse happen in the Kombolcha subcatchment. The mean annual infiltration, which the catchment receives after actual evapotranspiration and runoff values are subtracted from the mean annual precipitation, is 56 mm. The climatic condition is subhumid traditionally called "Dega" and receives more rainfall than the Kombolcha subcatchment.

The river channel deposits are dominated by coarse sand and gravel and the corresponding channel is narrow and relatively the river is of effluent type. The river channel in this subcatchment has almost no odor, developed very thin and sparse population of algae and receives very small amount industrial effluents. As a result the corresponding pollution of the river with respect to algae is minimal. If the conditions were not this, we would have dense population of algae on the surface of the river.

5.6 Kombolcha subcatchment

This subcatchment is mainly located south of the town of Dessie and is characterized by groundwater inflow and relatively deep water table and more artesian wells.

The distribution of the different volcanic and alluvial aquifer with in the limits of the catchment is 55 % and 45 % and when combined accounts 64% of the whole catchment. The maximum elevation difference between the floor of the graben and the peak of mount Yegof is 900m. The topography and slope dies out from north, east, and west towards the central and southern regions of the catchment. The N-S faults are less common than the E-W faults. As it is reported by Ketema Tadesse, 1980, wells located on this subcatchment generate no more than 2 l/s however later drilled borehole data shows that variation in yield between 4.7 l/s and 17.9 l/s (Table 5.3).

Table 5.3 Water wells drilled later than 1975

N0.	Owner	Depth	DWL	SWL	Yield (l/s)	T(m^2/d)	EC	pH	HD
1	Textile	186	50.89	artesian	15	14.4	316	7.7	84
2	Textile 2	180	41.2	artesian	15	19.8	313.11	7.7	-
3	Textile 3	180	40.48	artesian	15	12	361.64	8	-
4	Textile 4	180	22.25	artesian	15	33.2	362	7.8	-
5	Textile 5	180	38.6	artesian	15	23	328.8	7.7	-
6	AWSSA	73	-	6.1	5	-	-	7.6	35
7	AWSSA	80.3	-	1.45	5.7	-	-	7.8	110
8	AWSSA	24	-	-	-	-	-	-	-
9	RRC	84	-	artesian	6	-	-	-	-
10	ERCA	96	-	3.33	6	-	-		-
11	Poultry Breeding Farm	77	-	artesian	7.2	-	573	8	215
12	WSSA1	114	-	artesian	17.7	-	336	7.7	92
13	WSSA2	112	-	artesian	17.9	-	362	7.6	96
14	WSSA	118	-	0.8	12.1	-	388	8.1	92
15	Rental House	90	-	-	-	-	543	8.2	-
16	National Insurance Company	102	-	8.7	4.7	-	442	7.8	176

Source: Amhara Regional State Water Works Construction and Design Enterprise, 1984 (AWWCE)

Note: HD = Hardness; T (m^2/d) = Transmissivity m^2/day; DWL = Dynamic Water Level; SWL = Static Water Level

The high yield of alluvial aquifer might be due to the horizontal flow from the upland volcanic aquifer; otherwise it is difficult to explain the high yield (Ketema Tadesse, 1980). The transmissivity values in the borehole drilled at Kombolcha varies between 12 m^2/day and 33.6 m^2/day and with static water level varies between 0 m and 8.7 m below the ground surface. The presence of more artesian well signifies a confined aquifer.

The drainage density in this unit is high and dominated by first and second order streams implying there is relatively high runoff with little recharge. The connection of the subcatchment to Dessie is via through deep cut V-shape Borkena River. The mean annual amount of infiltration the catchment receives is 99.6 mm and the type of climate that it experiences is subtropics that is traditionally called "Weigna Dega".

Concerning pollution, the subcatchment gets more industrial waste effluents and the river channel is relatively odorous and developed dense population of algae. The river channel in the subcatchment is characterized by wide flood plain with coarse gravel, cobble, pebble and large fragments of rocks. It was seen that some of the river discharge suddenly decrease in volume and in other parts, come out as groundwater seepage along the riverbed signifying both effluent and influent river systems developed there but the later is more frequent.

5.7 Springs discharge and electrical conductivity (EC)

More than twenty four sprigs are identified and mapped in the studied catchment (Fig. 2.1 and annex 11). These springs vary in discharge from 0.1 l/s to 9 l/s, the most voluminous being the E-W oriented fault controlled ones probably this is due to the crossing of E-W oriented fault with N-S faults. The electrical conductivity value measured at field shows that most of them lies below 400 μS/cm.

Generally the springs in the area can be classified into three (annex 11): A) fault controlled spring; B) contact spring and C) depression springs. Among others, the fault controlled springs are widespread and more common with reasonably moderate and constant discharge in the dry seasons (personal communication with local people).

The utilization of the springs are widespread and diversified. Specially the intensive utilization of the springs for irrigation practices in the dry seasons. Moreover they are intensively utilized for all type of domestic purposes, and even as water supply for small towns like Kutaber and Tita.

Even if there is a large difference between the smallest and largest yield springs, most of them show slight variation in their fairly constant discharge. The average discharge and EC value of the springs over the whole catchment is 1.2 l/s and 330.6 μS/cm.

Lithologically most of the springs are located within the colluvial and river channel deposits. So from water resource point of view, the colluvial and river channel sediments are most promising then followed by alluvial deposits. The majority of the springs are also located on topographically low lying and on the floor of the graben (Fig. 5.2). The absence of hot springs in the studied catchment shows that, the groundwater circulation is shallow.

The discharge of almost all the springs increase during the rainy months and gradually decreases and become fairly constant in the dry seasons. So this implies that the permeability of the aquifer in response to precipitation is rapid and the corresponding permeability of the geologic material is fairly good.

5.8 Groundwater Flow systems

Two types of groundwater flow systems are identified and mapped in the Borkena river catchment (Fig. 5.1). The regional flow system, which generally follow the trend of topographic relief difference between landmasses lying in northwestern and southeastern region of the catchment and also the pattern of the direction of the Borkena river flow while the local flow system follows the general elevation difference between the neighboring catchments located on both sides opposite the water divide. The local flow system in the studied catchment is further classified into the Dessie and Kombolcha in which case the Dessie subcatchment is characterized by groundwater outflow while the Kombolcha with groundwater inflow.

5.9 Groundwater-Surface Water Interaction

Along the Borkena River, the distribution of river channel deposit and their grain sizes varies with the area of the catchment and the number of tributaries entering into it. Accordingly sediment grain size tends to increase from upstream towards downstream direction of the catchment. Due response to this increase in grain size and probably to some geologic structures lies beneath the riverbed, it was observed that the discharge of the river decreases in volume and in other section of the stream, the groundwater appear as lines of seepage and springs feeding the river flow. Therefore, the river flow is characterized by effluent and influent type of discharge. This implies that there is some kind of mixing between the surface and groundwater along the river channel.

CHAPTER 6

Water Balance

6.1 Introduction

Evaluation of water balance of a given basin/catchment is essential in the practical sense of designing efficient planning, management and sustainable utilization of the different water resources available in the basin/catchment. In its treatment, water balance takes into consideration the inter-relationship between the various inflows, outflow and change in storage items within the extent of the drainage basin/catchment and in defined hydrologic period.

In the study area, the water balance mainly is used to estimate the rate of annual groundwater recharge. The equation of the form is given by :

Inflow = Outflow ± Change in Storage

Since analysis of the water balance is one of the main of objective this work, accordingly the water balance calculation is performed for the two subcatchments and for the entire catchment. Since there is a lack of discharge measurements in all of the springs, hand dug well and borehole on the full hydrological year, abstraction of water in any form is neglected in the evaluation of the water balance of the studied catchment.

On annual basis of calculation of the water balance, the change in storage item is considered to be zero. Since there is a lack of data on groundwater inflow and outflow items, they are generally assumed to be equal; although this is a simplification of the reality.

6.2 Water Balance of Dessie Subcatchment

The equation of the water balance for any water body in a given hydrologic system and period is given by:

$$P_i + S_i + G_i - E_{act} - S_o - G_o - I = \Delta S \qquad (6.1)$$

where P_i - precipitation

S_i - surface water inflow

G_i - groundwater inflow

E_{act} - actual evapotranspiration

S_0 - surface water outflow

G_0 - groundwater outflow

I - infiltration

ΔS - change in storage

with the assumptions made before:

$G_i = G_o$

$S_i = 0$ since no streams enter into the catchment

$\Delta S = 0$ on annual basis of water balance calculation then the equation is reduced to the form

$$I = P_i - S_{oc} - E_{act} \tag{6.2}$$

Where I - infiltration for the catchment

S_{oc} - total surface runoff for the catchment and is computed by

$$S_{oc} = S_0 * \text{runoff coefficient} \tag{6.3}$$

S_o - total surplus water available for runoff

E_{act} - actual evapotranspiration for the catchment

Inserting all the available data (annex 9) into eq.(6.2) results in 155.6 mm of mean annual recharge over the catchment, (Table 6.1). So to account for the Dessie subcatchment, it then multiplied by the catchment percentage proportion which is 0.36 and gives 56 mm.

$$I_d = 0.36*I \tag{6.4}$$

where I_d = infiltration for Dessie

0.36 percentage of area for the Dessie subcatchment (117.5 km^2)

Table 6.1 Computation of annual recharge over the catchment

Drainage area (km^2)	Computation of water balance for Dessie subcatchment			
117.5	P_i (in mm)	E_{act} (in mm)	S_{oc} (in mm)	I_d (in mm)
36% of the area	1027	860	12.43	56

In the Dessie subcatchment the only input is precipitation while outflow include actual evapotranspiration and surface runoff. The surplus water available for runoff is determined through (Thornthwaite and Mather, 1955) method is 113 mm per annum and accounts about 13% of the mean annual rainfall. From the computation made so far, the Dessie subcatchment would get a recharge of 56 mm of water per annum.

6.3 Water balance of Kombolcha Subcatchment

The calculation of water balance for this subcatchment follows the same procedure as for the Dessie subcatchment and use of same formula gives annual infiltration of 99.6 mm. Hence the general form of equation for the entire catchment is multiplied by the percentage of area (0.64) to account for the infiltration in Kombolcha subcatchment. It is then given by:

$$I = P_i - S_{oc} - E_{act}$$

$$I_k = I*0.64 \qquad (6.5)$$

Where I_k - infiltration for Kombolcha

S_{oc} - total surface runoff for the catchment

$E_{act.}$ - actual evapotranspiration for the catchment

After inserting relevant data (annex 9) into eq. (6.2) of the water balance equation given above and then multiplying the result with area percent proportion of the catchment (0.64) generate 99.6 mm of mean annual recharge for the Kombolcha subcatchment. In this subcatchment as in Dessie the only input is precipitation while the loss include surface runoff and actual evapotranspiration, (Table 6.2)

Table 6.2 Computation of annual recharge for Kombolcha subcatchment

Drainage area (km^2)	computation of water balance for Kombolcha subcatchment			
208	P_i (mm)	$E_{act.}$ (mm)	S_{oc} (mm)	I_k (mm)
64% of the catchment	1027	860	12.43	99.6

6.4 Water Balance for the Entire Subcatchment

Following eq. (6.1), water balance for the entire catchment is given by

$$I = P_i - S_{oc} - E_{act}$$

for estimation of water balance of the entire catchment, groundwater inflow equals to groundwater outflow is assumed and surface water inflow is also zero as there are no streams entering into the catchment.

Evaluation of eq. (6.2) results in 155.6 mm of mean annual recharge over the whole catchment. Since there is intensive utilization of the springs and rivers for irrigation practices in the dry seasons, this might underestimate the surface runoff and overestimate the evapotranspiration processes and then the two variables make a balance, hence the calculated value of annual recharge into the catchment seems logical

CHAPTER 7

Hydrochemistry

7.1 General

The chemical and physical characteristics of water is very important in terms of utilization of water for various purposes. Specifically the quality of water becomes crucial if there is a need to use it for domestic and industrial purposes. Even if there is a variation in the standard limit of chemical concentration of ions in water among various countries, it is unquestionable to set the upper and lower limit at least on a national base depending on the availability of water, technological advancement and economical status of the country.

Dissolved constituents in natural water depict the chemical evolution, man made impact and its mode of origin in the hydrologic cycle, (Freeze and Cherry, 1979). Hydrochemical data also reveals information on chemical constituent ions contained in it and hence it is a good tool to study different water and safely limit their utilization for various purposes.

The main objective of this chapter is to provide hydrochemical information in the waters of the Borkena river catchment and to examine the water from the perspective of water quality criteria set for drinking and agricultural practices. For this reason the standard limit set by WHO is compared with the analyzed water samples.

7.2 Water Sampling and Analysis

About 40 water samples were collected, however, due to severe financial constraint, only 14 water samples were analyzed depending on their geographic distribution and sound hydrogeological reasoning. Among which four were taken from rivers; five sample each from springs and hand dug wells respectively.

The analysis of these samples was conducted at the Ethiopian Geological Survey main laboratory. The analysis include major cations and anions, nitrate and nitrite, phosphate, some trace elements and total dissolved solids (TDS), (annex 12). Even if the analysis was conducted in ten samples with ten trace elements on each sample, unfortunately the reported result was crude and as a result nothing quantitative description can be said concerning the industrial effluents into the river from industries located in Kombolcha and Dessie.

Since more often certain parameters show changes compared to their field value as a result field EC value measurements are taken in all of the samples. Hem, (1970) strongly recommends in situ test to be conducted on the parameters of EC, pH and dissolved oxygen (DO). The field EC value measured shows that most of the water bodies have EC value less than 400 μS/cm, implying that they are fresh.

7.3 Major cations and anions

The analysis conducted on water bodies show slight variation with respect to bicarbonate, sulfate, and calcium while it shows relatively large differences in chloride, sodium and potassium combined, and in magnesium concentrations. Relatively speaking the river water is enriched with respect to cations and anions than the ground water bodies (Springs and hand dug wells), (Table 7.1 and Fig. 7.1). It is then followed by hand dug well and springs. The contribution of chloride and sulphate in river water is about 50 percent from the total chloride present in water bodies while it becomes about 55 percent in the case of sodium plus potassium combined. The enrichment of the river might be related either to evaporation concentration or high inflow of both domestic and industrial wastes into the river water.

Among all the analyzed ions, bicarbonate is the dominant anion while calcium is the dominant cation which is then followed by chloride and sodium plus potassium combined respectively, (Table 7.3a, & 7.3b and Fig. 7.3a & 7.3b).

Table 7.1 Percentage concentration of ions in water bodies (mg/l)

Sample Type	SP	HW	R	Total	% SP	% HW	% R
Bicarbonate	215	256.60	287.75	759.35	0.28	0.34	0.38
Chloride	10.2	17.40	25	52.60	0.19	0.33	0.48
Sulphate	7.2	9.20	15.5	31.90	0.23	0.29	0.49
Sod+Pot	15.88	21.96	44.83	82.67	0.19	0.27	0.54
Calcium	43.8	53.6	43.25	140.65	0.31	0.38	0.31
Magnesium	11.8	15	21.25	48.05	0.25	0.31	0.44

Note: SP = spring; HW = Hand dug well; R = rivers;

Sod+Pot = sodium plus potassium

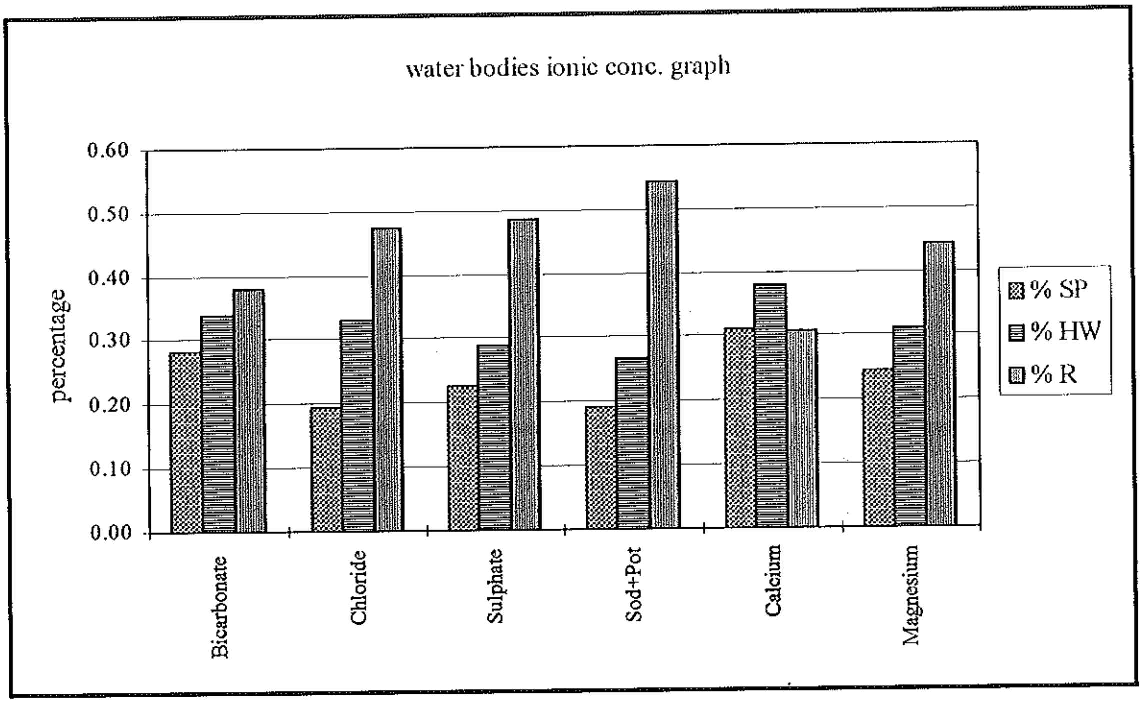


Fig. 7.1 Percentage concentration of ions for water bodies (R = rivers; HW = hand dug well; SP = springs; Sod+Pot = sodium plus potassium)

7.4 Accuracy Check

Before an attempt is made to interpret the results, the accuracy of the chemical analysis of water samples has to be checked through the calculation of cation-anion balance, when all the major cations and anions have been determined, the sum of the cations in milli equivalent per liter should equal the sum of the anions measured in the same units. The difference between the two will generally not exceed 2 or 5 percent of the total cation and anions present in water, Hem, 1970. Hence, the accuracy of the analyzed samples are well with in the reaction error and it ranges between 1 and 8 percent, as a result the interpretation can safely be performed in waters of the studied catchment.

7.5 Discussion of Chemical Composition of Water Bodies

7.5.1 Rivers

Four river samples were collected and analyzed for major cations and anions, nitrate and nitrite, phosphate, TDS and trace elements, (Table 7.2 and Fig. 7.2). Each two samples are taken from the upper (R_5 & R_{11}) and lower courses (R_7 & R_8) of the Borkena river catchment. As it is evident from the table, the percentage concentration of sodium and potassium combined is almost equal to calcium with 41 and 40 percents respectively where as the percentage concentration of magnesium is by far less and accounts only 19 percent of the cations. When comparison is made between the upper and lower course river waters, the lower course is relatively enriched with respect to sodium plus potassium combined and magnesium while lower in calcium concentration, (Table 7.3a and Fig. 7.3a).

Table 7.2 River water samples ionic concentration in mg/l

Rivers	Bicarbonate	Chloride	Sulphate	Sod+Pot	Calcium	Magnesium
R_5	255	18	10	25.5	52	13
R_7	334	19	20	63.6	27	31
R_8	305	26	15	52.2	39	21
R_{11}	257	37	17	38	55	20
Average	287.8	25	15.5	44.8	43.3	21.3
Total	1151	100	62	179.3	173	85

Table 7.3a Cation concentration in river waters (mg/l)

Field no.	R_5	R_7	R_8	R_{11}	Average	Percentage
Sod+Pot	25.5	63.6	52.2	38	44.8	0.41
Calcium	52	27	39	55	43.3	0.40
Magnesium	13	31	21	20	21.3	0.19

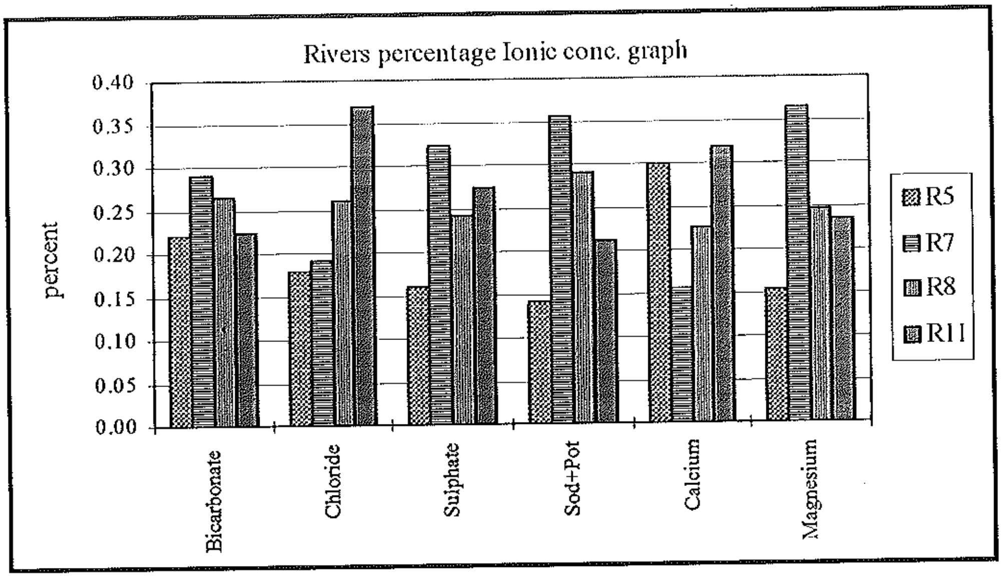


Fig. 7.2 Percentage concentration of ions in river water

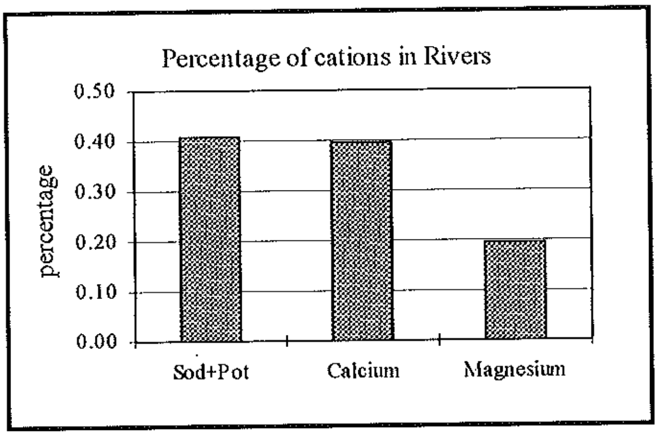


Fig. 7.3a Percentage of distribution of cations in river water

The analysis conducted on major anion of waters of river samples is presented in Table 7.3b and Fig. 7.3b as it is shown in these, bicarbonate is by far the most abundant and accounts 84 percent of the anions in river waters and then followed by chloride with 7 percent concentration. The lower course is enriched with respect to bicarbonate while lower in nitrate concentration. Slight variability are reflected in the upper and lower course river waters with their composition of chloride, sulfate, fluoride and phosphate.

Table 7.3b Percentage concentration of anions in river water (mg/l)

Field no.	R_5	R_7	R_8	R_{11}	Average	Percentage
Bicarbonate	255	334	305	257	287.75	0.84
Chloride	18	19	26	37	25.00	0.07
Sulphate	10	20	15	17	15.50	0.05
Fluoride	0.22	0.36	0.29	0.2	0.27	0.00
Nitrate	14.62	1.77	5.76	31	13.29	0.04
Phosphate	1.2	0.2	0.78	7.8	2.50	0.01

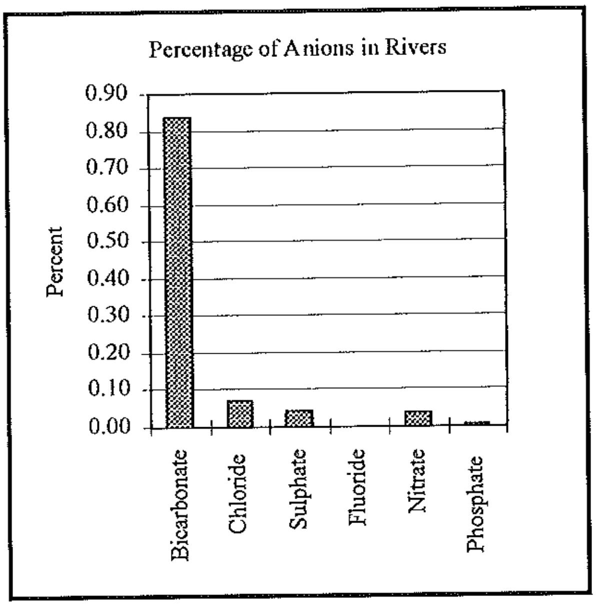


Fig. 7.3b Percentage concentration of anions in river water

The higher concentration of sodium plus potassium combined can be interpreted as to the larger plot area in the lower catchment and their corresponding utilization of fertilizer while the larger concentration of magnesium is attributed to their higher residence in water than calcium (Hem, 1970), as a result calcium might be precipitated out on the way to the lower courses.

The higher concentration of nitrate in the upper course might be due to oxidation of atmospheric nitrogen, direct discharge of sewage disposal specially at the site of R_{11} while the lower concentration of nitrate in the lower course might be explained as reducing environment prevail in the lower course and their utilization by algal population developed on the surface of the river water.

The removal of sewage toilet waste disposal into a stream is still practiced in by the Municipality of Dessie, hence the water analysis conducted for nitrate collected at the site (R_{11}) shows there is a higher nitrate concentration than other course water samples taken from the same stream. Accordingly the responsible government body have to take acute action to stop such irresponsible and deliberate disposal sewage toilet waste.

The field EC and laboratory TDS measurement shows that, the lower course have higher EC and TDS value than the upper course with exception of EC and TDS values taken at R_{11} waste disposal site.

7.5.2 Springs

Spring waters are more common and widely distributed all over the catchment. Five spring water samples were collected; three from the upper course, and two from the lower courses. The same type of analysis was conducted as for river waters, (annex 12 and Table 7.4). The analysis of major cation and anion is presented in (Table 7.4a & 7.4b and Fig. 7.4a & 7.4b). Calcium is the dominant cation and accounts 61 percent of the cations concentration where as magnesium, sodium and potassium combined accounts 22 percent and 17 percents respectively (Table 7.4a). Excluding SP_{15}, the variability of cations among the analyzed springs are minimal as compared to others, SP_{15} is enriched with respect to cations.

As in the river waters, bicarbonate is the most abundant and dominant anion in the spring waters too and accounts 87 percent of the anions in water, it is then followed by nitrate and chloride with 6 percent and 4 percents respectively. The percentage contribution of phosphate and fluoride as compared to other anions in water is negligible. The variability of the anions among springs is minimal excluding the concentration of bicarbonate in SP_{15}. Field EC and laboratory TDS measurements shows that the lower course springs have higher EC and TDS values than the upper course springs, (Table 7.4b and Fig. 7.4b).

Nitrates are higher in the lower course springs than the upper course springs. This might be due to the higher utilization of nitrate fertilizer, open latrine and more disposal of toilet sewage waste with its larger corresponding catchment area.

The slight variability in the cations might be related to the direct rainfall recharge assisted by shallow circulation of spring waters and relatively lower residence time.

Table 7.4a Concentration of cations in spring waters

FIELD No.	SP_{15}	SP_2	SP_6	SP_{12}	SP_{24}	Average	Percentage
Sod+Pot	16.6	10.2	17.2	14.9	20.5	15.88	0.22
Calcium	63	41	41	37	37	43.80	0.61
Magnesium	18	12	9	10	10	11.80	0.17

Table 7.4b concentration of anions in spring waters

FIELD No.	SP_{15}	SP_2	SP_6	SP_{12}	SP_{24}	Average	Percentage
Bicarbonate	294	197	236	178	170	215	0.87
Chloride	12	10	7	10	12	10.2	0.04
Sulphate	9	7	6	4	10	7.2	0.03
Fluoride	0.22	0.12	0.16	0.13	0.12	0.15	0.00
Nitrate	12.85	11.96	0.44	16	30.88	14.42	0.06
Phosphate	0.2	0.86	0.42	0.19	0.15	0.36	0.00
TDS	355	244	240	218	244	260.2	

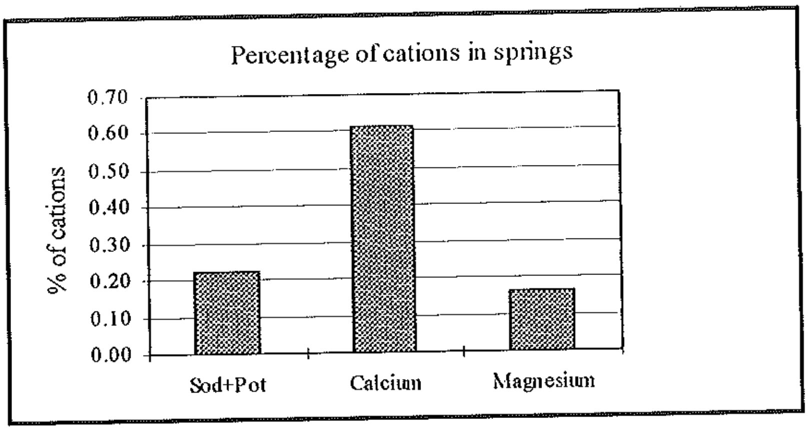


Fig. 7.4a Percentage concentration of cations in spring waters

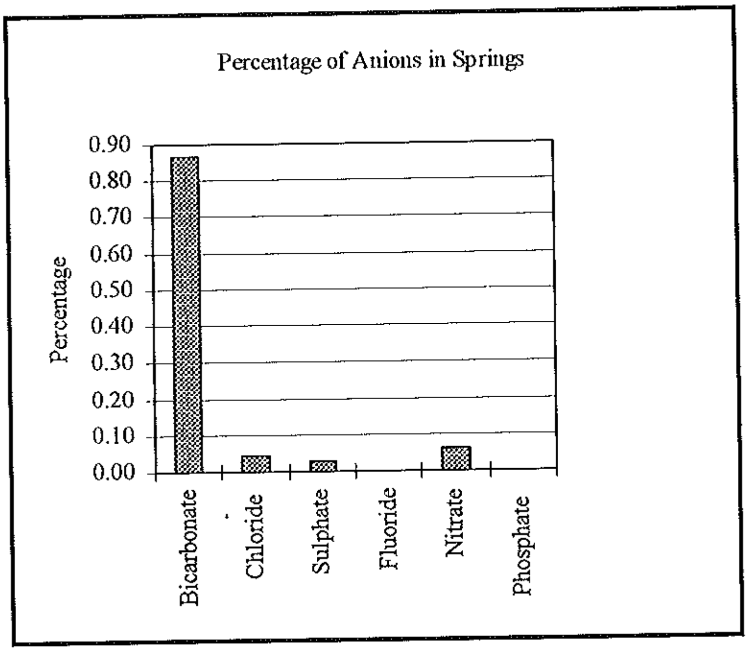


Fig. 7.4b Percentage concentration of anions in springs

7.5.3 Hand Dug Well and Borehole

Five samples were collected from the wells: four from hand dug well and one from borehole. Two samples were from the upper course (HW_1 & BH_2) where as the rest were collected from the lower course of Borkena catchment (HW_6, HW_8, & HW_{11}). The type of analysis conducted on this samples are given in (annex 12). The separate analysis of cations and anions are presented in Table 7.5a & 7.5b and Fig. 7.5a & 7.5b, as it is shown in the tables and figures, calcium is the dominant cation and accounts 59 percent while magnesium, sodium and potassium combined accounts 17 and 24 percent respectively. The variability of cations with respect to calcium is large where as variability is slight in the cases of magnesium, sodium and potassium combined concentrations. Among hand dug wells analyzed, HW_{11} shows higher concentration of cations and anions than other wells.

Table 7.5a Distribution of cations (mg/l) in hand dug well water samples

Field no.	HW_6	HW_1	HW_{11}	BH_2	HW_8	Average	Percentage
Sod+Pot	27.9	9.6	37.7	19.7	14.9	21.96	0.24
Calcium	70	43	84	27	44	53.60	0.59
Magnesium	18	12	20	12	13	15.00	0.17

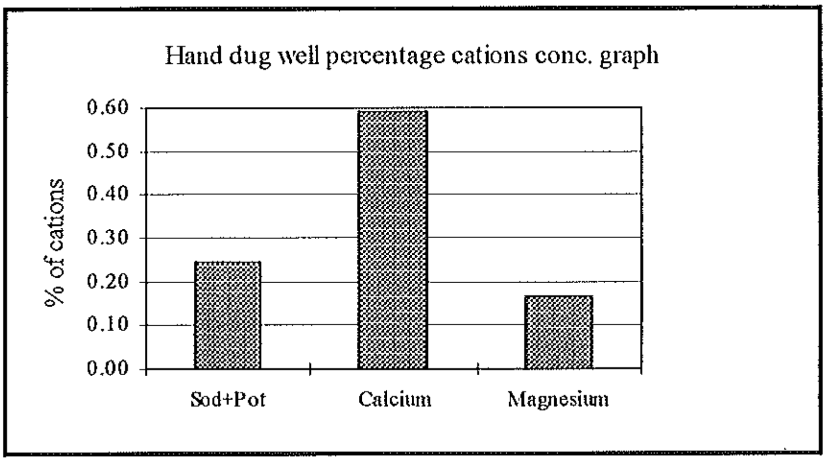


Fig. 7.5a Percentage concentration of cations in hand dug well water samples

From Table 7.5b & Fig. 7.5b, it obvious that bicarbonate is the dominant anion and account 84 percent of the anions in the analyzed well water samples. It is then followed by nitrate and chloride with 7 and 6 percents contributions respectively. The variability of bicarbonate among the analyzed well samples is large. Leaving the anionic concentration of HW_{11}, the variability of other anions is minimal. The higher concentration of anions and cations in HW_{11} might be due human impact. As it is open to the atmosphere and no surface protective cover is made, surface inflows probably loaded with wastes are directly entering into it during the rainy season moreover people used wash their close and animals used to drink the same water. As in the spring waters, the percentage concentration of phosphate and fluoride is negligible, (Table 7.5b & Fig. 7.5b)

Table 7.5b Concentration of anions (mg/l) in hand dug well water samples

Field no.	HW_6	HW_1	HW_{11}	BH_2	HW_8	Average	Percentage
Bicarbonate	366	226	295	177	219	256.6	0.84
Chloride	11	8	49	10	9	17.4	0.06
Sulphate	10	3	25	3	5	9.2	0.03
Fluoride	0.26	0.12	0.28	0.1	0.15	0.18	0.00
Nitrate	14.62	8.86	66.45	7.97	10.63	21.71	0.07
Phosphate	0.24	0.17	0.35	0.45	0.29	0.3	0.00

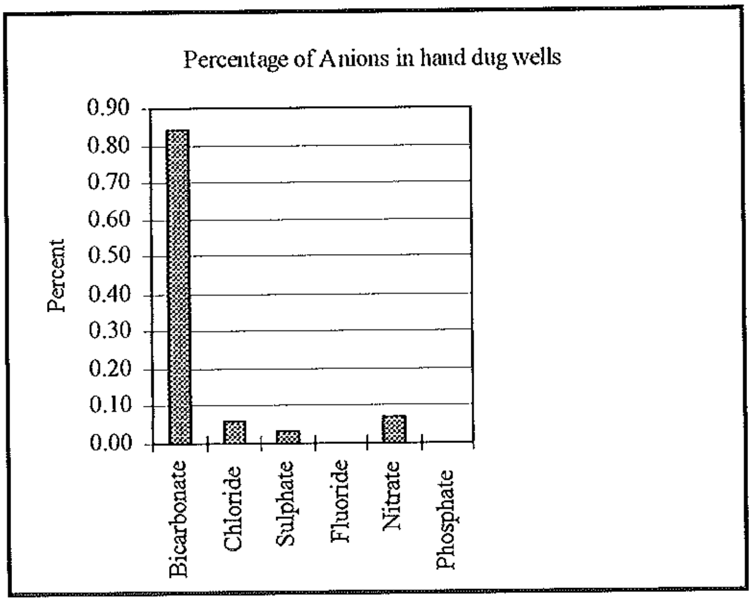


Fig. 7.5b Percentage distribution of anions in hand dug wells

7.6 Classification of Water Types

In order to identify the surface groundwater interaction and utilization of water for various purposes, it is essential to categorize and classify water on the basis of their respective percentage composition of cations and anions. The classification and grouping scheme was done for water of springs, hand dug wells and rivers.

The plotting points on a tri-linear diagram was done based on a computer program called Aquachem. As it is shown in the Fig. 7.3a, the river shows similarity with respect to sodium and potassium combined, and calcium where as lower in magnesium concentration on the contrary the groundwater shows calcium dominance with relatively equal proportion of sodium and potassium combined and magnesium. The percentage concentration of calcium, sodium and potassium combined and magnesium is 40, 41 and 19 percents while in the case of spring and hand dug well waters, it becomes 61, and 59 percent in calcium, 17 percent each in magnesium and 22 and 24 percents in sodium and potassium combined respectively.

The analysis conducted on all water samples of the studied catchment shows that bicarbonate is the dominant anion in all water bodies with percentage concentration slightly varying between 84 and 87 percent in groundwater and surface water respectively. When comparison is made between ionic concentration among various water bodies, it is the river water that shows dominance in both major cations and anions which is then followed by hand dug well and springs, (Table 7.1 and Fig. 7.1).

Based on the analysis and discussions conducted so far on water bodies of the studied catchment and their respective plot on a bar graph and in a tri-linear diagram shows that the river water is ,classified under sodium-calcium bicarbonate type water where as the groundwater (springs, hand dug wells and boreholes) is classified under calcium-sodium bicarbonate type water. Accordingly two types of water are identified in the studied catchment, (Fig. 7.6a, b, and c).

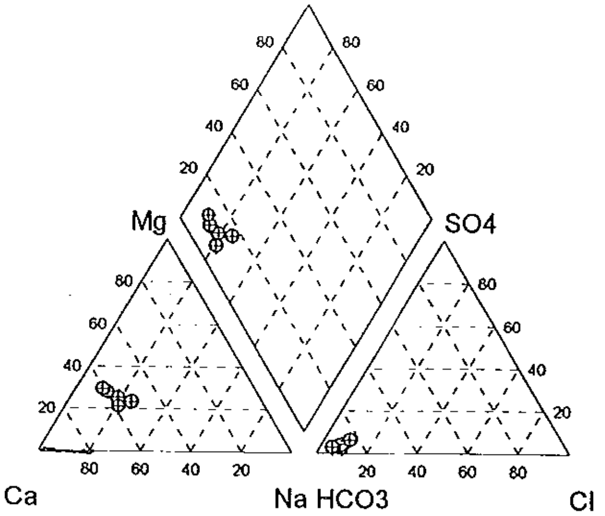


Fig. 7.6a Tri-linear plot of spring water samples

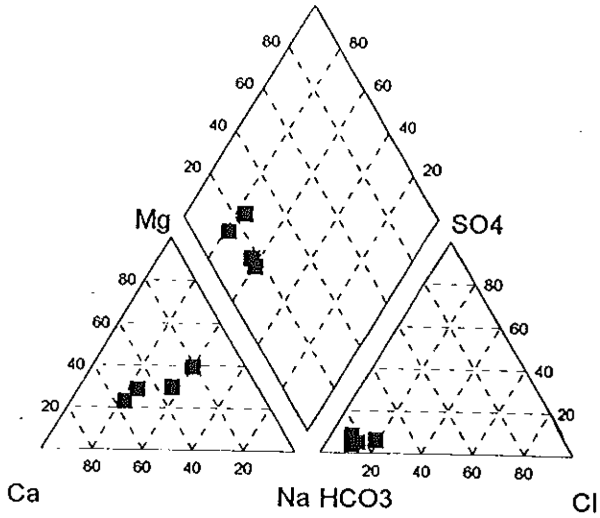


Fig. 7.6b Tri-linear plot of river water samples

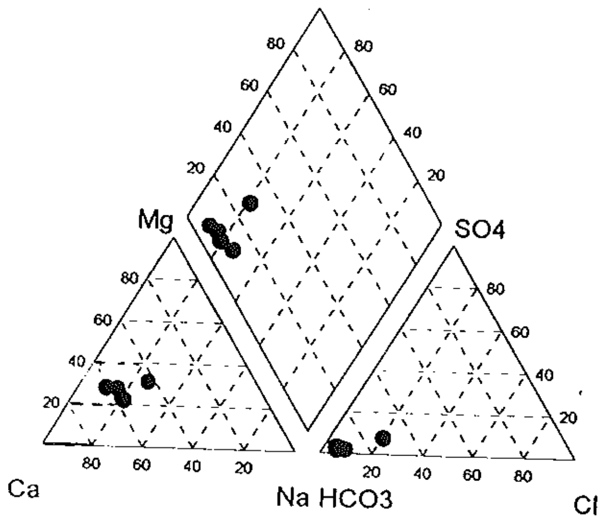


Fig. 7.6c Tri-linear plot of hand dug wells

Fig. 7.6 Tri-linear plot of water bodies

7.7 Other Relevant Parameters

7.7.1 Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The field measured variables included in this work is only EC value. The EC value measured on the field shows that most of the water bodies have EC value less than 400 μS/cm, (annex 11). Of the fourteen water samples, eight of them have EC below 400 μS/cm, six of them have EC between a little more than 400 μS/cm and 560 μS/cm (Table 7.6).

Table 7.6 Field EC values of water samples

Sample type	R_5	R_7	R_8	R_{11}	HW_1	HW_6	HW_8	HW_{11}	BH_2	SP_2	SP_6	SP_{12}	SP_{15}
EC (μS/cm)	275	402	377	433	270	428	286	555	220	274	240	243	509

The low and slight variability in their EC values are typical of volcanic terrains in which the dissolution and leaching of minerals of the rock is minimal unless the water is of aggressive in nature (i.e., having higher concentration of dissolved carbondioxide). The highest EC value measured in the catchment is 555 μS/cm, this higher value in EC is also reflected in the analyzed major cations and anions. The average EC value for water bodies are plotted in Fig. 7.7 and it is evident that the river water has higher EC and TDS value than the groundwater. This might be associated either with the higher effluents from town and industries (slaughter house and Tannery) waste disposals located within the catchment into the river course or due to evaporation concentration.

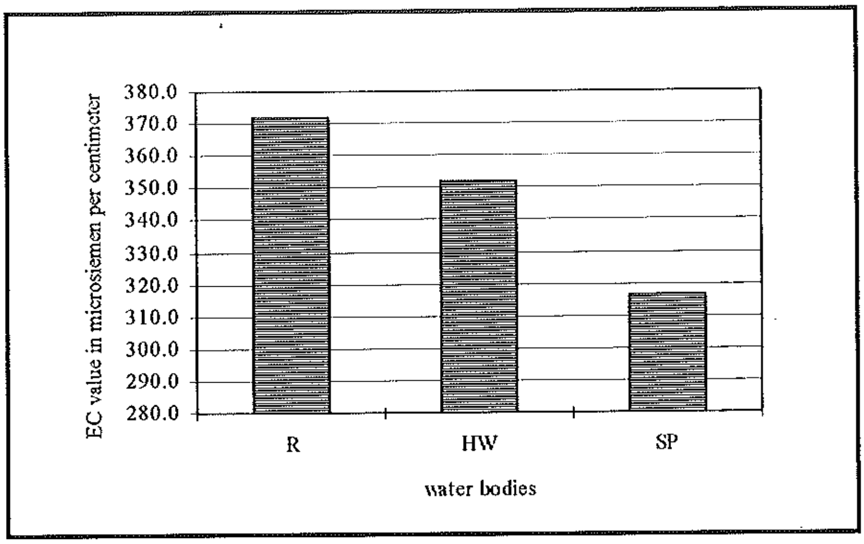


Fig. 7.7 Mean EC value of water bodies

7.7.2 Fluoride

The fluoride concentration in the studied catchment is well with in the limit of the water quality criteria set by WHO for drinking water purpose. Even it is lower than the lower limit which is 0.5 mg/l. In the studied catchment, the overall average concentration of fluoride is about 0.2 mg/l. The concentration of fluoride shows slight variability between 0.1 mg/l and 0.36 mg/l.

The concentration of fluoride in natural water bodies comes from chemical weathering of acidic igneous rock, atmospheric dust of continental source and often associated with volcanic and fumarolic gases, (Hem, 1970). The exposure of acidic volcanic rock is very limited, hence their contribution of fluoride into the water bodies is minimal, so that is why fluoride has very low concentration in the studied water bodies as compared to the rift water which their higher concentration is reflected by tooth mottling. The contribution from atmospheric and industrial source are safely ignored as there are no such sources in the region of interest.

7.8 Water Quality

Water quality standard are regulations that are set specific limitation on the chemical constituents present in water. Accordingly their utilization and consumption for various purposes are examined in view of rejecting or accepting it for domestic, agricultural and industrial uses (Fetter, 1994).

The quality of water is as important as its quantity. The quality of water is determined through the analysis of its physical, chemical and biological parameters. In this work emphasis is mainly given to the chemical water quality in relation to the WHO standard for drinking purposes.

7.8.1 Water Quality Criteria

The quality of water is determined through comparison of the analyzed results with the standard limit set by WHO. Hence, this determines their usefulness for industry, agriculture and domestic purposes (Todd, 1980).

More often TDS and EC values measured at the laboratory/field is used as one of the basic tool limiting their utilization. Accordingly the average TDS and EC measured for the water in the catchment was 303 mg/l and 347 μS/cm, as a result all water can be grouped as fresh water and is used for all purposes.

Another parameter which can be used as water quality parameter is hardness which is generated due to the presence of divalent metallic cations such as Mg and Ca present in water.

The higher concentration of this divalent cations in water limit their utilization for house hold cleaning purposes. The main problem in utilizing this water is the development of scale on water surface and needs extra consumption of soap (Todd, 1980).

Hardness (H_T) of a water where Ca and Mg are in milligram per liter can be given by the eq. below (Todd, 1980)

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

The degree of hardness in water is commonly based on the classification listed in Table 7.7.

Table 7.7 Hardness Classification of water
(Sawyer and McCarty, 1967 cited in Todd, 1980)

Hardness, mg/l as $CaCO_3$	Water class
0-75	Soft
75-150	Moderately hard
150-300	Hard
over 300	very hard

Accordingly water bodies in the studied catchment are classified as soft water (Table 7.8)

Table 7.8 Range of hardness in water bodies

Sample type	hardness, mg/l	water class
SP	9.5	soft
HW	11.8	soft
R	12.7	soft

I. Drinking Water Quality

Almost all the analyzed water bodies in the studied catchment lies well with in the standard limit set by UK (1989) and WHO (1993). For the sake of comparison, (Table 7.9)

Table 7.9 Comparison of water quality guideline values with the analyzed water samples

Parameter	UK (mg/l)	WHO (mg/l)	Sample type		
			SP	HW	R
SO_4	250	250	7.2	9.2	15.5
Mg	50	30	11.8	15	21.3
Na	150	200	20.2	21	41
K	12	10	0.8	1	3.8
NO_3	50	50	14.4	21.7	13.3
NO_2	0.1	3	< 0.01	< 0.01	< 0.01
F	1.5	1.5	0.2	0.2	0.3
Cl	400	250	10.2	17.4	25
Ca	250	100	43.8	53.6	43.3
B	0.2	0.3	0.45	0.27	0.52
EC	1500	-	316.5	351.8	371.8
Ag	0.01	-	<0.1	<0.1	<0.1
Cd	0.005	0.003	<0.1	<0.1	<0.1
Cr	0.05	0.05	<0.1	<0.1	<0.1
Pb	0.05	0.01	<0.1	<0.1	<0.1
Ni	0.05	0.02	<0.1	<0.1	<0.1
Zn	5	-	<0.1	<0.1	<0.1
Cu	3	2	<0.1	<0.1	<0.1
Fe (tot)	-	-	<0.1	<0.1	<0.1
Mn	0.05	-	<0.1	<0.1	<0.1

UK, 1989 and WHO, 1993 after Tebbutt, 1998

Since there is a problem in the precision of the instrument used to determine trace element, hence no comparison is made between the water quality criteria set by UK (1989) and WHO (1993) and the analyzed water samples, (Table 7.9). Generally it can be said that the water bodies in the studied catchment can safely be used for drinking purposes basically on the chemical analysis results of major cations and anions. If just to be more safe from the danger of pathogens and trace elements, bacteriological analysis and precise trace element analysis is essential.

II. Irrigation water Quality

The suitability of water for irrigation depends on the chemical composition of the water and its adverse effect on the soil and plant (Todd, 1980). For instance salt may harm plant growth physically by limiting the uptake of water or chemically by metabolic reactions such as those caused by toxic constituents. Effects of salt on soils, causing changes in soil structure, permeability and aerations indirectly affect plant growth.

An important factor related to plant growth is drainage. If the soil has well drainage, salinity problem is that much significant. Accordingly salinity problem in the study area is by far out of trouble, so from the point of salinity view, the water bodies can safely be used for irrigation.

The concentration of sodium in water is an important factor in determining its utilization for irrigation because higher concentration of sodium in soil results in soil hardening by reducing permeability of the soil. Soil containing large quantities of sodium with bicarbonate predominant anion is termed as alkali soil; those with chloride or sulphate as the predominant anion is termed as saline. Ordinary either type of sodium-saturated soil support little or no plant life (Todd, 1980).

The danger of utilizing water containing higher quantities of sodium is expressed by sodium adsorption ratio, SAR; given below (Todd, 1980)

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

where concentration of ions are expressed in milli equivalent per liter

As indicated in Fetter, (1994): if SAR value is 2 to 10, then there is little hazard, between 7-18, medium hazard, SAR between 11-26, high hazard, SAR value over 26 then there is very high hazard. The comparison of SAR values given in Fetter, (1994) and those calculated for the catchment is presented in Table 7.10.

Table 7.10 Comparison of SAR values of water sample

Sample Type	Computed SAR	SAR in Fetter, 1994	Designation
R	1.3	2-10	Little hazard
HW	0.6	7-18	Medium hazard
SP	0.5	11-26	High hazard
		> 26	V. high hazard

As it is presented in Table 7.10, there are no potential hazard of soil hardening resulting from the utilization of water bodies in the studied catchment for irrigation practices.

Another important parameter in irrigation requirement is the quantity of boron present in water. If the concentration of boron exceed a certain limiting value, it becomes toxic to plants. The quantities required varies with the crop type; in case sensitive crop require minimum boron where as tolerant crop withstand higher quantities. The relative tolerance of crop to boron is summarized in Table 7.11, Wilcox, (1955) cited in Todd, (1980).

Table 7.11 Quality classification of water for irrigation (After Wilcox, 1955 cited in Todd, 1980)

			Boron, mg/l		
Water class	% Na	EC (μS/cm)	Sensitive crop	semitolerant crop	Tolerant crop
Excellent	<20	<250	<0.33	<0.67	<1
Good	20-40	250-750	0.33-0.67	0.67-1.33	1-2
Permissible	40-60	750-2000	0.67-1.00	1.33-2.00	2-3
Doubtful	60-80	2000-3000	1.00-1.25	2.00-2.50	3-3.75
unsuitable	>80	>3000	>1.25	>2.5	>3.75

As it is shown in Table 7.12 and annex 12. All the analyzed water samples falls within the standard limit of Boron. Hence no danger of boron is expected in utilizing the water for irrigation scheme.

Table 7.12 Computed sodium percent ratio and boron in water samples

Sample Type	Water Class	% Na	B
HW	Good	20	0.27
SP	Excellent	18	0.45
R	Good	33.6	0.52

III. Industrial water quality

The water quality criteria for industries varies with the type of industries and the process plants. More commonly salinity, silica and hardness are important parameters for industrial process waters. The recommended limiting concentration for various industries process water are presented in (annex 13) (Todd, 1980). Accordingly most of the analyzed water samples fall within the accepted limit. However, some ions like nitrate and nitrite do not satisfy the requirements set for dairy, food canning and freezing industries. Hence the quality of the final product processed in this plants might be lowered.

7.9 Pollution of water bodies

The air we breath, the water we ingest and the soil in which we cultivate our plants largely determine our chance of living longer and more productive life or in the contrary our chance of developing serious health problems (Boktin and Keller, 1987).

When the concentration of a certain substances exceed a standard limit and cause adverse effect to humans, domestic animals and to the ecology then it is said unfit for that purpose. If the limit of substances in water exceeds the standard criteria, then it is called polluted and unfit for any use. The pollution of water can be caused either naturally or through man-made effects, for instance the higher concentration of fluoride in the rift valley water is natural pollution where as the pollution Akaki river by nitrate and other trace elements released from industries is man made (ENDA Ethiopia, 1999). Accordingly the probable pollution of the Borkena river catchment is examined with this perspective.

Stream pollution control has become one of the principal problems facing modern civilization. The effect of pollution in one part is economic as in the added cost of purifying the water for municipal or industrial use. Pollution may make natural water unfit as an environment for fish or other wild life and has caused extensive killings of fish on numerous occasions. Pollution of streams, lakes and even coastal waters has rendered this natural resource unsuitable for recreation, preventing the enjoyment of swimming, boating and similar water side activities. Waters that are severely polluted may be esthetically offensive to the eyes and nose (Gurnham, 1965).

Industrial waste is considered one of the cause of stream pollution. It is roughly comparable in its nation wide pollutional effect with municipal sewage and other sanitary and domestic wastes. A third major source of contamination is agriculture, which discharge both excessive quantities of silt and chemicals leached or washed from the soil (Gurnham, 1965).

In any case the pollution of water has adverse effect both on the environment and the ecology. If there is a need to conduct as to how much a water is polluted, one should conduct a survey of how many incidences of illness or death or both is reported from using the polluted water (Pandey, 1997).

Since there are more industries (such as Textile, Tannery, Poultry, Brewery, Steel, Food processing and Slaughter house) located with in the catchment and almost all of them release their wastewater directly into the river, there is a potential danger of contaminants due to the increment of Biological Oxygen Demand (BOD), Mn, Cr, As. Even if there are no trace element data supporting the idea, the analysis conducted on the major cation and anions of the river water is higher than both the springs, hand dug well and boreholes. Hence this might indirectly indicate high inflow of effluents into the stream otherwise the concentration of the ions in stream should be less than the groundwater bodies. Accordingly the potential danger of effluents of each industries are discussed below

A) Slaughter house, meat canning and poultry farm industry

The main waste from such industries is the release of higher quantities organic material into the stream. In effect, the decomposition of these materials create unpleasant odor onto the environment and severely deplete the dissolved oxygen (DO) in the river.

B) Leather Industry

Tannery waste is mainly water borne and has all the undesirable characteristics which make for pollution: High biological oxygen demand (BOD), high solids, suspended solids, soluble material, color and odor (O'Flaherty, 1965).

The toxicity of tannery waste is minor consideration, but such material as arsenic (As), chromium (Cr), high alkalinity or acidity and sulfides present can be objectionable if they are in high concentration (O'Flaherty, 1965).

C) Textile Industry

The main waste characteristics from such industries include dyes, starches and detergent which undergo biological and chemical change that consume dissolved oxygen from stream and destroy aquatic life. Metals such as chromium (Cr) and zinc (Zn) are toxic to aquatic life (Souther, 1965). The decomposition of organic waste also create obnoxious odor. Hence, such industry present in the studied catchment, the potential harm from metals mentioned above is possible.

D) Metal Industry

The wastewater from metal industry generally include high suspended solids, acid water such sulfuric, phosphoric, nitric and hydrochloric acids which are repeatedly used in the stainless steel processes and high grease and oil which are washed out from the different sector of process lines. The adverse effect include depletion of dissolved oxygen, changing of the natural pH condition of the water there by affecting aquatic life (Bramer, 1965).

D) Brewery Industry

The wastewater from such industries is highly loaded with organic material. The discharge of such waste into the river and their corresponding decomposition results in depletion of dissolved oxygen and creation of bad odor and their settlement to the bottom of the river bed is deleterious to bottom dwelling organisms. Indirectly it reduces the permeability of the riverbed sediments.

E) Nitrate Pollution

There is a potential of nitrate pollution in almost 50 percent of the analyzed samples. Specially one of the hand dug well (HW_{11}) is strongly polluted with respect to nitrate with concentration reaching about 70 mg/l. As stated in Tebbutt, (1997), if a baby below six month is bottle fed with milk made up with water containing more than 10-20 mg/l of nitrate, there is a possibility of the nitrite absorbed in the blood preventing oxygen transport and causing methaemoglobinaemia, 'blue baby' disease.

Even if there is high inflow of nitrate from sewage disposal into the rivers, the corresponding percentage concentration is only 4 percent of the total anions and is less than the groundwater bodies, this might be explained by the removal of nitrate by algal population in river water. The percentage concentration of chloride and sulphate in all water bodies show slight variability but their actual concentration in the river water is higher than both in the springs and hand dug wells.

CHAPTER 8

Conclusion and Recommendation

Hydrogeological investigation of the Borkena River catchment was done by conventional geological description and mapping of the different lithologic unit, analysis of hydrometeorological data, river discharge and spring discharge measurements. Accordingly four hydrostratigraphic units are recognized and mapped at the scale of 1:50,000. The water chemical analysis conducted shows that two water types are available and characterize the ground and surface water bodies. Basically two rock units are identified. These are: the volcanic and Quaternary sediment with volcanic being outcropping in the topographically elevated, steep slope region and on the recharge zone while the Quaternary sediments are exposing in topographical lows, gentle slopes and on the discharge zones.

The climate of the region varies between subtropical and subhumid. The catchment is characterized by rugged topography that results in dense drainage patterns dominated by first and second order streams. The river flow direction generally follows the decrease in elevation from north to south.

From field investigation and review of regional works, seven lithologic units are identified in the studied catchment. These are very recent river channel deposits, alluvial and colluvial deposits, colluvial deposits, fractured massive basalt, welded and unwelded tuff, scoraceous and basaltic lava flow and rhyolite. Among which the scoraceous and basaltic lava flow and the

Quaternary sediments cover more than 70 percent of the studied catchment. Structurally, the studied catchment is affected by three set of fault having NNW-SSE, NNE-SSW and E-W orientations. In the study area, the N-S faults are more common than the E-W fault and locally it was observed that the E-W fault crosses the N-S fault implying the later is older. The basalts and the rhyolite in the studied catchment corresponds to the Tarmaber (26-28Ma) and Alaji unit (28-32Ma).

From the analysis of meteorological variables recorded in the five stations located in and around the catchment, the mean annual rainfall the catchment receive is 1028mm. The computed potential evapotranspiration from the existing meteorological variables through the application of modified penman method generates 1339 mm.

Actual evapotranspiration and soil moisture were calculated from the Thornthwaite and Mather (1955) soil-water balance approach and is obtained as 860 mm and 226 mm. From the surplus calculated by Thornthwaite and Mather, 50 percent is available for surface runoff. The computed runoff coefficient would become 0.11. Therefore, the catchment receives 50.7 million cubic meter (mcm) of recharge water per annum.

Four hydrostratigraphic are recognized in the catchment. The most promising being the river channel and colluvial deposits followed by scoraceous and basaltic lava flow however its topographic and geomorphic position largely reduce and limits the storage capacity.

From wells drilled in the catchment, the Kombolcha subcatchment is characterized by many artesian type wells. Basically two subcatchments are identified and mapped depending on the hydrogeological conditions of the rocks and local groundwater flow patterns.

Water balance analysis for the subcatchment and the entire catchment results in the following:

- The Dessie subcatchment receives 18 mcm of recharge water per annum and 102 mcm water leaves the catchment through runoff and evapotranspiration
- The Kombolcha subcatchment receives 32.4 mcm of recharge water while 181.5 mcm leaves the area as runoff and evapotranspiration.

The hydrochemical studies conducted showed that the surface water is dominated with respect to major cations and anions than the corresponding groundwater bodies. Accordingly the plotting of percentage concentration of values on a tri-linear diagram enabled to identify two types of waters. Under this condition, the river water is classified as sodium-calcium-bicarbonate where as the groundwater (springs and hand dug well) is characterized by calcium-sodium bicarbonate type. Except some deviation in nitrate and boron concentration, the water bodies in the studied catchment falls with in the standard limit set for domestic, industrial and agricultural purposes by WHO.

Even if there are no trace elements analysis supporting pollution from industrial effluents located with in the catchment, the potential hazard of these industries are still there as most of them scarcely have treatment plant in their compound.

The following recommendations are forwarded

- To calculate the water balance efficiently, better to install additional stream gaging stations in the catchment.
- pumping test data are lacking, so further pumping test data are required to efficiently compute the groundwater reserve and characterize the aquifer.
- Instruments with high precision are required to accurately determine the degree and extent of pollution from industrial wastewater.
- Since the pollution is still there, further planning, utilization and management should take into account the effects of nitrate pollution.
- Further bacteriological and trace elements analysis are recommended in order to be sure that the danger from pathogenic organism and toxic trace elements is safe.
- Since there is a potential pollutional risk of the water bodies of the studied catchment, policy maker in the region should put clear environmental policy and properly follow their implementation otherwise future generation will not be out of these problem.
- There is unwise waste disposal system. Specifically the release of toilet waste disposal by the Municipality of Dessie into the Borkena river. Hence in order to rescue down stream dwellers from health risk and pollution of aquifer from nitrate, the Municipality should stop releasing waste into the water body.

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Annex 1 Monthly Stations Rainfall (1962-1999)

Monthly Rainfall Data of Dessie												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average	27.5	38.2	80.3	95.7	75.5	40.4	282.3	291.6	149.9	53.2	24.2	20.3
Yearly average	1149.6											
Monthly minimum rainfall	0.0	0.0	19.5	18.5	0.0	0.0	67.9	91.3	60.9	0.0	0.0	0.0
Monthly max.	108.5	118.5	211.0	275.1	292.5	203.6	555.0	485.0	305.1	172.5	131.5	98.0

Monthly Rainfall Data of Kombolcha												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average	30.4	42.6	77.3	95.4	65.4	32.7	261.1	256.3	123.0	37.4	19.9	17.0
Yearly average	1050											
Min.	0	0	0	7.3	0	0	50.1	46.6	37.3	0	0	0
Max.	168.7	184	265.9	239.9	272	118.2	542.8	427.6	247.1	154.6	100	104

Monthly Rainfall Data of Cheffa												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average	32.51	49.01	77.72	98.05	75.23	26.04	195.31	247.46	102.10	38.66	25.60	14.58
Yearly average	848.9											
Min.	0	0	0	2.8	0	0	0	92.5	8.1	0	0	0
Max.	167.6	161.9	281.2	217.6	219.1	92.7	408.4	370.5	222	133.9	147	76.9

Monthly Rainfall Data of Kutaber												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average	12.60	25.17	51.54	57.92	70.03	40.19	272.52	309.36	119.10	35.02	13.23	6.63
Yearly Average	798.7											
Min.	0	0	0	3	0	0	11	39.3	0	0	0	0
Max.	65	75.6	151	136.3	341.2	212.6	584.8	456.8	244.4	167.5	89.8	28

Monthly Rainfall Data of Haik												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average	33.98	64.69	120.11	118.87	75.09	25.35	254.08	249.28	134.21	40.08	19.06	17.07
Yearly average	1136											
Min	0	0	14.4	19.1	6	0	40	26.3	76.6	0	0	0
Max.	119.1	192.5	318.5	239.2	219.7	151.3	503.4	442.1	221.6	161.5	133.8	74.9

Annual Rainfall					
Year	Cheffa	Kombolcha	Dessie	Kutaber	Haik
1952		956.1			
1953		1293.9			
1954		1144.1			
1955		1183			
1956		936.7		235	
1957		1205.3		269	
1958		1071.7		0	
1959		1195.4		123.6	
1960		913.6		672	
1961		1073		919.8	
1962	193.4	1102.9		950.2	
1963	753.7	1095.3		323.5	
1964	694.8	1324.6		101	
1965	750.5	741.5		576	
1966	499.4	913		210	
1967	1012.5	1131.1			
1968	1254.5	1076.1			
1969	1320	1307.6			
1970	929.8	1067			
1971	931.5	859.5			
1972	927.4	822			
1973	841.6	719.5			
1974	1207.2	1034.4			

Continued

1975	1119.1	1135.3	1101.7		
1976	956.8	1057.9	914.1		
1977	1180.6	1091.9	1229.7		
1978	875	857.5	942.1	1007.7	
1979	1166.2	1021.6	1206.3	464	
1980	863.7	995.7	967.9	1021.3	990.2
1981	934.1	983.8	1131	672.2	1340.6
1982	1215.8	1111.5	1105.1	1066	921.2
1983	487.5	1032.1	632.5	1022.5	1235.5
1984		598.5	706.8	480.7	572.8
1985	523.3	1005.3	1111.3	997.9	1004.5
1986		1085	1254.8	1242.3	1152.3
1987	511.3	800.2	914.4	1095.3	1038.9
1988	74	1194.1	1439.3	1253.8	1368
1989		1149	975.8	974.4	703
1990		893.8	810.7	139.9	1088.8
1991		672	1160.9	1077	1161.2
1992		1451.1	1191.5	1003.1	1290.2
1993		1280	1439.5	988.5	1216.9
1994		1204.9	1337.1	1418.8	1153.7
1995		1096	1434.7	1129.6	1234.9
1996		1127.5	1320.7	1220.4	1364.5
1997		1016.5	1248.6	1218.5	1330.1
1998		1319.3	1486.3	1289.8	1453.6
1999		1053.4	1053.4	1191.8	1107.1

Annex 1A Isohyetal method of computing monthly Rainfall

Effective rainfall depth of January Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
13-14	0.9	13.5	0.003	0.037
14-18	16.4	16	0.050	0.805
18-22	16.4	20	0.050	1.006
22-26	18.1	24	0.056	1.333
26-30	114.8	28	0.352	9.860
30-33	159.4	31.5	0.489	15.402
Total	326			28.443

Effective rainfall depth of february Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
25-28	3.9	26.5	0.081	2.155
28-32	9.85	30	0.092	2.762
32-36	11.425	34	0.104	3.548
36-40	29.85	38	0.117	4.432
40-44	118.225	42	0.129	5.414
44-48	115.925	46	0.141	6.495
48-52	34.45	50	0.153	7.673
52-56	2.175	54	0.166	8.950
Total	325.8			41.431

Effective rainfall depth of March Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
52-54	1.075	53	0.003	0.175
54-58	3.075	56	0.009	0.529
58-62	5.625	60	0.017	1.036
62-66	6.6	64	0.020	1.297
66-70	7	68	0.021	1.461
70-74	20.45	72	0.063	4.521
74-78	84.65	76	0.260	19.753
78-82	100.075	80	0.307	24.581
82-86	38.775	84	0.119	10.000
86-90	29.8	88	0.091	8.052
90-94	19.225	92	0.059	5.430
94-98	8.575	96	0.026	2.527
98-102	0.775	100	0.002	0.238
Total	325.7			79.600

Effective rainfall depth of April Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
58-60	0.275	59	0.001	0.050
60-64	4.55	62	0.014	0.868
64-68	6.25	66	0.019	1.269
68-72	5.85	70	0.018	1.260
72-76	5.675	74	0.017	1.292
76-80	6.025	78	0.019	1.446
80-84	6.375	82	0.020	1.608
84-88	7.395	86	0.023	1.957
88-92	9.35	90	0.029	2.589
92-96	14.525	94	0.045	4.201
96-96	158.875	96	0.489	46.926
96-100	45.65	98	0.140	13.764
100-104	11.475	102	0.035	3.601
104-108	42.75	106	0.132	13.942
Total	325.02			94.774

Effective rainfall depth of May Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
65-68	59.55	66.5	0.183	12.149
68-72	74.75	70	0.229	16.053
70-72	25.8	71	0.079	5.620
72-75	132.85	73.5	0.408	29.957
75-78	33	76.5	0.101	7.745
Total	325.95			71.524

Effective rainfall depth of June Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
26-28	2.45	27	0.008	0.203
28-32	86.75	30	0.266	7.988
32-36	146.825	34	0.451	15.322
36-40	87.825	38	0.270	10.244
40-42	1.95	41	0.006	0.245
Total	325.8			34.002

Effective rainfall depth of July Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
208-212	0.125	210	0.000	0.081
212-216	4.15	214	0.013	2.727
216-220	6.925	218	0.021	4.636
220-224	7.775	222	0.024	5.300
224-228	8	226	0.025	5.552
228-232	7.95	230	0.024	5.615
232-236	8.1	234	0.025	5.820
236-240	8.625	238	0.026	6.304
240-244	8.5	242	0.026	6.317
244-248	8.3	246	0.025	6.270
248-252	10.45	250	0.032	8.022
252-256	26.45	254	0.081	20.630
256-260	30.225	258	0.093	23.946
260-264	23.25	262	0.071	18.706
264-268	34.275	266	0.105	27.997
268-272	71.65	270	0.220	59.406
272-276	42.75	274	0.131	35.970
276-280	15.575	278	0.048	13.296
280-282	2.575	281	0.008	2.222
Total	325.65			258.816

Effective rainfall depth of August Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
248-252	32.1	250	0.099	24.643
252-256	32.8	254	0.101	25.583
256-260	23.375	258	0.072	18.519
260-264	22.575	262	0.069	18.163
264-268	26.325	266	0.081	21.503
268-272	27.775	270	0.085	23.029
272-276	29.8	274	0.092	25.074
276-280	29.325	278	0.090	25.034
280-284	29.1	282	0.089	25.199
284-288	26.25	286	0.081	23.054
288-292	17.725	290	0.054	15.785
292-296	8.675	294	0.027	7.832
296-300	8.65	298	0.027	7.916
300-304	6.45	302	0.020	5.982
304-308	3.625	306	0.011	3.406

308-309	1.1	308.5	0.003	1.042
Total	325.65			271.762

Effective rainfall depth of September Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
104-108	2.65	106	0.008	0.862
108-112	7.1	110	0.022	2.397
112-116	11.65	114	0.036	4.075
116-120	30.525	118	0.094	11.053
120-124	51.75	122	0.159	19.374
124-128	47.225	126	0.145	18.260
128-132	39.15	130	0.120	15.618
132-136	36.85	134	0.113	15.153
136-140	38.95	138	0.120	16.494
140-144	37.175	142	0.114	16.199
144-148	21.1	146	0.065	9.453
148-150	1.75	149	0.005	0.800
Total	325.875			129.738

Effective rainfall depth of October Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
35-36	7.325	35.5	0.023	0.799
36-40	106.675	38	0.328	12.456
40-44	70.65	42	0.217	9.118
44-48	83.675	46	0.257	11.827
48-52	56.45	50	0.173	8.673
52-53	0.675	52.5	0.002	0.109
Total	325.45			42.980

Effective rainfall depth of November Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
13-16	24.85	14.5	0.076	1.108
16-20	81.95	18	0.252	4.535
20-24	164.65	22	0.506	11.136
24-28	53.825	26	0.165	4.302
Total	325.275			21.081

Effective rainfall depth of December Isohyet				
Contour interval	area b/n contour	ave. contour	% of total area	weighted ppt (mm)
6-8	10.8	7	0.033	0.232
8-12	23.425	10	0.072	0.719
12-16	23.5	14	0.072	1.009
16-16	268.225	16	0.823	13.166
Total	325.95			15.126

Annex 1B Thiessen polygon method of computing weighted monthly rainfall

Weighted precipitation of each month for five stations using Thiessen polygon method														
Station	Areal influence(km^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Cheffa	32.9	3.28	4.95	7.84	9.90	7.59	2.63	19.71	24.98	10.31	3.90	2.58	1.47	132.05
Kombolcha	129.5	12.06	16.92	30.72	37.92	25.98	13.00	103.73	101.83	48.88	14.87	7.90	6.75	550.06
Dessie	106.5	8.98	12.47	26.22	31.28	24.66	13.19	92.24	95.26	48.96	17.37	7.90	6.64	491.68
Kutaber	53.325	2.06	4.12	8.43	9.48	11.46	6.57	44.58	50.61	19.48	5.73	2.16	1.08	219.10
Haik	3.725	0.39	0.74	1.37	1.36	0.86	0.29	2.90	2.85	1.53	0.46	0.22	0.20	16.89
Effective uniform rainfall depth		26.77	39.19	74.59	89.93	70.54	35.68	263.18	275.53	129.16	42.33	20.77	16.14	1083.82

Annex 1C Computation of mean monthly rainfall by using arithmetic mean method

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Cheffa	32.51	49.01	77.72	98.05	75.23	26.04	195.31	247.46	102.10	38.66	25.60	14.58	
Kombolcha	30.36	42.58	77.32	95.44	65.38	32.73	261.09	256.31	123.03	37.43	19.89	16.99	
Dessie	27.47	38.16	80.26	95.73	75.46	40.36	282.32	291.56	149.85	53.17	24.18	20.34	
Kutaber	12.60	25.17	51.54	57.92	70.03	40.19	272.52	309.36	119.10	35.02	13.23	6.63	
Haik	33.98	64.69	120.11	118.87	75.09	25.35	254.08	249.28	134.21	40.08	19.06	17.07	
Total	27.39	43.92	81.39	93.20	72.24	32.93	253.06	270.79	125.66	40.87	20.39	15.12	1076.97

Annex 1D Comparison of rainfall computed using different methods

Month	Arithmetic mean method	Thiessen Polygon method	Isohyetal method	Average of the three methods	Average of thiessen and isohyetal method
Jan	27.385	26.770	28.510	27.555	27.640
Feb	43.923	39.191	41.430	41.515	40.310
Mar	81.389	74.593	79.600	78.527	77.096
Apr	93.202	89.927	94.770	92.633	92.348
May	72.237	70.540	71.524	71.434	71.032
Jun	32.931	35.682	34.003	34.206	34.843
Jul	253.063	263.175	258.816	258.352	260.996
Aug	270.793	275.532	271.763	272.696	273.647
Sep	125.656	129.164	129.738	128.186	129.451
Oct	40.872	42.333	42.980	42.062	42.657
Nov	20.393	20.772	21.081	20.749	20.926
Dec	15.120	16.143	15.126	15.463	15.635
Total	1076.966	1083.822	1089.341	1083.376	1086.582

Annex 2 Monthly Temperature At Kombolcha

Monthly Maximum temperature at Kombolcha												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	23.91	24.85	26.19	26.67	28.27	29.97	27.45	26.17	25.59	24.75	24.11	23.61
Min.	21.5	21.5	23.2	23.8	25.8	24.3	23.6	20.8	20.6	20.4	20.9	20.4
Max.	28.3	27.6	29.3	29.7	30.6	31.9	30.7	28.9	27.5	26.7	26.2	25.5

Monthly Minimum Temperature at Kombolcha												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	9.82	11.01	12.43	13.12	13.52	14.27	13.93	13.59	12.88	10.19	8.40	8.56
Min.	4.1	4.8	6.4	7.1	7	7.2	6.3	5.9	4.8	2.6	1.5	4.5
Max.	15.4	14.8	16.8	14.9	15	16.4	16.2	15.9	14.5	13.1	12.2	13.1

Annex 3 Monthly Relative Humidity At Kombolcha

Mean monthly relative humidity of Kombolcha at 6:00												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	78.57	77.52	77.32	78.42	66.95	56.52	76.59	82.14	80.73	79.64	78.55	77.71
Min.	64	57	41	47	35	24	39	41	56	52	38	36
Max.	94	97	92	96	81	74	89	90	90	92	94	91

Mean monthly relative humidity of Kombolcha at 12:00												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	49.91	49.53	47.70	47.37	38.24	31.04	46.96	53.00	52.13	45.57	44.27	47.10
Min.	30	28	23	27	24	21	24	33	43	30	31	31
Max.	70	73	63	67	52	43	63	65	65	64	63	71

Mean monthly relative humidity of Kombolcha at 18:00												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	57.02	55.77	55.74	53.15	41.98	32.86	51.35	57.85	59.48	52.81	50.02	54.85
Min.	35	30	33	25	24	20	29	33	45	28	31	33
Max.	91	93	85	92	87	60	70	84	89	91	90	89

Annex 3A Mean Minimum Relative Humidity At Kombolcha

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min at 6:00	64	57	41	47	35	24	39	41	56	52	38	36
Min at 12:00	30	28	23	27	24	21	24	33	43	30	31	31
Min at 18:00	35	30	33	25	24	20	29	33	45	28	31	33
Mean min	43	38.33	32.33	33	27.67	21.67	30.67	35.67	48	36.67	33.33	33.33

Annex 3B Mean Maximum Relative Humidity At Kombolcha

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max at 6:00	94	97	92	96	81	74	89	90	90	92	94	91
Max at 12:00	70	73	63	67	52	43	63	65	65	64	63	71
Max at 18:00	91	93	85	92	87	60	70	84	89	91	90	89
Mean max	85.00	87.67	80	85	73.33	59	74	79.67	81.33	82.33	82.33	83.67

Annex 4 Computed Mean Monthly Saturation and Actual Vapor Pressure At Kombolcha

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temp.(°C)	16.9	17.9	19.3	19.9	20.9	22.1	20.7	19.9	19.2	17.5	16.3	16.1
Sat. vapor pressure (e_a)	16.0	17.2	19.0	19.8	21.2	23.0	20.9	19.8	18.9	16.7	15.3	15.1
Mean Rel. humidity	61.8	60.9	60.3	59.6	49.1	40.1	58.3	64.3	64.1	59.3	57.6	59.9
A.Vapor pressure (e_d)	988	1051	1144	1179	1038	922	1217	1270.5	1211	990	881	905

Annex 5 One Year Daily Piechie Evaporation At Kombolcha

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mean	5.50	4.80	4.50	3.68	5.46	8.03	4.99	3.29	3.67	4.31	4.47	3.96
Daily total	170.5	134.4	139.6	110.5	169.4	240.8	154.8	102.1	110.2	133.6	134.1	118.7
Min.	3	0.6	2	1.1	1.4	4.2	1.5	1.5	1.7	1.4	1.2	1.3
Max.	7	10.7	9.3	7.8	8.6	11.4	11.4	5.6	6.2	6.3	6.4	5.8
Annual	1203.1											

Annex 6 Monthly Wind speed At Kombolcha

Mean monthly wind speed at 2m in m/sec. of Kombolcha												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly mean	1.39	1.53	1.46	1.44	1.41	1.60	1.59	1.43	1.08	0.94	1.01	1.16
Min.	1	1.1	1	1	1	1.26	1.15	1.03	0.67	0.57	0.8	0.81
Max.	1.8	1.85	1.71	2.99	1.82	1.91	2.1	1.81	1.5	1.4	1.5	1.4

Annex 7 Monthly Sun shine Hour At Kombolcha

Mean monthly Sunshine Hour of Kombolcha												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	7.40	7.26	6.74	6.85	7.74	6.30	5.04	5.70	5.76	7.89	8.47	7.94
Min.	4.20	4.1	3.9	3.8	5.1	2.8	1.8	3.4	3.3	4.7	6	3.4
Max.	10	10.2	9.3	9.1	10.9	9.1	8.9	9.8	8.5	9.4	10.5	10.2

Annex 8 Computation of potential evapotranspiration by Penman (1)

Month	T (^{0}c)	e_a	R	e_d	U_2	T (^{0}F)	T (^{0}K)	n	N	n/N	f_a	R_a	^1R_I	^AR_o	^1R_o	H	E_a	Δ	E_o	PE
Jan	16.9	13.80	0.618	8.53	73.65	62.36	289.87	7.40	11.54	0.64	0.533	12.6	6.38	13.77	2.77	3.61	2.28	1.22	104.35	73.04
Feb	17.9	14.83	0.609	9.04	81.10	64.28	290.93	7.26	11.76	0.62	0.519	13.75	6.78	13.96	2.65	4.14	2.66	1.30	108.67	84.22
Mar	19.3	16.26	0.603	9.80	77.26	66.76	292.31	6.74	12	0.56	0.489	14.72	6.84	14.23	2.40	4.44	2.88	1.40	129.78	90.84
Apr	19.9	16.90	0.596	10.08	76.46	67.81	292.89	6.85	12.34	0.56	0.485	15.2	7.01	14.35	2.36	4.65	3.02	1.45	131.75	95.30
May	20.9	18.05	0.491	8.86	74.91	69.61	293.89	7.74	12.64	0.61	0.517	15.07	7.40	14.55	2.77	4.63	4.02	1.53	140.70	98.49
Jun	22.1	19.56	0.401	7.85	84.81	71.81	295.12	6.30	12.76	0.49	0.451	14.9	6.39	14.79	2.48	3.91	5.52	1.63	124.27	89.89
Jul	20.7	17.82	0.583	10.39	84.31	69.24	293.69	5.04	12.66	0.40	0.399	14.99	5.68	14.51	1.79	3.89	3.49	1.51	118.63	83.04
Aug	19.9	16.89	0.643	10.86	75.53	67.78	292.88	5.70	12.44	0.46	0.432	15.04	6.17	14.35	1.94	4.23	2.65	1.44	123.52	86.47
Sep	19.2	16.18	0.641	10.37	57.14	66.62	292.23	5.76	12.12	0.48	0.441	14.76	6.19	14.21	2.03	4.16	2.18	1.39	115.23	83.35
Oct	17.5	14.37	0.593	8.53	49.76	63.45	290.47	7.89	11.8	0.67	0.548	14.07	7.32	13.89	2.90	4.43	2.04	1.27	124.23	86.96
Nov	16.3	13.24	0.576	7.63	53.69	61.25	289.25	8.47	11.56	0.73	0.583	12.92	7.15	13.66	3.23	3.92	2.04	1.18	107.22	77.55
Dec	16.1	13.09	0.599	7.84	61.58	60.96	289.09	7.94	11.44	0.69	0.562	12.29	6.56	13.62	3.04	3.52	2.05	1.17	97.30	70.38

Where

e_d	Actual vapor pressure
e_a	Saturation vapor pressure
R	Relative humidity in percent
U_2	Wind speed in mile/day
n	Daily mean bright sunshine hour
N	Maximum possible sunshine hour determined by latitude and season and available in standard meteorological table
f_a	a function of sunshine hour and is given by eq. 4.14
R_a	solar radiation fixed by latitude and season
^1R_I	Incoming solar radiation given by eq. 4.12
$^AR_0$	$= \sigma * T_a^4$ theoretical black body radiation
T	Temperature in degree Kelvin (^{0}k)
σ	Stephan Boltzman constant ($5.67*10^{-8}*Wm^{-2}k^{-2}$)
$^1R_0$	Out going solar radiation and given by Eq. 4.13
H	Available heat, given by eq. 4.11

E_a	Energy for Evaporation (mm/day), given by eq. 4.15
Δ	The slope of the Saturation vapor pressure plotted against temperature and given eq. 4.8
E_0	Open water evaporation (mm/month) given by eq. 4.10
PE	Potential evapotranspiration (mm/month) and given by eq. 4.16

Annex 8A Computation of potential evapotranspiration by using modified Penman method (Penman 2)

Month	T(°c)	e_a	R.	e_d	U_2	T (°F)	T(°K)	n	N	n/N	f_a	^2R_I	^2R_o	R_a	^AR_o	E_{at}	Δ	H_T	PE^{2nd}
Jan	16.9	13.80	0.618	8.53	73.65	62.36	289.87	7.40	11.54	0.64	0.56	5.55	2.43	12.6	13.77	99.23	1.22	3.12	97.26
Feb	17.9	14.83	0.609	9.04	81.10	64.28	290.93	7.26	11.76	0.62	0.54	5.89	2.33	13.75	13.96	102.78	1.30	3.56	111.06
Mar	19.3	16.26	0.603	9.80	77.26	66.76	292.31	6.74	12	0.56	0.51	5.91	2.13	14.72	14.23	124.27	1.40	3.78	118.33
Apr	19.9	16.90	0.596	10.08	76.46	67.81	292.89	6.85	12.34	0.56	0.50	6.05	2.10	15.2	14.35	126.37	1.45	3.96	123.87
May	20.9	18.05	0.491	8.86	74.91	69.61	293.89	7.74	12.64	0.61	0.54	6.42	2.43	15.07	14.55	174.54	1.53	3.99	131.30
Jun	22.1	19.56	0.401	7.85	84.81	71.81	295.12	6.30	12.76	0.49	0.47	5.48	2.23	14.9	14.79	227.22	1.63	3.26	120.02
Jul	20.7	17.82	0.583	10.39	84.31	69.24	293.69	5.04	12.66	0.40	0.41	4.82	1.66	14.99	14.51	148.56	1.51	3.16	105.65
Aug	19.9	16.89	0.643	10.86	75.53	67.78	292.88	5.70	12.44	0.46	0.44	5.27	1.76	15.04	14.35	114.71	1.44	3.52	109.89
Sep	19.2	16.18	0.641	10.37	57.14	66.62	292.23	5.76	12.12	0.48	0.45	5.30	1.83	14.76	14.21	95.78	1.39	3.47	106.15
Oct	17.5	14.37	0.593	8.53	49.76	63.45	290.47	7.89	11.8	0.67	0.57	6.39	2.53	14.07	13.89	94.97	1.27	3.86	115.35
Nov	16.3	13.24	0.576	7.63	53.69	61.25	289.25	8.47	11.56	0.73	0.61	6.27	2.79	12.92	13.66	90.56	1.18	3.48	105.11
Dec	16.1	13.09	0.599	7.84	61.58	60.96	289.09	7.94	11.44	0.69	0.59	5.73	2.64	12.29	13.62	89.10	1.17	3.09	95.06
Total																1488.10			1339.04

Where

f_a	function of wind speed, given in eq. 4.21
^2R_I	Incoming solar radiation, given in eq. 4.20
$^2R_0$	Outgoing solar radiation, given by eq. 4.22
E_{at}	Energy for evaporation, given in eq. 4.19
H_T	Available heat, given by eq. 4.18
PE^{2nd}	potential evapotranspiration (mm/month), given in eq. 4.17

Annex 9 Computation actual evapotranspiration (ET_m) from Soil-water balance approach developed by Thorntwaite and Mather. The maximum soil moisture holding capacity of all the soil is 150 but the mean value (116.67mm) was used for calculation actual evapotranspiration of the catchment.

Month	Pm	PE_m	Pm - PEm	Awl	S_m (FS)	S_m (SL)	S_m (CL)	Mean S_m	ΔS_m	ET_m	D	S
Jan	27.64	97.26	-69.62	-305.92	4.69	19.51	4.69	9.63	-6.99	34.63	62.64	0
Feb	40.31	111.06	-70.75	-376.68	2.31	12.18	2.31	5.60	-4.03	44.34	66.72	0
Mar	77.10	118.33	-41.23	-417.91	1.53	9.25	1.53	4.10	-1.50	78.59	39.74	0
Apr	92.35	123.87	-31.52	-449.43	1.12	7.50	1.12	3.24	-0.86	93.21	30.66	0
May	71.03	131.30	-60.27	-509.70	0.61	5.02	0.61	2.08	-1.16	72.20	59.10	0
Jun	34.84	120.02	-85.18	-594.87	0.26	2.84	0.26	1.12	-0.96	35.80	84.22	0
Jul	261.00	105.65	155.35		100	150	100	116.67	115.55	105.65	0	39.80
Aug	273.65	109.89	163.76		100	150	100	116.67	0	109.89	0	163.76
Sep	129.45	106.15	23.30		100	150	100	116.67	0	106.15	0	23.30
Oct	42.66	115.35	-72.69	-72.69	48.34	92.39	48.34	63.02	-53.64	96.30	19.05	0
Nov	20.93	105.11	-84.18	-156.87	20.83	52.71	20.83	31.46	-31.57	52.49	52.62	0
Dec	15.63	95.06	-79.43	-236.30	9.41	31.04	9.41	16.62	-14.83	30.47	64.59	0
Total	1086.58	1339.04								859.72	479.34	226.86

Where
P_m Monthly precipitation
PE_m Monthly Potential Evapotranspiration
Awl Accumulated Potential Water Loss
S_m Soil Moisture
FS, SL and CL Fine Sand, Sandy loam and Clay loam respectively
ΔS_m Change in Soil moisture
ET_m Actual Evapotranspiration
D Soil moisture deficit
S Soil moisture surplus

Annex 10 Daily discharge (m^3/sec) measurement of Borkena River near Boru meda

1989												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.157	0.147	0.258	0.299	0.173	0.138	0.409	1.496	0.643	0.134	0.109	0.165
Mean total	421027.2	356313.6	691286.4	774057.6	462412.8	357264	1096675.2	4007145.6	1665964.8	359424	282009.6	442972.8
Max	0.173	0.204	1.318	0.954	0.396	0.204	2.965	12.646	2.522	0.237	0.118	0.237
Min	0.118	0.118	0.094	0.173	0.144	0.118	0.118	0.173	0.204	0.094	0.073	0.094
Monthly T	4.873	4.124	8.001	8.959	5.352	4.135	12.693	46.379	19.282	4.16	3.264	5.127

1990												
	Jan	Feb	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean	0.107	0.152	0.164	0.232	0.174	0.325	2.195	4.457				0.133
Mean total	287712	367372.8	438480	140486.4	376704.0	842054.4	5879347.2	7316524.8				344044.8
Max	0.173	0.204	0.204	0.237	0.204	0.703	22.764	26.536				0.144
Min	0.063	0.118	0.094	0.204	0.144	0.173	0.396	0.352				0.118
Monthly T.	3.33	4.252	5.075	1.626	4.36	9.746	68.048	84.682				3.982

1991												
	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.111	0.177	0.188	0.191	0.138	0.129	2.804	3.901	0.806	0.192	0.158	0.119
Mean total	298425.6	429148.8	502329.6	494553.6	369187.2	335491.2	7509801.6	10447574.4	2090016.0	514512.0	408326.4	318297.6
Max	0.144	0.312	0.396	0.237	0.204	0.173	8.459	26.536	6.332	0.312	0.173	0.144
Min	0.094	0.118	0.144	0.144	0.118	0.094	0.173	0.237	0.173	0.173	0.144	0.118
Monthly T.	3.454	4.967	5.814	5.724	4.273	3.883	86.919	120.921	24.19	5.955	4.726	3.684

1992												
	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.255	0.830	0.304	0.808	0.265	0.179	0.823	1.998				0.233
mean T.	684288.0	2079993.6	814665.6	2094681.6	708566.4	464659.2	2204668.8	3798144.0				523756.8
Max.	0.888	3.443	1.738	4.36	0.441	0.204	6.006	7.9				0.396
Min.	0.118	0.173	0.173	0.204	0.173	0.144	0.144	0.352				0.173
Monthly T.	7.92	24.074	9.429	24.244	8.201	5.378	25.517	43.96				6.062

1993												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.191	0.121	0.052	0.620	0.408	0.162	0.818	1.661	0.641	0.564	0.223	0.160
Mean total	510710.4	292291.2	138499.2	1607990.4	1092096.0	419817.6	2190412.8	4449254.4	1662508.8	1511222.4	578016.0	428284.8
Max	0.273	0.237	0.094	2.112	1.563	0.273	5.688	21.567	1.921	0.824	0.312	0.173
Min.	0.094	0.055	0.039	0.055	0.204	0.118	0.118	0.204	0.396	0.352	0.204	0.144
Monthly T	5.911	3.383	1.603	18.611	12.64	4.859	25.352	51.496	19.242	17.491	6.69	4.957

1994												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.125	0.094	0.158	0.100	0.070	0.142	9.683	12.993	1.232	0.357	0.460	0.284
Mean total	333504.0	227404.8	423964.8	260150.4	188697.6	368323.2	25934860.8	34801660.8	3193171.2	954892.8	1192320.0	759801.6
Max	0.144	0.094	0.539	0.441	0.144	0.396	57.437	166.926	3.502	0.626	2.294	0.303
Min	0.094	0.094	0.094	0.055	0.025	0.025	0.237	1.226	0.375	0.303	0.258	0.244
Monthly T.	3.86	2.632	4.907	3.011	2.184	4.263	300.172	402.797	36.958	11.052	13.8	8.794

1995												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.208	2.050	4.767			0.289	0.799	18.570	0.633	0.404	0.256	0.251
Mean total	557798.4	4959792.0	10296115.2			149558.4	2139696.0	49739011.2	1639526.4	1080777.6	662774.4	672278.4
Max	0.225	11.012	31.022			0.329	6.021	209.811	1.803	0.947	0.28	0.251
Min	0.19	0.19	1.44			0.265	0.265	0.581	0.295	0.28	0.251	0.251
Monthly T.	6.456	57.405	119.168			1.731	24.765	575.683	18.976	12.509	7.671	7.781

1996												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.371	0.214	0.195	0.234	0.483	0.399	1.633	26.964	1.031	0.162	0.146	0.128
Mean total	992822.4	536019.4	521510.4	605750.4	1294185.6	1035072.0	4374518.4	72219340.8	2671056.0	434764.8	377913.6	343180.8
Max	2.344	0.28	0.237	0.581	1.44	1.255	7.586	418.715	8.821	0.212	0.169	0.134
Min	0.251	0.19	0.19	0.19	0.19	0.225	0.329	0.525	0.19	0.151	0.134	0.127
Monthly T.	11.491	5.99	6.036	7.011	14.979	11.98	50.631	835.872	30.915	5.032	4.374	3.972

1997												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.128	0.107	0.128	0.098	0.084	0.106	1.584	3.455	0.329	0.367	0.892	0.193
mean total	341971.2	257817.6	343267.2	255264.0	225417.6	273542.4	4242758.4	9254044.8	852595.2	984009.6	2311286.4	516412.8
Max	0.134	0.127	0.265	0.134	0.094	0.169	4.751	27.197	0.675	1.198	7.302	0.312
Min	0.127	0.083	0.073	0.088	0.078	0.078	0.179	0.225	0.169	0.142	0.225	0.134
Monthly T.	3.958	2.984	3.973	2.659	2.609	3.166	49.106	107.107	9.868	11.389	26.751	5.977

1998												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.133	0.142	0.125	0.118	0.102	0.079	27.216	7.178	0.885	0.319	0.192	0.178
mean total	357091.2	342662.4	333849.6	306892.8	273456.0	204336.0	72894124.8	19224518.4	2294697.6	853113.6	497232.0	475977.6
Max.	0.151	0.295	0.169	0.329	0.142	0.083	272.646	51.578	4.043	0.581	0.212	0.179
Min.	0.119	0.119	0.112	0.083	0.078	0.078	0.083	0.525	0.312	0.212	0.179	0.169
Monthly T.	4.133	3.966	3.864	3.552	3.165	2.365	843.682	222.506	26.559	9.874	5.755	5.509

1999												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	0.171	0.138	0.130	0.122	0.120	0.121	3.886	4.621	1.767	1.400	0.225	0.191
Mean total	458438.4	334540.8	347414.4	315273.6	320544.0	314668.8	10407830.4	12376454.4	4580582.4	3748464.0	584323.2	512697.6
Max.	0.237	0.142	0.134	0.134	0.169	0.169	37.661	46.987	24.611	9.504	0.329	0.201
Min	0.151	0.134	0.119	0.119	0.112	0.112	0.169	0.16	0.265	0.251	0.19	0.179
Monthly T.	5.306	3.872	4.021	3.649	3.71	3.642	120.461	143.246	53.016	43.385	6.763	5.934

Annex 11 Springs geographic location, EC and corresponding discharge

Spring code	Name	Spring type	Ownership	EC (µS/cm)	E. discharge(l/s)	Latitude(UTM)	Longitude(UTM)	Elevation (m)
Sp_1	Bireye	FC	community	257	0.3-0.5	1240908	566205	2613
Sp_2	Ulaula	FC	"	274	2.5-3.0	1247081	560034	2659
Sp_3	Kotu	CS	"	-	-	1246127	559673	2644
Sp_4	Abite	DP	"	260	0.1-0.12	1228288	568440	2432
Sp_5	Salayesh	FC	"	480	1.5-2.0	1228585	568652	2432
Sp_6	Sire	FC	"	240	1.0-1.5	1230873	568443	2554
Sp_7	Weluko	DP	"	400	1.5-2.0	1231554	568842	2542
Sp_8	Mume	FC	"	220	2.0-2.5	1232333	568677	2547

	Ambo Gideb		"	441	-	-	-	-
Sp_9	Mume1	FC	"	227	2.5	1240406	566835	2652
Sp_{10}	-	FC	Boru hospital	237	8.0-9.0	1241184	566851	2653
Sp_{11}	Mado Gojo	FC	Community	244	1.0-1.2	1240943	566823	2653
Sp_{12}	Mume2	FC	Community	243	2.5-3.0	1241732	566917	2653
Sp_{13}	Guto Beriho	DP	"	380	1.0-1.5	1231963	581386	2538
Sp_{14}	Teg Amba	DP	"	368	0.5-0.7	1231963	581386	2538
Sp_{15}	Aba Kolba	CS	"	509	0.2-0.5	1232627	578869	2514
Sp_{16}	Sholla	CS	"	443	0.1-0.2	1225745	574336	1955
Sp_{17}	Chefae	CS	"	343	0.3-0.35	1225747	574336	1956
Sp_{18}	Sholaw Metene	CS	"	385	0.2-0.3	1225380	571733	1962
Sp_{19}	GRP	FC	"	-	0.12-0.15	1232108	568753	2536
Sp_{20}	Zeritu Abegaz	CS	"	-	1.0-1.5	1233198	568463	2568
Sp_{21}	Ismano	DP	"	-	0.1-0.15	1238223	566693	2656
Sp_{22}	Soste Gedel	DP	"	-	0.3-0.5	1234794	572548	2503
Sp_{23}	Aba kasu	CS	"	-	0.3-0.35	1221721	572248	2491
Sp_{24}	-	DP	"	-	0.4-0.5	1221773	573426	2436
Sp_{25}	Bambowuha	DP	"	-	0.2-0.3	1222840	573685	2406
Sp_{26}	Badowuha	CS	"	-	0.1-0.15	1220042	583542	2025

Note: FC = fault controlled spring; CS = contact spring; DP = depression spring; E. discharge = estimated discharge

Annex 12 Results of chemical analysis of selected water samples

FIELD No.	HW_6	HW_1	HW_{11}	SP_{15}	SP_2	SP_6	SP_{12}	SP_{24}	R_5	R_7	R_8	R_{11}	BH_2	HW_8
LAB No.	4025/01	4026	4027	4028	4029	4030	4031	4032	4033	4034	4035	4036	4037	4038/01
Carbonate (CO_3^{-2})	-	-	-	-	-	-	6	-	-	8		-	-	-
Bicarbonate (HCO_3^-)	366	226	295	294	197	236	172	170	255	326	305	257	177	219
Chloride (Cl^-)	11	8	49	12	10	7	10	12	18	19	26	37	10	9
Sulphate(SO_4^{-2})	10	3	25	9	7	6	4	10	10	20	15	17	3	5
Fluoride(F^-)	0.26	0.12	0.28	0.22	0.12	0.16	0.13	0.12	0.22	0.36	0.29	0.2	0.1	0.15
Nitrate (NO_3^-)	14.62	8.86	66.45	12.85	11.96	0.44	15.95	30.88	14.62	1.77	5.76	31.01	7.97	10.63

Annex 13 Ranges Recommended Limiting Concentration For Industrial Process Waters (units are mg/l, except as noted) (After Amer. Water Works Asso.[5])

Use	Turbidity, unit	Color, unit	Taste and odor threshold	Dissolved solids	Hardness, as $CaCO_3$	Alkalinity, as $CaCO_3$	pH, units	Chloride, as Cl	Sulphate, as SO_4	Iron, as Fe	Manganese, as Mn	Iron plus Manganese	Hydrogen sulphide	Fluorides, as F	Other requirements
Air conditioning	-	-	low	-	-	-	-	-	-	0.5	0.5	0.5	-	-	Not corrosive or slime promoting
Baking	10	10	none-low	-	a	-	-	-	-	0.2	0.2	0.2	0.2	-	Potable
Boiler feed															Potable if steam is used for food preparation
Brewing	0-10	0-10	none-low	500-1500[b]	c	75-80[d]	6.5-7.0[e]	60-100	-	0.1	0.1	0.1	0.2	1	Potable, numerous other requirements
Carbonated beverage	1-2	5-10	none-low	850	200-250	50-130	-	250	250	0.1-0.2	0.2	0.1-0.4	0-0.2	0.2-1	potable; COD, 1.5; organic matter, infinitesimal; alga and protozoa, none
Confectionery	-	-	low	50-100	soft	-	>7.0	-	-	0.2	0.2	0.2	0.2	-	Potable
Dairy	-	none	none	500[f]	180	-	-	30	60	0.1-0.3	0.03-0.1	-	-	-	Potable; NO_3-N, 5.5; NO_2-N, 0; NH_3-N, trace only; COD as $KMnO_4$, 12
Drinking	5	15	3, inoffensive	500	-	-	-	250	250	0.3	0.05	-	-	1.4-2.4[g]	Potable
Food canning and freezing	1-10	-	none	850	h	30-250	>7.5	-	-	0.2	0.2	0.2-0.3	1	1	Potable: free from saprophytic organisms; NaCl, 1000-1500; NO_3-N, 2.8; NH_3-N, 0.4
Food equipment, washing	1	5-20	low	850	10	-	-	250	-	-	-	0.1	-	1	Potable; organic matter, infinitesimal
Food processing general	1-10	5-10	low	850	10-250	30-250	-	-	-	0.2	0.2	0.2-0.3	-	1	Potable
Ice manufacture	5	5	-	170-1300	-	-	-	-	-	0.2	0.2	0.2	-	i	Potable, SiO_2, 10
Laundering	-	-	-	-	0-50	60	6-6.8[e]	-	-	0.2-1	0.2	0.2-1	-	-	
Paper and pulp, fine	10	5	-	200	100[j]	75	-	-	-	0.1	0.05	-	-	-	Soluble SiO_2, 20; free CO_2, 10; residual chloride Cl_2, 2
Paper, groundwood	50[k]	30	-	500	200	150	-	75	-	0.3	0.1	-	-	-	Soluble SiO_2, 50; free CO_2, 10
Paper, kraft, bleaching	40	25	-	300	100	75	-	200	-	0.2	0.1	-	-	-	Soluble SiO_2, 50; free CO_2, 10
Paper, kraft, unbleaching	100	100	-	500	200	150	-	200	-	1	0.5	-	-	-	Soluble SiO_2, 100; free CO_2, 10
Paper, soda, and sulphate pulps	25[k]	5	-	250	100[j]	75	-	75	-	0.1	0.05	-	-	-	Soluble SiO_2, 20; free CO_2, 10
Rayon and acetate fiber															

pulp production	5	5	-	100[f]	8	50-75	-	-	-	0.05	0.03	0.05	-	-	Al_2O_3, 8; Si, 25; Cu, 5
Rayon manufacture	0.3	-	-	-	55	-	7.8-8.3	-	-	0	0.0	0.0	-	-	
Sugar	-	-	-	low	low	-	-	20	20	0.1	-	-	-	-	Ca, 20; Mg, 10; bicarbonate as $CaCO_3$, 100; steril, no saprophytic organisms
Tanning	20	10-100		-	50-500	130	6-8	-	-	0.1-0.2	0.1-0.2	0.2	-	-	Bicarbonate hardness, low; COD, 8; heavy metals none; Ca, 10; Mg, 5; bicarbonate, as $CaCO_3$, 200
Textile	0.3-25	0-70	-	-	0-50	-	-	100	100	0.1-1	0.05	0.2-1	-	-	Bicarbonate hardness, low; COD, 8; heavy metals none; Ca, 10; Mg, 5; bicarbonate, as $CaCO_3$, 200

Note:
[a]Some calcium is necessary for yeast action. Too much hardness retards fermentation, but too little softens the gluten to produce soggy bread. Water of zero hardness is required for some cakes and crackers.
[b]Not more than 300 mg/l of any one substance.
[c]$CaSO_4$ less than 100 - 500 mg/l; $MgSO_4$ less than 50-200 mg/l
[d]For dark beer alkalinity as $CaSO_4$ may be 80-150 mg/l
[e]Range lower to upper limits
[f]Total solids
[g]Tolerance limit depends on annual average daily maximum air temperatures for a minimum of five years
[h]For legumes 25-75; for fruits and vegetables, 100-200; for peas, 200-400
[i]1.5 mg/l of fluoride has been reported to cause embrittlement and cracking of ice.
[j]Calcium hardness 50
[k]No gritty material
[l]Calcium hardness 50; magnesium hardness 50

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.

Mesfin Sahele

Signature: ________

Place and date of submission: School of graduate studies, Addis Ababa, July, 2001