

HYDROGEOLOGICAL CONTROLS IN SANDSTONE OF AMBO AREA

A thesis submitted to the School of Graduate Studies
Addis Ababa University



In partial fulfillment of the requirements for the degree of Master of
Science in Geology

By

Lemessa Mekonta

June 2001
Addis Ababa



**HYDROGEOLOGICAL CONTROLS IN SANDSTONE OF AMBO
AREA**

By

Lemessa Mekonta

Faculty of Science

Board of Examiners:

Approved by:

Dr. Bekele Abebe

Chairman

Dr. Tamiru Alemayehu


Advisor

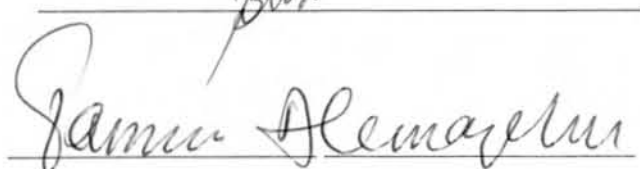
Dr. Tenalem Ayenew


Internal examiner

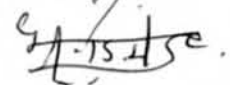
Ato Gebretsadik Eshete

External examiner









ACKNOWLEDGEMENT

I am deeply grateful to my advisor Dr. Tamiru Alemayehu who has been guiding me with patience, and sharing me his time for frequent discussions during the whole research work as well as letting me use his personal research materials and managing maps on computer.

My sincere thanks go to Ato Tariku Negera, head of Oromia Water, Mines and Energy Resources Development Bureau (OWMERDB) for his encouragement and assistance during my study as well as during the fieldwork of the research in arranging me a car.

The staffs of the Geology and Geophysics department are duly acknowledged; particularly, Dr. Bekele Abebe, head of the department, who has undertaken the task of my official correspondence, Dr. Tenalem Ayenew, for his discussion on the subject matter of the work, and Ato Seifu Kebede, for his discussion as well as accompanying me during the field work for some days.

Institutions from which data have been taken are greatly acknowledged. Among them are: Ministry of Water Resources, National Meteorological Service Agency, Ambo Agricultural Research Institute (AARI), OWMERDB and the Zonal department of Western Shewa, Western Shewa Zone Agricultural development department, and Water wells drilling enterprise.

I gratefully acknowledge for the help, discussions and constructive comments of the geologists of Mines department at OWMERDB, and the staffs of the Laboratory Service for the timely analysis of the water samples.

I am also indebted to Dr. Tsegaye Abebe for sharing me his time for fruitful discussions and letting me use the results of his own specialist investigations, and Ato Tesfa Tusguri for his discussions on the well data of the study area.

My deepest heart-felt gratitude goes to my fiancée, Deginesh Dhufera, for her patience, understanding and very efficient help during my study as well as in typing the paper.

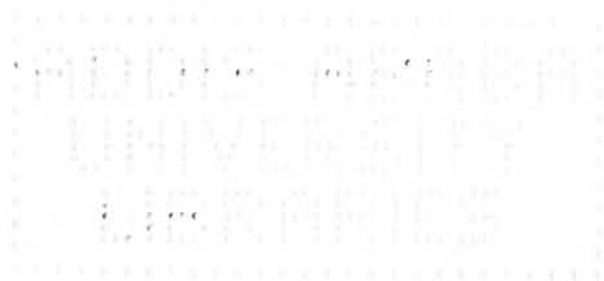
Finally, my parents always deserve great appreciation for their invaluable effort in educating me since my childhood.

Table of contents

	<u>Page</u>
ACKNOWLEDGEMENT.....	I
TABLE OF CONTENTS.....	II
LIST OF TABLES.....	V
LIST OF FIGURES.....	V
ABSTRACT.....	VII
I. INTRODUCTION.....	1
1.1 GENERAL.....	1
1.2 LOCATION AND AREAL EXTENT.....	3
1.3 OBJECTIVE.....	3
1.4 PHYSIOGRAPHY.....	4
1.5 CLIMATE.....	5
1.6 LAND USE.....	5
1.7 SOIL.....	6
1.8 PREVIOUS WORK.....	7
1.9 MATERIALS AND METHODS USED.....	7
II. GEOLOGY.....	9
2.1 REGIONAL GEOLOGY.....	9
2.2 LOCAL GEOLOGY.....	15
2.2.1 <i>Volcanic rocks</i>	16
2.2.2 <i>Sedimentary rocks</i>	20
III. HYDROMETEOROLOGY.....	26
3.1 METEOROLOGICAL PARAMETERS.....	26
3.1.1 <i>Rainfall</i>	27
3.2 SURFACE HYDROLOGY.....	30
3.2.1 <i>Rivers and streams</i>	30

3.2.1 Rivers and streams.....	30
3.2.2 Lakes.....	31
3.2.3 Stream discharge.....	33
3.3 WATER BALANCE.....	36
3.3.1 Estimation of Potential Evapotranspiration, PET.....	37
3.3.2 Actual Evapotranspiration (AET).....	42
3.3.3 Lake water evaporation.....	44
3.3.4 Summary of the water balance.....	48
IV. HYDROGEOLOGY.....	50
4.1 HYDROSTRATIGRAPHIC UNITS.....	51
4.1.1 Volcanic rocks.....	52
4.1.2 Sediments and Sedimentary rocks.....	55
4.2 AQUIFER CHARACTERISTICS.....	56
4.3 SPRINGS.....	64
4.3.1 Thermal Springs.....	65
4.3.2 Gravity /Cold springs.....	67
V. HYDROGEOCHEMISTRY.....	71
5.1 SAMPLING TECHNIQUES AND ANALYSIS.....	71
5.2 ORGANOLEPTIC PARAMETERS.....	73
5.3 PHYSICOCHEMICAL PARAMETERS.....	73
5.3.1 pH.....	74
5.3.2 Temperature.....	74
5.3.3 Total Dissolved Solids (TDS) and Electrical Conductivity (EC).....	77
5.3.4 Major cations and anions.....	77
5.3.5 Minor ions.....	80
5.3.6 Other chemical parameters.....	82
5.4 PRESENTATION OF ANALYTICAL RESULTS.....	86
5.4.1 Piper tri-linear diagram.....	86
5.4.2 Stiff (Pattern) diagram.....	87
5.4.3 Schoeller diagram.....	87

5.4.4 Interpretation and classification of water samples	87
5.5 WATER QUALITY	93
5.5.1 Drinking water quality	93
5.5.2 Agricultural/irrigation water quality	94
5.6 GEOCHEMICAL MODELING	95
5.6.1 Carbon dioxide (CO ₂)	95
5.6.2 Calcium Carbonate/or travertine deposits	96
5.6.3 Saturation Index (SI)	98
5.6.4 Possible sources of some cations in water	103
5.6.5 Silica Sinter	104
VI. CONCEPTUAL MODELING	106
VII. CONCLUSION	109
VIII REFERENCES	113



List of Tables

	Page
Table 3.1 Summary of mean monthly meteorological data for the study area.....	27
Table 3.2 Mean monthly rainfall and rainfall coefficient	28
Table 3.3 Run off coefficient for various catchments.....	34
Table 3.4 Monthly PET of Ambo area using Thornthwaite method.....	39
Table 3.5 Monthly PET of Ambo area using Penman method.....	41
Table 3.6 Comparison of PET values using Thornthwaite & Penman.....	41
Table 3.7 Estimation of AET using Thornthwaite-Mather method.....	43
Table 3.8 Lake water evaporation for Dandi and Wanchi using Penman method.....	45
Table 3.9 Summary of Dandi & Wanchi lake water evaporation using Pan evaporation method with pan coefficient of 0.75.....	41
Table 4.1 Some well data at Ambo Agricultural Research Institute (AARI).....	60
Table 4.2 Some well data for Meti well.....	62
Table 4.3 Boiling temperature of water at various pressures.....	66
Table 5.1 Physicochemical parameters for water samples in Ambo area.....	76
Table 5.2 Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) For water samples in Ambo area.....	95

List of Figures

Fig. 1.1 Location map of the study area	2
Fig. 2.1 Geological map of Ambo area.....	19
Fig. 3.1 Meteorological parameters plotted against month	29
Fig. 3.2. Comparison of precipitation, PET and AET for the study area.....	47

Fig. 4.1 Hydrogeological map of Ambo area63

Fig. 4.2 Schematic diagram for springs.....70

Fig. 5.1 Map showing water sampling points72

Fig. 5.2 Various physicochemical parameters for water samples.....84

Fig. 5.3 Piper tri-linear diagram for water samples in Ambo area89

Fig. 5.4 Stiff diagram for water samples in Ambo area.90

Fig. 5.5 Schoeller diagram for water samples in Ambo area92

Fig. 6.1 Conceptual modeling of thermal springs.....108

ABSTRACT

The study area is a sub catchment of Abay drainage basin with a total surface area and perimeter of 838km² and 171km respectively. Two other regional drainage basins border the catchment: the Awash drainage basin to the east and southeast, and the Ghibe- Omo drainage basin to the south.

The main rock outcrops in the area are the basaltic lava flow of Tertiary and Quaternary age, trachytic lava flow and pyroclastic deposits of Quaternary age, and the Mesozoic sandstone. Application of different modeling techniques shows that the sandstone is part of the Upper sandstone sequence.

On annual basis, the area has 1143.3mm, 809mm and 162.8mm of mean total rainfall, Actual Evapotranspiration (AET), and groundwater recharge respectively. There exist various water bodies in the area: two crater lakes (Lake Dandi and Lake Wanchi with a total surface area of 7.4 and 4km² respectively), river, streams, and springs (both thermal and cold springs).

Hydrogeological descriptions of the lithological units in the area is mainly based on qualitative interpretation employing various approaches such as degree of weathering and fracturing, existence/or absence of springs, vegetation cover, soil cover, etc. Despite the presence of many wells there is only a limited well data. However, there are some wells with well data from which some hydraulic parameters have been determined. The existing well data as well as the qualitative interpretation show that the main aquifer in the area are the fractured and/or weathered basaltic lava flow

followed by alluvial sediments along some streams, and sandstone. The first two are aquifers for cold groundwater whereas the sandstone is mainly an aquifer of the thermal/or mineral water. Some hydraulic parameters have been determined for these aquifers; accordingly, the basaltic lava flow has a hydraulic conductivity and transmissivity of $3.7 \times 10^{-5} \text{m/s}$ to $3.9 \times 10^{-5} \text{m/s}$ and 97- 100 m^2/day respectively. The alluvial sediments have a transmissivity of $23.9 \text{m}^2/\text{day}$ on average. Where as, the sandstone has a transmissivity of $76.5 \text{m}^2/\text{day}$.

The existence of highly permeable units (intensively fractured trachytic lava flow and unwelded tuff) at the elevated lands of Dandi and Wanchi at the southern part of the study area favors them to be a recharge area. If comparison is made with in the limit of the study area, good ground water potential with low Total Dissolved Solids (TDS) is found to the eastern side of Ambo town.

Thermal and/or mineral water in the area is structurally controlled; the alignment of the thermal springs along the nearly east- west oriented fault line in Ambo area can justify the situation. Currently, the thermal springs are limited to a given area, mainly in Ambo town; but their past extent can be inferred from the travertine deposit in the area whose thermal origin can be verified from the existence of silica sinter with it.

I. INTRODUCTION

1.1 General

The Ambo area is known for its mineral water (Ambo Tebel), and construction stone "Ambo Sandstone". The Ambo town is also known for its thermal water, and it has a total population of 27,636 according to the 1994 population census.

The livelihood of the people in the area mainly depends on agriculture, both animal husbandry and crop cultivation. The area has a good agricultural and tourism potential as it is endowed with fertile soil, surface water (river, streams and lakes), groundwater including cold and thermal springs and a beauty scenery of landscape resulted from volcanism in Wanchi area. Despite the presence of such resource potential, the area is less developed, particularly concerning the utilization of water resources.

The town of Ambo is currently getting potable water supply from a stream that crosses the town, Huluka stream. The main problem of the water supply at and in the surrounding of the town is not the quantity/or absence of water but the quality. The water is either thermal and/or highly mineralized (groundwater) or highly turbid (streams during summer). Hence, the rapid population growth along with increasing living standard, and also its future prospects of tourist attraction center put an impetus on high water demand of the area. Even though there are such water resources and its high development demand in the area, less has been investigated, especially concerning its hydrogeology that has a core place in the efficient and appropriate utilization of the resources.

This is one of the main reasons to undertake the research work in the area besides the complex hydrogeological system of it that has a scientific interest.

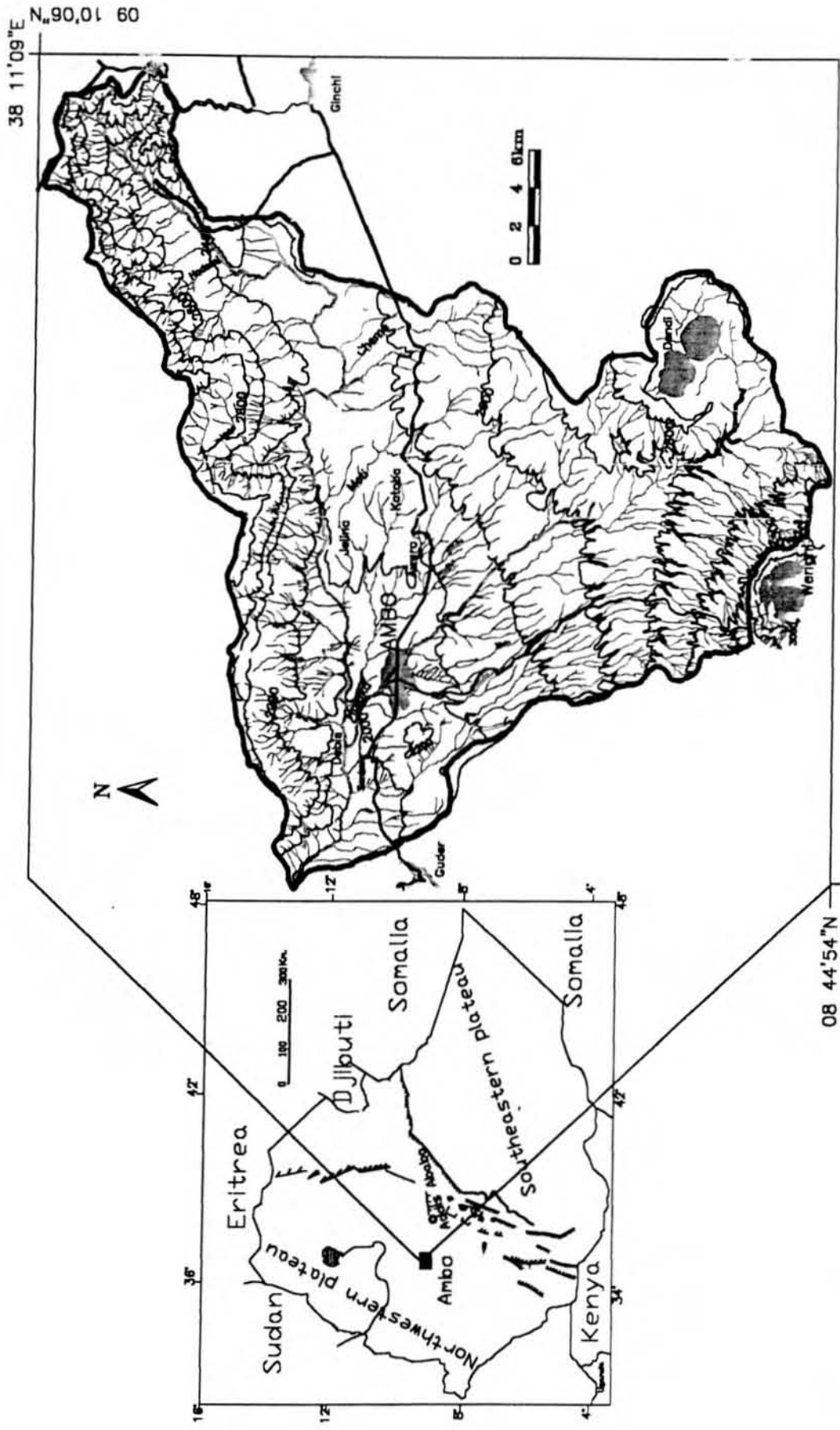


Fig.1.1 Location map of the study area (Ambo).

1.2 Location and areal extent

The study area, Ambo, is located at 125km west of Addis Ababa. The town is on the main asphalt road that runs from Addis to Nekemt. The area is bounded by a geographical coordinate 08°46' 11" to 09° 09' 25" N latitude and 37° 45' 15" to 38° 08' 40"E. longitude.

It is delineated based on water divide/river catchment, located in Abay basin. It includes parts of three administrative districts: Ambo, Dandi and Wanchi with a total surface area of 838km². Parts of Dandi and Wanchi are included only partially; otherwise the majority of the area is in Ambo district. The location map of the study area is shown in fig. 1-1.

1.3 Objective

The general objective of this research work is an understanding of the system dynamics of the groundwater in Ambo area with emphasis given to the mineral and/or thermal water.

Specific objectives:

The specific objectives of the project are as follows:

- Identification of the aquifer systems in the area both for soft and mineral and/or thermal water, and their hydraulic relationships.
- Identification of the recharge area and estimation of the recharge to groundwater
- To investigate the nature of cold and thermal springs.

- To understand/or characterize the geo-chemical controls and evolution of groundwater in the area, and also to understand the state of saturation of thermal water with respect to some minerals such as calcite
- To investigate the mechanism of the thermal enrichment in the groundwater of the area.
- Determination of the hydraulic parameters of the aquifers in general, for that of the mineral water in particular.
- Determination of the suitability of water (both surface and groundwater) for different water uses.
- To establish a conceptual model for the groundwater in general, and thermal/or mineral water in particular, as well as to reconstruct the stratigraphy of the area based on different modeling techniques

1.4 Physiography

Being part of the Ethiopian central plateau, volcanism later followed by erosion and deposition has played significant role in developing the current landscape of the study area. The area comprises both rugged mountains dissected by streams at its northern and southern, and plain at its central part. The northern part of the area is formed by an east-west oriented elevated land that is considered to be fault escarpment, and from which a number of streams emerge. This fault escarpment also acts as a surface water divide. Similarly, the southern part of the study area is also a mountainous land comprised by high lands of Wanchi and Dandi that are thought to be the recent volcanic center. Lying between the northern and southern elevated lands, which are slopping toward each other, is a tract of land receiving sediments eroded from both sides and

acting as a depositional area. The general slope of this central plain is toward the northwest. Sparsely distributed in the southern central part of the area are also scoria cinder cones. The highest peak in the area is the Wanchi high point that raises to 3390m.a.s.l; and the lowest is the area around the outlet of the catchments- its confluence with Guder river- having an altitude of 1868 m. a. s. l.

1.5 Climate

Based on rainfall, the climate of the area can be categorized into two broad seasons: the dry season (winter) and the wet season (summer) with autumn and spring receiving a slight amount of rain. The total annual rainfall in the area is 1143.3mm on average; and the mean annual temperature is 17.7°C. The maximum and minimum recorded temperatures are 27.5 and 8.5°C respectively in March and November. Hence, the annual range is about 19°C.

1.6 Land use

Apart from inconvenient areas for farming such as hills and/or ridges e.g. Mi-esa area and the ridges on the northern side of the Dabis river as well as areas reserved for grazing, the majority of the study area is covered with cultivation. On a regional scale, the area is classified as moderately cultivated land, BCEOM, *et al* (2000). Residential areas are found either as town/or villages (e.g. Ambo, Meti and Asgori) or as sparse settlements of family/or relatives. Among the relatively densely populated rural areas are the surrounding of Dandi Lake, Golja, and Altufa areas. Factories, if there is any, are limited to Ambo town and Sankale area.

One can categorize the vegetation cover of the area into three main groups: grass lands, shrubs, and forests along streams /or rivers and also on slopes of mountain. The forests are mainly constituted by Juniperous Procera (Tid) and Podocarpus. Areas covered by such forest include the steep slope sides of Wanchi and the escarpment at the northern side of the study area. The Shrubs cover some part of Wanchi and Dandi high lands, the escarpment on the northern side of the study area, and the Mi-esa ridge. They include Carissa Edulis and Ilex Mitis. The central part of the study area is grassland. The main crops cultivated include Wheat (*triticum aestivum*), Barley, Guwaya (*Lathyrus Sativw*) and Kocho (*Ensete Ventercosum*).

1.7 Soil

There are different soil types in the study area; the variations are being attributed mainly to the parent materials and topography. On the southern and northern elevated lands only very shallow soils are developed. But they differ in that the northern are developed on basic volcanic rocks, where as in the southern elevated lands such as Wanchi and Dandi, the soils are derived from acidic pyroclastic deposits and intermediate (trachytic) lava flow respectively. Soils at the immediate adjacent of lake Dandi (in the depression) are deep eutric vertisols, but the elevated land in the surrounding is comprised by chromic luvisols that are poorly fertile, BCEOM, *et al* (2000). Generally, soils in the southern elevated land are more of sandy nature unlike the central tract of land, which is dominantly comprised by black cotton soil.

To sum up, one may categorize the soil in the area into those that have high permeability (sand dominated soil) and those that have low permeability (clay dominated soil) from hydrogeological

point of view. Accordingly, areas to the south of the Goremti are those of the first category where as the central plain areas are of the second category except those that are covered by sandstone.

1.8 Previous work

Unlike other parts of the country such as the Rift zones, Ambo area is less investigated both from geological and hydrogeological point of view. The investigations carried out so far in the area are either too general (on a regional scale) or limited by lack of data. Among the important geological and hydrogeological investigations are: the work of Smeds (1964) on the volcanic activity of Ethiopian plateau particularly, in Wanchi area, Kondo (1967) on thermal springs of Ethiopia, Mohr (1971), Herick, *et al* (1983) on mineral waters of Ambo and Sankale area, Tsegaye Abebe (1992) on Yerer- Tulu Welel- Volcano-Tectonic- Lineament that includes Ambo area.

1.9 Materials and methods used

In order to achieve the goal of the research work, the following materials and methods have been employed:

- Topographic map and aerial photos of the area at a scale of 1: 50,000 produced by Ethiopian mapping agency
- Common geological field instruments such as hammer, compass, altimeter, and also GPS.

- pH and Eh meter of model HI 9025 microcomputer, and TDS meter of model ISO 9001 manufactured by Hanna instrument Company, and Conductivity meter of model HD 8706 manufactured by Delta OHM company, and Thermometer.
- Plastic bottles for water sampling.
- Geological mapping at scale of 1: 50,000
- Classification of lithostratigraphic units into hydrostratigraphic units mainly based on the degree of weathering and fracturing
- Springs and Well inventory
- Water sampling from different sources and analyzing for various physico- chemical parameters
- Hydrogeological mapping

II. GEOLOGY

2.1 Regional geology

The oldest rock in the country, which forms the basement, is of Precambrian age. Overlying this basement rock is the Mesozoic sedimentary successions and/or Cenozoic volcanics. There are some exceptions to this generalization such as where the basement rocks are overlain by Paleozoic sedimentary rocks, Quaternary sediments or simply exposed to the surface.

The Precambrian rocks are found exposing at peripheral areas of the country including the northern (Tigray), the southern and the western part of the country. High-, medium- and low-grade metamorphic rocks of various types that include gneisses, schists and other meta-volcano-sedimentary rocks along with different intrusive bodies comprise them.

The history of the currently existing sedimentary rocks in the country has started since the late Paleozoic era. Since then various sedimentary rocks have been formed. The late Paleozoic and Mesozoic sedimentary rocks, and the Quaternary sediments generally constitute 25% and 20% of the total outcrop in the country respectively.

Late Paleozoic sedimentary rocks are found only in a limited area including the Enticho sandstone and the Edaga Arbi glacial deposits in Tigray, and Wayu sandstone in Ogaden.

The deposition of Mesozoic sedimentary rocks is attributed to the Sea transgression and regression caused by epeirogenic sinking and rising (uplifting) of horn of Africa respectively. The axis of the sea transgression was in SE-NW direction, and viceversal for regression.

Two major with one minor Sea transgression -regression took place during Mesozoic era, Mohr (1971).

The Mesozoic Sedimentary sequence of central Ethiopia, Abbay basin, is the result of the major Sea transgression and regression cycle. This sedimentary succession being includes the study area that will be discussed later is briefly explained here.

The Mesozoic sedimentary rocks sequence in Abbay basin from bottom to top is as follows:

- Lower sandstone /Adgirat sandstone: mainly comprised by sandstone.
- Antalo group: includes Abbay beds, Antalo limestone, and Mugher mudstone; it is comprised by shale, gypsum, limestone and mudstone, Kazmin (1975)
- Upper sandstone /Ambaradom formation.

According to Mohr (1971), the above three- fold grouping of Mesozoic rocks is based on Lithology rather than in age as the age range varies with in each unit along the SE-NW axis of transgression and regression. The lower sandstone and upper sandstone were deposited respectively during sea transgression and regression, the Antalo group being formed during the time gap in between the two events, Mohr (1971).

In general speaking, the lower sandstone is characterized by fine to medium grain size, massive, thickly bedded with occasional cross bedding, iron rich conglomerates, especially near its base, and predominance of quartz over feldspar as a result of which it is considered to be a quartz sandstone. The thickness of lower sandstone is more or less similar for a given region but varies from region to region. In Abay basin the thickness is about 500m on average, Mohr (1971).

Layers other than sandstone are found inter bedded with in the lower sandstone. The most important are siltstone and shale in a central Ethiopia, Mengesha, *et al* (1996). In this region, the lower sandstone directly overlies the basement rocks and is in turn overlain by Abay formation and /or Tertiary volcanic.

According to Kazmin (1975), the Abay bed, Antalo limestone and the Agula Shale (corresponds to Mughher Mudstone) are categorized under one group-Antalo group.

Unlike in some places of southeastern Ethiopia, the Antalo limestone does not directly overlie the basement both in northern and central Ethiopia (Mohr 1971).

The western limit of the Mesozoic sedimentary rocks in the southern side of the Abay basin exceeds that of on the northern side by about 20km. Accordingly, Mohr (1971), has identified the following most westerly exposure of Mesozoic strata: Lower sandstone at $38^{\circ} 18'E$, Antalo limestone at $37^{\circ} 43'E$, Upper shale- gypsum horizon, $37^{\circ} 50'E$, and Upper sandstone at $38^{\circ} 18'E$.

Overlying the Antalo group is the Upper sandstone deposited from sea regression. This unit is well exposed in the eastern side of Abay basin (in Wollo along the tributaries of Abay) than in

the western side reaching a thickness of more than 300m due to its south-easterly dipping, Mohr (1971). The same author suggested two possibilities for the thinning or absence of Upper sandstone toward west in Abay basin, and variation of its thickness in Tigray:

- Pre-Trappean and post Mesozoic erosion/or denudation of the sediment due to its soft and easy erodability nature.
- Original thinning during deposition.

But he inclined to the first possibility for the Abay basin and the second possibility for Tigray region. Accordingly, he pointed out that the degree of denudation is more severe toward the west than north or east of the country.

Where it is found in Abay basin, the Upper sandstone is predominantly white but occasionally red. It is generally massive with some cross bedding.

Both Upper sandstone and the Antalo limestone are missing in Guder valley close to the confluence with Abay, and the most westerly exposure of Upper sandstone in the Abay basin is found in Mughher gorge, Mohr (1971).

The large part of the country (about 32%) is covered by volcanic rocks of different ages and types. One can categorize these volcanic rocks based on various factors such as age (Tertiary and Quaternary volcanics), and taking Rift formation as a reference (pre-rift and post rift volcanics). Another widely used terms in describing the volcanic rocks of the country are the Trap series volcanics and the Aden volcanic series, which is the same as to say post rift (middle Miocene to

Quaternary) volcanic. The Trap series represent the oldest volcanic rocks in the country, where as the Aden volcanic series is relatively younger.

The major uplifting followed by cracking of horn of Africa gave rise to the formation of Trap series. It is comprised mainly by flood basalt with some trachytes and rhyolites, especially on its upper part. This trap series forms the NW and SE plateau, reaching its maximum development in central Ethiopia attaining a thickness of up to 3km, Mengesha *et al.* (1996); its complete stratigraphy can be observed in deep gorges.

The trap series is hardly distinguished from the Aden volcanic series based on the petrographic analysis, Mohr (1971). Hence, though not conclusive, morphological distribution may be employed to distinguish them. The trap series being, predates the rift faulting, usually occupies the great height of the Ethiopian and Somalian plateau, where as the Aden volcanic series are associated with well-preserved volcanic cones or lava flows, Mohr (1971). Such morphological-temporal distinction of the trap series and Aden volcanic series should be applied with caution because a discrepancy may happen in some cases of the Rift and the plateau. Volume wise, the trap series is much more abundant than the Aden volcanic series.

Some of the common trap series that are found in NW Ethiopian Plateau are Ashangi, Aiba, Alaji and Termaber volcanic rocks from oldest to the youngest.

Quaternary volcanism was not confined to Rift; it also took place on the plateaus, Mohr (1971). Some of the Quaternary volcanics on the NW Plateau are found in western Shewa Zone, and they are Quaternary alkaline basalts mainly, Mengesha, *et al* (1996). These Quaternary alkaline basalts

and tachytes were erupted along the pre-existing structures on the north- west and south- east plateaus. Their well-preserved structures and/or unmodified geomorphologic features such as cinder cones and small collapse craters, especially in heavy rainfall and perennial stream region indicate their recent age, Mengesha *et al* (1996).

Though the major geological structures in the country mostly parallel the Rift system, some faults run transversally to it on NW Ethiopian plateau. Can be mentioned as an example is the E-W oriented lineament that extends from Cassam river in the east through Addis Ababa to Ambo in the west. This lineament, called Ambo fault belt, starts from the western escarpment of the rift, and goes even farther to Wollega, Mengesha, *et al* (1996).

Horst formation in Karakore area by uplifting of the long strip of escarpment took place at more or less similar time with the faulting of E-W oriented Ambo fault belt that cuts across the escarpment and uplifted its northern block. This was nearly during the late Miocene time, Mohr (1971).

2.2 Local geology

The study area, Ambo, is part of the Ethiopian central plateau comprising both volcanic rocks of various types, mainly basaltic and trachytic lava flows, pyroclastic deposits such as unwelded tuff, and Mesozoic sedimentary rocks, particularly sandstone.

On 1:2,000,000 geological map of Ethiopia, the area was mapped under plateau basalt of Quaternary age comprising alkaline basalt and trachytes. But the northern part of the study area that forms an east-west oriented basaltic escarpment is part of the Ethiopian trap series having an age of Oligocene to Miocene. According to the revised geological map of Ethiopia (1996), it is categorized under Termaber- Magazaz formation of transitional alkaline basalt. This older basaltic lava flow is separated from the younger Quaternary volcanics of Ambo area by the Addis-Ambo-Guder fault escarpment. To the southern side of the fault escarpment including Ambo is covered by Quaternary volcanics; and the escarpment and its northern side is of Tertiary age. Some researchers such as Tsegaye Abebe (1993) define the fault escarpment as Addis-Guder fault escarpment.

The Quaternary volcanics in the area are thought to be originated from the central type volcanoes such as Wanchi and Dandi that are located at the southern part of the study area, Kondo (1967), Mohr (1971), Herick, *et al* (1983), and Tsegaye Abebe (1993). The Wanchi and Dandi volcanic centers are central type volcanoes on Ethiopian plateau, and they are part of the east-west oriented volcano tectonic lineament represented as Yerer-Tullu Wellel-Volcano-Tectonic-Lineament, Tsegaye Abebe, *et al.* (1997).

The escarpment to the northern side of Dabis river has two main steps: the first step next to the Dabis river is the cliff formed by the Mesozoic sandstone. This cliff pinches out when it reaches at the opposite side of Awaro area. Volcanic rocks, mainly basalt, comprise the next very steep cliff to the north of the sandstone. This second step has continuity through out the study area, even farther to the east.

The general stratigraphy (from youngest to the oldest) for the study area is as follows:

- Quaternary volcanics: Comprised by basalt, trachytes and pyroclastic deposits
- Tertiary volcanics: Mainly comprised by basaltic lava flow
- Mesozoic Sandstone

This stratigraphy will be refined farther and verified after the discussion and description of the geology of the area in the following part.

2.2.1 Volcanic rocks

One may categorize the volcanic rocks of the study area into two main groups:

- Lava flow: This comprises basalts and trachytes
- Pyroclastic deposits: This is mainly comprised by unwelded tuff.

2.2.1.1 Lava flows

The exposure of the basaltic lava flow in the study area is found at two distinct geomorphic features: the older Oligocene - Miocene succession part forms the elevated fault escarpment on

the northern side of the study area; particularly, areas of Dobi, Yubdo, etc are covered by this basalt. The age of this basalt varies from 31-20.6Ma according to various authors having a total thickness of more than 400m, Tsegaye Abebe (1993). On the other hand, the younger Quaternary basaltic lava flow occupies geographically lower positions such as in stream and /or river valleys of Dabis, Huluka, and Aleltu. Exception to these distributions is the basaltic lava flow that forms Mi-esa ridge to the western side of Ambo town.

At some places such as in Dabis and Aleltu river valley and stream cut respectively, the basalt is found interbedded with thin layer (about 1m thick) of pyroclastic deposits. On macroscopic scale, the basalts show two main textures: aphanitic and non-vesicular basalt, and porphyritic and vesicular basalts having plagioclase and olivine as a phenocryst (e.g. in Aleltu stream cut). Distribution wise, basalts of the latter texture dominate the former. These basaltic lava flows found at peripheries of the central volcanoes are the oldest volcanic rocks exposed to the southern side of the Addis-Guder fault escarpment for the study area, Tsegaye Abebe (1993). The inability to see the base of this basalt is the limitation to know its thickness; but geological well logging data from drilling shows a thickness of more than 100meters.

The second lava flow exposed in the study area is the trachytic lava. This lava flow is found at the SE and eastern part of the area, specifically, Dandi and its surroundings are totally comprised by trachytic lava flows. Besides these, the exposures are observed at Golja and Golole to the north of Dandi high land; these exposures also extend up to the immediate adjacent of Meti village. The source of this trachytic lava flow is thought to be Dandi volcanic center whose crater rim and slope are totally covered by the lava. The lava shows a good flow structure. One typical feature of the lava as observed at the slope of Dandi high land is that it is highly fractured, which

is thought to be originated from cooling process rather than from tectonic and /or weathering processes. The fractures do have one dominant orientation, NE-SW, dipping to the SE.

2.2.1.2 Pyroclastic deposits

The pyroclastic deposits in the area are dominantly comprised by unwelded tuff. It contains sizes ranging from ash through lapilli up to bomb. There exist different types of pyroclastic deposits: falls, flows, and surges. The exposure of the pyroclastic deposits is found covering the high lands of Wanchi and its crater rim, and also found irregularly as a patch up to Ambo town (e.g. at the rare side of Ambo swimming pool and at the pumping station of Huluka stream - up stream of the town). Unlike Dandi volcanic center, Wanchi and its surrounding is dominantly covered by pyroclastic deposits. But both Wanchi and Dandi show collapse crater structures, Tsegaye Abebe (1993). At some places the pyroclastic deposits show dipping toward the crater. The grain size of the pyroclastics decrease as one goes away from Wanchi area toward Ambo that confirms Wanchi crater to be a source.

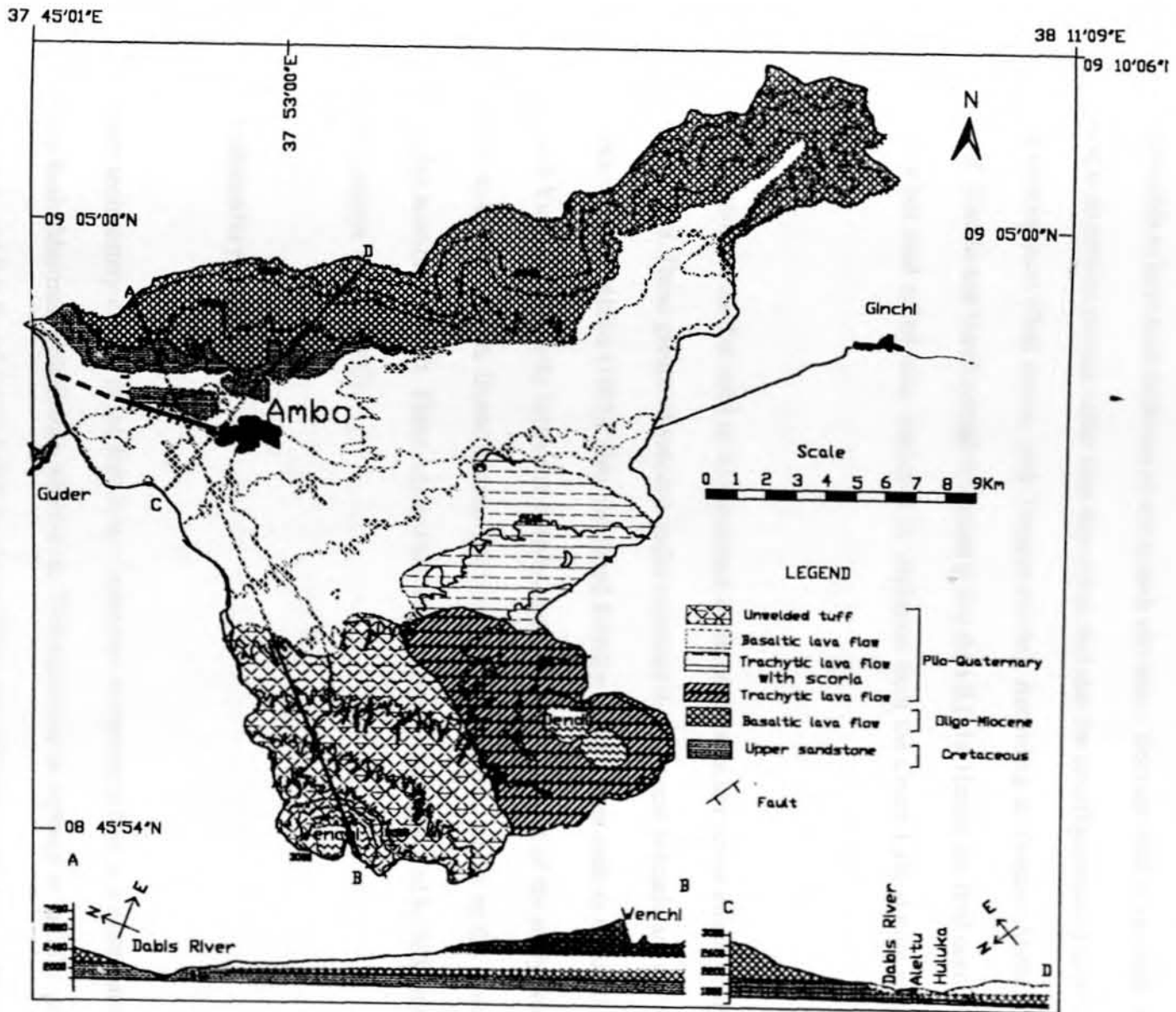


Fig. 2.1 Geological map of the study area (Ambo).

In Altufa area, on the way from Ambo to Wanchi, 1/2 - 1m thick greenish and brownish gray layer of soil that seems paleosol is observed interbedded with the pyroclastic deposits. But it is hardly possible to have such thickness of soil at such elevation. Because what is expected at such elevation is an erosion process rather than deposition; and also the time (Quaternary) is very short for soil development (Oral comm. with Tsegaye Abebe); According to Tsegaye Abebe (1993), the age of Wanchi and Dandi central volcanoes is less than 0.1Ma. Hence, the final conclusion is that it is a hot mud called lahar deposited by explosion from the Crater Lake during magmatic eruption.

The last volcanic rocks that need to be mentioned in the study area are scoria cinder cones and associated flows. These groups of volcanic rocks represent the youngest volcanic activity in the study area, Tsegaye Abebe (1993). They are found forming cinder cones such as Goromti, Tulu Dimtu and Yubdo respectively located at western, central and eastern part of the study area. As compared to the other, Tulu Dimtu is dominantly comprised by scoria, whereas the other two contain also scoraceous basalt. These scoria cinder cones are possibly controlled by NW-oriented fracture, Tsegaye Abebe (1993).

2.2.2 Sedimentary rocks

The main sedimentary deposit in the area is the Cretaceous sandstone, which is a continuation of the Abay basin Mesozoic sedimentary succession. This sandstone is exposed at the NW part of the study area, and it is found forming cliff (on the northern side of Dabis river), and ridge (on the western side of Ambo town). Different studies carried out so far in the area considered it to be the Lower sandstone that directly overlies the crystalline basement, e.g. Mohr (1971), Herick, *et al.*

(1983) and Merla, *et al.* (1979). The arguments forwarded by most of these authors are the presence of lime stone (?) and gypsum on top of the sandstone at the western side of Ambo town. But what they considered as limestone is not a part of the actual Mesozoic sedimentary succession, instead it is a travertine that is deposited by thermal spring as will be discussed later. On the other hand, Beauchaup (1977) categorized the sandstone under Upper sandstone by relating it to the stratigraphy in Mugher, Tsegaye Abebe (1993).

Similarly, by applying different modeling techniques, the sandstone outcrop in Ambo area is grouped under Upper sandstone in this work.

In the area between Ambo and Sankale, the sandstone is found forming an E-W oriented ridge. Since a long time, this sandstone has been used as a construction stone; and it is known by the name "Ambo sandstone". Its attractive color (whitish gray and pinkish to reddish gray) and easy workability (can easily be quarried and shaped manually) as well as its durability have made the sandstone a good construction and decorative stone for houses, fence and cemetery works.

The sandstone is well sorted with some very thin layer of conglomerate. Color wise, it can be grouped into two: the whitish gray at its lower part, and reddish color at its upper part. The latter category possibly shows that the cementing material is dominantly oxide of iron.

In some areas such as Manqata, on the right side of the Dabis river, calcareous sandstone has been observed. This sandstone doesn't occur as a uniform outcrop but as a fragment on the surface.

Other than the randomly distributed joints, three main joint sets can be identified in the sandstone: the NW-SE, NE-SW and the E-W oriented joint sets. The majority of the joint sets do have a nearly vertical dip angle. According to Herick *et al.* (1983), the joints have been resulted during the Tertiary volcanic activity. But the same author has also mentioned the presence of E-W oriented joints that are thought to be of Quaternary age.

In Huluka stream valley, the sandstone is directly overlain by the Quaternary basaltic lava flow. Here, a clear contact between the two units is observed. The distribution of the sandstone, especially on the southern side of Dabis river seems a structurally controlled. For example, at the immediate adjacent of Ambo town to its west along Teltele stream, the sandstone lies side by side (even at higher elevation) with the Quaternary volcanics that clearly shows a fault line (fig. 2-1).

In addition to the sandstone, there exists also mud along with gypsum and shale fragments in the study area. The exposure of this unit is well observed on the northern side of Dabis river valley, particularly in Manqata area. In this area the unit is observed to lie both above and below the sandstone; and it is found forming a gentle slope as compared to the sandstone. Hence, based on such morphological feature, all the areas that form gentle slope above and below the sandstone are inferred to be comprised by the mud- gypsum-shale unit, especially on the right side of the Dabis river. To the Eastern side of Manqata up to its pinching to basaltic lava flow, the mud-gypsum- shale unit dominates the sedimentary rock. This unit can be distinguished from a distant by forming gully and having pinkish color.

The mud-gypsum-shale unit is very friable, and characterized by pinkish, greenish and whitish gray color. The exposure of the unit is also found as a small patch between Ambo town and the

sandstone quarry on the southern side of the asphalt road. From its morphological (topography) observation in the area, the unit seems to continue further to the west forming a gentle slope under Mi-esa ridge. Due to its irregular exposure and also scale of the map, the unit is mapped under the sandstone unit. But from hydrogeological point of view, it has great significance acting as a barrier for subsurface water out flow.

2.2.2.1 Travertine and silica sinter

Both travertine and silica sinter are secondary chemical sedimentary deposits. The importance of these two chemical sediments in the study area is neither from surface geological nor hydrogeological point of view but from geochemical /or hydrogeochemical point of view in inferring the subsurface geology /or geochemistry; because they have only a limited areal extent.

Travertine is calcareous sediments formed by evaporation of spring and river water; it is more dense and banded deposit as compared to tufa, which is also calcareous sediment. According to Pettijohn (1984 and references there in), tufa is a surficial deposit about springs and seeps and exceptionally in rivers; where as travertine deposition is common in limestone caverns forming flow stone and drip stone including stalactites and stalagmites. But other authors such as Emmons, *et al.* (1953) defined the two terms from impurity point of view. Accordingly, tufa is a general calcareous deposit, where as travertine is a tufa that is purely of calcium carbonate. In spite of such discrepancy, the term travertine is adapted in this work because the deposit in the study area is more porous at its top part but slightly banded at its lower part; these features are clearly observed in the creek in front of the sandstone quarry on the opposite side of the asphalt road.

Silica sinter is also a porous material deposited by waters of hot spring; besides the compositional difference with travertine, silica sinter can only be deposited from thermal springs where as travertine can be deposited from moderately thermal to non thermal water, Trainer (1981). Therefore, the presence of travertine along with the some silica sinter in Ambo area clearly indicates their thermal origin. Herick *et al* (1983) also mentioned the absence of fossil in the travertine deposit to be an evidence for its chemical origin and young age.

The deposit of silica sinter is very small as compared to the travertine, and it is exposed only at few places; for example, around the Ambo swimming pool.

The deposit of travertine shows an east-west trend following a fault line that is a conduit for the thermal spring. It is found starting from Ambo town up to Sankale, where there is a lime factory using the travertine as a main raw material. There exist also an indication of travertine deposit farther to the east of Ambo town in Dabis river valley. Even if it is out side of the study area, there is also a travertine deposit in Guder on the western side of the town.

The travertine along with the silica sinters is the youngest deposit in the study area as compared to other geological units. This can clearly be observed from its relation with the pyroclastic deposit in Ambo town at and behind the swimming pool. At these places, the travertine is seen to be deposited with in the narrow fractures of the pyroclastic deposit crossing it. Though it is not uniform in the area, the thickness of the travertine deposit can be up to 17m as observed from the geological well logging of Sankale area.

All the above discussions, particularly, the chemical and thermal origin of the travertine deposit in Ambo area will enable us to infer /or deduce the subsurface geology of the area. This means that there has to be a subsurface geological materials that supplies calcium / or calcium carbonate and silica to the thermal springs. These can be possibly, limestone, gypsum, or anhydrate and sandstone; but as it will be explained later under the hydrogeochemistry part, it is more likely that the source is limestone. Whether the source is limestone or gypsum for the calcium/calcium carbonate, the implication is that these layers are found below the sandstone outcrop in Ambo area. By taking into consideration the regional Mesozoic sedimentary succession of Abay basin, the presence of limestone and /or gypsum under the sandstone will enable us to conclude the sandstone in Ambo area is Upper sandstone.

Therefore, the reconstructed stratigraphy of the study area from the youngest to the oldest is as follows:

- Quaternary volcanics
- Tertiary volcanics
- Upper sand stone
- Limestone unit
- ?

III. HYDROMETEOROLOGY

3.1 Meteorological parameters

Generally, there are four meteorological stations in the study area: two stations in Ambo town (one in Ambo Agricultural Research Institute, AARI, and the other is under the National Meteorological Agency). The other two stations are found in Guder and Ginchi. Only the meteorological station in Ambo town is a first class, the others are not. The meteorological stations at Ginchi and Guder are outside the boundary of the study area; but they are very near to the area and also from their geographical distribution point of view, it is reasonable to use data from these stations for the study area. Accordingly, meteorological data from the four stations have been used for the study area. A simple arithmetic mean method is applied in order to estimate the areal distributions of the different meteorological parameters for the study area. This method is chosen only because of the spatial distribution of the meteorological stations in the area, which is not convenient to apply other methods such as isohyetal or Thiessen polygon method. The stations (Guder, Ambo and Ginchi) are aligned in an almost E-W direction.

The over all meteorological parameters available for the study area are: rainfall, temperature, relative humidity, wind speed, duration of sunshine, and pan evaporation. The summary of the average monthly values for these parameters is shown in table 3- 1. The duration over which the parameters are averaged varies.

Table 3- 1 Summary of the mean monthly values of meteorological data for the study area

Parameters	Stations	Months												Total
		Jan	Feb	Mar	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Rainfall (mm)	Gudar	18.20	37.00	82.60	85.40	113.80	219.60	251.40	245.80	137.00	39.70	17.10	10.70	1258.30
	Ambo	26.72	27.00	53.50	70.70	92.00	161.10	231.90	192.50	115.00	44.70	9.20	9.20	1033.50
	Ginchi	24.10	49.20	70.00	87.10	89.70	128.30	244.00	231.80	153.30	38.20	12.60	9.80	1138.10
Average		23.00	37.90	68.70	81.10	98.50	169.70	242.40	223.40	135.10	40.90	13.00	9.90	1143.30
Temperature °c	Gudar	16.60	17.70	18.70	23.80	18.60	18.10	17.70	17.50	16.90	16.00	15.60	15.50	212.70
	Ambo	17.70	18.60	19.60	19.20	18.90	17.20	16.20	16.30	16.70	16.80	16.90	17.20	211.30
Average		17.20	18.20	19.20	21.50	18.80	17.70	17.00	16.90	16.80	16.40	16.30	16.40	212.40
R. H. (%)	Ambo	59.47	53.68	52.56	56.01	56.59	74.78	81.38	82.87	77.32	67.47	59.88	59.56	781.57
	Ginchi	56.33	60.66	52.78	60.50	57.75	70.00	80.67	81.50	76.42	62.33	60.45	59.33	778.72
Average		57.90	57.17	52.67	58.26	57.17	72.39	81.03	82.19	76.87	64.91	60.17	59.45	780.18
Sunshine Hour	Ambo	8.40	8.20	7.50	6.70	7.10	5.70	3.40	3.30	5.30	7.90	8.90	8.30	80.70
Average		8.40	8.20	7.50	6.70	7.10	5.70	3.40	3.30	5.30	7.90	8.90	8.30	80.70
Pan evap. (mm/day)	Ambo	6.3	7.5	7.7	7.5	5.7	4.5	2.24	2.32	3.4	4.6	5.7	5.98	
Average		6.3	7.5	7.7	7.5	5.7	4.5	2.24	2.32	3.4	4.6	5.7	5.98	

3.1.1 Rainfall

Being located in tropical region, rainfall is the main form of precipitation in the country. There are two main sources of rainfall in Ethiopia: the Atlantic equatorial westerly wind, and the southerly and easterly Indian Ocean air currents. The first source supplies rainfall to the high lands as well as western low lands of the country mainly due to orographic effect where as the southerly and easterly air currents bring rain to the eastern low land; rainfall in the country is highly controlled by altitude and moisture laden wind direction.

The distribution of rainfall in the area is more or less similar to that of the Ethiopian central plateau. Based on temporal rainfall distribution, generally two main seasons can be identified for the study area: the dry and the wet reason. More quantitative seasonal category based on rainfall

distribution can be explained by using the rainfall coefficient (R. C.) which is the ratio between mean monthly rainfall and one twelfth of the annual mean of the total rainfall, Daniel Gamachu (1977).

$$R.C. = 12P_m/P_a,$$

Where R.C.= rainfall coefficient (unit less)

P_a =annual total rainfall of the area, which is 1143.3mm

P_m =mean monthly rainfall

Table 3- 2. Mean monthly rainfall (p_m) and Rainfall coefficient (R. C.) for the study area.

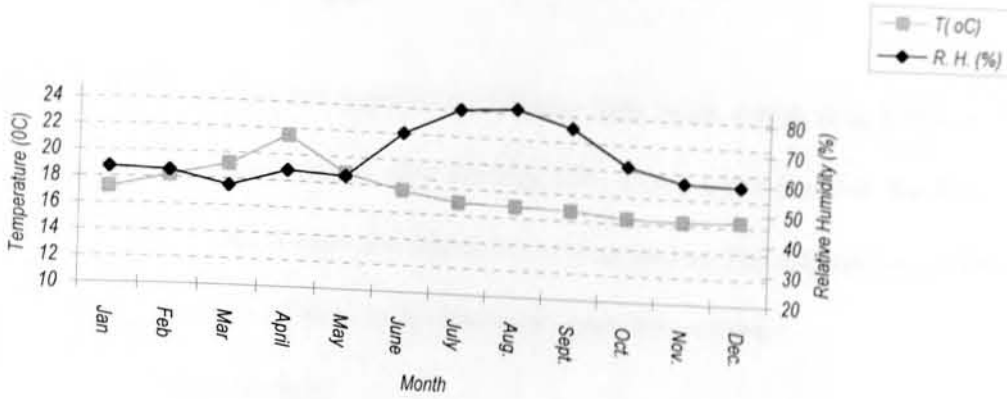
Month	J	F	M	A	M	J	J	A	S	O	N	D	Total
P_m (mm)	23.0	37.9	68.7	81.1	98.5	169.7	242.4	223.4	135.1	40.9	13.0	9.9	1143.3
R.C.	0.242	0.398	0.721	0.851	1.034	1.782	2.541	2.345	1.418	0.429	0.136	0.104	

Based on R.C. values the following precipitation category can be made for Ambo area:

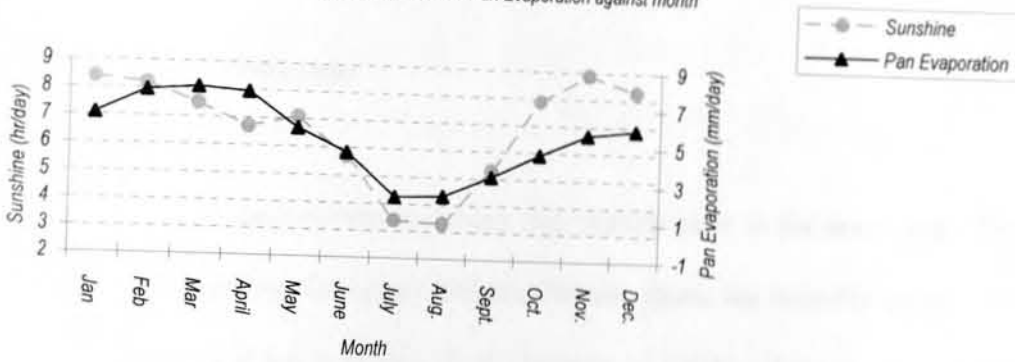
- *Dry months* (R.C.< 0.6): October, November, December, January and February.
- *Rainy months* (R.C. \geq 0.6): This can be further grouped into the following:
 - *small rain* (0.6 _ 0.9): March and April
 - *big rain* (\geq 1.0):
 - *moderate concentration* (1.0 - 1.9): May, June and September.
 - *high concentrations* (2.0 - 2.9): July and August
 - *very high concentrations* (\geq 3.0).

Fig.3- 1 various meteorological parameters versus time (month)

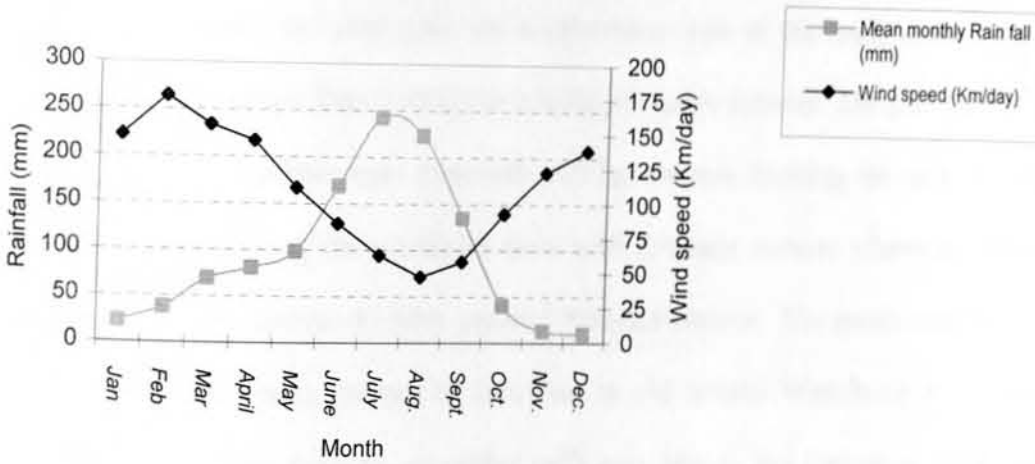
a) Temperature & Relative Humidity plotted against month



b) Sunshine hour & Pan Evaporation against month



c) Rainfall and Wind speed versus month



3.2 Surface hydrology

The study area is a sub catchment of Guder river basin, which is in turn one of the sub basin of Blue Nile on the southern side. Besides this, it is a triple junction for three regional drainage basins: Blue Nile, Awash and Ghibe- Omo river basins. The different water bodies that are found in the catchment and need to be discussed under this part are:

- River and streams
- Lakes

3.2.1 Rivers and streams

Both perennial and intermittent rivers and streams exist in the study area. The main river and perennial stream are Dabis and Huluka. Huluka drains the majority of the southern part of the catchment, and it has a general flow direction of NWN; where as the northern as well as the eastern part of the study area is drained by Dabis river. In addition to these, two perennial streams, Taltale and Boji drain the southwestern part of the study area. Some streams such as Huluka and Taltale form a waterfall gaining attractive scenery. The prevailing drainage pattern in the area is a dendritic type. Especially, all the streams draining the east- west oriented ridge on the northern side of the catchment show such drainage pattern; where as, streams that drain the high lands of Wanchi do have parallel drainage pattern. The catchment has a fifth order river network. The nearly absence of lava flow at and around Wanchi (it is exclusively covered by loose pyroclastic deposits- unwelded tuff) gave rise to the formation of a rugged morphology resulting in deep stream cut.

3.2.2 Lakes

One of the surface water reservoirs in the study area is lake. There are two natural lakes of volcanic origin, called crater lakes, in the area: Lake Wanchi and Lake Dandi located at southern and southeastern parts of the study area respectively. Lake Wanchi has a total surface area of 4km^2 , and a total drainage area of 11km^2 excluding the water body. It is also reported to have a maximum depth of 82m, Molla Gudeta and Meseret Taye (1998). There is no clear surface water out let for the lake; but from morphological point of view, Walga river that drains to Ghibe basin on the southern side of the lake seems to have a surface hydraulic connection with the lake; especially during high lake level. The lake is situated in a steep sided crater rim from which a number of springs emerge.

Lake Dandi is located in a relatively open crater, i.e. the rim of the crater is a little far from the water body. The lake forms the source head for Huluka stream that flows across Ambo town. It has a total drainage area of 16.6km^2 excluding the water body; where as the area of the lake is 7.4km^2 .

In spite of their economic potential and scientific interest, the lakes are less investigated so far. There is no access road for car that takes to the lakes; this is one and the main hindrance for the development of the lakes. A gravel road that goes from Ambo to Walliso passes on the western side of the Wanchi Lake. Hence, the distance between this road and the lake water, which is exclusively the rim of the crater, has to be covered on foot.

According to Oromia Agricultural Resources Development Bureau, Lake Wanchi has been investigated for fishing since recent time. Accordingly, the lake is found to be suitable for fishing both from physical and chemical parameters (dissolved oxygen, pH, temperature, etc) point of view. Some species of fish are found in the lake introduced into it six years ago; and currently the fishes are found in a good situation (oral comm. With the Zonal Agricultural Department).

3.2.3 Stream discharge

There is no gauged stream in the catchment of the study area. At the upstream of Ambo town it has been started to gauge Huluka stream since recent years. But complete stream flow data is unavailable even for a single year. Hence, in order to calculate the runoff, which is to be estimated for the study area, the values of the neighbouring gauged streams are used. There are four gauged streams (or gauging stations) in Guder catchment to which the study area is also a sub catchment. The streams that do have a gauging station are: Guder at Guder, Fatto near Guder, Bello near Guder, and Indris at Guder. For each gauging station, the following parameters are available over a long duration: monthly runoff, monthly maximum discharge, and monthly minimum discharge of the streams.

The monthly minimum stream discharge is considered to be equal to the base flow. Actually, it has been mentioned by Wundt (1978) that the monthly minimum stream discharge best approximates the base flow, especially, for humid climate. Accordingly, by taking monthly minimum stream flow as a base flow, it has been subtracted from the monthly total runoff to get the component that forms over land flow from which the runoff coefficient is calculated.

$$Rc = D/PA$$

Where:

Rc= Runoff coefficient

D = overland flow

P = annual precipitation

A = drainage area

For the sake of comparison, R_c has been calculated for all the gauged streams mentioned above as shown below:

Table 3-3 Runoff coefficient (R_c) calculated for various catchments

Gauging station (stream)	Area (Km ²)	Precipitation (mm)	Total minimum annual discharge (m ³)	Total annual runoff (m ³)	R_c .
Guder at Guder	524	1143.3	209,664,979.20	409,933,000	0.328
Bello near Guder	490	1143.3	112,918,233.60	205,157,000	0.165
Indris at Gudar	111	1143.3	31,960,742.40	81,253,000	0.389
Fatto near Gudar	96	1143.3	34,290,000.00	74,773,000	0.369

The implication of the runoff coefficient, R_c is that higher R_c value means much component of precipitation is lost from a catchment through runoff. Accordingly, if we compare R_c values for all the gauged streams shown above, they show that more than 30% of the precipitation component is lost from the catchment through runoff except for Bello catchment that has only about 16.5%.

There are various factors that control runoff; among them are geology, physiography, vegetation, land use, climate, and soil type. For example, a catchment with steep slope, less permeable soil and sparse vegetation cover could have higher R_c value than a similar catchment with gentle slope, more permeable soil and dense vegetation cover other factors being similar for the two catchments. Hence, in order to correlate/ or use R_c value of one catchment for another, all these

different factors have to be considered. Among those streams gauged in Guder catchment, the Bello sub catchment is found to show similarity with the study area in geology, morphology and vegetation cover. The different meteorological parameters are also similar for the two catchments. The Bello catchment is totally comprised by volcanic rocks dominantly basaltic lava flow. It is a plain covered with transported soil at its central part, and elevated as well as rugged at its peripheries.

Hence, the value of runoff coefficient for Bello catchment with some correction (based on geology) is considered. Accordingly, a runoff coefficient of 0.15 is taken for the study in estimating the runoff of the study area.

Therefore, the runoff depth for Ambo area is given as:

$$RO = RC \times P$$

Where RO = run off depth in mm/yr

$$RC = \text{run off coefficient} = 0.15$$

$$P = \text{precipitation depth} = 1143.3 \text{ mm/yr}$$

$$\text{Hence, } RO = 0.15 \times 1143.3 \text{ mm/year} = 171.5 \text{ mm/year}$$

If the runoff volume is required, we need to multiply the runoff depth by the area under consideration.

3.3 Water balance

By water balance it is meant equating /or balancing the amount of water inflow and outflow for a given system, such as hydrogeologic system, over a given duration for a given area; hence it is a dynamic system, Detay (1997). The hydrogeologic system can be a drainage basin/or catchment, groundwater basin, soil layer, or any surface water reservoir (natural or artificial).

The method can be employed for different purposes: computation of groundwater recharge, evapotranspiration, continuous record of soil moisture, and stream flow from a meteorological record and a few observation on the soil and vegetation, seasonal and geographic patterns of irrigation demand, the flux of water to lakes, and prediction of human effect on hydrologic cycle. Leopold and Dunne (1978) Generally, water balance is a valuable tool in the analysis of water availability in a region.

Among these, its purpose in this paper is aimed at groundwater recharge estimation. The basic assumption that is considered in this case is that the surface water divide coincides with the subsurface drainage basin. Accordingly, other than the water that is percolated with in the limit of the surface water divide, there is no inter basin flow (inflow or out flow) of groundwater.

The basic equation of water balance is:

$$\text{Inflow} = \text{outflow} + \Delta S$$

For the study area, the main inflow component is precipitation, but the outflow components are evapotranspiration and runoff assuming all other components such as water abstraction by human

for other purposes to be negligible. Besides this, the change in storage can be considered to be zero if the water balance is made by taking water year /or hydrologic year. Hence, the value of ΔS will be negligible/or zero since the calculation is to be made on annual basis.

Since rainfall record can be obtained from meteorological stations in the area, the main task left is to estimate /or calculate the potential evapotranspiration from which the actual can be derived for the catchment. In addition to this, the runoff has also to be estimated/or calculated for there is no actual measurement of this component in the study area. In the following section, methods and estimation of these different components will be discussed.

3.3.1 Estimation of Potential Evapotranspiration, PET

Evapotranspiration is the total of all water that leaves a region through direct evaporation from surface water bodies, snow, and ice, Plus that which is evaporated after passing through the vascular systems of plants (transpiration), Dingman (1994).

Evapotranspiration generally depends on different factors: climate (temperature, wind speed, relative humidity, solar radiation, barometric pressure, etc.), Plant physiology, water quality, etc. If evapotranspiration takes place under an unlimited water condition, i.e. sufficient water quantity, it is said to be Potential Evapotranspiration, PET. A number of methods have been formulated and are currently in use for PET estimation; but their applicability is limited by availability of different required parameters, and some methods are site-specific; i.e. they are best

valid only under a given climatic zone. In this paper, Thornthwaite, Penman, and Pan evaporation with a pan coefficient methods have been used among the different methods.

Thornthwaite Method

Thornthwaite in eastern USA developed this method for grassland in 1948. It requires only air temperature as an index of energy available for evapotranspiration. One of the main advantages of this method is that it is easily determined, because it requires only single parameter, temperature, which can be obtained from meteorological station. But its limitation is that a number of parameters that affect evapotranspiration have been neglected. Hence, it under estimates potential evapotranspiration of an area.

The empirical equation of Thornthwaite is given by:

$$PET = 1.6 (10t_a/J)^a$$

Where, PET = Potential evapotranspiration (cm/month)

t_a = Mean monthly air temperature ($^{\circ}C$)

J = Annual heat Index = $\sum (t_a/5)^{1.514}$

$a = 0.49 + 0.0179J - 7.71 \times 10^{-5} J^2 + 6.75 \times 10^{-7} J^3$

For the study area the values of 'I' and 'a' are calculated to be 81.565 and 1.803369044 respectively. Therefore, Thornthwaite equation is reduced to:

$$PET = 0.036336062 (t_a)^{1.803369044}$$

Based on this equation, the monthly potential evapotranspiration has been calculated for the study area as shown in table 3-4.

Since Thornthwaite equation was developed for standard month of 360 hours of daylight, correction has to be applied to adjust for the number of days per month and the length of day, both are a function of latitude. In the table shown below this correction has been applied taking an average latitudinal position of the area to be 9° 00' 00'' N.

Table 3-4 Monthly PET of Ambo area in mm using Thornthwaite method

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep	Oct	Nov.	Dec	Total
PET (mm)	59.78	66.81	74.92	94.36	75.38	68.18	61.78	61.66	59.95	55.9	54.3	54.35	787.29

Penman Method

Penman method combines the energy balance and the mass transfer methods. Hence, unlike Thornthwaite's method, parameters other than temperature are considered. Such factors being affecting ET differently, Penman's method gives more reasonable value of PET of an area as compared to Thornthwaite. Its equation is given by the following formula:

$$PET = (AH_n + E_a\gamma) / (A + \gamma)$$

Where: PET = daily potential Evapotranspiration in mm/day

A = Slope of saturation vapor pressure versus temperature curve, in mm of Mercury/°C

H_n = Net radiation in mm of evaporable water per day

E_a = Mass transfer evaporation

γ = Psychrometric constant = 0.49 mmHg/ °C

$$H_n = H_a(1-r) (a + bn/N) - \sigma T_a^4 (0.56 - 0.092\sqrt{e_a}) (0.10 + 0.90 n/N)$$

a = a constant depending up on the latitude ϕ , and is given by $a = 0.29\cos \phi$; For the study area $\phi = 9^{\circ} 00' 00''$ N; Hence, $a = 0.29 \times \cos 9^{\circ} = 0.28643$

b = a constant with an average value of 0.52

n = actual duration of bright sunshine in hours

N= Maximum possible hours of bright sun shine (it is the function of latitude)

σ = Stefan- Boltzman constant= 2.01×10^{-9} mm/day.

T_a= Mean air temperature in degrees Kelvin

H_a= incident solar radiation out side the atmosphere on a horizontal surface, expressed in mm of evaporable water per day. It varies with latitude and period of the year

r= reflection coefficient (albedo), usually varies between 0.15 – 0.25, 0.05- 0.45, and 0.05 respectively for close-ground crops, bare lands, and water surface, Subramanya (1988).

$$E_a = 0.35(1 + U_2/160)(e_w - e_a)$$

e_w = saturation vapor pressure at mean air temperature in mmHg

e_a = actual vapor pressure

U₂ = Mean wind speed at two meter above ground in km/day.

The following table 3-5 shows the monthly values of PET and other parameters for the study area.

Table 3-5 Potential evapotranspiration, PET (mm/month) for Ambo area using Penman method

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Parameter													
Hn	3.315	3.816	4.013	4.689	4.013	3.927	3.515	3.592	3.91	3.951	3.54	3.142	
Ea	4.222	4.967	5.489	5.404	4.167	2.281	1.36	1.18	1.602	2.741	3.442	3.738	
A	0.95	0.978	0.978	1.164	1.002	0.958	0.92	0.914	0.908	0.884	0.878	0.884	
PET	112.34	121.81	139.66	147.04	125.97	101.1	85.75	85.25	93.04	109.11	105.14	103.99	1330.2

Table 3-6 Comparison of PET values obtained using Thornthwaite and Penman along with the precipitation in the study area

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Thornthwaite	59.78	66.81	74.92	94.36	75.38	68.18	61.78	61.66	59.95	55.9	54.3	54.35	787.29
Penman	112.34	121.81	139.66	147.04	125.97	101.1	85.75	85.25	93.04	109.11	105.14	103.99	1330.2
Precipitation	23	37.9	68.7	81.1	98.5	169.7	242.4	223.4	135.1	40.9	13	9.9	1143.6

As can be seen from the table, the PET value of Thornthwaite method, 787.29 mm/year, is very small as compared to the value from Penman method, which is 1330.2 mm/year, for Ambo area. Thornthwaite method is valid best for mid latitude climates for which it developed where air temperature is fairly good index of net radiation. The method gives erroneous results in tropics resulting in serious underestimation of PET. Hence, Penman method is preferable in such regions, Leopold and Dunne (1978). Accordingly, in the calculation of Actual Evapotranspiration (AET) both results obtained from Penman and Thornthwaite methods are used along with the Turc method (discussed next) and then their average will be taken.

3.3.2 Actual Evapotranspiration (AET)

Actual Evapotranspiration is the real evapotranspiration that takes place under the existing moisture condition. Various approaches exist for the determination of AET. It varies from empirical relations or factors gained from direct measurement to highly sophisticated computer models. The method employed in this paper is that developed by Thornthwaite and Mather (1957). The method is based on the PET value obtained using different methods, and the soil moisture. Besides these, there are other conditions that are to be specified in order to apply the method such as soil type, vegetation cover and root depth. Accordingly, the area is considered to be covered with clay loam soil of field capacity 200mm, and the vegetation cover is a moderately deep root crops such as cereals with a root depth of 80cm on average.

The Procedure is as follows:

- Accumulated potential water loss (AC. P.WL) of a soil is calculated for months in which PET exceeds precipitation (P) starting from the beginning of dry month (October in this case).
- Moisture retained in the soil, SM, while it is subjected to accumulated potential water loss is estimated using standard curve for dry months ($PET > P$). For wet months, it is the sum of P less PET and soil moisture of the previous month. In case, this sum exceeds the field capacity of the soil, 200mm in this case, only 200mm is taken. Because a soil cannot store more water than its field capacity.

Finally, AET is obtained. During water surplus, AET equals PET, Example, during July, August, and September.

Table 3-7 gives the summary of the Actual Evapotranspiration, AET estimated using Thornthwaite-Mather method for Ambo area both for Thornthwaite and Penman.

Table 3-7 Estimation of Actual Evapotranspiration, AET by using Thornthwaite-Mather method

a) PET determined by using Thornthwaite method

Month	Jan	Feb	Mar	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
P	23.00	37.90	68.70	81.10	98.50	169.70	242.40	223.40	135.10	40.90	13.00	9.90	1143.60
PET	59.78	66.81	74.92	94.36	75.38	68.18	61.78	61.66	59.95	55.9	54.3	54.35	787.29
P-PET	-36.78	-28.91	-6.22	-13.26	23.12	101.52	180.62	161.74	75.15	-14.97	-41.2	-44.45	
AC.P.WL.	-137.4	-166.31	-172.53	-185.79	-	-	-	-	-	-14.97	-56.17	-100.62	
SM	100	92	85	80.6	98.72	200.00	200.00	200.00	200.00	195	170	130	
ΔSM	-30	-8	-7	-4.4	18.12	101.28	0.00	0.00	0.00	-5	-15	-18	
AET	53.0	42.9	82.6	96.00	75.38	68.18	61.78	61.66	59.95	45.9	28	49.9	725.25

Month	Jan	Feb	Mar	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
P	23.00	37.90	68.70	81.10	98.50	169.70	242.40	223.40	135.10	40.90	13.00	9.90	1143.60
PET	112.34	121.81	139.66	147.04	125.70	101.10	85.75	85.25	93.04	109.11	105.14	103.99	1329.93
P-PET	-89.30	-83.90	-70.90	-65.90	-27.50	68.60	156.70	138.20	42.10	-68.20	-92.10	-94.10	-186.30
AC.P.WL.	-343.70	-427.60	-498.50	-564.40	-591.90	-	-	-	-	-68.20	-160.30	-254.40	-2909.00
SM	40.00	27.00	20.00	14.00	12.00	80.60	200.00	200.00	200.00	150.00	90.00	58.00	1091.60
ΔSM	-15.00	-13.00	-7.00	-6.00	-2.00	68.60	119.40	0.00	0.00	-50.00	-60.00	-32.00	3.00
AET	38.00	50.90	75.70	87.10	100.50	101.10	85.75	85.25	93.04	90.90	73.00	41.90	923.14

b) PET determined by Penman method

* P= precipitation, PET= Potential Evapotranspiration, AC. P.WL= accumulated potential water loss, SM= Soil moisture, ΔSM= change in soil moisture, AET= Actual Potential evapotranspiration.

Turc method

This method determines the annual Actual Evapotranspiration, AET directly from two meteorological parameters, precipitation and temperature. It is an empirical formula developed based on data from various catchments of different climates, and hence could be applied in humid or arid climates, either hot or cold, Shaw (1988).

It is given by the formula:

$$AET = (P) / (\sqrt{0.9 + (p/L)^2})$$

Where AET= Actual Evapotranspiration of a year in mm

P = annual mean precipitation in mm

T = annual mean air temperature in °C

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

For the study area P and T are 1143.3mm and 17.7 °C respectively. Hence, $L = 1020\text{mm}$ and the value of AET becomes 778.6mm/year.

In order to have reasonable value of AET for the study area, the average value, which is 809 mm/year obtained from the three different methods (Thornthwaite, Penman, and Turc) is used. Because during the calculation of AET employing various methods, some parameters that may affect evapotranspiration are either estimated or totally neglected. Hence, if the value from a single method is used, either over estimation or under estimation of AET of the area could possibly occur. Therefore, the average AET value, which is 809mm/year, will be taken for any further water balance calculation of Ambo area.

3.3.3 Lake water evaporation

The amount of evapotranspiration from a water body is very high as compared to those from soil and vegetation cover, because there is no limitation of moisture. Hence, the Actual Evapotranspiration equals the potential value. As a result, even a small surface water body can loose a significant amount of water through evaporation. Therefore, evaporation from the lakes (Dandi and Wanchi) in the study area is treated separately from the study catchment.

In order to estimate lake water evaporation in the study area, two methods have been employed; and finally their arithmetic mean is taken as shown below:

Penman method

This method is more or less similar to the PET estimation for land body as explained before, but in the case of water body the reflection coefficient, albedo, value used is 0.05. The summary of this method along with different parameters is shown below (table 3-8).

Table 3-8 Lake water evaporation for Dandi and Wanchi using Penman method

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Parameter													
Hn	5.030	5.628	5.819	5.949	5.742	5.415	4.769	4.860	5.405	5.742	5.343	4.803	
Ea	4.222	4.967	5.489	5.404	4.167	2.281	1.360	1.180	1.602	2.741	3.442	3.738	
A	0.950	0.978	0.978	1.164	1.002	0.958	0.920	0.914	0.908	0.884	0.878	0.884	
PET=AET(mm/year)	147.4	156.8	176.9	173.6	161.9	130.6	104.1	110.9	122.2	144.8	139.9	137.1	1706.2

Pan evaporation method

There exist five years Pan evaporation data for the study area at Ambo Agriculture Research Institute (AARI). Since a pan -evaporation doesn't correspond to the actual/or real evaporation of water from lake/or reservoir, the so-called pan-coefficient is used to normalize the pan evaporation value to the lake evaporation. A pan coefficient between 0.75 and 0.85 is usually taken for open water evaporation of Ethiopian Rift, Seifu Kebede (1999). Tenalem Ayenew (1998) used a pan coefficient of 0.83 for Ziway-Shala lakes. A pan coefficient of 0.79 was considered by Seifu Kebede (1999) for crater lakes in Bishoftu area by pointing out that crater lakes are more protected from wind effect as compared to other lakes.

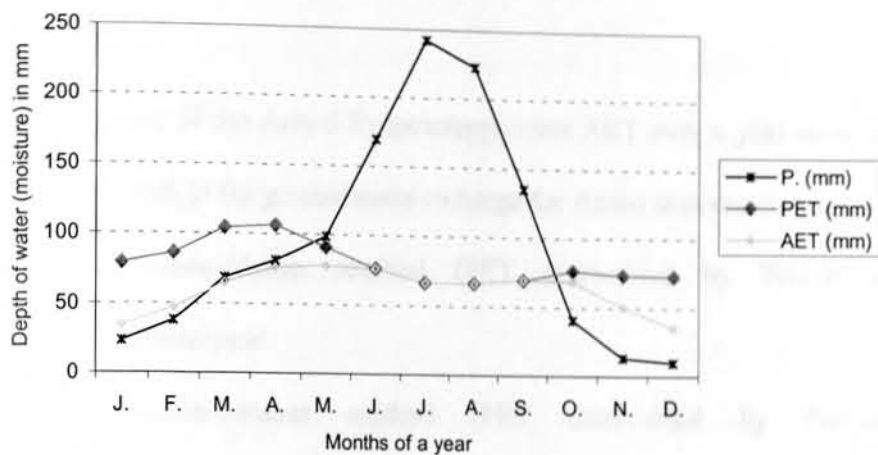
The study area being located at Ethiopian central plateau, it is found at higher elevation as compared to all the mentioned Rift lakes; as a result of these a number of meteorological parameters vary. By taking all these factors into consideration, a pan coefficient of 0.75 is considered for lake Wanchi and Dandi. Accordingly, an evaporation of 1448mm/year is obtained for the two lakes in the study area. The summary of the result is shown in table 3-9. It should be noted that, the evaporation from Dandi Lake should be higher than that of Wanchi Lake if their morphology is considered. Wanchi Crater Lake is more confined by the narrow and deep crater rim as compared to that of Dandi, which is more or less open as compared to the former. Hence, the Wanchi Crater lake is more protected from the effect of wind.

Table 3-9 Summary of the Dandi and Wanchi lake water evaporation by using Pan evaporation method with a pan coefficient of 0.75.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Evaporation (mm)	146.5	163.1	179.0	168.8	132.5	101.3	52.1	53.9	76.5	107.0	128.3	139.0	1448.0

As can be seen from the results of the two methods, Penman and pan evaporation, the value obtained by Penman is higher for lake evaporation. But in this work the average value from the two methods, which is 1577 mm/yr, is taken for the two lakes.

Fig. 3-2 Comparison of Precipitation (P), potential evapotranspiration (PET) & Actual evapotranspiration (AET) in Ambo area



3.3.4 Summary of the water balance

The estimation of the Actual Evapotranspiration AET over a year undertaken by using different methods as well as the groundwater recharge for Ambo area can be summarized as follows:

- Thornthwaite-Mather method (PET determined by Thornthwaite method), AET= 725.25mm/year.
- Thornthwaite-Mather method (PET determined by Penman method), AET= 923.14mm/year.
- Turc method: AET= 778.6mm/year.

The mean values from the three methods give an AET of 809mm/year for the study area. As mentioned before, the area has a total annual rainfall of 1143.3mm, and an estimated overland flow of 171.5mm/year. Hence, the annual total precipitation less the actual evapotranspiration and the overland flow on a yearly basis give the annual groundwater recharge of the area, which is equal to 162.8mm/year. This value is in a good agreement with the groundwater recharge estimated for Ethiopian central plateau (high land) by Tesfaye Chernet (1993).

Since no clear surface water outlet has been observed for Lake Wanchi, the following summary of the water balance can be made for it:

- Annual precipitation on the lake: 1143.3mm/year
- Annual evapotranspiration from the lake: 1577mm/year
- Drainage area (excluding the lake): 11km²
- Area of the lake: 4 km²

- Water added to the lake from overland flow: $1,886,445\text{m}^3/\text{year}$

Hence, if a balance between the inflow and outflow to /from the lake is made only for the surface hydrologic condition, there is a net surplus of $37.91\text{mm}/\text{year}$. As has been observed in the area, water abstraction from the lake for various purposes is negligible for there exist many springs that flow to the lake from the rim of the crater. Based on this condition, the lake is expected to show a rise in level every year at least by some amount. But this is not the case for it as the surrounding people say. Therefore, there should be some subsurface out flow from the lake. Actually, it needs a thorough investigation to come to such conclusion.



IV. HYDROGEOLOGY

The behavior of geological materials toward the interaction, storage and transmissions of subsurface water constitute the basic part of hydrogeology. Some materials can store and transmit water (aquifer). Others can only store but do not transmit (aquiclude); still others neither store nor transmit water (aquifuge). These properties of geological materials depend on lithology, structure, grain size, sorting, cementing materials and the degree of cementation, degree of weathering, tectonics, etc. Both lateral and vertical extent, shape and distribution of the geological formation play a role in the hydrogeology of an area. The presence of highly permeable geological formation is not enough by itself for groundwater storage, there has to be also a bottom-confining layer (barrier) that up holds the subsurface water.

Thus, an understanding of the hydrogeology of a given area /or region requires a knowledge of both surface and subsurface geology and structure in addition to the hydrometeorology of that area /or region. The subsurface knowledge is obtained either directly from borehole or indirectly from geophysics. Hence, a well-documented well data for a given area is a good hydrogeological asset for that area.

In areas where we do not have sufficient subsurface geologic/or hydrogeologic data, the best approach to evaluate the aquifer productivity of the geological formation is to use the surficial approach in such a way that we can arrive at qualitative interpretation of the permeability of the materials. Some of such features that enable us to have a qualitative interpretation are: presence

or absence of springs, degree of weathering and fracturing, thickness of the formation, sorting, degree of cementation, etc.

In the study area, in spite of the presence of a number of ground water wells, they are mostly lacking well data; for some of them even geological well logging is rarely available; in addition to this, there is no access to take groundwater level measurement in the well and also to take sample directly from it due to the absence of piezometers. Hence, the reliable techniques of hydrogeological description is to follow a qualitative approach that involves a description of how surface materials behave in order to come up with the information about the geologic materials. Actually, there are some few wells from which it has been tried to estimate the hydrodynamic parameters of some geological formations as will be seen later.

4.1 Hydrostratigraphic Units

Based on the qualitative approach mentioned above, different lithological units in the study area can be categorized into the following hydrostratigraphic units:

- The highly fractured and/or weathered lava flow (basalts and trachytes) and the loose lapilli dominated pyroclastic deposit (un welded tuff) at Wanchi.
- The Upper sandstone unit
- The pyroclastic deposits dominated by ash size around Ambo and the mud-shale-gypsum units intercalating the sandstone.

4.1.1 Volcanic rocks

Groundwater storage capacity of volcanic rocks is attributed to both primary and secondary structures. These structures include vesicles, joints (due to weathering, tectonic or cooling processes), tree molds, lava tubes, and voids between successive flows. Therefore, the prudence of searching groundwater in such terrain lies in identifying such potential structures.

Lava flows

This comprises the basaltic and the trachytic lava flow. The basaltic lava flow exposed at northern part of the study area occupies the elevated land as compared to those exposed in river / stream valley of Dabis, Huluka and Aleltu. But their macroscopic structures as well as other surface features such as fracturing, degree of weathering and vegetation cover can bring them under similar hydrostratigraphic unit. Basaltic lava flows exposed in stream cuts /or those that cover the plain area show high degree of cooling fractures but they are moderately weathered, where as those basaltic lava flow constituting the elevated lands such as Dobi, Yubdo, and Waddessa are highly weathered and where the un weathered one is observed, it shows high degree of cooling fractures. Hence, the lack of one criterion can be compensated by another bringing them under similar hydrostratigraphic unit.

Besides these, there are a number of springs that emerge from this basaltic lava flow. Some of the most important springs are: Ebicha and Dule spring on the northern side of Dabis river, Wachani, Buqisa, Chafe (Mi-esa) and Kilinto springs on the southern side of the Dabis river valley.

The bottom barrier layer for the outflow of these springs is either the volcanic ash size dominated pyroclastic deposits or the mud-shale- gypsum unit underlying the basaltic lava flows. Some of the basalts are scoriaceous, especially, where there are scoria cinder cones, e.g. At Tullu Dimtu, Goremti and Yubdo areas.

The trachytic lava flow covers Dandi area and also some of the eastern part of the study area. This lava flow shows also high degree of fracturing and moderate weathering. The fracturing seems to be originated dominantly from cooling. Unlike the high lands of Wanchi, that of Dandi is less covered by vegetation but it is intensively cultivated. About 5m thick on average, dominantly of silty soil, covers most part of the Dandi high land. A deep gully cut forming the head of most streams start from this high land. The gully/deep stream cut in the case of Wanchi highland passes through the friable unwelded tuff. Like the basaltic lava flow mentioned above there are also springs that emerge from this trachytic lava flow. Some of them to mention are: Molche, Qeransa and Ela springs. The barriers for the outflow of these springs are not clearly observed; but it is most likely that the less fractured lower part of the same rock.

Pyroclastic deposits

Pyroclastic rocks associated with lava flows are generally porous but not very permeable except blocky, coarse material near volcanic vents and tuffs that have been reworked by water, Davis (1966).

The pyroclastic deposits in the study area are mainly comprised by unwelded tuff. It covers all areas around Wanchi, and extends to north uniformly up to Goremti area. The tuff is highly

friable, as a result there are a number of streams/ gully cut that gave rise to the rugged morphology of Wanchi Mountain slope, especially on its northern side.

The hydrogeological significance of this unit is that it shows a spatial variation of grain size as one goes away from Wanchi lake area, which is the source of the product. Accordingly, the bomb through lapilli to ash sized pyroclastics at Wanchi and its surrounding becomes dominantly of ash size toward the north (e.g. at Ambo). Besides this, the pyroclastics are generally covered by natural vegetation on Wanchi high lands facilitating infiltration; and the soil development on this high land is also very poor. All these features can bring the unwelded tuff of the Wanchi high land under the highly permeable geological formation like the previously mentioned lava flow from hydrogeological point of view.

Though not frequent a layer of lahar deposit/or hot mud of about 1m thick has been observed with the unwelded tuff at Altufa area. Such less permeable layer could be the barrier for the out flow of some springs from the pyroclastic deposits, especially in the crater of Wanchi to the lake.

The thickness of the pyroclastic deposits can be estimated from the elevation difference between the peak of Wanchi high land and the foot of the mountain slope above which it uniformly covers. Hence, the thickness of the pyroclastic deposits at Wanchi area exceeds 600m. A productive deep well drilled in these pyroclastic deposits in Altufa area strikes scoraceous basalt at a depth of 150m (Oral comm. with Tesfa).

The selective deposition of pyroclastic materials, coarser grain size near the source and the finer of ash size away from the source has resulted in materials of the same source but different

hydrogeological properties. Hence, the ash dominated pyroclastic deposits in Ambo area are less permeable, and act as upper or lower confining layer for an aquifer unlike those found in Wanchi area. For example, the outflow of Buqisa spring to the east of Ambo is due to such pyroclastic deposits. In addition to this, it has been observed from the geological well logging of Awaro test well that the ash-dominated pyroclastic deposits act as a confining layer.

Therefore, the pyroclastic deposits around Ambo are under the category of the mud-shale-gypsum unit from hydrogeological point of view as will be discussed later.

4.1.2 Sediments and Sedimentary rocks

Sandstone

The hydrogeological property of sandstone depends on both primary and secondary structures and/or textures. The main sedimentary unit that is exposed in the study area is sandstone. It is found at northwestern part of the catchment. The sandstone has been considered as the lower sandstone by different authors, but now it has been justified that it is Upper sandstone as mentioned before. Unlike in the northern part of country where it usually acts as an aquiclude due to laterization, Upper sandstone is an aquifer of high productivity in southern and eastern part of the country, Tesfaye Chernet (1993). It is a well sorted, reddish and whitish gray in color and shows some cross lamination. The sandstone is moderately cemented by silica and iron oxide; the reddish to brown color at its upper part shows the presence of iron oxide as cementing materials in it. This moderate degree of cementation could hardly reduce the primary porosity and/or permeability of the sandstone; hence its groundwater storage potential is attributed to both the secondary and primary porosity and/or permeability (fracture porosity) that have been produced

by tectonics. Generally, three main joint systems can be observed in it: NW-SE, NE-SW and the nearly E-W oriented joint systems. These later formed joints have similar trend with the E- W oriented fault in the area. The joints are thought to be formed during Tertiary tectonic activity, Herick *et al.* (1983). But it has also been mentioned by the same author that the E-W oriented fractures in Ambo area, are of Quaternary age. No spring has been observed coming out from the sandstone on the northern side of the Dabis river with in the range of the study area. This may be due to mud-shale-gypsum unit that is found overlying the sandstone but underlies the basaltic lava flow. Where as, on the southern side of the same river valley it has been observed that there are springs emerging from the sandstone, for example, the Shamme spring at the northern side of the sandstone quarry facing toward Huluka stream. This sandstone is surrounded by faults almost in all directions (see the geological and Hydrogeological map of the area).

Mud- Shale –Gypsum unit

Inspite of its few areal distribution, the mud- shale- gypsum unit has a significant role from hydrogeological point of view due to its low permeability as compared to the geological materials it is interbedded with. As a result there are some springs in the study area that are emerging both from sandstone and basaltic lava flow due to the impermeable mud- shale- gypsum unit underlying them. Some of them to mention are Shamme and Dule spring.

4.2 Aquifer characteristics

An aquifer is a hydrogeological formation that stores and transmits a significant quantity of water in such a way that a reasonable amount of water can be abstracted from it economically. It is both

a hydrogeologic and hydrodynamic system that can be defined by the following quantifiable characteristics, Detay (1997):

- Its dimension (geometry) and boundary conditions that give rise to its volume
- Its hydrodynamic, hydrochemical and hydrobiological behavior respectively characterizing water storage and transmission, geochemical interaction, and biological purification of the aquifer.

Geological, hydrogeological, and hydrogeochemical investigations are the most important sources of data for knowing such aquifer characteristics. Under this section more emphasis is given to the hydrogeological investigation, particularly well data and springs, in order to define the hydrodynamic/ or hydraulic parameters of aquifers in the study area.

Based on the hydrogeological investigation as well as the existing well data, the main aquifers identified in the study area are sandstone, fractured and weathered basaltic lava flow, and the alluvial deposits along streams. Fractured volcanic rocks, mainly basalts and ignimbrites, as well as Quaternary sediments are also the main aquifers in the country, Tamiru Alemayehu (1993). Each of the aquifer type in the study area will be treated separately as shown below:

Sandstone

The Mesozoic sandstone in Ambo area is an aquifer for the popular mineral water in the country- Ambo mineral water. It forms a confined aquifer, the upper confining layer being volcanic rocks, Herick *et al.* (1983). But according to geological well logging for one of the abandoned well in Sankale area, the confining layer is more likely the Mudstone-Shale unit.

Much subsurface information for the sandstone comes from wells drilled in Sankale area at Ambo mineral water bottling factory for the exploitation of the mineral water.

There are three wells drilled to the sandstone before two decades among which only one is functional currently. Geological well logging exists only for the earlier abandoned (due to the falling down of the pump in the well) well.

The other well is abandoned very recently. The three wells have a depth of 157m, 112m and 117m, and water was encountered below the surface for the first two wells at 110m, and 98m, MCE (1999).

Herick *et al* (1983) carried out a pumping test on the two wells (whose geological logging is absent); and analyzed the pumping test data by using Jacob's semi logarithmic method. Accordingly, he determined a transmissivity and specific capacity value of $76.5\text{m}^2/\text{day}$ and $2.34\text{m}^2/\text{hour}$ respectively for the sandstone. But he mentioned that these values are only estimation as the wells are only a partially penetrating and the pumping test was carried out only for short time in order not to interrupt the factory's mineral water production. This is also the limitation to determine the hydraulic conductivity.

It has not been possible to reanalyze the pumping test data for the two wells due to the absence of time draw down/or time-residual draw down (for the recovery test) data.

As has been observed from the geological well logging of the abandoned well, the upper part of the sandstone layer is encountered at a depth of 123.44m above which is an intercalation of mudstone and shale along with some calcareous clay having a total thickness of 86.84m. Clay

and stream detritus, travertine along with basalt fragments, and soil on top part constitute the remaining 36.6m to the surface.

Ambo mineral water bottling factory has also got drilled one new well into the sandstone near the bottling factory in the late of the year 2000. But it was difficult to access the data.

Basaltic lava flow

There are many springs that emerge from basaltic lava flow in the study area. This shows the basaltic lava flow is an aquifer at least for the shallow groundwater /or it forms unconfined aquifer. Besides this, there are some shallow and deep wells that are drilled to this aquifer tapping groundwater. According to the data from these wells, the basaltic lava flow is found to form a multi layer aquifers: the shallow/ or unconfined aquifer, and the deep /or confined aquifer. Pyroclastic deposits of ash size and clay form the upper confining layer. Some of the wells to mention are: two wells in Awaro area (to the east of Ambo town) – one shallow well and the other is deep test well, and three deep wells at Ambo Agricultural Research Institute (AARI). Hence, in order to have an insight into the hydrodynamic behavior of the aquifers, the data from the wells at AARI and the deep test well in Awaro area are used.

The three wells at AARI were drilled in 1975 with a total depth of 150m (well-1), 131m (well-2) and 105.55m (well-3); except well No 3, the other two are abandoned. For well No. 1, only geological well logging is present. Well No. 2 has both geological well logging and pumping test data like well No. 3. The following table gives some of the data for the three wells at AARI.

	Well No. 1	Well No.2	Well No.3
Depth (m)	150	131	105.55
Static W. level (m)	-	32.89	42.31
Dynamic W.level (m)	-	83.80	42.55
Draw down (m)	-	51	0.24
Geological logging	-0-4m: Basalt -40-100m: Volcanic ash -100-150m: Sandstone	-0-5m: Weathered basalt and travertine -5-20m: Basalt -20-35: Tuff and pumice -35-93m: Tuff at its upper part then clay - 93-131: Basalt	-0-2m: Soil with basalt fragment -2-55m: Basalt with some gravel, tuff mud and small clay proportions -55-103.5m: dominantly clay with small proportions of peat and gravel - 103.5 – 105.55m: Basalt

Table 4-1 Some well data for AARI wells

As can be observed from the geological well logging of well No. 2 and 3, the layers between 35-93m and 55–103.5m are the possible confining layers respectively for the underlying formations. Besides this, the layers above the mentioned intervals should have at least some water though this has not been mentioned in the well report

The groundwater from well No. 3 is thermal water having a temperature of 38 °C, and also it is highly mineralized as observed from its TDS. Besides, the water is similar with that of Ambo thermal springs. Hence, such physicochemical parameters of the water may put a doubt on whether the aquifer for the water is the basaltic lava flow or another underlying layer (sandstone?). The geological well logging of the abandoned well No. 1 also shows the presence of sandstone below a depth of 100m from the surface. For well No.2 the presence of crack/or big fracture between depths of 126- 129m has been reported. In spite of such a doubt, the analysis of the pumping test data for both well No.2 and 3 has been carried out employing Theis and Jacob

method using “Aquitest” software. Accordingly, the following values of the hydraulic parameters are obtained.

	Well No.2		Well No. 3	
	Jacob	Theis	Jacob	Theis
Transmissivity (m ² /day)	0.342	0.244	792	710
Hydraulic conductivity (m/sec.)	7.9×10^{-7}	5.65×10^{-7}	4.5×10^{-3}	(4×10^{-3})
Specific capacity (m ² /sec.)	3.83×10^{-5}			

The deep test well in Awaro area was drilled in 1999 in view of locating well field for Ambo town water supply. The well has a complete data as summarized below:

Depth	Static water level	Dynamic water level	Depth at which water is encountered	Yield
96m	33.70m	41.17m	43 and 77m below surface	10 l/s
Geological Well logging	0- 30m: Clay and ash size dominated pyroclastic deposits 30- 68m: Fractured and weathered basalt along with some scoraceous basalt with tuff intercalation. 68- 96m: Fresh basalt (fractured?).			

According to these well data, two confined aquifers both of which are comprised by fractured and weathered basalt, and with some scoraceous basalt for the lower aquifer exist in the area. The aquifers are encountered at 43- 67m and 77- 86 m below the surface having a thickness of 24 and 9 meters respectively. The first confining layer is mainly comprised by clay and volcanic ash dominated unwelded tuff, and the second (middle) confining layer is comprised by massive and fresh basalt.

Analysis of the pumping test data using **Jacob’s** and **Theis** method gave the following values of hydraulic parameters:

	<i>Transmissivity (m²/day)</i>	<i>Hydraulic conductivity (m/s)</i>
Theis method	99.5	3.84 x 10 ⁻⁵ m/s
Jacob method	97.92	3.78 x 10 ⁻⁵ m/s

Actually, the values of these parameters are an integrated result for the two confined aquifers as it has not been possible to treat the two aquifers separately. Hence, a hydraulic conductivity value of 3.7 x 10⁻⁵ m/s to 3.9 x 10⁻⁵ m/s can be considered for the aquifers of the basaltic lava flow in Ambo area.

Alluvial deposits along either current or ancient streams usually have a good groundwater potential. In the study area, there is one well drilled at immediate adjacent of the stream channel tapping good yield of groundwater from alluvial sediments. This well is currently supplying potable water for Meti village, and it was drilled in 1998 adjacent to the Meti stream. The following table shows some of the well data:

Depth (m)	Static water level (m)	Dynamic water level (m)	Lithological logging
106m	1.51m	16.6m	-0-6m: loose sediments (soil, gravel and boulders) -16-58m: basalt (only slightly weathered and fractured) -58- 76m: alluvial deposits (sand, gravel, pebble with some highly weathered pyroclastic deposits) -76- 82m: slightly weathered and fractured basalt -82- 106m: gravels and pebbles

Table 4-2 Some well data for Meti well

Analysis of the pumping test data by using Theis and Jacob with “aquitest” soft ware gave a transmissivity value of 27.65 m²/day and 20.0 m²/day respectively. Hence, based on the values of the transmissivity from various methods, an average value of 23.9m²/day can be considered for the alluvial deposits.

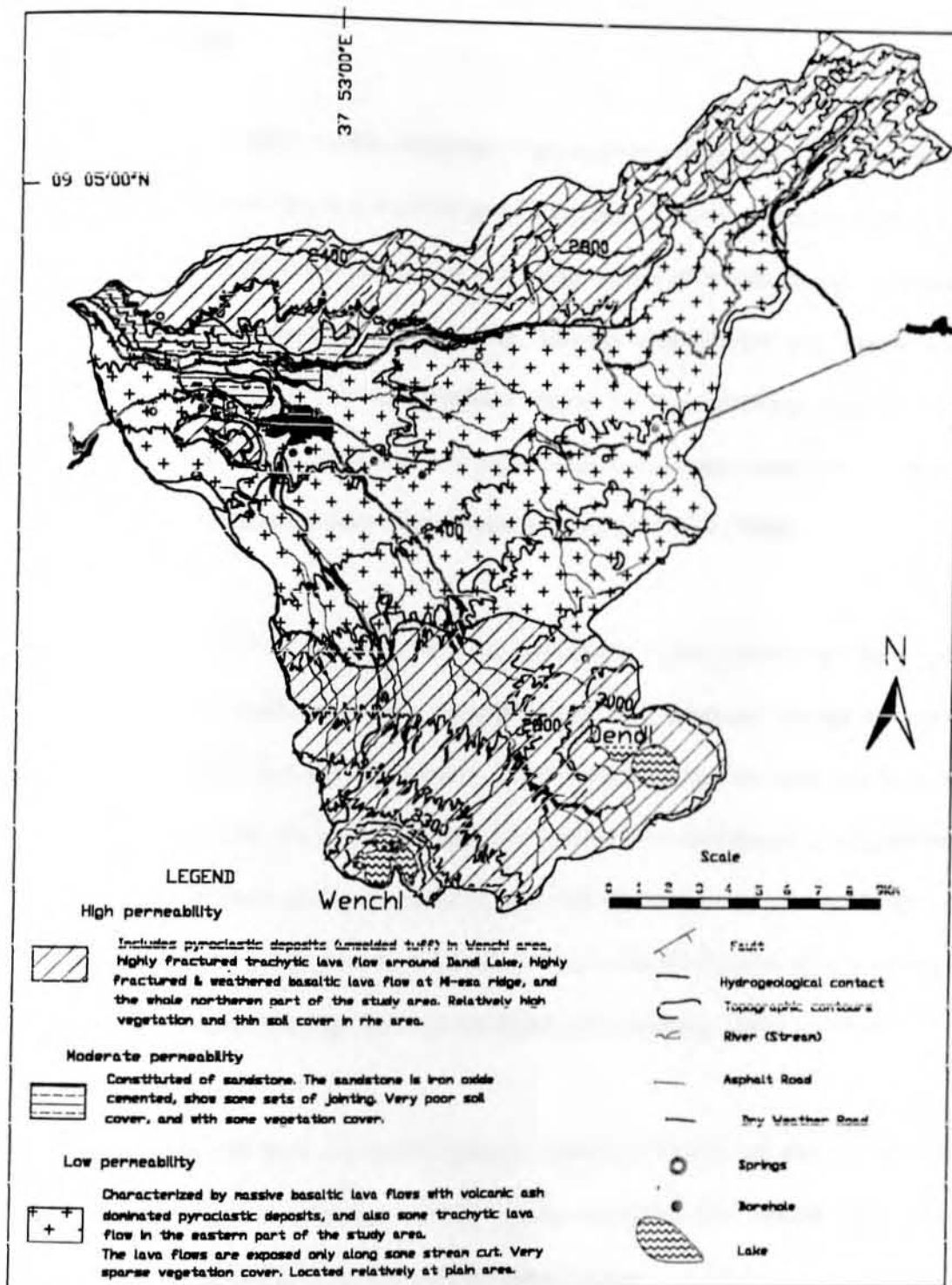


Fig.4.1 Hydrogeological map of Ambo area ,

4.3 Springs

A spring is a natural surface discharge of groundwater large enough to flow in a small rivulet; discharge smaller than this is called surface seepage. A number of parameters may be employed to classify springs. Some of them are temperature (thermal or cold spring), chemical composition, rate of flow and seasonal variation (e.g. Meinzer classification and intermittent or perennial spring), and geological or topographical reason for their discharge (e.g. fault spring, contact spring, depression spring etc). Due to such complex and many parameters for their classification, there is no really satisfactory classification for springs, IWES (1986).

Genetically, in the study area, there are both thermal (non gravity) and cold (gravity) springs. Taking into consideration their mode of origin, the dominant springs are contact and fault controlled types. Actually, the majority of the thermal springs are emerging from weak zones/ or faults. Hence, they are of fault springs; where as the cold springs are mostly contact springs. For the latter case there are many conditions under which it can occur: permeable layer over laying an impermeable layer e.g. presence of paleosol with in fractured and/or weathered sequences of lava flow, or the same lithology but different degree of weathering and/or fracturing.

In addition to the fault and contact springs, depression springs are also unavoidable in the study area, especially, in low/or plain area e.g.: springs supplying Meti stream. Infact, this is not a point source but it covers some small area like marsh/swamp.

4.3.1 Thermal Springs

The lower limit temperature of the thermal springs varies according to different authors. Hence, there is no widely accepted standard of water temperature for definition of thermal, some researchers consider spring as thermal if the water is appreciably warmer by 5 °C to 10 °C than the local shallow groundwater, Trainer (1981). But Kondo (1967) used 25 °C as a boundary between cold and thermal springs. Accordingly, he classified the thermal springs of Ethiopia into four as follows:

- Very hot springs: $T > 90\text{ }^{\circ}\text{C}$
- Hot spring: $T\ 42\text{-}90\text{ }^{\circ}\text{C}$
- Warm spring: $T\ 37\text{--}42\text{ }^{\circ}\text{C}$
- Tepid spring: $T\ 25\text{--}37\text{ }^{\circ}\text{C}$

Thermal springs can be found either in the area of volcanic activity centers or at considerable distance from such centers. In the case of the former, the heat is obviously derived from the magmatic body; where as the latter case is attributed to geothermal gradient. The earth's crust has a geothermal gradient of 2.5 °C/100m on average in stable continental area, Todd (1980), but in active continental areas such as in Ethiopian Rift, a geothermal gradient of 1 °C/6m has been calculated, Tamiru Alemayehu and Vernier (1997). Hence, meteoric water infiltrating to the ground attains high temperature before it boils/or rises up, because with increasing depth, pressure increases rising the boiling temperature of water (table 4-3). Once the condition of certain pressure and temperature is reached in such away that the infiltrated water boils, it rises

up to the surface through the available weak zones such as faults. Such water is surely hotter than surface water even if it cannot reach on the surface with its original temperature that may be due to mixing with cold water on its way to the surface. For such deep circulation of water in subsurface, there should be a conduit such as faults.

Table 4-3. Boiling temperature of water at various pressures (adapted from Emmons et al., 1953).

Water Temperature (°c)	Pressure, atmospheres	Depth in water column where this pressure exist (m)
100	1	0
120	2	10
180	10	90
225	25	240

Many thermal springs and the hottest ones are found in volcanic areas suggesting a connection between certain thermal springs and cooling igneous rocks.

The thermal springs in Ambo area show peculiar distribution pattern; all are concentrated along nearly east-west oriented fault. These springs have been used for thermal therapy and bathing since long time under the supervision of Ambo Ethiopian Hotel.

Although the majority of thermal springs in the study area are concentrated in Ambo town, their lateral extent out side the town can be inferred from some wells drilled (e.g. in AARI and Ambo mineral water bottling factory) out side the town, and the travertine deposit.

Ambo thermal springs are among the thermal springs of Ethiopia that are found outside the rift zone, particularly on Ethiopian central plateau. As has been mentioned under the “Local geology part”, the area is located with in the Yerer-Tullu Wellel- Volcano-Tectonic Lineament that is

comprised by an east-west oriented central type volcanoes. Dandi and Wanchi, being located within the study area, are part of these central volcanoes. Hence, the presence of the thermal springs in the area may be attributed to this volcanic activity. In addition to these, Kondo (1967) pointed out the association of thermal springs of Ethiopia with volcanism and crustal movement, particularly the acidic volcanism of alkaline type. The geothermal gradient could also have contribution for the source of heat for the thermal springs.

4.3.2 Gravity /Cold springs

Many cold springs have been observed in the study area. The majority of them are issuing from volcanic lava flows. The main geological and/ or hydrogeological conditions for their outflow are the presence of less permeable/or impermeable layer under the more permeable layer. The springs have been observed during the supposed low discharge time (March). Qualitative comparison of the discharge of the springs show that three springs with relatively high discharge (Dule, Wachani and Buqisa) are located in areas where they can get high recharge area. The following are some of the important gravity/or cold springs that need to be discussed for the study area. The representative models for the springs are also shown in figure 4.2.

Buqisa spring

This spring is located near to the main asphalt road; and it has been developed supplying the surrounding people with potable water. The spring has relatively high discharge; hence, it is used for irrigating (growing) vegetables such as onion, potatoes and tomatoes. The spring is emerging from highly fractured basalt; and its underlying impermeable layer is ash dominated unwelded tuff.

Wachani spring

This spring is located at NNW of Meti village near the Dabis river. Like the Buqisa spring it has high discharge serving a lot of settlements; besides this it is also used to grow vegetables. The spring is emerging from fractured lava flow. Being located near the river valley side, it has been tried to get the outcrop of the impermeable layer in the valley for the out flow of the spring. But other than basalt nothing has been observed. Hence, the same basaltic lava flow but with less degree fracturing could be the reason for the outflow of the spring.

Ela spring

This spring is located at the southeastern part of the area, near Golja. It is emerging from highly fractured trachytic lava flow at the foothill of the Dandi high land. The underlying rock that causes the outflow of the spring is rock of the same type with the aquifer but different degree of fracturing. In the case of Ela spring, a slight difference in the permeability of the rock is enough for the outflow of the spring as it is observed from the morphology of the area.

Dule spring

This spring is found at the northern central part of the study are, at the northern side of the Dabis river. The spring is emerging from fractured basaltic lava flow. The barrier for the outflow of the spring is the mud- gypsum- shale unit.

Shamme spring

This spring has very small discharge; actually the spring has been visited during the supposed low discharge time (March). It is located on the northern side of the sandstone quarry between Ambo town and the mineral water bottling factory. The aquifer for the spring is sandstone; and

the underlying impermeable layer is the mud-gypsum- shale unit. The very small discharge of the spring may be attributed to the limited areal extent of the recharge area; because the sandstone outcrop from which it is emerging has a small lateral extent.



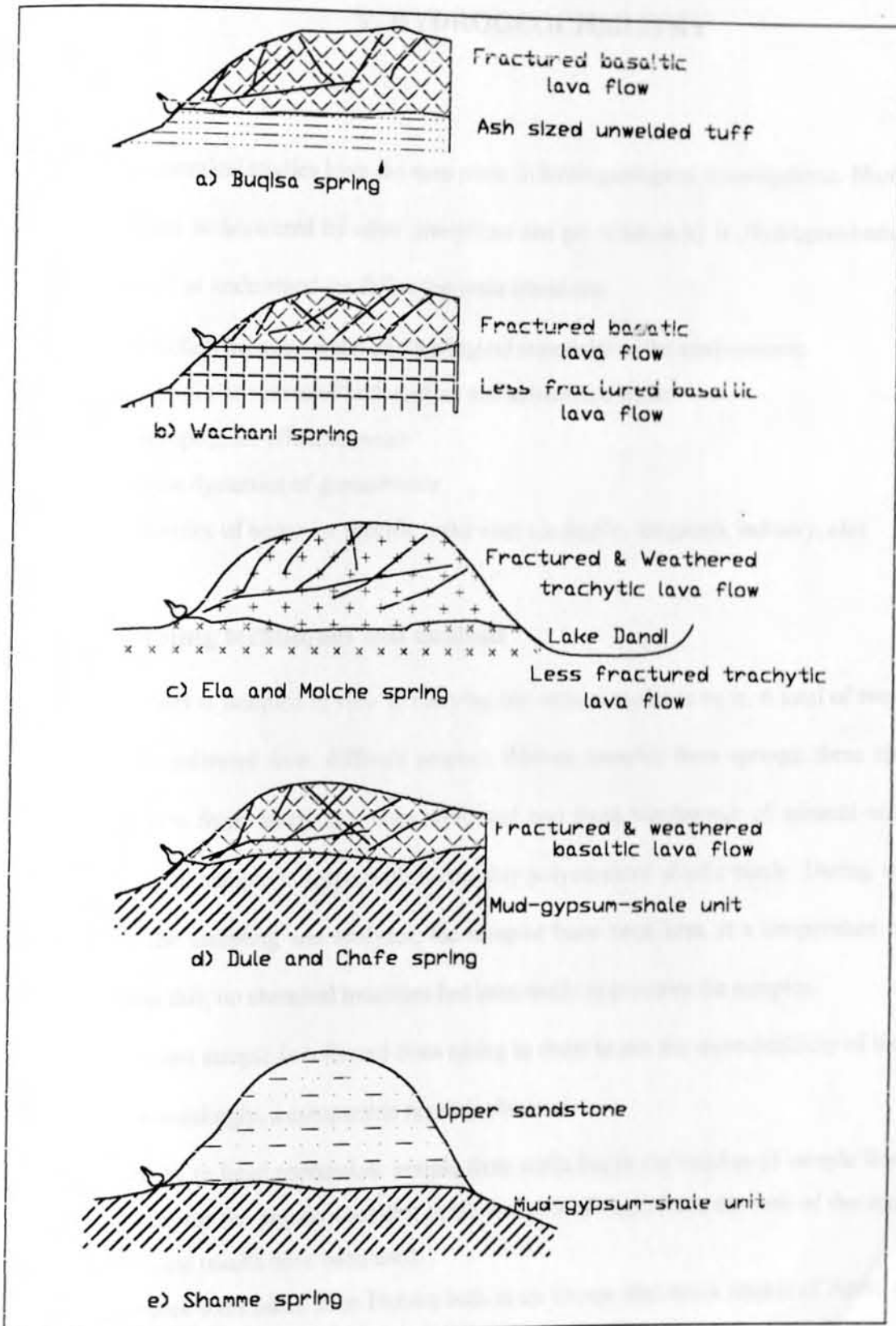


Fig.4.2 Schematic diagram of springs

V. HYDROGEOCHEMISTRY

Hydrogeochemical studies have the core place in hydrogeological investigations. Many questions that may not be answered by other disciplines can get solution by it. Hydrogeochemistry enables us to know / or understand the following main situations:

- Interaction between water and geological materials/ or the environment
- The origin/or source of both surface and subsurface water
- Anthropogenic effect on water
- System dynamics of groundwater
- Suitability of water for specific water uses (domestic, irrigation, industry, etc)

5.1 Sampling techniques and analysis

Natural water is sampled in view of carrying out various analyses on it. A total of twenty samples have been collected from different sources: thirteen samples from springs, three samples from streams, two from lakes, one from well, and one from wastewater of mineral water bottling factory. Each sample is taken with a one-liter polyethylene plastic bottle. During the time gap between the sampling and analyses, the samples have been kept at a temperature below 4 °C. Other than this, no chemical treatment has been made to preserve the samples.

One duplicate sample is collected from spring in order to see the reproducibility of the laboratory results. Accordingly, a comparable result is obtained.

The inability to have appropriate sample from wells limits the number of sample from it only to one. Hence, for the physicochemical result analysis of water from the well of the study area, the available past results have been used.

Two samples were taken from Huluka both at up stream and down stream of Ambo town to see the influence /or effect of the town on the water quality.



Fig.5.1 Water sampling points for chemical analysis

5.2 Organoleptic Parameters

Organoleptic parameters characterize the aesthetic values of water. They include color, odor, taste and turbidity. The existence of an objectionable situation in one of these properties of water have to be tested whether they meet some standards or not for specific water use. Except taste, other properties have been tested for the collected samples from the study area; the results are shown in table 5-1.

The presence of organic or inorganic suspended matter such as clay, silt, colloidal organic particles in water cause turbidity. Turbidity is an expression of certain light scattering and light absorbing properties of water. It has two main effects in water: cause an objectionable taste or appearance to consumers, reduces the effectiveness of disinfectants by providing protection to microorganisms, WHO (1984). Its guideline value, according to WHO (1984) is 5 NTU. High value of turbidity is observed for Huluka stream as it has been raining during the sampling time. The spring and lake samples do have low turbidity.

Odor in water is usually caused by the presence of organic matter in it. All the samples collected for the investigation are tested to be odorless.

5.3 Physicochemical Parameters

The physicochemical parameters analyzed for the water samples can be categorized into two: those that have been measured both at field and laboratory, and those that have been analyzed only in laboratory.

Since the measurement of pH, Redox-Potential (Eh), Temperature (T), Total Dissolved Solids (TDS) and Electrical Conductivity (EC) are made both at field and laboratory, both results are shown in table 5-1.

5.3.1 pH

This represents the negative common logarithm of hydrogen ion concentration /or activity; $\text{pH} = -\log [\text{H}^+]$. Based on pH value, a solution can be acidic ($\text{pH} < 7$), basic ($\text{pH} > 7$), or neutral ($\text{pH} = 7$); the extreme value is being at $\text{pH} = 0$ (extremely acidic) and $\text{pH} = 14$ (extremely alkaline). The pH value of natural water has a profound effect on the mobility of many elements. Only few ions such as Na^+ , K^+ , NO_3^- and Cl^- remain in solution through out the entire range of pH values found in normal groundwater, Fifield *et al.* (1996). In natural water, pH is mostly controlled by carbon dioxide- bicarbonate-carbonate equilibrium of the system.

The pH value of the samples in the study area ranges from 6.2 to 8.2. The lower value is measured for the thermal water, and the higher value is for samples from some cold springs and in Wanchi Lake. In order to compare the results among the sample, pH is plotted against the sample source as shown in fig. 5.2.

5.3.2 Temperature

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

Based on the water temperature, the collected samples can be categorized into two groups: the cold water having temperature values below 25 °C, and the thermal water above 25 °C. The samples taken from spring (Ambo thermal spring) and well at AARI have a temperature of 35 °C and 38 °C respectively. Actually, these values should be considered to be the lowest temperature for the water as it is measured on the surface where they are cooled below the original temperature at the source.

Table S-1 Physicochemical analysis of water

Local name	Chemical	Sample code	Source	Location (UTM)	Altitude (meters)	Date of collection	Date of analysis	pH	EC (µmhos/cm)	TDS (mg/l)	Turbidity (NTU)	Colour (Pt-Co)	Other	Ca ²⁺ (mg/l)	Mg ²⁺ (mg/l)	Total Hardness (CaCO ₃) (mg/l)	Total Alkalinity (CaCO ₃) (mg/l)	Total Acidity (CaCO ₃) (mg/l)	Total Chloride (mg/l)	Cations (mg/l)	OH ⁻	Cl ⁻	NO ₃ ⁻	NO ₂ ⁻	HCO ₃ ⁻	CO ₃ ²⁻	CO ₃ ²⁻	SO ₄ ²⁻	PO ₄ ³⁻	F ⁻				
		07	Spring		2200	27/02/01	27/02/01	7.4	17.5	17.5	17.5	17.5	37	0.024	0.11	0.11	0.22	0.05	0.05	0.16														
		02	Spring		2800	27/02/01	27/02/01	8.1	18.2	18.2	18.2	18.2	102	0.3338	0.29	0.29	0.01	0.01	0.12															
		23	Spring		2110	27/02/01	27/02/01	6.44	18.2	18.2	18.2	18.2	37	0.3338	0.29	0.29	0.01	0.01	0.12															
		04	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		05	Spring		2070	27/02/01	27/02/01	7.68	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		06	Spring		1854	27/02/01	27/02/01	7.44	16.1	16.1	16.1	16.1	13	0.27	0.27	0.27	0.06	0.06	0.01	0.01	0.07													
		08	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		09	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		10	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		11	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		12	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		13	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		14	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		15	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		16	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		17	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		18	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		19	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		20	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		21	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		22	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		23	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		24	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		25	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		26	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		27	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		28	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		29	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		30	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		31	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		32	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		33	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		34	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		35	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		36	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		37	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		38	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		39	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		40	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		41	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		42	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		43	Spring		2070	27/02/01	27/02/01	7.81	18.1	18.1	18.1	18.1	1700	0.27	0.478	0.478	0.05	0.05	0.02	0.02	0.11													
		44	Spring		2070	27/02/01	27/02/01	7.81	18.1																									

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

These are two interrelated parameters that indicate the state of water salinity. Based on the TDS value, water can be grouped into fresh (0-1000ppm), brackish (1000- 10,000ppm), salty (10^4 - 10^5 ppm), and brine ($>10^5$ ppm), Davis (1966).

All water samples collected from the study area have a TDS value of less than 1000ppm except the wastewater taken from Ambo mineral water bottling factory that has 2200ppm. Hence, they are all fresh water; where as the latter is a brackish water. But even if the value is less than 1000ppm, some samples show high TDS value such as the thermal water (Ambo thermal spring and AARI well), spring samples whose bottom barrier is mud-gypsum-shale unit (Kilnto, Chafe and Dule springs), and the spring that is thought to have contact with sewage disposal/or latrine (Hotel spring). The values are shown in fig.5.2.

5.3.4 Major cations and anions

The major cations and anions that have been analyzed for the collected samples are calcium, magnesium, bicarbonate, chloride and sulphate. Sodium content of the samples have been calculated based on the ionic balance of the analyzed cations and anions; the same is true for potassium.

Cations

In the majority of the samples the dominant cation is calcium. The concentration varies from 11.2mg/L up to 220mg/L. The higher values of calcium (>100 mg/L) is observed for those springs

that come in contact with mudstone-gypsum-shale unit, such as Dule, Chafe and Kilinto, and also for the sample taken from Ambo thermal spring.

For the mentioned springs, high calcium is obviously derived from the underlying lithology, mainly gypsum. The value obtained for Dule spring is exceptionally high amounting to 220mg/L. Being the lithology from which the springs emerge is a volcanic rock, particularly basaltic lava flow, calcium can also be derived from the weathering of the plagioclase feldspar and pyroxene mineral groups that are the rock forming minerals of basalt.

Another major cation is magnesium. Its value varies from 2.4mg/L (for Wanchi Lake) to 62.4mg/L (for sample taken from the well at AARI). Actually, the wastewater from mineral water bottling factory has 78.72mg/L of Mg^{2+} . Magnesium in the area is possibly derived from the weathering of the ferromagnesian minerals such as olivine, biotite, hornblende and augite. The relatively higher value of magnesium (>30mg/L) for the thermal water and for those springs underlain by mud-gypsum- shale unit may indicate also the contribution from the sedimentary rocks such as dolomite if any. Unlike Wanchi Lake that has the lowest value of magnesium among the samples, Lake Dandi has relatively higher value (38mg/L). This may be attributed to the lithological difference in the surrounding of the two lakes, which is a trachytic lava flow for Dandi, and unwelded tuff (pyroclastic deposits) for Lake Wanchi.

The value for sodium varies from 5.5mg/L (for Kilinto spring) up to about 275mg/L for the thermal water from the AARI well. Sodium can be derived either from the natural processes such as weathering of the plagioclase feldspars, particularly albite, or from anthropogenic effect such as discharge of effluents (domestic, industrial, or commercial sources). Higher values of Sodium

(>100mg/L) is observed for the samples of thermal water, for Huluka stream at down stream of Ambo town, and for Hotel spring in Ambo town along the Huluka stream. The high Na^+ values for the latter two sources are attributed to the discharge of effluents (domestic and commercial sources). But for the thermal water, the high sodium concentration may be derived from the dissolution of feldspars, and by cation exchange. The extremely high sodium content (336.8mg/L) in wastewater from mineral water bottling factory is explained by the fact that the factory uses sodium chloride for processing the mineral water.

Anions

The predominant major anion in all the analyzed samples, except one, is bicarbonate. It varies from 120mg/L (for Lake Wanchi) to 1281mg/L for AARI well. Ambo thermal spring has also more or less similar value to the well. The high HCO_3^- content of the thermal water in the area is not a surprise as they are the source of travertine deposit in the area. Most bicarbonate ions in groundwater are derived from the carbondioxide from the atmosphere, carbondioxide in the soil, and the solution of the carbonate rocks, Davis (1966). The high bicarbonate content in the thermal water of Ambo area can also be realized from the carbonate precipitation in the distribution systems and surface casing as well as the rising main of the AARI well.

Sulphate in water is generally derived from weathering of rocks, recycling from atmosphere, or from volcanic exhalations. In the study area, the sulphate content in water is highly attributed to the first source. This can be verified by high sulphate content of the samples taken from Dule spring (650mg/L) that is derived from gypsum found in the area.

The high value of chloride concentration is observed for Hotel spring, Huluka stream at down stream of Ambo town, and for the wastewater from the mineral water bottling factory. As other samples in the area do not show such high chloride content (they show very low value), the source is obviously attributed to the anthropogenic effect. As mentioned earlier, the mineral water bottling factory uses sodium chloride; hence, chloride is derived from it for the wastewater. But for the Hotel spring and Huluka stream, chloride is derived from effluents of domestic and commercial sources.

The absence of chloride in the sample from AARI well is questionable. Normally, for such deep source of thermal water some chloride content is expected. But this is not the case for the water from the well; on the other hand, 24mg/L Cl^- is obtained for Ambo thermal spring.

5.3.5 Minor ions

All the ions other than those mentioned under the “major ions” obtained from the results of the chemical analyses of the water samples are discussed in this category.

Both surface- and ground- water in the area show low nitrate concentration. The majority of the samples have less than 10mg/L nitrate as NO_3^- . Three samples from spring (Kilinto, Sankale and Dule) show relatively higher values; but still they have less than 35mg/L of NO_3^- . The exceptionally high value of nitrate (157.52mg/L) is observed for Hotel spring in Ambo town. The Maximum Permissible Contaminant Level (MPCL) for nitrate according to WHO (1984) drinking water quality standard is 50mg/L. Such high NO_3^- content in water is usually derived

from anthropogenic sources: utilization of nitrogen-bearing fertilizers and effluents from domestic sources mainly latrines/or septic tanks.

For the Hotel spring in Ambo town, both chloride and sodium are also very high. These along with the personal observation in the area will enable us to suggest the connection of the spring with the effluents from the latrine in the surrounding.

The relatively higher NO_3^- values for the three springs mentioned above is attributed to the agricultural practices. All the springs are located at a downstream of extensively cultivated farmland. In this case both the synthetic fertilizers and the manures should have their own contribution as peoples use both in upgrading the soil fertility of their farmland in the area. The concentration of NO_2^- is very low ($<0.03\text{mg/L}$) in the majority of the samples. This can be explained by either scarcity from the source or its rapid oxidation to NO_3^- . Slightly higher value of NH_4^+ (2.4mg/L) is observed for Huluka stream at down stream of the town. But surprisingly NO_3^- is nil for this sample. This can possibly be due to microbial reduction of NO_3^- to NO_2^- or nitrogen gas and subsequently released to atmosphere.

The value for chromium (Cr^{6+}) varies from nil to 0.1mg/L . The oxidation state in which chromium exists determines whether it is toxic or not. Hence, trivalent chromium (Cr^{3+}) that is slightly soluble in water is essential for metabolism in man and other animals, where as hexavalent chromium (Cr^{6+}) is considered to be toxic, and it causes human carcinogen, WHO (1984). The maximum Cr^{6+} value (0.1mg/L) is obtained for Huluka stream at downstream of Ambo town. Infact, some springs and also the wastewater from mineral water bottling factory have also high value of Cr^{6+} (0.01mg/L). The high Cr^{6+} content in Huluka stream at down stream

of the town is attributed to the anthropogenic effect. It is also known that high chromium content is also associated with hardness of water, WHO (1984).

Manganese is present in very low amount in most of the analyzed samples. It is less than 0.2mg/L. There is no a clear indication of anthropogenic effect for it; but the wastewater from the mineral water bottling factory has relatively higher value (0.2mg/L) like the well from AARI.

Similarly, the concentration of copper (Cu^{2+}) is very low except in Dule spring (2.76mg/L). Copper can be derived from some inorganic fertilizers and also from the weathering of some rocks.

5.3.6 Other chemical parameters

As has been observed from the results of the chemical analysis, the groundwater in the area do have a total hardness of greater than 100mg/L. Both thermal and cold water have such high value; the highest, 780mg/L, is obtained for Dule spring. Hardness is simply defined as the soap neutralizing power of water, Davis (1966); it is usually caused by bicarbonates and sulphates of calcium and magnesium. Hardness that can be removed by boiling/ or parts calcium and magnesium concentrations, which are balanced by HCO_3^- (expressed as meq/L) and can thus precipitate as carbonate is a temporary hardness. Where as, those that cannot be removed by boiling/or those that are in excess of HCO_3^- (expressed in meq/L) are a permanent hardness. According to WHO (1984), the degree of hardness of drinking water can be classified in terms of its equivalent CaCO_3 concentration as follows:

Soft	Medium hard	Hard	Very hard
0- 60mg/L	60- 120mg/L	120- 180mg/L	≥ 180mg/L

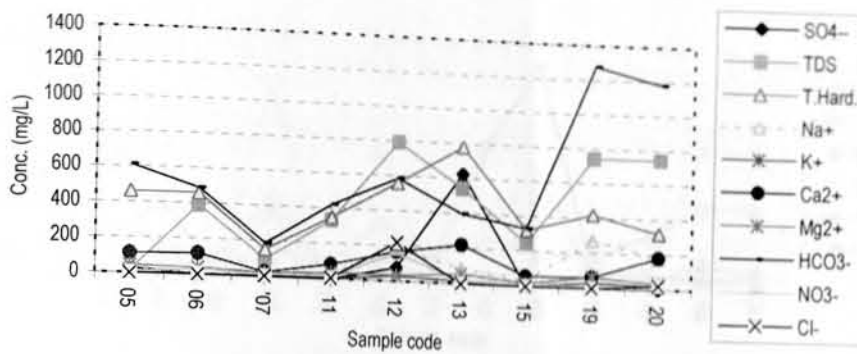
But it should be realized that there exist different ranges of values for the classification of water based on hardness. Accordingly, water that is considered to be soft by one classification criterion can be of a medium hard in another.

The groundwater of the study area varies from hard to very hard, based on the above classification. Samples taken from surface water (lakes and stream) show that Lake Wanchi is a soft water, where as, Lake Dandi is very hard water. Generally, the hardness of the surface water is not comparable with that of the groundwater as the latter shows a very high degree of hardness in the area.

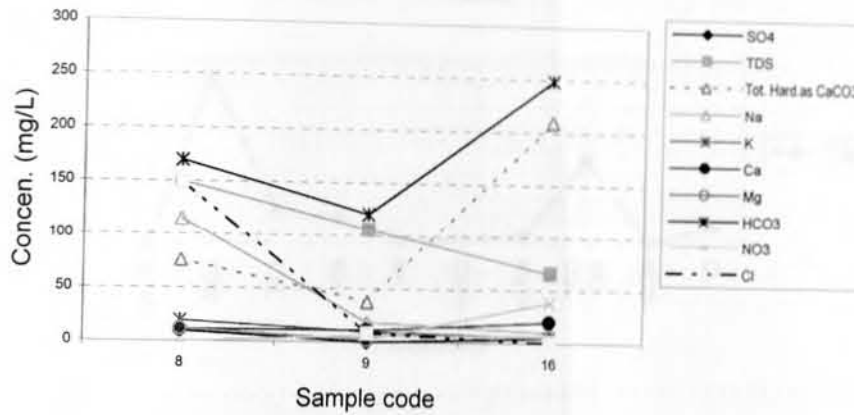
For all the collected samples, total alkalinity has also been determined. Alkalinity is caused by CO_3^- , HCO_3^- , OH^- anions. The predominance of one over the other depends on pH. Between pH 4.5 and 8.2, it is dominantly caused by HCO_3^- ; above pH 9.0, OH^- constitute a significant component; and below pH 4.5, HCO_3^- is changed to H_2CO_3 . For all the analyzed samples, the total alkalinity is similar with the bicarbonate anion indicating that it is exclusively caused by bicarbonate; hence, even one may call it as bicarbonate alkalinity.

Fig 5- 2 Various physico- chemical parameters for water samples in Ambo area

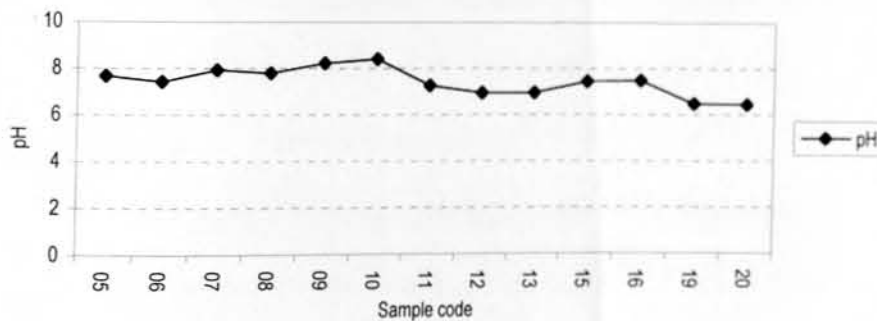
a) Some chemical parameters of Ground water in Ambo area



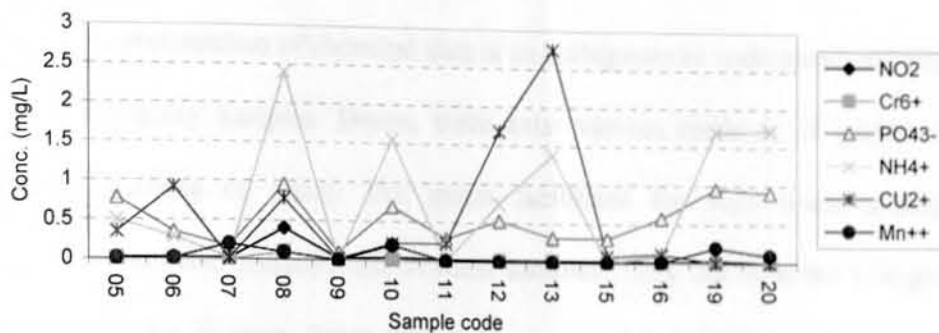
b) Some Chemical parameters for surface water in Ambo area



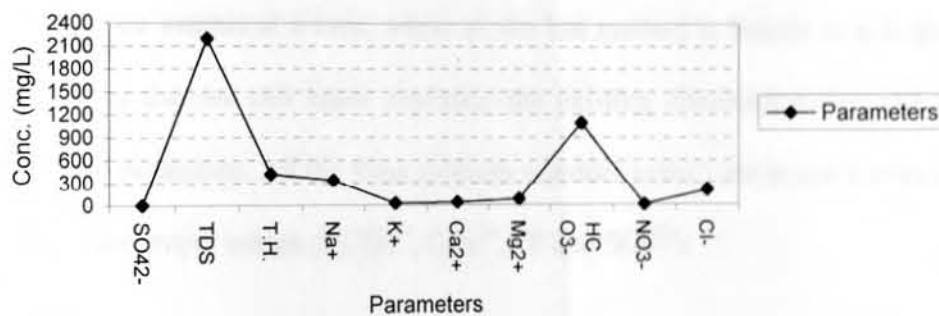
c) pH values of various water samples



d) Some minor ions in water samples of Ambo area



e) Various physico-chemical Parameters for Wastewater from mineral water bottling factory



5.4 Presentation of analytical results

The tabular presentation of chemical data is an ambiguous to understand and interpret, especially, if there are many samples. Hence, there exist various methods of graphical presentation of chemical analysis of water. The graph facilitates for easy understanding, interpretation, comparison and also classification of water samples. They can be either a single sample diagram or many samples diagram. Some of the common graphical methods of presenting hydrochemical data that will be discussed here are the Piper tri-linear diagram, the Schoeller (semilogarithmic) diagram, and the Stiff (pattern) diagram. Among these, the first two methods are used to present more than one sample at a time, where as the last method is limited to a single sample; but its advantage is that we can know explicitly the existing dominant cation and anion except for sodium and potassium. All the three methods consider mainly the major cations (Ca^{2+} , Mg^{2+} , and $\text{Na}^+ + \text{K}^+$) and major anions (HCO_3^- , CO_3^{2-} , Cl^- and SO_4^{2-}).

5.4.1 Piper tri-linear diagram

Piper tri-linear diagram involves the utilization of two separate triangles along with one central rhombus. The two triangles are used for plotting the percentage miliequivalent/litre of cations and anions independently. The cations comprise Ca^{2+} , Mg^{2+} , and $\text{Na}^+ + \text{K}^+$; and the anions HCO_3^- , Cl^- and SO_4^{2-} . Finally, the plotted two points from the two triangles are transferred to a single point on the rhomb. The rhomb has different compartments each presenting various water types; Water from the similar source is usually plotted in the same field. For water samples of the study area the results are plotted as shown in fig.5.3.

5.4.2 Stiff (Pattern) diagram

The Stiff method uses a scale for concentration of ions in meq/L along the x-axis. The ions are arranged along y-axis in such a way that the cations (Na^+ , Ca^{2+} , Mg^{2+}) to the left of the center of the plotting scale, and the anions are to the right of it. It is shown for some of the analyzed samples in fig.5.4.

5.4.3 Schoeller diagram

The Schoeller (Semilogarithmic method) arranges the concentration of cations and anions along a separate but parallel graduated vertical lines. Water of similar source (type) shows a similarly shaped curve, where as water of different types show differently shaped curves. The Schoeller diagram is plotted for samples of the study area as shown in fig.5.5.

5.4.4 Interpretation and classification of water samples

The three methods of hydrochemical graphs shown above will enable us to classify the water samples.

Based on the Piper tri-linear diagram, the following groups of water can be identified:

- The alkaline fresh water of chloride type: sample from Huluka stream
- Normal alkaline earth fresh water of bicarbonate type: Qeransa, Wachani, Chafe, Kilinto and Sankale springs as well as Dandi lake.

- The alkaline fresh water of bicarbonate type: Samples from Wanchi lake, AARI well, and the waste water from mineral water bottling factory
- The alkaline earth fresh water with higher contents of alkalis:
 - With prevailing sulphate type: Dule spring
 - With prevailing bicarbonate type: Hotel spring and Ambo thermal spring



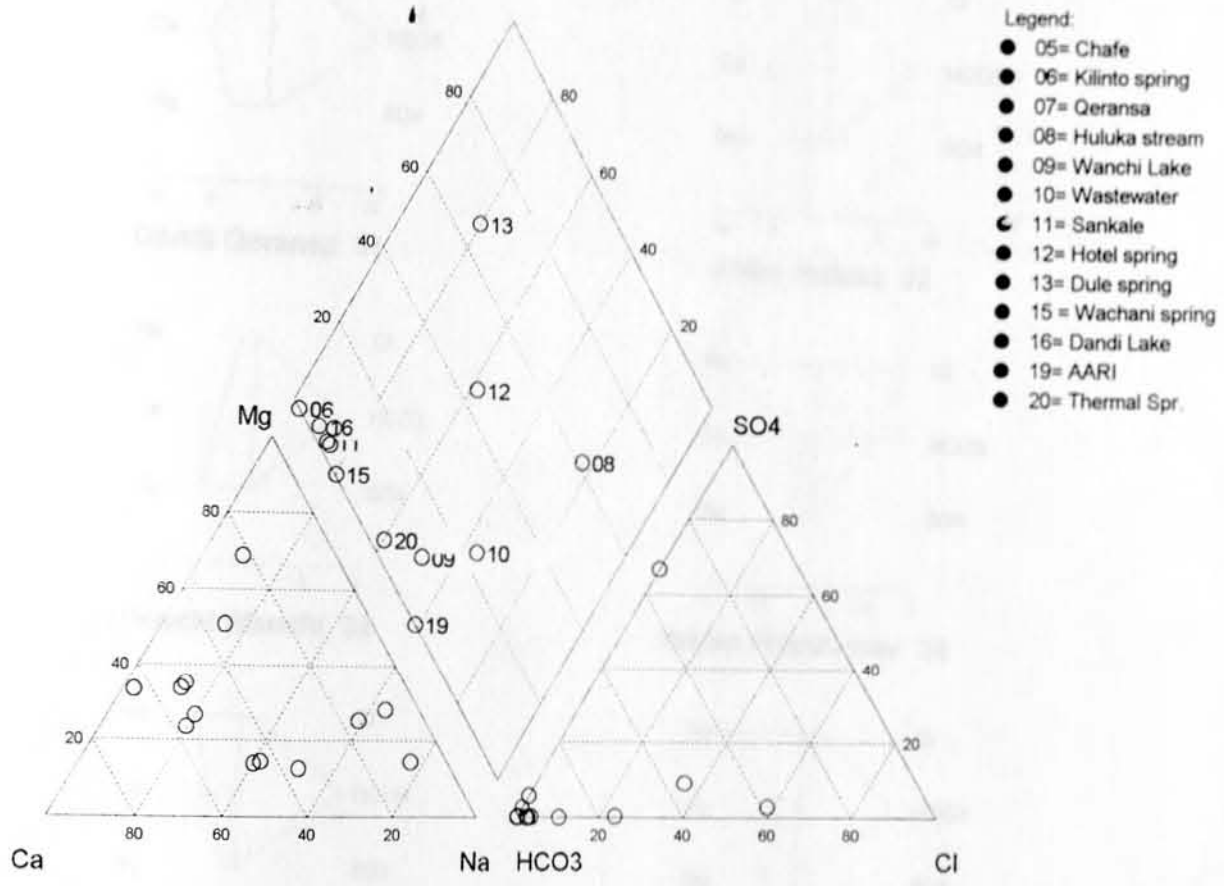
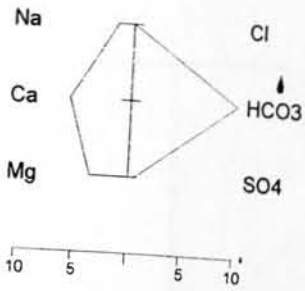


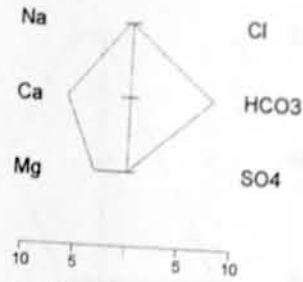
Fig. 5.3 Piper tri-linear diagram for water samples in Ambo area

Fig. 5.4 Stiff (Pattern) diagram for some water samples in Ambo area

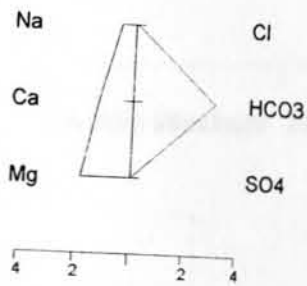
Ambo Chafe 29



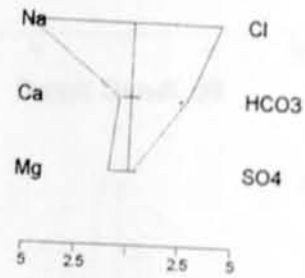
Ambo Kilinto 30



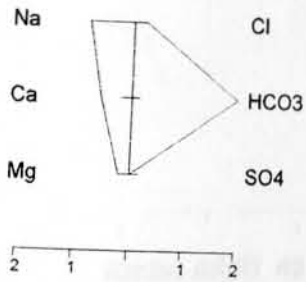
Dandi Qeransa 31



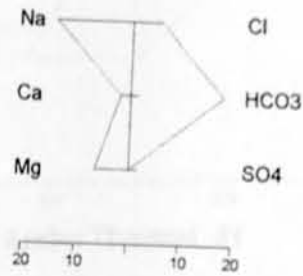
ambo Huluka 32



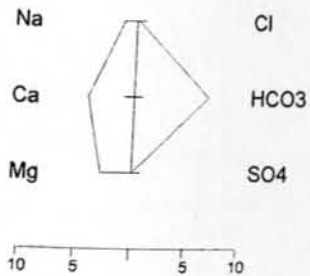
Wanchi Wanchi 33



Ambo Wastewater 34

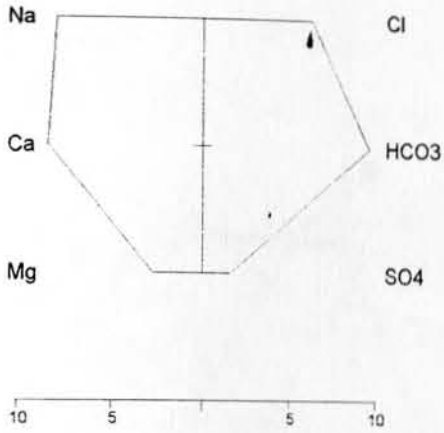


Ambo Sankale 35

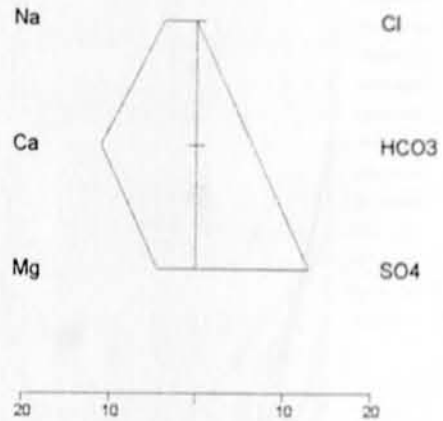


Stiff (Pattern) diagram (continued)

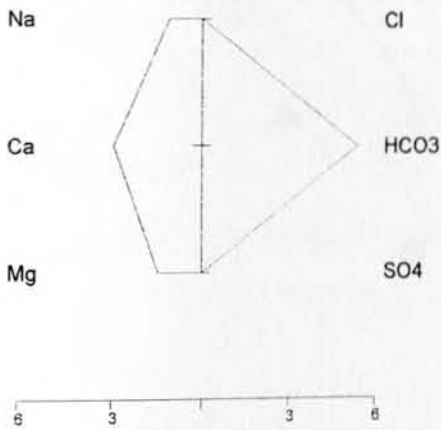
Ambo Hotel 36



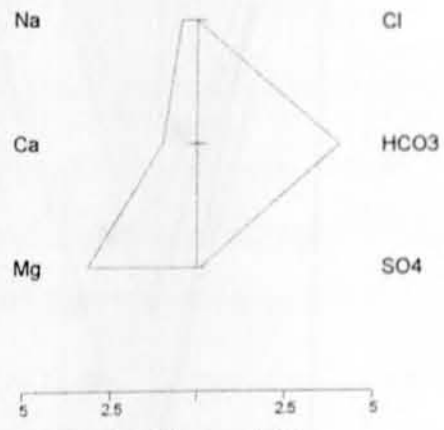
Ambo Dule 37



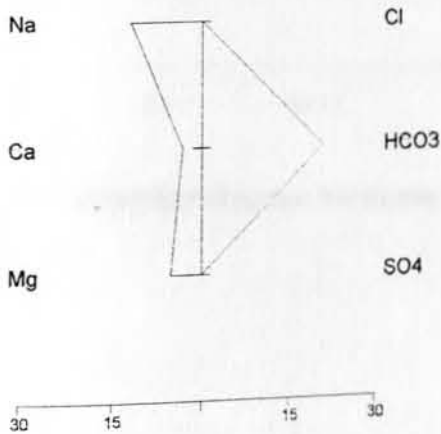
Ambo Wachani 38



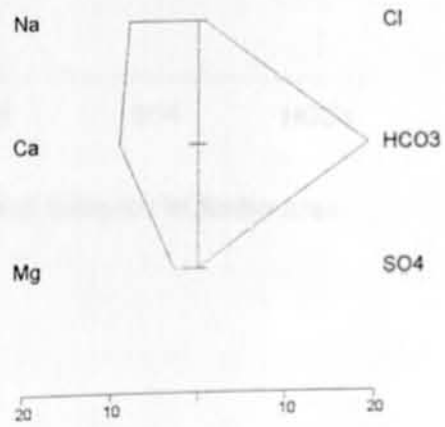
Dandi Dandi 39



Ambo AARI 40



Ambo Thermal 41



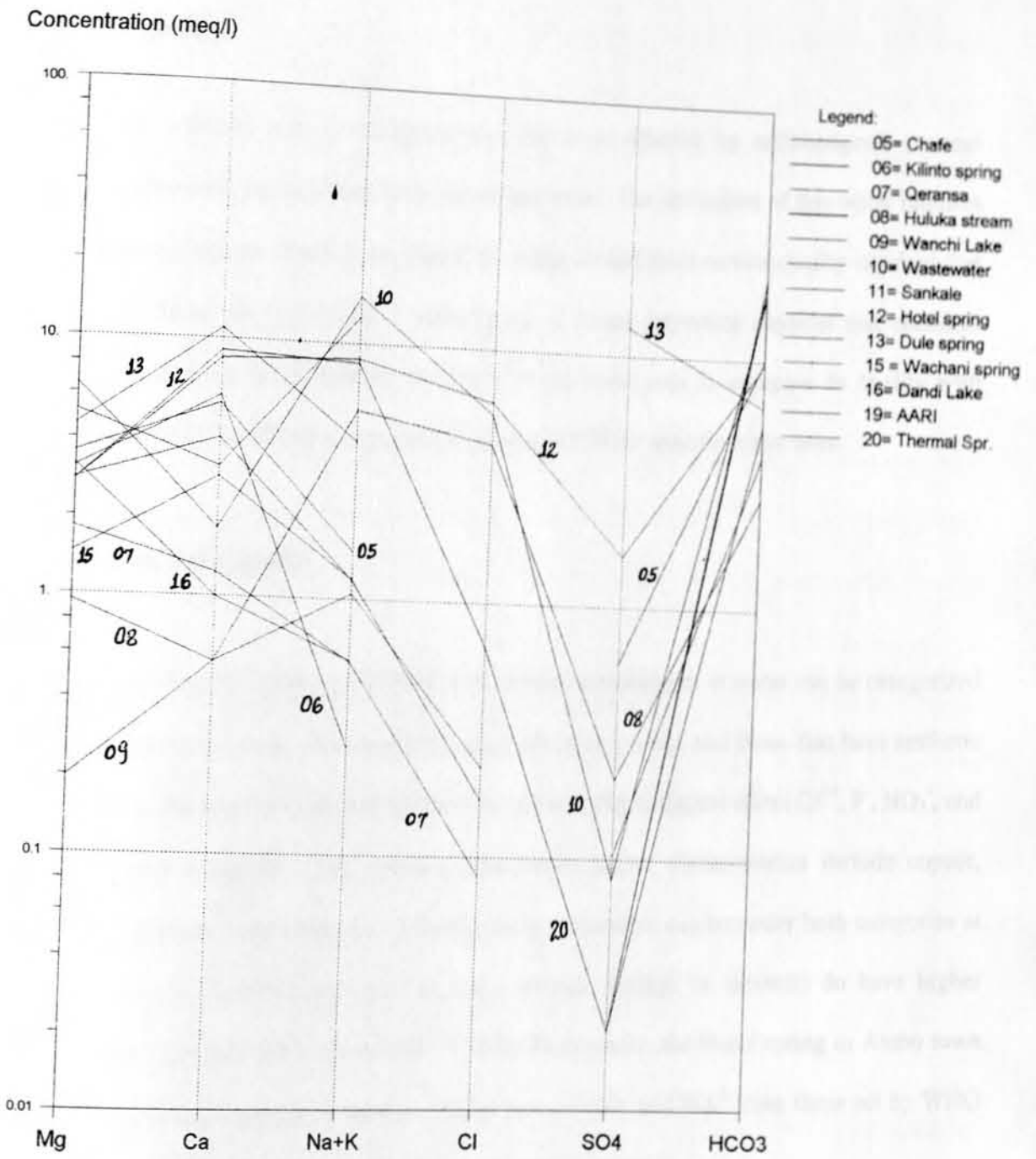


Fig. 5.5 Schoeller diagram for some water samples in Ambo area

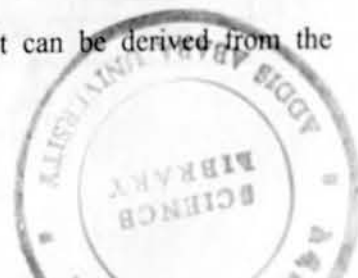
5.5 Water quality

Natural water interacts with environment, and also it is affected by anthropogenic process changing its chemical, physical and biological constituents. The utilization of this water requires an understanding of such constituents. Hence, the water should meet certain quality standard that is set mainly based on its purpose in order to use it. Some important physical and chemical parameters have been determined for the water of the study area to compare its quality with certain standards set by different organization such as WHO for specific water uses.

5.5.1 Drinking water quality

Based on water uses for drinking, chemical and physical constituents in water can be categorized into two: those that have an adverse physiological effect on a body, and those that have aesthetic characteristics. Among the chemicals that have an adverse physiological effect Cr^{6+} , F^- , NO_3^- , and NO_2^- have been analyzed. The aesthetic constituents and/or characteristics include copper, manganese, sulphate, odor, taste, etc. Actually, some parameters can be under both categories at the same time. Cr^{6+} , NO_3^- , and SO_4^{2-} in some sources (springs or streams) do have higher concentration than the MPCL set by WHO (1984). Particularly, the Hotel spring in Ambo town and the Dule spring respectively having a higher content NO_3^- and SO_4^{2-} than those set by WHO drinking water quality standard are serving a lot of people currently.

All the water samples do have less than 1000mg/L TDS, which is the guideline value recommended for drinking water by WHO, except the wastewater taken from the mineral water bottling factory. Fluoride exceeds 1mg/L only in lake Wanchi; it can be derived from the



weathering of acidic volcanic rocks. Similarly, Copper exceeds 1mg/L only in Dule and Hotel springs. The maximum contaminant level established for drinking water by the United States Environmental Protection Agency (USEPA) for fluoride and copper are 4mg/L and 1.3mg/L respectively.

5.5.2 Agricultural/irrigation water quality

Agricultural suitability of water depends on crop type, climate, soil type, and amount of irrigation water use, Davis (1966). The main parameters to be analyzed to evaluate irrigation water quality are: Boron content, Sodium hazard, and Salinity. These parameters affect plants either directly (e.g. by causing an adverse physiological effects) or indirectly (e.g. by limiting plant root nutrient or moisture uptake). Salinity is estimated based on Electrical Conductivity (EC) value, where as sodium hazard is assessed by the so-called Sodium Adsorption Ratio (SAR). SAR is calculated as follows:

$$SAR = \left\{ \frac{[Na^+]}{\sqrt{0.5 ([Ca^{2+} + Mg^{2+}])}} \right\}$$

Where the concentration of each cation is expressed in meq/L

According to Todd (1980 and references there in), the water quality evaluation for irrigation based on SAR and EC are as follows:

Water class	Excellent	Good	Fair	Poor
SAR	< 10	10- 18	18- 26	>26

Water class	Excellent	Good	Permissible	Doubtful	Unsuitable
EC (µs/cm)	<250	250- 750	750- 2000	2000- 3000	>3000

In order to evaluate water quality for irrigation from Salinity and Sodium hazard point of view for the study area, the parameters have been measured and calculated as shown in table 5-2. Accordingly, all water samples show low Sodium hazard; and they are all below 10, which is of an excellent quality. But from salinity point of view, the quality varies from excellent to bad (from low to very high salinity hazard). Surface water such as Lake Dandi and Wanchi have an excellent quality both from sodium hazard and salinity point of view.

Table 5-2. SAR and EC values for surface and groundwater in Ambo area

Sample code	05	06	07	08	09	10	11	12	13	15	16	19	20
EC ($\mu\text{s}/\text{cm}$)	651	665	162	281	171	3940	620	1320	950	379	120	1447	1470
SAR	0.654	0.113	0.421	5.77	0.99	7.187	0.582	3.362	1.359	0.739	0.306	5.863	3.258

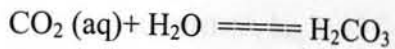
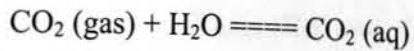
5.6 Geochemical modeling

Under this part the geochemical roles and/or the possible source of CO_2 , CaCO_3 , cations and anions enrichment in water as well as silica sinter in the study area will be discussed.

5.6.1 Carbon dioxide (CO_2)

Carbon dioxide can be derived from different sources; some of them are: atmospheric input, metamorphism of carbonate rocks, biological process in soil, and volcanic exhalations (release from cooling magma). Unlike the volume of CO_2 in atmosphere, which is only 0.03% that of soil atmosphere can reach up to about 9%, Ollier (1975), or it is greater by 10 to 100 times, Davis (1966).

Hence, the infiltrated water to the ground reacts with CO₂ derived from various sources forming carbonic acid that will be reactive toward the dissolution of some minerals, especially calcium carbonates. The formation of carbonic acid from CO₂ can be written as:

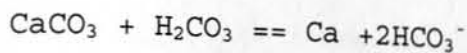


The role of this carbonic acid will be seen in the formation of travertine deposit in Ambo area. In addition to the CO₂ that forms carbonic acid, others are found as a free CO₂. Thermal waters including the mineral water in Ambo area show high gas bubble (CO₂). Although not analyzed in the current research work, the past analysis from Herrick, *et al* (1980) for the mineral water shows very high free CO₂ content that is 4497 mg/L on average. The source for such high free CO₂ content can be attributed mainly to the release from cooling magma chamber that forms the Wanchi crater.

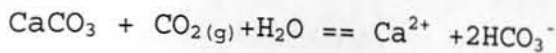
5.6.2 Calcium Carbonate/or travertine deposits

As has been seen above, the generated carbonic acid/or bicarbonate when it moves down in soil (during infiltration) can leach any calcium carbonate present in the soil. It should be noted that slightly acidic water dissolves more calcium carbonate as compared to CO₂ free water. For example, pure water at 23 °C can dissolve only about 13ppm calcium carbonate, or about 5ppm calcium. Hence, much higher calcium carbonate is soluble in the presence of CO₂. In addition to this, the presence of sodium and potassium salts also increase the solubility of calcium carbonate, Davis (1966).

The dissolution of calcium carbonate can be written as shown below, Lang Muir (1997).



Or in another form the reaction can be presented as:



The equilibrium constant, K_{eq} at 25 °C for the equation is:

$$K_{\text{eq}} = \frac{[\text{Ca}^{2+}][\text{HCO}_3^-]^2}{P_{\text{CO}_2}} = 10^{-5.97}$$

In terms of H^+ , the reaction is given as:



$$K_{\text{eq}} = \frac{[\text{Ca}^{2+}][\text{HCO}_3^-]}{[\text{H}^+]} = 10^{+1.85}$$

According to these equations, addition of more CO_2 to the system favors the forward reaction, i.e. calcite dissolution (or any other carbonate dissolution is favored by an increase in CO_2 pressure and a decrease in pH). On the other hand, the removal of CO_2 by any means from the system for that matter an increase in pH favors the backward reaction precipitating calcium carbonate.

The precipitation of calcium carbonate from the solution can happen under one of the following conditions:

- Evaporation
- Increase in temperature
- The release of CO_2 by any means such as a decrease in pressure

If we consider the travertine deposits of Ambo area, the most likely mechanism for its formation is the release of CO₂ due to pressure release when the thermal water comes to the surface. Infact, all the above mechanisms are interrelated; and therefore it is difficult to attribute only a single mechanism to a given travertine deposit.

Gypsum and/or anhydrite is also another possible source of calcium to react with hydrogen carbonate forming calcium carbonate. According to Langmuir (1997), the dissolution of gypsum can be written as:



This possibility can also be attributed to the source of travertine deposits in Ambo area provided that there exists gypsum layer beneath the surface. But in order to consider this possibility, the sulphate content of the thermal water (spring) that is thought to precipitate the travertine should be reasonable; On the contrary, the SO₄²⁻ content of the Ambo thermal spring is very low, 1mg/L. Hence, gypsum cannot be at least the major source for the travertine. Therefore, the major source for the travertine should be the dissolution of calcium carbonate. The implication of this is that there is limestone layer deep in the earth beneath the Sandstone, which in turn will lead us to the conclusion that the sandstone outcrop in Ambo area is not the Lower sandstone but Upper sandstone.

5.6.3 Saturation Index (SI)

The quantification of the degree of saturation of a given solution with respect to a given solute (mineral) requires the calculation of saturation index (SI). Based on the SI, one can know whether

a given solution is under saturated, saturated (at equilibrium), or super saturated. The commonly used method of calculating SI is by comparing the solubility product K_{sp} with the analogue product of activities/or Ion Activity Product, IAP derived from chemical analysis, Appelo and Postma (1994).

$$SI = \text{Log} (IAP/K_{sp}) \text{-----} (1)$$

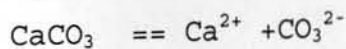
If $SI = 0$, the equilibrium is reached between the mineral and the solution

$SI < 0$, the solution is subsaturated with respect to a given mineral

$SI > 0$, the solution is supersaturated with respect to a given mineral, hence, precipitation occurs.

Although the method has not been applied for all the samples/ or minerals in the study area, the calculation has been carried out for Ambo thermal spring in order to know its state of saturation with respect to calcium carbonate (calcite). The calculation is explained as follows:

The dissolution of calcium carbonate in water can be represented as:



The method involves first the calculation of the activities (α) of Ca^{2+} and CO_3^{2-} from which IAP of calcite is obtained as:

$$IAP_{\text{calcite}} = \alpha_{\text{Ca}^{2+}} \cdot \alpha_{\text{CO}_3^{2-}} \text{-----} (2)$$

$$\alpha = \gamma m \text{-----} (3)$$

Where, α = chemical activity

γ = Activity coefficient

m = molal concentration

The activity coefficient γ for ionic species i, is given by Debye- Huckel equation as:

$$-\text{Log } \gamma_i = \{AZ_i^2\sqrt{I}\} / \{1 + a_iB\sqrt{I}\} \text{----- (4)}$$

Where:

A and B are temperature dependent constants, and are 0.5175 and 0.3297 respectively at T= 35 °C, Fetter (1994).

a_i = effective diameter of the ion

Z_i = the charge of ionic species

I = the ionic strength of a solution

$$I = 0.5 (\sum m_i Z_i^2) \text{----- (5)}$$

Where, I= as defined before

m_i = the molality of the i^{th} ion in the solution

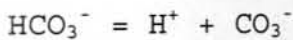
Z_i = charge of the i^{th} ion in the solution

For Ambo thermal spring, the following physicochemical field and laboratory parameters are obtained:

Parameters	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	NO ₃ ⁻	HCO ₃ ⁻	SO ₄ ²⁻	T	pH
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	°c	
Concentration	181.488	19.707	180	33.6	24	5.28	1183.4	1	35	6.2
Molality	7.894×10^{-3}	5.04×10^{-4}	4.491×10^{-3}	1.382×10^{-3}	6.77×10^{-4}	8.515×10^{-5}	1.939×10^{-2}	1.041×10^{-5}		

Hence, the ionic strength, I of the solution is found to be 0.026041895. By applying equation (4), the activity coefficient γ for Ca^{2+} and HCO_3^- are 0.5582 and 0.8534 respectively. The value of the effective diameter, a_i is taken to be 6 and 4 respectively for Ca^{2+} and HCO_3^- . Again by applying equation (3), the activity α of Ca^{2+} and HCO_3^- are calculated to be 0.002507 and 0.016547 respectively.

In order to have the IAP of calcite, we need to know also the activity of CO_3^{2-} , which is not detected in the analysis result shown above. This can be obtained by knowing the field pH value of the sample, and the dissolution equation of bicarbonate, HCO_3^- as follows:



The equilibrium constant K for this dissolution reaction is written as:

$$K_{\text{HCO}_3^-} = (\alpha_{\text{H}^+} \cdot \alpha_{\text{CO}_3^{2-}}) / (\alpha_{\text{HCO}_3^-}) \text{----- (6)}$$

At 35 °C, which is the measured field temperature of the water sample, $K_{\text{HCO}_3^-}$ at 1 atmosphere pressure is 5.5223×10^{-11} (interpolation from standard table). Similarly, knowing the pH of the sample, which is 6.2, α_{H^+} is found to be $10^{-6.2}$.

Therefore, by substituting the values of the activities and equilibrium constant in equation (6) the activity of CO_3^{2-} is calculated to be 1.44823×10^{-6} .

Hence, the calculated Ionic Activity Product, IAP for the calcium carbonate (considered to be calcite in this case) is 3.631×10^{-9} .

The temperature dependant equilibrium constant/or solubility product, K_{sp} of calcite can be obtained from either the Van't Hoff equation or from the analytical expression, Appelo and Postma (1994).

The simplest form of the Van't Hoff equation is given as:

$$\text{Log } K_{T_1} - \text{Log } K_{T_2} = (-\Delta H_r^\circ / 2.303R) (1/T_1 - 1/T_2)$$

Where as the analytical expression is given as:

$$\text{Log } K_{\text{calcite}} = -171.9065 - 0.077993T + (2839.319/T) + (71.595 \text{ Log } T)$$

Where:

K_{T_1} and K_{T_2} are equilibrium constants at two different temperatures

ΔH_r° = reaction enthalpy at 25 °C, 1atm (J/mol or Kcal/mol)

R = Gas constant = 8.314 J/mol.deg.

T = Temperature in Kelvin

Since the analytical expression involves only a single parameter, it has been applied here at a temperature of 35 °C (=308.15 °k).

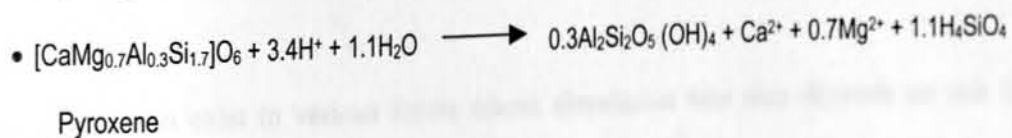
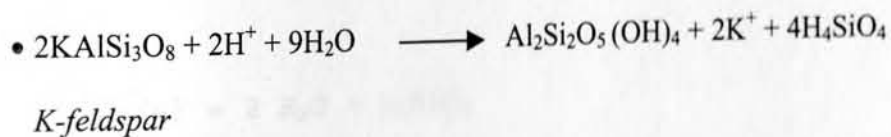
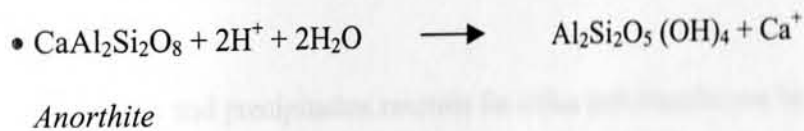
Accordingly, $\text{Log } K_{\text{calcite}} = -8.5429$; hence, $K_{\text{calcite}} = 2.8649 \times 10^{-9}$

Therefore, the saturation Index (SI) for calcium carbonate in Ambo thermal spring is found to be 0.103. Hence, the Ambo thermal spring is supersaturated with respect to calcite. Actually, this

can be observed from the precipitation of calcium carbonate on the water supply systems around the spring as well as at AARI well.

5.6.4 Possible sources of some cations in water

The main sources of major cations as well as some minor ions in natural water are the weathering of rocks. Especially, in volcanic terrain, the weathering of silicate minerals constitutes the dominant source of cation. The weathering of such minerals usually occurs at the expense of proton (hydrogen ion) that is commonly supplied by carbonic acid, Appelo and Postma (1994). Other than those contributed from anthropogenic effect, the contributions of some cations from silicate weathering can be represented by the following reaction equation:



As can be seen from these reaction equations, the weathering of silicate minerals releases various cations such as K^+ , Ca^{2+} , Na^+ , and Mg^{2+} . These are in addition to those released from sedimentary rocks. Therefore, such various weathering processes are responsible for different ion

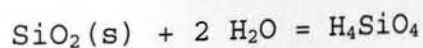
concentration as well as other species such as silica in water along with the anthropogenic sources.

5.6.5 Silica Sinter

The major sources of silica in natural water are weathering of silicate (e.g. olivine, pyroxene) and aluminosilicate minerals. Its concentration in groundwater depends mainly on rock types; High silica concentration is usually found in rocks that contain very reactive minerals (ferromagnesian minerals), which release silica on weathering. On the contrary least silica concentrations is found in areas containing dominantly quartz and carbonates.

The solubility of silica increases with increasing temperature. The strong temperature dependence of its solubility makes it to be used as a geochemical thermometer, Trainer (1981).

The dissolution and precipitation reaction for silica polymorphs can be described by:



In fact, SiO_2 can exist in various forms whose dissolution rate also depends on this form. The highly soluble form is the amorphous $\text{SiO}_2(\text{s})$; where as, the least soluble form is quartz.

Silica sinter is formed by the precipitation of SiO_2 from silica-saturated solution. As it can only be deposited from thermal waters, it can be used as an evidence for the presence of high temperature usually exceeding 180°C at depth, Trainer (1981 and the reference there in).

In Ambo area, silica sinter is found associated with travertine deposits; therefore, this shows the thermal origin of the travertine deposits as well as its original (initial) high temperature. The possible mechanism of formation for the silica sinter can be explained as follows: Since the solubility of silica increases with increasing temperature, large amount of silica will be in solution when the thermal water attains maximum temperature at depth. The out flow of this thermal spring to the surface is followed by a reduction in temperature reducing the solubility of silica that is resulted in the precipitation of silica sinter.

VI. CONCEPTUAL MODELING

A model is any representation/ or simulation of a real system. In hydrogeology, modeling technique is employed for various purposes. For example, to reason out groundwater flow system, and also to understand how the groundwater flow behaves when the system is subjected to a given stress such as pumping.

A conceptual modeling is usually the first step to be undertaken in such modeling. It is a method of conceptualizing (e.g. by sketch) what the system (e.g. hydrogeologic system) looks like geologically and hydrogeologically. Its quantification and verification is hardly possible by current study, but it paves the way for the subsequent investigation. One of the main advantages of the conceptual model is that it is less complicated than the real system.

All the previous discussions including geological, structural, hydrogeological, and hydrogeochemical investigations in Ambo area will help us to develop/or establish a simplified relationships among the recharging meteoric water in Wanchi area, the existing hydrostructures that control the thermal and/or mineral water, and their mode of discharge in a nearly east-west trend in Ambo area. These relationships are presented in a simplified sketch (or model) shown in fig 6.1.

The topographically high land along with the existing geology (highly permeable unwelded tuff overlying the basaltic lava flow) in Wanchi area favors the groundwater recharge that flows toward Ambo area. The deep circulation of the recharging water may also be related with the

northwest- southeast oriented fractures that are supposed to form the youngest scoria cinder cones in the area. Finally, the outflowing of the thermal water in Ambo area is favored by the transversally oriented fractures to the supposed groundwater flow direction.

Thermal springs are generally, non gravity springs, hence their outflowing is not controlled by hydraulic gradient instead it is due to reduction in density caused by heating; as a result it rises up to the surface through the available fractures/or conduits as shown in the figure.

This model also explains why the thermal and/ or mineral water in Ambo area is generally limited to Ambo town and its western side.

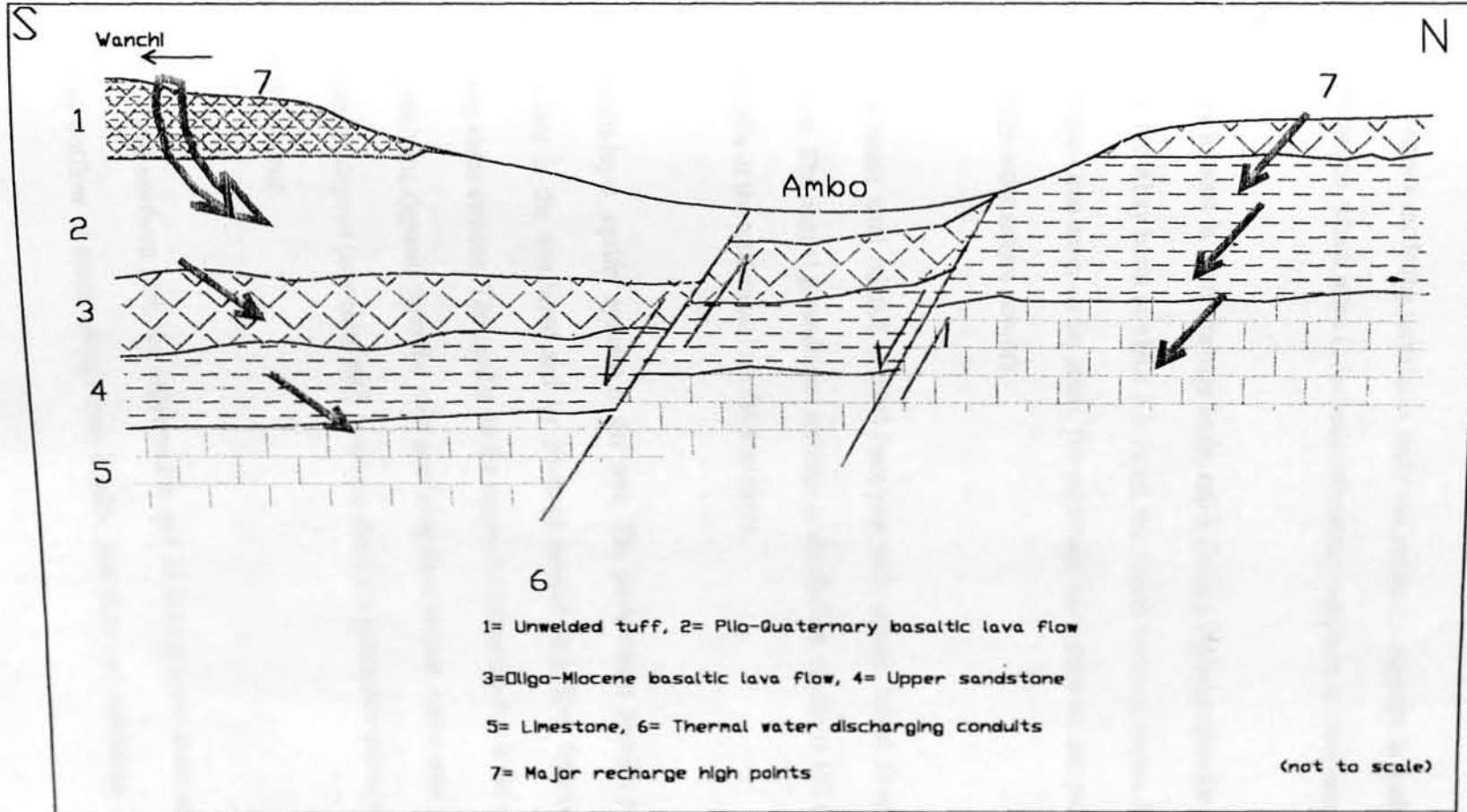


Fig.6.1 Schematic model showing major recharge and discharge areas

VII. CONCLUSION

Applications of various modeling techniques show that sandstone outcrops in Ambo area is part of the Upper sandstone, which is the Cretaceous sedimentary sequence in Abay basin.

The study area is located in Abay drainage basin, and it forms a triple-junction for three regional drainage basins: the Abay basin in which it is found, the Awash basin on eastern & southeastern side, and the Ghibe-Omo basin on the south. The catchment has a dendritic and parallel drainage pattern with a fifth order stream network.

The area has a mean total rainfall of 1143.3mm/year with annual Actual Evapotranspiration (AET) of 809mm. The annual groundwater recharge to the shallow aquifer is 162.8mm, which is only about 14.24% of the total annual rainfall it receives.

There exist multi-layer aquifer systems in the area. The predominant aquifer, particularly for soft/or cold water is the weathered and /or fractured basaltic lava flow followed by alluvial sediments along some streams. The aquifer for the thermal/or mineral water is the sandstone. Ash dominated pyroclastic deposits form the main confining layer around Ambo area, but in Wanchi area the pyroclastic deposit (unwelded tuff) forms the dominant permeable units due to its coarser grain size at the source.

At the western and northern part, the impermeable unit of mud-gypsum-shale acts as a barrier resulting in the outflow of some springs from basaltic lava flow and sandstone. Relatively less

fractured/or weathered lava flows (basaltic & trachytic) also cause the emergence of some springs.

Based on their origin two categories of springs can be identified in the area: the non- gravity (thermal) springs and the gravity (cold) springs.

The favorable geological, structural and geographical conditions of Wanchi and Dandi high lands cause them to be recharge areas both for thermal and cold groundwater; where as the gentle slope of land stretched in an east-west direction between the northern and southern elevated area forms the main ground water discharging area.

The thermal/or mineral water is a structurally controlled; the nearly east-west oriented fault in Ambo area forms the main discharging conduits for the thermal water, and also it is most likely the northern limit of the thermal/or mineral water. Similarly, Ambo town seems the eastern limit of the thermal/or mineral water as no indication of thermal/or mineral water has been observed to the east of the town.

The presence of silica sinter along with travertine deposits in Ambo area shows their thermal origin as well as the original high temperature of the thermal water as compared to the currently observed/or measured on the surface. The main source of heat supply for the thermal water should be a magmatic body in Wanchi area. For the deep circulation of meteoric water to come in contact with such magmatic body and subsequently discharged to the surface, there should be a fault. The implication of this condition is that the fault in Ambo area is also of a deep origin.

✓ The dominant groundwater in the study area is bicarbonates of calcium and magnesium. For the thermal water and those springs that show anthropogenic effect, sodium is also the dominant cation. High sulphate and chloride concentrations present in areas of mud-gypsum-shale unit and for anthropogenically affected sources respectively. In comparison to the cold groundwater, thermal waters show low pH value; where as, surface water shows higher pH value. Heat/or temperature & lithology are the dominant controlling factors for the physicochemical characters of groundwater in the area.

High anthropogenic effect is observed in some sources of water: Hotel spring in Ambo town (high Na^+ , Cl^- & NO_3^-), wastewater from mineral water bottling factory (high Na^+ , Cl^-), and Huluka stream at down stream of Ambo town (high NH_4^+ , Cl^- & Cr^{6+}).

The thermal waters in Ambo area are still saturated with respect to calcium carbonate (calcite); hence, the precipitation of this mineral around thermal springs as well as in some water distribution systems can be verified.

Recommendation

- Isotope techniques, particularly oxygen isotope and carbon isotopes may be employed for farther verification of the source of travertine (or presence of limestone beneath the sandstone), as well as for the verification of the magmatic origin of heat in thermal water. In order to know the contribution of heat from geothermal gradient, temperature well

logging is also a useful technique; this can also be used to estimate the temperature of the thermal water at the source.

- A good structural investigation for the area is an invaluable tool in understanding as well as establishing the relationships between cold/ or soft and thermal /or mineral water in Ambo area; hence, structural synthesis of the area should be made.
- In order to see the current saturation state of the thermal water with respect to silica, the analysis of the silica & its saturation index has to be made.
- Geochemical, geological, structural, and hydrogeological investigations in the area are still at their infant stage, especially the geochemical modeling approach to reconstruct the stratigraphy of the area as well as to understand the nature of groundwater in the area should not be considered as final; hence, all such investigations should be further verified.
- Oromia Water, Mines & Energy Resource Development Bureau should make a close follow up on some contaminants such as NO_3^- & Cr^{6+} observed in some water sources.



VIII REFERENCES

- Appelo C. A. J. & Postma D., 1994: *Geochemistry, Groundwater & Pollution*, A. A. Balkema, Rotterdam, Netherland, 536p.
- Chow V. T., Maidment D. R. & Mays L. W., 1988: *Applied hydrology*, McGraw-Hill book Co., Singapore, p572.
- Daniel Gamachu, 1977: *Aspects of climate and water budget in Ethiopia*, Addis Ababa University press, Addis Ababa, 71p.
- Davis S. N. & DeWiest R. J. M., 1996: *Hydrogeology*, John Wiley and Sons Inc. New York, 463p.
- Detay M., 1997: *Water Wells- Implementation, Maintenance & Restoration*, John Willey & Sons- Masson, Paris, 379p.
- Dingman S. L., 1994: *Physical hydrology*, Prentice Hall Inc., Englewood Cliffs, New Jersey, 575 p.
- Emmons W. H., Thiel, Stauffer & Allison, 1953: *Geology- Principles and processes*, 3rd ed., McGraw- Hill book Co. Inc., USA, 502p.
- Fetter C. W., 1994: *Applied hydrogeology*, 3rd ed., Prentice- Hall Inc., Englewood, New Jersey, 691p.
- Fifield F. W. & Haines P. J., 1996: *Environmental analytical chemistry*, 1st ed., Chapman & Hall, London.
- French Engineering Consultants (BCEOM) in association with BRGM & ISL consulting Engineers, 2000: *Abay River Basin Integrated Development master plan project, Phase 2, Vol. 1c, Ministry of water resources*, Addis Ababa.

- Getaneh Assefa, Solomon Tadesse, Bosellini A., Russo A. and Fantozzi P. L., 1997: The Mesozoic succession of the Mekele outlier (Tigre Province), *Estratto da memorie Di Scienze Geologiche*, Vol. 49, Padova, Italy, pp95- 116.
- Herick F., Gifawosen Tefera, Ayalew Legese & Tesfahun Haile, 1983: Mineral waters of Ambo and Sankale, *EIGS Hydrogeology division*, Note no 197, Addis Ababa.
- Institution of Water Engineers & Scientists (IWES) 1986: Groundwater- Occurrence, development & protection, Water practice manuals, *IWES*, London, 615p.
- Kashef A. I., 1986: Groundwater Engineering, *McGraw- Hill Inc.*, USA, 512p.
- Kazmin V., 1975: Explanation of the geological map of Ethiopia, *EIGS*, bul. No. 1
- Kondo C., 1967: Thermal springs of Ethiopia, *EIGS*, Addis Ababa.
- Langmuir D., 1997: Aqueous Environmental Geochemistry, *Prentice- Hall Inc.*, Upper Saddle River, New Jersey, USA.
- Leopold L. B. & Dunne Th., 1978: Water in Environmental planning, *W. H. Free man and Company*, USA.
- Mengesha Tefera, Tadiwos Chernet and Workneh Haro, 1996: Explanation of the Geological map of Ethiopia, Ministry of mines and Energy, *EIGS*, Bull. No 3 Addis Ababa.
- Metaferia Consulting Engineers, MCE, 1999: Feasibility study and Engineering design of Ambo and Nekemte towns water supply and sanitation project; *Oromia Water, Mines and Energy Resources Development Bureau*, Vol. II, Addis Ababa.
- Mohr P.A., 1971: The geology of Ethiopia, *Haile Sellassie I University press*, reprinted, Addis Ababa, 268p.

- Molla Gudeta and Meseret (?) Taye, 1998: A report on evaluation of stocking (fishing) on Lake Wanchi, *Western Shewa Agricultural Department*, un publ. Report.
- Nata Tadesse, 1994: Hydrogeology of Jimma area, M.Sc. thesis, *Addis Ababa University*, Addis Ababa.
- Ollier C., 1975: Weathering- Geomorphology text, *Longman Inc.*, New York, 374p.
- Pettijohn F. J., 1984: Sedimentary rocks, 3rd ed., *CBS publ. & distributors*, Delhi, 628p.
- Russo A., Getaneh Assefa and Balemwal Atnafu, 1994: Sedimentary evolution of the Abay River (Blue Nile) basin, *N. Jb. Geol. Palaont. Mh.*, 1994(5): 291- 308; Stuttgart.
- Seifu Kebede, 1999: Hydrology and hydrogeochemistry of Bishoftu crater lakes, hydrological, hydrochemical and oxygen isotope modeling, M.Sc. thesis, *Addis Ababa University*.
- Shaw M. E., 1988: Hydrology in practice, 2nd ed., *Van Nostrand Reinhold Int. Co. Ltd.*, Britain, p539.
- Smeds H., 1964: A note on recent volcanic activity on the Ethiopian plateau; as witnessed by a rise of the level of Lake Wanchi 1400± 140 B. P., *Societas Geographica Fenniae, Acta Geographica 18, No1*, Helsinki- Helsingrofs.
- Subramanya K., 1988: Engineering hydrology, *Tata McGraw- Hill Pub. Co.ltd.*, New Delhi, 316p.
- Tamiru Alemayehu & Vrenier A., 1997: Conceptual model for Boku hydrothermal area (Nazareth), Main Ethiopian Rift valley, *Sinet: Ethiop. J. Sci.*, 20 (2) 283- 291, Addis Ababa University.
- Tamiru Alemayehu, 1993: Preliminary analysis of the availability of groundwater in Ethiopia, *Sinet: Ethiop. J. Sci.*, 16(2): 43- 59, Addis Ababa University.

- Tenalem Ayenew, 1998: The hydrogeological system of the Lake district basin, Central main Ethiopian Rift, Ph. D. thesis, *ITC publ. No 64*.
- Tesfaye Chernet, 1993: Hydrogeology of Ethiopia and Water Resources development, *EIGS, Ministry of Mines and Energy*, un publ., Addis Ababa.
- Teshome Dechasa, 1999: Water balance and effect of irrigated agriculture on groundwater quality in the Wonji area/ Ethiopian Rift valley, M. Sc. thesis, *Addis Ababa University*, Addis Ababa.
- Todd D. K., 1980: Groundwater hydrology, 2nd ed., *John Wiley & Sons Inc.*, New York, 535p.
- Trainer F. W., 1981: Thermal springs. In *pollution and Water Resources* Columbia University Seminar series. Vol. XIV, part 1, hydrogeology and other related reports edited by Halasi-Kun J. G., *Pergamon press*, New York, pp113- 119.
- Tsegaye Abebe, Mazzarini F., Innocent F., and Manneti P., 1998: The Yerer- Tullu Wellel- Volcano- Tectonic- Lineament . A transitional structure in central Ethiopia and the associated magmatic activity, *Jour. Of African Earth Sci.*, Vol. 26, No. 1, *Pergamon, Elsevier Sci. Ltd.*, Britain.
- Tsegaye Abebe, 1993: The Yerer -Tullu Wellel- Volcano –Tectonic- Lineament (YTWVTL), central Ethiopia, Magmatological, Tectonics and chronological constraints, Ph. D. thesis (Draft copy).
- UNESCO, 1984: Methods of computation of the water balance of large Lakes and reservoirs, Case studies, Vol. II, a contribution to the IHP, *Egyetemi, Budapest, 7. place de Fontenoy, 75700 Paris*.

- Viessman W. J. & Lewis G. L., 1996: Introduction to hydrology, 4th ed., *Harper Collins College publ.*, New York, 760p.
- Ward R. C. & Robinson M., 1990: Principles of hydrology, 3rd ed., *McGraw-Hill book Co.*, London, 365p.
- World Health Organization (WHO), 1984: Guidelines for drinking water quality. Health criteria and other supporting information, Vol. 2, Geneva.

DECLARATION

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

Name: *Lemessa Mekonta*

Signature: *Lemessa Mekonta*

Place and date of submission: *School of Graduate Studies,*

Addis Ababa University, June 2001