Addis Ababa University

School of Graduate Studies

College of Natural Science

Department of earth sciences

HYDROCHEMICAL AND ISOTOPIC CHARACTERISTICS OF THE GROUNDWATER SYSTEM OF ALLEYDEGE PLAIN

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

BY

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ABSTRACT

On the bases of geomorphology which is controlled by en echelon normal faults, the area is classified into two parts; the Alleydege plain, and Awash River valley. The groundwater dynamics of the area with emphasis given to surface water and groundwater interaction, origin of recharge; groundwater flow direction, groundwater evolutionary trend and direction, causes and origin of salinity and general groundwater quality issues relative to temporal variation are studied in this research using hydrochemical and isotopic data. Ultimately conceptual hydrochemical groundwater model of the area is constructed.

XLSTAT _Pro version 7.5.2; for agglomerative cluster analysis, Aquachem 4.0 software package; for graphical plots and representation of hydrochemical data, PHREEQC built in aquachem 4.0 version; for inverse geochemical modeling, ArcGIS _9.3 software version; for Analysis of areal distribution and variation of hydrochemical and isotopic data and for production of different maps and Autocad-2007 version; for production of longitudinal geologic and hydrogeologic profiles, are employed in this study.

Hydrochemical and isotopic studies reveal that there is interaction of Awash River with the groundwater of the alluvial aquifer of the Awash River valley and the Alleydege plain that lie within few kilometer distances from the Awash River during rainy season; during dry season such interaction is not observed. Recent meteoric water contribution to the groundwater reserve of the Alleydege plain is very limited. As a result subsurface inflow or percolation along the slope from southern, southeastern, and eastern highlands are found to be the major recharge mechanism for the Alleydege plain. Towards the rift, from the recharge areas of southern, southeastern, and eastern highlands; the ionic concentration, salinity and isotopic enrichment (δ^2H and $\delta^{18}O$) increase following the groundwater flow paths. In general the groundwater flow and evolutionary trend direction follows the surface topography flowing from the south, southeastern and eastern elevated areas to the Alleydege plain and finally to the rift floor converging to the Awash River in the northern direction. The recharge area is characterized by Ca-HCO_3, Ca-Mg-HCO_3 or Ca-Na-HCO_3 water type, where as the Alleydege plain and the marginal areas are characterized by a Na-Ca-HCO_3-Cl water types. Na-HCO_3-Cl and Na-HCO_3 are the dominant water types in the Awash River valley and rift floor. K-mica, olivine, pyroxene, plagioclase and illite are the primary minerals of the Alleydege plain groundwater system.

ACRONYMS

AAU	Addis Ababa University
BH	Borehole
DD	Draw down
EC	Electrical Conductivity
EIGS	Ethiopian Institute of Geological Survey
EU	European Union
FAO	Food and Agricultural Organization
GMWL	Global Meteoric Water Line
HDW	Hand dug well
HCA	Hierarchical Cluster Analysis
KM	Kilometer
KM^2	Kilometer square
LMWL	Local Meteoric Water line
MAC	Maximum Acceptable Concentration
M	Meter
m.a.s.l	Meter above sea level
m/s	meter per second
m^3/s	meter cube per second
mg/l	mili gram per liter
MWoR	Ministry of Water Resource
MER	Main Ethiopian Rift
NNE-SSW	North North East- South South West
NW-SE	North West –South East
NTU	Nephelometric Turbidity Unit
pH	the negative logarithm of hydrogen ion
SI	Saturation index
SDZFZ	Silty- Debrezeit Fault Zone
SP	Spring
SWL	Static Water Level
TDS	Total Dissolved Solids
UTM	Universal Transverse Mercator
UTME	Universal Transverse Mercator Easting
UTMN	Universal Transverse Mercator Northing
WWDSE	Water Works Design and Supervision Enterprise
WFB	Wonji Fault Belt
WHO	World Health Organization

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1 INTRODUCTION

Water from beneath the ground has been exploited for domestic use, industrial, livestock and irrigation since the earliest times. Irrespective of its availability and general water quality related problems, it is customary to think of groundwater as being more important in arid or semi-arid areas like the Afar regional state where alternative means of surface water is barely present.

It is very well understood that geochemical characteristics change from recharge, to discharge zone according to the regional groundwater flow system (Stuyfzand, 1999; Toth, 1999). Chemical processes may provide evidence for groundwater flow. The chemical composition of surface water and groundwater can be used as a tracer for hydrograph separation of base flow and direct runoff, and for the identification of groundwater flow paths (Eshleman *et al*., 1994; O'Brien, 1994; Katz *et al*., 1997; James *et al*., 2000). Surface water usually has an isotopic signature resulting from evaporation. Interactions in the semi-arid plain are not as active as those in headwater wetland or karst areas, where the surface water–groundwater head difference is significant (Devito *et al*., 1996; Devito and Hill, 1997).

Generally interactions between groundwater and surface water are complex and dependant on many factors including landform, geology, climate and the exploitation of local water resources (Adams et al, .2001). The hydrology and water quality of rivers are strongly controlled by exchanges of water and solutes with adjacent river banks and uplands (Sikdar et al., 2001; Ray et al., 2002). Ground- and surface water can be seen as linked components in a large hydrological continuum that should be considered for sustainable development (Eikenberg et al, .2001; Nẻgrel et al., 2003).

In many cases conventional hydrogeochemical studies are not sufficient to characterize groundwater hydrodynamics or to detect recharge areas and source areas of recharged water. Since the isotopic composition of O and H in groundwater does not change as a result of rock–water interactions at low temperatures, it provides a helpful means to bridge this knowledge gap (e.g. Sidle, 1998).

Several studies using hydrochemistry and stable isotopes of water have already been realized to characterize hydrogeochemistry and recharge processes in similar hydrogeologic environments (Marfia et al., 2003; Long and Putnam, 2004; Barbieri et al., 2005).

Environmental isotopes are the naturally occurring isotopes of elements found in abundance in the environment (Clark and Fritz, 1997). In hydrogeological investigations, environmental isotopes are routinely used; complementing geochemistry and physical hydrogeology, as they can provide information about e.g., groundwater quality, geochemical evolution, recharge processes, rock-water interaction, and the origin of salinity (Clark and Fritz, 1997; Kendall and McDonell, 1998; Cook and Herczeg, 2000).
Previous recharge investigation in the Alleydege area have tended to rely on a single recharge technique and lacked a corroborating evidence to substantiate predictions of

recharge. Some studies depicted that component of groundwater of the Alleydege plain flows towards Awash River as base flow while others contemporaneously concluded that part of the Awash River flows towards the Alleydege plain to feed the groundwater of the Alleydege plain. Nevertheless, a comparison of the results from a number of recharge studies in this environment does reveal some common characteristics. No previous study, however have used stable isotope tracers to determine the source of recharge nor conformed the timing of recharge events. Only recent study done by WWDSE provided an estimate of the magnitude of recharge from different sources.

1.1 Problem identification and justification of the research

As it has been enumerated in most of the reviewed previous works a lot of studies have been undergone in the area since 1972 by the ministry of water resource and different bodies. The studies were carried out with respect to hydrogeological and groundwater potential evaluation of the area on general and regional basis. Even though the majority of the studies were conducted on the absence of sufficiently available data, all of the studies more or less consent that the area possesses a potential groundwater resource.

Nevertheless, there are tremendous data gaps with respect to detail hydrogeologic description of the area especially data related to aquifer characteristics, groundwater flow system, detail hydrochemistry and geochemical evolution of groundwater, inflow ,outflow, storage, and circulation condition, groundwater and surface water interaction etc. Beside that there are different thoughts about the groundwater recharge and flow system; for instance *Asfaw, 2006* and *Currey D.T, 1972* said that the aquifer of the Alleydege plain gets its recharge from Awash River; contrary to that *Ketema et al., 1983* assumed that groundwater flows from the alluvial aquifer to the Awash river. In addition to this *EVDSA Halcrow, 1989* said that the aquifer of the Alleydege plain gets its recharge from direct precipitation and percolation from adjacent highland slopes. Other recent report by *WWDSE, 2009* stated that the Alleydege plain gets its recharge mainly from infiltration of direct precipitation followed by indirect recharge from the Awash River and subsurface inflow from adjacent eastern highlands. Also no previous studies have followed isotope hydrology approach in the investigation of groundwater potential of the area. Therefore in this study, hydrochemistry and isotope hydrology approach will be integrated and used to verify the different thoughts on groundwater flow system and recharge condition of the Alleydege plain. Beside that other hydrogeological information such as groundwater origin, recharge, discharge, and groundwater evolutionary trend will be addressed. Furthermore, conceptual hydrogeochemical groundwater model of the area will be constructed and enhance the hydrogeologic understanding of the area by bridging some of the existing gaps.

1.2 Aim and objectives of the study

1.2.1 General objective

The major aim of this study is to investigate groundwater dynamics of the Alleydege plain groundwater system.

1.2.2 Specific objectives

- Assess the source of recharge, discharge, flow direction and evolution of the Alleydege plain groundwater system.

- Determine the hydrochemistry of groundwater from the aquifer by determining the chemical characteristics and the most relevant controls on the groundwater composition.

- Assess the surface water and groundwater interaction of the Alleydege plain in order to investigate the future head variation on Awash River and its impact on the groundwater of the Alleydege plain during abstraction since this site is future target area for irrigation.
- Construct conceptual hydro geochemical groundwater model.

2 THE STUDY AREA CHARACTERIZATION

2.1 Location access, and climate

The Alleydege plain is an elongated north south running, flat laying ground enclosed between Asebot Mountain in the east and Awash River and Dofen ranges of mountains in the west. The plain covers about 1690 Km^2 areal extent and is found within the main Ethiopian Rift (MER) around 250 km northeast of Addis Ababa along the main road to Djibouti between Awash Arba and Gedamitu towns of the Afar regional state. The main access roads to the site are the Awash Arba-Djibouti road in the north- south direction and the Awash Sebat kilo –Dire Dawa road in east- west direction. In addition to that there are various routes made of gravel that aid access to different parts of the plain. Geographically the area is situated between of 0990000 and 1070000 UTM N and 610000 and 690000 UTM E.

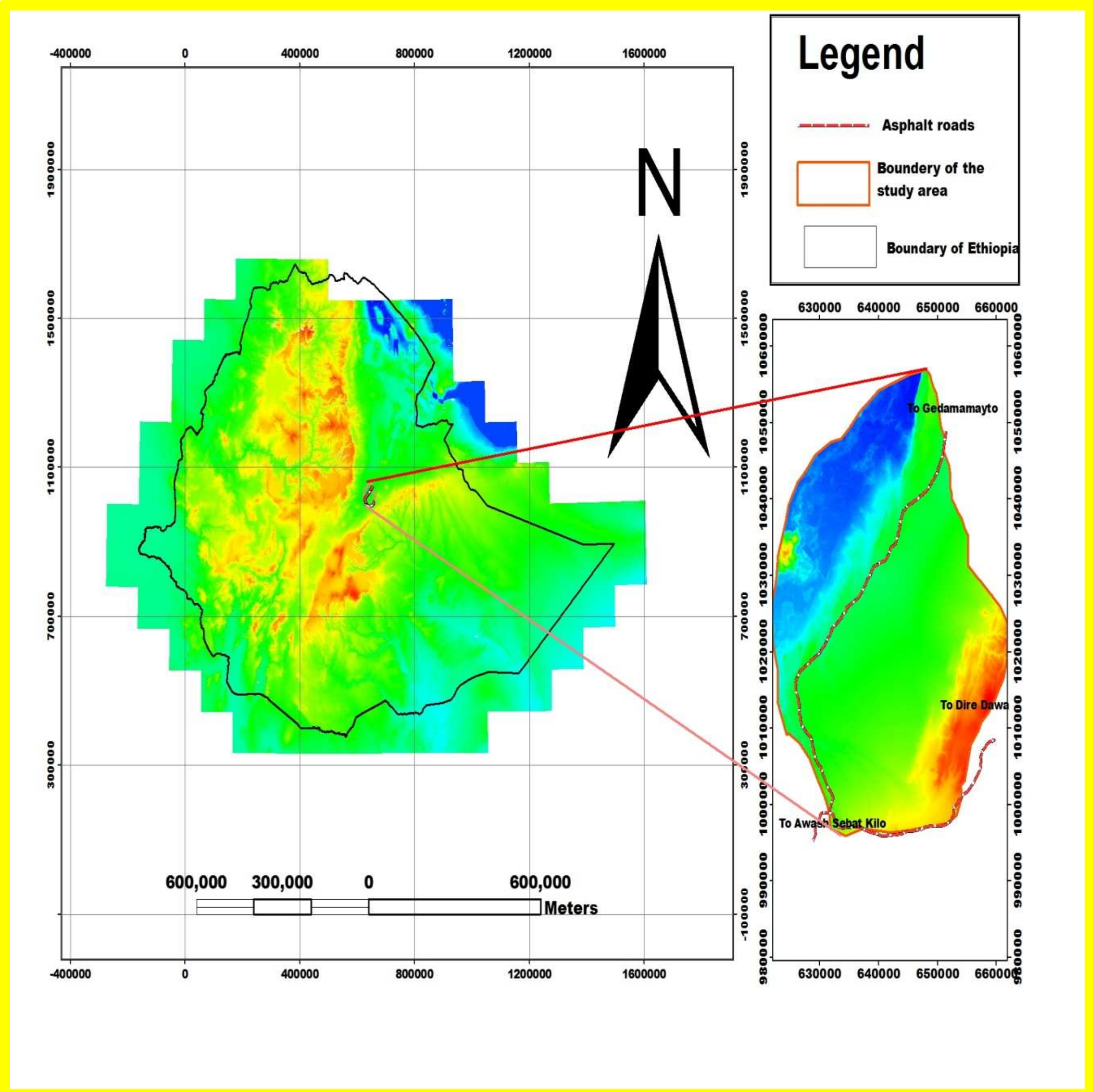


Figure 2. 1 Location map of the study area

The climate of the Awash basin comes under the influence of the Inter Tropical Convergence Zone (ITCZ). This zone of low pressure marks the convergence of dry tropical easterlies and the moist equatorial easterlies. The seasonal rainfall distribution within the study area results from the annual migration of the ITCZ. The ITCZ starts its advance across the study area from south in March bringing small spring rains. From June to September the ITCZ moves rapidly from north part of the country to the project area bringing heavy summer rain. Along with the ITCZ the orography has significant effect for the formation of rain in the study area.
The rainfall pattern of the area is bi-modal type with most of the rainfall occurring in wet season (i.e. July-September) and minor rainy season (March-May). The minimum rainfall occurs during the driest months from October to January. (WWDSE.draft final Alleydege Hydrology, 2009)The temperature of the area has two phases depending upon the topography of the area; the lowlands of the Afar regional state are hot where as the adjacent eastern highlands of the Oromia regional state are relatively moist and cool.

2.2 Geomorphology and drainage pattern

The Ethiopian highlands are characterized by high runoff and high sediment load transport, whereby Ethiopia looses a lot of water and sediment to adjacent countries. On the other hand Ethiopia, the Ethiopian rift valley and the Afar region gain surface waters and sediments, which are discharged from adjacent highland areas.

The area attains topographically contrasted regions which influence climate and vegetation, resulting in various physico –chemical processes operating at different rates. The geomorphology of the area is governed by landforms as a function of the structure process and stage.

The site is characterized by a system of en echelon normal faults which control the geomorphology of the area. The last phase of faulting in the area is the NNE trending Wonji Fault Belt (WFB) that resulted in the development of the two major grabens; the Alleydege plain graben and the Awash Valley graben. (fig.2.2) (WWDSE Geological Report, 2009).

All of the streams except Arba that drain from the eastern highlands to the Awash River are seasonal streams. The drainage condition of the area is totally controlled by the Awash River catchments. Most of the streams vanish within the Alleydege plain before reaching the Awash River. The streams mainly emanate from south eastern and eastern highlands and they never exceed stream order of three. The drainage density from these highlands is relatively dense as compared to the western highlands which are deciphered by low drainage density and where the tributaries hardly exceed stream order of two. Streams of western highlands flow north or north east to feed the Northward or north east flowing Awash River. The flow path of the Awash River is controlled by the Wonji Fault Belt (WFB) structure in the area.

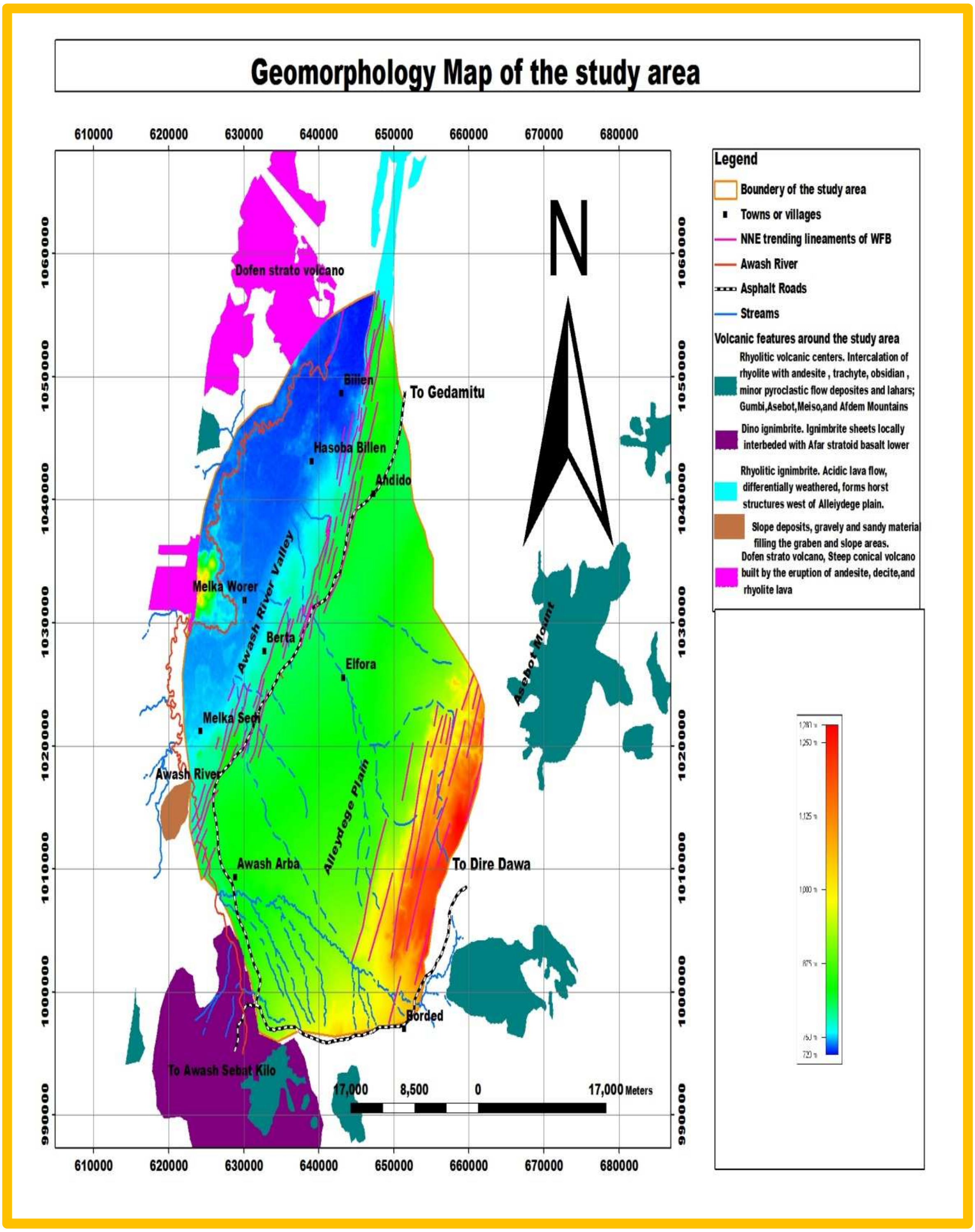


Figure 2. 2 **Geomorphology and drainage pattern of the study area as controlled by en echelon normal faults**

2.3 Geology

2.3.1 Regional geology

The regional geology of the area as compiled by different authors is briefly described here under:

2.3.1.1 The Precambrian (Hu)

They consist of granites, gneisses, and migmatites. Metallic deposits are known to occur. The Precambrian rocks are subjected to several orogenic episodes since their formation. Rifting associated with the development of the Red sea and African- Ethiopian Rift Valley has resulted considerable fracturing and shattering. (Kazmin, 1972).

2.3.1.2 Silicic centers (N1-2ar)

This formation occurs as small patches in the vicinity of the central volcanoes. They are dominantly of rhyolitic in composition, intercalated in the Stratoid series. The rhyolites are end – products of fissural basaltic activity; alkaline rhyolites, commendites, pantellerites, rhyolitic trachytes and dark trachytes are found mainly as lava flows (Barbery F. and Varet J. 1976).

2.3.1.3 Nazret group B

Bofa basalts (N1b) are fissure flood basalts named after their type locality called Bofa village (V. Kazmin and Seife Michael Berhe, 1978). Ignimbrites and flows, separated by paleosoils and scoracious horizons occur at other places.

2.3.1.4 Pleistocene to Holocene

Dino ignimbrites (QWD) occur in the southern part of the area, south of Mount Fantale, where they occur topographically low and relatively flat areas. They can be distinguished on Landsat image by their light tone, due to partly grass cover. They comprise a number of flows of compact fiamme ignimbrites, in places intercalated with aphiric basalts and unwelded pyroclastics (V.Kazmin and Seife Michael Berhe).

2.3.1.5 Basalts of the rift floor

Pleistocene basalts (QWbp) – fissure flows (transitional basalts, ferro basalts and hawaiites) are locally found around volcanic centers, like Dofan, Hertale, Ayelu, Abida, etc…

Recent basalts (QWbh) – basaltic lava flows and spatter cones (picritic basalts, porphyritic plagioclase basalts, andesine basalts of transitional nature with alkaline tendencies) are associated with the former.

2.3.1.6 Middle to Upper Miocene

Anchar basalts (N1n) and Arba Guuracha silicics (N1ar) have been recognized in the Escarpments Margins of the Ethiopian Rift or the Afar. The two units are more or less contemporaneous (Middle to Upper Miocene). The Anchar basalts form the lower part of the rift volcanic succession and should not be confused with the pre-rift “traps” or plateau basalts (V. Kazmin and Seife Michael Berhe, 1978). Anchar basalts are flood basalts and siliceous rocks (several intercalations of ignimbrites) exposed at the Eastern margins of the rift where as Arba Guuracha silicics (predominantly of acidic varieties like welded and unwelded ash flows) are exposed at the eastern margin of the rift and in some parts of the Western Escarpments.

2.3.1.7 Upper Miocene to Pliocene Nazret Group (A)

Stratoid silicics, ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes (N1-2N) are exposed in the southern part of the study area. Gara Gumbi rhyolites (N1-2gg) are exposed at Mount Asebot and Mount Afdem and at other small hills in the vicinity. The two units which belong to the Nazret group attain a thickness of about 250 mts and are restricted to the sagging rift. (V.Kazmin and Seife Michael Berhe, 1978). The per – alkaline nature of these rocks was mentioned by Di Paola (1972).

2.3.1.8 Afar group

i) Dalha basalts (N1-2db) are mainly composed of basaltic flows with intercalation of ignimbrites and detritic deposits (up to 800mts.of thickness). They are deeply eroded and often unconformably covered by the Stratoid series of the Afar.

ii) Stratoid series (N1-2ab) covers about 2/3 of the rift floor. It is composed of Plio- Pleistocene volcanic units which are dominantly basalts. Sedimentary units and hyaloclastite layers are intercalated within the stratoid series.

This series is affected by faulting and block tilting; the lowest parts are deeply weathered and altered.

2.3.1.9 Central volcanic complexes

The central volcanic complexes of Fantale, Dofen and Ayelu are built mostly from alkaline and peralkaline rhyolites (QWa). The central volcanic complexes of Abida, Yangudi and Gabilema are mostly composed of peralkaline rhyolites, ignimbrites and pumice fall (QWi).lavas of intermediate composition-mugearites, rhyolitic trachytes, hawaiites and ferro basalts are associated with the letter, and hence are grouped together for the present purpose.

The sequence of rocks ranging from basalt to rhyolites observed around these volcanic complexes has been explained by Barbery F. and Varet J.1976 as being the result of a process of crystal fractionation.

2.3.1.10 Soil units

Quaternary to recent alluvial sediments (Qa) cover a large part (about 1/3) of the study area. Lacustrine deposits of different age (Upper Pleistocene: 50000-20000 years before present) occur at several places along the Middle Awash area. They are mostly composed of limestones and diatomites. Younger deposits (less than 2500 years before present), composed of lacustrine sediments, silt, clay, diatomites, volcanoclastic- sediments and tuffs occur in the Middle Awash area. Due to ecological conditions (total salinity, alkalinity) organic remains are practically none existence within these deposits (F.Gasse, 1978).Continental conglomerates, gravel, sand, silt, and clay occur at foot slope areas and within the grabens of the escarpments. The age of these sediments could extend from Pliocene to Holocene up to the present time. Eolian Sediments mainly occur in the interior part of the rift floor. Flood terraces are common along the Awash River where as sheet flood deposits occur along intermittent and seasonal streams.

2.3.2 Local Geology

2.3.2.1 Rhyolitic Ignimbrite (Nrig)

The Rhyolotic ignimbrite forms a NNE – SSW running horsts (Berita, Nuntiweli, Naleldela, Be-Aditeda, Billen Ridges, etc*)* between the Alleydege and Awash graben. (WWDSE, 2009)

2.3.2.2 Afar stratoid basalt lower (N1ab)

This unit outcrops in the south central part of the area, in the east around Hardim and low grounds of Asebot Mountain. It forms low-lying hills. It is massive to vesicular, affected by dominant horizontal jointing and unsystematic dipping joints. (WWDSE, 2009)

2.3.2.3 Afar stratoid basalt upper (N2ab)

The unit forms both high and low lying hills, uconformably overly the lower Stratoid Afar basalt. The Afar stratoid basalt upper is Pleistocene – sub recent in age. The basalt is fine grained massive to strongly vesiculated. (WWDSE, 2009)

2.3.2.4 Outwash Gravel (Qog)

Outwash gravel in the area derived from breakdown products of basaltic and acidic materials from the elevated areas, which have been transported towards the centre of the basin to form extensive outwash, gravel plain. Locally, it is intebeded with basic lava, conglomeratic bed, lenses of clay beds and tuff layer. (WWDSE, 2009 draft geological report)

2.3.2.5 Alluvial Fan (Qaf)

The alluvial fan in the area represent a compositionally immature sediments consisting of gravel, sand and silty layer, showing fining direction to the west. (WWDSE, 2009 draft geological report)

Quaternary slope deposits represent a breakdown materials of the elevated areas, consists of mainly sand and gravels - the clasts in the gravel are basaltic and ignimbrite material, which seems to be transported from the nearby horsts. The gravel shapes differ from angular to sub-rounded indicating a proximal source. (WWDSE, 2009 draft geological report)

2.3.2.6 Quaternary Elluvium (Qel)

Quaternary elluvium in the area consists of brown and black clays, sand and silty materials including the lacustrine sediments of the Alleydege plain, Melka Worer, Melka Sedi etc. The brown sand, brown silt and clays may represent pre-lake sediment, might have been derived from acidic sequences in the area. The Black clays are confined to a former river system and show cracking and are a product of the breakdown of the basaltic rocks of the region. (WWDSE, 2009 draft geological report)

2.4 Structural and tectonic setting

Important stages in rift development occurred around 10m.y ago and at that time a faulted eastern escarpment of the Rift was formed on the Nazreth area (V.Kazmin 1978).Faulting in the Ethiopian Rift at 10m.y coincide with major faulting of the western and eastern and southern escarpment of the Afar (Christeinen et al 1975). The type of tectonics in the Afar Region depends on the attenuation of the crust through tensional movement. The faulting of the Afar shows synthetic and antithetic fractures of tensional types. Strike slip faults are few and the existence of transform faults and big transcurrent faults is contested (Mohr 1962).

The major fault trend in the region generally confirms to the NW-SE Red Sea trend and NE-SW Ethiopian rift trend. In the Southern Afar and in the main Ethiopian Rift the Wonji Fault Belt (WFB) (Mohr 1962) came in to existence at the end of Pliocene and during Pleistocene. In the SW Afar this fault belt shows a SSW/NNE striking fault zones NNW to NW/SE striking fault system also cut through the Wonji Fault Belt as well through the western parts of the SE plateau. In the main Ethiopian Rift the Wonji Fault Belt is younger and began after the Nazreth phase 1.8 to 1.6 m.y ago (Mayer et al 1975).

In relation to tectonic setting of the study area the major structures dominating the Alleydege plain water catchments are normal faults, bedding plain and jointing. Especially the north-north east trending Wonji Fault Belt (WFB) can be mapped from Landsat images and aerial photographs (WWDSE, 2009), (Woldegebriel, G.et.al 1990).

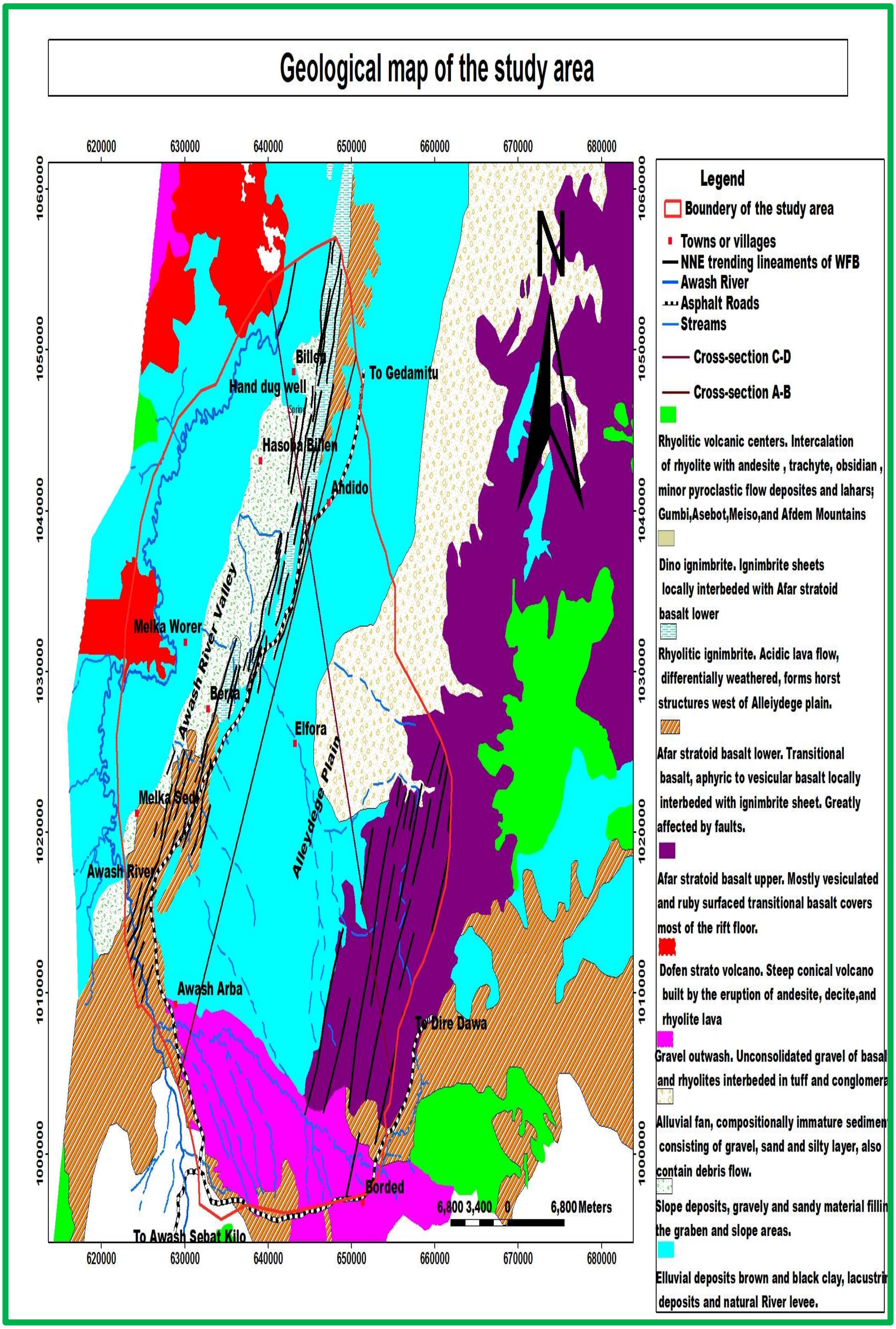


Figure 2. 3 **Geological map of the study area (Source: WWDSE, 2009 unpublished inception report)**

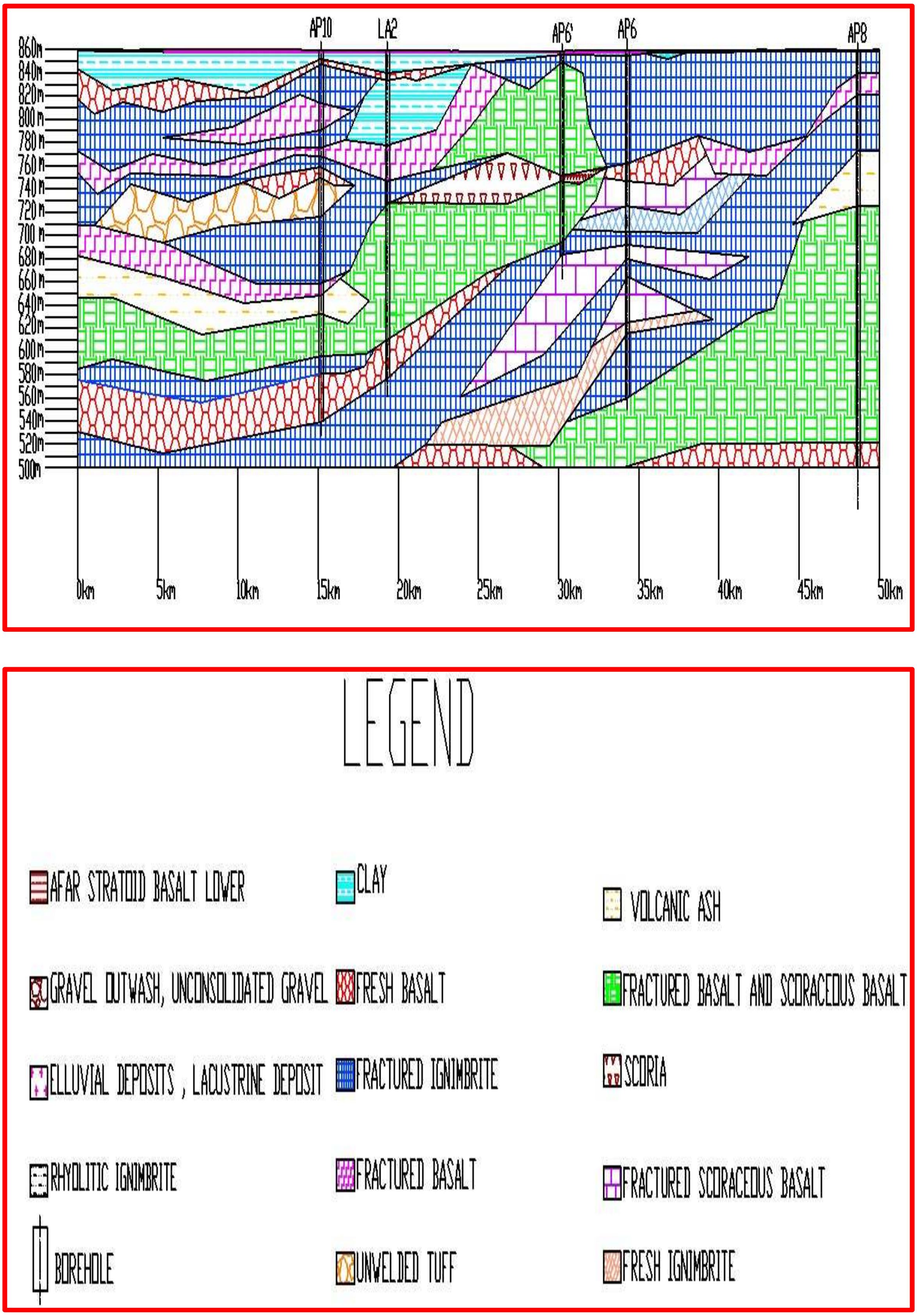


Figure 2. 4 Longitudinal cross-section from A to B showing the geology of the study area in the north south direction

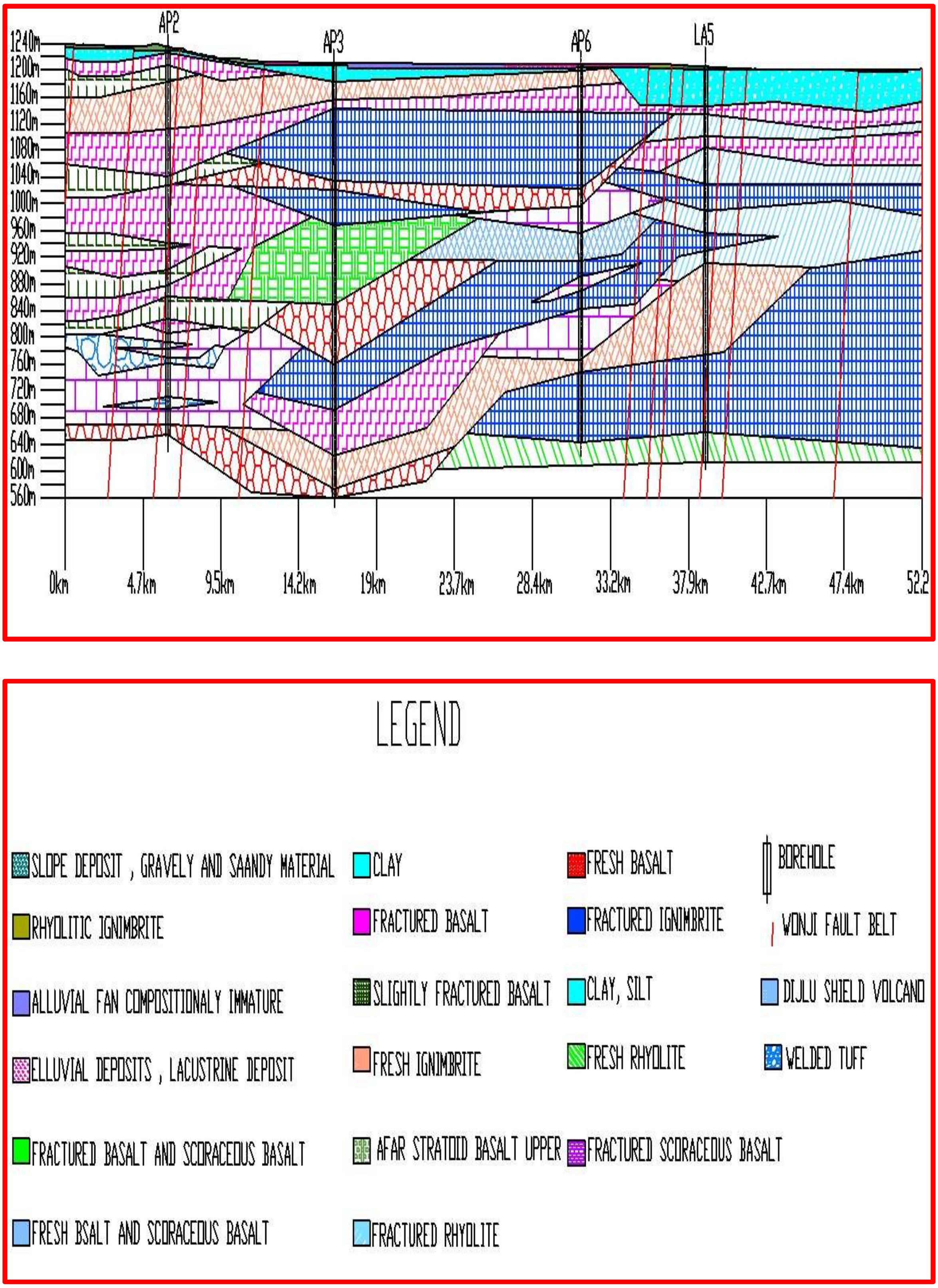


Figure 2. 5 **Longitudinal cross-section from C to D showing the geology of the study area in the North West – South East direction.**

2.5 Hydrogeological setting

With the rapid evolution of the basin through the plio-Pleistocene, a reasonable thickness of the alluvium and volcanic accumulated in the bottom of Awash Valley (Halcrow 1989).

Alluvial deposits cover only the western part of the Alleydege plain while the North-North east running, high standing geomorphology in the east central part are rhyolitic volcanic centres and the eastern marginal water catchments form part of the eastern Ethiopian highland**.**

The hydrogeology of the region is intimately associated with the geological features. In the highlands, the Ashenge Group fractured volcanics is favorable for highland recharge, formation contact and fault- controlled springs at different elevations. Some impermeable volcanic layers regionally restrict vertical flow and favours formation of contact springs in the escarpments. The presence of less permeable layers reduces deeper recharge in the lower escarpment slopes. Locally, regional faults may allow preferential flow at deeper levels. Groundwater flow modeling in the adjacent Ziway–Shala basin revealed that groundwater in highland volcanics flows substantially at a relatively shallow depth and percolates in the lower aquifers through large marginal faults before it reaches the rift floor (Ayenew, 2001).

The groundwater level of the Alleydege plain varies spatially. The western side of the Alleydege area, mainly western part of Awash Arba- Gedamitu road, is known to possess shallow groundwater with static water level less than 60meters. Especially the groundwater level around Melka Sedi and Melka Worer (LA4) area is over the surface. The eastern and the north eastern part of the Alleydege area, in particular, eastern, south eastern and north - eastern part of the Awash Arba – Gedamitu road generally has deep groundwater whose static water level extends to a depth of 150 meters.

The analysis of water points in the study area demonstrates that there are shallow wells and hand dug wells, deep wells and springs. Nevertheless the dominant water point in the area is boreholes. Among the six hand dug wells inventoried only one of them is still functional. It was possible to get water samples for isotopes and chemical analysis from this hand dug wells located around Keleat area, north of the Alleydege plain. The rest of the hand dug wells are not working either due to the lowering of the water level below the depth drilled or malfunctioning of the installed pump. Recently dug undeveloped hand dg wells around Keleat area shows that the water level is at near surface at about 3 meters below the ground.

The majority of the shallow wells are drilled and concentrated in the alluvial, western part of the Alleydege plain where it possibly gets its recharge from irrigation back water, Awash River, or both. Only some shallow wells drilled in the utmost south of the Alleydege plain drilled through the weathered basalt to a depth of 37 meters. Boreholes drilled passing through the volcanics to a depth of 272m, for instance around Bordede towns are found in the area. Furthermore there are thirteen deep test wells with almost complete hydrodynamic data (Static water level/Depth to groundwater, borehole discharges, specific yield and transmissivity) which were recently drilled under the study and supervision of WWDSE to a depth of penetration reaching to 350 meters. However, only two test wells, AP2 around Silsalabure and AP5 around Hardim, area currently servicing their surrounding community were sampled for isotopes and chemical analysis.

There is one hot spring, SP4, about Billen area. The temperature of this spring was measured at two different times; one at the end of September, 2010 and the other at the beginning of January, 2011 more or less, at the same time, at about 2 to 3 pm in the afternoon. The temperature of the spring in September was about 41^0c and in January was 42^0c, almost attaining constant temperature throughout the three months duration. The spring covers relatively larger area into which cattle and human can swim. The existence of such spring could be deciphered as surface manifestation of geothermal field.

2.5.1 Types of aquifer and aquifer characteristics

In general the Alleydege area is characterized by two different forms of aquifer characteristics, the shallow groundwater or aquifer and deep groundwater or aquifer systems.

a. Shallow aquifer system

This aquifer system in general extends throughout the Awash River valley in the river alluvium sediments of sand and gravel with clay. The aquifer system in most places consists of sand and gravels being found in a semi confined nature below a sandy clay layers and sometimes found in unconfined system. This situation is observed from the different shallow wells and open dug wells drilled on the river banks of Awash. The shallow wells observed at Billen, Sheleko, Melka-Worer, and Melka-Sedi (Kerensa) where a shallow sand and gravel aquifer system are encountered under a sandy clay layers at a depth of around 30 meters for the wells drilled to a depth of 50 meters exemplifies the semi confined nature of sand and gravel aquifer systems.

The summer rainfall results in seasonal floods ultimately recharging the alluvial aquifers. This groundwater recharge is estimated to be 10% of the rainfall (Halcrow, 1989). The water levels in wells drilled in the alluvial aquifer rise up to a depth of 10-15 meters and a well yield of about 5.7 l/s with a relatively lower draw down of 2 meters and higher transmissivity values. Nonetheless the transmissivity for the same aquifer system but with more clay intercalation is lower and the draw down values are higher; for instance the Hasoba deep well has a transmissivity value of $31.88m^2/d$ and a drawdown of 14 meters. Permeability of aquifers is reduced due to the presence of clay material. The unconfined shallow aquifer units as observed from open dug wells close to the river bank of Awash, such as, Keleat, Hasoba, Ambash, Sheleko and Melka-Sedi, the water level in the clayey sand exists at very shallower depths 3-7 meters below the ground surface (WWDSE, 2009).

The major granular sediments derived from hydro-geomorphologic processes, and their permeability characteristics subsequently reflected, are qualitatively evaluated and summarized as:

Major unconsolidated deposits Permeability

i) Alluvial: river side deposits (gravel, sand and fines) -------------------- high
ii) Alluvial fans: high level terraces along river beds (inter fingering of coarse and fine sediment-- very high
iii) Colluvials: incoherent and loose deposits of fine medium to coarse Sediments--- very high

b. Deep aquifer system

The deeper aquifer units in the area are generally volcanic rocks (basic, intermediate, acidic varieties) and intrusive type in origin.

The fracture pattern of volcanic rocks may create a type of porosity known as fracture porosity, which could, in turn, affect permeability. Permeability of a mass of rock units depend on collective permeability of the fractures of the inter-connecting system.

Ayenew et.al., 2007, verifies that deep groundwater is associated with fractured volcanics. The various flows of the Trap Series form multi-layer aquifers in the highlands. The layers are separated by paleosoils and river gravel. Locally, the existence of faults creates semi-confined aquifers. Very deep groundwater (up to 274 m) occurrence is encountered in southern Awash valley.

Most of the shallow & deep wells tap water from deeper aquifer system i.e. fractured volcanics and volcanic sands particularly for the areas adjacent to the Awash River grabens, i.e., the Alleydege plains and its related pediment plains and upland areas to west and east of the river valley. This is a highly weathered and fractured aquifer interbeded with old pediment gravel existing at a depth of 80 to 350 meters confined between massive volcanic units. The depth of boreholes drilled particular to the Alleydege plain ranges in depth from 80 to 310 meters with absolute groundwater elevation of 728 to 846 meters a.m.s.l. The yield of these boreholes varies with maximum of 50 l/s around Molalita area and minimum of 2.95 l/s about Kerensa –Deyilu area. The maximum drawdown is 42.6 m corresponding to the borehole with the minimum yield .The transmissivity of the boreholes varies spatially with maximum of 3952 m^2/d observed around Molalita area close to the foot of the horst that separates the plain from the river grabens. The higher transmissivity value is due to secondary porosity in fractured basaltic aquifer which is resulted from recent intense tectonic event (development of WFB) that caused the formation of the horst separating the Alleydege plain from the Awash Valley River graben. The minimum drawdown is 10 m observed around Hardim area, close to the foot of the ridge, which separates the plain from adjacent upland.

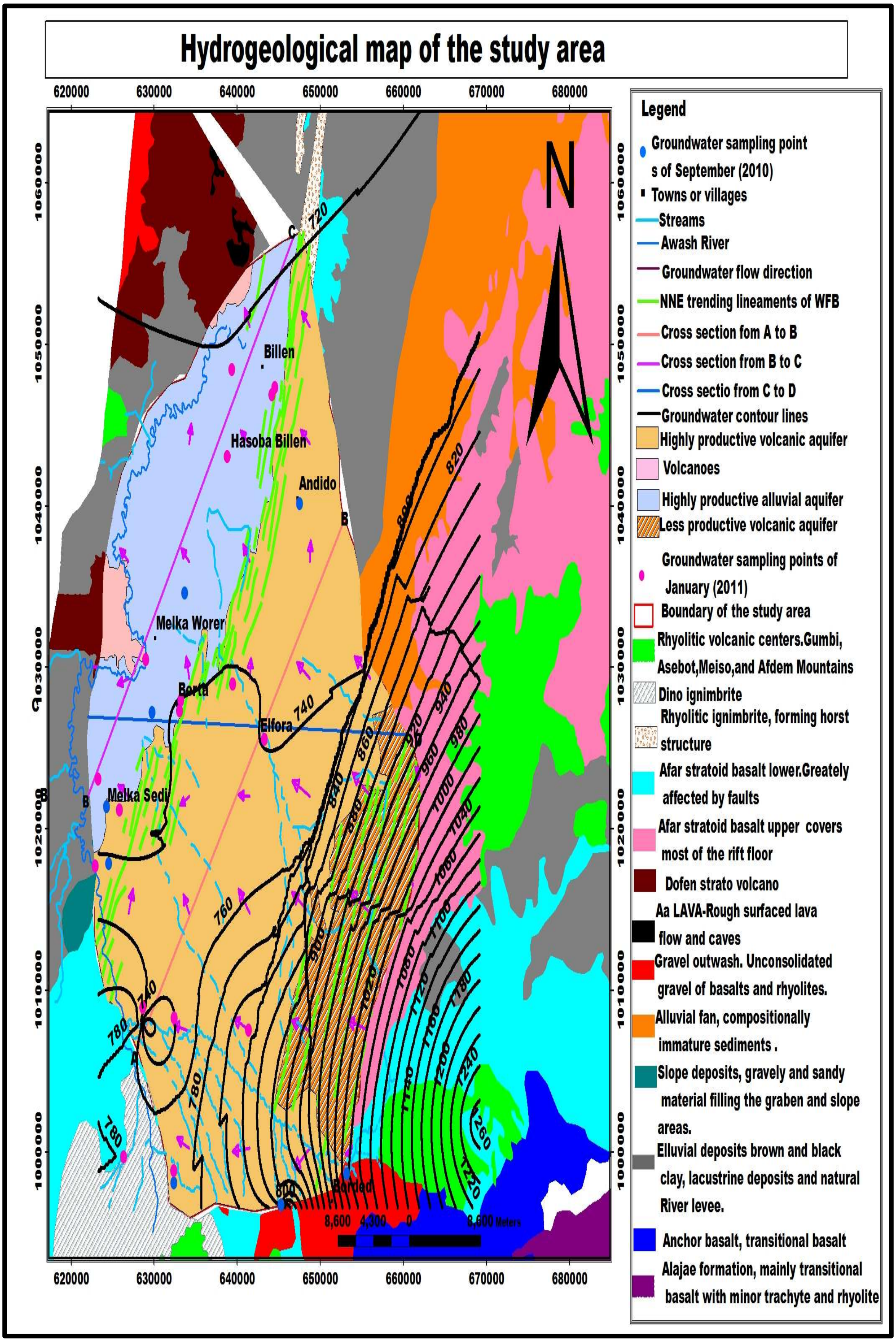


Figure 2. 6 **Hydrogeological map of the study area (Source: WWDSE, 2009, unpublished inception Hydrogeological report)**

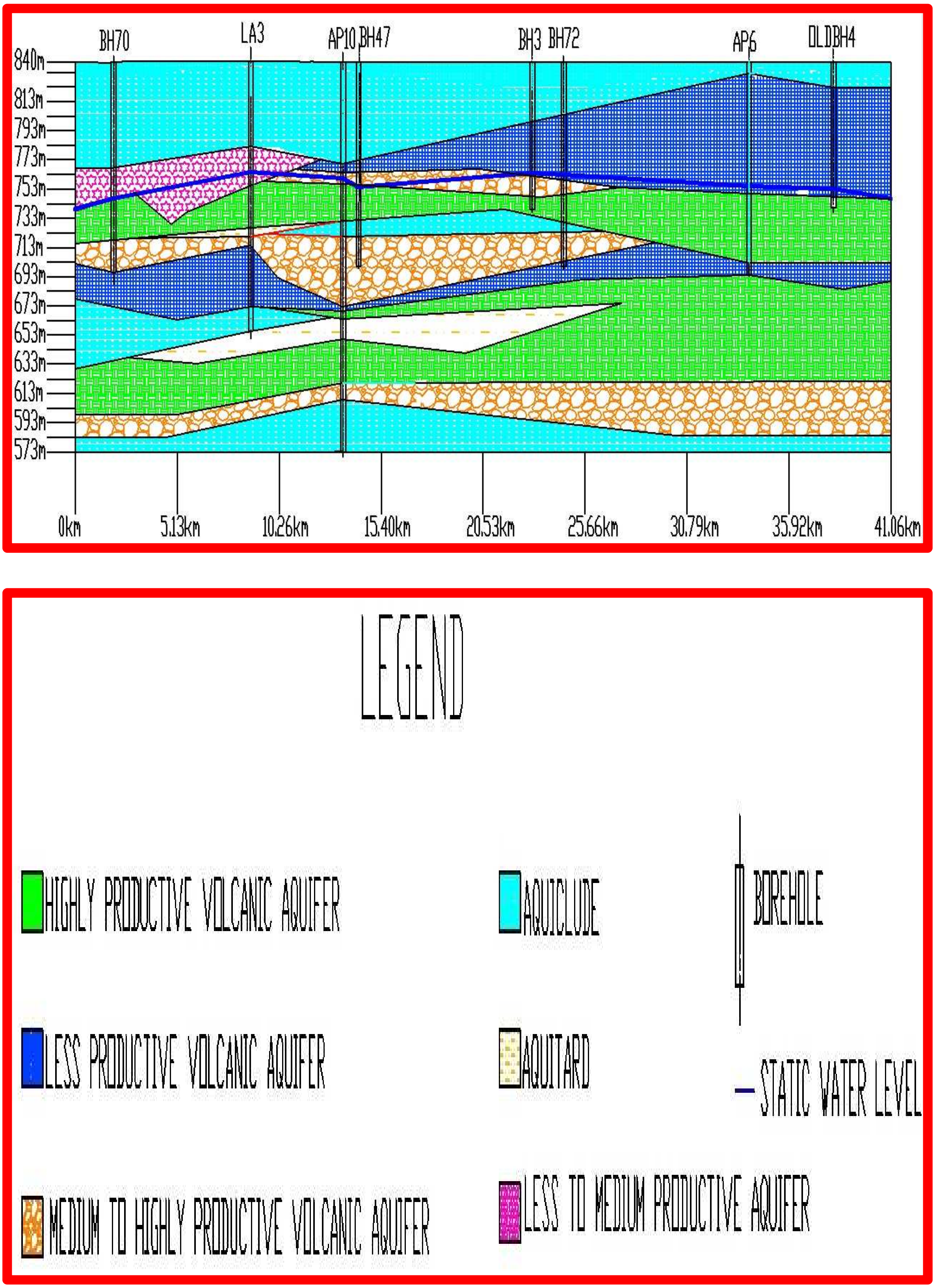


Figure 2. 7 Longitudinal cross-section along the line A to B showing the hydrogeology of the area in north-east south west direction (Alleydege plain)

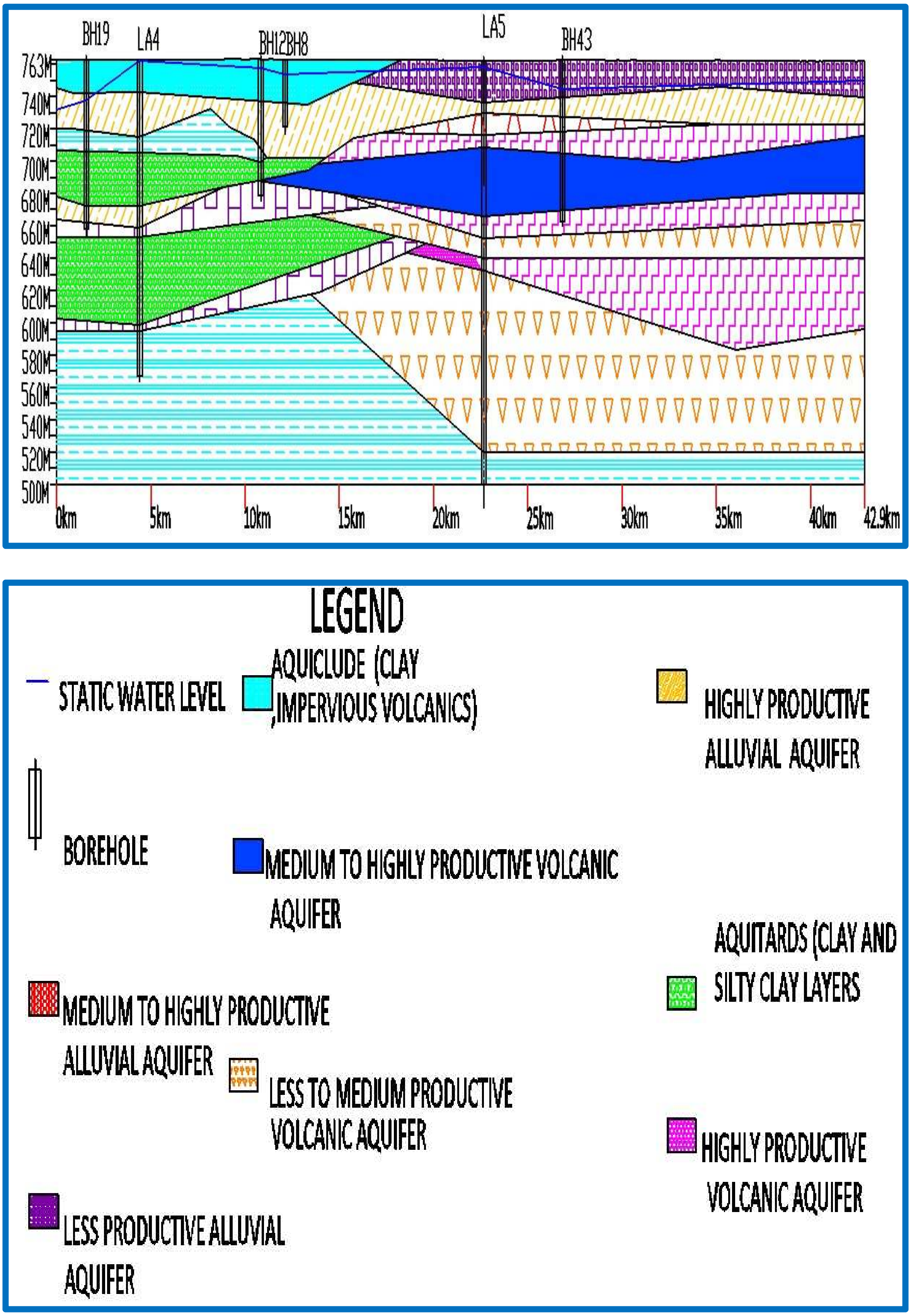


Figure 2. 8 Longitudinal cross-section along the line B to C showing the hydrogeology of the area in north-east south west direction (Awash River valley and rift floor).

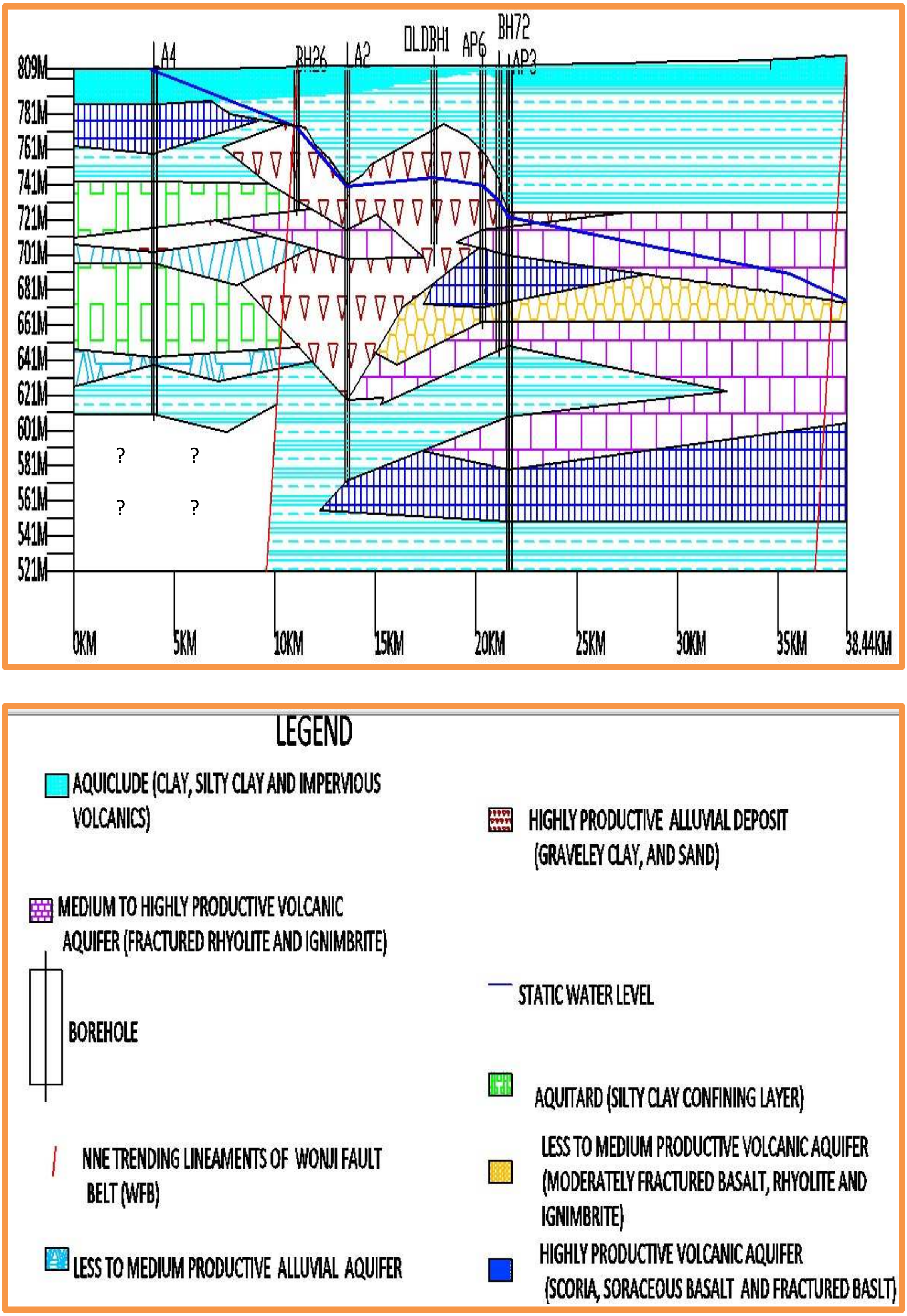


Figure 2. 9 **Longitudinal cross-section along the line C to D showing the hydrogeology of the area from West to East (rift floor, Awash River valley and Alleydege plain).**

The Ethiopian rift system represents the northern half of the East African Rift that consists of three zones with distinct volcanic assemblages and tectonic features. These are the Afar Rift system to the north, the Main Ethiopian Rift (MER) valley at the central and the south western part. The central sector is more than 200 km long and about 75 km wide. The Afar rift forms a triangular depression formed by triple tectonic interactions of the Red Sea and Gulf of Aden oceanic rifts with the continental MER. Rift extension in the MER is generally NW-SE (Mohr and Wood, 1976; Korme et al., 1997) and it is strongly affected by NNE-SSW oriented active normal faults of the Wonji Fault Belt (WFB) on the east and the Silti−Debre Zeyt Fault Zone (SDZFZ) on the west, with a large displacement of about 1500−2000 m between the rift floor and the plateau (Mohr 1962, Di Paola, 1972; Woldegabriel et al.,1990).

Previously as an integral component of the Awash River basin the Alleydege plain was studied for its potential groundwater resource by Ethiopian Ministry of Water Resource (MWoR), Food and Agricultural Organization (FAO), Water Works Design and Supervision Enterprise (WWDSE) and some individuals on general and regional levels. To state the reviewed previous works;

I. *Alleydege Plain Groundwater Resources Evaluation Project Hydrogeological Report, Water Works Design and Supervision Enterprise (WWDSE), 2009*

In this report the primarily intended work as per the agreement between the MoWR and WWDSE was to drill 16 test wells and 4 observation wells for the purpose of hydrogeological investigation of the Alleydege plain. However due to some inconvenience only 13 test wells were drilled and of which on 8 of them pumping test was conducted and the rest work was suspended. Despite the created data gaps, on the basis of the available data, the report classified the Alleydege plain in to two groundwater bearing formations: the unconsolidated sediment aquifer with intergranular permeability, and extensive volcanic aquifers with fractured permeability. The report concludes that the unconsolidated aquifer is highly productive where as the fractured volcanic aquifer is moderate to highly productive.

The report also stated that the Alleydege groundwater plain receives its recharge mainly from direct infiltrations of rainfall followed by indirect recharge from Awash River and then from subsurface percolations from highlands of adjacent slopes. Altogether the crude estimated annual groundwater recharge to the basin using Darcy method was defined to be 112 x 10^6 m^3.

II. *Hydrogeology of the Alleydege Plain and its Environs (Middle Awash Valley, Afar Region), prepared by Asfaw Aymeku, Unpublished Msc.thesis, Addis Ababa University, 2006.*

This report stated that the Alleydege plain has got a deep groundwater system whose groundwater level varies northwards from 60 m to more than 80 m over the plain. Fractured basalts and ignimbrite interbeded with old outwash plain gravels and volcanic sand is the major aquifer unit of the area and its related pediments. Groundwater recharge to these aquifers is most possibly from precipitation on the eastern mountain range. The Aquifer units in the Alleydege plain relatively shows better transmissivity Values than the alluvial aquifer of the river valley. Transmissivity values ranges from 200-600 m^2 /d with minimum drawdown of less than three meters. The major source of recharge for the aquifer of the river valley is the indirect percolation of the Awash River to the valley.

III. *Geomorphic geological and Groundwater studies in the Awash valley, prepared by D.T.Currey, Hydrogeologist consultant FAO, 1972.*

This report evaluated the available groundwater resource of the middle awash valley. The study was accompanied by drilling and conducting pumping test on three boreholes each with a depth of 100 m located in different localities. From the pumping test result the report concluded that the valley has got sufficient groundwater resource. Furthermore the report also revealed that the valley has got its major recharge from the Awash River where the aquifer is exposed to the river along the river course.

IV. *Additional Geomorphic, Geological and Groundwater Studies in the Awash Valley, D.T. Currey, FAO, May 1973.*

This report also discussed about the groundwater resource potential of the valley by employing additional geologic and geomorphic studies. The study further stated that by deepening the boreholes additional aquifer that strengthens the availability of enormous amount of groundwater beneath the Alleydege plain can be encountered.

V. *Hydrogeology of South Afar and Adjacent areas (Ethiopia) supported by interpretation of Landsat imagery, prepared by Mezmure Haile Meskale, Unpublished Msc.thesis, International Institute for Areal Survey and Earth Sciences (ITC) Enschede, The Netherlands, December 1983.*

This study tried to decipher possible hydrogeological information from the interpretation of Landsat imagery covering an area of about 175000 km^2 for an area that encompasses southern Afar and adjacent escarpments and some parts of the Ethiopian and Ethio-Somalian Plateau.

This report presented a hydrogeological map and report of South Afar and adjacent areas by integrating various hydrogeological data with information obtained from interpretation of Landsat imagery. The study focused on a hydrogeological system of an almost closed basin that only considers surface water inflow from the southern part and precipitation as input components. The only output considered is evapotranspiration. Groundwater inflow into the basin is considered to be equal to groundwater outflow from the basin.

The study concentrated on various aspects of input and output relations and analyses different aspects, such as climate, hydrology, geology, geomorphology, and vegetation.
The water balance of eleven catchments, sub- basins and basins is calculated in different ways on a monthly and yearly basis. The report stated that in all the methods, the order of

magnitude of the water that is stored in to the whole area is about 55 millimeters per year. Beside that this study also used and statistically analyzed hydrochemical data of 139 water samples.

VI. *Earth Resources Technology Satellite I Uses and Additional Groundwater Studies in the Awash Valley. D.T. Currey, FAO, April 1974.*

Like the previous report the objective of this report was evaluating the groundwater resource potential of the Alleydege plain by adopting new scheme which is EARTH Resources Technology Satellite I Imagery and description and logs of new boreholes. This study also concluded that there is extensive amount of groundwater in the Alleydege plain.

VII. Groundwater Resources of the Alleydege Plain by Ketema Tadesse and Heroic Ferdinand, 1983.

In this report the study covered an area of 1950km^2 for the area that extends from Awash Arba to Gewane towns. The study was conducted to investigate the groundwater resource of the Alleydege plain.

As per the study the area is dominated by alluvium with some volcanic outcropping and the hydraulic conditions disclose that ground water is conveyed from the surrounding alluvium and the volcanic aquifers to the Awash River. Moreover the groundwater level of the plain ranges from 60 m to 80 m depth with groundwater temperature range of 39^{o}c to 43^{o}c.

VIII. Master Plan for the Development of Surface Water Resources in the Awash Basin, Final report, Volume, EVDSA, HALCROW, December 1989

This report demonstrated that the awash valley acts as a sink that receives recharge from through flow from the escarpment slopes and direct infiltration from the rainfall. The depth to groundwater level ranges from 60 to 90 m and the well yield from such boreholes ranges from 1 to 10 l/s which the report mentioned that exploiting the groundwater from such aquifers is not feasible. Furthermore the report stated that fluoride concentration of the area ranges between 1.2 mg/l and 3.3mg/l while the TDS of the area extends up to 8000mg/l.

IX. Well Completion report on wells drilled in Awash Arba and Awash Sebat Kilo, WWDSE, 2004

This, well completion report portrayed two boreholes drilled in Awash Sebat kilo and Awash Arba military camps. The water strike point for the Awash Sebat Kilo borehole is at a depth of 160 m while the Awash Arba is at a depth of 180m.The water quality analysis result of this boreholes show that the groundwater is suitable for both drinking and domestic uses.

4 METHODOLOGY AND DATA

4.1 Methodology

Representative set of samples were collected from 24 active water supply boreholes penetrating different lithological units (annex 1 and 2). Boreholes prior to sampling had been pumping for several years. Sampling was also taken from one hot spring and Awash River.

Temperature, electrical conductivity, total dissolved solids (TDS), and PH were measured in the field using EC-Meter and thermometer to ensure the inclusion of atmospheric contamination and to improve measurement stability.

All stable isotopes measurement was carried out at Addis Ababa University where as inorganic major cation and anion measurement was carried out at laboratory of Water Works Design and Supervision Enterprise (WWDSE).

4.1.1 Isotopes (deuterium, oxygen-18) and hydrochemistry (major ions) techniques

A) Isotopes (deuterium, oxygen-18) technique

Deuterium and $\delta^{18}O$ in natural waters are subject to fractionation processes during their transport between the earth`s surface and the atmosphere. These processes are sometimes easily interpreted and can yield valuable information on particular parts of the water circulation. However, the fractionation processes are often complicated by subsequent mixing processes in the atmosphere, which makes interpretation more difficult.

Deuterium and oxygen – 18 are stable isotopes of water and are found in all waters in proportions which are determine by their abundances on earth and on small differences in their physical properties as compared with the main bulk species, hydrogen and oxygen–16.

The stable isotope species of the water molecule are HDO^{16} and H_2O^{18}. Both have slightly lower saturation vapour pressures than the ordinary water molecule H_2O^{16}. In all evaporation and condensation processes there will therefore be a slight fractionation of deuterium and oxygen – 18. They are somewhat enriched in the liquid phase and depleted in the vapour phase. As a result different sources of recharge (e.g. precipitation vs. surface waters) and rain falling at different times during the year (e.g. dry season vs. rainy season) feature different isotopic signatures. It follows that under favorable conditions, the timing of direct recharge events may be deduced through a comparison of the isotopic signatures in groundwater with those of precipitation. In addition, the interaction between the groundwater system and the regional surface water bodies may be explored.

The depletion and enrichment of deuterium and oxygen – 18 in different condition along with water chemistry also enables to characterize spatial heterogeneity between the Awash River and the riverbank [alluvial] aquifers.

Measurement of the stable isotope composition of salinized water is a useful method for discriminating the cause of salinity because water that is saline due to evaporation will be isotopically more enriched than the source water, whereas water that is saline due to salt addition or transpiration will not change isotopic composition.

Isotopic abundances may be given by their isotopic abundance ratios, for instance $_2H/_1H$ or $^{18}O/^{16}O$. For practical reasons, instead of using the *isotope ratio* R, isotopic compositions are generally given as δ values, the relative deviations with respect to a standard value, as defined by:

$$\delta = \frac{\text{Rsample}}{\text{Rstandard}} - 1$$

Where R represents the ratio of heavy to light isotope (e.g.$^{2}H/^{1}H$ or $^{18}O/^{16}O$)

The accepted standard for the isotopes in water is VSMOW (Vienna Standard Mean Ocean Water), which is close to the original standard of SMOW as defined by Craig (1961b). These abundances are the values reported for the reference standard VSMOW, defining the value of δ= 0 on the VSMOW scale. The δ values of water samples are then given as:

$$\delta_{\text{VSMOW}} = \frac{\text{Rsample}}{\text{RVSMOW}} - 1$$

4.1.2 Q-mode Hierarchical cluster analysis

The hydrochemical data have been used to categorize the waters into different objective water classes on the basis of Q-mode statistical cluster analysis. Statistical classification of geochemical data by Q-mode hierarchical cluster analysis (HCA) has been proven to provide a suitable basis for objective classification of water composition into hydrochemical facies (Meng and Maynard, 2001; Güler et al., 2002, Güler and Thyne2003; Kebede et al., 2005). Q-mode statistical cluster analysis is conducted using Microsoft- Excel addinsoft XLSTAT _Pro version 7.5.2 program to describe the major hydrochemical facies in the study area, and to gather information on groundwater circulation patterns, hydrochemical evolution, and interactions between the groundwater and Awash River and finally to use these hydrochemical facies as tracers to identify groundwater flow paths in the aquifer system of the Alleydege plain. In addition to that, the Q-mode hierarchical cluster analysis (HCA) is also used to see the water types and investigate the presence of any temporal changes in the water quality. This classification is useful especially to understand geological controls on water chemistry under conditions where useful geochemical data are available but clear hydrogeologic models have not yet been developed.

The term hierarchical cluster analysis (HCA) encompasses a number of different algorithms and methods for grouping objects of similar kind into respective categories. This tool sorts different objects into groups such that the degree of association between the objects is maximal if they belong to the same group and minimal otherwise.

In this study, and in order to perform HCA, an agglomerative hierarchical clustering was developed using a combination of the Ward's linkage method as a clustering algorithm and Euclidean distances as a measure of similarity. The Euclidean distance is the geometric distance in multidimensional space. Ward's method is known to be distinct, as it uses an analysis of variance approach to evaluate the distances between clusters. The result of such analyses is a graph, called dendrogram.

For the analysis only the 11 most common variables (specific conductance, pH, Ca, Mg, Na, K, Cl, SO_4, HCO_3, CO_3 and temperature) were used in the statistical analysis. These data were analyzed in Q-mode in order that similarities between specimens or samples could be discovered (Ashley and Lloyd, 1978,). The advantage of HCA is that many variables such as physical, chemical or isotopic composition can be used to classify waters. In order that the variables have equal weight the raw chemical data should first be log-transformed and standardized. This restricts the influence of or the biases caused by the variables that have the greatest or the smallest variances or magnitudes on the clustering results. The database treatment procedures and detailed explanation of the hierarchical cluster analysis technique used by this study can be found in the article by Swanson et al., 2001.

4.1.3 **Inverse geochemical modeling**

As part of a systematic and sequentially developed groundwater hydrochemical evolution

model, inverse geochemical models were done and have been used based on the water chemistry for each group and the mineralogy of the area.

(Thyne et al., 2004; PHREEQC, Parkhurst and Appelo, 1999; Plummer et al., 1983; Kenoyer and Bowser, 1992; Varsanyi and Kovacs, 1997; Hidalgo and Cruz-Sanjulian, 2001; Wang et al., 2001).This tool is very essential to determine the type and amount in moles of minerals that dissolve or precipitate along a groundwater flow path. In the presence of information on the hydrogeology of the area, the flow path can be determined from hydrogeological knowledge of the area. The initial and the final member can be chosen by taking into account the location of the point, the hydraulic heads of the aquifer system and observed trends in chemical evolution of the water (Kenoyer and Bowser, 1992; Varsanyi and Kovacs, 1997; Hidalgo and Cruz-Sanjulian, 2001). In areas where information on groundwater flow direction is lacking, the initial and final waters can be selected from the HCA groups. This is based on the logical assumption that waters which fall in a statistical group may have similar residence time, similar recharge history, and identical flow paths or reservoir (Swanson et al., 2001; Gu¨ ler and Thyne, 2004). The PHREEQC computer code (Parkhurst and Appelo, 1999) was used to simulate the geochemical evolution among the average composition of statistical clusters.

4.2 Limitation related to field work and data

One of the major limitations to the field work in the study area is that boreholes are sparsely located and some boreholes are difficult to access by car; as a result, one has to walk through dense, poisonous, thorny trees despite the higher temperature of the area. Data on the hydraulic head distribution for the different aquifer system prevailing in the area are totally difficult to obtain. Monitoring boreholes do not exist, and hydraulic head measurements in the production boreholes would be influenced by abstraction of groundwater. Furthermore monitoring of hydraulic heads in production boreholes is not possible, unless hand pumps or electric pumps are dismounted from the boreholes. About thirteen deep test wells whose data would have been more realistic if they were accessed were recently drilled under the study and supervision of WWDSE for investigation purpose. Nevertheless, among the thirteen boreholes only in two of them pump is installed and groundwater sample can be obtained. The rest of the boreholes are simply left caped and could not be accessed. To access these boreholes it is required to have a welder with a welding machine and a grinding machine, a track, a generator and a groundwater sampler minimum to 170 m depth. This has not been realistic and possible as part of this research given the logistical problems, the additional workload, and the resistance from the local communities it would generate. Therefore, flow directions have been deduced based on the hydrochemical evolution of groundwater and hydrochemical facies.

Borehole logs are not available for many of the investigated boreholes. However, borehole depths and groundwater level are known for about half of the boreholes. The presence of hand dug wells, shallow wells, and boreholes let the analysis more difficult and complex since the samples collected from each scheme represent different aquifer system. Furthermore, because of lack of groundwater sampler, the sample obtained from a borehole cannot represent to a unique depth and specific aquifer rather it represents the borehole as a hole and so is for the result of the analysis.

Overall 34 deep wells (depth $\geq$ 100 m), 6 intermediate depth wells (depth between 60 and 100 m), 11 shallow wells (depth $\leq$ 60 m), 2 hand dug wells (depth $\leq$ 6 m) and 1 spring are taken from the previous works. Beside that two boreholes with stable isotopes of water and tritium and one borehole with ^{14}C and data are also taken from previous works. Overall the data are not complete; 75% of the boreholes lack borehole log, 25% of them lack data on static water level and 22% of all water schemes lack water quality data.

To assist this research new data of stable isotope for 24 groundwater samples one spring and one river (Awash River) together with water quality data are generated for the wet season (September, 2010) and dry season (January, 2011). For this research sampling points of boreholes are systematically selected in order to cover all over the area based on static water level.

Therefore despite the existence of data gaps it is reasonably possible to undertake this research with the available data of previous works and the primary data generated.

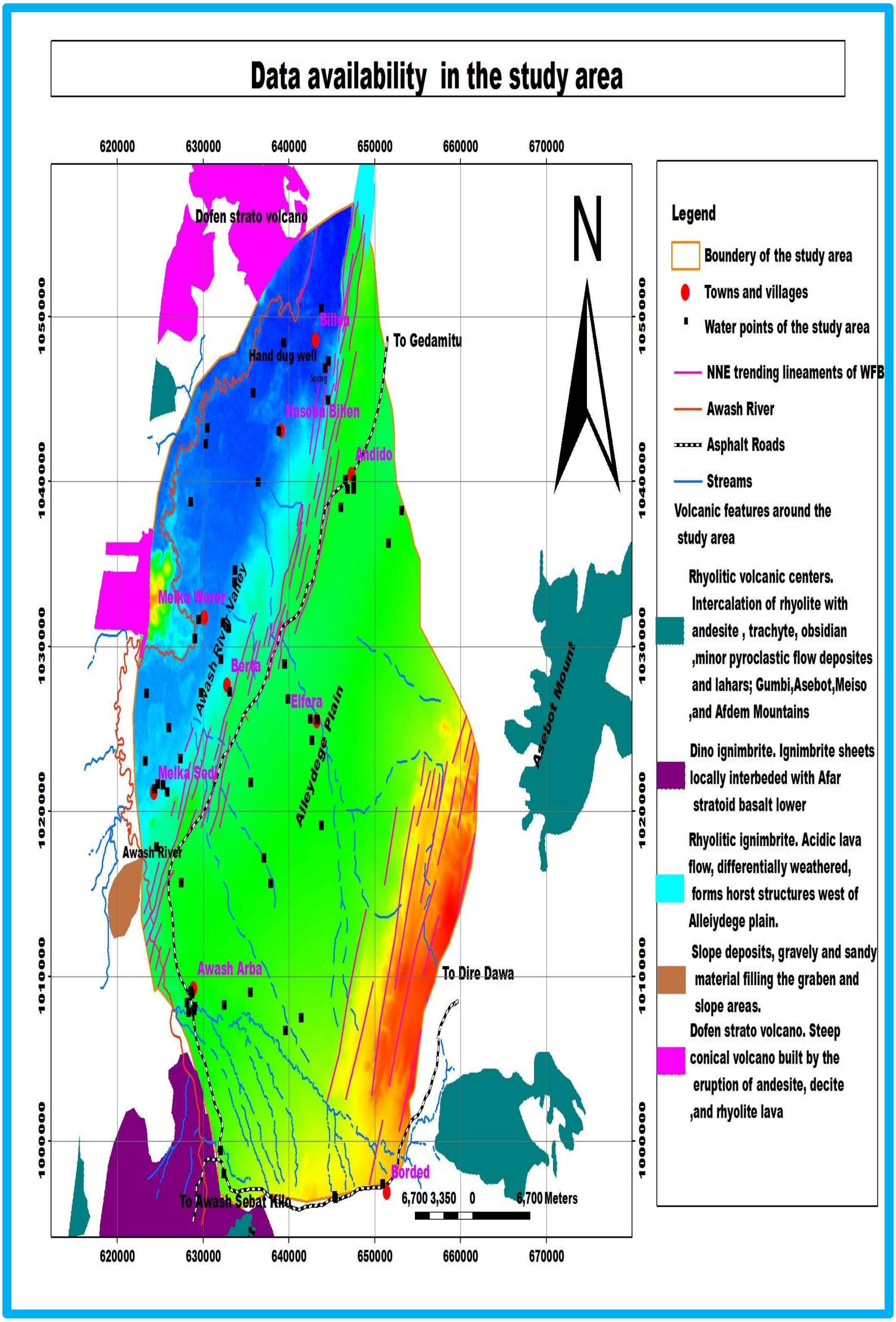


Figure 4. 1 Distribution of data availability in the study area

5 RESULTS AND DISCUSSION

For graphical and numerical analysis of hydrochemical data AquaChem software package 4.0 versions is used. This software package features a fully customizable database of physical and chemical parameters and it provides a comprehensive selection of analysis tools. In addition, AquaChem features a built-in link to the popular geochemical modeling program PHREEQC for calculating equilibrium concentrations (or activities) of chemical species in solution and saturation indices of solid phases in equilibrium with a solution. As a result the inverse geochemical modeling of the water quality data is analyzed by the geochemical modeling program PHREEQC which is linked with this Aquachem software package. Beside that areal distribution and trend of hydrochemical and isotopic data are analyzed by using graduated symbols in ArcGIS software packages.

5.1 Evaluation of chemical analysis results

- Data Quality

Prior to the analysis, the water quality results of the two sampling seasons are summarized in tables (5.2,and 5.3) providing additional water standards of Maximum Acceptable Concentration (MAC) of (European Union, 1998; WHO, 1993, 1998) and show the percentage of samples above maximum concentration limits.

In order to evaluate the correctness of the laboratory results various methods of reliability check are undertaken as per Hounslow (1995).The reliability check results of the analysis Show that over 90.5% of the total samples collected are within ≤ 5% calculation of reaction error for ionic compositions. This could be due to the presence of systematic error which could arise from overestimation of one or more cation species or underestimation of one or more anion species in the water.

Despite the presence of systematic errors in nearly 10% of the samples the overall quality of the data is within the acceptable range to accompany the research.

Test	Permissible value	Number of samples	Comments
Anion – Cation Balance % diff= $\frac{(cation-anion)}{(cation+anions)}$	>5%	2	9.5 % of the total samples collected (4.25% from shallow wells and 4.25 % from deep wells).
$K^+/(Na^+ + K^+)$	>20%	-	All the samples are < 20%
$Na^+/(Na^+ + Cl^-)$	<50%	-	All the samples are >50%
$Ca^{+2}/(Ca^{+2} + SO4^{-2})$	>50%	8	36.36 % of the samples collected of which 4.5% of Spring,22.72% of shallow wells and 9% of intermediate depth wells (Between 60 and 100 m depth)

Table 5. 1 Reliability check for the correctness of laboratory results for the samples collected at the end of the rainy season (September, 2010).

Test	Permissible value	Number of samples	comments
Anion – Cation Balance % diff= $\frac{(cation-anion)}{(cation+anions)}$	>5%	3	15.79 % of the total samples collected, from which 5.26 % is from Awash River and 10.53 % are from shallow wells
$K^+/(Na^+ + K^+)$	>20%	-	All the samples are < 20%
$Na^{+/}(Na^+ + Cl^-)$	<50%	-	All the samples are >50%
$Ca^{+2}/(Ca^{+2} + SO4^{-2})$	>50%	11	61.1 % of the samples collected of which 5.5% of Spring,5.5 % of hand dug well, 22.2% of shallow wells and 27.8 % of intermediate depth wells (Between 60 and 100 m depth)

Table 5. 2 Reliability check of the correctness for laboratory results of the samples collected during the dry season (January, 2011).

Parameter	Unit	Min.	Med.	Max.	EU standard	WHO standard	>MAC (%)
TS(105 ^oC)	Mg/l	298	584	1480			
TDS(105 ^oC)	Mg/l	238	580	1480			
EC	µS/cm	380	893	2320			
pH		7.31	7.79	8.61	>6.5 ,<9.5		
NH_3	Mg/l	0.16	0.23	0.45			
Na	Mg/l	35	122	500	200(MAC)		23.8
K	Mg/l	2.4	12	20.5			
Ca	Mg/l	2.28	22.8	79.04			
Mg	Mg/l	0.91	10.03	27.36			
Fe	Mg/l	0.01	0.04	0.02	0.2 (MAC)		
Mn	Mg/l	0.89	0.89	0.89	0.05	0.05	4
F	Mg/l	0.62	1.47	103.75	1.5	1.5	47.6
Cl	Mg/l	0.08	55.52	321.26	250		4
NO_2	Mg/l	0.01	0.01	5.02	0.5 MAC	200	
NO_3	Mg/l	1.14	5.55	420	50MAC	50	4
Alkalinity	Mg/l	126	354.9	609			
Carbonate (CO_3)	Mg/l	10.08	15.12	512.4			
HCO_3	Mg/l	73.02	353.56	742.98			
SO_4	Mg/l	0.94	56.36	161.53	250		
PO_4	Mg/l	0.36	0.7	1.12			

Table 5. 3 Analytical results [minimum (Min.), median (Med.) and maximum (Max.) values] of boreholes, hand dug wells , springs and Awash River collected at the end of the rainy season (September, 2010) in the study area.

Parameter	Unit	Min.	Med.	Max.	EU standard	WHO standard	>MAC (%)
TS(105 ^oC)	Mg/l	382	600	1360			
TDS(105 ^oC)	Mg/l	378	598	1356			
EC	µS/cm	579	916	2060			
pH		7.1	7.67	8.51	>6.5 ,<9.5		
NH_3	Mg/l	0.16	0.23	1.3			
Na	Mg/l	76	184	540	200(MAC)		27.77
K	Mg/l	2.7	11.4	26.20			
Ca	Mg/l	4.80	23.2	92			
Mg	Mg/l	0.96	5.76	16.32			
Fe	Mg/l	0.01	0.04	0.05	0.2 (MAC)		
Mn	Mg/l	-	-	-	0.05	0.05	
F	Mg/l	0.5	2.26	52	1.5	1.5	55.55
Cl	Mg/l	19.88	62.46	219.57	250		
NO_2	Mg/l	0.01	0.01	0.01	0.5 MAC	200	
NO_3	Mg/l	0.17	3.26	13.18	50MAC	50	4
Alkalinity	Mg/l	218.5	340	836			
Carbonate (CO_3)	Mg/l	20.52	23.4	34.2			
HCO_3	Mg/l	266.57	950.38	403.65			
SO_4	Mg/l	19.08	63.68	219.94	250		
PO_4	Mg/l	0.27	0.41	1.53			

Table 5. 4 Analytical results [minimum (Min.), median (Med.) and maximum (Max.) values] of boreholes, hand dug wells , springs and Awash River collected during the dry season (January, 2010) in the study area.

5.2 Groundwater quality

5.2.1 Groundwater quality and water quality indicators

The quality of groundwater depends on the composition of recharge water, the interaction between the water and the soil, soil-gas and rock with which it comes into contact in the unsaturated zone, the residence time and reactions that takes place within the aquifer.

The physical parameters such as temperature, pH, turbidity and the chemical parameters like, alkalinity, bicarbonate, nitrate, sulfate, fluoride, chloride, sodium adsorption ratio (SAR), total hardness and electrical conductivity are considered during the assessment of water quality of the study area.

5.2.1.1 Physical Parameters

- **Temperature**

The temperature of the study area ranges between minimum of 29.4^{0}C and maximum of 40.4^{0}C. The minimum temperature is observed in the shallow well of the Awash River valley and the maximum temperature is recorded in the shallow well of the Alleydege plain and the hot spring of Billen area. The spatial temperature variation shows that the southern, south eastern and eastern parts of the area are characterized by a relatively of lower temperature and the temperature gradually increases towards the rift floor along the flow direction. There is no appreciable temporal variation of temperature between the samples collected at the end of the rainy season and during dry season.

- **pH**

pH is the negative logarithm of hydrogen ion and it is characterized by a minimum of 7.31 at Awash Arba in the Alleydege plain and a maximum of 8.61 about Melka Sedi area in the Awash River valley. Generally 100% of the samples collected during the two sampling seasons are within the Acceptable concentration limits of WHO and EU standard for drinking water.

- **Turbidity**

The groundwater of the Alleydege plain is non turbide. One shallow well and a hand dug well lying close to the Awash River has a turbidity of 5 and 1.83 NTU (Nephelometric Turbidity Units). Two deep wells, AP2 in the Alleydege plain and New age lying close to the south eastern highlands, show 5.11 and 11 NTU each. The maximum turbidity is observed in the Awash River which is 212.8 NTU in the sample at the end of the rainy season, however, its turbidity normally lowered during the dry season.

5.2.1.2 Chemical Parameters

- **Salinity**

In general the groundwater of the area is characterized by low salinity of 126 to 358 mg/l around the south eastern and eastern highlands and the Alleydege plain. Nevertheless traveling to the rift floor along the flow direction the concentration gradually increases to a value of 409 to 609 mg/l. The areal distribution of salinity is inversely related with the concentration of Ca^{+2} ions while by and large it portrays an increasing trend with the concentration of HCO_3^- ion (fig.5.1, 5.2, 5.3). The south western, southern and south eastern parts of the study area are depicted by low HCO_3^- ions. The $HCO3^-$ions generally increases in the rift floor along the flow direction. The Ca^{+2} ions markedly decrease from south eastern and eastern highlands to the rift floor in the north western and northern directions displaying a general decreasing trend along the flow direction and areas of low salinity zones coincide with high Ca^{+2} ions. Beside that there is no significant temporal concentration variation of salinity in the samples at the end of wet season and during dry season.

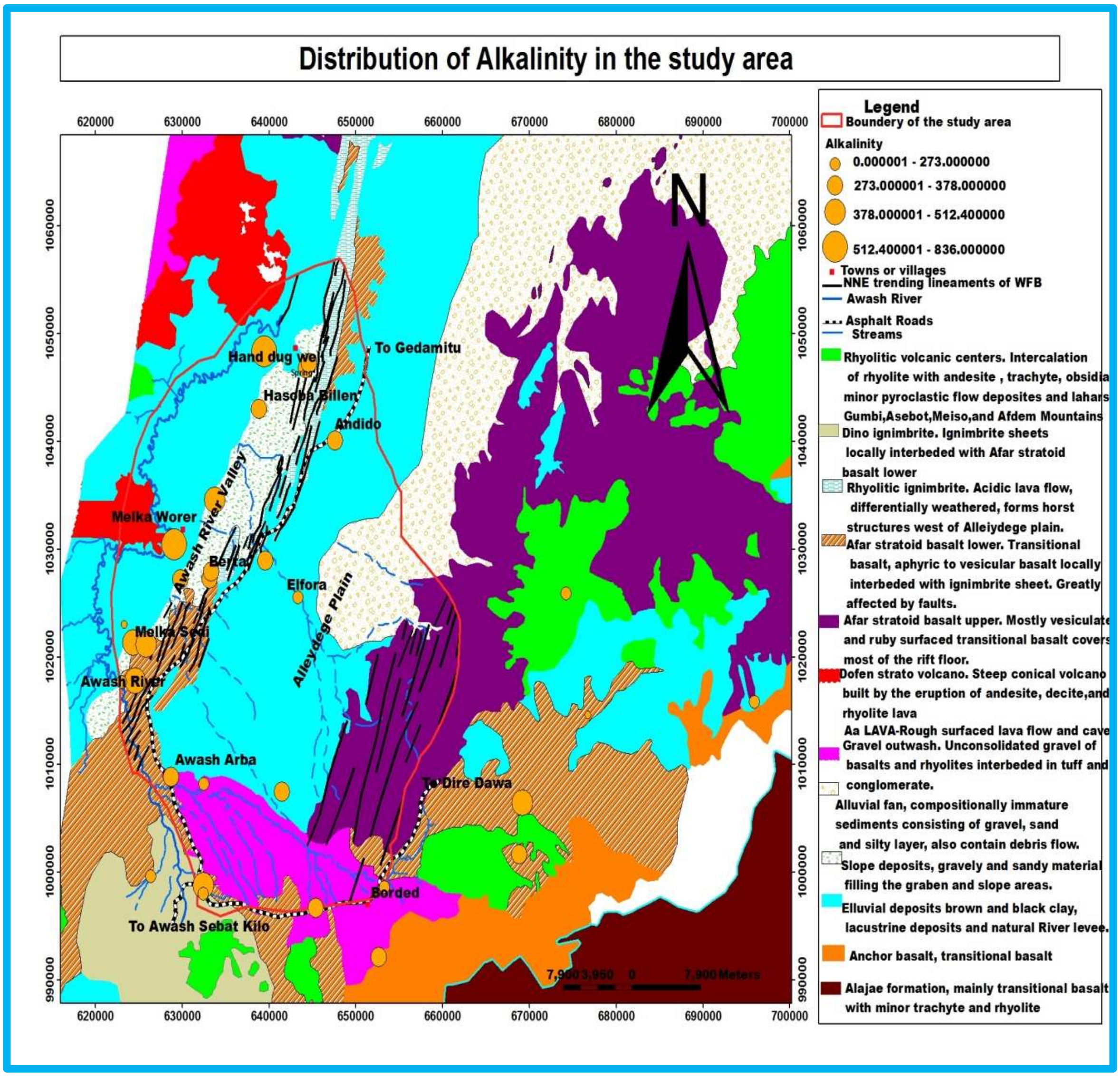


Figure 5. 1 distribution of Salinity in the study area

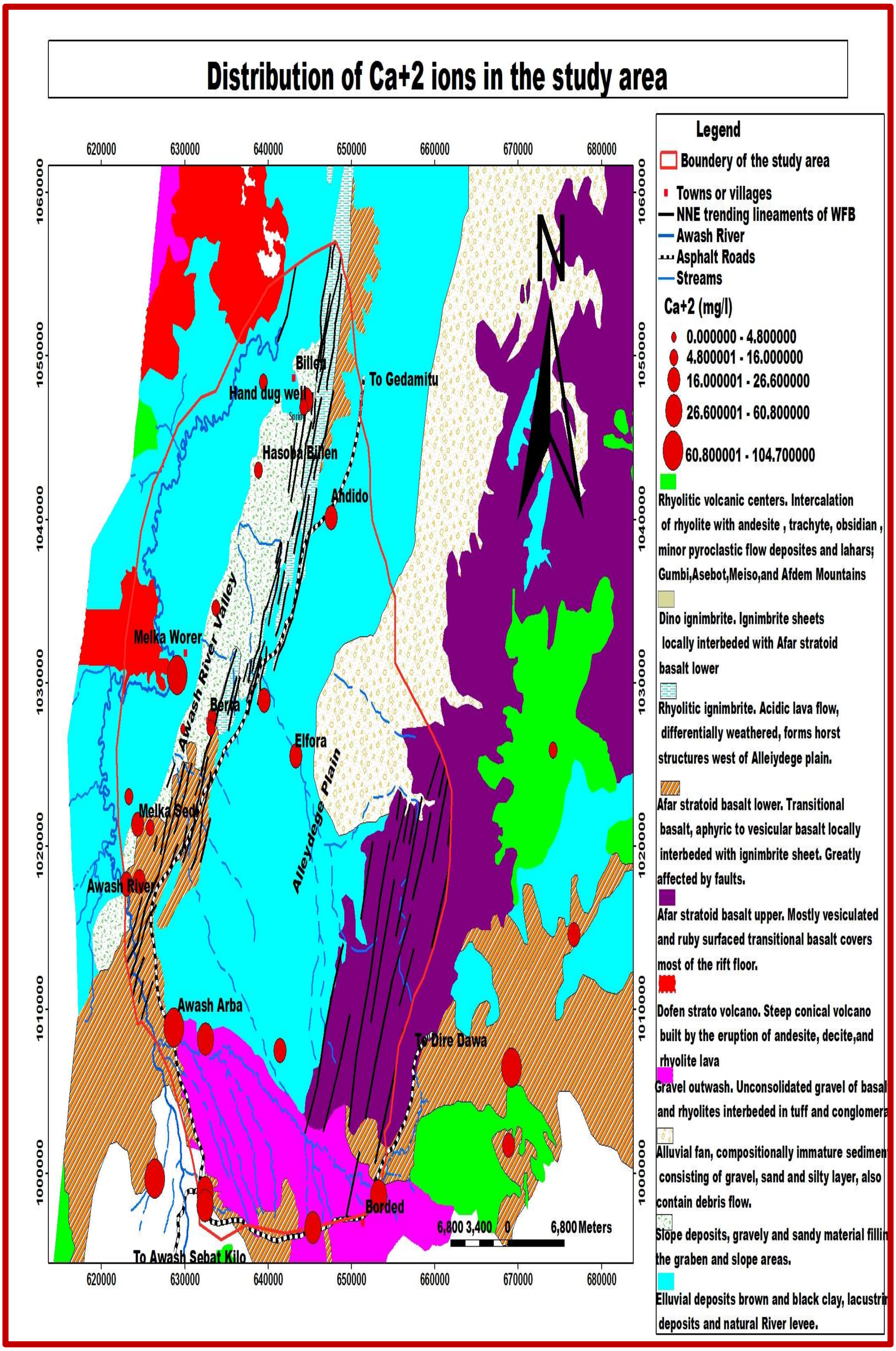


Figure 5. 2 Distribution of Ca^{+2} ions in the study area

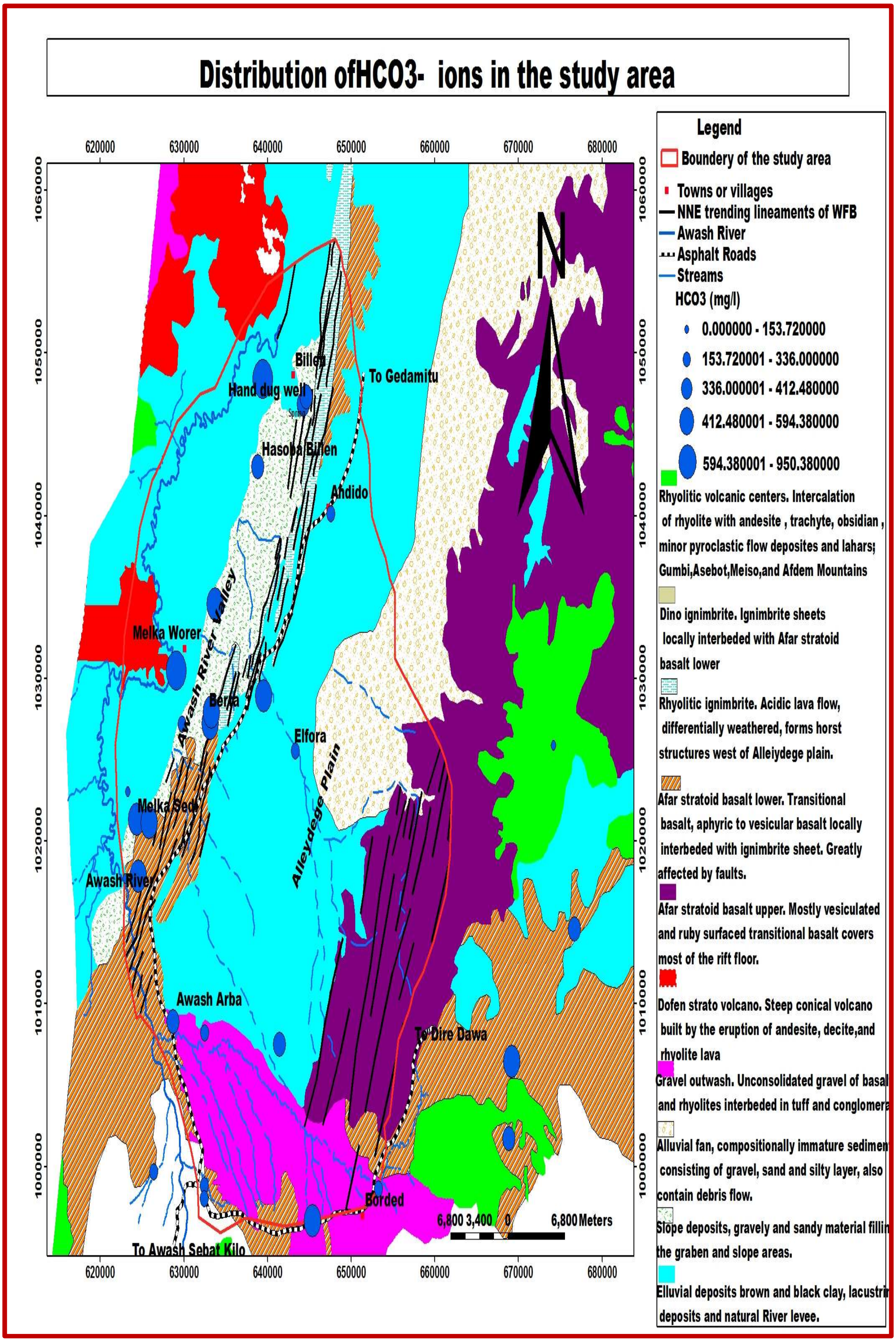
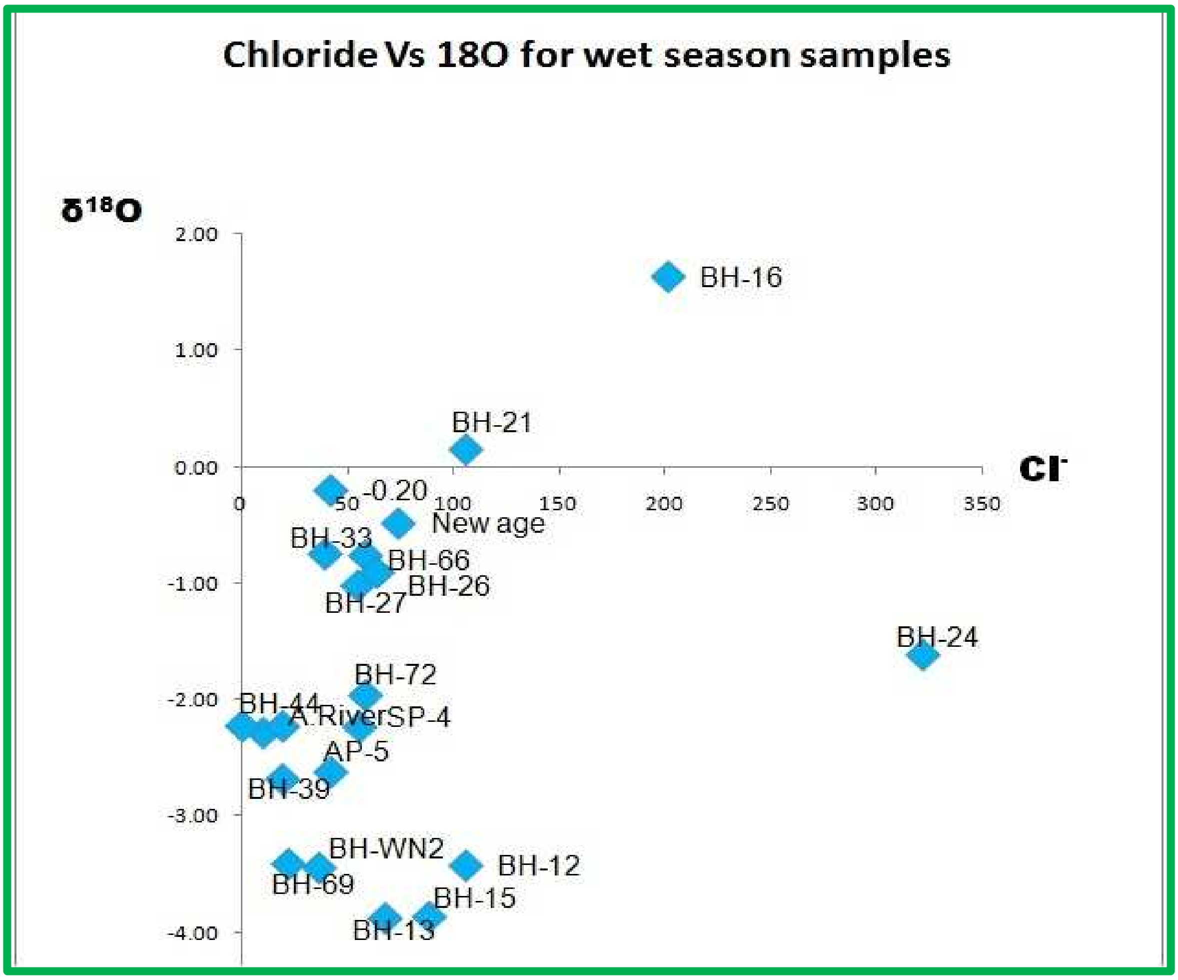


Figure 5. 3 Distribution of $HCO3^-$ ion in the study area

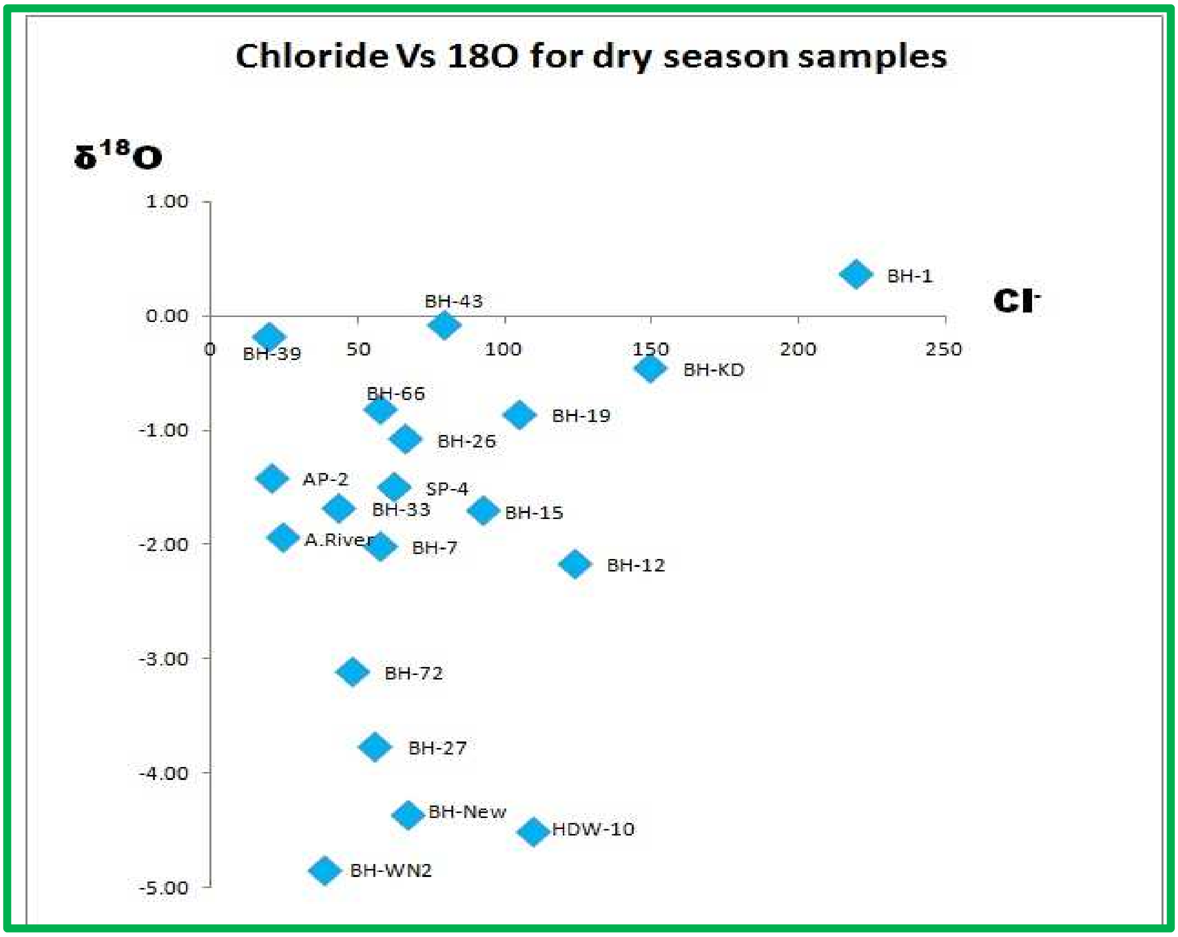
- **Causes of salinity**

Measurement of the stable isotope composition of salinized water is a useful method for discriminating the cause of salinity because water that is saline due to evaporation will be isotopically more enriched than the source water, whereas water that is saline due to salt addition or transpiration will not change isotopic composition.

The rise in the concentration of salinity is more pronounced in boreholes located in the Awash River valley and rift floor (fig.5.1). Boreholes of the Awash River valley for which measurement of stable isotopes of water conducted show enriched isotopic signatures while there is no significant change in the concentration of chloride ion. This condition elaborates that the cause of salinity in the Awash River valley and rift floor is due to salt addition by dissolution of salts from the soil of the alluvial aquifer. A similar event is observed for groundwater samples of the dry season where the groundwater samples portray isotopic enrichment while there is no change in the concentration of chloride ion. Therefore it can be deduced that the causes of salinity in the salinized areas of the Awash River valley and rift floor, for both the wet and dry season data, is mainly due to addition of salts by the process of dissolution (fig.5.4a, and b).



(A)



(B)

Figure 5. 4 **Correlation of $\delta^{18}O$ Vs chlorine (a= for rainy season sample, b= for dry season sample)**

- **Distribution of ions**

The dominant cations in the area are Na^+ and Ca^{+2} ions. $HCO3^-$ ions followed by chloride and sulfate ions are the dominant anions. The south eastern and eastern highlands` have Na^+ ion concentrations that lay within the acceptable limits of European standard (< 200 mg/l). Due to the hydrothermal effect which is the common activity in the rift valley, and the presence of enormous acidic volcanics, there is a gradual increase in the concentration of this ion towards the rift floor in the north western direction reaching to a value of 500 mg/l around Melka-Worer area (fig.5.5). Unlike the Na^+ which increases towards the rift floor, the Ca^{+2} ions concentration is high towards the highlands of basic volcanic rocks (fig.5.2).

Over all 23.8% of the samples collected at the end of rainy season (September, 2010) and 27.77 % of the samples collected during the dry season (January, 2011) show Na^+ ion concentration above the maximum Acceptable Concentration (MAC) limits of European Union and WHO standards for drinking water.

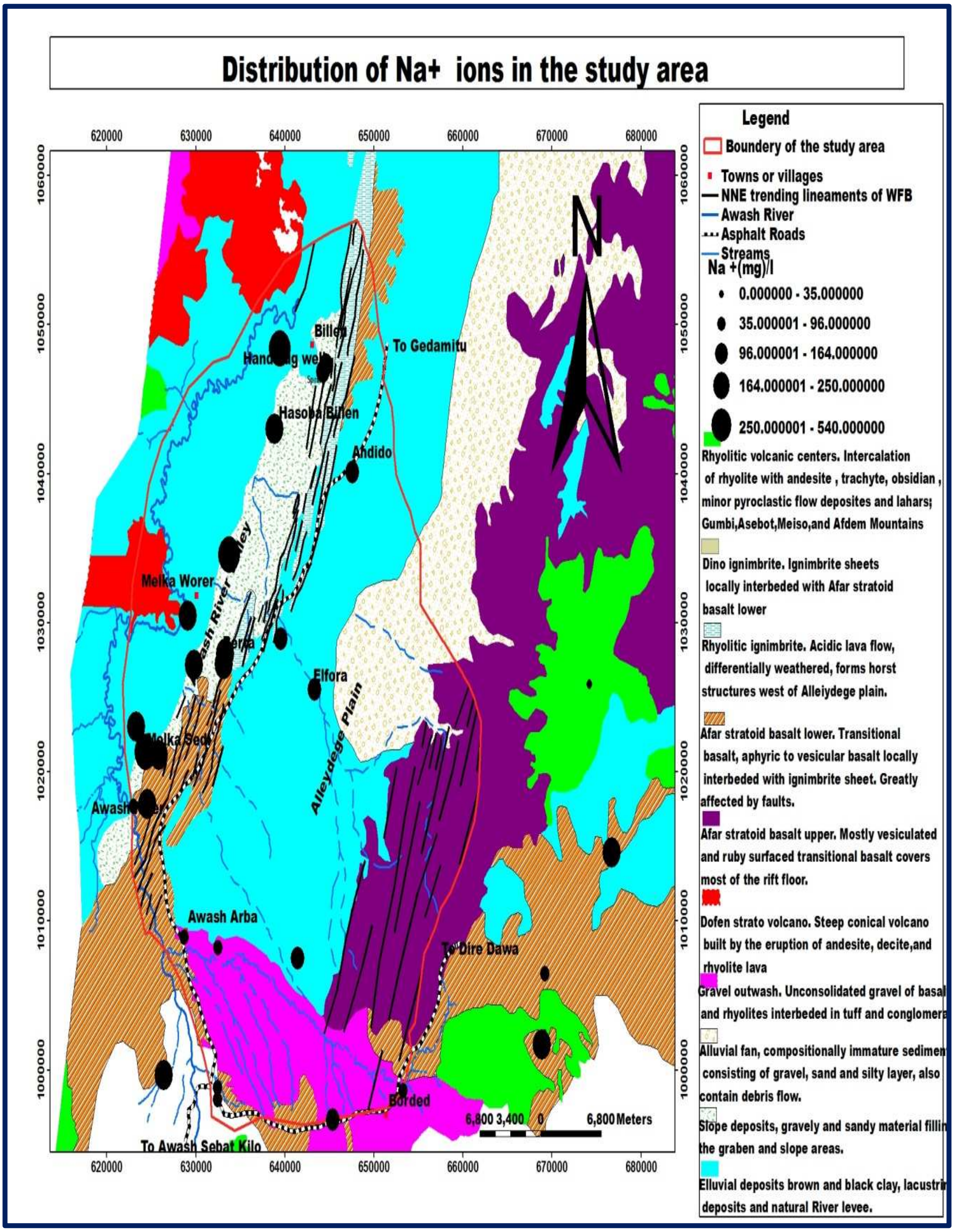


Figure 5. 5 Distribution of Na^+ ion in the study area

- **Nitrate**

About 96% of the samples analyzed for nitrate concentration in the area fall within the acceptable limits of EU and WHO standards (below 50mg/l).The rest 4% of the nitrate concentration which exceeds the MAC of EU and WHO standards is observed in the shallow wells, dug close to the Melka Sedi Camp, of the Middle Awash State farms. Shallow wells of this particular area show significantly higher concentration of NO_2/NO_3

that amounts to 420 mg/l. This might have pointed out towards contamination from fertilizers being used for the intensive state farming practice in the area. In addition to that human source and animal source of contamination are the other possible causes for the rise in NO_2/NO_3 concentration in this area. Wells with high NO_2/NO_3 values should be checked for bacterial contamination. The areal variation of NO_2/NO_3 portrays that the north eastern and south eastern parts of the study area are characterized by a relatively lower concentration while the south western part show a relatively higher concentration.

- **Sulfate**

The SO_4^{-2} ion concentration varies from a minimum of 0.94 mg/l to maximum of 161.53 mg/l. The majority of the shallow wells show higher concentration greater than 100 mg/l. However intermediate and deep wells have a relatively lower concentration of SO_4^{-2} ion that ranges between 17 mg/l and 78 mg/l.

The areal distribution of sulfate ion indicates an increasing concentration towards the rift floor along the flow direction in the Awash River valley. The Alleydege plain shows a relatively lower concentration of less than 78 mg/l. The southern and south western and south eastern parts of the study area are characterized by lower sulfate concentration of less than 57 mg/l.

The sulfate ion concentration depicts higher concentration in the samples of the dry season than the samples of the wet season.

- **Fluoride**

The fluoride concentration portrays a general increasing trend along the flow direction. The southern, south eastern and south western parts of the study area show a relatively lower concentration. On the other hand the northern, north western and north eastern parts take a relatively higher concentration of fluoride (fig.5.6).

About 47.6 % of the samples of the wet season and 55.55% of the samples of the dry season show fluoride concentration that exceeds the MAC of EU and WHO standards (<1.5 mg/l).

The minimum fluoride concentration in the area is 0.62 mg/l in the deep well of Awash Arba town water supply well found on the Alleydege plain and the maximum is 103.75 mg/l observed in the shallow well of Melka Sedi camp of the Middle Awash State farms located in the rift floor of the Awash River valley.

All over the area, the fluoride concentration in the shallow wells is recorded to be above the MAC of EU and WHO standard for drinking water. The majority of the shallow wells are found in the rift floor of the Awash River valley and hence the higher concentration of fluoride in these shallow wells is probably due to the hydrothermal process which is the common activity in such areas. The deep wells show fluoride concentration that lay within the acceptable concentration limits of EU and WHO standard.

The fluoride concentration of the wet season shows higher concentration as compared to the dry season.

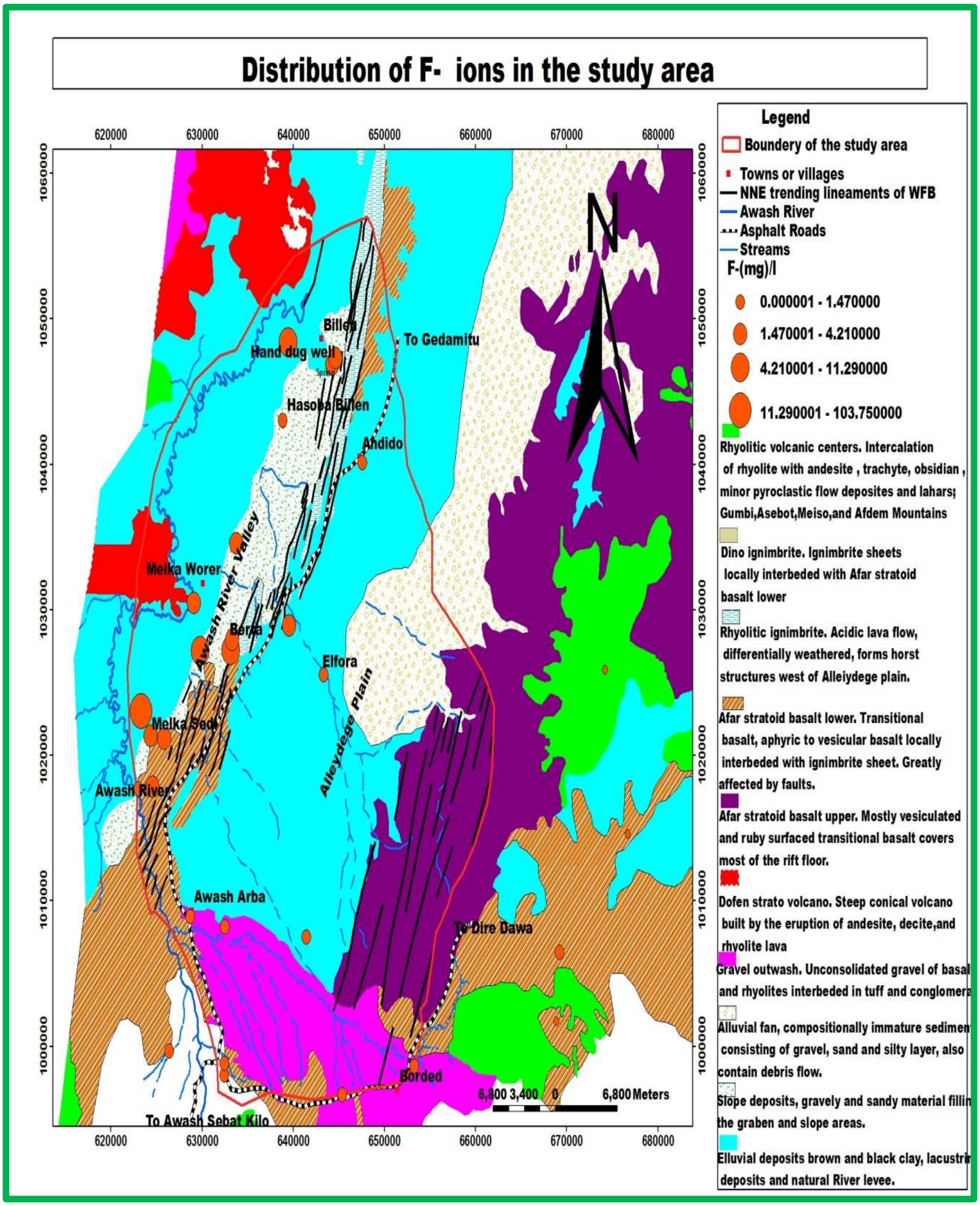


Figure 5. 6 Distribution of fluoride concentration in the study area

- **Chloride**

The chloride concentration shows an increasing trend from the topographic highs of the south western, south eastern and southern parts of the study area towards the rift floor along the flow direction. The maximum chloride concentration of the area is about 321 mg/l obtained in the shallow wells of the Awash River Valley around Melka- Worer area and the minimum is about 0.08 mg/l recorded in the shallow well of the Awash River valley about Melka-Sedi area.

- **Sodium Adsorption Ratio (SAR)**

The sodium adsorption ratio (SAR) is used to evaluate the suitability of water for irrigation and it is defined as:

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

The ratio estimates the degree to which sodium will be absorbed by the soil as elevated sodium in certain soil types can degrade soil structure thereby restricting water movement and affecting plant growth. High values of SAR imply that the sodium in the irrigation water may replace the calcium and magnesium ions in the soil, potentially causing damage to the soil structure.

The SAR distribution in the area is shown to increase along the flow direction. The south, south eastern, and south western parts of the study area are characterized by a relatively low SAR, while the northern, north eastern, and north western parts possess higher concentration of SAR (fig.5.7)

The maximum concentration of SAR is 40.85 meq/l and is found in the rift floor around the town of Melka –Worer and the minimum is 1.16 meq/l indicated in the eastern highlands about the area of Huse-Sodoma.

The Wilcox diagram in fig.5.8 shows that 35% of the samples are within low sodium hazard and medium salinity hazard zone. These water schemes are totally deep wells of the Alleydege plain and they are parts of the same cluster as per the result obtained from agglomerative hierarchical cluster analysis. Among the deep wells of the Alleydege plain, about 70% of the deep well groundwater samples show low sodium hazard and medium salinity hazard while the rest 30% of the deep well groundwater samples of this plain falls under low sodium hazard and high salinity hazard zone. The Awash River is characterized by low sodium hazard and medium salinity hazard. A total of 28.57 % of the water samples from various water schemes are within the medium sodium hazard and high salinity hazard zone. The majority of these schemes which cover about 66.6% are shallow wells of the rift floor in the Awash River valley. They belong to same cluster. Finally about 19 % of the samples are within high to very high sodium hazard and high salinity hazard zone. These are mainly shallow wells of the Awash River valley.

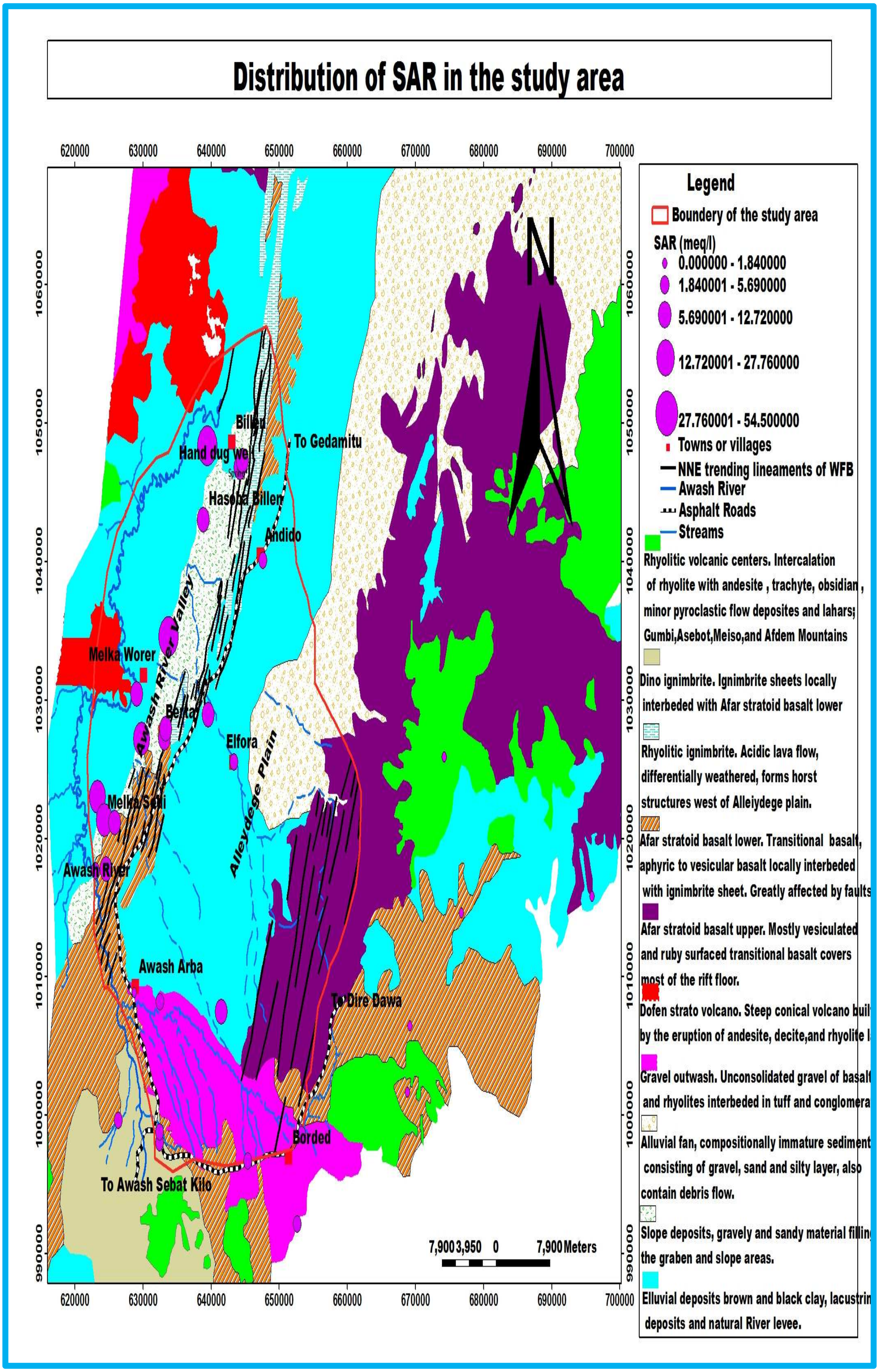


Figure 5. 7 distribution of SAR in the study area

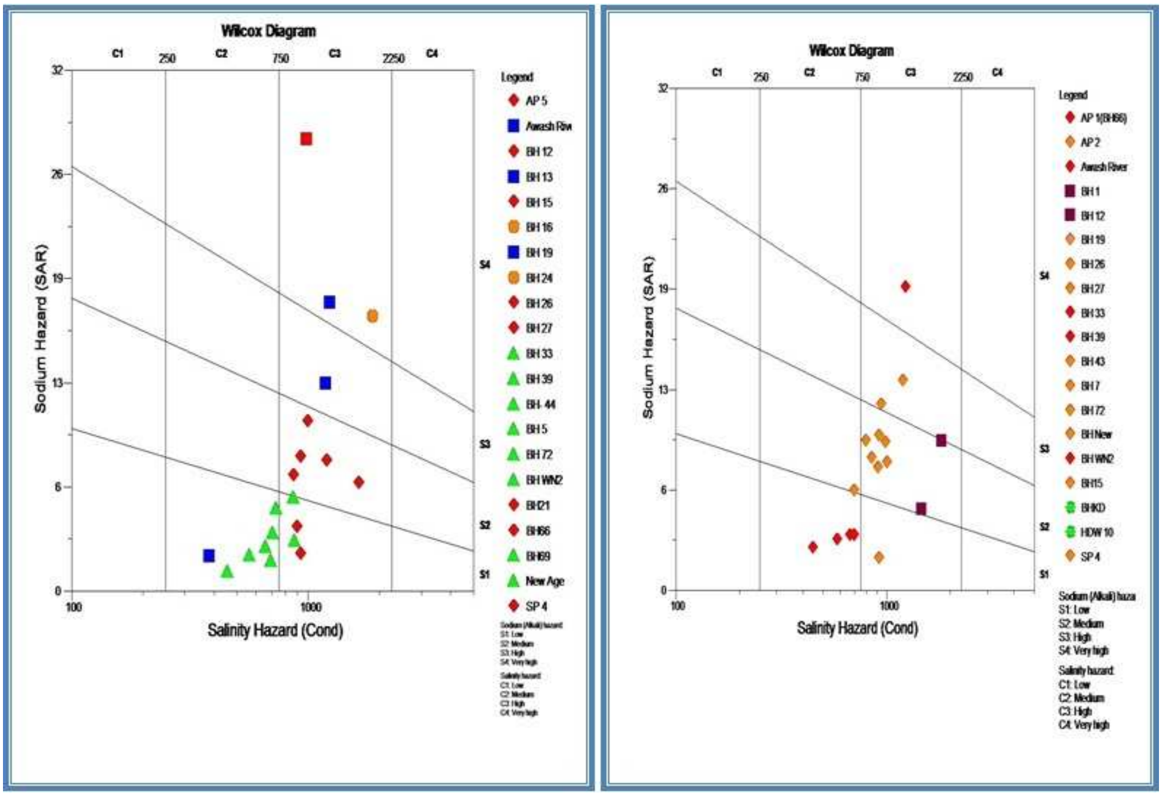


Figure 5. 8 (a) Distribution of SAR- salinity hazard (wet Season) (b) Distribution of SAR-salinity hazard (during dry season).

- **Electrical conductivity**

The electrical conductivity of the area increases along the flow direction towards the Awash River valley in to the rift floor from 454µs/cm in the highlands around Huse Sodoma to a maximum of 2230 µs/cm around Melka Worer town. Comparison of electrical conductivity of the shallow wells with deep wells in general shows that the shallow wells possess higher concentration of electrical conductivity. The Awash River takes the lowest concentration of electrical conductivity (380 µs/cm) in comparison to the shallow wells and deep wells of the study area. However comparison of the concentration of Awash River for the two sampling seasons depicts that the sample of the dry season possess higher concentration of electrical conductivity as compared to the samples of wet season. The correlations of the electrical conductivity with TDS shows that hat the two parameters are strongly correlated (fig5.9, 5.10, and 5.11).

Overall the electrical conductivity of the area shows an increasing trend along the flow direction (Fig.5.12).

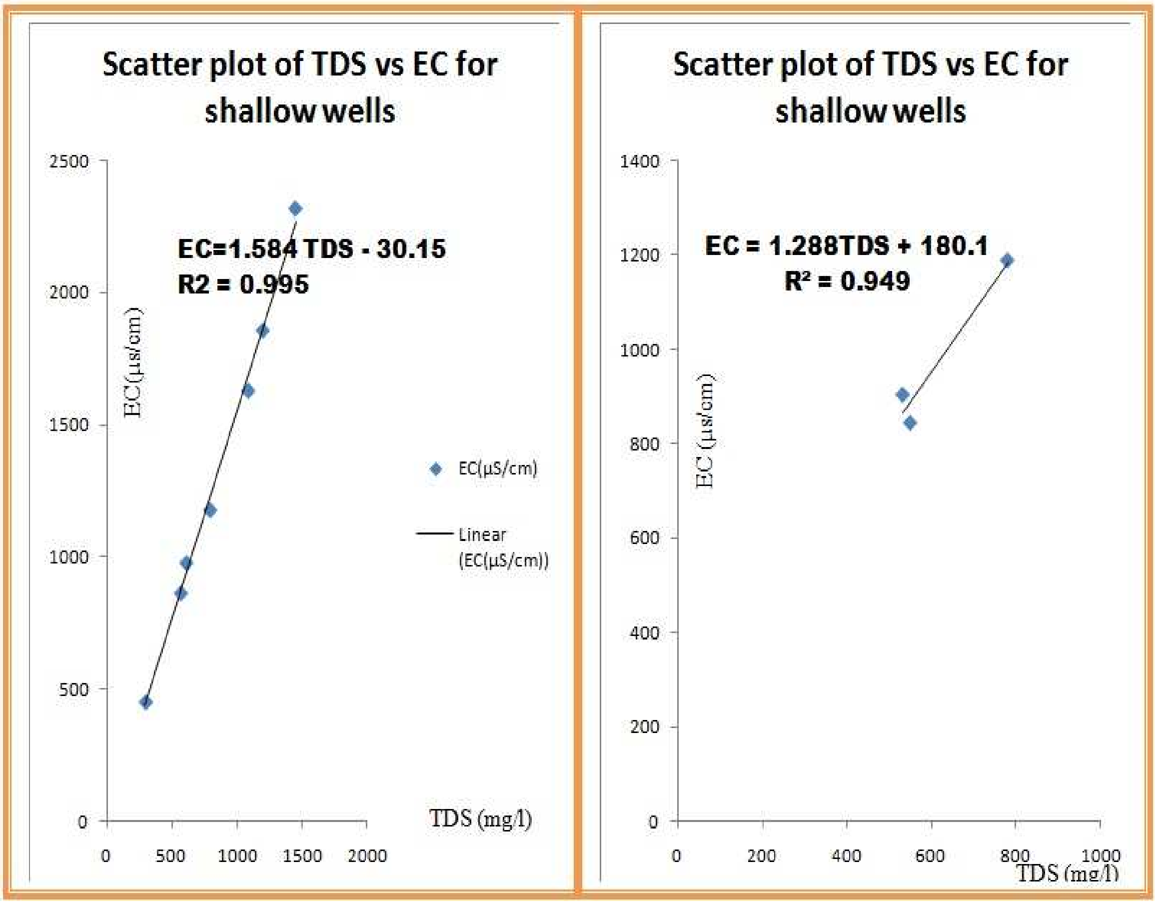


Figure 5. 9 **Correlation of electrical conductivity and TDS in the shallow wells (the left figure represent the wet season sample and the right for the dry season sample)**

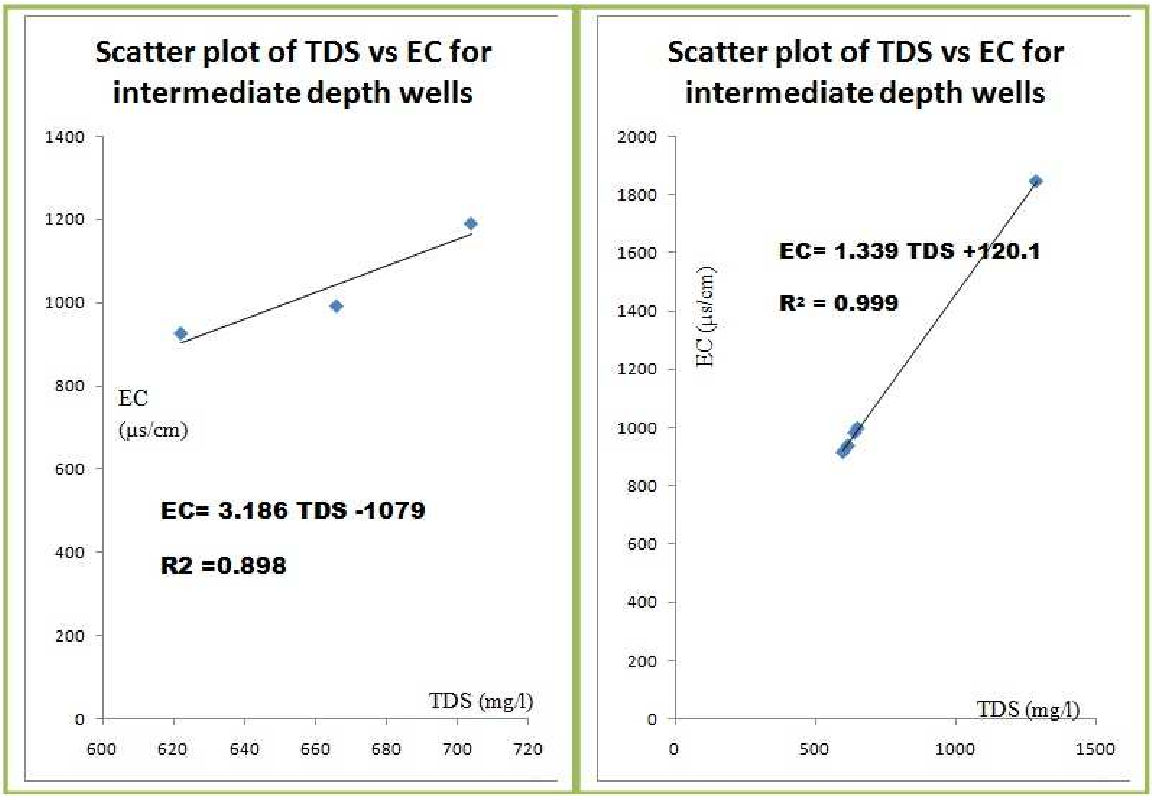


Figure 5. 10.Correlation of EC and TDS in the intermediate depth wells (the left figure represents the wet season sample and the right for the dry season sample)

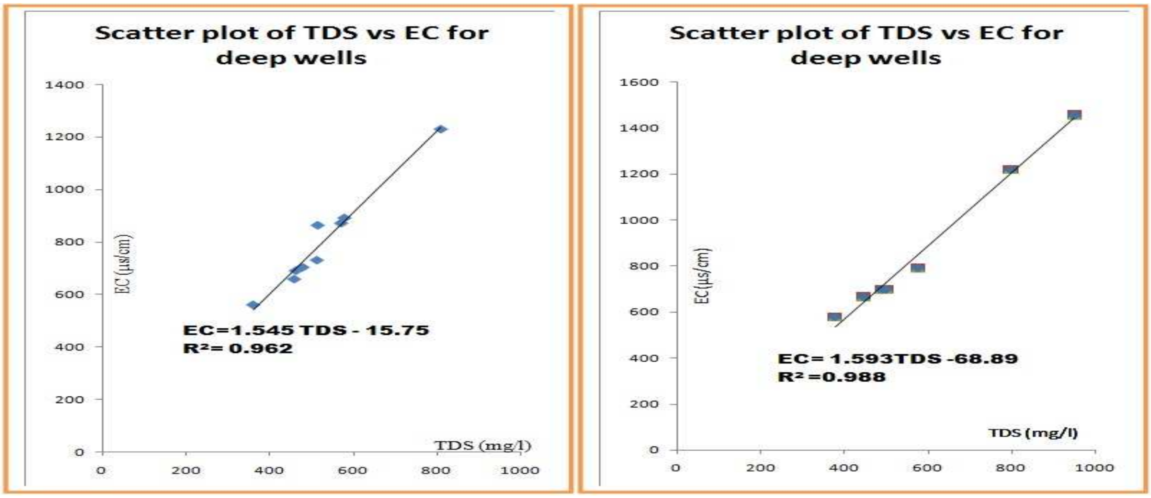


Figure 5. 11 Correlation of EC and TDS in the deep wells (the left figure represent the wet season sample and the right for the dry season sample)

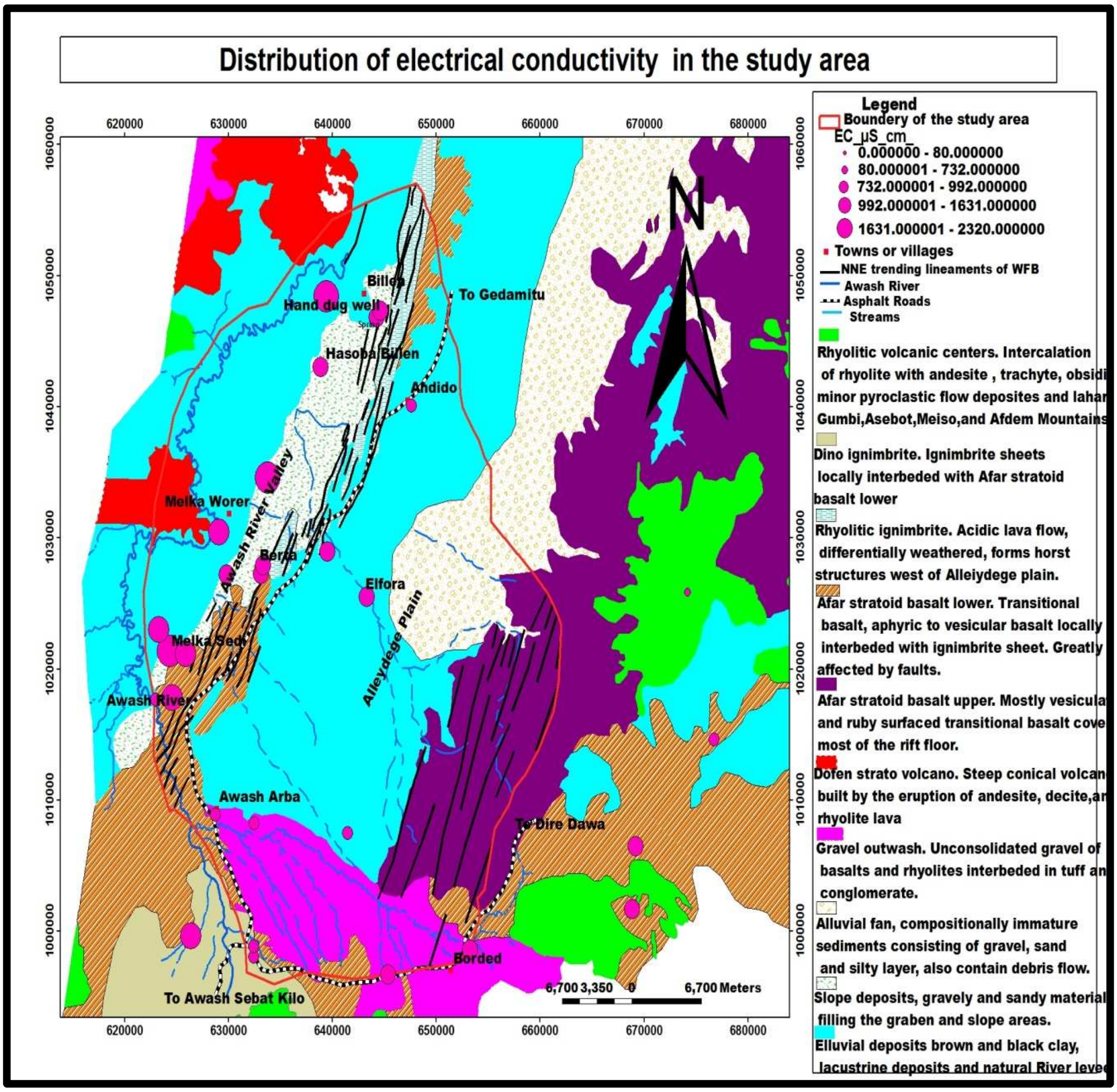


Figure 5. 12 Distribution of Electrical conductivity in the study area

5.3 Correlation of selected hydrochemical parameters

Correlation matrix of the eleven hydrochemical parameters (pH,Na^{+},K^{+},Ca^{+2},Mg^{+2},Cl^{-} ,SO_4^{-2},HCO_3^{-},CO_3^{-2}, EC,and Temperature) shows that there is a strong positive correlation between certain parameters (table 5.5). The four differnt symboles indicated on the legend of each figure represents the four major subgroups of hydrochemical facies.Correlation between these variables describes the groundwater circulation patterns ,hydrochemical evolution and groundwater flow direction.

Correlation of Chloride ion with electrical conductivity and sodium ion (fig.5.13 and 5.14) is the only strong positive correlation observed repeatedly in the two sampling seasons. Chloride has also a positive correlation with sulfate ion (fig.5.13). There is also negative correlation between Na^{+} ion and Ca^{+2} and Mg^{+2} ions. Thsese conditions declares that the flow direction is towards the increasing concentration of electrical conductivity/TDS and Cl^{-} and Na^{+}.Furthermore, the negative correlation of Na^{+} ion with Ca^{+2} and Mg^{+2} ions shows that the groundwater is evolving from somewhat Ca^{+2} and/or Mg^{+2} ions dominance to a Na^{+} ions dominance in the identified flow direction. As a result of precipetation of Ca^{+2} ions bearing minerals, Ca^{+2} and Mg^{+2} ions are decreasing in the groundwater following the flow direction.

Total Number of Samples: 28

Unit: mg/l

Correlation coefficient

	pH	Na	Mg	Ca	Cl	K	SO4	Cond	Temp	HCO3	CO3
pH	1.0	0.648	-0.441	-0.718	0.432	4.5E-4	0.356	0.531	0.103	0.273	0.0
Na		1.0	-0.391	-0.441	0.719	0.159	0.685	0.945	0.347	0.716	0.0
Mg			1.0	0.488	-0.168	0.111	-0.157	-0.218	-0.291	5.2E-2	0.0
Ca				1.0	-3.3E-2	-8.9E-3	9.1E-2	-0.202	-0.253	-0.134	0.0
Cl					1.0	0.249	0.855	0.84	0.337	0.427	0.0
K						1.0	0.423	0.192	0.664	0.146	0.0
SO4							1.0	0.773	0.435	0.52	0.0
Cond								1.0	0.296	0.685	0.0
Temp									1.0	0.226	0.0
HCO3										1.0	0.0
CO3											1.0

Table 5. 5 Correlation matrix of the selected variables for Hierarchical cluster analysis

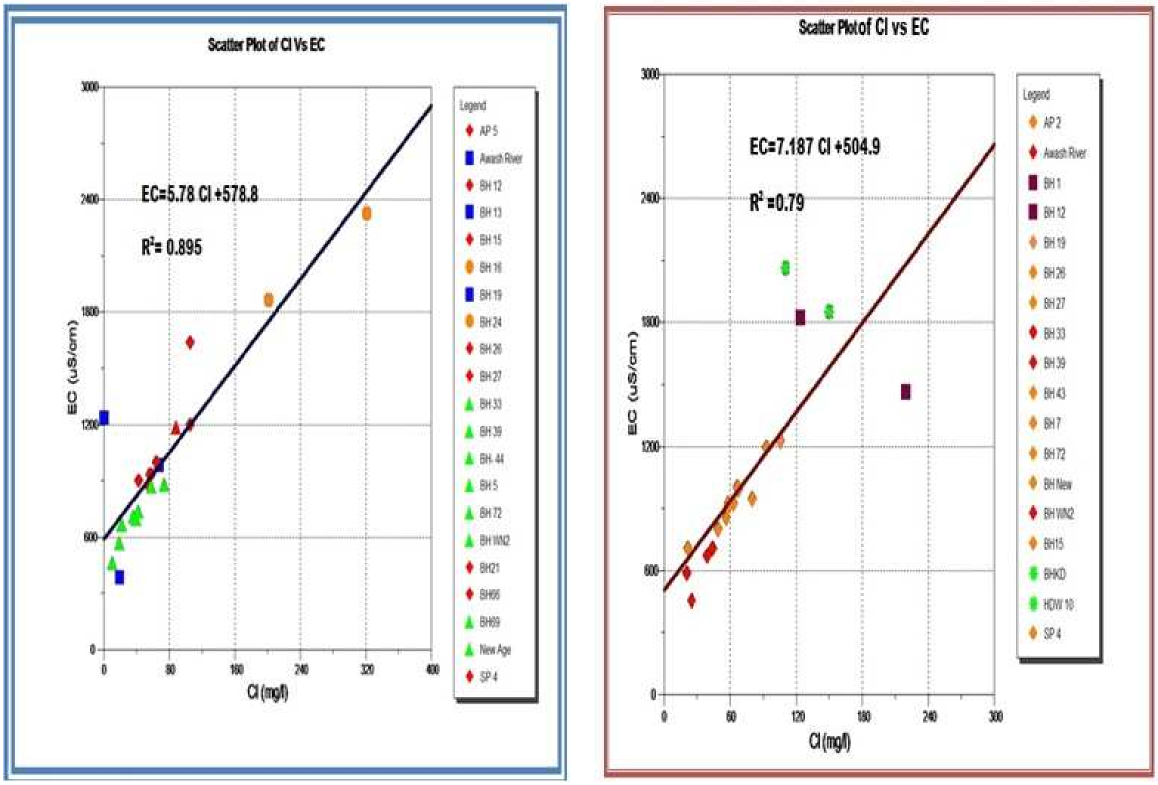


Figure 5. 13 Correlation of chloride and electrical conductivity (left figure is wet season sample and right figure is dry season sample)

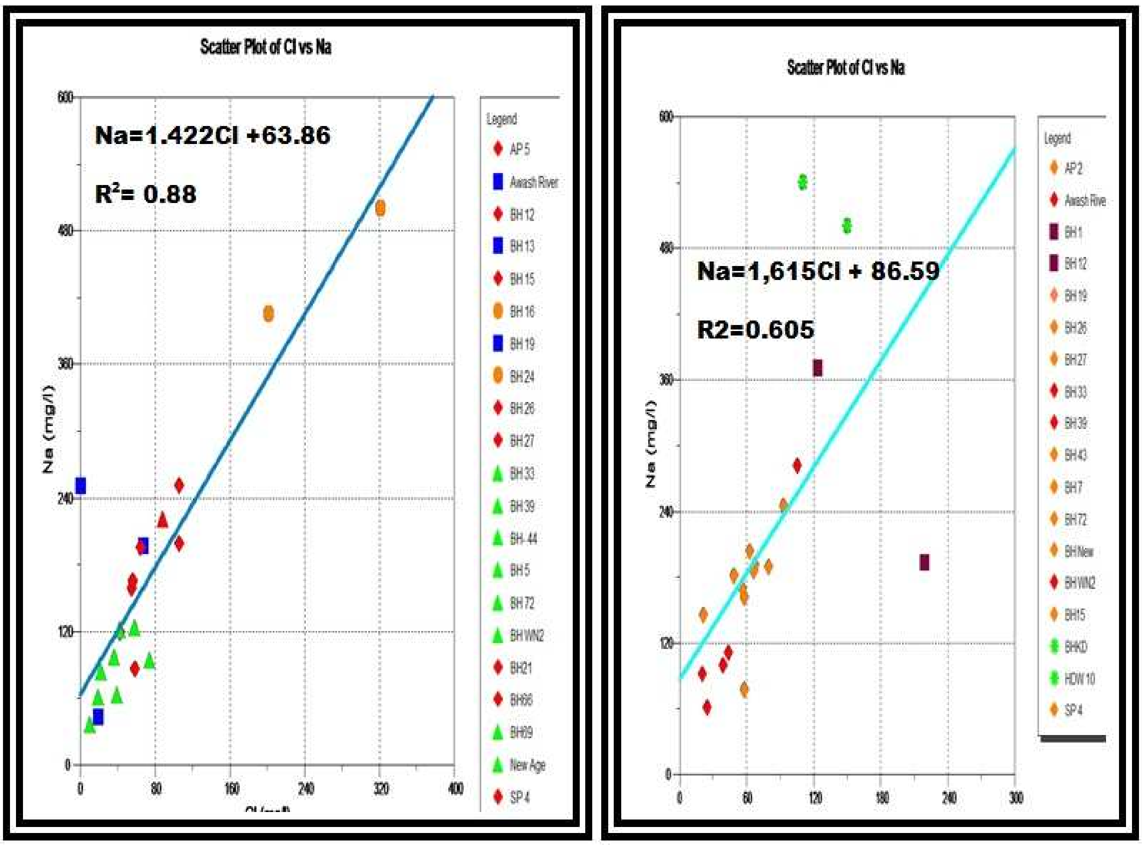


Figure 5. 14 Correlation of Chloride Vs sodium ion (left figure is wet season sample and right figure is dry season sample)

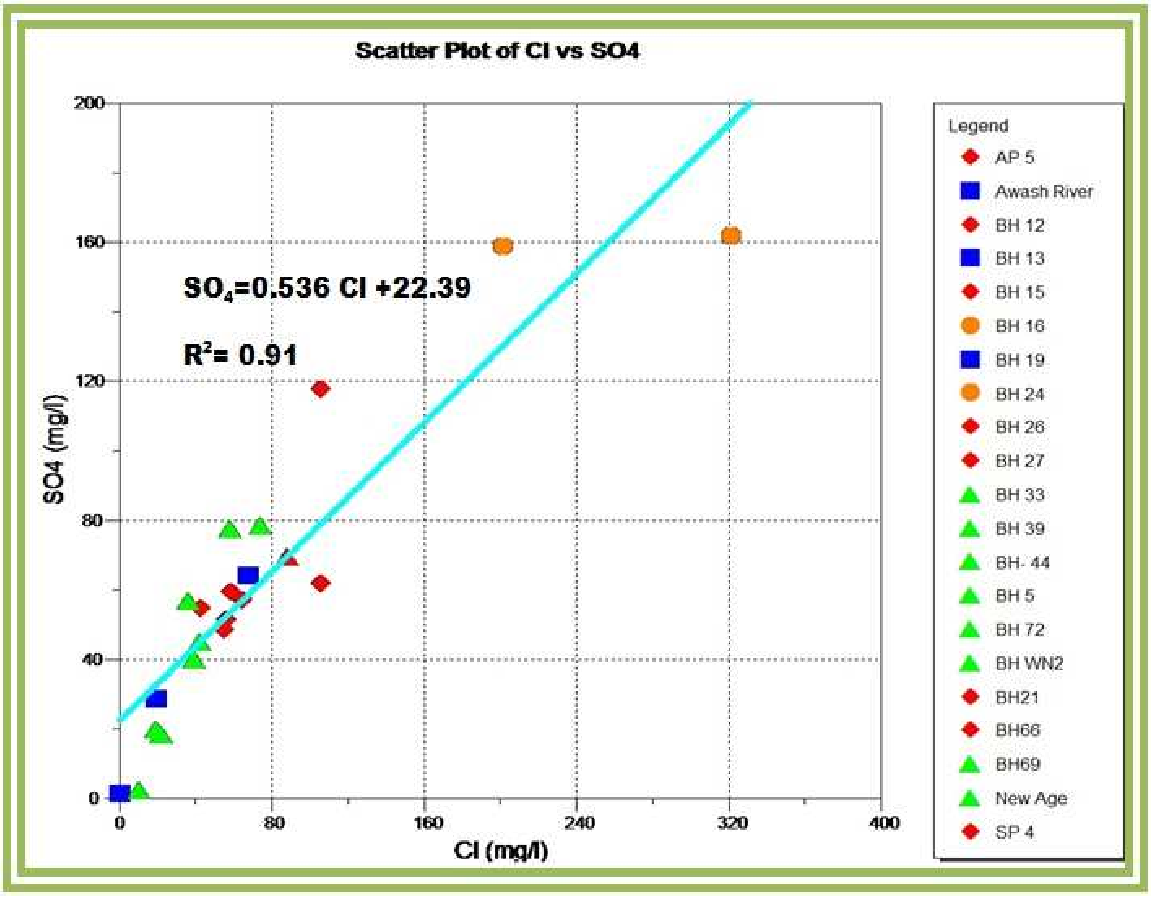


Figure 5. 15 Correlation of chloride Vs sulfate ion (for wet season sample)

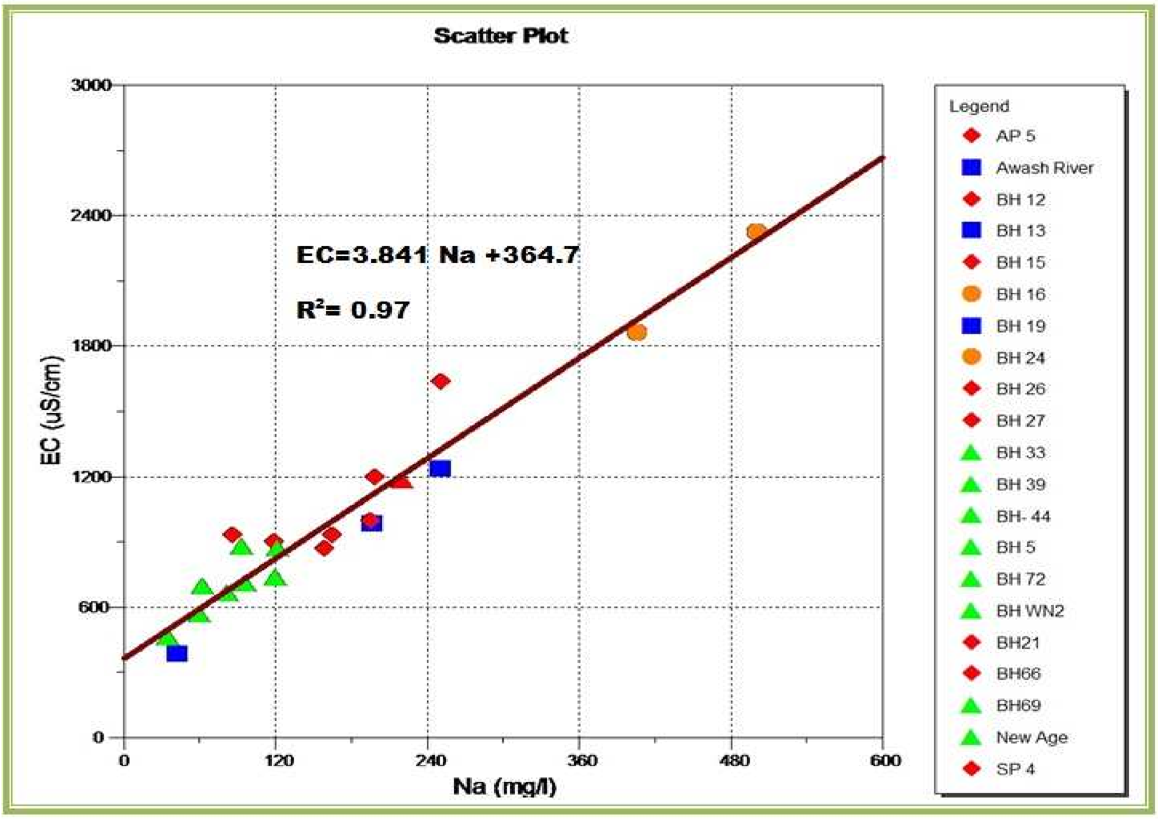


Figure 5. 16 Correlation of sodium Vs electrical conductivity (wet season sample)

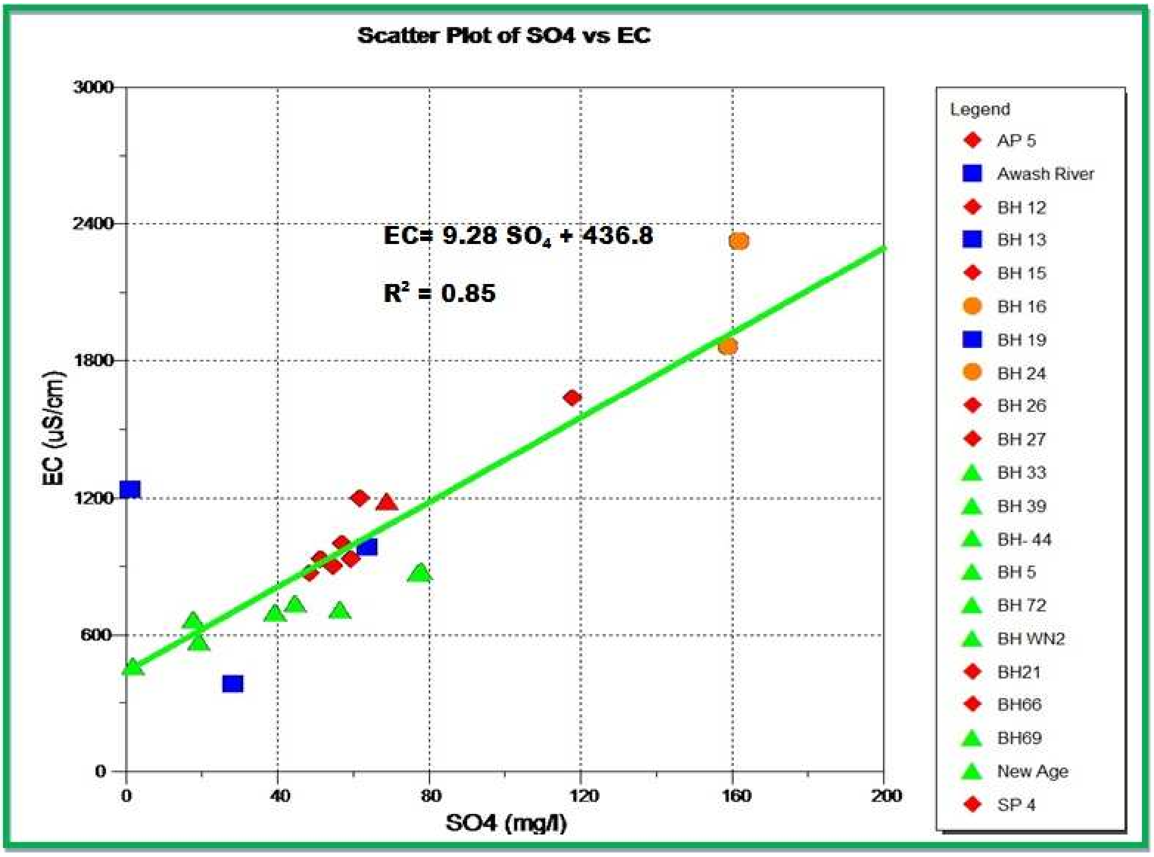


Figure 5. 17 Correlation of sulfate Vs electrical conductivity (wet season sample)

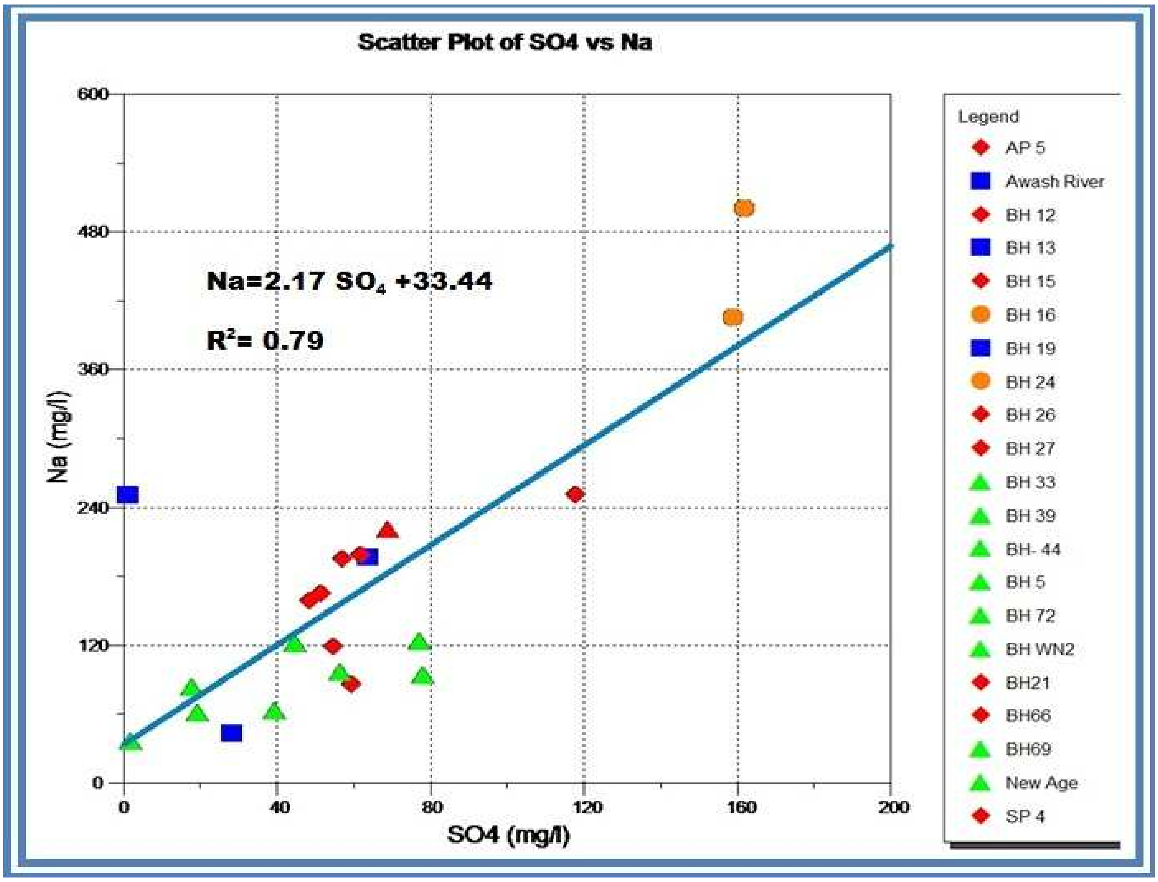


Figure 5. 18 Correlation of sulfate Vs sodium ions (wet season sample)

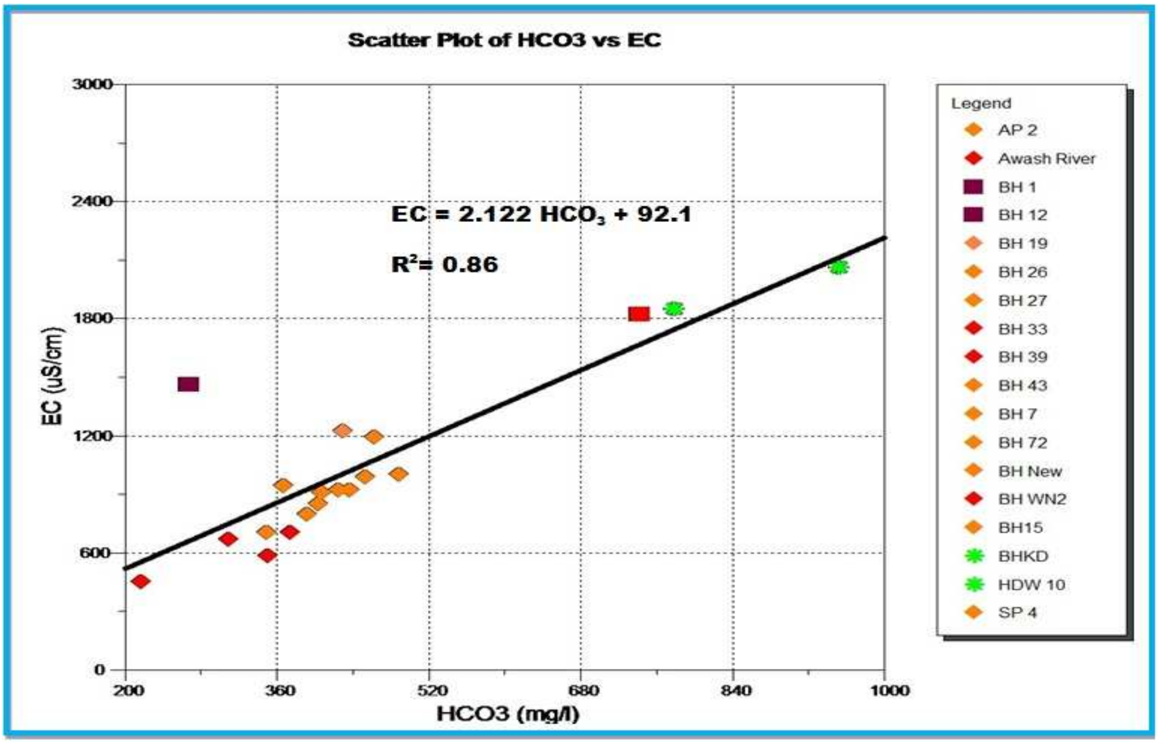


Figure 5. 19 **Correlation of $HCO3^-$ Vs electrical conductivity (for dry season sample)**

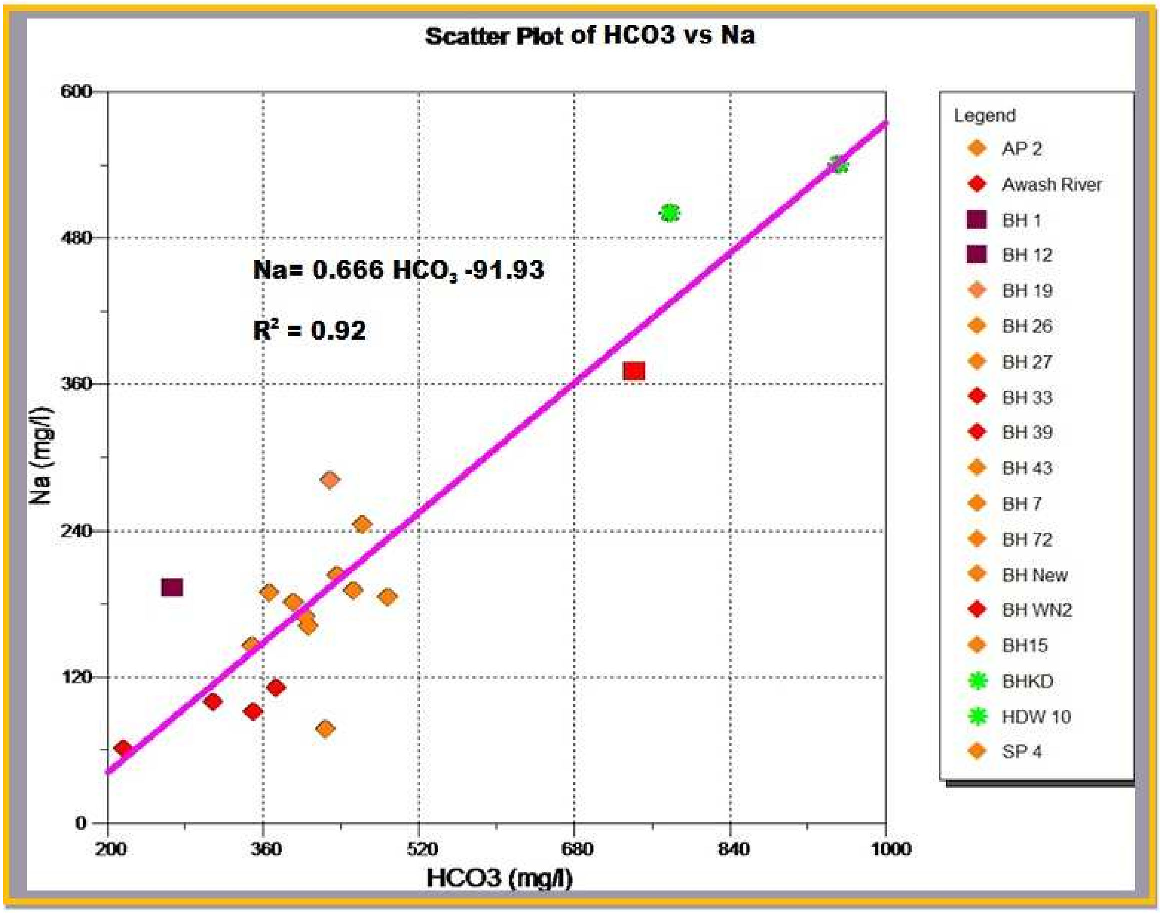


Figure 5. 20 **Correlation of $HCO3^-$ ion Vs Na^+ ion (dry season sample)**

5.4 Water types

Piper plot and Durov`s diagram are used to classify water types in the Alleydege plain groundwater system (fig.5.21 and 5.22) for the two groundwater sampling seasons. Accordingly, the groundwater is classified into six major groundwater types for the samples of the wet season and five types for that of the dry season.Na-HCO_3 and Na-HCO_3-Cl are the dominant facies. The areal extent and distribution of these facies are shown on fig.5.22 and the distribution of each water types is explained here under.

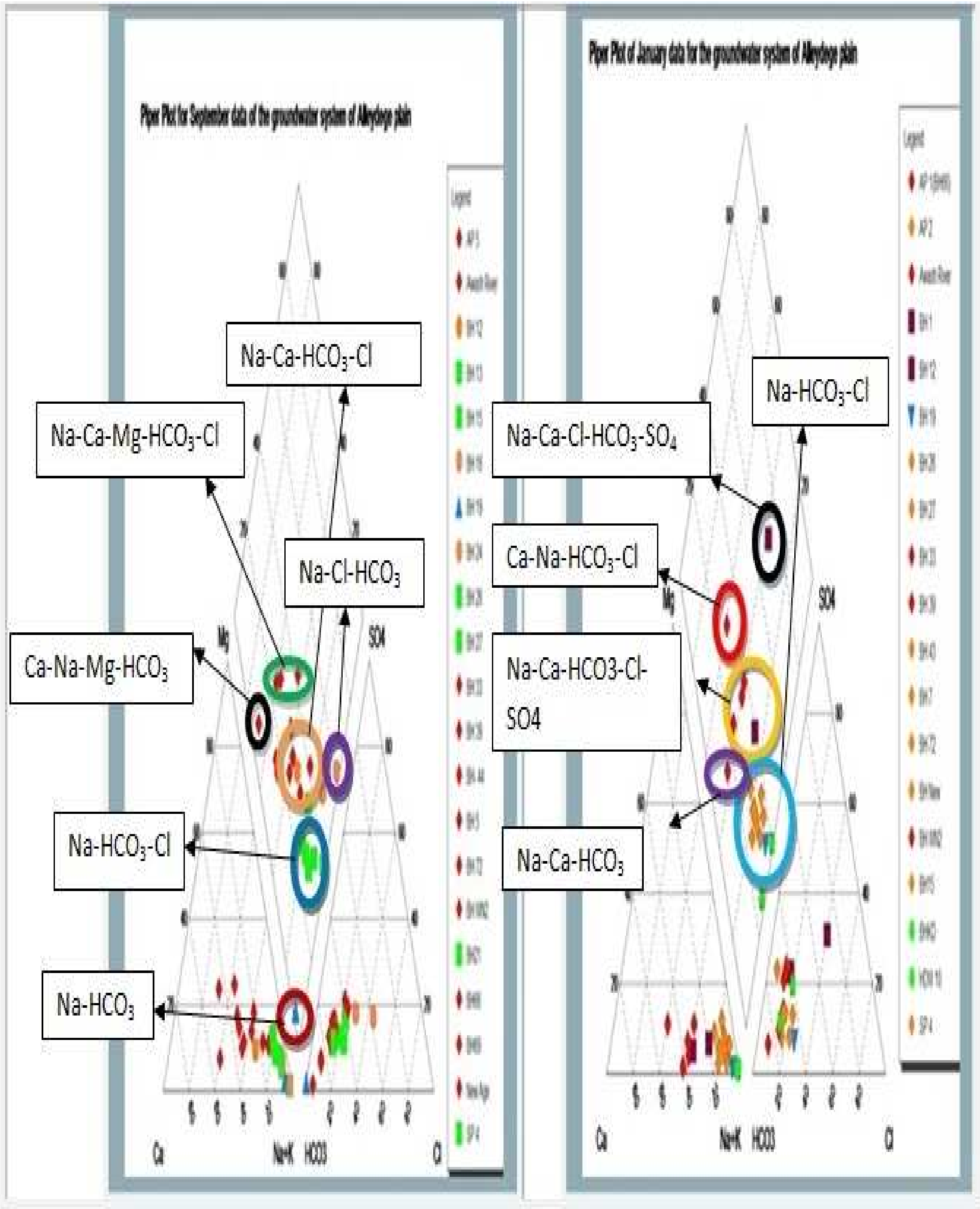


Figure 5. 21 Piper plot of the water samples (the left side is samples of the wet season and the right side correspond to the samples of the dry season).

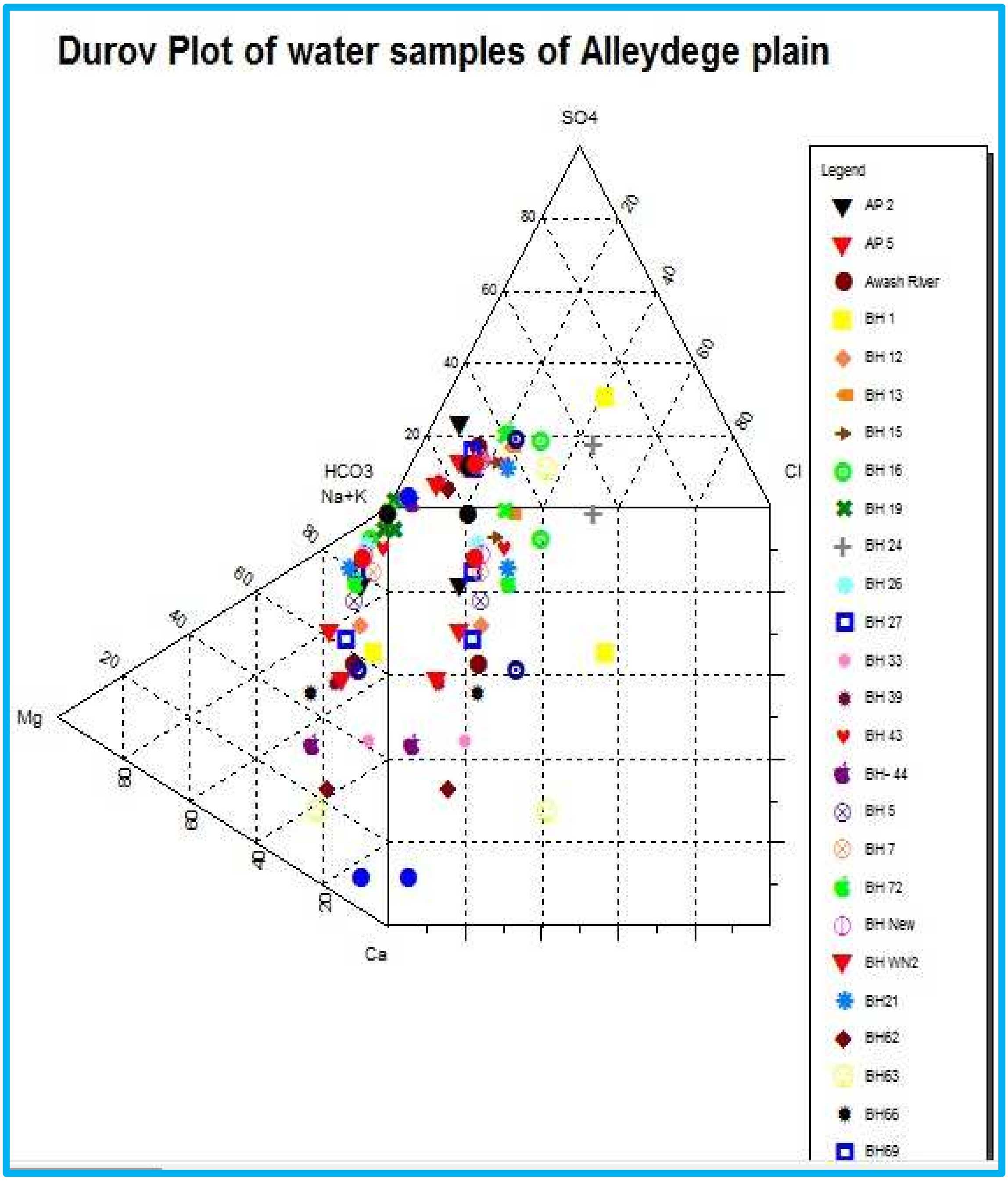


Figure 5. 22 Durov diagram of the water samples (the left side is samples of the wet season and the right side correspond to the samples of the dry season).

- Na-HCO_3-Cl – type

This type of water is mainly dominated by Na^+ and HCO_3^- ions with minor inclusions of chloride and relatively higher pH value of 8.2 to 8.6.It is mainly found in the discharge area of the rift floor of the Awash River valley. Due to the strong cation exchange of Ca^{2+} ion with Na^+ and, and the presence of acidic volcanics in the rift floor, the chloride and sodium ions concentration increases into the rift floor following the flow direction.

- Na-Cl-HCO_3 – type

This type of water is mainly characterized by higher concentration values of fluoride, Cl^-, TDS, EC and SAR (Na^+).The sodium and chloride ions are the dominant ions and bicarbonate is present in minor constituents in this type of water. The areal extent and distribution of this type of water is concentrated at the south western part of the Alleydege plain and deep into the rift floor with minor presence of SO_4^{-2} ions.

- Ca-Na-Mg-HCO_3 –type

In this type of water Ca^{+2} and Na^+ ions are the prevalent ions and Mg^{+2} and HCO_3^- ions are also present in appreciable amount. It has low TDS and pH value of nearly neutral. It seems rapidly circulating groundwater which is undergoing a pronounced water–rock interaction. In the general groundwater chemical evolution model (Plummer et al., 1990; Adams et al., 2001; Edmunds and Smedley, 2000), Ca–Mg–HCO_3 types of waters are often regarded as recharge area waters which are at their early stage of geochemical evolution. Hence the Ca-Na-Mg-HCO_3 type of water which is found in the recharge areas of the eastern highlands around Huse Sodoma area is a dynamically circulating and evolving groundwater.

- Na-HCO_3 –type

This type of water is enriched by Na^+ and HCO_3^- ions. It is characterized by depletion of ^2H and ^{18}O.The TDS value of this type of water ranges from medium to high as compared to the other groundwater samples of the area. Fluoride concentration of this water is completely above the MAC limits of EU and WHO standard. Generally it is found at the middle of the Alleydege plain and the Awash River valley where the Ca^{+2} ion dominance from the southern, south western and south eastern part of the study area decreases continuously down along the flow direction and finally completely vanish.

- Na-Ca-HCO_3-Cl- type

This type of water is dominated by Na^+, Ca^{+2} and HCO_3^- and Cl^- ions are seldom present at some borehole samples. It is mainly found at south western part of the study area.

- Na-Ca-Mg-HCO_3 - type

Na^+, Ca^{+2}, Mg^{+2} ions are the dominant cations where as HCO_3^- ion is the dominant anion in such type of water. It is found in the southeastern part of the study area around Bordede town close to the basic volcanic outcrop.

- Na-Ca-HCO_3-Cl-SO_4 –type

This type of water is observed in the groundwater samples (mainly of shallow wells) of the dry season and Awash River.Na^+,Ca^{+2},HCO_3^- are the dominant ions where as $SO4^{+2}$ and Cl^- ions concentration are also significantly important as they are increasing down along the flow direction to the rift floor in the alluvial aquifer of Awash River valley.

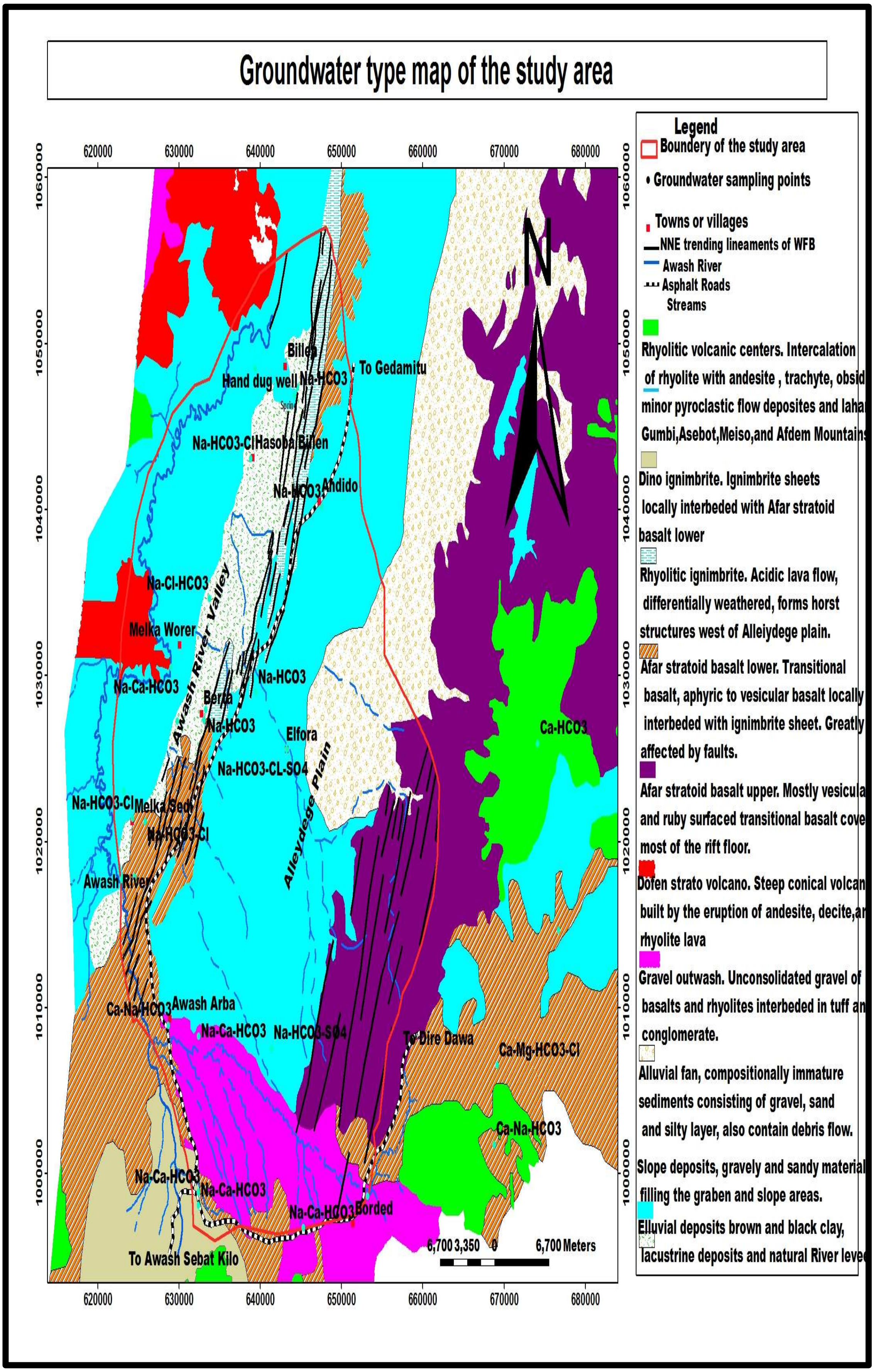


Figure 5. 23 Groundwater types in the study area

5.5 Origin of recharge

According to previous studies of the Alleydege plain groundwater system the origin of the groundwater of the Alleydege plain was determined to be Awash River, *Asfaw, 2006* and *Currey D.T, 1972* .Despite the above declared statement, *Ketema et al., 1983* concluded that the groundwater of Alleydege plain acts as a source of recharge for the Awash River. *EVDSA Halcrow, 1989* stated that the origin of the groundwater of the Alleydege plain is from direct precipitation and percolation from adjacent highland slopes. Recent studies by WWDSE, 2009 also reported that the origin of the groundwater of Alleydege plain is mainly from infiltration of direct precipitation followed by indirect recharge from Awash River and subsurface inflow from adjacent highland slopes.

The environmental isotopic results, δ^2H and $\delta^{18}O$, for this study are analyzed on the basis of the local meteoric water line ($\delta^2H=7.18*\delta^{18}O+10.83$) established from the local meteoric water of Addis Ababa and the GMWL ($\delta^2H=8*\delta^{18}O+10$) established from Vienna standard mean ocean water (VSMOW). The study of the samples collected at the end of the rainy season depicts that except some deep wells, intermediate depth wells and shallow wells of the Alleydege plain, and the Awash River valley which lie along the LMWL, the rest water schemes fall above the LMWL and GMWL indicating depletion with both deuterium and oxygen-18.This explains the insignificant contribution of the local meteoric water in recharging the Alleydege plain aquifer system. Those water schemes which lie on the meteoric water line show the influence of the local meteoric water (fig5.24). However, on fig.5.24 we can see that one shallow well from the rift floor in the Awash River valley located at the margin of the WFB portrays enrichment in both deuterium and oxygen-18 with a remarkably high deuterium excess. This is probably due to the influence of evaporation resulting from the hydrothermal effect controlled by the adjacent WFB. The shallow wells of the Awash River valley on fig.5.24 of wet season data show an abnormal depletion in deuterium and oxygen-18 instead of showing enrichment. These shallow wells are located close to the Awash River within few kilo meter distances from the Awash River. This demonstrates the limit of distance to which influence of the Awash River as a source of recharge to the Awash River valley and the Alleydege plain aquifer system extends. This is true because the other shallow wells of the Alleydege plain and the Awash River valley which are also far from the Awash River (BH-24, BH-44, and BH-27), show a relative enrichment with heavier isotopes (fig5.24).The Isotopic enrichments in these shallow wells which are farther away from the Awash River together with the deep wells and intermediate depth wells which show a relative enrichment with the heavier isotopes but which are not also influenced by the local precipitation, portray that they are being recharged from other source. Almost all of these wells are wells of the Alleydege plain (fig.5.26). Therefore these wells are being recharged from southeastern and eastern highlands, either by percolation along the slopes or through subsurface inflow from adjacent catchments.

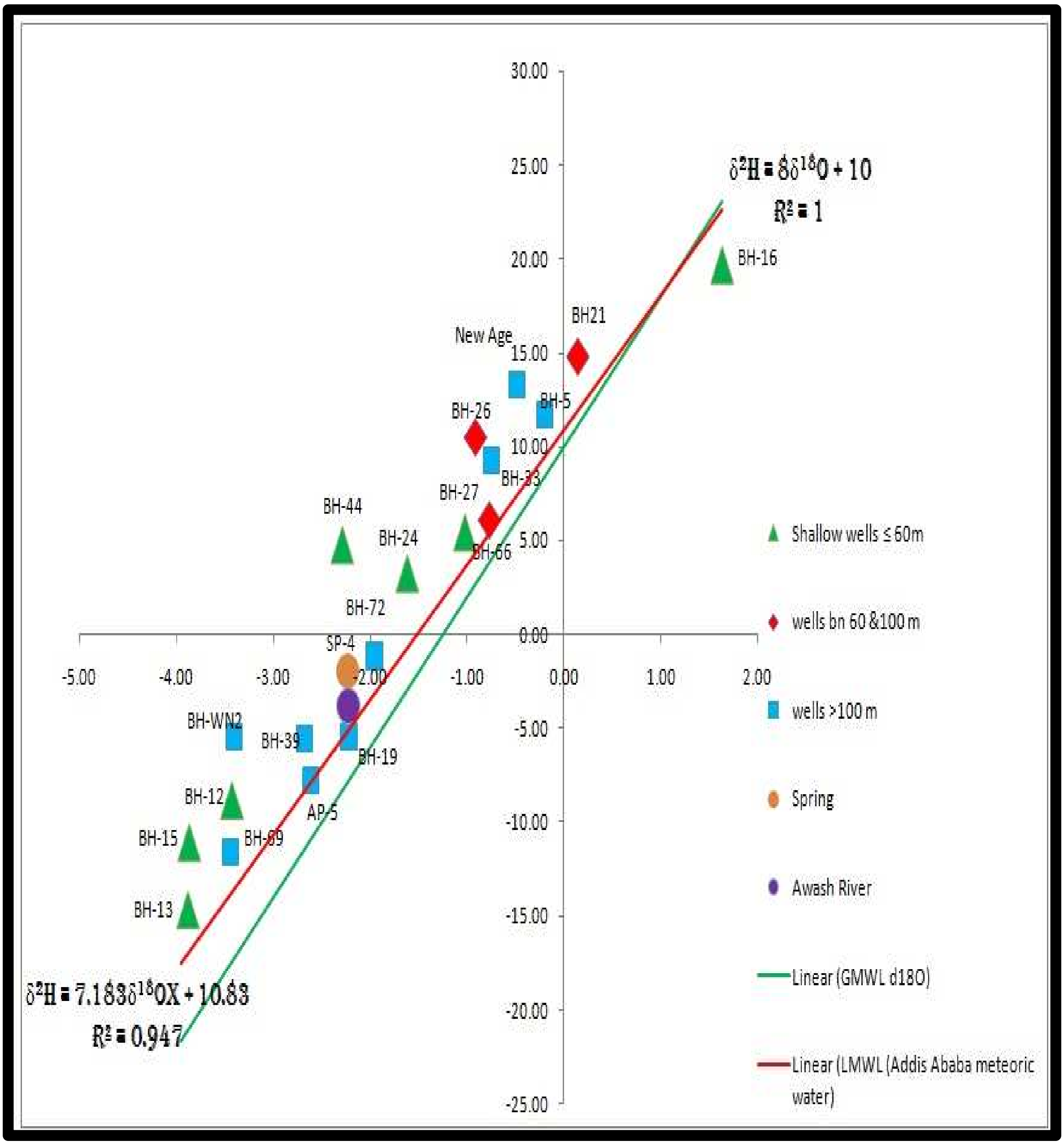


Figure 5. 24 Scatter plot of stable isotopes of water for September, 2010 data in the study area

Some shallow wells and deep wells of Alleydege plain which were relatively enriched in the samples of the wet season (BH-27, BH-72) are relatively more depleted in the samples of the dry season. This might have been due to relatively colder water coming from deep wells of adjacent eastern highlands and mixing with the groundwater of theses boreholes. Because when we look at the hydrochemical data on (annex-2) of these boreholes there is a decrease of temperature, TDS, EC, alkalinity, HCO_3, pH, etc., in the samples of the dry season as compared to the wet season. Hence it can be deduced that the relative isotopic depletion of these wells during the dry season in comparison to the wet season is due to mixing with colder water of deep wells from adjacent highlands. Like the wet season samples few deep wells and intermediate depth wells lie along the local meteoric water line. However, despite the majority of wet season samples which lie above the local and global meteoric water line, the data of dry season samples lie below the LMWL and GMWL showing a relative enrichment of heavier isotopes.

The deep well (BH1) on figure 5.25 of Awash - 7 kilo at locality called Dudu from Awash Sebat Kilo show enrichment in both deuterium and oxygen-18. Another borehole from Kesem Dam (BH-KD) together with the intermediate and deep wells of the Alleydege plain which are shifted to the right of the LMWL and GMWL show a relative enrichment of heavier isotopes. This depicts that the southern elevated areas are also hydraulically connected to the Alleydege plain groundwater system indicating that the Alleydege plain gets additional groundwater recharge from the southern elevated areas.

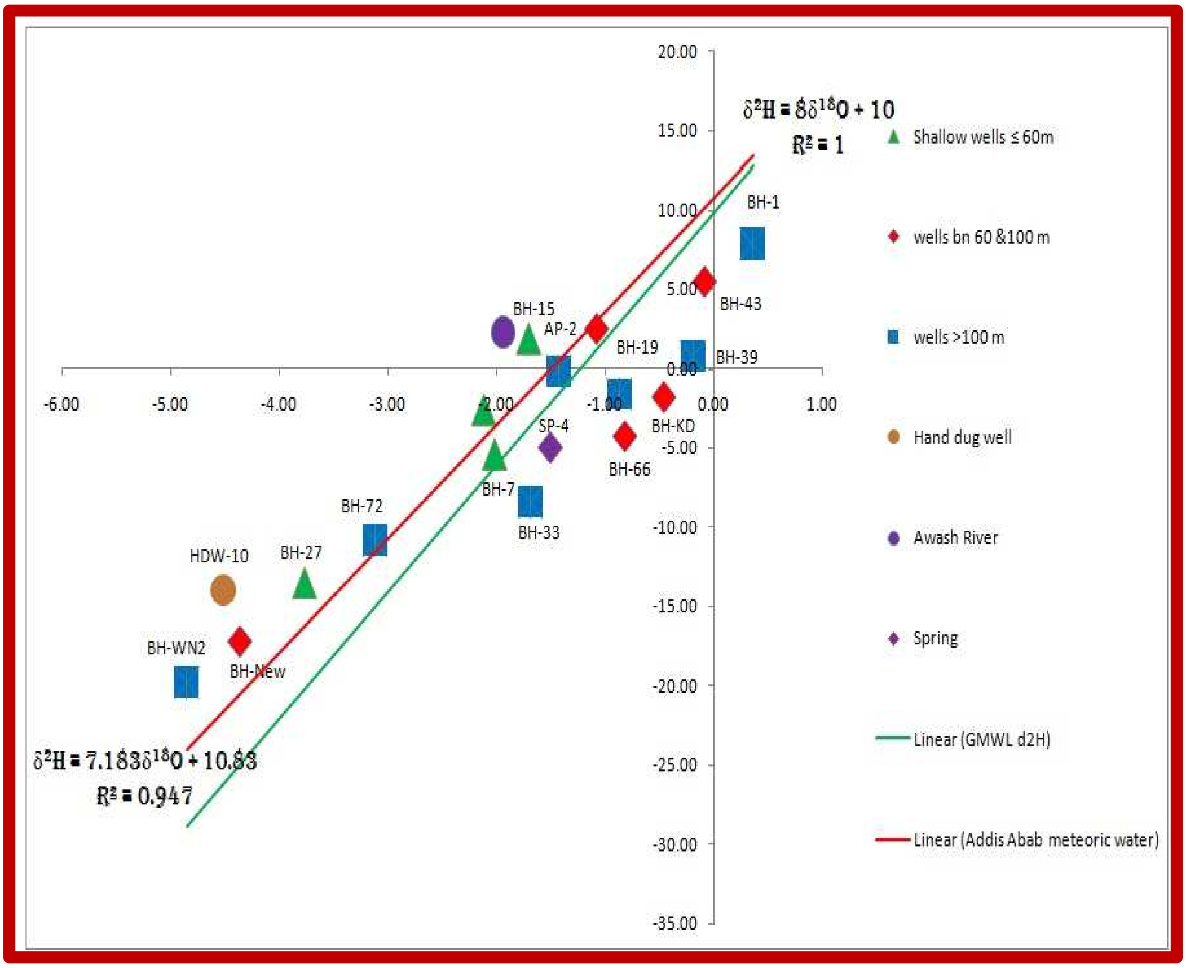


Figure 5. 25 Scatter plot of stable isotopes of water for January, 2011 data in the study area

5.5.1 Groundwater and surface water interaction

The analysis of δ^2H and δ^{18}O values of boreholes of shallow wells, intermediate depth wells and deep wells within few kilo meter distance from the Awash River show the influence of Awash River, however, boreholes located farther away from the Awash River do not show the influence of Awash River. Hence The Awash River recharges parts of the Alleydege plain and the Awash River valley aquifers which lie along the Awash River within few kilo meter distances from the Awash River.

Further analysis of $\delta^{18}O$ values of these boreholes illustrate that the influence of Awash River within few kilo meter distances from the Awash River is limited to borehole samples collected immediately after the rainy season. Those borehole samples collected during the dry season (fig.5.28) do not show the influence of Awash River. This justifies that the Awash River Recharges parts of the Alleydege plain and the Awash River valley aquifer that lie within few kilo meter distances from the Awash River when the Awash River water level rises. Beside the Awash River head variation, the return irrigation water from Middle Awash state farms may also directly influence the isotopic signature of the shallow wells of the Awash River valley aquifer.

The intermediate depth wells (depth between 60 & 100 m) and deep wells (depth ≥100 m) of the Alleydege plain show an enrichment of ^{18}O and D (fig.5.24 and 5.25) for both seasons as compared to that of the shallow wells. This isotopic enrichment indicates that surface water which has undergone evaporation is mixing with groundwater in deeper parts of the aquifer of Alleydege plain. These surface waters are most probably flood water coming from adjacent highland slopes during rainy season and undergone evaporation along its course prior to recharge before intercepting fractures or cavities that leads it to mix with the groundwater at deeper parts. Mixing of surface water with groundwater at depths greater than 60 m is probably facilitated by water moving downward through big fractures, or cavities.

It also seems that at the extreme north of the study area, following the flow direction in the rift floor, the groundwater flows to the Awash River as base flow.

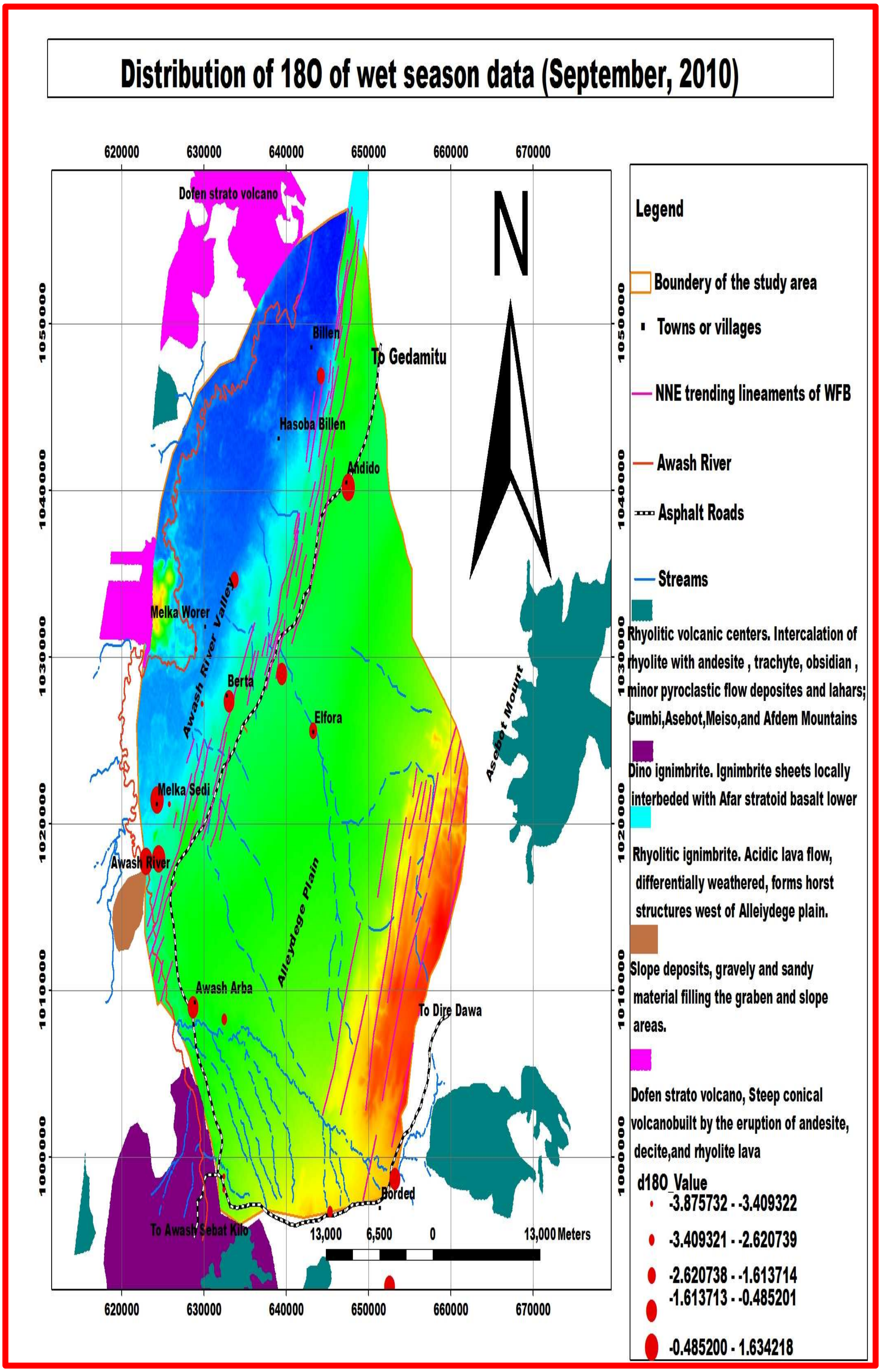


Figure 5. 26 Distribution of $\delta^{18}O$ value at the end of rainy season in the study area

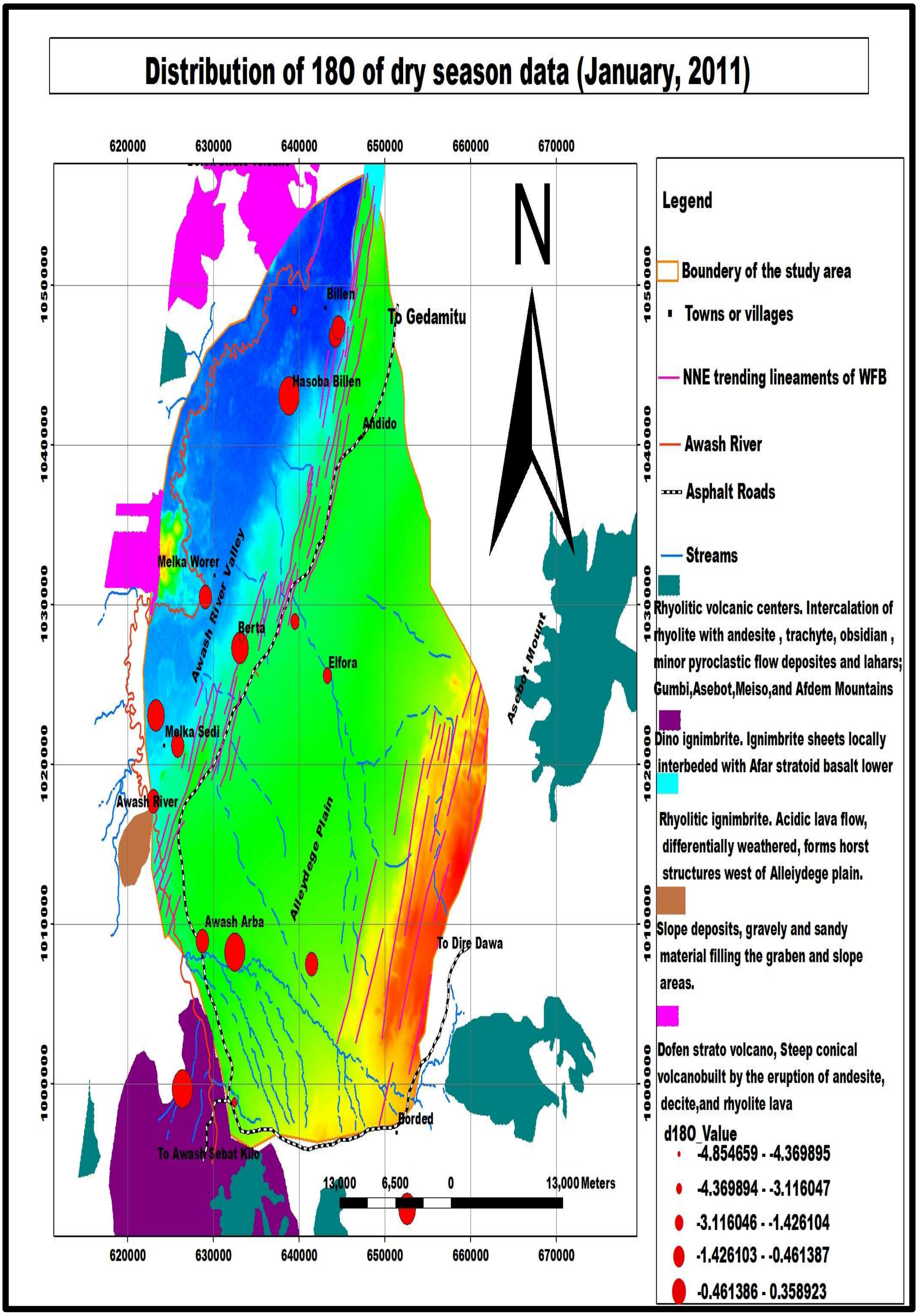


Figure 5. 27 Distribution of $\delta^{18}O$ of for the samples of dry season in the study area

5.5.2 Groundwater age estimation

For the groundwater age estimation there is only one borehole in the Alleydege plain with ^{14}C data (Kebede, 2004). Three sampling stations from Alleydege, Meteka and Gewane area, obtained from the previous works of Alemayehu et.al., 2006 have a tritium value of 0.02, 0.5 and 0.5 TU each. There are no other tracers in the previous works or in this study. Tritium (^{3}H) is an unstable isotope of hydrogen with a half life of 12.3 years. Groundwater with less than 2-4 TU is dated prior to 1953 i.e., prior to the detonation of nuclear bomb 1952 & 1962. Therefore despite the absence of sufficient data for the groundwater age estimation, the groundwater of the Alleydege plain may be estimated to be recharged prior to 1953.Further more according to the borehole in the Alleydege plain with ^{14}C and ^{13}C data, the groundwater age of the area is estimated by different models. The result shows that the groundwater age is estimated to be 2264, 3224, 3365, and 2223 years as per Age-Tamers, Age-Mokes, Age-Fontes and Granier and Age- IAEA models, respectively.

5.5.3 Factors controlling the temporal variation of stable isotopes of water

The temporal variation on the $\delta^{18}O$ and $\delta^{2}H$ value of borehole samples for all types of boreholes; shallow wells, intermediate depth wells and deep wells for the two sampling seasons, Sep.2010 (end of rainy season) and Jan. 2011 (dry season), can be related with changes occurring in short time scales, mainly with seasonal temperature changes. The samples collected at the end of the rainy season portray more enrichment than the dry season samples. This is probably governed by the higher temperature followed right after the rain which is typical characteristics of arid and semi – arid areas and the topography of the area. Once the rain drops, the rain water and the flood from the topographic highs around the study area flows to the topographic lows where the water finds a relatively higher residence time to flow. This condition provides suitable situation for the evaporation effect to take place evaporating the lighter isotopes and leaving behind the recharging water enriched with the heavier isotopes.

5.6 Hierarchical classification analyses and its relation to groundwater dynamics

HCA is used to classify groundwater into objective groups based on the squared Euclidean distance between the different hydrochemical variables. Data was analyzed in Q-mode in order to get similarity information between cases. For the analysis the eleven variables (pH, Ca^{2+}, $Mg^{2+,}$ K^{+}, Na^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-} , EC, CO_3^{-2} and Temperature) are used to analyse the classification of water composition into different hydrochemical facies, groundwater circulation patterns, hydrochemical evolution. It is also used to identify the interactions between the groundwater and Awash River and finally to use hydrochemical facies as tracers to identify groundwater flow paths and directions in the aquifer system of the Alleydege plain.

5.6.1 Hydrochemical facies

To avoid any discrepancy and ensure the presence of equal weight between variables, the variables used in the HCA are log transformed and normalized. The major output of this Q-mode hierarchical cluster analysis is a graph known as dendrogram (fig.530) from which different groups of hydrochemical facies are visually selected.

Table 5. 6 Hydrochemical facies of groundwater of Alleydege plain

Sample Id	Geology	Hydrochemical Facies of wet season	Hydrochemical facies of dry season
BH66		Na-Ca-Mg-HCO3	Ca-Na-HCO3
AP 5		Na-Ca-HCO3	Not taken
BH 13		Na-HCO3-Cl	Not taken
BH 27		Na-HCO3	Na-HCO3
BH WN2		Na-Ca-HCO3	Na-Ca-HCO3-SO4
BH21		Na-HCO3-Cl	Not taken
BH 24		Na-Cl-HCO3	Not taken
BH 15		Na-HCO3-Cl	Na-HCO3-Cl
BH- 44		Ca-Na-Mg-HCO3	Not taken
New Age		Na-Ca-HCO3-Cl	Not taken
BH 26		Na-HCO3	Na-HCO3
BH69		Na-Ca-HCO3	Not taken
BH 19		Ca-CO3-F-NO3	Na-HCO3-Cl
BH 39		Na-Ca-HCO3	Na-Ca-HCO3
BH 16		Na-HCO-Cl	Not taken
BH 33		Ca-Na-HCO3	Na-Ca-HCO3
BH 72		Na-HCO3-Cl-SO4	Na-HCO3-SO4
BH 12		Na-Ca-HCO3	Na-Ca-HCO3-SO4
BH 5		Na-HCO3	Not taken
SP 4		Na-HCO3	Na-HCO3
Awash River		Na-Ca-HCO3	Na-Ca-HCO3-SO4
HDW 10		Not taken	Na-HCO3
BH New		Not taken	Na-HCO3
BH 7		Not taken	Na-HCO3
AP 2		Not taken	Na-HCO3-SO4
BH 1		Not taken	Na-Ca-Cl-SO4-HCO3
BHKD		Not taken	Na-HCO3
BH 43		Not taken	Na-HCO3-Cl

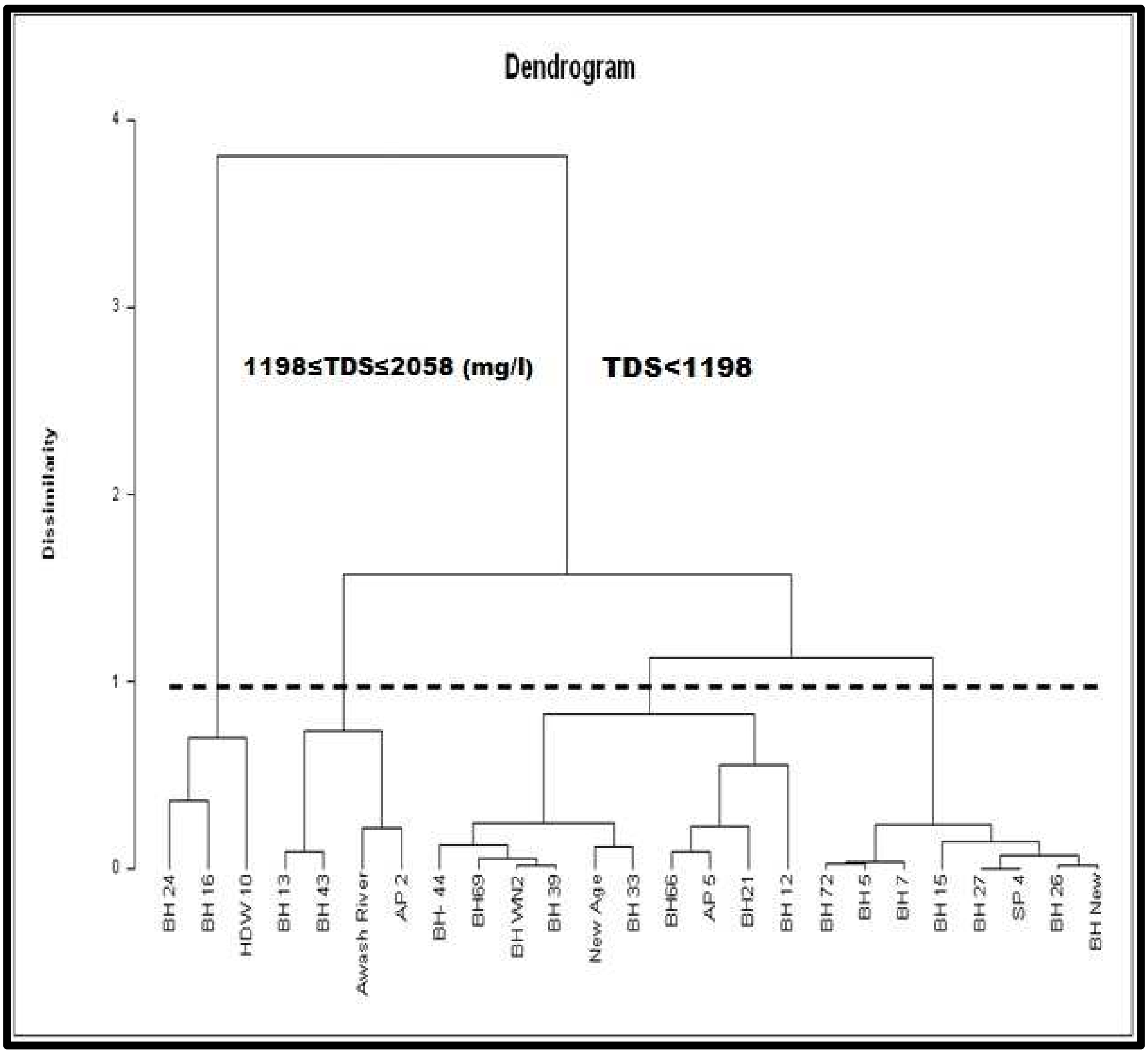


Figure 5. 28 Dendrogram of the Q – mode hierarchical analysis.

The phenon line is chosen at the index of dissimilarity of 0.978 to select the four subgroups. The left most subgroup is subgroup I and the right most is subgroup IV.

The broken line" phenon line "is chosen at the index of dissimilarity of 0.978 to get the two major hydrochemical facies which are further classified into four sub-groups (fig.5.30). The first hydrochemical facies is characterized by high pH,Na^{+},HCO_3^{-}, Cl^{-}, SO_4^{-2}, TDS, and EC and lower Ca^{+2} ions (Table5.8). In general this facies is peculiar to the shallow wells of the rift floor in the Awash River valley. The increase of HCO_3^{-} ion together with the Na^{+} ion and TDS being accompanied by a decrease of Ca^{+2} portray that the groundwater is flowing towards the Awash River valley into the rift floor evolving into a Na-HCO3 type of water by gradual elimination of Ca^{+2} ion from the groundwater through dissolution of calcium bearing minerals followed by cation exchange.

Cluster	PH	Ca	Mg	K	Na	HCO3	Cl	SO4	EC	CO3	Tempe rature
Cluster1	8.33	11.53	6.56	9.70	481.67	674.62	210.73	143.66	2079.67	19.73	34.73
Cluster2	8.27	16.47	4.01	5.00	142.63	291.15	46.72	58.46	749.00	19.95	32.55
Cluster3	7.60	49.86	14.73	10.39	107.90	402.02	51.15	50.56	858.70	0.00	34.80
Cluster4	7.92	17.82	8.75	14.93	166.00	401.45	60.90	59.03	930.88	1.58	38.25

Table 5. 7 Clusters and cluster results of the parameters used in HCA

Opposite to the first facies, the second hydrochemical facies is recognized by possessing the lowest concentration of Mg^{+2}, K^{+},HCO_3^{-}, and Cl^{-} ions and EC/TDS in comparison to the other three facies (Table.5.7). This facies is peculiar by possessing highest concentration of CO_3^{-2} and is mainly distributed at the margin of the Awash River valley and the Alleydege plain. It is either a Na-HCO_3-Cl or Na-HCO_3-SO4 type of water. The chloride concentration of this facies starts to raise from its nonexistence in the south eastern, eastern, and south western highlands of less productive volcanic aquifer, passing through the relatively productive volcanic aquifer of the Alleydege plain where the groundwater comparatively circulates significantly, to its existence and minimum concentration limits at the margin of the productive volcanic aquifer of the Alleydege plain and the highly productive alluvial aquifer of the Awash River valley. The majority of water schemes falling in this category are boreholes with a reasonably of lower temperature in contrast to the other three facies. The Awash River is also part of this facies.

The third hydrochemical facies is distinguished by its lowest concentration of Na^{+}, SO_4^{-2}, and CO_3^{-2} ions and pH. Comparatively Ca^{+2} and Mg^{+2} ions are in their highest concentration relative to the other three facies (Table.5.7). This facies is either a Ca-Mg-HCO_3 or Na-Ca-HCO_3 water type. 70% of the water schemes of these facies are deep wells of the south eastern, eastern and south western highlands and Alleydege plain. The rest 20% and 10% of water schemes are shallow wells from the south western topographic highs of the Alleydege plain and eastern highlands respectively. This part of the area is the major recharging area of the Alleydege plain where the groundwater of the study area is dynamically evolving from somewhat Ca/Mg-HCO_3 fresh groundwater type to a progressively sodium dominance groundwater type down the gradient following the flow direction into the rift floor.

The last hydrochemical facies is mainly recognized by its high thermal property and high concentration of HCO_3^{-}, Cl^{-}, $SO4^{-2}$, and Na^{+} ions and high TDS (Table.5.8).The thermal spring of Billen is categorized in this facies. The water type of this facies is Na-HCO_3-Cl, Na-HCO_3-Cl-SO_4 or Na-HCO_3. This facies is distributed from the central part of the Alleydege plain along the flow direction to the north eastern and northern part of the study area.

5.6.2 Hydrochemical evolution and groundwater circulation patterns

Despite the complexity in the lithology of the volcanic rocks, the systematic increment in EC, and other major ions such as Na^+, K^+, Cl^-, HCO_3^-, SO_4^{-2} from south eastern, south western, and eastern highlands passing through the Alleydege plain and the Awash River valley to the rift floor in the north direction explains the existence of a hydraulic continuity between the different aquifers and hydrochemical evolution following the flow direction. In general the Durov diagram in fig.5.29 demonstrates the overall evolutionary trend of the groundwater system of the Alleydege plain. The arrow indicated in the Durov diagram shows the groundwater ageing and evolution direction. The groundwater evolves from Ca-HCO_3 or Ca-Mg-HCO_3 water type at the elevated part of the Alleydege plain close to the basic volcanics in the east or south east to a Na-HCO_3-Cl-SO_4 or Na-HCO_3-Cl at the margin of the Alleydege plain and the Awash River valley. The groundwater at this part/margin of Alleydege plain and Awash River valley/ of the study area has typically low concentrations of Ca and Mg, showing significant hydrochemical evolution. Finally the Na-HCO_3-Cl-SO4 or Na-HCO_3-Cl water type at the margin of the Alleydege plain and the Awash River valley evolves to a Na-Cl-HCO_3 or Na-HCO_3 water type in the rift floor. These Na–HCO_3 waters, also high in TDS, may have evolved through Ca–Na–HCO_3 and Ca–HCO_3 water type where Ca^{+2} ions are lost through $CaCO_3$ precipitation at elevated temperatures and cation exchange.

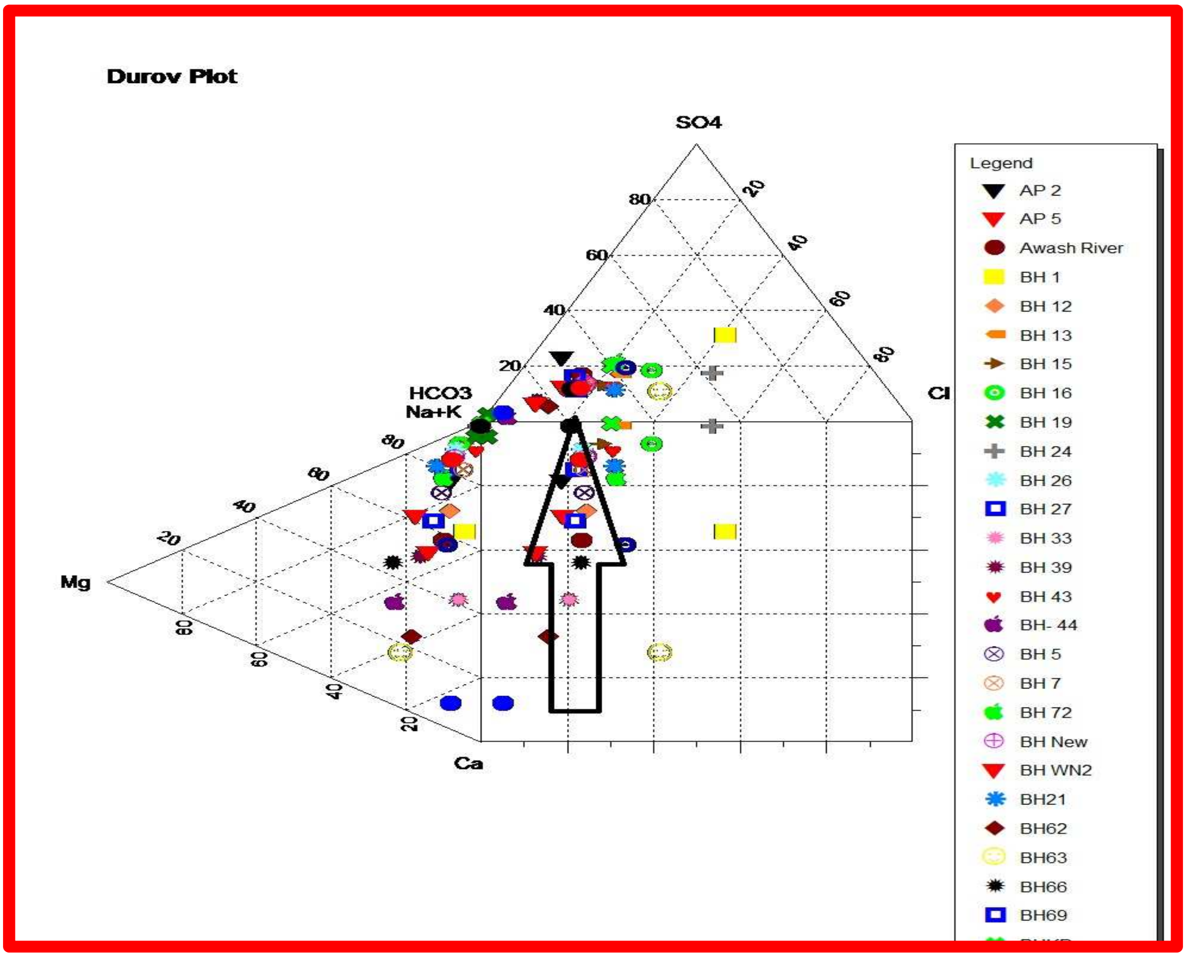


Figure 5. 29 Durov plot of the groundwater samples showing water types and the geochemical evolutionary trend.

5.6.3 Hydrochemical facies as tracers to constrain groundwater flow paths and direction of flow

The hydrochemical tracers used in this study are, RA (residual alkalinity= [(HCO_3^- (meq/l))-[(Ca^{+2} (meq/l)) + (Mg^{+2} (meq/l))]]), saturation index (SI) with respect to calcite and Ca/Mg molar ratio. Of course the choice of tracer depends on the situation. In most cases, the tracer is used to follow water movement and hence should move with the water. It therefore needs to be mobile and soluble; it should not be strongly retarded by the soil or aquifer matrix. Ideally, the tracer should be non-reactive and should not transform during transport. Of course, the tracer needs to be easily measured and extracted from the soil. If artificial tracers are used additional constraints need to be satisfied, such as low natural levels of the tracer in the environment, low toxicity, and low radioactivity.

In this regard the aforementioned hydrochemical tracers are applied to constrain the flow paths and direction of flow.

As it has been discussed in groundwater quality part of this research, the TDS of the groundwater samples generally increases from south east and eastern highlands, which are deduced to be the main recharge area for the Alleydege plain groundwater system to the rift floor in the northern direction (fig.5.12). Like the TDS, the residual alkalinity (RA) also show normally the same character as the TDS, increasing from the south east and eastern highlands to the rift floor in the northern direction (fig.5.32).

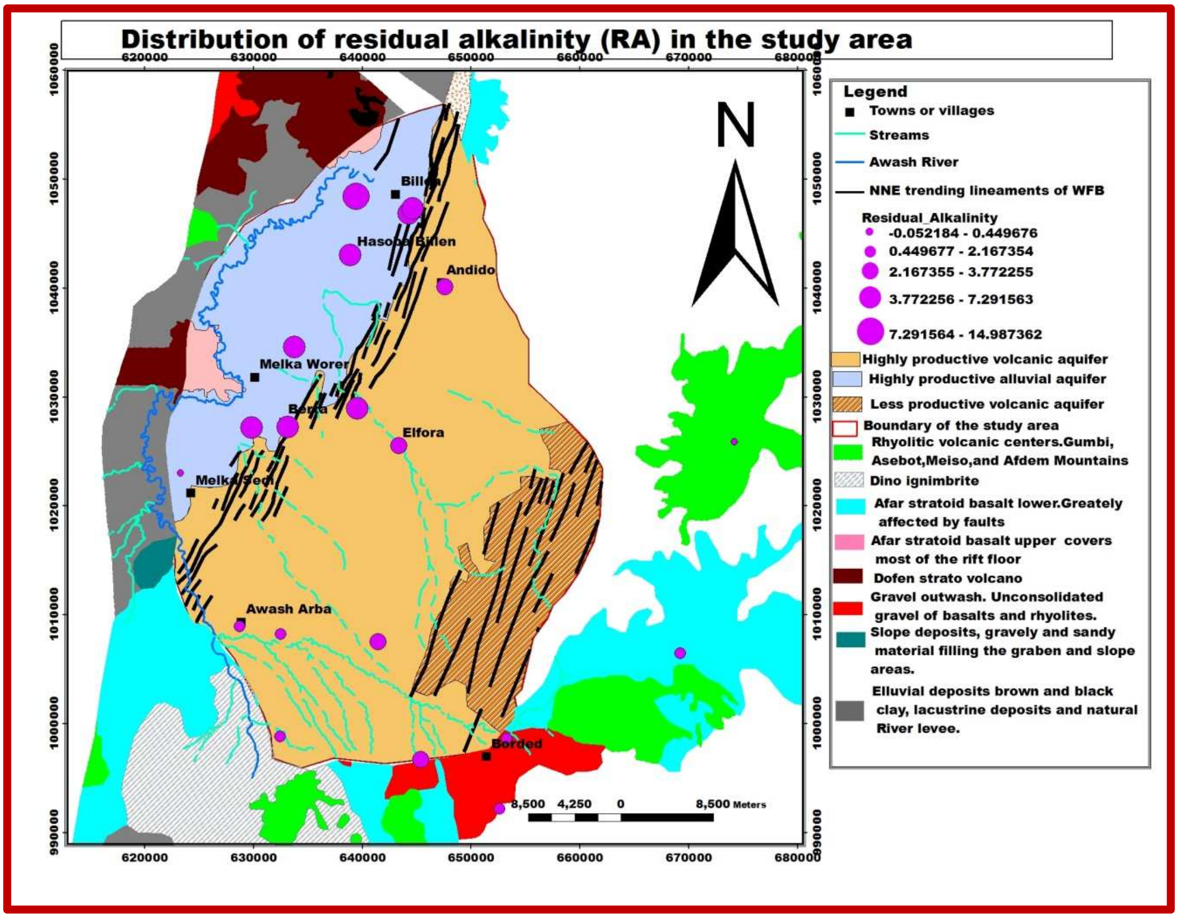


Figure 5. 30 Distribution of residual alkalinity (RA) in the study area

Moreover to determine which minerals are likely to be at or near equilibrium with the groundwater, saturation indices for different mineral species are calculated by inverse geochemical modeling using the PHREEQC software attached to the aquachem 4.2 package. The groundwater of the Alleydege plain demonstrates an increasing saturation index with respect to calcite, dolomite and aragonite from the south eastern and eastern highlands to the rift floor in the northern direction (fig.5.33). The saturation of these minerals in the groundwater along the flow direction demonstrates that dissolution of these minerals was increasing in the flow direction and a thermodynamic (unstable) equilibrium already exists for each of these mineral species.

$SI = \log (IAP/K_T) = \log (IAP) - \log (K_T)$, where

(SI) = saturation index,

(IAP) = Ion activity product,

(KT) = reaction equilibrium constant

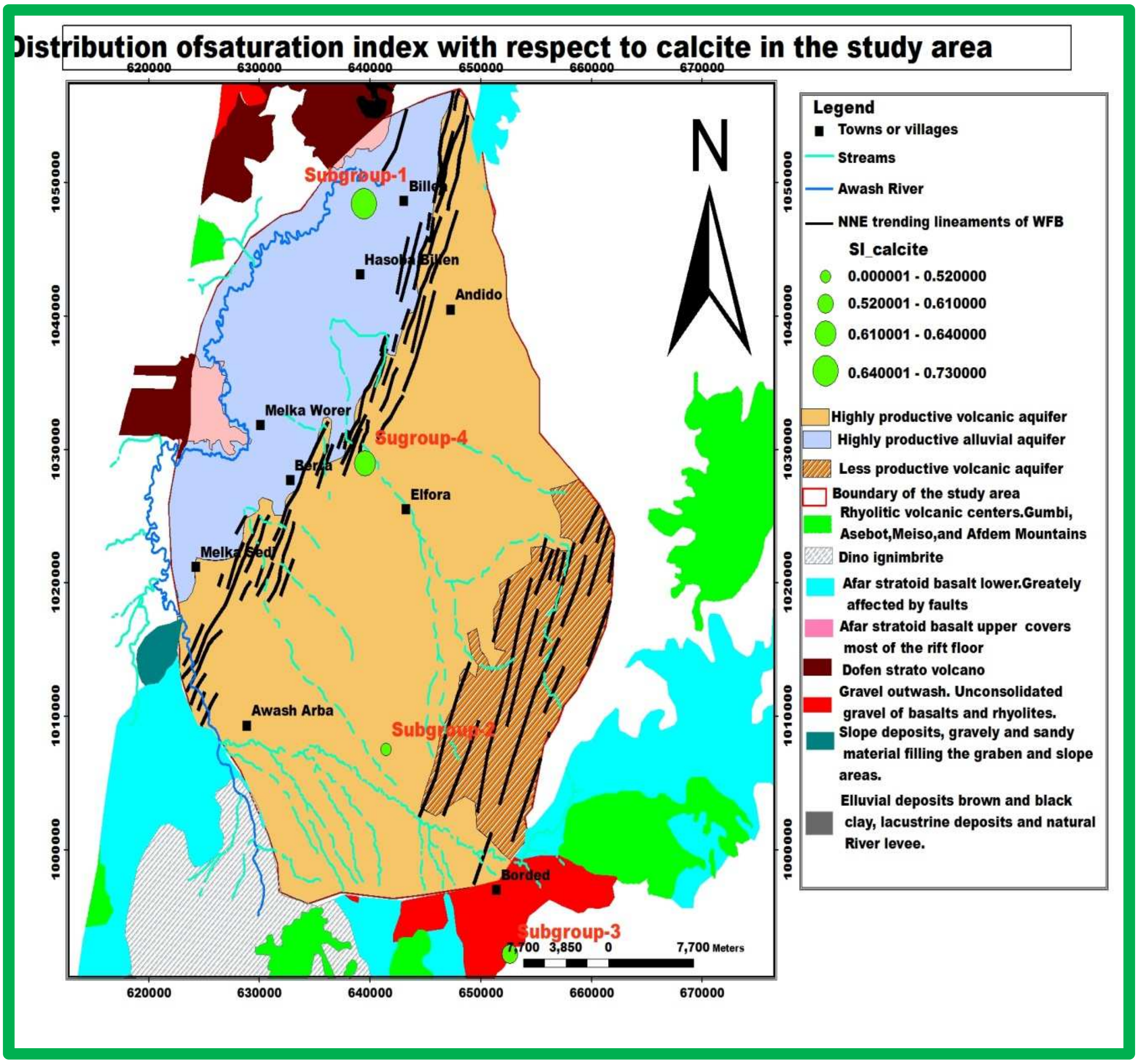


Figure 5. 31 Calcite saturation index trend in the study area

The molar ratio of Ca to Mg increases from 1.25 for group one waters with high TDS value to a median value of 3.1 for group two waters of low TDS value indicating that dissolution of calcite or other calcium-carbonate minerals together with significant cation exchange between Ca^{+2} and Na^{+} ions as observed in the inverse geochemical modeling results (section 5.6) are contributing Ca and Mg with a lower Ca: Mg molar ratio (less than 1.25) along the flow direction. Despite the local variation at places which demonstrates the local variation in lithology, the overall trend of Ca/Mg molar ratio shows a decreasing trend from the south, east and southeast elevated areas to the rift floor in the northern direction (Fig.5.34).

Therefore in addition to the conventional hydrogeology, groundwater head distribution and groundwater evolution trend, the hydrochemical tracers clearly demarcated that the Alleydege plain groundwater system flows from the south eastern and eastern highlands to the rift floor in the northern direction.

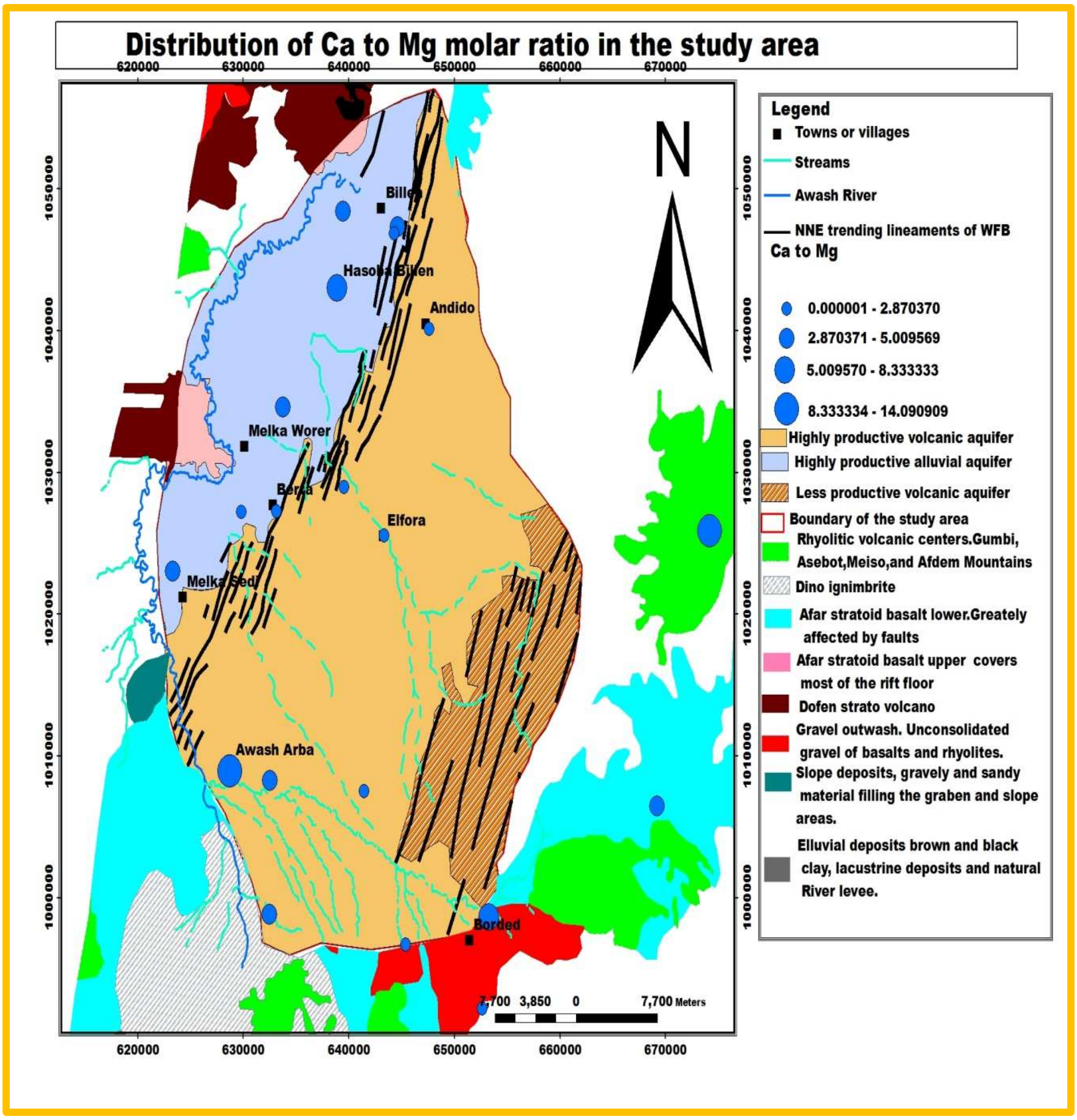


Figure 5. 32 Distribution of Ca to Mg molar ratio in the study area

5.7 Inverse geochemical modeling

The inverse modeling code PHREEQC is very essential to determine the type and amount in moles of minerals that dissolve or precipitate along a groundwater flow path. The flow paths are determined from hydrogeological knowledge, hydraulic heads of the aquifer, groundwater evolution direction, and information from hydrochemical tracers already discussed so far in this paper. In this study the inverse geochemical modeling is conducted for the average chemical composition of the four subgroups of water resulted from the Q- mode hierarchical cluster analysis (HCA).

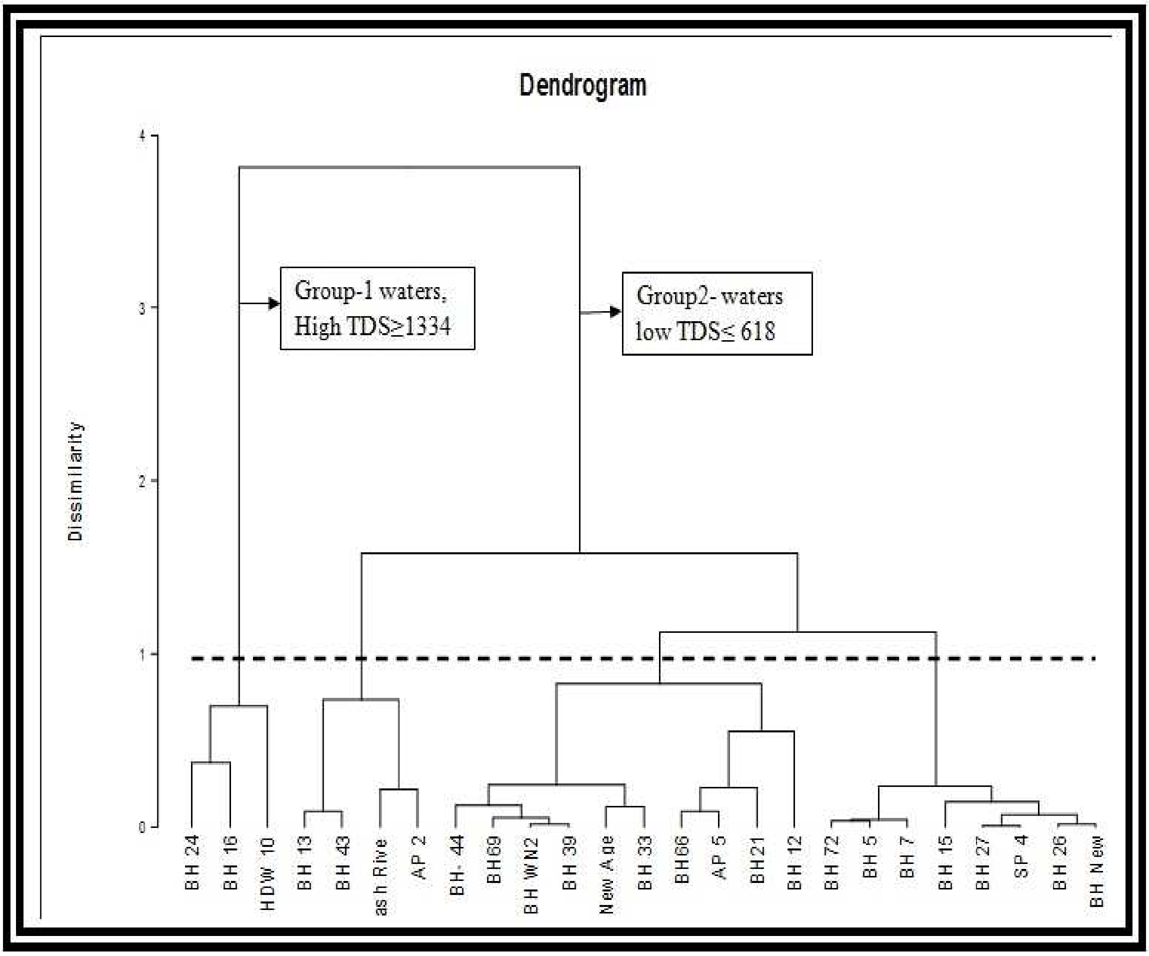


Figure 5. 33 Dendrogram of the Q – mode hierarchical analysis.

The phenon line is chosen at the index of dissimilarity of 0.978 to select the four subgroups of water. The left most subgroup is subgroup I and the right most is subgroup IV.

The water which is assumed to be pristine is taken from a shallow well (BH-44) from recharge area, eastern highlands, around Huse Sodoma. Each of the following four models are developed by taking the chemical composition of this shallow well (BH-44) as an initial solution and the final solution is the average chemical composition of the four subgroups of water. The results of each model are presented hereunder.

Model I (BH-44 to subgroup water type - 1)

This model is obtained at input uncertainty of 0.07. For this case two possible models are obtained:

Phase mole transfers:	
Halite	5.827e-003
Illite	-1.132e-002
Pyroxene	5.035e-003
Plagioclase	3.727e-003
Fluorite	1.415e-004
K-mica	6.962e-003
CaX2	-4.926e-003
NaX	9.851e-003
Chalcedony	3.923e-003

A) Model - I- I

Phase mole transfers:	
Halite	5.827e-003
Illite	-2.139e-002
Olivine	2.518e-003
Plagioclase	7.376e-003
Fluorite	1.415e-004
K-mica	1.300e-002
CaX2	-3.794e-003
NaX	7.589e-003
Chalcedony	1.400e-002

B) Model - I - II

Model II (BH- 44 to subgroup water type - 2)

With input uncertainty of 0.05 four possible models are found, however two models are selected for the analysis.

Phase mole transfers:	
Halite	1.116e-003
Illite	-3.232e-003
Olivine	1.769e-004
Plagioclase	1.070e-003
Fluorite	4.736e-005
K-mica	1.985e-003
CaX2	-1.258e-003
NaX	2.517e-003
Chalcedony	2.374e-003

C) Model - II – I

Phase mole transfers:	
Halite	1.116e-003
Illite	-2.524e-003
Pyroxene	3.538e-004
Plagioclase	8.138e-004
Fluorite	4.736e-005
K-mica	1.561e-003
CaX2	-1.338e-003
NaX	2.676e-003
Chalcedony	1.666e-003

D) Model - II – II

Model III (BH- 44 to subgroup water type- 3)

With input uncertainty of 0.05 only one possible model is found:

Phase mole transfers:	
Halite	1.089e-003
Illite	-3.083e-003
Pyroxene	1.707e-003
Albite	9.965e-004
Fluorite	1.345e-005
K-mica	2.032e-003
CaX2	-6.613e-004
NaX	1.323e-003

E) Model - III

Model IV (BH – 44 to subgroup water type- 4)

With input uncertainty of 0.05 two possible models are found:

Phase mole transfers:	
Halite	1.436e-003
Illite	-4.417e-003
Pyroxene	1.765e-003
Plagioclase	9.253e-004
Fluorite	7.243e-005
K-mica	2.960e-003
CaX2	-2.000e-003
NaX	3.999e-003
Chalcedony	2.388e-003

F) Model – IV- I

Phase mole transfers:	
Halite	1.436e-003
Illite	-7.946e-003
Olivine	8.825e-004
Plagioclase	2.204e-003
Fluorite	7.243e-005
K-mica	5.078e-003
CaX2	-1.603e-003
NaX	3.207e-003

Model – IV-II

Table 5. 8 (A to F). Results of mass transfer from inverse geochemical modeling for each four models found for the four subgroups of water.

Phases	SI (BH-44)	SI(Cluster-I)	SI (Cluster - II)	SI (Cluster - III)	SI (cluster - IV)
Aragonite	-0.12	0.64	0.58	0.47	0.38
Calcite	0.02	0.77	0.72	0.61	0.52
CO2(g)	-1.87	-2.4	-2.74	-1.87	-2.16
Dolomite	-0.1	1.78	1.28	1.14	1.21
Fluorite	-1.53	-0.53	-1.02	-1.17	-0.72
H2(g)	-22.66	-24.66	-24.66	-23.2	-23.84
H2O(g)	-1.48	-1.27	-1.27	-1.26	-1.18
Halite	-8.03	-5.64	-6.77	-6.87	-6.61
O2(g)	-37.47	-30.64	-30.64	-33.53	-31.18

Table 5. 9 Results of mineral saturation indices for the initial solution (BH -44) and the four subgroups of water

5.7.1 Evaluation of inverse modelling results

Negative values of saturation index (SI) indicate undersaturation with respect to a particular solid phase; positive values of SI indicate oversaturation; and a value of zero indicates equilibrium. Table 5.10 indicates that the groundwater in the study area is undersaturated with respect to all gaseous phases and solid phases of halite and fluorite in both the initial solution (BH – 44) and final solutions (subgroup water type 1 to 4) for the four models generated. With respect to dolomite and aragonite, the initial solution is undersaturated whereas the final solutions are oversaturated. The only solid phase oversaturated in both the initial solution and final solutions is calcite.

All the four models are generally identical except there is a change in number of mole transfer. K–mica, plagioclase, olivine, pyroxene, and halite and illite are the primary minerals of the Alleydege plain aquifer system. The only mineral species that precipitates along the flow path is illite. The rest stated primary minerals undergone dissolution.

The results of these four models highly illustrate the deep aquifer system of the Alleydege plain where fractured volcanics and scoraceous basalts are the main aquifer of the Alleydege plain groundwater system. This can be observed clearly from the geological cross-sections (fig.2.4 and 2.5) and hydrogeological cross-sections (fig.2.7, 2.8, and 2.9). Moreover, the models result indirectly elaborates the surface water and groundwater mixing at greater depths resulting in the isotopic enrichment of deep wells with heavier isotopes as compared to shallow wells as explained in the isotope hydrology part of this paper.

Because the Na^+ concentrations exceed Cl^- concentrations in almost all groundwater samples, ion- exchange is used to control Na^+ gains. Hence it can be clearly observed that cation exchange between Na^+ and Ca^{+2} ions is very significant in all the four models where the Ca^{+2} ion is being replaced by the Na^+ ion along the flow path.

5.7.2 Conceptual hydrochemical groundwater model

The conceptual model is based on information about variations in the chemical composition of ground water, the composition of aquifer material from previous works of WWDSE, 2009 and the geochemical study results of this paper. This conceptual geochemical model is that frequent precipitation containing dilute concentrations of major ions charged with dissolved oxygen and carbon dioxide reacts with the basic volcanics and acidic volcanic rocks at places covering most of the rugged terrain of the eastern water catchments. This reaction brought about a dissolution of plagioclase, olivine and pyroxene in the basic volcanics which resulted in saturation condition of groundwater with respect to calcite, dolomite, and aragonite where as an undersaturation condition of the groundwater with respect to gaseous forms of H_2O (g), CO_2 (g), H_2 (g),) and O_2 (g) (table 5.10). Furthermore as a result of plagioclase dissolution in particular, there is a release of Ca^{+2} ions which facilitate the cation exchange behavior.

The dissolution of largely soluble minerals such as olivine, pyroxene and plagioclase (Colman, 1982; and Eggleton and others, 1987) in the basic volcanics results in a Ca-Na-HCO_3, Ca-Mg-HCO_3-Cl or Ca-HCO_3 type of water which can be considered as the starting solution for the geochemical evolution of the groundwater in the Alleydege plain and Awash River valley. As the groundwater flows along the flow direction the concentration of Na^+, Cl^-, EC, SAR and HCO_3^- ions are progressively increasing where as the concentration of Ca^{+2} and Mg^{+2} ions decrease subsequently. This ultimately results in a Na-Cl-HCO_3 or a Na-HO_3 type of water in the Awash River valley and rift floor with a relatively increasing sodium and salinity hazard.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The Alleydege plain groundwater system is found about 250 km from Addis Ababa in the northeastern Ethiopia in Main Ethiopian Rift (MER), Afar regional state, along the main Addis Ababa-Djibouti road within the geographic location of 0990000 and 1070000 UTM N and 610000 and 690000 UTM E.

The groundwater hydrodynamics of this plain was studied by using hydrochemistry, Q-mode hierarchical cluster analysis (HCA), inverse geochemical modelling and isotope hydrology.

The results of the study reveal that the Alleydege plain groundwater system gets its recharge mainly from the, south-eastern and eastern elevated areas through subsurface inflow or slope percolation.

There is also isotopic signature that portrays the hydraulic connectivity of the Alleydege plain with the southern elevated areas.

The Awash River recharges the Alleydege plain and the Awash River valley aquifer that lie within few kilo meter distance from the Awash River during rainy season. However, during dry season such interaction is not observed significantly.

The local precipitation hardly recharges the groundwater of the Alleydege plain.

The groundwater from the southern, south-eastern and eastern highlands flows towards the rift floor in the northern direction.

Except the Na^{+}, F^{-} and NO_3^{-} whose concentration exceeds the maximum acceptable concentration limits of WHO and EU standard for drinking water, the rest major ions are in the MAC limits of WHO and EU standard for drinking water.

Along the groundwater flow direction the groundwater evolves from Ca-Mg-HCO_3-Cl or Ca-HCO_3 water type in the recharge areas to a Na-HCO_3-Cl or Na-HCO_3 water type in the discharge area, in the rift floor.

The groundwater evolution along the flow direction is accompanied by an increasing calcite saturation and cation exchange between Ca^{+2} and Na^{+} ions as a result of dissolution of calcite or, calcium-carbonate containing minerals.

Depending on the TDS value, the dendrogram produced from Q-mode hierarchical cluster analysis (HCA), manifests that the groundwater of the Alleydege plain is classified in to two major groups and four subgroups.

K-mica, plagioclase, pyroxene, and illite are the primary minerals of the Alleydege plain groundwater system.

6.2 Recommendation

Since detail longitudinal aquifer classification of the Alleydege plain is almost nil and groundwater sampler that enable to sample water for different aquifer system at different depth is absent, during the study of this research, the hydrochemical results and the conclusions made from the results does not reveal to a particular aquifer system rather to the whole aquifer in a borehole and ultimately extended to the whole aquifer system of the plain. Therefore in order to make use of the Alleydege plain groundwater, it is highly recommended to undertake detail geologic and hydrogeologic study.

For a better understanding of the interaction between the Alleydege plain groundwater and the regional surface water (Awash River), it is recommended to undertake monitored time variable isotopic, and hydrochemical study.

Regarding water quality issues, the concentration of NO_3, and concentration of Na^+ and F^- ions in the majority of rift groundwater seek close attention since these ions concentration exceed by far the EU and WHO water quality standards for drinking purpose.

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Annex-1: Lithologic logs

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL)	remark
AP-2	641424	1007510	892	Silsalabur	Fro	T o		72.95	
					0	4	Clay		
					4	8 6	Fractured Basalt		
					8 6	100	Slightly fractured basalt		
					100	190	Fractured Basalt		
					190	196	Fractured scoraceous Basalt		
					196	200	Welded tuff		
					200	206	Fractured scoraceous Basalt		
					206	210	Welded tuff		
					210	232	Fractured Scoraceous Basalt		
					232	240	Welded tuff		
					240	250	Fractured scoraceous Basalt		
					250	257	Fractured Basalt		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
AP-3	643798	1019148	835		From	To		86.4	T=34.3m^2/day
					0	6	Clay		DD=42.6m
					6	12	Clay		
					12	24	Slightly fractured Ignimbrite		
					24	30	Moderately fractured Basalt		
					30	78	Moderately fractured Igimbrite		
					78	84	Slightly fractured Basalt		
					84	108	Moderately fractured Igimbrite		
					108	116	Moderately fractured Scoraceous Basalt		
					116	138	Slightly fractured Basalt		
					138	154	Moderately fractured Basalt		
					154	160	Moderately fractured Scoraceous Basalt		
					160	200	Slightly fractured Basalt		
					200	238	Moderately fractured Igimbrite		
					238	260	Moderately fractured Basalt		
					260	282	Slightly fractured Ignimbrite		
					282	288	Slightly fractured Basalt		

BH-ID	X	Y	Z	Local name	Depth (m)		Lithologic description	SWL(m)	Remark
AP1	0652507	0996029	1118	Bordede	From	To		53.28	$T=10m^2/day$
					0	2	Clay		DD=56.06m
					2	50	Fractured basalt		
					50	52	Ignimbrite		
					52	72	Fractured basalt		
					72	74	Ignimbrite		
					74	88	Fractured basalt		
					88	98	un welded tuff		
					98	104	Fractured Basalt		
					104	122	unwelded tuff		
					122	148	Fractured scoraceous Basalt		
					148	178	welded tuff		
					178	192	Fractured Basalt		
					192	214	un welded tuff		
					214	248	welded tuff		
					248	266	Fractured Basalt		
					266	282	Unwelded Tuff		
					282	294	Welded Tuff		
					294	304	Fractured Basalt		
					304	310	Fractured Scoraceous basalt		
					310	350	Fractured Basalt		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
AP-5	645334	996709	996	Hardim	Fro	To		149.86	T=10 m^2/day
					0	6	Clay		DD=23.49m
					6	36	Highly weathered Ignimbrite		
					36	46	Highly weathered Basalt		
					46	52	Highly weathered Scoraceous Basalt		
					52	86	Moderately fractured Basalt		
					86	92	Highly weathered Scoraceous Basalt		
					92	102	Highly weathered Ignimbrite		
					102	114	Moderately fractured Basalt		
					114	118	Highly weathered Scoraceous Basalt		
					118	134	Highly fractured Ignimbrite		
					134	152	Moderately fractured Basalt		
					152	160	Moderately fractured Scoraceous Basalt		
					160	192	Slightly Fractured Basalt		
					192	198	Slightly fractured Scoraceous Basalt		
					198	208	Slightly Fractured Basalt		
					208	224	Slightly fractured Scoraceous Basalt		
					224	230	Slightly Fractured Basalt		
					230	238	Slightly fractured Scoraceous Basalt		
					238	244	Slightly Fractured Basalt		
					244	252	Slightly fractured Scoraceous Basalt		
					252	266	Slightly Fractured Basalt		
					266	270	Slightly fractured Scoraceous Basalt		
					270	282	Slightly Fractured Basalt		
					282	286	Slightly fractured		
							Scoraceous Basalt		
					286	294	Slightly Fractured Basalt		
					294	300	Highly Fractured Basalt		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description		SWL(m)
AP-6	0645495	1034311	808	5km east of Andido	Fro	T o			8 5
					0	3	B r o w n C l a y		
					3	8	Highly weathered & fractured8 Ignimbrite		
					8	40	Highly weathered & fractured Surge		
					40	64	Highly weathered Scoraceous basalt		
					64	76	Highly weathered basalt		
					76	82	Highly fractured Scoraceous basalt		
					82	86	Slightly fractured basalt		
					86	90	Moderately fractured basalt		
					90	94	Highly weathered Scoria		
					94	98	Highly fractured Scoraceous basalt		
					98	104	Slightly fractured Scoraceous basalt		
					104	110	Moderately weathered Scoraceous Basalt		
					110	120	Moderately fractured Basalt		
					120	134	Slightly fractured Basalt		
					134	138	Moderately fractured Scoraceous Basalt		
					138	146	Moderately fractured Ignimbrite		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
AP-6`	0642503	1031094	813		Fro	To		68.17	
					0	4	Clay		
					4	12	Moderately weathered & fractured Ignimbrite		
					12	82	Circulation loss		
					82	94	Slightly fractured Basalt		
					94	104	Highly weathered & fractured Scoraceous Basalt		
					104	106	Moderately weathered Ignimbrite		
					106	112	Moderately weathered Scoraceous Basalt		
					112	114	Moderately fractured Ignimbrite		
					114	120	Slightly Fractured Basalt		
					120	128	Slightly fractured Scoraceous Basalt		
					128	130	Moderately fractured Basalt		
					130	140	Moderately fractured Ignimbrite		
					140	150	Moderately Fractured Scoraceous Basalt		
					150	162	Moderately fractured Ignimbrite		
					162	182	Moderately fractured scoraceous basalt		
					182	196	Slightly fractured scoraceous basalt		
					196	204	Slightly fractured Ignimbrite		
					204	250	Highly fractured Ignimbrite		

BH-ID	X	Y	Z	Local name	Depth (m)		Lithologic description	SWL(m)	Remark
AP-8	645424	996570	822	Medene	From	To		72.27	T=8 m^2/day
					0	16	Moderately fractured Ignimbrite		DD=89.64
					16	32	Moderately fractured basalt		
					32	72	Moderately fractured Ignimbrite		
					72	112	Volcanic ash		
					112	202	Moderately fractured basalt		
					202	206	Moderately fractured scoraceous basalt		
					206	226	Highly fractured basalt		
					226	228	Highly fractured scoraceous basalt		
					228	280	Highly fractured basalt		
					280	282	Highly fractured scoraceous basalt		
					282	300	Highly fractured basalt		

H-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
AP-10	0637170	1016759	830	Gonita Birka'	From	To		79.4	
					0	6	Clay/gray/		
					6	10	Slightly fractured Basalt		
					10	16	Moderately fractured Ignimbrite/gray/		
					16	18	Moderately fractured Basalt		
					18	38	Moderately fractured Ignimbrite		
					38	44	Moderately fractured Basalt		
					44	50	Moderately fractured Ignimbrite		
					50	58	Moderately fractured Basalt		
					58	70	Moderately fractured Ignimbrite/gray/		
					70	76	Moderately fractured Basalt		
					76	84	Moderately fractured Ignimbrite/gray/		
					84	92	Slightly fractured Basalt		
					92	120	Unwelded tuff		
					120	154	Slightly fractured Ignimbrite/bluish/		
					154	168	Moderately fractured Ignimbrite		
					168	176	Moderately fractured Basalt		
					176	190	Volcanic ash		
					190	196	Moderately fractured basalt		
					196	206	Moderately fractured scoraceous basalt		
					206	212	Slightly fractured scoraceous basalt		
					212	220	Moderately fractured scoraceous basalt		
					220	232	Moderately fractured Ignimbrite		
					232	267	Slightly fractured basalt		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
LA-1	0633633	0995257	962	Awash Shisht	Fro	To		101.17	T=102.4m^2
					0	4	Ignimbrite		DD=37.64m
					4	8	Sand		K=2.05m/day
					8	14	welded tuff		
					14	20	Fractured scoraceous Basalt		
					20	26	welded tuff		
					26	36	weathered vesicular Basalt		
					36	100	Fractured Basalt		
					100	130	Fractured scoraceous Basalt		
					130	194	Fractured Basalt		
					194	200	Fractured scoraceous Basalt		
					200	202	Fractured Basalt		
					202	206	Fractured scoraceous Basalt		
					206	218	Tuff		
					218	242	Fractured vesicular Basalt		
					242	252	Welded Tuff		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
AP-11	0657056	1065134	840	8 kms before reaching Gedamaitu from Awash Arba town	Fro	To		149.7	
							Clay		
					0	4	Highly weathered Scoraceous basalt		
					4	10	Moderately weathered Ignimbrite(Bluish)		
					10	22	Highly weathered Ignimbrite(Bluish)		
					22	28	Highly weathered Ignimbrite(Gray)		
					28	52	Moderately weathered scoraceous basalt		
					52	64	Moderately weathered basalt		
					64	76	Highly weathered scoraceous basalt		
					76	90	Slightly weathered scoraceous basalt		
					90	110	Highly weathered scoraceous Basalt		
					110	136	Slightly fractured Basalt		
					136	142	Volcanic ash		
					142	156	Moderately weathered basalt		
					156	178	Moderately fractured basalt		
					178	202	Unwelded Tuff		
					202	220	Clay		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
LA-2	0635543	1021775	817		Fro	To		68.42	T=325m^2/day
					0	10	Silty Clay		DD=26.41m
					10	12	Boulder		
					12	16	Clay		
					16	22	Boulder		
					22	68	Clay		
					68	92	Fractured basalt		
					92	94	Volcanic Ash		
					94	110	Factured Ignimbrite		
					110	226	Fractured Scoraceous basalt		
					226	235	Fresh Scoraceous basalt		
					235	236	Slightly fractured basalt		

BH-ID	X	Y	Z	Local name	D e p t h (m)		Lithologic description	SWL(m)	Remark
LA-3	627464	1015684	823	Molal ita	From	To		75.66	T=39528m ^{2}/day
					0	2	Clay		DD=1.12m
					2	54	Weathered Basalt		
					54	58	Fresh basalt		
					58	85	Unwelded Tuff		
					85	86	Boulder		
					86	114	Fructured Basalt		
					114	120	Unwelded Tuff		
					120	126	Fructured Basalt		
					126	168	Unwelded Tuff		
					168	192	Fructured Basalt		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
LA-4	0626003	1025081	745	Chew Meret /Arategna	Fro	To		0.8	
					0	20	Clay(gray)		
					20	48	Clay +gravel intercalation		
					48	58	Boulders		
					58	64	Clay		
					64	68	Silt		
					68	78	Circulation loss		
					78	90	Silt		
					90	104	Fine sand		
					104	110	Silt		
					110	164	Clay(dark and expansive)		
					164	168	Silt		
					168	196	Clay(dark and expansive)		

BH-ID	X	Y	Z	Local name	Depth(m)		Lithologic description	SWL(m)	Remark
LA-5	636415	1039961	733	Arage	0	6	Clay	3.6	T=161m^2/day
					6	26	Silt		D.down=26.61 m
					26	78	Fractured Basalt		
					78	92	Fractured Ignimbrite		
					92	96	Fractured Basalt		
					96	110	Fractured Rhyolite		
					110	122	Fractured Ignimbrite		
					122	130	Fractured Rhyolite		
					130	138	Fractured Ignimbrite		
					138	142	Fractured Basalt		
					142	242	Fractured Ignimbrite		
					242	262	Fractured Rhyolite		

Annex-2: Chemical data of boreholes and spring

Secondary hydrochemical data obtained from WWDSE data base

SAR(meq/l	4	8	22	18	24	12	15	11	18	32	8	13	14	9	6	7	2	2	2	1	3
PO4(mg/l	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SO4(mg/l)	366	441	922	940	455	503	548	456	517	573	500	602	415	464	410	381	320	338	354	361	351
HCO3(mg/l	46	36	304	80	73	74	132	61	77	75	48	41	50	58	44	50	26	37	33	18	22
CaCO3(mg/l)																					
NO_3(mg/l)	5	2	10	18	1	7	8	5	1	5	7	10	7	8	8	8	20	10	8	8	8
Cl(mg/l)	39	58	365	358	68	83	158	71	119	121	92	239	58	65	53	50	30	41	38	23	30
F(mg/l)	2	2	3	4	4	4	3	3	2	4	3	4	3	4	2	2	2	1	1	1	1
Mn(mg/l)																					
Fe(mg/l)																					
Mg(mg/l)	30	22	40	37	5	13	20	13	13	5	21	32	9	18	25	21	47	73	62	83	49
Ca(mg/l)	16	8	19	24	2	9	11	7	3	2	17	15	3	11	13	8	17	17	13	18	12
$CaCO_3$(mg/l)																					
K(mg/l)	12	12	8	7	2	17	17	13	10	5	11	20	4	16	14	13	7	9	9	6	9
Na(mg/l)	116	174	660	585	248	240	325	208	276	335	204	355	190	186	135	144	72	56	74	43	81
NH_3(mg/l)																					
p H	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	7	7	8
EC(µs/cm)	734	906	2970	3010	1060	1149	1588	1008	1302	1464	1095	1888	894	1004	846	797	640	683	689	649	666
TDS(mg/l)	508	608	1936	1840	686	708	952	626	800	926	672	1212	584	630	592	516	386	440	478	424	458
Turbidity	1	3	2	2	4	2	3	2	4	2	3	2	1	1	0	1	1	2	1	0	2
Temp.(°C)	37	38	28	----	31	31	33	38	36	31	37	30	37	28	38	25	31	26	28	33	34
SWL(m)																					
BH.depth(m)																					
Z(m)	815	735	744	742	752	754	753	750	748	740	782	741	740	776	803	817	727	827	817	798	860
Y(UTM)	1039522	1047321	1031634	1030474	1027212	1021173	1021359	1021649	1023044	1027152	1017845	1031448	1034606	1027266	1028955	1025611	1068549	1008918	1007852	1007946	999422
X(UTM)	646837	644586	629485	629045	629784	625836	624305	624705	623270	623396	624546	632337	633726	633107	639503	642486	641074	628683	628311	628925	632047
Local name	Andido-1	Andido-Bilen	Melka worer	Melka worer	Badulale	Melka hida	Middle Awash	Middle Awash	Muz camp	Halaisomale	Kerenssa/Deyilu	Eiei-1	Kilito-1/Serkemo	Berta	Udileisi	Elfora	Halidebe	Awash Arba town	Defence/ Whua Net	Lalibela construc	Kurkura
Sample Id	BH6	BH7	BH8	BH12	BH13	BH15	BH16	BH18	BH19	BH20	BH21	BH22	BH24	BH26	BH27	BH30	BH31	BH33	BH34	BH36	BH37

SAR(meq/l	5	11	2	1	1	2	38	6	0	7	5	1	30	5	1	3	0	0	0	0	0
PO4(mg/l	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0
SO4(mg/l)	176	69	4	17	69	56	143	2780	1	46	41	22	385	47	39	131	36	50	77	75	41
HCO3(mg/l	269	400	328	407	492	423	1686	743	49	430	290	197	507	281	221	401	441	415	517	573	602
CaCO3(mg/l)																					
NO_3(mg/l)	20	10	18	18	29	12	9	800	5	3	12	14	3	7	7	2	2	7	1	5	10
Cl(mg/l)	236	78	11	37	188	56	425	3836	1	56	37	18	434	68	39	116	58	58	119	121	239
F(mg/l)	1	1	1	1	0	1	18	2	0	3	3	2	3	2	1	1	2	3	2	4	4
Mn(mg/l)																					
Fe(mg/l)																					
Mg(mg/l)	25	4	14	21	45	24	15	616	1	17	7	27	5	9	22	28	8	3	3	2	15
Ca(mg/l)	87	16	59	105	209	82	30	2093	16	20	27	98	18	35	55	101	22	9	13	5	32
$CaCO_3$(mg/l)																					
K(mg/l)	25	4	8	8	5	21	6	77	1	17	8	9	7	19	9	25	12	4	10	5	20
Na(mg/l)	220	190	54	43	60	82	1020	1250	1	172	110	52	565	123	28	115	174	190	276	335	355
NH_3(mg/l)																					
pH	7	8	7	8	8	7	8	7	7	8	8	7	8	8	8	7					
EC(µs/cm)	1523	949	572	765	1451	893	4410	17090	80	915	615	416	2840	885	632	1189	906	894	1302	1464	1888
TDS(mg/l)	960	600	362	486	958	588	2956	14066	54	586	390	280	1704	534	364	771	608	584	800	926	1212
Turbidity	2	1	1	2	1	1	2	6	150	180	2	5	0	0	0	0	0	0	0	0	0
Temp.(^oC)	34	28	31	31	31	0	31	28	25	40	24	29		34	37	37					
SWL(m)																					
BH.depth(m)																					
Z(m)	871	738	820	1333	1235	1105	724	728	2266	731			733	823	962	1118					
Y(UTM)	999671	1043036	1040111	1001716	1006483	996169	1048416	1045364	1025893	1046853			1039961	1015684	995225	996029	1047321	1033917	1023044	1027152	1031094
X(UTM)	626351	638824	647560	668814	669172	652583	639409	635843	674163	644235			636415	627464	633633	652507	644586	633683	623270	623396	632988
Local name																					
Sample Id	BH42	BH43	BH5	BH62	BH63	BH66	HD-9	HD-10	SP-3	SP-4	Awash River	Awash River	LA-5	LA-3	LA-1	AP-1	BH-53	BH-54	BH-19	BH-59	BH-60

Primary hydrochemical data generated for this research (WWDSE laboratory)

A) Wet season data ,September, 2010

SAR(meq/l	2.27	3.92	27.76	7.08	2.68	7.97	40.85	12.72	1.16	3.07	10.39	3.53	17.68	2.15	16.86	1.84	5.69	6.59	5.03	8.21	2.13
PO4(mg/l	0.81	0.94	0.58	0.81	1.1	0.95	0.36	0.43	0.71	0.68	0.78	1.12		0.44	0.81	0.67	0.57	0.69	0.79	0.4	0.36
SO4(mg/l)	59.02	54.45	63.78	48.17	17.9	61.4	161.53	69.02	2	78.06	56.74	56.36	0.94	19.42	158.6	39.51	77.02	117.48	44.65	51.03	28.27
HCO3(mg/l	435.54	435.54	297.19	430.42	336	471.41	479.09	473.97	294.63	307.44	461.16	333.06	73.02	310	594.38	353.56	281.82	742.98	294	412.48	153.72
CaCO3(mg/l)	nil	nil	35.28	nil		nil	10.08	12.6	nil	nil		nil	512.4	nil	15.12	nil	nil	nil	nil		nil
NO_3(mg/l)	15.43	13.74	1.14	3.52	5.55	8.63	2.3	5.75	4.82	1.69	3.17	4.73	420	6.56	13.8	10.48	3.79	19.82	5.22	2.65	7.54
Cl(mg/l)	58.25	41.86	67.45	54.61	21.84	105.57	321.26	88.28	10.01	73.72	63.71	36.4	0.08	19.11	201.13	39.13	58.25	105.57	41.86	55.52	19.11
F(mg/l)	0.81	0.89	6.73	2.45	0.66	2.31	4.21	2.56	0.67	0.73	10.24	1.06	103.75	0.62	2.62	0.72	1.47	3.41	0.92	4.21	1.27
Mn(mg/l)													0.89								
Fe(mg/l)	trace	trace	0.04	0.04	trace	0.05	0.02	Trace	0.01	0.02	0.11	0.01	trace	0.03	trace	0.05	0.02	trace	trace	0.15	0.2
Mg(mg/l)	27.36	19.15	0.91	11.4	12.77	16.87	2.28	6.84	14.14	9.12	9.12	11.86	2.74	11.86	15	5.93	9.12	18.24	10.03	9.12	4.56
Ca(mg/l)	60.8	37.24	2.28	19	50.16	19	7.6	11.4	45.6	54.72	11.4	36.48	10.64	39.52	19	76	19.76	79.04	26.6	15.2	22.8
$CaCO_3$(mg/l)	266	172.9	9.5	95	178.6	117.8	28.5	57	172.9	174.8	66.5	140.6	38	148.2	114	214.7	87.4	273.6	108.3	76	76
K(mg/l)	13.5	10.7	2.4	15.5	8.7	12	6.4	20.5	2.8	17.5	17	13	10.2	9.4	20	9.3	13.5	7	12	16	6.8
Na(mg/l)	85	118	196	158	82	198	500	220	35	93	194	96	250	60	405	62	122	250	120	164	42.5
NH_3(mg/l)	0.33	0.21	0.2	0.23	0.26	0.26	0.16	0.23	0.22	0.21	0.21	0.19	0.23	0.23	0.31	0.23	0.22	0.29	0.2	0.21	0.45
p H	7.61	7.79	8.61	8.07	7.43	8.2	8.42	8.3	7.53	7.36	7.96	7.44	8.11	7.66	8.34	7.31	7.74	7.65	7.64	8.07	7.95
EC(µs/cm)	926	893	980	866	660	1191	2320	1180	454	873	992	705	1231	562	1859	692	865	1631	732	924	380
TDS(mg/l)	622	580	610	566	460	704	1448	792	296	572	666	480	810	362	1198	464	516	1086	514	582	238
Turbidity	nil	nil			nil	5	nil	Nil	nil	11		nil	nil	nil	nil	nil	nil	nil	nil		212.8
Temp.(^oC)	35.6	32.3	36.2	40.4		29.4		35.9		35.5	35.1	36.2	35.9		36.9	34.1					
SWL(m)		150			126	39				?????? ?66	34	121	25	66		?????? ?55	77		?????? ?81		
BH.depth(m)	100	310	<60	60	210	81	<60	<60	51	194	82	242	105	194	<60	126	162	<60	120		
Z(m)		1007	752		894	782	740	754	1386	1083	776	891	748	833	753	827	815	742	820	731	
Y(UTM)	992169	996699	1027212	1028953	998837	1017845	1034606	1021173	1015842	998628	1027266	998037	1023044	1008252	1021359	1008918	1025542	1030474	1040111	1046853	1017702
X(UTM)	652583	645330	629784	639505	632421	624546	633726	625836	695877	653235	633107	632418	623270	632471	624305	628683	643300	629045	647560	644235	622962
Local name	Bordede	Hardem	Badulale	Udaliese	D.combined army	Kerensa	Melka Worer	Melka-Hida	Huse Sodoma	Jatropha farm	Berta	D.combined army	Muez-camp	Lalibela	Middle Awash	Awash Arba Town	Elfora	Worer	Andido	Billen	At Weir
Sample Id	BH-66	AP-5	BH-13	BH-27	BH-WN2	BH-21	BH-24	BH-15	BH-44	New-age	BH-26	BH-69	BH-19	BH-39	BH-16	BH-33	BH-72	BH-12	BH-5	SP-4	Awash River

B) Dry season data , January, 2011

SAR(meq/l	13.72	2.7	3.49	43	9.39	8.1	7.8	8.39	9.51	9.52	9.85	6.35	3.48	5.15	3.18	2.00	54.5	11.83	19.3
PO4(mg/l	0.36	0.49	0.43	1.18	0.47	0.38	0.39	0.36	0.48	0.41	0.4	0.27	0.29	0.37	1.53	0.49	0.33	0.44	0.43
SO4(mg/l)	38.81	51.16	87.35	110.86	65.42	64.88	60.2	31.72	212.98	113.8	62.64	87	34.57	219.94	19.08	63.68	193.84	54.78	39.06
HCO3(mg/l	461.28	215.57	308.29	950.38	452.1	488	405.65	402.6	741.76	390.4	435.78	347.7	373.32	266.57	348.92	424.19	776.53	366	428.83
CaCO3(mg/l)	416.1	176.7	252.7	836	370.5	400	332.5	330	608	320	357.2	319.2	306	218.5	286	347.70	674.5	340	408.5
NO_3(mg/l)	2.25	3.41	4.39	0.4	2.77	3.41	3.26	2.74	3.35	2.25	1.25	0.27	4.73	13.18	0.6	10.19	4.93	0.71	5.4
Cl(mg/l)	92.75	24.61	38.8	109.79	67.2	66.25	57.73	55.84	123.98	48.27	62.46	20.82	43.54	219.57	19.88	57.73	149.54	79.5	105.05
F(mg/l)	2.07	1.02	0.5	11.29	3.24	2.88	2.26	6.12	4.35	3.52	5.48	0.66	0.68	1.2	0.6	0.73	2.91	0.68	52
Mn(mg/l)	0.22	0.64	0.04	0.05	0.01	0.02	0.05	0.04	0.04	0.04	0.05	0.03	0.01	0.03	0.05	0,01	0.01	0.03	0.04
Fe(mg/l)	8.16	1.92	9.6	2.4	9.12	14	5.28	1.44	16.32	4.8	7.2	8.64	0.96	8.16	5.76	11.52	0.96	1.92	2.4
Mg(mg/l)	12	34.4	44	8	16	16	23.2	28	88	19.2	20	24.8	74.4	92	51.2	89.60	4.8	16	12
Ca(mg/l)	64	94	150	30	78	100	80	76	288	68	80	98	190	264	152	272.00	16	48	40
$CaCO_3$(mg/l)	14.4	7.7	11.4	2.7	13.8	15	11.1	13.6	6.5	12	17.2	6.9	8.6	18.6	9.1	17.40	26.2	3.9	9.1
K(mg/l)	244	60	98	540	190	184	160	168	370	180	202	144	110	192	90	76.00	500	188	280
Na(mg/l)	0.17	3.64	0.16	0.31	0.17	0.22	0.19	0.19	0.33	0.21	0.24	0.19	0.23	0.37	1.3	0.26	0.23	0.64	0.21
NH_3(mg/l)	8.22	7.61	7.6	8.22	7.88	7.86	7.67	7.66	7.46	7.65	7.65	8.26	7.41	7.81	7.38	7.10	8.28	8.25	8.51
pH	1188	445	666	2060	983	999	905	846	1817	791	915	698	699	1458	579	916.00	1845	938	1220
EC(µs/cm)	780	292	446	1356	640	650	532	550	1198	576	598	490	500	950	378	598.00	1288	616	798
TDS(mg/l)	92.75	24.61	38.8	109.79	67.2	66.25	57.73	55.84	123.98	48.27	62.46	20.82	43.54	219.57	19.88	57.73	149.54	79.5	105.05
Turbidity	nill	117.53	nill	1.83	nill	nill	nill	Nill	nill	nill	0.37	5.11	nill	Nill	nill	0.00	nill	nill	nill
Temp.(°C)			37.8	32	37	38		38		43	38	28	31.6		35.50	35.60	50		
SWL(m)			126			34				77		72.95	55	91.75	66		0	18	25
BH.depth(m)			210		≥82	82	42	60		162		257	126	139	194	100	70	100	105
Z(m)	754		894	723	771	776	729		742	815	731	892	827	871	833			738	748
Y(UTM)	1021173	1017702	998837	1048416	1027936	1027266	1047320	1028953	1030474	1025542	1046853	1007510	1008918	999671	1008252	992169	1011337	1043036	1023044
X(UTM)	625836	622962	632421	639406	633278	633107	644582	639505	629045	643300	644235	641424	628683	626351	632471	652583	597136	638824	623270
Local name	Melka -Hida	At Weir	D.Combined Army	Keleat	Berta	Berta	Billen Ende-Bury	Udaliessie	Worer	Elfora	Billen	Silsalabur	Awash Arba Town	Dudu	Lalibela	Bordede	Kesem Dam	Hasoba-Billen	Muez Camp
Sample Id	BH15	Awash River	BH WN2	HDW 10	BH New	BH 26	BH 7	BH 27	BH 12	BH 72	SP 4	AP 2	BH 33	BH 1	BH 39	(BH66)	BHKD	BH 43	BH 19

Annex 3: Stable Isotope, Tritium and Carbon -14 data

Primary data (stable isotopes of water) generated four this research

Sample-ID	X	Y	Z	Local name	Isotope of wet season Sep,2010		Isotope of dry season Jan,2011		BH-depth
					$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	
BH 66	652583	992169		Bordede	-0.76184	6.042887	-0.82	-4.26	100
AP 5	645330	996699	1007	Hardem	-2.62074	-7.84205	---	---	310
BH 13	629784	1027212	752	Badulale	-3.87573	-14.6921	---	---	<60
BH 27	639505	1028953		Udalisie	-1.01796	5.421077	-3.77	-13.48	60
BH WN2	632421	998837	894	Defence Combined Army	-3.40932	-5.47677	-4.85	-19.80	210
BH21	624546	1017845	782	Kerensa Deylu	0.149668	14.7445	---	---	81
BH 24	633726	1034606	740	Melka werer	-1.61371	3.238066	---	---	<60
BH 15	625836	1021173	754	Melka Hida	-3.86297	-11.0915	-1.71	1.91	<60
BH- 44	695877	1015842	1386	Huse Sodoma	-2.28357	4.75308	---	---	51
New Age	653235	998628	1083	Jatropha Farm	-0.4852	13.24362	---	---	194
BH 26	633107	1027266	776	Berta	-0.90588	10.44964	-1.08	2.50	82
BH 69	632418	998037	891	Defence Combined Army	-3.44184	-11.614	---	---	242
BH 19	623270	1023044	748	Muz Camp	-2.22342	-5.520523818	-0.87	-1.57	105
BH 39	632471	1008252	833	Lalibela	-2.68188	-5.59196	-0.19	0.80	194
BH 16	624305	1021359	753	Middle Awash	1.634218	19.66234	----	----	<60
BH 33	628683	1008918	827	Awash Arba town	-0.74804	9.217621	-1.69	-8.42	126
BH 72	643300	1025542	815	Elfora	-1.96032	-1.20018	-3.12	-10.86	162
BH 12	629045	1030474	742	Worer	-3.42245	-8.84574	-2.17	-2.57	<60
BH 5	647560	1040111	820	Andido /Intiaso	-0.20128	11.67825	---	---	120
SP 4	644235	1046853	731	Billen	-2.23146	-1.98	-1.50	-4.97	
Awash River	622962	1017702		At the Weir of Melka-Sedi (Farm)	-2.22672	-3.80641	-1.94	2.30	
HDW 10	639406	1048416	723	Keleat	-------	-------	-4.52	-13.99	
BH New	633278	1027936	771	Berta (For Worer town)	-------	-------	-4.37	-17.20	
BH 7	644582	1047320	729	Billen (Ende Buri)	-------	-------	-2.02	-5.36	42
AP-2	641424	1007510	892	Silsalabur	------	------	-1.43	-0.14	257
BH1	626351	999671	871	Awa.Dudub	------	------	0.36	7.91	139
BH-KD	597136	1011337		Kesem Dam	------	------	-0.46	-1.78	70
BH- 43	638824	1043036	738	Hasoba Billen	-----	------	-0.09	5.47	100

Secondary data of stable Isotopes, Tritium, and Carbon-14

Sample Id	Type	X	Y	Local name	$\delta^{18}O$	$\delta^{2}H$	^{3}H	^{14}C	^{13}C	Source
Gewane		682104	1123451	Gewane			0.5			AAU
Meteka		668788	1102348	Meteka			0.5			AAU
Alleydege		644550.7	1044764	Alleydege				39.2	-6.46	Dr.Seifu(AAU
Arba Bordede		681274.8	996987.4	Arba Bordede				46.84	-4.59	Dr.Seifu(AAU)
Borehole		682104	1123461	Gewane	-2.8	-14.7	0.5			AAU
Borehole		642540	1025602	Alleydege	-2.88	-12.3	0.02			AAU
Borehole		652608	1242467	Elwoha	-2.37	-9.9	2.4			AAU

DECLARATION

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

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Date of Submission: May, 2011