Groundwater & Surface Water Interaction in Lake Tana sub-basin using Isotope and Geochemical Approach

A Thesis Submitted to the School of Graduate Studies
Addis Ababa University
Faculty of Science
Department of Earth Sciences

In partial fulfillment of the requirement for the degree of
Master of Science in Hydrogeology

Submitted By: Girum Admasu Nadew

June 2010
Addis Ababa
Ethiopia

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Abstract

This investigation was made to figure out the interaction between the surface water and groundwater bodies in Lake Tana sub-basin using isotope and geochemical approach.

The main objectives of this investigation were:

- To map the spatial and vertical distribution of water geochemical composition in the area.
- To identify the origin & evolution of the isotopic and geochemical characteristics of the water in the Lake Tana sub-basin.
- To investigate the interaction between surface water and groundwater.

Isotope and Geochemical method has indicated that two major evolution processes of the salinity operate in Lake Tana sub basin. These are evapotranspiration on the the flat plain and Deep circulation associated with silicic dykes.

Evapotranspiration is the main cause of Pockets of highly saline areas in the permanent and seasonal parts of the wetlands. It causes water to be transported by a plant through capillary action of vessels from the soil to the air by leaving dissolved matter with no net isotope fractionation causing salinity.It is mostly observed at the Dembia and Fogera plain close to the wetlands and trees. It is not distributed uniformly but random and is moderately depleted isotopically.

The saline water associated with deep circulation is found close to silicic dykes. Fluid movement under pressure change due to the occurrence of the dyke and osmotic processes has often residual components because of the long relaxation time of the pressure gradient and thus salinity occurs.

The shallow pocket salinities observed in this study may be exacerbated if other additional processes contribute to salinity of the area. Therefore, a comprehensive groundwater investigation is a priority to implementing large schemes such as irrigated agricultural development in the flat wetlands. This can be done by implementing a micro geo-morphological investigation in combination with diurnal water quality monitoring.

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1 Introduction

Investigating the groundwater and surface water interaction in the Lake Tana Sub-basin has indicated that pockets of highly saline areas occur in the permanent and seasonal parts of the wetlands. This occurrence is observed on the flat wetlands showing shallow high salinity anomaly in a generally fresh environment. Pockets of highly saline areas also occur close to silicic dykes associated with Tarmaber basalts. The salinisation on the flat Dembia and Fogera plain is caused primarily by evapotranspiration. Where as the salinity associated with dykes occur due to deep circulation. These processes are dependent on water flow, solute transport, mineral deposition, geomorphologic processes and vegetation dynamics. Hence, their distribution, interaction with the surface water and groundwater and origin is studied.

The main objective of this paper is to understand the groundwater and the surface water dynamics including spatial and vertical distribution of water geochemical composition and to identify the origin & evolution of the isotopic and geochemical characteristics of the water

The determination of the extent of interaction between a lake and the adjacent groundwater field or the river water and a borehole can be done through delineation of the mixing zone down gradient from the lake or river reflecting the mixing of local recharge and the lake water outflow. Moreover, the sample points plotting close to each other on the Deuterium (δ^2H) versus Oxygen (δ^{18}O) isotope curve are supposed to have similar source. However, points plotting away from each other may have no interaction.

Adequate characterization of the mixing zone is also of particular importance for aquifers being exploited for water supply or a river recharging the groundwater. Combining isotopic and geochemical method was necessary due to the fact that physicochemical parameters of lake water (e.g. conductivity, temperature) or the groundwater cannot be used as the only tools for this purpose as they are usually not sufficiently well preserved in the downstream aquifer.

In case of Lake Tana sub-basin the interaction between the lake, rivers, groundwater (shallow and deep) and recharge mechanisms were investigated. Thus, the recharge source, the salnisation process, the vulnerability of the water points to pollution and in general the flow systems were scrutinized in this investigation.

Previous geochemical and isotope investigations have shown that shallow wells are recharged by traveling short distance to give rise to low total dissolved waters while deep groundwater has more residence time generating high total dissolved waters (Kebede et al, 2005).

On the other hand, Pockets of shallow salinity areas were identified in the wetlands particularly the salinity in the Rib sub-basin and lower Megech plain and were associated with evaporation (Zenaw, 2009, unpublished).

However, isotopic signatures have proved that salinity of shallow wells on the Dembia and Fogera plain occurs due to evapotranspiration enhanced by wetlands and trees. The second type of salinity is associated with dykes and has come due to deep circulation and interaction with sedimentary origin as disclosed by the isotopic, geochemical and deep circulation model.

It is known that Lake Tana is being flooded for seven months every year starting from June to December. According to Yohannes, 2008, flooding occurs due to backwater flow from lake, along river lines, out flow from the banks and rainfall that did not drain rapidly due to the flat nature of the topography. On the contrary, isotopic and geochemical information did not show backwater flow signature of Lake Tana in the river or ground water. Besides, waters from the hand dug wells in the wetland and the surrounding area have a depleted isotopic signature as compared to the river and Lake water. Thus, back water effect of the Lake Tana did not contribute to the flooding the sub-basin.

It is also noted that deep aquifers are recharged by rainfalls on the highland and shallow aquifers are recharged by local rainfall. However, there is some shallow and deep groundwater recharge derived from the rivers.

In this respect, three geochemical evolution models are presented to show how the surface water and groundwater interaction goes on. These are evaporation model (successive evaporation-dissolution cycling), evapotranspiration model and deep circulation model (highly mineralized waters).

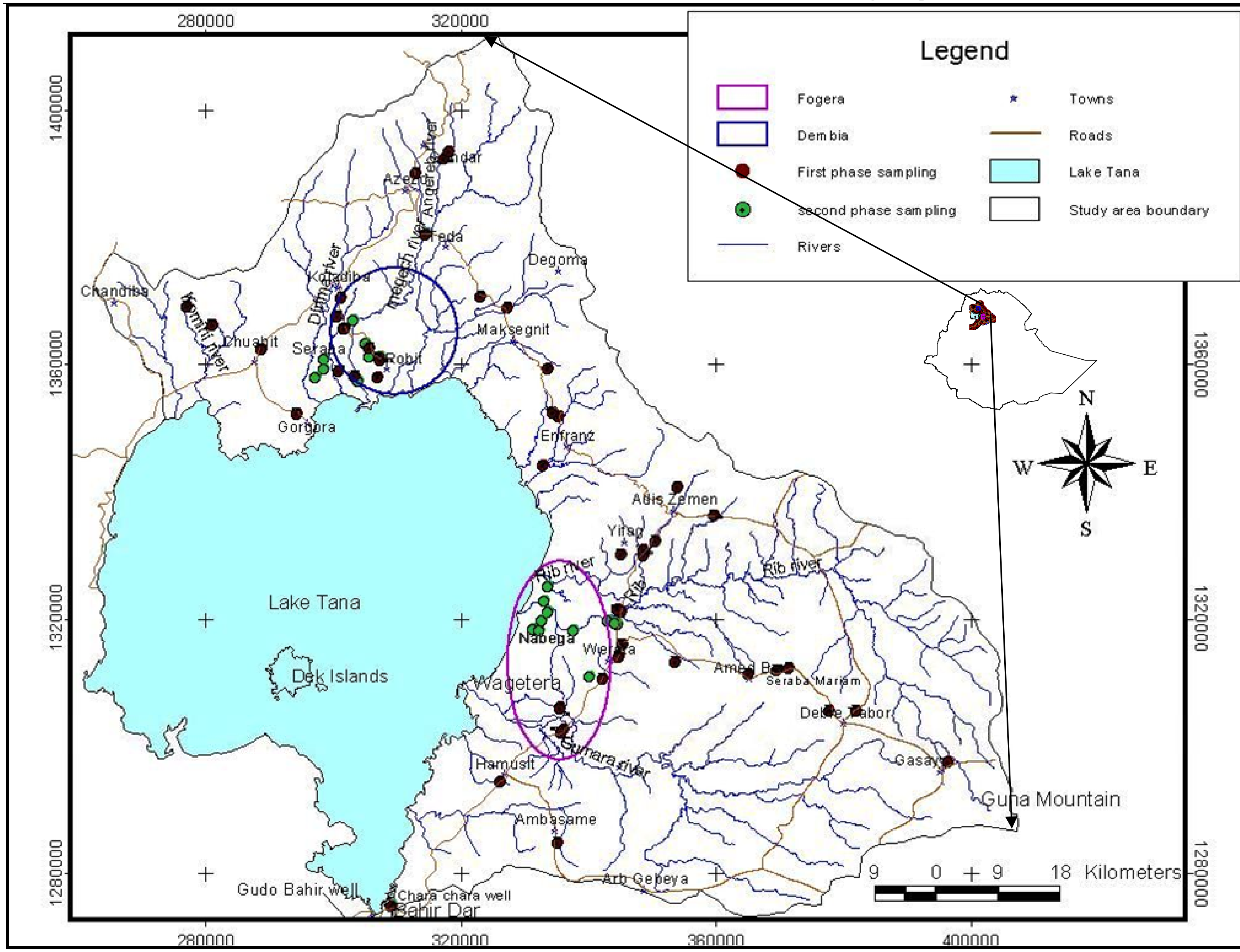

Figure 1-Location map and sampling sites of the study area

2 Objective of the investigation

The main objectives of this investigation are:

- To map the spatial and vertical distribution of geochemical composition of water in the area. The mapping of the geochemical composition of waters can lead to the understanding of variation of fresh, polluted and saline waters in the area and thus the groundwater and surface water interaction can be identified.
- To identify the origin & evolution of the isotopic and geochemical characteristics in the Lake Tana sub-basin. Understanding the origin of pollution or salinity is very useful to suggest methods of minimization of long term geo-environmental degradations due to water resources development activities.
- To investigate the interaction between the surface water and groundwater.

3 Methodology

3.1 General

The methodologies of this research were previous data collection, sampling new water points and Geochemical and Isotopic analysis and interpretation.

3.2 Data collection and analysis

Secondary geochemical and isotope data were collected from the previous studies and also field water samples were collected onsite twice (in October and March).

About 50 randomly selected groundwater and surface water samples were collected from hand dug wells equipped with hand pumps, deep wells fitted with submersible pumps, Lake Tana, rivers, springs and flood water at the first stage of sampling (Feb 17-26/2010).

Twenty four samples were also collected at the second stage narrowing the location of sampling towards Robit and surroundings in the Megech sub-basin and Nabega and surroundings in the Rib sub-basin. Samples were always collected after purging the hand pump installed wells or on working boreholes. Some wells that did not work at the time of sampling were noted as exception. Field water sample analyses were made for electrical conductivity, total dissolved solids, temperature and dissolved oxygen. Additionally, the name of the site, the location (UTMx and UTMy and Elevation) and the geological setup of the well location have been registered for reference.

The aggregate samples were collected as it was not possible to collect depth specific samples. The sampling was done using a 1 liter IAEA standard polyethylene (PE) bottles and 2 liter PVC bottles for geochemical, Deuterium (δ^2H) and Oxygen 18 ($\delta^{18}O$) analysis and Tritium (δ^3H) analysis respectively. The analysis was made by reducing 5ml water from the polyethylene (PE) bottles for Deuterium (δ^2H) and Oxygen 18 ($\delta^{18}O$) analysis to be analyzed at the Department Earth science Laboratory and then the rest was transported to the Water Works Design and Supervision Enterprise Laboratory. The 2 liter samples analysis was done at the laboratory of Department Earth science for tritium. The deuterium and oxygen 18 samples were analyzed using Liquid water isotope analyser model DLT-100 where as the tritium analysis was counted using scintillation counter. Geochemical analysesis was carried using basic Titration methods.

3.3 Geochemical methods

Geochemical method is a well recognized method used to trace the source and destination of surface water, groundwater and lake or pond water. Systematic geochemical sampling of the river water (upstream and flooded area), shallow and deep groundwater and lake water was carried out.

Laboratory analysis has been executed for cation and anion concentration at the Water Works Design and Supervision Enterprise Enterprise laboratory. Using the analysis result, graphical and statistical analyses methods were applied to identify different groups of hydrochemical facies in the study area.

Reaction error analysis, plots of error percentage and laboratory versus field electrical conductivity, were used to investigate whether there is an error in the laboratory analysis.

The change of electrical conductivity with depth is also one of the methods used to analyze the variation of salinity with depth.

It was also possible to determine polluted wells using chloride (Cl^-) versus Nitrate (NO_3) plot. Besides, Oxygen isotope ($\delta^{18}O$) versus Chloride (Cl^-) plot was used to determine which wells have undergone evaporation, evapotranspiration, hydrolysis, leaching and dissolution processes.
Piper diagram is one of the methods that help water sample data to determine whether a specific water sample may be a simple mixture of others for which analyses are available or whether it is affected by solution or precipitation of a single salt (Piper, 1944 & Hem, 1985)
Statistical analysis is another method applied to show statistical relationships among their dissolved constituents and environmental parameters, such as lithology, using multivariate statistics (Drever, 1997). This method is unique in the fact that it uses multiple parameters of water sample. In this case, nine parameters were used utilizing the previous and new data in combination.
Among the different methods, hierarchical analysis has been used to classify the data in a relatively simple and direct manner, with the results being presented as a dendogram, an easily understood and familiar diagram. This method was used to test water quality data and determine if samples can be grouped into distinct populations (hydrochemical groups) that may be significant in the geologic context, as well as from a statistical point of view (Güler et al., 2002). The 99 sample points presented in the annex table 8 have resulted in six groups.

3.4 Isotopic methods

3.4.1 Oxygen isotope (δ18O) and Deuterium (δ2H)

Isotopic method is one of the prominent sciences used to trace active rainfall, river, storage reservoir water, groundwater flow, intermixing of waters, pollution source and other important applications.
In this study deuterium (δ^2H) and oxygen ($\delta^{18}O$) were used. It is known that water is composed of hydrogen and oxygen occurring with different isotopic combination in its molecules.
The isotopic composition of water is expressed in comparison with the isotopic compositions of Ocean water and is expressed in per mil (‰) deviation from the standard mean ocean water (SMOW) (Craig, 1961).

The deviations of deuterium (δ^2H), oxygen ($\delta^{18}O$) is expressed as:

$$\delta^2H\ \text{‰} = \frac{(^2H/H)_{sample} - (^2H/H)_{smow}}{(^2H/H)_{smow}} \times 1000$$

where δ^2H‰=deuterium in per mil, ^1H= hydrogen

Similarly, the deviationof $\delta^{18}O$

$$\delta^{18}O\ \text{‰} = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{smow}}{(^{18}O/^{16}O)_{smow}} \times 1000$$ where

Where $\delta^{18}O$‰= oxygen 18 in per mil, ^{16}O= oxygen 16,

The stable isotopic method is used assuming that the isotopic signature does not change unless it is affected by fractionation processes. The water that underwent this process shows a change in its isotopic signature.

The alteration of $\delta^{18}O$-δ^2H composition of groundwater gives insights in to its subsurface history and geochemical reactions (Clark, 1997).

Meteoric water line is a convenient reference line for understanding and tracing of local groundwater origins and movements (Mazor, 1997). In this case, the local Meteoric water line as calculated by Schoell, and Faber (1976) was taken as "$\delta^2H = 8\delta^{18}O + 15$". Isotopic studies have been carried out by different authors; Mackenzie et al, (2001); Kebede et.al. (2005), and Mola et. al(2007); and Kebede et.al. (2008). Water samples collected from groundwater, lake, river, and flood water were plotted and interpreted.

Isotopic study was used to identify evaporation and evapotranspiration signatures in the sub basin. Evaporation is a physical process in which energy loaded water molecules move from water phase in to the vapour phase. Isotopically, light water molecules evaporate more efficiently than the heavy ones. As a result, an isotopic fractionation occurs at partial evaporation of water; the vapour is enriched in light water molecules, reflected in negative $\delta^{18}O$ and δ^2H values (Mazor, 1997). In contrast, the residual water phase becomes relatively enriched in heavy isotopes, reflected in more positive $\delta^{18}O$ and δ^2H signatures. On the contrary, evapotranspiration is a process of removal of water by a plant through capillary action of the plant vessels. Evapotranspiration leaves the chemical constituents in the groundwater and accumulates dissolved constituents which results in high salinity close to the surface. In spite of the accumulation of dissolved solids, isotopic signatures are not fractionated (Mook, 2000).

In the study area, flood lake and river waters are highly enriched whereas samples from deep wells at Debretabor, Gasay and Woreta were highly depleted.

4 Characterization of Lake Tana

4.1 Location and topography

The study area is found in Amhara National Regional State North and east of Lake Tana at about 564 km from Addis Ababa.

Lake Tana is a fresh water lake and is the source of Abay River (Blue Nile), which is the biggest and the longest river in Ethiopia. Tributaries from the North, East, South and west direction feed the lake. Lake Tana sub-basin occupies an area of 15,046 Km^2. Out of this; Lake Tana occupies an area of 3600 Km^2. The study area lies between 1,281,495 to 1,410,891 North UTM and 281,317 to 417,692 East UTM (figure 1)

The basins elevation ranges from 1785 m at Lake Tana up to 4135 m above mean sea level on Guna Mountain, east of Lake Tana. Starting from North of Gondar town there are chains of high rising mountains extending all the way to Guna.

Most of the Megech and Gumara and some part of the Rib river mouth pass through a flat flood plain with little topographic variation.

4.2 Climate & Hydrology

The climate of the region is 'tropical highland monsoon' with unimodal rainy season between June and September. The seasonal distribution of rainfall is controlled by the northward and southward movement of the inter-tropical convergence zone (ITCZ). Moist air masses are driven from the Atlantic and Indian Oceans during summer (June–September).During the rest of the year the ITCZ shifts southwards and dry conditions persists in the region between October and May. Generally, the southern part of the Lake Tana sub-basin is wetter than the western and the northern parts (Kebede et al. 2005).

The main rainy months around Lake Tana are June to September; whereas dry months are from October to May. The Mean annual rainfall varies from 900 mm to 1500 mm. In the study area the highest monthly rainfall is recorded in Dek estifanos (1900mm) and the lowest at Gorgora (908 mm) (figure 2).

The mean annual temperature reaches up to 23^{o}C in the low-lying areas (below 2000 masl) and in the range of 15 to 20^{o}C in the middle and high altitudes (above 2000 masl).

According to the Ethiopian mapping agency (1998) climatic classification, the study area is found in "Kur" (Alpine) ranging from 3000m and above, "Dega" (Temperate) ranging from 2300 m to 3000 m and "Woina dega" (subtropical) ranging from 1500 to about 2300m.

The hydrology of Lake Tana sub-basin has been studied by various authorities and researchers. The objective of these studies were calculating the water balance, studying the groundwater and surface water resources around the lake, studying the ungauged area of the basin and studying the whole Abay basin (Pelgrum(2006), Melkamu, (2005), Kebede et al (2006), Tarekegn (2005), Yilma et al (2006), CES and Tropics (2003), BCEOM(1999), Alebachew (2009) and others).

Table 1-mean annual rainfall and runoff

River	Gauging site	Mean Annual rainfall (mm)	Watershed area (Km2)	Mean Annual Flow (m3/s)	Mean Annual Flow (Mm3)
Megech	Azezo	1095	462	6.08	192
Gumara	Bahir Dar	1300	1394	30.19	952
Rib	Addis Zemen	1350	1592	12.60	397
Upper Rib	Deberetabor	1450	844	8.42	266

Lake Tana is fed by over 40 rivers and streams flowing from the surrounding mountains (Alebachew, 2009). The Estimated mean annual inflow to Lake Tana based on gauged catchments is about 3,556 million m3 and the mean annual outflow from Lake Tana is about 3,750 million m3, as estimated over the period 1960-2001(World Bank/MoWR, 2007,unpublished).

In the study area, the main rivers feeding Lake Tana are Sewgedel, Komni, Dirma, Megech, Ribb and Gumara. The inflow of some rivers is given in table 1.

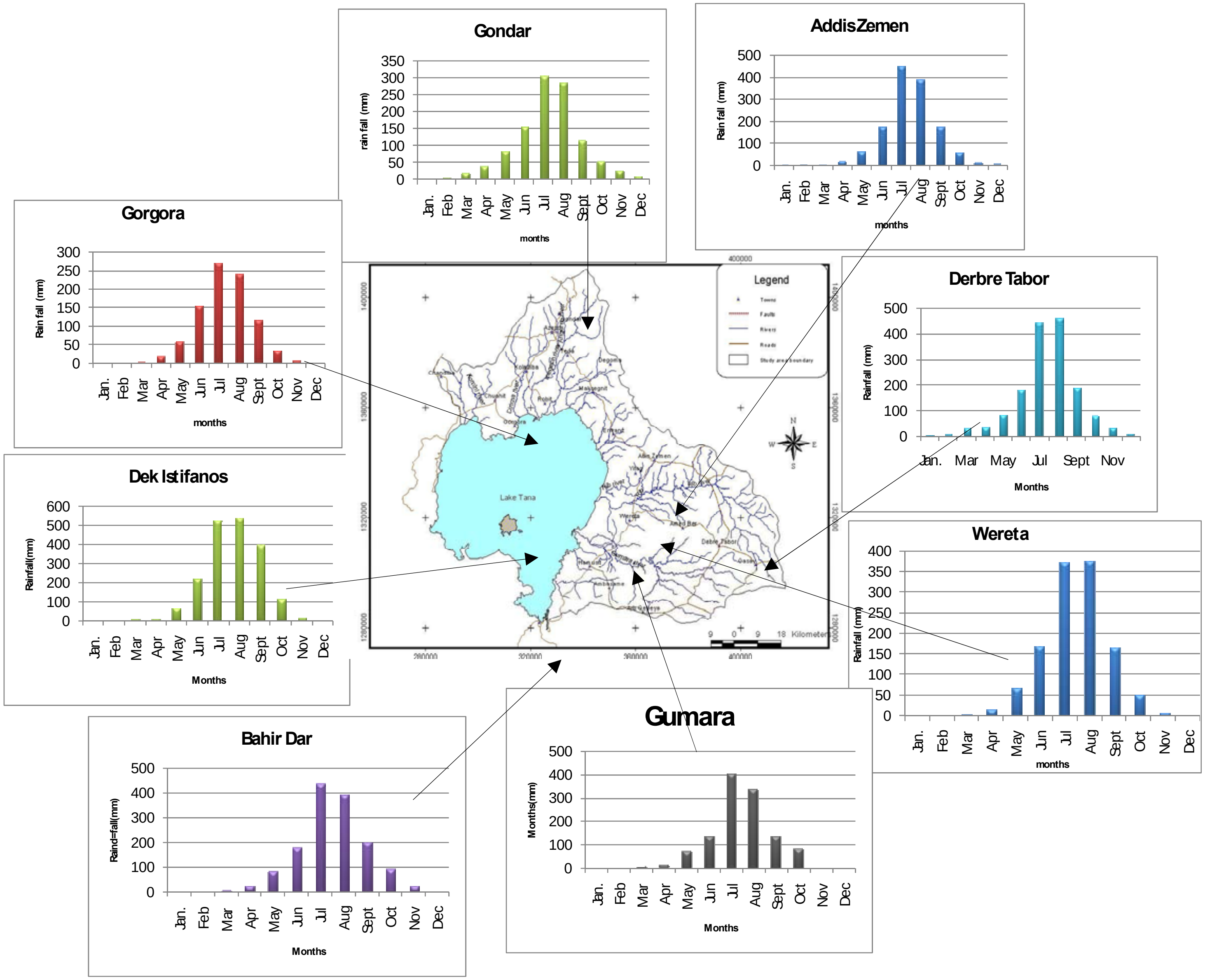

Figure 2-Rainfall pattern in the Lake Tana Basin

4.2.1 Soil and Land Use

The soils in most of the Tana basin are derived from the weathered basalt profiles, and are highly variable. In low lying areas particularly north and east of Lake Tana is developed on alluvial sediments. The Major Soil Groups characterized by Abay basin master plan study include Euteric Fluvisols, Chromic luvisols, Haplic Luvisols, Euteric Leptosols, Euteric vertisols and Haplcic Nitosols. According to Yohannes Daniel (2008), Luvisols are soils that are derived from various volcanic and undifferentiated lower complex rocks. They are common on flat and gently sloping topography in cooler climates of west Gojam and North Gonder. They are identified in color as Brown /reddish brown with clay to silty clay texture. These soils are Friable to firm, sticky and slightly plastic.

Leptosols are on the other hand developed in relatively younger surface and were probably moderately deep to deep by origin. The top soil has a thickness ranging from 10 to 30 cm and is mostly brown /yellowish brown in color and clay loam to clay in texture.
Vertisols are soils that are mostly imperfectly to poorly drained, dark grayish soils, formed on flat to almost flat plains. The clay fraction of these soils is dominated by expansible 2:1 lattice clays. Vertisols are very to extremely hard when dry and very sticky and plastic when wet.
Euteric Fluvisols are found at the middle and lower Rib, Lower Megech and some patches are also found north of Kola diba, around chandiba and on Dek islands.
Haplic Nitosols and Euteric Leptosols are found on the eastern highlands covering the basins eastern side. Haplic Nitosols cover a small area east of Tana basin as compared to Euteric Leptosols. Euteric Leptosols cover wide area north of Azezo and east of Tseda, Enfranz & Addis zemen
Chromic Luvisols cover most of the upper Rib, middle Gumara river basin and south west of Hamusit town. Euteric vertisols are found at the lower Rib, Megech and Dirma river courses covering the areas around Lake Tana.
Land use condition of the area is dominated by cultivated land while, there is some grassland and shrub land north of Yifag and Addis Zemen.

4.2.2 Evaporation and evapotranspiration

Evaporation and evapotranspiration are some of the factors that influence the water balance of a given landscape. Evaporation of surface water or groundwater increases the concentration of suits of minerals in the soil water (Appelo & Postma, 2007) including isotopic content. However, evapotranspiration increases only the concentration of minerals in the ground with out affecting isotopic content. It is presumed that both processes have a role to play in this basin even if it is variable.

The evaporation from the lake has been estimated using different methods and authors. The lowest estimated potential evaporation from the lake is 1588mm/yr (Pelgrum et al, 2006) and the highest was calculated as 1948 mm/yr (Coin Belier & Humphreys, 1996). Another author has calculated the lake potential evaporation to be 1563 mm/yr (Perera,2009)

Evapotranspiration is also one of the aspects of nature in determining the interaction of the groundwater and surface water interaction by leaving the dissolved solids in the ground. As the process continues each season the deposition increases

It is variable due to the variation in the presence, type and root depth of the vegetation covers. Evapotranspiration was estimated for Lake Tana sub-basin by Janaka Perera on his paper entitled «ungauged catchment hydrology » in 2009 (table 2).

Table 2-potential evapotranspiration at gauged and ungauged catchments (source: Janaka Perera, 2009)

River basin	Gauged Catchment (Km2)	Potential Evapotranspiration (mm/Yr)
Megech	531	1442
Gumara	1281	1307
Rib	1408	1300
River basin	**Ungauged Catchment(Km2)**	**Potential Evapotranspiration (mm/Yr)**
Megech	437	1359
Gumara	287	1386
Rib	736	1300
Tana west	546	1498

In general, the evapotranspiration is very high from Gondar to Gorgora and Gondar to Enfraz. It is the lowest from Gasay to Woreta and Adis zemen to Arb Gebeya.

4.2.3 Geological and Tectonic setting

The geology of Lake Tana has been studied by different researchers and authorities in relation to its deposition (volcanism), Graben formation, dam site investigations and local hydrogeological interest.

Lake Tana lies in a large basin formed by structural deformation, erosion and extrusions of volcanic rocks. It is considered to owe its present form due to damming by a 50-km-long Quaternary basalt flow, which filled the exit channel of the Abbay River to a possible depth of 100m (Chorowiz et al. 1998).

There is also a new data from digital elevation modeling and satellite imagery analysis that confirms the basin's location is at the junction of three grabens: the Dengel Ber (buried), Gondar (exposed by erosion) and Debre Tabor (reactivated). (Chorowiz et al. 1998; Feseha, 2002).

The geology of the Lake Tana sub-basin is dominated by outcrops of basaltic volcanic rocks in the highland areas and alluvial deposits around the lake margin (SMEC, 2007). According to the USBR (1964) report the stratigraphy of the Lake Tana sub-basin includes Quaternary age younger volcanics, Tertiary age lake beds (variably colored, mostly clay, ash, and shaly sandstone) and older Horizontally layered massive flows of plateau basalts , Mesozoic age sedimentary rocks, sandstone and Shaly, sandstone and Precambrian basement rocks from top to bottom. This investigation is a multipurpose master plan study encompassing the geology, hydrogeology, hydropower, irrigation etc.

The geological map of the area adopted from the study by BCEOM is shown in figure 3.and the east-west cross section on 12^{O} 00 is also presented below in figure 4

4.2.3.1 Alluvial deposit and quaternary basalt

Alluvial deposits of quaternary sediments are found from Degoma up to Chuahit and North of Wereta town along the lower reaches of Rib River. The lithology includes sizes clay to gravel grain size of unknown thickness and extent. At Woreta, up to 50m of inter bedded gravel, sand and clay was recorded in the town water supply borehole (SMEC, 2007).

A nomenclature used by BCEOM includes a separate geological unit in this sediment. It is named as Marsh soils that cover most of the Gumara, Megech and Dirma sub-basins and small patches around the lower reaches of Rib sub-basin. In the hydrogeological map of Ethiopia (Chernet, 1988) this unit is described as lacusrine and swamp deposit. This map shows a regional scale classification of aquifers and broad scale groundwater potential and also describes that there is a dominantly low salinity groundwater occurring in moderately productive basaltic and alluvial aquifers in Lake Tana Basin.

Basalts and volcanic centers that resulted in thick cover over the Mesozoic sediment are found East of Lake Tana, in Gumara sub-basin and close to the Abay river outlet. The quaternary basaltic flow resulted in the damming of Abay River which resulted in the present shape of Lake Tana and its environment. The age of this lava flow is estimated to be 10,000 years B.P.(Chorowicz et al., 1988).

Magneto telluric imaging carried out south and east of Lake Tana revealed that there is a consistent NW-SE trending sedimentary basin beneath the lava flow (Sophie et al 2006).

The Tana area is characterized by widespread dike and pipe feeders which contributed to the mid-Tertiary flood basalt flows of this sector of the Ethiopian plateau. Especially during the later stages of volcanism, however, magmatic egress became focused and built-up large shield volcanoes (Chorowicz et al., 1988).

The rocks east of Lake Tana are sub-alkaline rhyodacites displaying evidence of chemical differentiation, whereas those on Dek Island (within Lake Tana) and in the Gimjabet and Kosober areas are alkali basalts.(Abate et al, 1998).

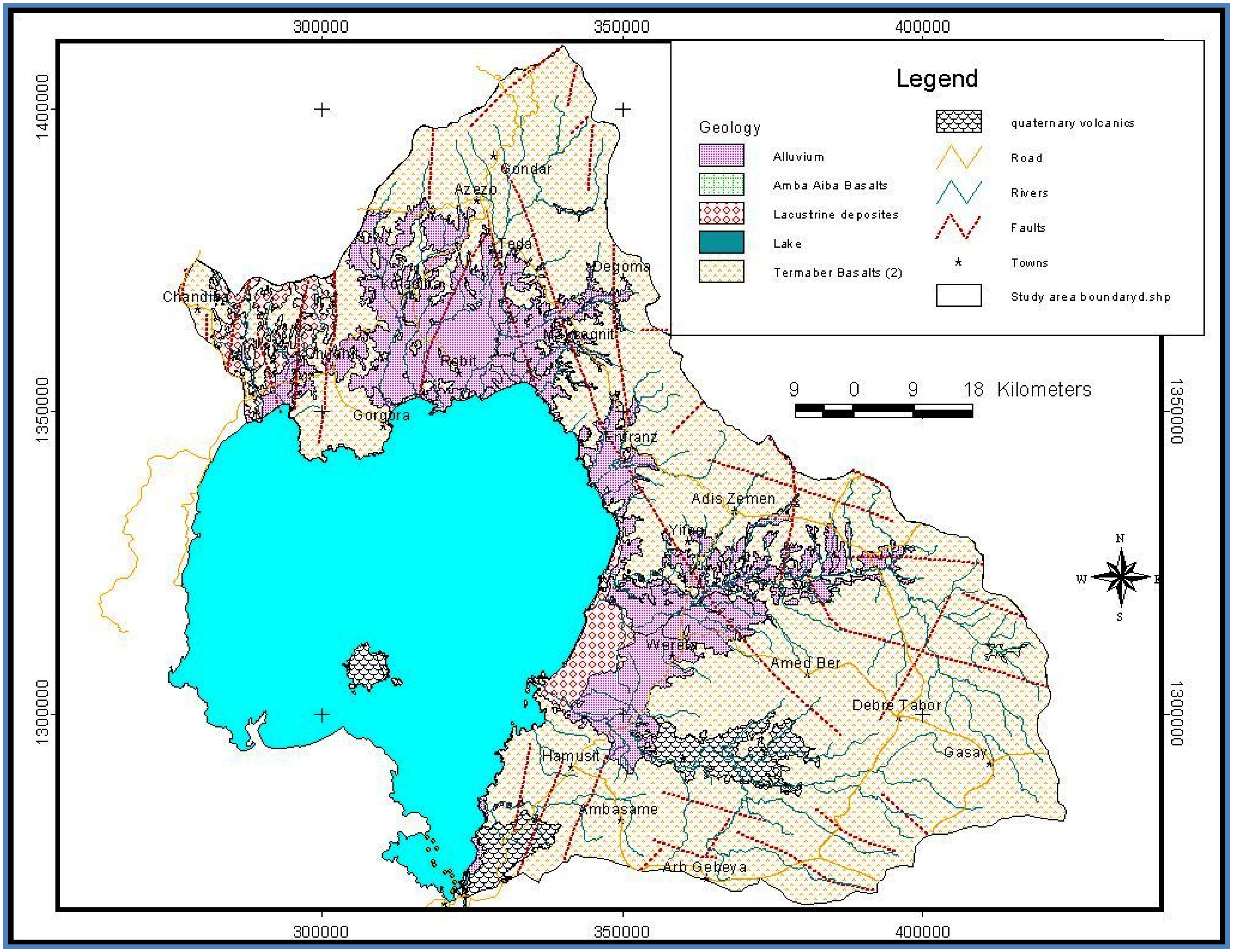

Figure 3-Geological map of North Lake Tana sub-basin (Modified from BCEOM, 1998, Abay basin master plan study)

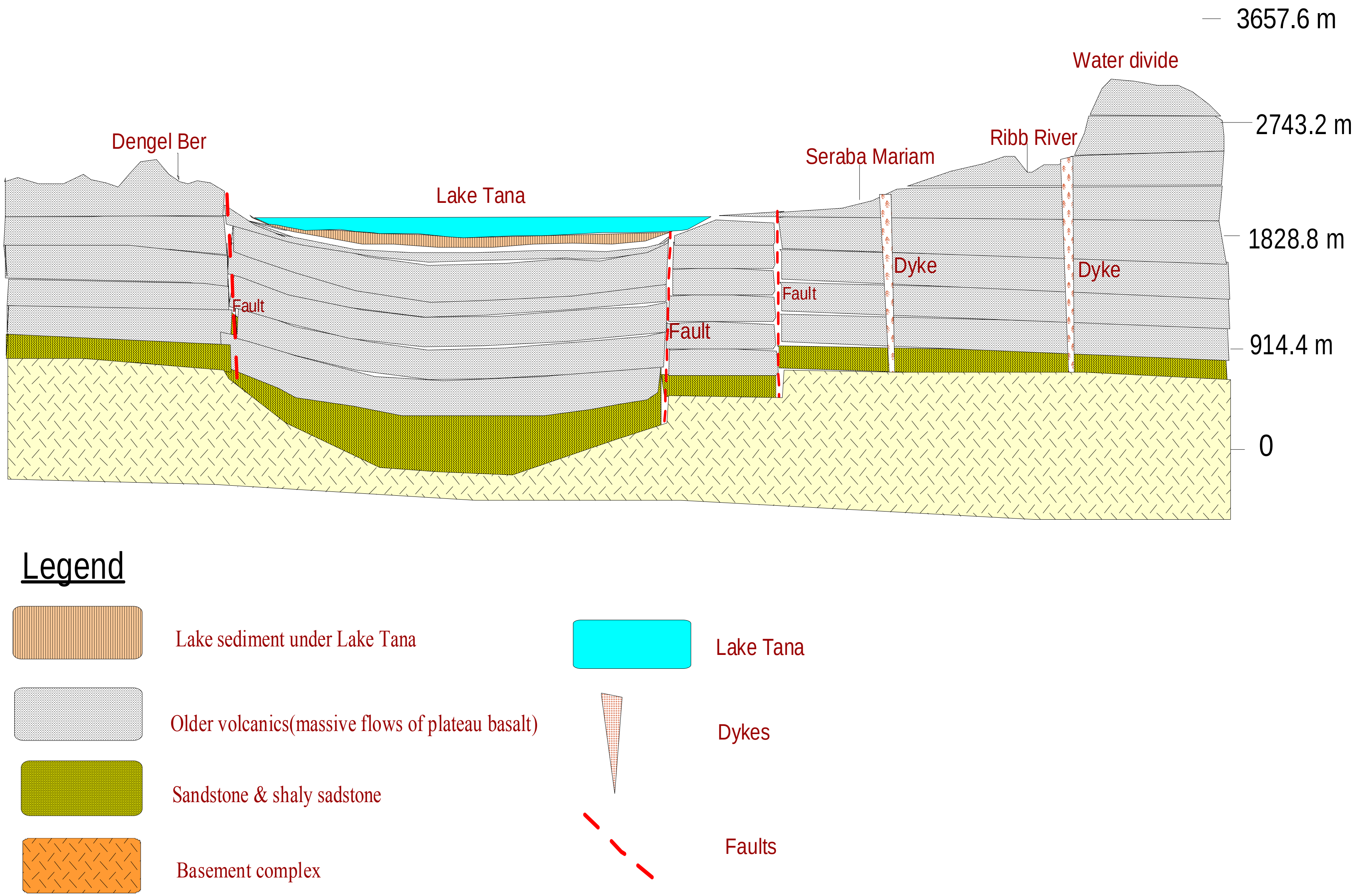

Figure 4-East west schematic geological cross section of Lake Tana sub-basin (modified after USBR, 1964), (not to scale)

4.2.3.2 Lacustrine sediment

Lacustrine sediment takes the third largest coverage in the study area excluding the lake area according to BCEOM report. It is found North West of Chuahit and west of Wereta towns surrounding Lake Tana. North of the lake, at least 130 m of Oligocene fluvial sediments were deposited in the Chilga basin (S. Hautot et al., 2006). On the other hand, on the geological map compiled by USBR (1964) lake beds were mapped North West of Gorgora, chuahit and around Chandiba towns. This deposit is comprised by Ash, clay, fine sand stones and occasionally carbonaceous material.

Moreover, lacustrine deposits comprising dominantly fine silt and clay cover the bed of Lake Tana. These deposits have been identified from high resolution seismic studies, supported by extensive analysis of cores drilled up to 9.5m deep (Lamb et al, 2007). The geophysical study shows that the thickness varies across the Lake, from a minimum of 9m across the entire lake bed to at least 40m at the northern end of the lake. Several stiff silt horizons have been mapped across the lake. Recent drilling information (Lamb et.al. 2007) indicates that up to 80m of stiff clay covers the floor of the Lake (SMEC, 2007). In eastern (Deberetabor sub graben) and the north western (Chilga sub graben) sub catchments of the Lake Tana Graben, the late Miocene ligniteferous lacustrine deposits exist embedded in the trap series basalts (Chorowiz et al., 1998; Feseha, 2002). The Miocene lacustrine deposits contain mainly reworked volcaniclastics, thin layers of lignites, claystones, and siltstones. In places these sediments may have a thickness of about 130 m.

Colluvium deposit is found around Enfraz, Wereta and south of Adis Zemen towns following river valleys. This deposit is classified as part of aluvio-colluvial formation since it is classified as alluvial deposit in most of the past investigations (Ethiopian Geological survey, 1996).

4.2.3.3 Tarmaber Basalts

Lake Tana is surrounded mostly by Tarmaber basalts, superimposed basalt lava flows with intercalated tuffs, scoriaceous strata and typical red paleo-soils. It has two phases of eruption in the Abay basin. However, the study area is occupied only by the second event of Tarmaber basalts.

According to BCEOM, French engineering consultants (1997), Tarmaber formation represents Oligocene to Miocene basaltic shield volcanism on the North western and south western plateaus.

Tarmaber basalts are typically alkaline in nature. On the northern plateau, Tarmaber shield volcanoes become progressively younger from north to south. Trachitic and phonolitic plugs occur in association with this formation (Ethiopian Geological Survey, 2003).
Geophysical profiling by Hautot et. al. (2006) suggests a thickness of only 250m of basalt is found above Mesozoic sediments in the eastern part of the Gilgel Abbay. To the north at Gondar, a minimum thickness of 210m has been encountered in bores, although the base of the basalt was not intersected (SMEC, 2007).

Another basaltic exposure found overlying the Tarmaber basalt is Amba Aiba basalts. It is found in the Ribb valley, north of Debre Tabor. It covers a small area in the study area comprised of flood basalt flows with scarce tuffs overlying the Tarmaber basalt. This unit is exposed overlying the Blue Nile Basalt at the northern part of plateau area. It is a flood basalt flow with closely spaced columnar joint. In hand specimen it is aphanitic in texture and dark grey in color.

4.2.3.4 Tectonic setting

The tectonic setting of the area shows a gently inward-directed dips of the Tertiary stratoid basalts toward the centre of the Tana sub-basin. According to the geological cross section the west, north and east of the lake display these features(USBR, 1964). Besides, dips as steep as 20º to the south are observed near Gondar. Lake Tana therefore occupies a structural basin with narrow shoulders and a broad flat floor (Chorowicz et al, 1998).
In general, there is a view that Tana basin and northwest Ethiopia is uplifted dome possibly related to the Afar mantle Plume (Pik et al, 2003), and after this event, the basin was formed by faulting of mid-Tertiary basalts.

4.2.4 Hydrogeology

4.2.4.1 General

The hydrogeology of the area is comprised by three major aquifer systems; Tertiary volcanics mostly including the Tarmaber basalts, the Quaternary Basalt aquifer and the Quaternary alluvial deposits, and Amba Aiba basalts (SMEC, 2007). Mostly, the permeability is related to fractures and weathering of the basaltic flows and inter-granular media for storing and transmission of groundwater. The vast portion of the study area is covered by the fractured aquifer with NNW (North- North west) SSE (south-south east) trending faults.

A hydrogeological report including an inventory of drilled bores, hand dug wells and springs in the Northern Ethiopia was carried out by Ethiopian Geological survey in 2003. In this report areas around the margins of Lake Tana are reported to be potential areas for future groundwater development (Bayissa Asfaw, 2003).

Hydrograph separation from groundwater contribution to surface flow shows that infiltration coefficient ranges from 2% in the Rib to 7% in Gumara sub catchment out of the total rainfall in the basaltic plateau (BCEOM, 1999).

Recharge to the groundwater is mostly linked to rainfall infiltration. Surface water infiltration is expected during higher water level conditions (BCEOM, 1998). The Abay basin report has presented the description of geology and aquifers in the Blue Nile basin, including data sources, groundwater discharge to streams based on base flow analysis, aquifer characteristics and hydrochemistry.

Groundwater table generally follows the ground surface contours, with the groundwater flow directions largely consistent with the surface water catchment boundaries. (figure 5, 6 &7).

As part of a detailed Lake water balance investigation, it was also suggested that the likely groundwater flow direction is from surrounding areas towards the Lake, although the groundwater component is considered to be only a minor component of the water balance (Kebede et al 2006).

Moreover, isotope and geochemical data were used mainly from springs and hand dug wells to identify that recharging groundwater migrates through short local groundwater flow paths to discharge low TDS (Ca-Mg-HCO3 dominated) groundwater. Deeper, more regional flow systems have greater residence time in the aquifer and undergo geochemical alterations to generate higher TDS (Na-HCO3 dominated) waters.

Deeper flow systems and resultant hydrochemistry are influenced by structural effects from basin faulting (Kebede et al, 2005)

Besides, an investigation initiated by the Ministry of Water Resources summarizes groundwater information available from a number of reconnaissance groundwater studies, particularly Bahir Dar, Dangila, Debra Tabor and Werota and suggests that there is potential for development of groundwater at around Lake Tana, although it recognizes that the groundwater systems are not studied in detail (MoWR/World Bank, 2007).

Another investigation was carried out using remote sensing techniques combined with runoff estimation using the SCS method and Watbal model to undertake a water balance for the Lake Tana sub-basin. (Yohannes Daniel, 2007).

Generally, the surface water contribution to groundwater is estimated as 35mm/yr at Rib, 90 mm at Gumara and 55 mm at Megech catchment (BCEOM, 1998).

In conclusion, according to the hydrogeological map compiled by the Geological survey of Ethiopia, 2002 there are two types of aquifers in the study area. The quaternary basalt aquifer rated as fractured aquifer with high productivity where as the aluvio-colluvial deposit and Tarmaber basalt is classified as moderate productivity aquifer(figure 5)..

4.2.4.2 Alluvial aquifers

Alluvial aquifers are found dominantly at the north and eastern part of the study area following the lower Rib and lower reaches of Gumera (figure 5). It has shallow water level depth, moderate thickness of about 50 meters and may have moderate groundwater potential. Groundwater is stored within the pores of the gravel and sand layers in the sediments and flows through the aquifer by inter-granular flow. Quaternary alluvial sediments have the highest transmisivity (in places more than 700 m^2/day)

(Kebede et al, 2005). The specific capacity of the wells of the quaternary alluvial deposit was calculated as 0.02 to 0.53 l/s/m (SMEC, 2007).

The available data on this aquifer indicate high productivity with boreholes yielding more than 6l/s with depth of up to 60m (Samson M., 2010).

4.2.4.3 Quaternary basaltic aquifers

In the study area quaternary basalts are found at Bahr dar , east of Woreta towns and on the Dek Islands(figure 5).. The Quaternary basalts surrounding Lake Tana are characterized by high transmisivity (100–200 m2/day) compared to the basalts of the trap series (Kebede et al., 2005). This shows that the quaternary basalt aquifer is highly porous and fractured.

Three major springs which discharge from these highly fractured basalts approximately 8km west of Bahir Dar discharge flows of >120L/sec at the Areke Spring and around 60 L/sec from Lomi and Tikur springs.

The specific capacity of the wells of the quaternary basalt was calculated as 0.34-6.43 l/s/m (SMEC, 2007).

4.2.4.4 Tarmaber Basaltic aquifer

The transmissivity of the Tertiary basalt aquifers are relatively low apart from one well observed at Gondar with a transmissivity of 32.8 m2/day. The well depth in the basaltic plateau ranges from 30 to 120 m and also the majority of cold springs emerge from the basaltic plateau (Kebede et al, 2005).

The productivity of this aquifer is highly controlled with intensity of the fracture and the presence of the major structure affecting the area. Tarmaber basalts of the second eruption phase shows medium yields (BCEOM, 1998) (figure 5)

The Yields of Tarmaber basaltic aquifer is in the order of 0.7 -17 L/sec, in general a mean yield of 3.63 l/sec was recorded for tertiary basalts. The specific capacity of Tarmaber basalt ranges between 0.18 to 3.31 l/s/m.

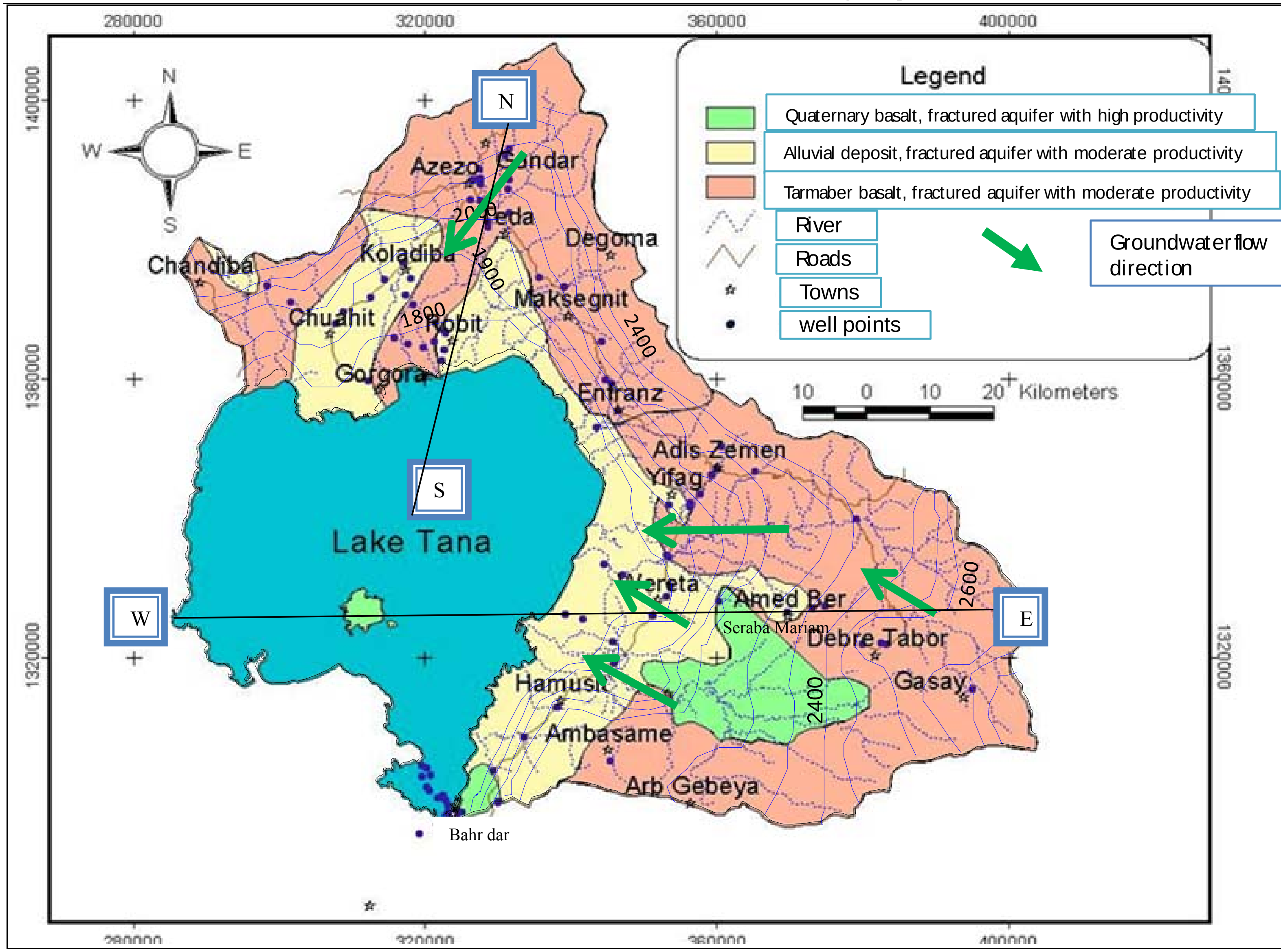

Figure 5- Hydrogeological map of the study area (modified from, hydrogeological map of northern Ethiopia, (Geological survey of Ethiopia, Bayssa et al ,2002)

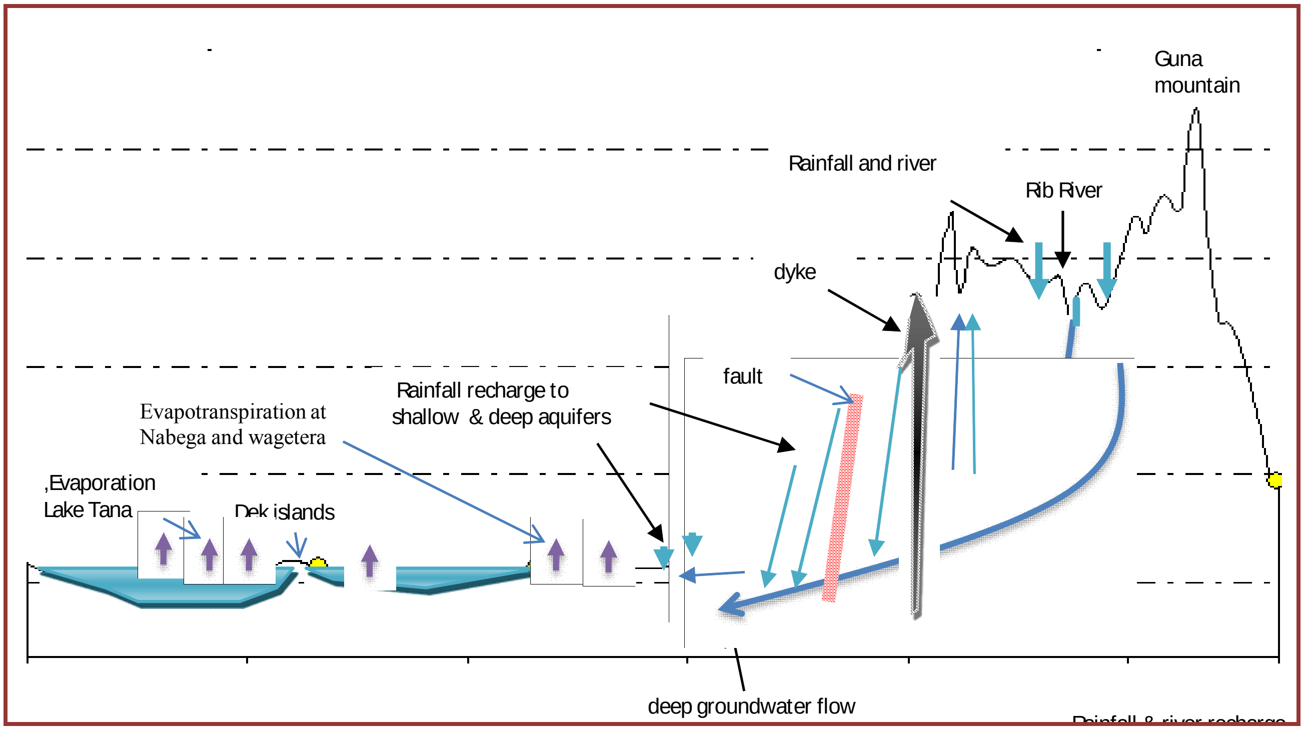

Figure 6-Groundwater flow from East to west (Guna –Woreta-Lake Tana) conceptual model (not to scale)

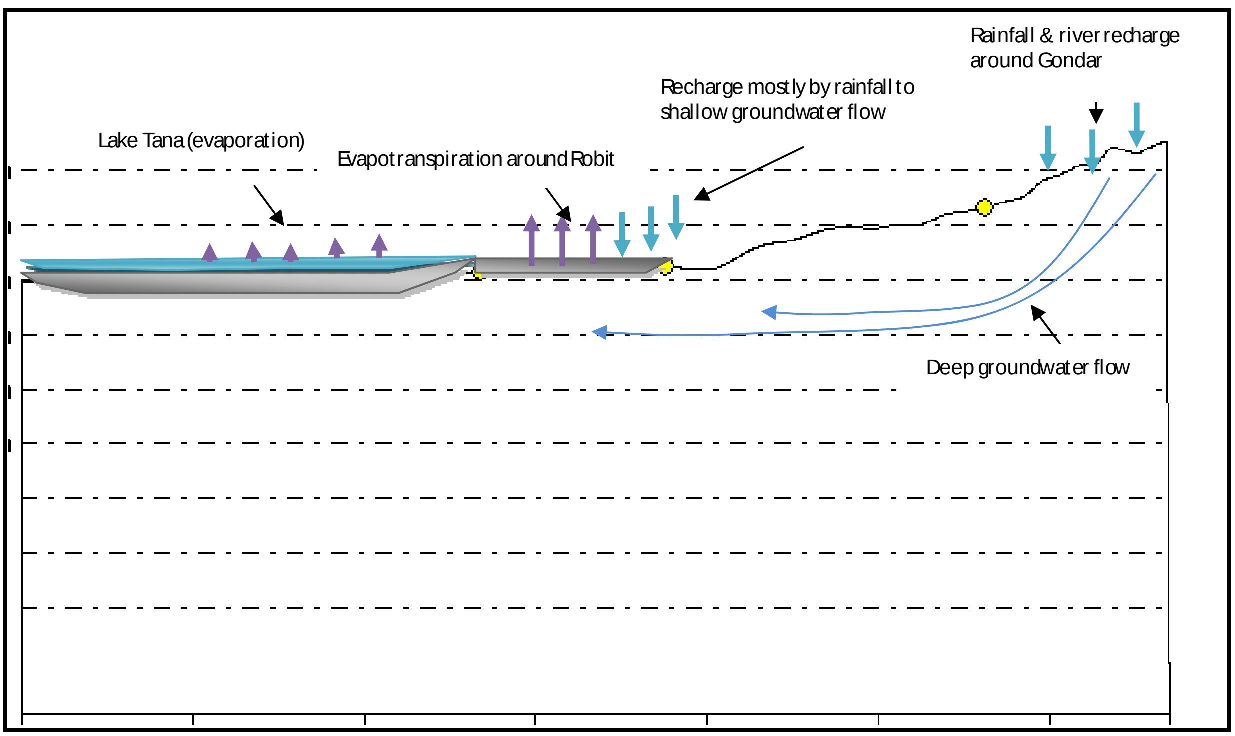

Figure 7-Groundwater flow from North to South (Gondar –Robit -Lake Tana) conceptual model (not to scale)

4.2.4.5 Conceptual groundwater flow

The groundwater flow in the Lake Tana basin starts from high groundwater heads in the east around the shield volcano of Guna and in the north around Gondar town with the hydraulic gradient radiating from these points. There is a steep hydraulic gradient at the highlands and flattens towards Lake Tana on the plains adjacent to the lake (Figure 6&7).

According to the isotopic evidence, rainfall recharge to deep groundwater starts on the high lands and this flow goes on deeper in to the basaltic aquifer. The alluvial aquifer gets local rainfall recharge and may also have a hydraulic interconnection with the basaltic aquifer that feeds the regional groundwater. Rivers might recharge at the upstream and downstream aquifers.

Although, there is no deep well in the flat plain confirming the interconnection, the deep well at Woreta (the closest to the Fogera plain) is grouped with the Debretabor and Gassay wells (Figure 12). These wells show a depleted Oxygen isotope ($\delta^{18}O$) implying the recharge to be from the coldest highlands.

On the other hand, there was no similar isotopic enrichment between the deep groundwater on the high lands and shallow groundwater and surface water on the flat plain. This signifies that the ground water on the highlands flows as a regional groundwater system than appearing on the flat plain. This was also confirmed by seasonally artesian semi confined wells at Gondar and Koladiba (wonfela well). These wells were grouped in a similar class in the hierarchical classification too.

Therefore, Recharge at higher altitudes percolates down and flows from the highlands in to the regional flow and to some extent recharge on the plains might feed the deep groundwater evenif it is not confirmed due to lack of deep wells on the Dembia and Fogera plain. However, shallow wells in Robit are enriched to some extent indicating a recharge by the Megech river.

4.2.5 Geochemistry

Electrical conductivity values show a general increase from Gondar and Chuahit towards Seraba and Robit area in the megech basin. There is also a general increase from Gasay, Addis zemen and Hamusit towards wagetera and Nabega area (west of Woreta) (figure. 11).

The geochemical and isotope study carried out in the past show two types of groundwater systems in the upper Blue Nile basin. These are the low salinity, Ca–Mg–HCO3 type, isotopically relatively enriched cold (13–25^{o}C) groundwater from the basaltic plateau and the high TDS, Na–HCO3 type, isotopically relatively depleted low temperature (25–40^{o}C) thermal groundwater systems from the deeply faulted grabens (Kebede et al, 2005).

It has been observed that the Lake Tana water, river water and most deep groundwater wells have very low electrical conductivity. This confirms what has been observed by Kebede et.al. 2005.

However, there are some indications of very high salinity waters in the shallow hand dug wells in the basin, contrary to the low salinity observed in deep wells. Pockets of shallow salinity areas were also identified in the wetlands in the study made by Zenaw T. in 2009.

In this study, it was found out that there is bell-shaped vertical salinity distribution with a maximum of 3 m below ground surface in lower reaches of Rib River. Similarly, it was found out that lower Megech plain falls in a high salinity area (Class 3) and suggests monitoring wells to monitor the groundwater level and electrical conductivity.

The majority (89%) of the water samples taken in this investigation have an EC below 1000mg/l. In this investigation, about 11% of the samples have an electrical conductivity of more than 1000mg/l. This was observed around Robit (south of Kola diba) and Nabega village (west of Woreta town).

There are several oozing springs in the study area such as Seraba Mariam holy spring with high salinity related to a silicic plugs. This spring is found outside Amed Ber town on the way to Debre Tabor. It has an electrical conductivity of 10,660 μS/cm. It is higher than the highest saline waters in the flat Dembia and Fogera plain wetlands.

In this investigation, seven types of waters were identified from the piper diagram. These include Ca–Mg–HCO3, Na–Ca-HCO3, Ca–HCO3, Na–HCO3, Ca-Na–HCO3, Ca-Mg-Na-HCO3 and Ca-Na-Mg-HCO3. Ca–Mg–HCO3 type waters from samples in dug wells, boreholes, rivers, Lake Tana and a spring. The majority of Ca–Mg–HCO3 and single cation bicarbonate water types are of low electrical conductivity (less than 1000 mg/l). On the other hand, multi cation water types (Na-Ca, Ca-Mg and Ca-Na-Mg) waters have higher Electrical conductivity (Greater than 1000 Mg/l). Major cations and anions concentrations show similar pattern as the electrical conductivity.

In general, the groundwater chemistry has become complex due to the geologic, geo-morphological and natural processes (evaporation, evapotranspiration, leaching, dissolution etc.) and localized nature.

5 Results

5.1 Major anion and cation composition of the waters

The Geochemistry of Lake Tana sub-basin was studied by Kebede et al in 2005 as part of the Blue Nile River in Ethiopia. Both isotope and geochemical method were used to characterize the groundwater system and gain the first regional picture of groundwater recharge, circulation and its hydrochemical evolution in the upper Blue Nile River basin. Although it is a regional study covering the whole Abay basin in Ethiopia, it gives a very good understanding of the groundwater evolution using environmental isotopes and other geochemical constituents.

The second study on the geochemistry of Lake Tana waters was done by Zenaw in 2009. It was specifically targeted to study the hydrogeology of Rib and Megech river sub catchments. This study was intended to support the ongoing irrigation projects. This study has found out that there are pockets of shallow salinity areas in the wetlands. The occurrence of these saline waters has been related to poor drainage system and direct evaporation of shallow groundwater body (Zenaw, 2009).

The other regional study is the Abay master plan study that includes geology, hydrogeology, hydrology, soil, Environment, Geochemistry etc. Specifically, the study of the water chemistry has described the source of calcium, Magnesium, sodium, potassium, carbonates, bicarbonates, chloride, sulphate and Nitrate. The sources are from weathering of igneous rock (weathering of plagioclase feldspar), sedimentary rock, carbon dioxide in the air and soil, evaporation, solution, industrial and agricultural sources (BCEOM engineering consultants, 1998). The report also characterizes the water types as Bicarbonate, Calcium-Sodium or sodium-calcium types.

Other previous works are concerned with water supply study describing the hydrogeology of a specific area and water quality for drilled wells. These reports were a good source of water quality analysis data and also borehole logs.

During this field work, it was possible to measure electrical conductivity, total dissolved solids, and dissolved oxygen including the location and setup of the area. The lowest electrical conductivity was recoded in Hamusit (129 μS/cm) borehole and the highest was recorded in Seraba Mariam holy spring (10,660 μS/cm l) and Seraba and Dablo, specifically woinit hand dug well (4050 μS/cm).

The temperature of the groundwater is mostly related to the elevation of the well. The lowest temperature was recorded at Gassay (14.6 ^{o}C) and Gondar well (20.1 ^{o}C) and the highest was recorded at Addis Zemen boreholes (27.4 & 27.5 ^{o}C).

The dissolved oxygen content also ranges from 7 mg/l at Gassay to 4.4 mg/l at Komini River.

After the samples were analyzed in the Water Works Design and Supervision Enterprise Laboratory the data were tested for charge balance error (Freeze and Cherry, 1979) prior to the interpretation of the data. The charge balance was calculated using the following formula:

$$\text{Charge Balance error (\%)} = \frac{\sum cation - \sum anion}{\sum cation + \sum anion} \times 100$$

where the sum of anions and cations are in milli equivalent per liter.

The Charge balance error of two samples was above 5% in the data from the first phase of sampling and one sample in the second phase of sampling. The rest of the data have charge balance errors below 5% which is an acceptable analysis error.

Additionally, the presence of systematic error was also checked using the curve in figure 8. In this case the distribution of positive and negative errors were compared to check this error (52% is a positive error and 48 % is a negative error). From this it can be observed that there is no systematic error which can result in overestimation or underestimation of geochemical parameters.

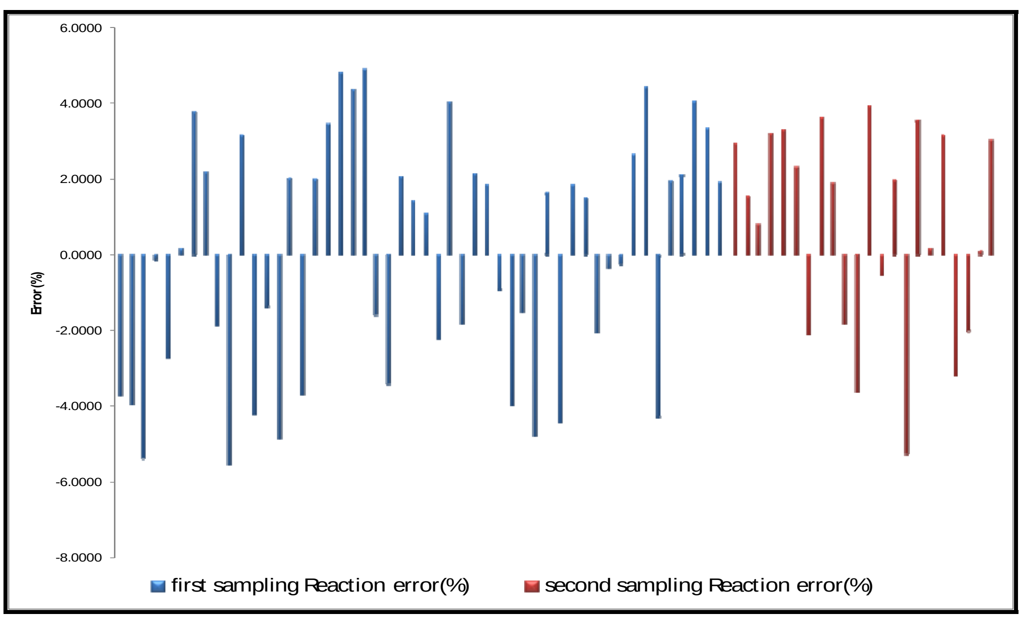

Figure 8- Error percentage distributions of cations and anions for the two sampling phases

A plot of field measured versus laboratory measured electrical conductivity shows that there is a good correlation in most of the values. However, there is a slight underestimation of the laboratory measured values in the first and second phase sampling data.

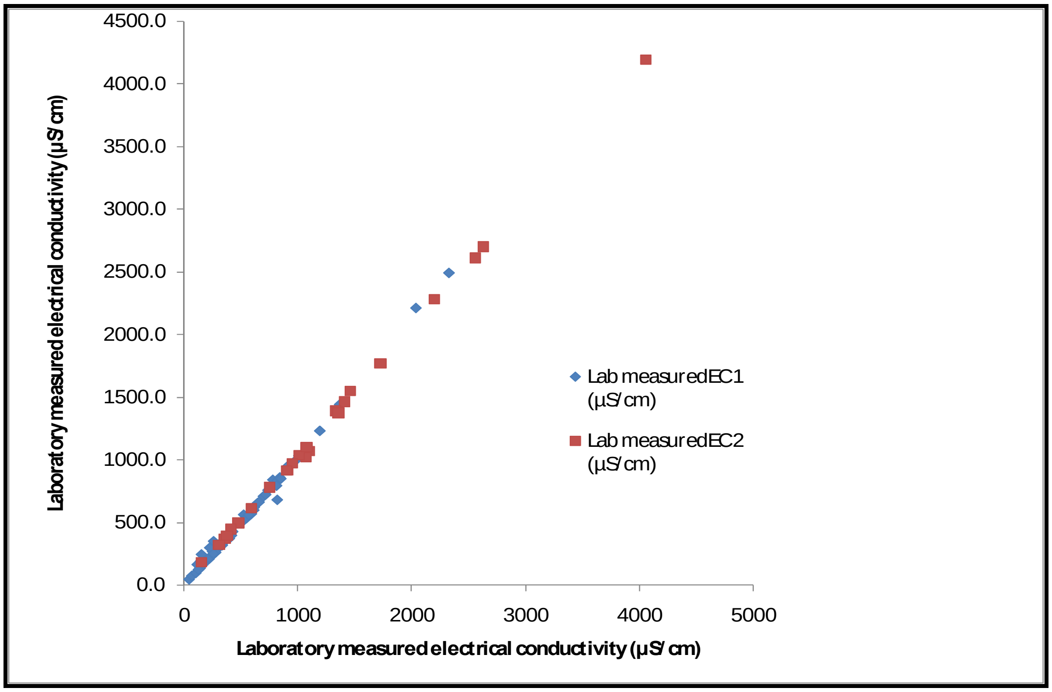

Figure 9–Field measured versus Lab measured Electrical conductivity

Major cation and anion concentration observed in the Lake Tana sub-basin show different conditions. It is assumed that reactive elements such as Calcium (Ca^{2+}), Magnesium (Mg^{2+}), potassium (K^{+}), Sodium (Na^{+}), Fluoride (F^{+}) and sulphate ($SO4^{2-}$) concentration should increase initially towards the groundwater flow gradient until it reaches saturation with respect to soluble salts. Likewise, residual alkalinity /($HCO3^{-}$)-(Ca^{2+})-(Mg^{2+})meq/ increases. However, Ca, Mg, and Ca/Mg ratio decreases in a regional groundwater flow system.

The geochemical analysis shows that, Sodium (Na^{+}), Calcium(Ca^{2+})+, Magnesium(Mg^{2+}), Bicarbonate ($HCO3^{-}$), Chloride (Cl^{-}), Fluoride (F^{-}) and Sulphate($SO4^{2-}$) ions generally increase from Gondar and Chandiba towards Robit, Gassay to woreta and Addis Zemen. Exceptionally high values were registered at Seraba Mariam holy spring. Gondar Boreholes also show higher values as compared to those samples found downstream. Besides, it has been observed that there is a slight decrease of these cations from Robit and Seraba-Dablo area towards Lake Tana.

Potassium (K^+) concentration shows variable trends. However; there is an increasing trend from Gondar up to Maksegnit and Addis zemen to Woreta and a decreasing trend from Tseda to Robit and Gassay to Debretabor. As observed in other cations and anions exceptionally high values of potassium were also observed at Seraba Mariam holy spring.

High values of Nitrate was recorded near big towns and villages such as Gondar, Bahr Dar, Chuahit, Robit, Bahir Gimb village where as low nitrate values were observed where there is little or no settlement (Seraba and Dablo). It is also observed that there are smaller values of Nitrate in most deep boreholes other than the above mentioned areas.

Looking at the values of residual alkalinity, increasing trends was observed from Gondar towards Seraba & Dablo and from Gasay towards Addis Zemen, Yifag and woreta. The highest record was registered at Seraba Mariam Holy Spring.

Extreme variations of water chemistry have been observed in this investigation. This could be due to the variation in the source of recharge, geology, geomorphology and processes that change the geochemistry and its dynamics.

More over, seven water types were identified from the piper diagram analysis during the first sampling phase as mentioned in section 5.2.5-Geochemistry (figure 10).

Ca–Mg–HCO3 water types includes dug wells, boreholes, rivers, Lake Tana and a spring and thus can be considered as the major water type in the basin. On the other hand Na–Ca-HCO3 and Na–HCO3 water types are found in some shallow and deep ground waters. These types of waters have high electrical conductivity ranging from 1745 to 2075.

It is also observed that the evolution of the water starts with Ca–Mg–HCO3 and goes on to Na–Ca-HCO3 and also to Na-HCO3 when the source is of deep circulation (figure 10).

The piper diagram in figure 10 shows group I waters have Ca–Mg–HCO3 water type and constitute major part of the fresh waters. In this water type rivers lakes springs and wells are included.

Group II waters are waters close to the mixing area between dams and rivers. These waters are found at Gondar(close to Angereb Dam), Robit, Achera Mariam, Angorbt,Guramba and Keha.

Group III waters are highly saline waters with water type Ca-Cl-HCO3, NA-Ca-Cl and Ca-Mg-HCO3-Cl water types. These in clued Woinit, Azage and Bahr Gimb hand dug wells. These wells are highly saline except Bahr Gimb Dug well.

Group IV waters are deep wells and some hand dug wells having Na-HCO3, Ca-HCO3 and Ca-Mg-Na-HCO3 water types. Although it has evolved from Ca-Mg-HCO3 most of them are fresh except the spring at Seraba Mariam which is of the highest Salinity in the basin.

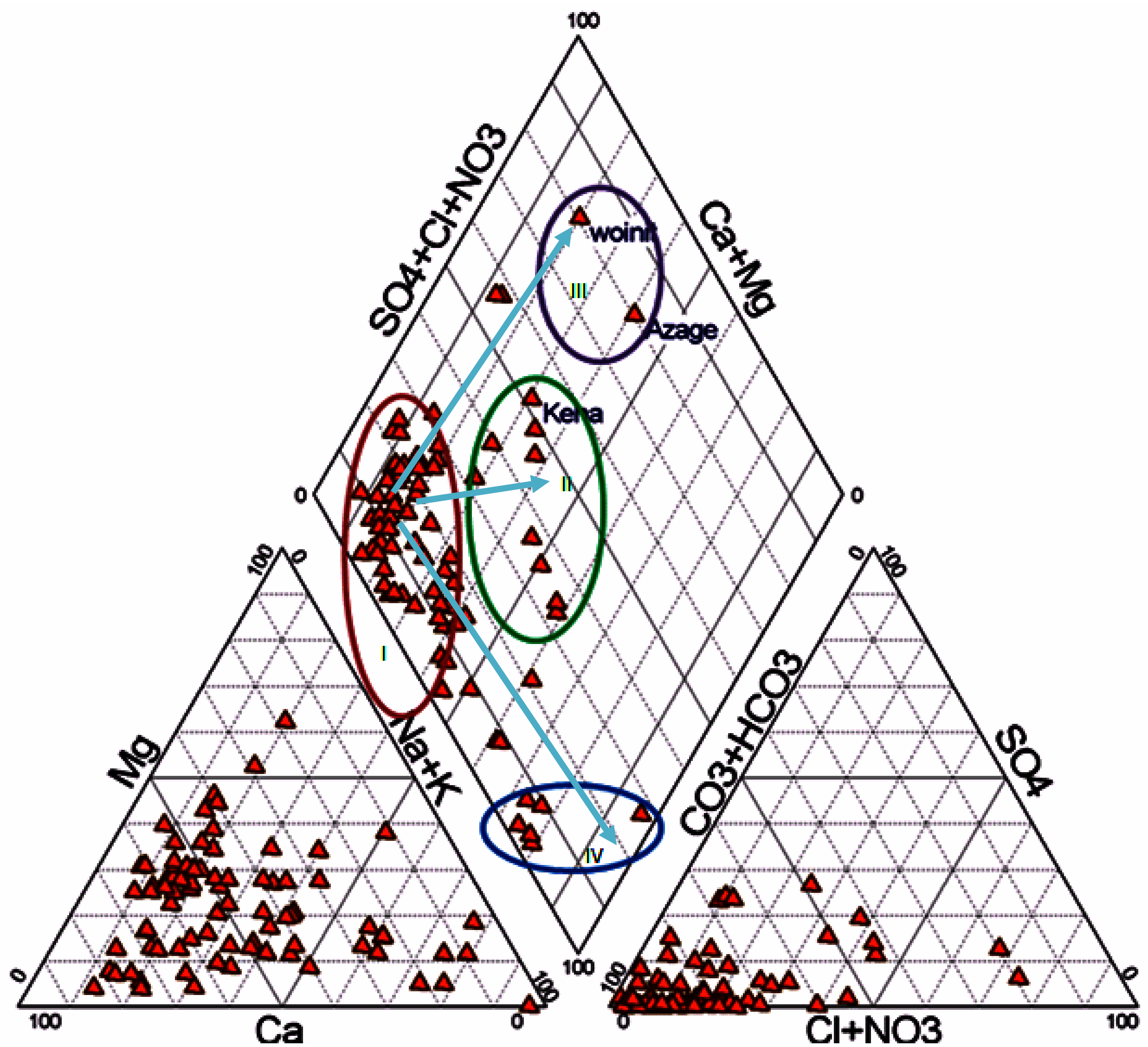

Figure 10- Piper diagram of Northern Lake Tana sub-basin water samples indicating the evolution of the groundwater system.

5.2 Spatial hydrochemical patterns

The spatial hydrochemical patterns can be shown using stiff, pie charts and also using GIS method. Using the newly collected samples and old data, the GIS map plot was used and shows that there is high electrical conductivity between Seraba and Robit area hand dug wells in the Megech & Dirma sub-basins. The electrical conductivity decreases outward as one goes to Chandiba, Gondar and Maksegnit. However, relatively higher values were registered in Gondar boreholes (figure. 11).

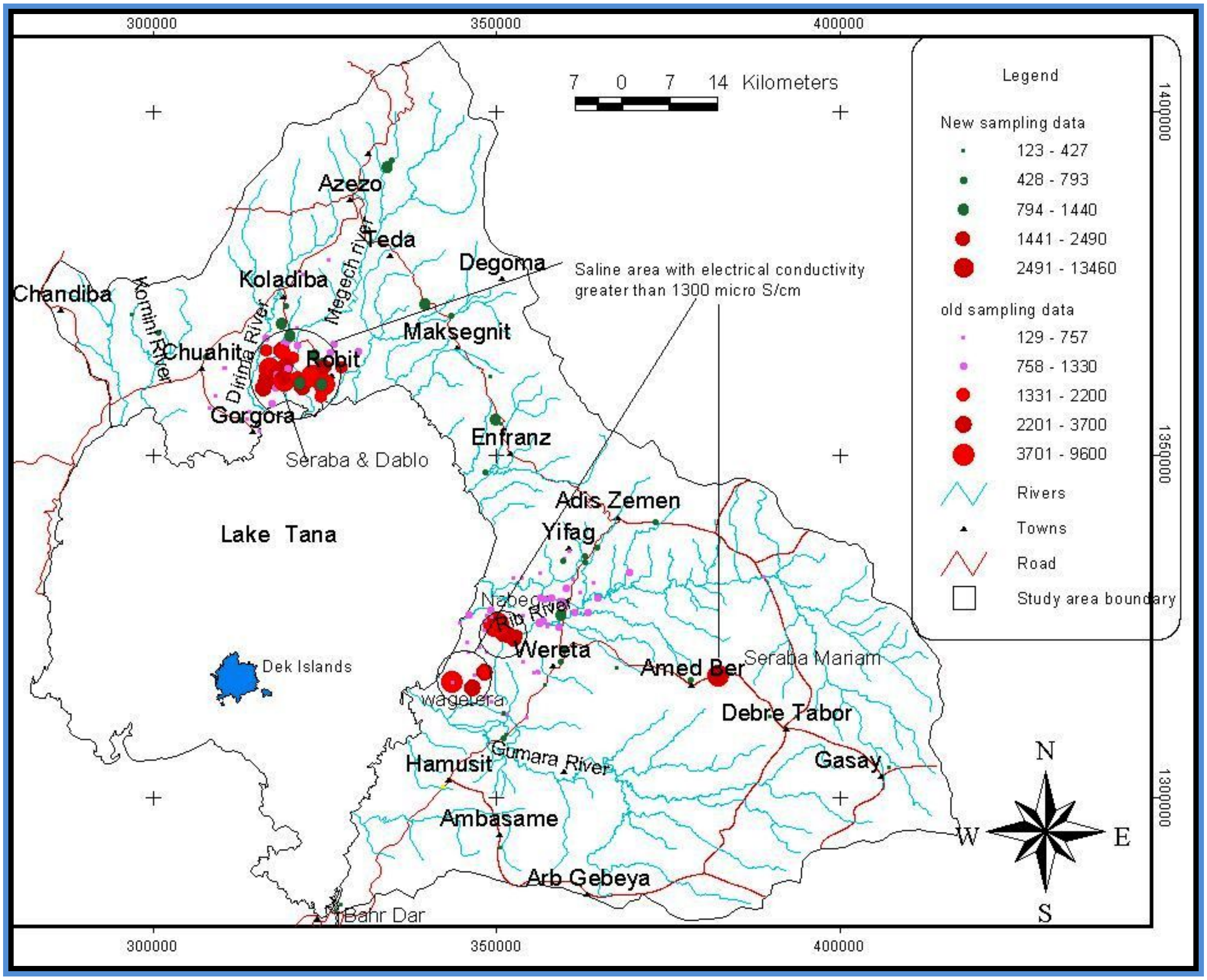

Figure 11 -The change in electrical conductivity in the Tana sub-basin using previous and current study

In the Rib & Gumara sub-basins, the concentration of higher Electrical conductivity was observed from Wagetera to Nabega area hand dug wells. Except the extreme values at Seraba

Mariam holy spring, most of the electrical conductivity get smaller and smaller away. In Reality, it is expected that the deep boreholes should have become more saline, on the contrary, shallow hand dug wells show very high salinity in the Lake Tana sub-basin.

As described before, the same behaviour is observed by the cations and anions except some elements like Potassium where it is impossible to observe visible trends. Besides, it is observed that the salinity decreases towards Lake Tana as observed in the Megech and Dirma sub-basins.

Ca–Mg–HCO3 type water is the dominant water type found starting from Bahr dar to Chandiba at higher elevations in samples coming from Rivers, lake and wells. This water type fresh water ranging in electrical conductivity from 123 to 700 µS/cm. Most of them are very close to a river, lakes and might be recharged by the rivers. Tarmaber basalt is the main aquifer that these water types are observed.

Na-Ca-HCO3 is the second dominant water according to the first phase of sampling. It was observed in boreholes and hand dug wells and is found in the alluvial deposit close to the boundary between Tarmaber basalt and the alluvium. It is found from Seraba to Robit and in Gondar wells.

Na-HCO_3 water types are found in deep wells and in relation to tarmaber basalt and the silicic dykes. Similarly, Ca-HCO_3 water types are found in the alluvial deposits or at the boundary of Tarmaber basalt in shallow hand dug wells. Other water types are found distributed and it is not possible to categorise them in particular area.

5.3 Isotope content of the waters

Isotopic enrichment or depletion is part of the hydrologic cycle that occurs due to fractionation processes. Using all the collected data, excluding the extreme values of the flood water sample the depletion in Oxygen 18 ($\delta^{18}O$) is 0.3%o/100m.

Water vapor originating from oceanic regions with strong evaporation moves to higher latitudes and altitudes with lower temperatures. The vapor gradually condenses to precipitation and loses $^{2}H_2{}^{18}O$ more rapidly than $^{2}H_2{}^{16}O$, because of isotope fractionation, causing the remaining vapor and also the later precipitation to become more and more depleted in both $\delta^{18}O$ and $\delta^{2}H$.

Physical processes such as diffusion, evaporation, condensation, melting, etc. produce isotopic differentiation (Gat et al, 2000)

Isotopic fractionation can occur due to Kinetic or equilibrium effects. Kinetic fractionations are associated with fast, incomplete, or unidirectional processes like evaporation, diffusion, dissociation reactions and biologically mediated reactions where as equilibrium fractionations arise from translational, rotational and vibrational motions of molecules, gasses, liquids and atoms in crystals. Systems in this case tend to minimise energy loss and thus isotopes will be distributed (White, 1999).

Isotopic enrichment can occur due to the delay of water near the surface before infiltration, infiltration of recycled irrigation water and evaporation of soil water from the uppermost soil layer.

Isotopically depleted waters are associated with cold regions and enriched waters are found in warm regions. This partitioning is a useful tool for characterizing groundwater recharge environments, and is now the basis of groundwater origin studies (Clark & Fritz, 1997).

Positive values of $\delta^{18}O$ and $\delta^{2}H$ indicate enrichment of the sample in $\delta^{18}O$ and $\delta^{2}H$ as compared to SMOW, whereas negative values imply depletion of these samples relative to the standard. On the basis of large numbers of meteoritic water collected at different latitudes, it has been shown that $\delta^{18}O$ and $\delta^{2}H$ values of meteoritic water are linearly related and can be represented by the equation $\delta 2H=8\delta^{18}O+10$, where as the local meteoric water line for Ethiopia is defined as $\delta 2D=8\delta 18O+15$ (Schoell, and Faber, 1976).

Deuterium ($\delta 2H$) and oxygen 18 ($\delta 18O$) analysis was carried out at the isotope Laboratory of Addis Ababa University. It was done using Liquid water isotope analyser model DLT-100. The analysis has a standard deviation of 1.13‰ for Deuterium ($\delta^{2}H$) and 0.13‰ for oxygen 18($\delta^{18}O$). The data was plotted on excel along with rainfall data from IAEA web page GNIP (figure 12).

In Lake Tana sub-basin, three water groups can be recognised according to their isotopic signature. Group A waters include Woreta w-3, Debretabor (sebara dildy), Gassay well and Seraba Mariam spring. These boreholes are highly depleted waters having $\delta^{18}O$ less than -4‰ and are located in different topographic environment in the Rib sub catchment. These groups of waters are on the upper side of the meteoric water line show exceptional isotopic signatures different from the present day rainfall.

In between -4‰ and 2‰ of oxygen isotope ($\delta^{18}O$) group B type of waters are included (group B). These waters are mostly recharged by the present day rainfall and rivers as their isotopic signature is closer to the rainfall and river water isotopic signature. This group includes the majority of the diluted waters in the Lake Tana basin.

Group C waters are highly enriched samples and include floodwater, Lake Tana, Robit and Guarhe hand dug wells, Komini River (chandiba road) and Yifag Dikule deep well (?).

These water samples are some of the highly enriched waters that were sampled in this investigation and have oxygen isotope ($\delta^{18}O$) greater than 2%o. The deep well at Yifag is not expected to show this much evaporation signature. However, the sample might have been taken from evaporated source.

The deuterium ($\delta^{2}H$) versus oxygen isotope ($\delta^{18}O$) plot indicates a lot of facts in relation to the surface water and groundwater interaction and accompanying processes.

It is possible to witness from the isotopic signature that there is no remnant of paleowater in the collected samples. The water type in group A are older waters that stayed on transit to the recharge point. This can be confirmed by the fact that the depleted samples are above the meteoric water line. This water type also shows an oxygen isotope ($\delta^{18}O$) exchange between water and carbon dioxide as observed on the plot (figure 12).

Minimum evaporation signature is observed in the shallow and deep groundwater regardless of the wetland and higher surface water evaporation rates. This can also be observed on the Box & whisker plot of Oxygen isotope (figure 19). In this diagram it is observed that the lowest oxygen isotope ($\delta^{18}O$) is registered in springs, hand dug wells and Boreholes.

Two regimes of salinity are observed from the isotopic signature of the samples that are the deep source showing very high depletion and shallow source depicting moderate isotopic enrichment comparable to the summer rain.

On top of this, most shallow and deep wells plot close to the meteoric water line and summer rainfall. This indicates that the recharge contributed by the summer rain is higher but the recharge contribution from spring rains is minimum.

The Rivers in the Lake Tana sub-basin show no prominent enrichment indicating fast flows between origin and destination similar to most rivers in Ethiopia. This fact is especially enhanced by the high slopes formed by the chain of mountains extending from Gondar to the highest mountain Guna.

Considering the isotopic signature of the cumulative rainfall data from GNIP (IAEA database, starting from 1961 to 2005) it is possible to observe rainfalls of February, March, April and June are highly enriched samples as compared to the other month rainfalls. Recycled moisture might have been the cause of the enrichment of these rainfall events (figure 12).

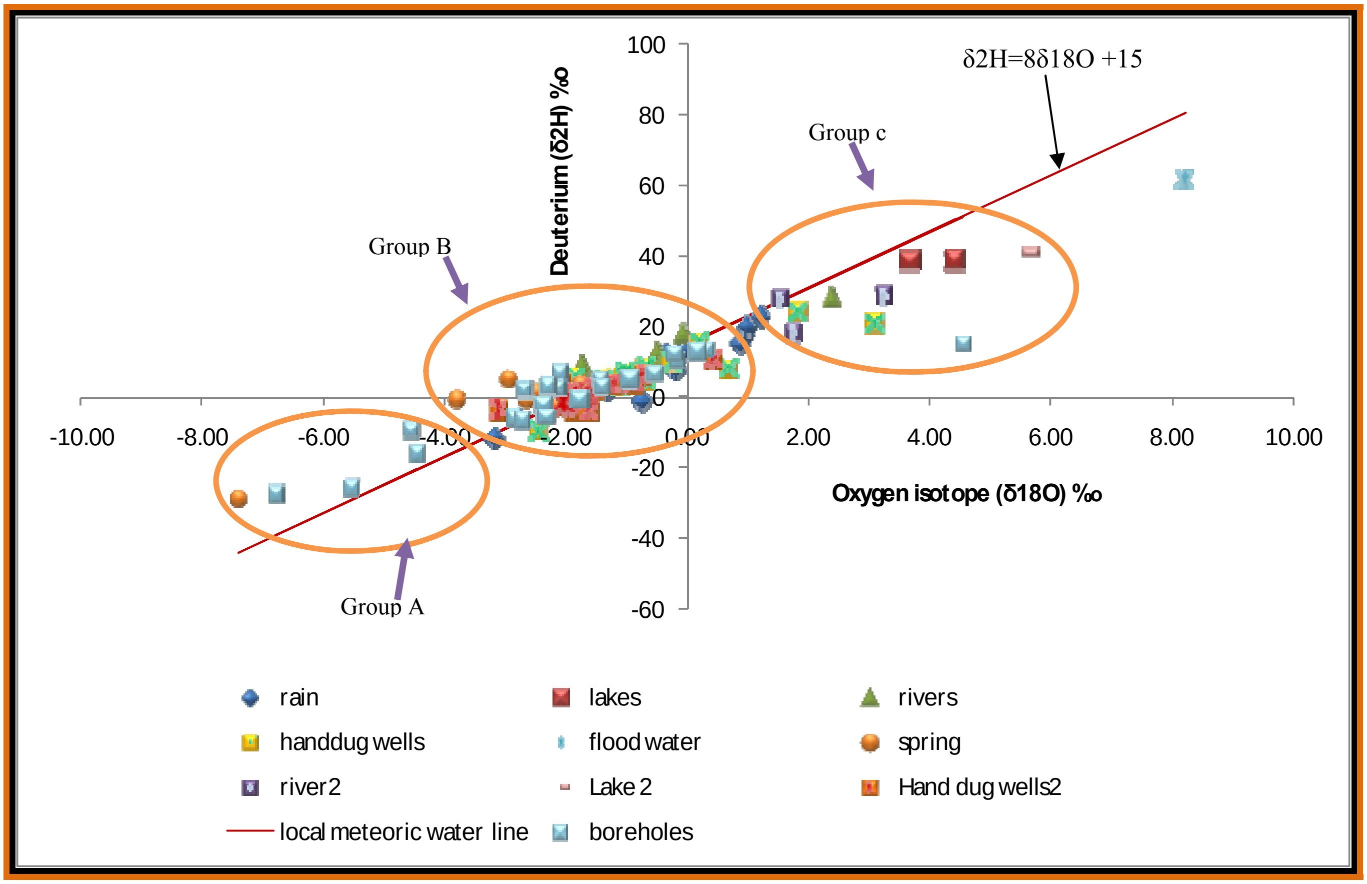

Figure 12-Deuterium (δ^2H ‰) versus Oxygen 18 ($\delta^{18}O$‰) scatter diagram

5.4 Hierarchical clustering and its spatial variation

Hierarchical clustering is a very useful tool to classify water samples in to their objective groups. This method is unique in the fact that it uses multiple parameters of water sample. In this case, nine parameters were used utilizing the previous and new data in combination.

These groups and sub groups are not predetermined at the beginning; however it is possible to understand the chemistry of water samples by investigating statistical relationships among their dissolved constituents and environmental parameters, such as lithology, using multivariate statistics (Güler et al., 2002).

In this investigation, 99 samples of the previous and new data was used. It was checked for errors and a sample with an error greater than 10% was rejected. The value of fluoride and nitrate was also not used due to the unreliability observed from the similarity of most of the records. The water quality analysis that is used for the construction of the Dendogram is attached in the annex table 8.

Excluding the PH all the eight parameters (EC, Na, K, Ca, Mg, Cl, SO4, HCO_3) were log transformed. It has a very good agreement with the clustering of the new data separately and also covers more area. The new data shows only a slight difference in cluster locations. This fact agrees with Güler et al, 2002 that there is little temporal effect on the water quality. Therefore, the spatial variability is the most important source of variation in the data, rather than the temporal factor during hierarchical clustering.

The Hirarchical classification was made using Xlstat 2010 software from the Addin soft that can be attached to Microsoft excel.

The similarity/dissimilarity measurement was found using Euclidean distance (straight line distance between two points in c-dimensional space defined by c variables) as similarity measurement, together with Ward's method for linkage. A dendogram is also drawn to show the groups. In both cases there are six classes constituted by a single or many samples (figure 13). The combined data shows five Groups from Gondar to Robit and Seraba-Dablo area in the Megech and Dirma river sub-catchments. The cluster sequence from the highland to the flat plain shows Group 1 (North of Azezo and the surrounding of Gondar town), Group 3 (between Azezo and Tseda and Kola diba up to chuahit), Group 1 (Tseda to Seraba and Dablo village), group2 (Kola diba to Chuahit) and Group 4 (Kaladiba to Robit town).

In the Rib sub-basin, the sequence from highland until it reaches Lake Tana follows the next sequence: Group 3 (Gassay to Debretabor and from Woreta to Anbesame town), Group 6 (Seraba Mariam), Group 1 (Debre Tabor to Woreta town), Group 4 (West of Woreta), Group 2 (Around Addis Zemen) and Group 5 (From Nabega to Wagetera villages).

Large part of the study area is covered by Group 1 and Group 3 followed by Group2 and then Group 5.

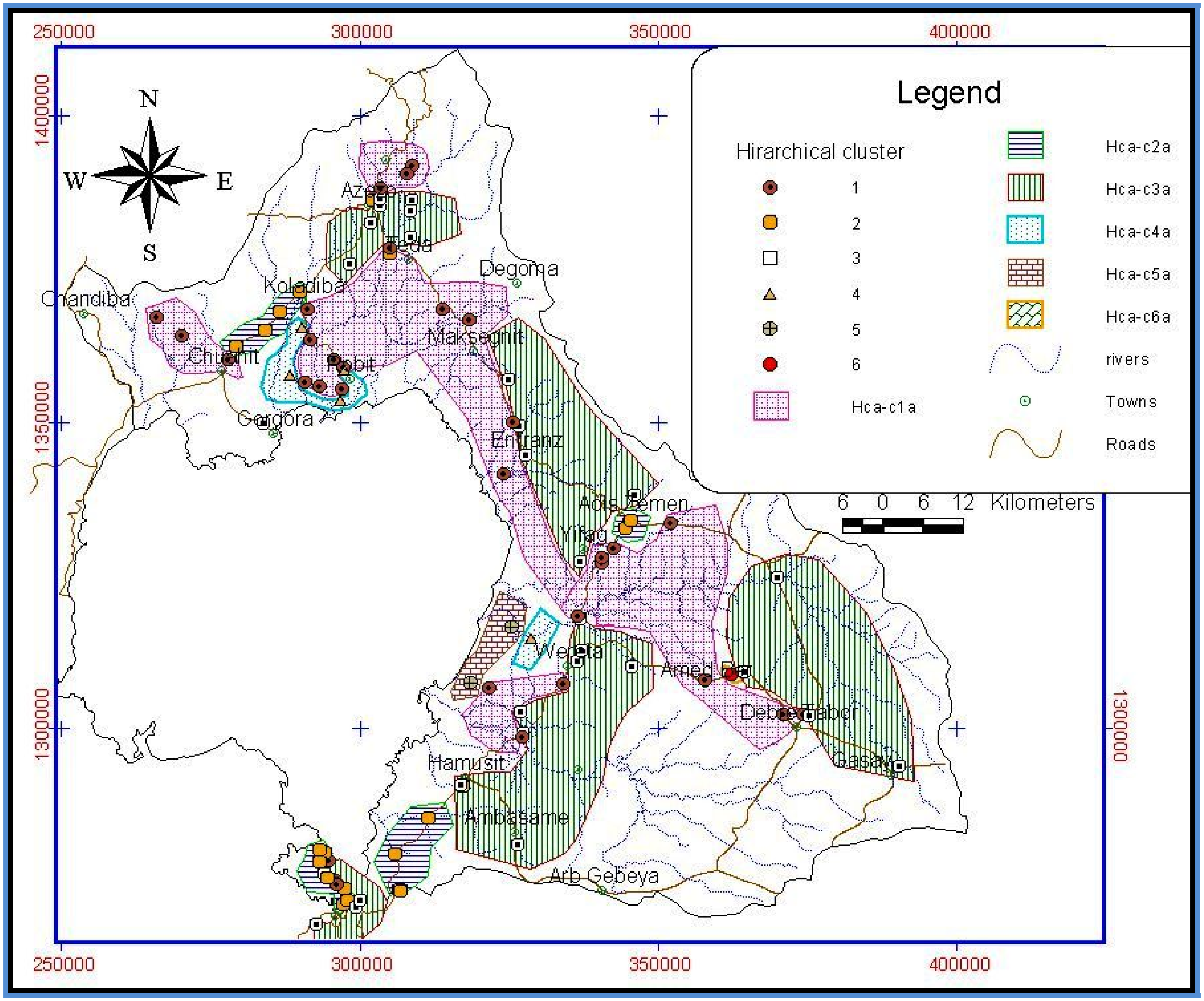

Figure 13-Agglomerative hierarchical clustering`(AHC) and its Spatial variation in north lake Tana basin (combined new & old data)

6 Discussion

6.1 Groundwater and surface water interaction

In Lake Tana sub-basin, it is of paramount importance to look at the interaction between surface water and groundwater when considering sustainable water resources development and ecosystem integrity. Water resource development practices in Lake Tana basin need proper planning, investigation and management not to tamper this fragile environment. Water resource practices such as irrigation, deep groundwater exploitation are some of the development schemes leading to harming the environment.

Flood and furrow irrigation systems for instance encourage percolation of surface water that is susceptible to increase in groundwater level. This in turn increases evaporation and evapotranspiration from surface water and groundwater leading to salinity of the soil and the groundwater.

The Lake Tana wet lands are ecosystems that harbor tremendous amounts of biodiversity. Lake Tana and the Fogera plain wetlands are habitats and are home to the vulnerable Wattled Crane and the Greater Spotted Eagle, the near threatened Pallid Harrier, the Lesser Flamingo and Roget’s Rail. It is also significant as it has 19 highland biome species (40% of Ethiopia’s highland biome) and 20,000 water birds as various congregational species. Lake Tana is also important as a migratory bird resting area (Water Works design Enterprise, 2007).

Available data suggest that aquatic biota will be affected as salinity exceeds 1000 mg/l (EC 1500 mg/l) (Hart et al, 1991). Therefore, it is very important to know the interaction not to harm this vast and fragile ecosystem. Measures should be planned to mitigate if an ecosystem disturbance is predicted.

Besides, in this groundwater system, shallow pocket spatially variable salinity is the main threat that can aggravate the salinisation unless it is taken care. This salinity is a result of high evapotranspiration from the wetlands and trees in the flat plain.

On the other hand, recharge area delineation can be done by understanding surface water and groundwater interaction. Recharge area can be recognised by its frequent interaction with surface water or looking at the meteoric water line as a reference line for understanding and tracing of local groundwater origins. Tracing recharge zone is also very useful to plan pollution protection and delineate discharge area for a groundwater resource exploration.

The wetland waters of the Lake Tana sub-basin inundating the flat plain from June to December are the result of collection of rain water on the flat topography and outflow from the banks of the rivers. The flood water comes very quickly from the highlands of Gondar and Debretabor.

Isotopic evidence has disclosed that backwater contribution on flooding of the wetlands was not observed. This can be confirmed by the depleted nature of the isotopic signature of most of the shallow groundwater in the wetland as compared to the Lake Tana water. There are exceptionally enriched groundwater samples such as Robit village and school hand dug wells which might be recharged by the Megech River after evaporation. This implies that there is some evaporated river recharge isotopic signature in the wetland but it is not clearly observed thatflood water coming by the backwater effect from the lake to recharge the sampled area.

In spite of the high evaporation rate, the flood water and the river water are fresh ranging from 140µS/cm to 400 µS/cm. This shows that significant water is not lost by evaporation as compared to the infiltration and evapotranspiration.

Besides, it is witnessed that there is depleted water in the rivers as compared to the upstream wells in Gondar in the Megech river catchment. On the other side, in the Rib catchment the upstream deep and shallow wells are highly depleted. This signifies that, in the Megech Catchment the groundwater doesn't emerge (recharge) as surface water. It is also uncertain in the Rib Catchment whether the shallow or deep aquifers recharge the surface water. The isotopic signature observed in the Woreta, Addis zemen and Yifag hand dug wells has wider variation with the Rib River (Table-3).

Table 3-Isotopic variation of the river samples with the upstream and downstream water points.

Location	Oxygen ($\delta^{18}O$)%o	Deuterium ($\delta^{2}H$)%o	Remark
Megech river bridge	-0.41	10.10	
Rib River	-0.10	18.57	
Gumara River	-1.78	9.25	
Woreta w3	-6.81	-27.27	Upstream of Rib
Addis Zemen, Angote Mariam well	-1.41	3.10	Upstream of Rib
Bura Hand dug (Yifag enterance)	-0.94	7.06	Upstream of Rib
Gondar (AngerbTw-7)	0.21	13.35	Upstream of Megech
Gondar (AngerbTw-3)	-0.18	10.34	Upstream of Megech
Gonar (Saint Rufael Blind school)	-0.22	12.53-	Upstream of Megech
Wonfela artesian well	0.32	13.63	Down stream of Megech
Tach chanqua hdw	0.14	12.93	Down stream of Megech
ShinaTsion Kebele hdw	-1.40	5.32	Down stream of Rib
Angorbit hand dug well	0.18	15.77	Down stream of Gumara
Robit Hand dug well	3.07	21.28	Down stream of Megech
Robit Village school	0.67	8.39	Down stream of Megech

Correspondingly, in the Rib, Gumara and Megech catchment, the river might recharge the deep aquifers on the highlands and the flat plain after some evaporation. This can be observed by isotopic signatures of downstream wells in table 3.

In conclusion, the source of water for the wetlands and recharge water is contributed by rainfall and rivers. Therefore, the isotopic and geochemical study has shown the surface water and groundwater interaction is enhanced by evapotranspiration and the geomorphology of the area.

6.2 Salinity sources and distribution

The groundwater and surface water interaction is the main factor that decides the groundwater dynamics and thus the water quality variation of an area. Groundwater salinity can result from dissolution of salt, evaporation of surface water, evapotranspiration, dry deposition, differential permeability of clay and shale, irrigation practice, deep source related with high temperature driven dissolution and leaching and silicate cation exchange.

In the Lake Tana sub-basin, two types of salinisation sources are recognized. These are salinisation process due to evapotranspiration in the wetlands and salinisation coming from deep sources.

Evapotranspiration a process where by water from the soil is taken up by a plant through capillary action of the plant vessels and subsequently evaporates from the leaf surface causing water to be transported by a plant from the soil to the air. Evapotranspiration leaves the chemical constituents in the groundwater and accumulates dissolved constituents which results in high salinity close to the surface.

In Lake Tana basin, evapotranspiration is very high as estimated by different authors. The potential evapotranspiration calculated using Penman Moneith method ranges from 1321 (average of all Lake Tana basin) to 1370 mm/yr (average of Gondar, Bahrdar and Debretabor).

The salinity that has come due to evapotranspiration effect is observed on the flat plains. It is observed to be very high from Seraba-Dablo to Robit area in the Megech river sub-catchment and from Wagetera to Nabega area in the Rib sub-basin. Highly saline spring was also observed at Seraba Mariam, east of Amed Ber town, which is also a common occurrence associated with the silcic dykes.

The salinity observed close to the termination of Rib and Megech was recorded in shallow wells that have installed hand pumps. This type groundwater is mostly recharged by rainfall as witnessed by the Deuterium (δ2H) and Oxygen 18 (δ18O) isotope plot (figure 12). There might also be river or flood water recharge before evaporation.

It has also been found out that cation and anion decreases with depth (figure 14) as observed from a plot of water level versus the electrical conductivity of shallow wells. This shows that the salinity of the groundwater decreases with depth along with cations and anions. It is also clear from this plot that the salinity has come due to Solid matter left after evapotranspiration.

From different data collected previously and during this investigation the electrical conductivity of the saline waters ranges from 1040 µS/cm at Mehal Woinit (Sraba and Dablo) to 7830 µS/cm at Wagetera. This value may vary during dry seasons as fresh recharge source is depleted and evapotranspiration becomes higher.

The second occurrence of salinity due to deep source is observed at Seraba Mariam holy spring and ranges from 9600 µS/cm to 10660 µS/cm. This is the highest of all the observed salinity ranges.

This water is coming below an impervious layer or most probably it may be related with the geological cycle of tectonics. The flow of the spring could have been initiated by the pressure change due to the dyke.

Altough, salinity due to evaporation has limited effect in the study area, it is of great importance to consider. Rice farming with other plantations is becoming accustomed in the area. Large scale irrigation schemes are also underway in Rib (Lake Tana), Megech and Gumara. Proper irrigation system planning should be practiced.to reduce the high salinity sources.

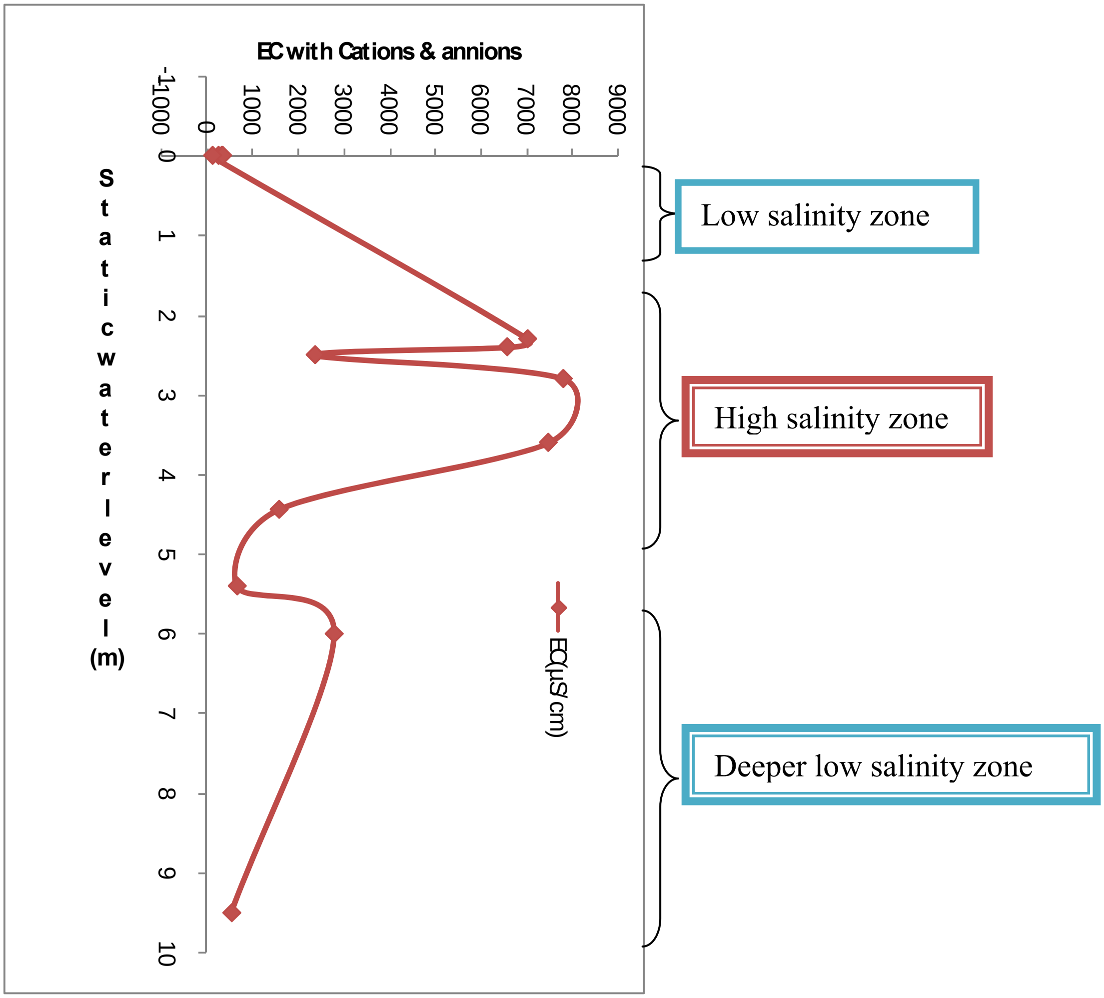

Figure 14-Static water level versus the electrical conductivity

6.3 Isotope & geochemical evidence on interactions of groundwater and surface water

Groundwater and surface water interaction can be identified by looking at the sample points plotting along a mixing line or away from each other on the Deuterium (δ^2H%o) versus oxygen ($\delta\ ^{18}$O%o) isotope plot. It is also possible that similar Groups in hierarchical clusters of geochemical data might belong to distinct groups interacting with each other as their recharge mechanism, source and its water type could be of similar origin.

Some of the evidences of the surface water and groundwater interaction are related with Deuterium (δ^2H%o) and oxygen isotope ($\delta\ ^{18}$O%o) relations of the samples.

The Deuterium ($\delta\ ^2H\%o$) versus oxygen ($\delta\ ^{18}O\%o$) isotope data for boreholes, hand dug wells, springs and river samples in group B (Figure 12) show a close correlation with the local Ethiopian meteoric water line "(δ^2H) =8*($\delta^{18}O$)+15" and rainfall data averaged from GNIP data (Global IAEA database from 1961-2005). Most of the samples plot specifically very close to summer rainfalls (July to December) where as group A boreholes at Gassay, Debretabor and Woreta plot away from the rainfall data. This shows that most of group A boreholes are not recharged by the present time rainfall.

As mentioned in other sections, group B (figure 12) samples especially hand dug wells located in the flat Dembia and Fogera plain are depleted than the surface water. However, most of them are saline. Their depletion and high salinity is described by the evapotranspiration effect. Otherwise, these wells should have been plotted along evaporation line if evaporation were involved. Recharge to these wells is expected to come mostly from local rainfall.
Megech River is depleted than the upstream wells in Gondar (Angereb Tw3, Tw 7and St. Rufael boreholes) and also downstream wells (Tach chanqua and Wonfela boreholes). The enrichment of Gondar wells can be explained by recharge from the evaporated Angereb dam. However, at the sampling point Megech river is a mixture of Angereb, Dimaza and Megech River itself. Therefore, its depletion could have come due to this fact.
The Saint Rufael blind school well may have been enriched due to the fact that it has been kept in a reservoir for some time. During the sampling it has been learned that this well was not used for a long time (starting from the rainy season). On the contrary, the enrichment of down stream wells implies that Megech River may recharge after some enrichment by evaporation. The other wells that might be recharged by Megech River are Robit and Robit school hand dug well. This is because these wells are more enriched and are closer to the river.
In the Rib Sub-basin, Shina hand dug well is at the vicinity of the river (50m away) and might be recharged by the river. It is enriched than the river and may have been evaporated before recharge. The isotopic signature of the boreholes in the Northern side of the river (Yifag and Addis Zemen) shows a does not show correlation with the southern side (Yifag dikule deep well). This suggests that Rib river doesn't recharge the deep wells or the hand dug wells sampled in this area. Addis zemen, Yifag and woreta boreholes might have been recharged by local rains North of Addis zemen (Bachila mountain) and Debre tabor and Gassay area (Guna) respectively.

On the Southern side of Rib River (Woreta up to Gassay) comparatively less enrichment is observed as compared to the northern side. This confirms that there is the influence of the high rising Debretabor and Guna mountains to the depletion and the ttwo sides might not have interaction.

There is little correlation between the hand dug wells and deep wells. The flood water collected in the flat plain, close to Gumara river is highly enriched and does not have any correlation with the hand dug well near by. This implies that it is not recharging the groundwater at that moment or any other times. Although the Angorbt hand dug well ($\delta^{18}O$=0.18%o) is enriched with respect to the Gumara river ($\delta^{18}O$=-1.78%o) it may recharge this well after evaporation.

Moreover, two boreholes sampled south of Lake Tana ($\delta^{18}O$=4.42%o), Chara chara well ($\delta^{18}O$=-2.69%o) 0.71 Km and Gudo Bahr wells ($\delta^{18}O$= -1.78%o) 3.66 Km away show a depleted isotopic content as compared to the lake. These wells are good examples showing that there is no interaction between the groundwater and Lake Tana in the immediate vicinity. These wells are supposed to represent the flow of groundwater as well as the surface water; nevertheless none of them show any correlation of their isotopic signature.

On the other side, Ca-Mg-HCO3 and Na-Ca-HCO3 type waters indicate an interaction with basaltic rock specifically an interaction with feldspars. These waters are mostly recharged on the highlands where basalt dominates.

The source of salinisation of brackish to highly mineralized groundwater and thermal water can be definitely detected by a δ18O/Cl- plot. Processes such as dissolution and leaching of salt, enrichment by evaporation or mixing of fresh water with saline water or seawater can be clearly and quantitatively distinguished (Mebus Geyh, 2000).

These processes are clearly observed on the δ18O/Cl- plot in the samples collected from the Lake Tana sub-basin (figure 15). Comparing the case in Lake Tana to the UNESCO/IAEA Series on Environmental Isotopes in the Hydrological Cycle evaporation, evapotranspiration, hydrolysis, mixing and leaching and some other intermediate processes can be observed.

Evaporation is confirmed clearly by this plot on samples of Lake Tana, Angorbit flood water, Rib river, Yifag dikule deep well, Robit Hand dug well, Komini river bridge(chandiba road) and Guarhe hand dug well. All of these samples were clearly seen on the Deuterium (δ^2H ‰) versus Oxygen 18 ($\delta^{18}O$‰) scatter diagram that they have undergone the evaporation process (Figure 12).

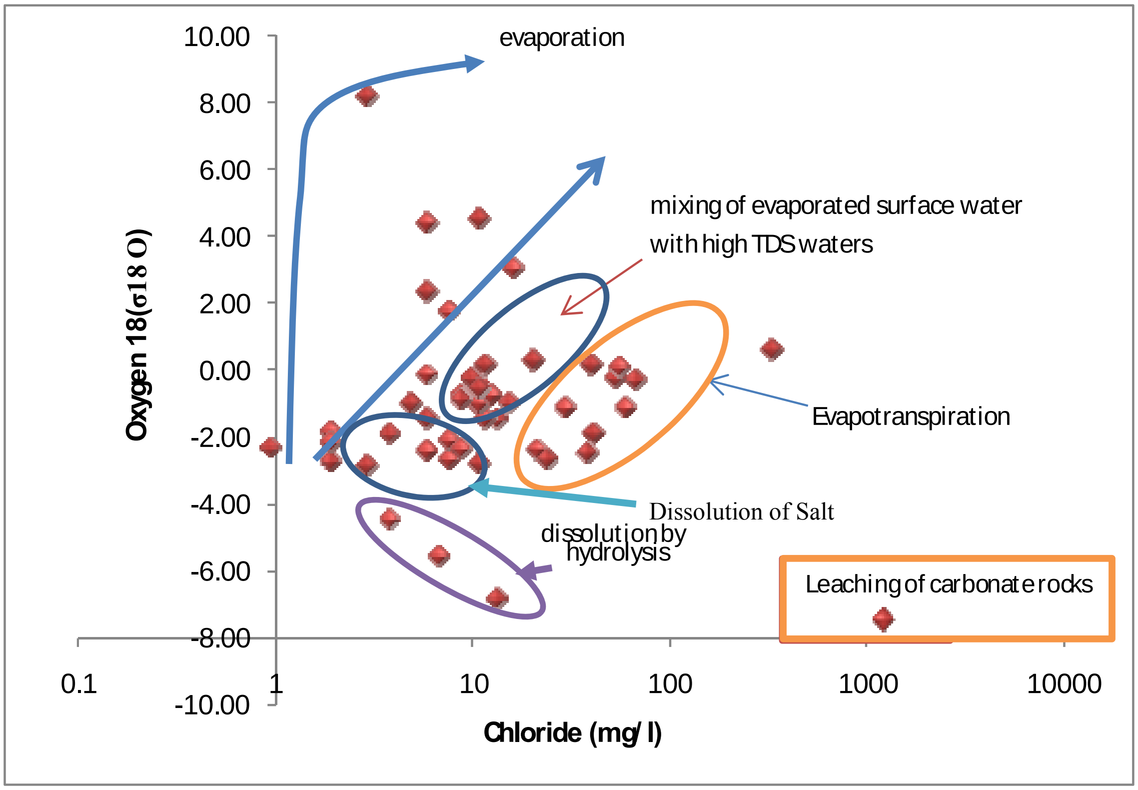

Figure 15-.Oxygen 18 (δ18O) versus Chloride (Cl^-) plot

The mixing zone is not observed clearly in this diagram. However, Gondar boreholes (Tw3 and Tw7) are Known to occur downstream of Angereb Dam occurring in the mixing zone between the dam water and other recharge.

The leaching process is observed on the highly depleted and high chloride concentrated sample in the Seraba Mariam holy spring.

Hydrolysis is another process that can be observed in Debretabor (Sebara dildy), Gasay and Woreta boreholes. This shows an increase in chloride and a decrease in oxygen isotope (($\delta^{18}O$‰).

Evapotranspiration process is observed in the lower Megech and lower Rib river sub catchment hand dug wells. These samples are distinguished from others with their high chloride content and relatively depleted oxygen isotope (δ18O%0).

6.4 The Q-mode Clustering analysis on the geochemistry of waters

The Q-mode clustering has resulted in six Groups using nine variables and 99 data points. These variables include electrical conductivity, PH, Na, K, Ca, Mg, Cl, SO4 and HCO3.

The grouping was set up to find the result automatically and was analysed to see if the similarity/dissimilarity cluster has any relation that is meaningful.

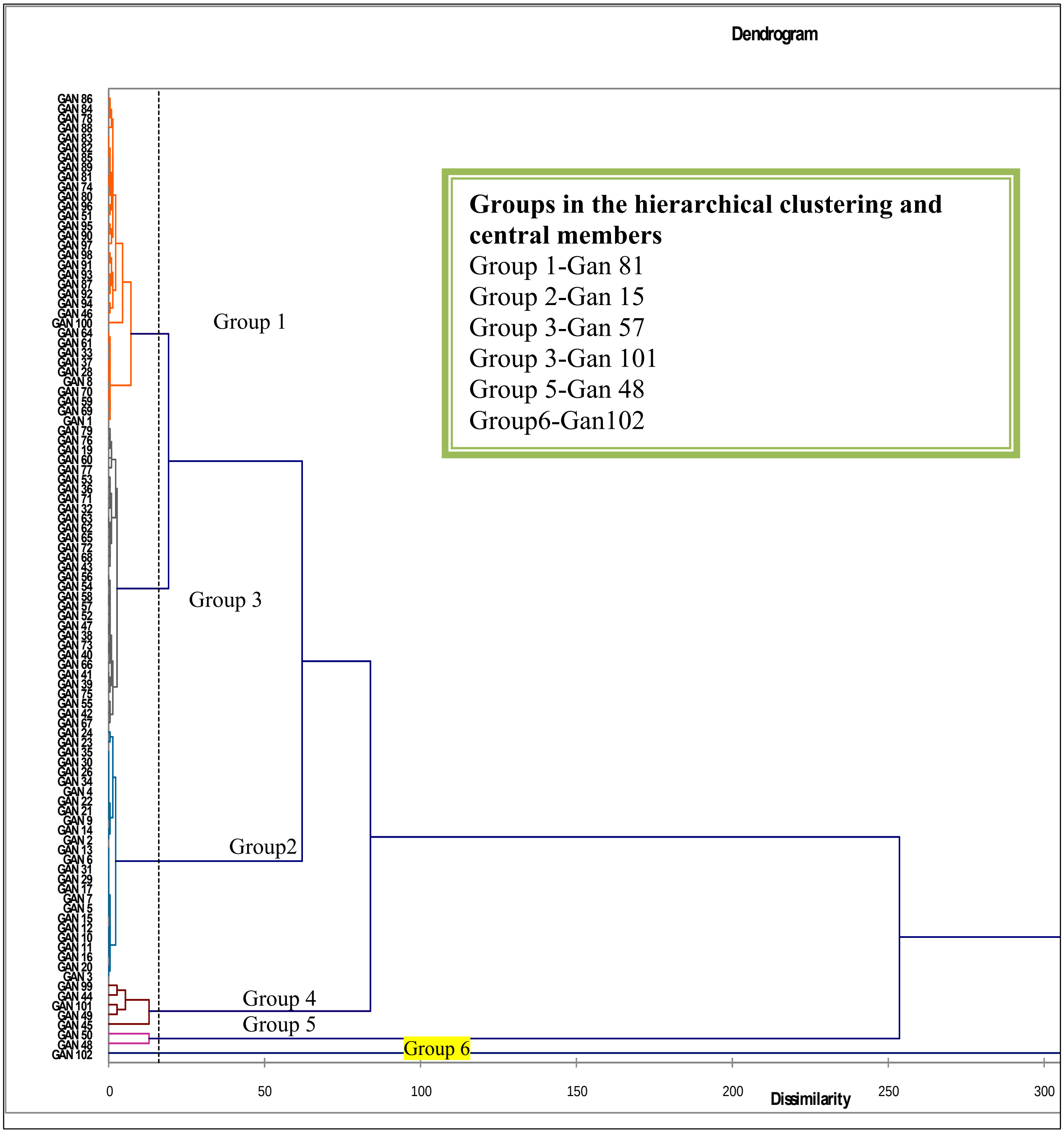

Figure 16-Hierarchical clustering dendogram showing the groups

Thus, group I waters are identified to be dilute waters having smaller to medium electrical conductivity. The electrical conductivity ranges from 82µS/cm to 1230 µS/cm. This water type follows the Megech river except that it is separated in the middle by group III waters. In this group there is an indication that the aquifer in Angereb valley, Gondar and the aquifer in Dembia plain (Kola Diba well) correlate well in terms of the water type and its being a semi confined aquifer. Ca-Mg-HCO3 and Na-Ca-HCO3 waters dominate in this group

Group II waters are the freshest waters of all the groups. The electrical conductivity of this group ranges from 77 to 505 µS/cm. This group of water is found mostly around Bahr Dar town Kola Diba to chuahit and Addis Zemen towns. It belongs to Ca-Mg-HCO3 water type and is mostly related to the quaternary basalt around Bahir Dar town.

Group III waters are very dilute waters that belong to an electrical conductivity range between 123 and 659 µS/cm. This group is found mostly around the recharge area of Megech, Rib and Gumara sub-basins next to Group I waters along the groundwater movement direction. It is also observed around Maksegnit and Addis Zemen area. In this group Na-Ca-Mg-HCO3, Ca-Na-HCO3, Ca-Mg-HCO3 and Na-HCO3 water types are found. Na and HCO3 are higher in the group but in general the amount of cations and anions is smaller than all the groups.

Group IV waters are saline and some of them are not drunk by people (only cattle). The electrical conductivity of the group ranges from 1440 to 4190 µS/cm. Most of this group belongs to Na-Ca-HCO3-SO4 and Mg-Ca-Cl-HCO3 water types. These wells are located specifically in Seraba and Dablo area extending from Guramba up to the lake. Although there is only one sample, it is also observed east of Nabega area. Cl and HCO3 are the highest as compared to the other ions. This might indicate that the chloride source might be from the evapotranspiration of the groundwater.

Group V water has the highest salinity and is found extending from Wagetera to Nabega area close to the termination of Rib River. Ca and Cl are the highest as compared to all the groups mentioned above. The electrical conductivity found in two of the wells is 7050 and 7830 µS/cm. This group is found at the end of the groundwater flow and Ca-Na-Mg-Cl (Wagetera) and Ca-Na-Mg-Cl water types are found.

Group VI waters are not related to shallow or deep potable waters found in the ground water flow system found in Tana sub-basin. However, it might have been related to deeper groundwater and became saline due to the leaching of carbonate, Magmatic source or weathering of felspar. This water comes out by oozing through one of the silicic dykes. Electrical conductivity of this spring was observed to be 10660 µS/cm in the field and 13460 µS/cm in the Laboratory & Na-HCO3 water type.

There is no strong correlation of hierarchical clustering result with the isotopic enrichment or depletion except at the Seraba Mariam holy spring (found in group Vi) which is highly depleted. However, it is possible to observe that group I waters are moderately depleted with the exception of the high enrichment at Robit town dug well. Group III is moderately to highly depleted where as, group IV is highly enriched. In group three flood water and Yifag well were found to be anomalously highly enriched waters. Unfortunately group II and Group V waters don’t have isotope data to relate it with the clusters.

The geology of the area is another factor that plays an important role in changing the geochemistry of the area. It is also possible to correlate the cluster groups with the geology. Therefore, group I waters are mostly found in the alluvio colluvium deposit and might be recharged by the basalts on the highland. The continuation of the group from Tarmaber basalt in to the alluvium implies that there might be an interaction.

Group II waters are mostly related with the quaternary basalt and alluvio colluvium located around Bahr dar and north east of Chuahit town.

The third group occupying larger cover is related in most cases with the Tarmaber basalt aquifer is found at the upper reaches of catchments where as group IV and V are found in the alluvio colluvium deposit. Group IV waters are unique in that it is found in the alluvium at the contact between the inter fingering Basaltic flow and alluvio colluvium deposit.

Owing to its high salinity that might have resulted from deep carbonate formation, Group VI waters are found in the silicic dyke separately from the nearby wells.

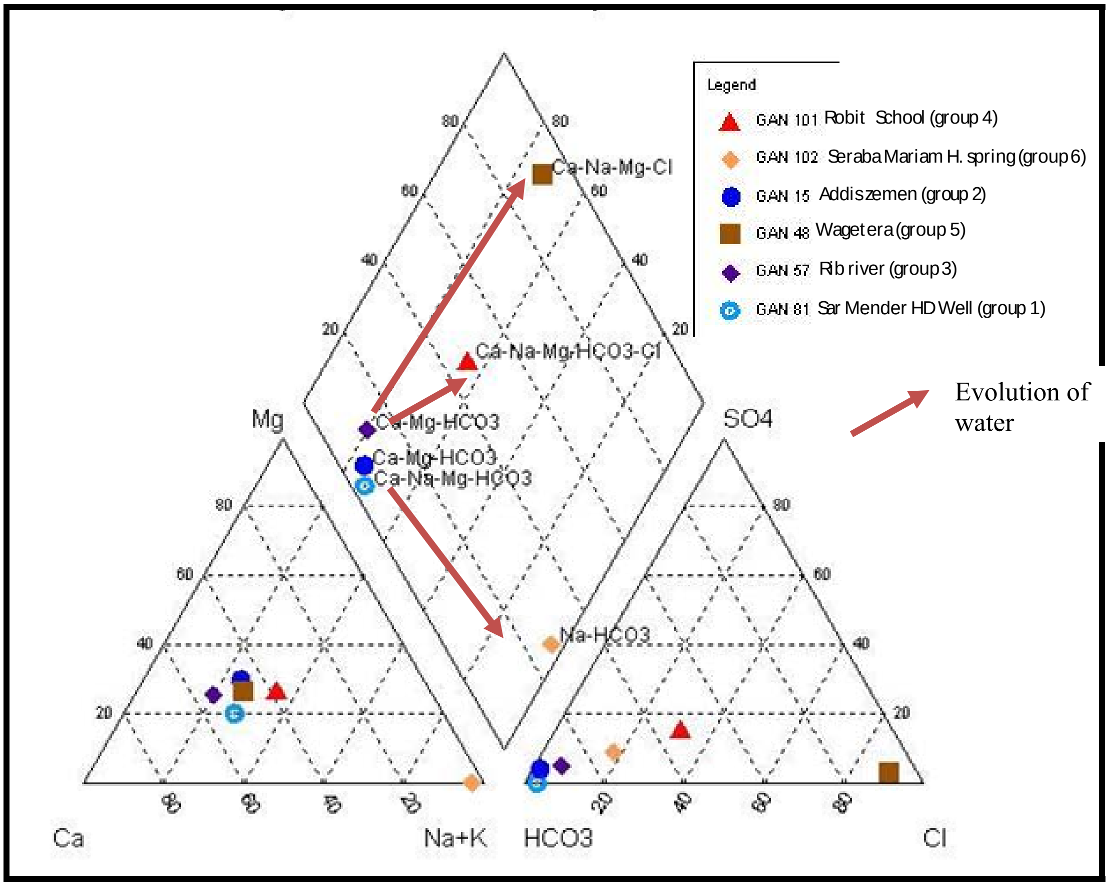

Figure 17-Centroid of cluster analysis and water types evolution

Looking at the piper diagram of the centroid, the fresh water from the recharge area group I, II and III clusters belong to Ca-Mg-HCO3 and Ca-Na-Mg-HCO3. Group four, five and six belong to Ca-Na-Mg-HCO3-Cl, Ca-Na-Mg-Cl and Na-HCO3 water types respectively (figure 17).

The concentration of Na and K generally increases from group I to VI, where as Ca, Mg and Cl increase from group I to V and then decreases. On the other hand, sulphate ($SO4^{-2}$), bicarbonate ($HCO3^{-1}$) and fluoride (F^{-1}) show similar behaviour. These ions increase from Group I to Group 4 and then decrease from group IV to V and finally increase in group VI. Nitrate shows a decreasing trend from group I to II and then increases from group III to IV and finally decreases from group IV to VI.

In general, the hierarchical groups can be summarised as follows

- Group I-is fresh and found in alluvial sediments and basalt, the EC ranges from 82µS/cm to 1230 µS/cm and belongs in Ca-Mg-HCO3 and Na-Ca-HCO3 water types
- Group II-is Fresh and found in quaternary basalt mostly, the EC ranges from 77 to 505 µS/cm, grouped in Ca-Mg-HCO3 water type

- Group III- is fresh and found in Tarmaber basalt at higher and intermediate elevations , the EC ranges from 123 to 659 μS/cm, grouped in Na-Ca-Mg-HCO3, Ca-Na-HCO3, Ca-Mg-HCO3 and Na-HCO3 water types
- Group IV- is saline and found in alluvial sediments in the wetland, the EC ranges from 1440 to 4190 μS/cm, belongs to Na-Ca-HCO3-SO4 and Mg-Ca-Cl-HCO3 water types
- Group V- is more saline than group IV and is found in sediments in the wetland, its Ec ranges from 7050 to 7830 μS/cm and is grouped as Ca-Na-Mg-Cl and Ca-Na-Mg-Cl water types
- Group VI-is highly saline and related with the silicic dyke, its EC was recorded as 10660 μS/cm and belongs to Na-HCO3 water type.

6.5 Geochemical evolution models: The origin of high salinity

The evolution of this groundwater system has resulted from the interaction of the surface water, groundwater, geological setup and processes that shape the present condition of the system. The interaction of all the systems has been discussed except the processes that are involved in changing the groundwater quality. These processes include evaporation, Evapotranspiration, deep leaching of the host rock.

6.5.1 Evaporation model: Successive evaporation-dissolution cycling

The evaporation model is one of the processes that shape the condition of the groundwater system of an area. This model is expected to represent a general change in the water quality related with the salinisation of large land cover.

Lake tana basin is a place where there is long term flooding of the lower reaches of Megech, Rib and Gumara sub catchments. The flooding occurs due to the flat topography of the area and outflow from the banks of the rivers. Flooding often starts at the beginning of June and stays up to December according to the Monthly five years average area (1998-2003) (Yohannes Daniel, 2008). It covers vast area in different sub-basins. The average maximum flooded area covers estmated from satellite imagery are 222km^2 in Rib (october), 150km^2 in (august) and 31km^2 in Gumara (October).

The evaporation model is dependent on the evaporation of flooding water (Figure 18). In the rainy season and afterwards (June to December) there is widespread flooding and gully storages. Some of this water percolates down and some of it evaporates. In the second event, the dry season where there is high temperature (30.4^o c in December and January) evaporation occurs. This results in salt encrustation on the surface and underground up to the depth of evaporation of groundwater. In the second year of the event second a flooding, percolation and evaporation occurs. During this event, direct and percolating pond water leaches the encrusted salt and goes down. The third event results in the salinity of the near surface groundwater all over the flooded area. This process goes on for the fourth event where leaching, evaporation and encrustations of salt continue. However, this process gives us a total of 403 Km2 of the study area having very high salinity when calculated comparable to the gauged catchment of Megech River (462 km2). This model presumes that the salinity should be distributed all over the flooded area. Hence, this evolution model may not be applicable as far as the salinity by evaporation is concerned. This is due to the fact that the observed salinity is found as pockets only. Moreover, there is evidence from the stable isotope data that there is little enrichment of the saline groundwater in the hand dug wells (only the Robit village and Robit school hand dug wells show evaporation signature). If the assumptions of the groundwater evolution were true more wells could have shown widespread evaporation effect and thus high deuterium (δ^2H) and oxygen18 (δ^{18}O) enrichment

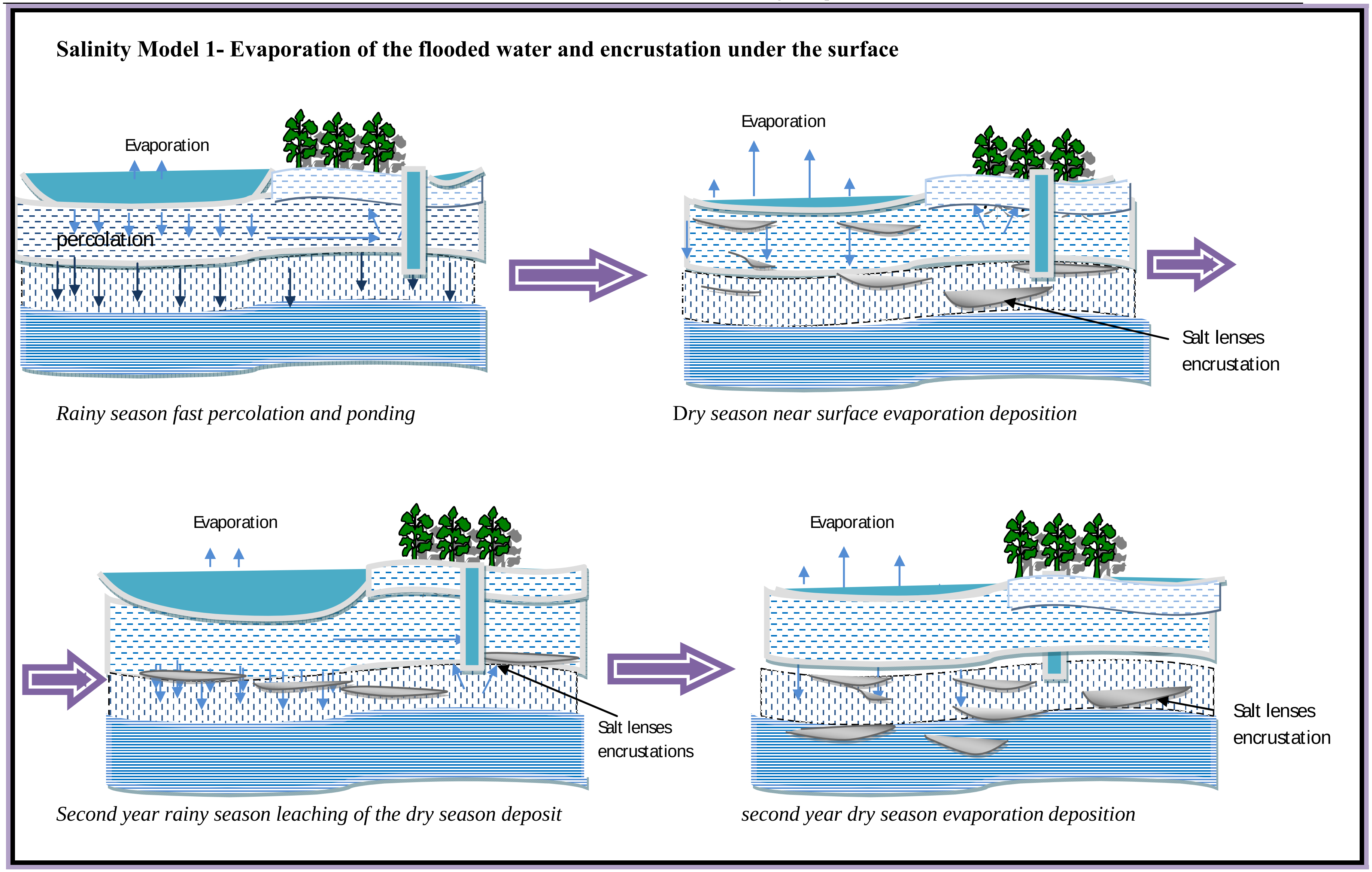

Figure 18-Evaporation model, salinisation due to evaporation

6.5.2 Evapotranspiration model

The second model for the evolution of the groundwater in the Lake Tana basin is evapotranspiration model.

Evaporation from a vegetated land surface is normally a combination of direct evaporation from a wet surface, and water consumption or transpiration by the vegetation. For a well-watered vegetated surface or a wet soil, evaporation is normally close to that of an open water surface and is indicated as potential evapotranspiration (Mook, 2000). Evapotranspiration causes water to be transported by a plant through capillary action of vessels from the soil to the air with no net isotope fractionation (Mook, 2000).

It has been found out that water in the unsaturated zone below uncultivated land that the concentration of Chloride ion is low and shows little variations, on the other hand, it is very much higher under the forest (Appelo et al, 2007).

Consequently, this model assumes that the trees planted in the flat Dembia and Fogera plain in combination with the wet lands affect the ground water chemistry of the area. High salinity and less isotopic enrichment are observed in the chemistry of such groundwater sample. In this model, evapotranspiration plays a major role in the process of Salinisation. Rainfall or other surface waters percolate down in to the unsaturated zone and then to the saturated groundwater zone. In between this process evapotranspiration causes the groundwater to flow in to the points of high evapotranspiration and accumulation of dissolved solutes increases (Milzow et al, 2009). This process goes on every season although it doesn't change the isotopic signature of the water (Mook, 2000).

This is evidenced by the pocket salinities occurring in the Lake Tana Basin that might have resulted due to this process. The evolution of the groundwater is depicted as follows in figure 19.

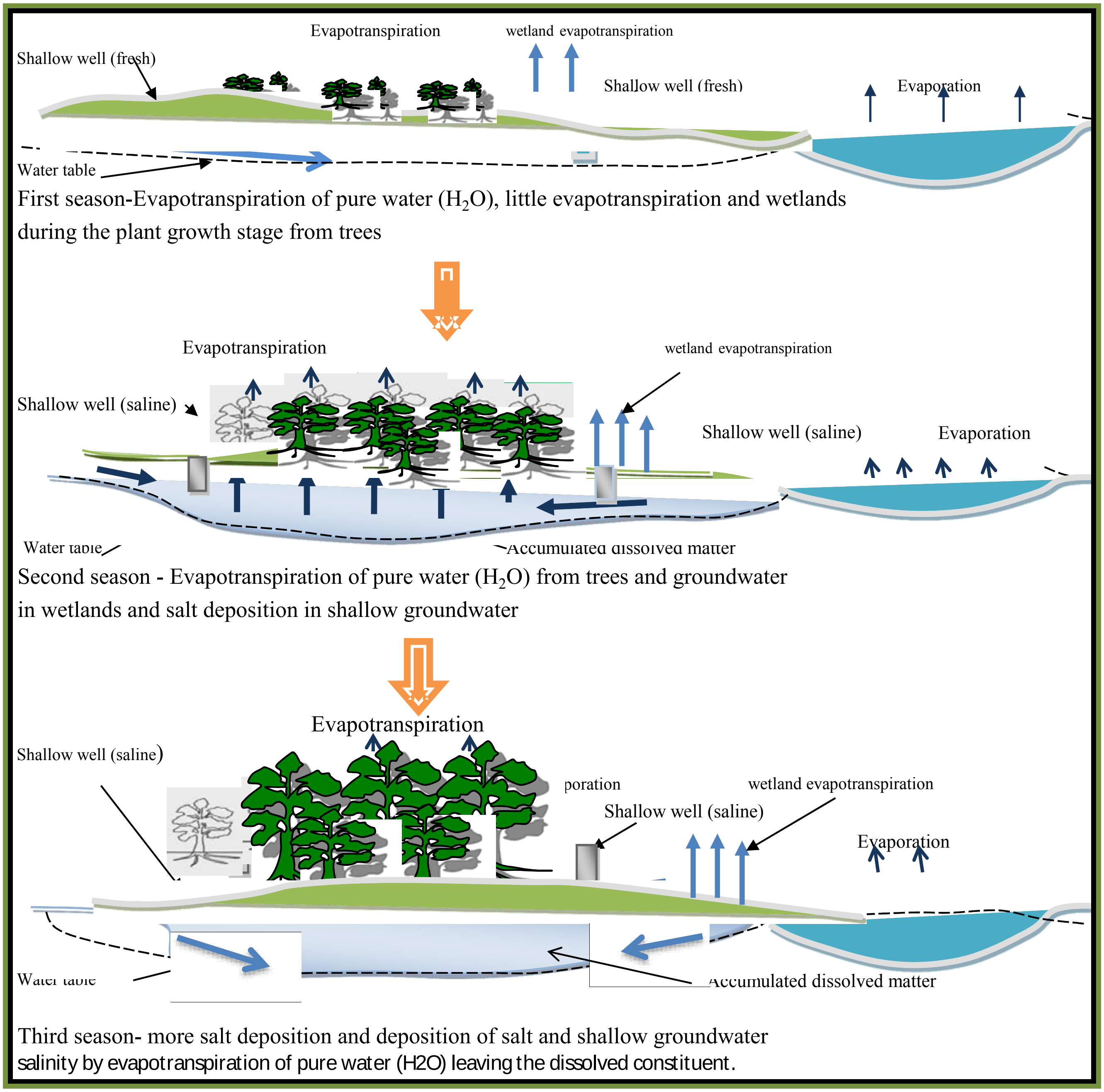

Figure 19-Evapotranspiration model

These samples were observed spread from Seraba & Dablo to Robit in the Megech sub catchment. Similar condition was also encountered from the second phase of sampling in the Rib river catchment starting from Nabega in the North to Wagetera in the south (figure 11).

On the other hand, it is observed that a flood water sample is enriched very much with oxygen isotope ($\delta^{18}O$=8.22). However, its electrical conductivity is much lower than these wells (138 µS/cm).

Therefore, this is one of the proofs that Evapotranspiration is involved in the process of salinisation than evaporation.

Moreover, box and whisker plot of Oxygen isotope (δ18O) of hand dug wells on the plain indicates lower enrichment due to evapotranspiration process (figure 20). This can be explained by higher enrichment of the Lake's and river's isotopic signature without increase in electrical conductivity. In this case the depletion observed in deep wells and springs can be explained by the depleted recharge on the highlands (Figure 20).

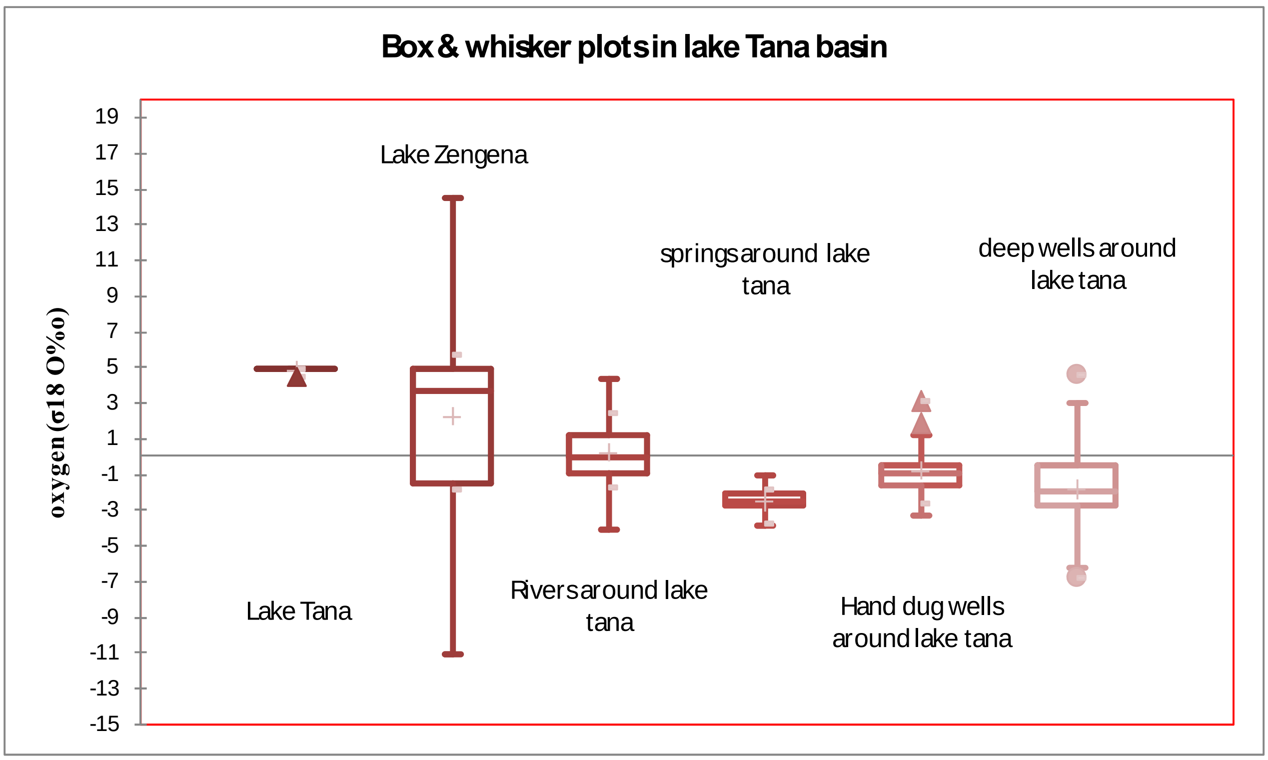

Figure 20-Box and Whisker plot in Lake Tana basin

On top of this, it has been shown in figure 14 that there is high salinity near the surface in shallow wells and this effect is enhanced specifically by the presence of high Chloride and Sodium ions. This may be an indication of the evapotranspiration process (Apelo et. al.,2007).

Therefore, evapotranspiration plays the main role in the wetlands salinisation of shallow groundwater system than any other processes.

6.5.3 Deep circulation Model: Highly mineralized waters

The deep circulation model was observed at, the Seraba Mariam holy spring (figure 21). However, this condition occurs at several places in the sub-basin where there are silicic dykes that are associated with the Tarmaber basalt. This spring is of low discharge ooze coming out through a large area close to a silicic dyke. It is a highly saline water and is used as a holy water. Dug wells in to the silicic rock collect this oozing saline water.

Groundwater occurrences at greater depths below impervious layers are more or less isolated from the active part of the hydrological cycle and their character is partly connate; i.e. they were trapped during sedimentation and are often of marine origin (Mook, 2000). This has been confirmed by carbon 13 ($\delta^{13}C$) rehydration of the Seraba Mariam holy water indicating carbonate origin (Kebede et. al, 2005)

These springs might be related with the geological cycle of tectonics and their dynamics are linked with these processes. Their flow is driven by processes on a geological time and areal scale probably by pressure change due to the occurrence of the dyke and osmotic processes.

Fluid movement under these conditions has often residual components because of the long relaxation time of the pressure gradient. The interaction of these deep seated systems with the active or meteoric part of the hydrological cycle occurs by slow upward seepage (Mook, 2000).

The geochemistry of this spring is very unique in that it has the highest concentration of bicarbonate (6954 mg/l), sodium (3750 mg/l), and chloride (1007 mg/l).

In this case, the sources of carbon dissolved in this groundwater might have come from carbonate minerals or CO_2 of geogenic origin or from magmatic CO_2 (from deep crustal or mantle sources) (Mook, 2000).

The main sources of sodium could be common feldspars. About 60 percent of the body of igneous rock in the Earth's outer crust consists of feldspar minerals. This may be from the plagioclase feldspar variety called Albite, which has a formula NaAlSi3O8. Some sodium may be present, substituting for potassium in orthoclase and microcline (john D. Hem, 1985).

In igneous rocks chloride can't be very high in concentrations in circulating natural water (john D. Hem, 1985). More important sources are associated with sedimentary rocks, particularly the carbonates. Thus, there might b a limited interaction with Holocene sediments (Figure 4).

It is supersaturated with respect to calcite (SI=1.05), aragonite (SI=0.9) and dolomite (SI=0.96) and is under saturated with respect to gypsum (SI= -0.88) and anhydrite (SI= -1.1). It can be understood from here that the supersaturated calcite, dolomite and aragonite will precipitate.

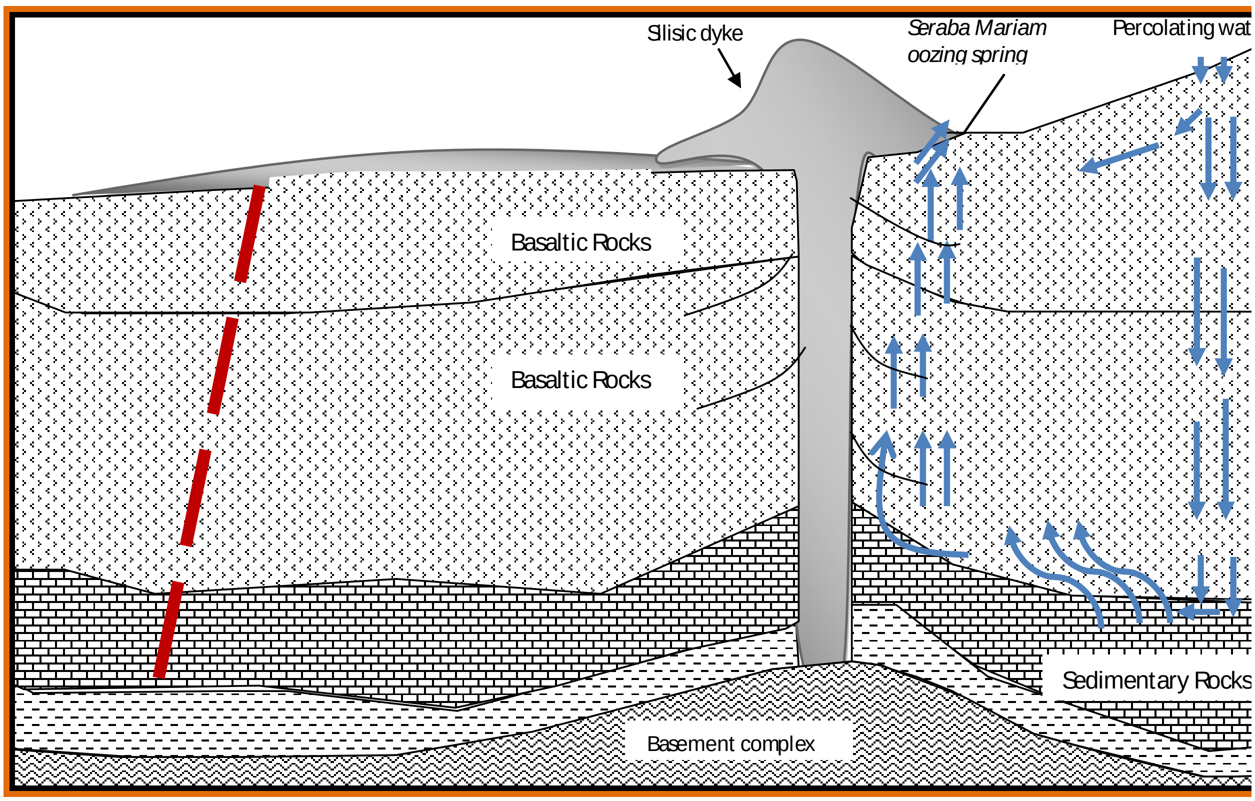

Figure 21-.Deep circulation model of groundwater evolution

6.6 Water resources development in Lake Tana sub-basin and its implications (irrigation, water supply and ecology)

The surface water and groundwater interaction is explained in different ways and implies that the water resource in Lake Tana basin has to be planned and developed in a sustainable way.

This interaction can facilitate recharge which can come from rainfall, river, flooding water and irrigation return. On the other hand, the interaction can be a treat by bringing surface water from polluted water body to the groundwater or the vice versa.

There is a shortage of sufficient and clean water supply in the high lands of Gondar and other areas. In understanding the interaction between the surface water and groundwater system, the hierarchical clustering geochemical data and isotopic information has shown that there is a connection between the rainfall recharge around Gondar and Debretabor high lands and the Dembia and Fogera plain.

Isotopic evidence shows that Angereb dam, Megech river and Rib river recharge the groundwater to some extent. Local rainfall is also one of the main recharges of the shallow groundwater on the Dembia and Fogera plain.

Moreover, as limited deep groundwater data signifies there is a fresh groundwater system that is found in a semi confined or confined aquifer. This was confirmed by hierarchical clustering and could be further reconfirmed by deep drilling.

Besides, the isotope and geochemical clustering result has indicated that there is a treat of pollution in the recharge zone where there is expansion of industries and housing (sewage and uncontrolled waste dump). There is evidence that some water points have been polluted indicating a nitrate level greater than 50 mg/l which is lethal to children (figure 22). Although, these wells are used by the population, it should be noted that precautions should be taken to reduce this pollution as these areas are close to towns. Some of the polluted deep and shallow wells are found at Bahrdar, Gondar, Robit, Chuahit, Tach chanqua etc. This can be observed on the Nitrate (NO_3^{-1}) versus Chloride (Cl^-) scatter diagram (Figure 22).

Considering salinity as one of the factors affecting water resource development, it is of utmost importance to identify where the source of the salinity could be and how to overcome this treat. Natural process such as evaporation, evapotranspiration, leaching, dissolution and precipitation of dissolved solutes can result in high salinity. In the case of this study, evaporation, evapotranspiration and Deep circulation models have shown how the interaction goes on.

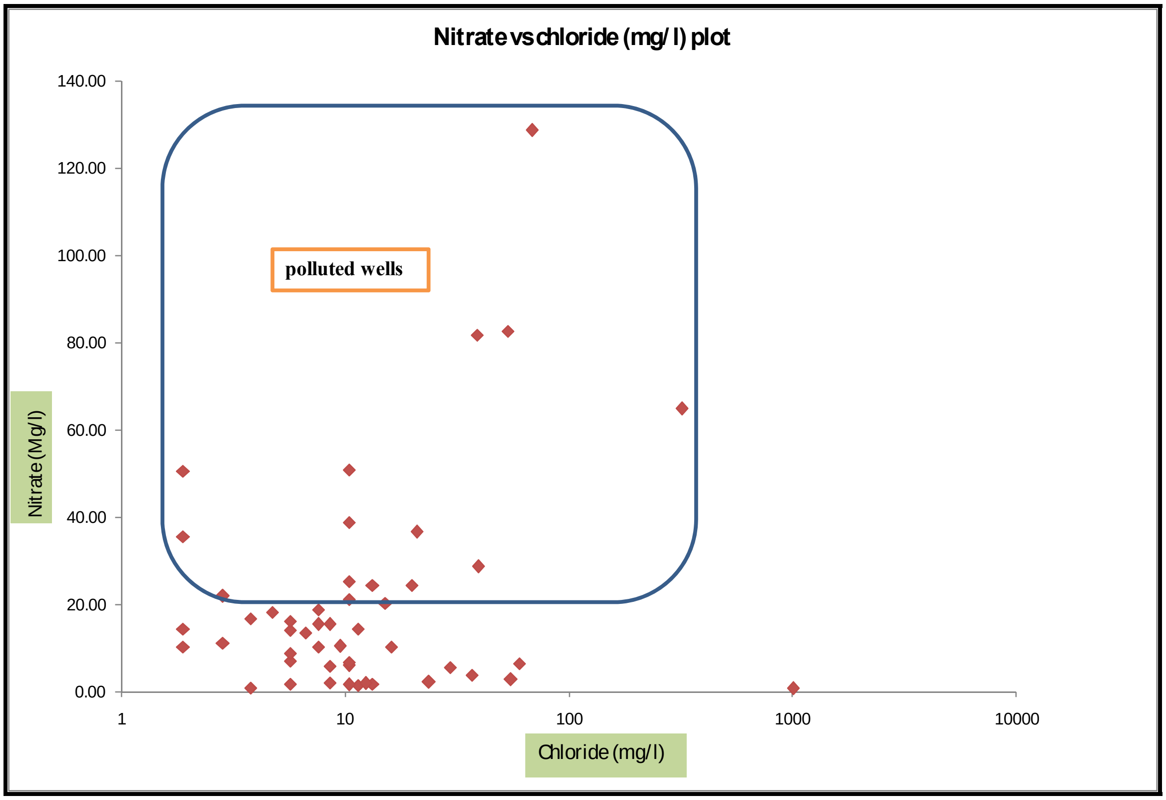

Figure 22-Pollution of water samples in the study area.

In the ongoing development of irrigation schemes, it has to be considered that high evaporation of the irrigation water, groundwater level rise, evapotranspiration and ultimately high salinity influences the sustainability of the schemes to be established. The salinity can be intensified by the presence of pocket shallow salinity identified in this investigation in case other sources of salinity are initiated due to human intervention. These pocket salinity areas are not patterned or uniform. However, priority should be given to devise mitigation measures.

Plantations resulting in high evapotranspiration are also a challenge that might result in certain amounts of shallow groundwater salinity problems. In the isotopic interpretation it was observed that the salinity due to evapotranspiration is high enough to give rise in soil salinity and then imply abandoning of a farm land.

It should also be noted that aquatic biota can be affected as salinity exceeds 1000 mg/l (EC 1500 mg/l). In this investigation, about 11% of the samples used in the hierarchical clustering have an electrical conductivity of more than 1000mg/l. Most of the sampled sites are located where yearly flooding occurs and aquatic biota can flourish before and after flooding.

Therefore, if the water resource is to be developed in a sustainable way it should be in mind that the groundwater and surface water interaction should be understood well.

It should also be noted that this treat is the result of a combination of processes considered in this investigation and other processes related with Lake Ecosystem (truncation of river valleys, changing direction of flow).

7 Conclusion

Most of the surface water and groundwater interaction in the wetlands of Lake Tana basin is explained by evapotranspiration although there are other processes such as deep circulation associated with silicic dykes.

According to the evapotranspiration evolution model, rainfall percolates down in to the groundwater and this water is removed by evapotranspiration leaving dissolved solutes. This process has lead to pocket ground water salinity in shallow groundwater of the Lake Tana Wet lands.

This salinity zone doesn't have a predictable pattern. It is found distributed irregularly in the wetlands. It was encountered in hand dug wells having a depth range of 1 to 4.5m (figure 14). These hand dug wells are spread from Seraba & Dablo in the west to Robit area to the east at lower Megech sub-catchment.

Similar condition was encountered from the second phase of sampling in the Rib river catchment starting from Nabega in the North to Wagetera to the south.

The other process that can explain the groundwater-surface water interaction is the salinity associated with deep circulation (figure 21). In the Lake Tana basin, close to the flank of the highlands silicic dikes are very common and are observed in association with Tarmaber basalt. These dykes initiate saline spring waters related to deep circulation process. This sample was encountered at Seraba Mriam (east of Amed ber town). However, such waters are distributed allover the basin as saline springs. Carbon 13 ($\delta^{13}C$) evidences have also shown that its salinity is of carbonate origin (Kebede et al, 2005).

Moreover, it is also confirmed that evaporation is not the process that changes the fresh water in to saline waters in this basin. The successive evaporation-dissolution model in combination with the isotopic evidence has revealed that the salinity of the groundwater should have become distributed allover the flooded area and also enriched isotopically if it had evaporation origin. On the contrary, the salinity is not uniform but occurs as pockets and most of the samples are depleted.

In general, the investigation has shown how the surface water-groundwater interaction goes on by using isotopic and geochemical methods. Consequently, this investigation has revealed that recharge to deep groundwater system occurs mostly on the highlands by rainfall.

It has also been noted that Megech river and Angereb dam have some contribution of recharge to shallow and deep aquifer systems. Shallow wells on the flat Dembia and Fogera plain are recharged by rainfall with limited recharge from the rivers as witnessed at around Robit. However, groundwater from the highlands was not observed to emerge on the plains as evidenced by the isotopic and geochemical information.

Thus, the risk of this salinity could be low since it is not deeper and widespread all over the basin. However, it is recommended that identifying these areas with a comprehensive groundwater investigation is a priority to implementing large schemes such as irrigated agricultural development in the flat wetlands. This can be done by implementing a micro geo-morphological investigation in combination with diurnal water quality monitoring. This is because geo-morphological changes can give rise to wetlands and in turn wetlands can give rise to evapotranspiration that creates high salinity.

Secondly, this wetland ecosystem is very sensitive as it harbours multiple biodiversity. Rising salinity due to the natural cause and artificial human intervention (Such as irrigation) could enhance salinisation leading to the high salinity and thus ecological imbalance. Therefore, it is also recommended that water resources development should be planned with precaution before implementation not to disrupt the ecological harmony.

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9 Annex -Tables

Table 4-Data for box & whisker chart

lake Tana	lake Zengena	rivers around lake tana	spring around lake tana	Hand dug well around lake tana	deep wells around lake tana
4.9	4.9	2.40	-3.83	-2.64	0.32
4.9	-1.9	-0.10	-2.96	-1.40	-0.53
4.9	5.7	-1.78	-2.50	-2.06	-2.32
4.9	-1.5		-2.35	-2.35	-2.76
4.42	3.68		-1.81	0.18	0.21
			-2.64	-1.86	-0.18
			-1.88	-1.03	-0.22
				-0.94	-2.15
				-0.74	-2.29
				-0.70	-2.85
				-2.37	-5.56
				-1.00	-4.44
				-0.97	4.55
				-0.28	-1.44
				0.14	-1.41
				-1.07	-0.70
				3.07	-4.54
				-2.47	-2.69
				-0.71	-1.79
				-1.13	-6.81
				0.67	
				-0.82	
				1.82	

Table 5 Chang of salinity with depth

Locality	SWL(m)	EC(µS/cm)	Ca	Mg	K	Na	Cl	SO4	HCO3	PO4	NO3
NabegaGirarge	2.3	7050	340	280	1.1	1120	3042	90	511		0.53
Addisgie dingie	2.4	6600	230	320	0.4	870	1872	779	767		0.58
Shaga	2.5	2380	230	112	3.2	310	1071	204	217		1.3
Wagetra	2.8	7830	760	260	3.3	500	2871	144	403		0.69
Addisgie dingie	3.6	7500	680	400	2	680	1489	2297	800		6.2
Kurtit	4.44	1590	137.09	74.45	2.03	32.8	134.95	325.17	281.57	3.48	7.19
HodGebeya	5.4	670	64.41	22.99	1.96	80.6	14.99	7.54	533.31	74.71	14.26
Mehal Weynit	6	2800	301.5	216.84	4.26	150.51	994.68	220.27	667.42	182.34	7.13
Guramba	9.5	550	50.4	35.97	1.6	32	11.98	11.24	417.51	15.51	2.42

Table 6-Isotope data

Sample Name	$\delta^{18}O$ Reportable Value (permil)	$\delta^{2}H$ Reportable Value (permil)
Gan 1	3.68	38.97
Gan 2	-3.83	-0.52
Gan 3	-2.96	5.11
Gan 4	-2.50	1.60
Gan 5	-4.54	-9.06
Gan 6	-0.50	13.22
Gan 7	-2.69	2.48
Gan 8	-2.09	7.09
Gan 9	4.42	38.85
Gan 10	-1.79	-0.30
Gan 11	-2.35	-1.34
Gan 12	-1.81	3.98
Gan 13	-2.64	1.59
Gan 14	-1.78	9.25
Gan 15	8.22	62.44
Gan 16	-6.81	-27.27
Gan 17	-0.10	18.57
Gan 18	-1.40	5.32
Gan 19	-2.06	0.99
Gan 20	-2.35	-1.43
Gan 21	-2.64	-0.58
Gan 22	0.18	15.77
Gan 23	-2.15	3.16
Gan 24	-2.29	3.32
Gan 25	-1.86	5.83
Gan 26	-2.85	-5.69
Gan 27	-5.56	-25.74
Gan 28	-4.44	-16.09
Gan 29	-7.39	-28.31
Gan 30	-1.03	7.39
Gan 31	-0.94	7.06
Gan 32	-0.74	7.39
Gan 33	4.55	15.22
Gan 34	-1.44	5.27
Gan 35	-1.41	3.10
Gan 36	-0.70	8.79
Gan 37	-2.37	-2.39
Gan 38	-1.00	5.96
Gan 39	-2.76	-6.59
Gan 40	-1.88	1.58
Gan 41	-0.97	5.01
Gan 42	-0.28	10.34
Gan 43	-0.41	10.10
Gan 44	0.21	13.35

Sample Name	δ ^{18}O Reportable Value (permil)	δ ^{2}H Reportable Value (permil)
Gan 45	-0.18	10.34
Gan 46	-0.22	12.53
Gan 47	0.32	13.63
Gan 48	0.14	12.93
Gan 49	-1.07	6.15
Gan 50	3.07	21.28
Gan 51	-2.47	-9.21
Gan 52	-0.71	5.30
Gan 53	-1.13	3.76
Gan 54	0.67	8.39
Gan 55	-0.82	6.01
Gan 56	-0.53	6.73
Gan 57	-2.32	-5.75
Gan 58	2.40	28.60
Gan 59	1.82	24.57

Table 7-Average Rainfall isotope data from GNIP (1961-2005)

Sample Name	δ ^{18}O Reportable Value (permil)	δ ^{2}H Reportable Value (permil)
February	0.86	15.40
March	0.93	18.11
April	0.96	20.05
May	0.17	13.71
June	1.23	22.94
July	-1.99	-2.28
August	-3.19	-11.67
September	-0.36	12.46
October	-0.20	8.10
November	-0.78	-0.96
December	-1.32	2.00

Table 8-Geochemical data combined Data used for Hierarchical analysis (previous data and new)

X	Y	ID	common ID	PH	CON	TDS	TEMP	NA	K	CA	MG	CL	SO4	HCO3
366967	1340389	BH10	GAN 1	7.00	328.00	143.9	22.4	21.38	5.87	37.68	16.17	6.38	6.72	262.36
332813	1285772	BH11	GAN 2	6.00	235.30	104.1	23.1	14.71	5.08	28.26	11.55	18.79	5.76	188.53
332748	1285660	BH12	GAN 3	5.50	374.10	163.6	21.0	24.60	6.26	42.28	18.48	0.00	7.20	262.36
332768	1285624	BH13	GAN 4	6.00	160.00	71.8	20.0	9.20	4.30	20.64	7.78	2.13	5.28	128.13
332056	1290966	BH14	GAN 5	5.50	152.60	68.7	21.5	8.74	4.30	19.84	7.42	1.77	4.80	122.03
336913	1296333	BH15	GAN 6	5.50	107.60	49.3	20.6	5.52	3.91	15.23	5.11	1.77	4.32	86.03
336956	1296387	BH16	GAN 7	5.50	152.10	68.5	26.0	8.74	4.30	19.84	7.29	1.77	4.80	122.03
342181	1301260	BH17	GAN 8	7.00	82.00	38.4	23.1	3.68	3.52	12.63	3.89	1.42	4.32	65.89
342186	1301202	BH18	GAN 9	6.00	123.40	56.1	26.7	6.67	3.91	16.83	5.96	1.77	4.80	98.84
342186	1301202	BH19	GAN 10	5.50	79.70	37.4	22.7	3.45	3.52	12.42	3.77	1.42	4.32	64.06
342186	1301202	BH20	GAN 11	5.50	82.50	38.6	22.9	3.68	3.52	12.83	3.89	1.42	4.32	65.89
342186	1301202	BH21	GAN 12	5.50	77.40	36.4	25.8	3.22	3.52	12.22	3.65	1.42	4.32	61.62
342086	1301185	BH22	GAN 13	5.50	121.50	55.3	25.3	6.44	3.91	16.63	5.84	1.77	4.80	97.01
366219	1339280	BH28	GAN 14	6.00	287.70	126.6	24.7	18.39	5.48	33.67	14.10	2.84	6.24	230.02
367020	1340527	BH29	GAN 15	5.50	206.50	91.8	22.4	12.64	4.69	25.25	10.09	2.13	5.76	165.34
328759	1387917	BH50	GAN 16	5.50	141.00	58.0	20.3	2.07	3.52	10.62	2.80	1.42	3.84	48.81
331196	1380074	BH51	GAN 17	5.50	155.90	78.0	19.3	7.82	4.30	18.64	6.81	1.77	4.80	112.87
330033	1384286	BH52	GAN 18	6.50	369.80	150.0	24.0	5.75	3.91	16.63	6.56	1.77	4.80	124.47
328517	1384497	BH53	GAN 19	8.00	295.00	121.0	23.9	24.37	5.87	41.88	18.23	3.19	7.20	295.91
317960	1374260	BH54	GAN 20	5.50	114.30	47.5	20.5	18.85	5.48	34.27	14.47	4.25	6.24	236.12
315015	1371379	BH55	GAN 21	6.00	167.90	67.0	23.1	5.98	3.91	16.03	5.47	1.77	4.80	91.52
312777	1368477	BH56	GAN 22	6.00	267.00	110.0	26.8	9.89	4.30	21.44	8.14	2.13	5.28	134.23
308527	1366191	BH58	GAN 23	6.50	505.00	201.0	25.4	42.53	8.21	67.74	31.00	4.61	10.09	500.31
324480	1283559	BH65	GAN 24	6.00	150.00	72.0	24.4	33.33	7.04	54.71	24.56	3.90	8.65	397.80
324900	1285160	BH66	GAN 25	6.00	146.00	71.0	25.4	5.75	2.74	13.43	4.13	1.77	4.80	120.20
324547	1286034	BH67	GAN 26	6.00	144.00	71.0	25.3	8.28	4.30	19.24	7.05	1.77	4.80	116.53
324179	1286705	BH68	GAN 27	6.00	143.00	70.0	25.7	9.20	5.48	32.46	7.54	2.13	4.80	115.31

X	Y	ID	common ID	PH	CON	TDS	TEMP	NA	K	CA	MG	CL	SO4	HCO3
322239	1290167	BH69	GAN 28	7.00	143.00	70.0	25.8	8.05	4.30	18.84	6.93	1.77	4.80	114.70
321596	1291257	BH70	GAN 29	5.50	144.20	70.0	26.9	8.05	4.30	18.84	6.93	1.77	4.80	114.70
320791	1291708	BH71	GAN 30	6.00	145.30	71.0	28.0	8.05	4.30	19.04	6.93	1.77	4.80	115.31
320906	1289952	BH72	GAN 31	5.50	143.90	71.0	27.0	8.28	4.30	19.04	7.05	1.77	4.80	116.53
321667	1288189	BH73	GAN 32	7.50	142.00	70.0	23.5	8.05	4.30	19.04	6.93	1.77	4.80	115.31
323455	1286465	BH75	GAN 33	6.50	142.00	69.9	25.0	8.28	4.30	19.24	7.05	1.77	4.80	116.53
321933	1287573	BH76	GAN 34	6.00	143.60	70.0	24.4	8.05	4.30	18.84	6.81	1.77	4.80	113.48
324901	1284098	BH77	GAN 35	6.00	146.70	72.0	24.5	8.05	4.30	19.04	6.93	1.77	4.80	114.70
351500	1350000	CS5	GAN 36	7.20	201.92	141.0		9.00	1.50	21.40	1.50	2.30	1.40	103.00
392680	1311750	DW3	GAN 37	7.00	284.59	199.0		18.00	4.50	20.00	7.80	4.00	0.10	143.00
334563	1387900	DW4	GAN 38	8.20	440.94	309.0		40.80	5.00	25.70	5.00	11.30	23.10	195.00
334470	1382400	DW5	GAN 39	8.20	608.97	426.0		110.00	0.70	4.80	1.00	14.00	0.10	293.00
334400	1386300	DW6	GAN 40	8.20	496.87	348.0		43.00	0.70	32.00	10.00	14.00	0.10	244.00
329990	1387000	DW7	GAN 41	8.20	659.91	462.0		120.00	1.20	5.50	1.00	14.00	0.10	317.00
329980	1388000	DW8	GAN 42	8.60	527.41	369.0		78.20	1.30	12.80	8.80	10.60	0.10	244.00
325285	1378388	MCS1	GAN 43	7.70	434.00	200.0		11.31	0.51	55.09	15.99	11.49	12.10	210.31
323991	1358237	MDW6	GAN 44	7.70	2320.00	820.0		32.80	2.03	137.09	74.45	134.95	325.17	281.57
316486	1361878	MDW9	GAN 45	7.60	4190.00	2940.0		150.51	4.26	301.50	216.84	994.68	220.27	667.42
346127	1315692	WDW10	GAN 46	7.90	860.00	420.0		80.60	1.96	64.41	22.99	14.99	7.54	533.31
388848	1332071	WRV1	GAN 47	8.20	301.00	120.0		12.30	3.75	37.09	4.80	10.00	20.85	130.99
343297	1316527	Wagetra	GAN 48		7830.00			500.00	3.30	760.00	260.00	2871.00	144.00	403.00
352287	1322914	Shaga	GAN 49		2380.00			310.00	3.20	230.00	112.00	1071.00	204.00	217.00
349457	1324778	NabegaGi	GAN 50		7050.00			1120.00	1.10	340.00	280.00	3042.00	90.00	511.00
346127	1315692	HodGebey	GAN 51	6.60	670.00	420.0		80.60	1.96	64.41	22.99	14.99	7.54	533.31
388848	1332071	Rib Rive	GAN 52	7.80	260.00	120.0		12.30	3.75	37.09	4.80	10.00	20.85	130.99
341996	1301294	Hamusit well	GAN 53	7.53	123	77	24.3	6.1	0.4	15.2	4.6	1.9	0.381	74.18
351217	1308882	Gumara river bridge	GAN 54	8.03	134	85.6	23.5	6.5	1.7	15.2	6.9	1.9	10.18	76.5

X	Y	ID	common ID	PH	CON	TDS	TEMP	NA	K	CA	MG	CL	SO4	HCO3
350776	1312078	Angorbit flood water	GAN 55	8.63	138	86	23.1	5.8	2.9	16.72	5.98	2.85	2.67	78.81
326297	1283157	Lake Tana	GAN 56	8.15	186	151	23.6	5.9	2	22.8	6.9	5.7	3.99	99.67
359583	1325967	Rib river bridge	GAN 57	7.95	217	195	23.5	10.4	2.7	28.88	8.28	5.7	5.71	127.49
320519	1280556	Gudo Bahr well	GAN 58	7.92	231	144	24.5	8.9	2.4	30.4	6.9	1.9	0.95	129.81
296613	1370446	Komimi river bridge(chandiba road)	GAN 59	7.01	245	259	25.7	10.4	2.3	32.68	11.5	5.7	0.47	148.35
407026	1304114	Gassay well	GAN 60	8.43	247	154	14.6	23	8.8	22.04	7.36	6.65	0.28	139.08
329878	1389685	st.Rufael Blind school	GAN 61	6.71	251	157.4	20.3	9.9	1.4	31.92	8.28	9.5	11.23	139.08
350471	1354457	Hand dug well (enfranz entrance)	GAN 62	7.78	261	168.2	23.8	19	0.7	34.2	5.98	4.75	0.381	162.26
350294	1292522	Momoshta well	GAN 63	7.78	269	151	24.1	17	0.8	29.64	9.66	0.95	2.8	169.2
389770	1311620	Debretabor well-11	GAN 64	6.83	284	173	20.6	29.5	1.5	34.2	5.98	2.85	0.11	176.17
348924	1361256	Ferenge wuha foutain	GAN 65	7.49	298	136.6	22.9	8.9	1.7	42.56	11.04	3.8	0.666	176.17
367342	1318729	Awramba hdw	GAN 66	8.15	318	191	25.3	8.3	1.8	49.4	5.06	7.6	1.71	185.44
350766	1312020	Angorbit hand dug well	GAN 67	9.04	330	202	25	23.5	1.3	36.48	10.12	11.4	41.89	155.31
327039	1284101	Chara chara well	GAN 68	7.95	342	197.2	26.7	12.5	1.4	45.6	16.1	1.9	1.43	215.57
356959	1316287	Tinish Minch spring	GAN 69	7.18	350	157	23.8	8.6	2.4	59.28	1.84	23.75	0.381	187.76
331192	1380758	megech river	GAN 70	7.07	368	226	23.3	11.9	2.3	45.6	16.1	10.45	5.71	208.62
393601	1311601	Debretabor(sebara dildy)	GAN 71	7.57	372	240	22.1	80	5.2	8.36	6.44	3.8	0.28	243.39
383954	1317915	hand dug well	GAN 72	7.84	397	251	23	18.5	1.1	60.8	6.9	10.45	0.19	174.22
367760	1344101	Alabo well	GAN 73	8.1	427	256	27.5	47	0.7	38	11.96	5.7	0.12	271.21
348183	1347233	Sarwuha borehole	GAN 74	7.24	513	314	24.1	34	2.2	64.6	22.54	5.7	0.286	354.65
359622	1334420	Yifag dikule deep well	GAN 75	7.84	515	310	25.6	101	0.7	25.84	3.68	10.45	0.48	324.52
312512	1354841	Gorgora well	GAN 76	7.82	533	330	25.6	72	7.3	53.2	6.9	8.55	0.76	331.5
359236	1319518	Woreta w-3 borehole	GAN 77	7.32	536	328	24.2	84	13.4	30.4	11.96	13.3	3.14	336.11
300350	1367758	Guarhe hand dug well	GAN 78	7.29	560	542	22.5	32	0.5	102.6	4.6	7.6	5.99	361.61
359731	1321238	Fogera pain(Twaza kana,r	GAN 79	7.71	562	315	24.6	36	6.4	82.08	12.42	20.9	0.85	312.93

X	Y	ID	common ID	PH	CON	TDS	TEMP	NA	K	CA	MG	CL	SO4	HCO3
378137	1316917	Amed ber hand dug well	GAN 80	7.29	568	358	24	10.8	0.9	64.6	29.6	39.6	0.12	301.34
350880	1308449	Sarmender Hand dug well	GAN 81	7.12	598	369	23.3	44	1.4	73.72	17.48	7.6	1.24	401.01
373010	1340011	ch. health center hand dug well	GAN 82	7.07	621	368	24.1	13.5	0.8	83.6	25.76	10.45	0.76	394.16
364497	1336280	Angote mariam well	GAN 83	7.07	655	388	27.4	31	1	79.8	27.8	11.4	0.19	417.24
307347	1364172	chalguaye well	GAN 84	6.91	662	397	24.1	27	1.5	125.4	6.9	10.45	0.286	394.06
343168	1370231	close to Gumaro river	GAN 85	7.01	680	493	23.5	30	1	85.88	26.22	10.45	0.38	452.37
362803	1334122	Bura hand dug well	GAN 86	6.91	708	419	25.5	29	1.1	108.68	16.1	15.2	0.19	452.01
334541	1392929	TW-7 well	GAN 87	7.4	722	432	20.1	104	2	44.08	12.42	38.95	19.23	347.7
362783	1334971	hand dug well(rope pump)	GAN 88	7.78	757	446	24.1	27	0.3	138.32	8.28	8.55	22.85	516.91
319025	1371679	Wonfela artesian well	GAN 89	6.92	793	489	23	31	0.6	108.68	28.98	19.95	0.11	458.35
339243	1371808	B.G. hand dug well	GAN 90	7.22	833	493	25.3	23	2.4	104.28	25.76	68.4	49.41	238.75
349594	1355006	Mina well	GAN 91	7.33	840	469	21.4	176	1.1	33.44	5.98	10.45	1.9	549.37
324264	1359992	Adisgei jara hand dug well	GAN 92	7.28	849	512	24.6	138	0.8	45.6	18.4	37.05	46.65	470.55
333851	1391781	TW-3 artesian well	GAN 93	7.24	859	506	20.8	93	2.1	76	12.42	53.2	23.61	306.09
359150	1326302	ShinaTsion Kebele hdw	GAN 94	7.79	956	553	25.3	44	1.6	97.3	52.44	13.3	1.43	649.04
324445	1363002	Robit Hand dug well	GAN 95	6.88	990	587	24.5	94	0.2	98.8	28.52	16.15	61.49	574.86
323085	1364310	Arabia diba hand dug well	GAN 96	6.8	1032	606	24.6	126	0.5	98.8	19.78	8.55	0.381	679.17
319520	1367241	Guramba hand dug	GAN 97	6.71	1094	649	24.1	48	4	123.12	56.58	29.45	32.65	718.58
320946	1360264	Achera Mariam hand dug well	GAN 98	7.18	1230	718	24.6	240	0.6	38	19.78	12.35	0.95	761.52
318351	1368918	Tach chanqua hdw	GAN 99	6.95	1440	822	23.5	218	0.5	82.08	34.96	55.1	184.69	637.45
318681	1360964	Seraba & Dablo hand dug well	GAN 100	6.41	2210	1224	24.2	390	2.1	144.4	39.1	59.85	14.08	1390.8
324574	1362610	Robit village school hand dug well	GAN 101	6.45	2490	1398	25.3	220	1.6	211.28	90.62	319.2	220.6	927.2
382080	1317523	Seraba Mariam T	GAN 102	6.41	13460	6410	20.3	3750	96	104.88	3.22	1007	675.92	6954

Table 9-Central objects of hierarchical objects

Class	PH	CON	NA	K	CA	MG	CL	SO4	HCO3
1 (GAN 81)	7.120	-0.109	-0.133	-0.267	0.144	-0.095	-0.213	-0.304	0.087
2 (GAN 15)	5.500	-0.339	-0.214	0.081	-0.397	-0.263	-0.226	-0.250	-0.252
3 (GAN 57)	7.950	-0.333	-0.219	-0.129	-0.356	-0.304	-0.218	-0.251	-0.307
4 (GAN 101)	6.450	1.003	0.320	-0.246	1.677	1.565	0.492	2.316	0.844
5 (GAN 48)	7.001	4.140	1.040	-0.066	7.794	5.411	6.265	1.401	0.090
6 (GAN 102)	6.410	7.448	9.401	9.731	0.491	-0.419	2.048	7.757	9.511

Table 10-water type classification

comon id	SOURCE OF SAMPLE	Water Type	El. Conductivity	Temperature	Total Dissolved Solids	Na	K	Ca	Mg	NH4	F	Cl	HCO3	CO3	NO3	SO4
Gan 1	Lake	Mg-Ca-HCO3	46		28	1.2	1.1	4.56	3.22	0.06	0.22	3.8	23.18	0	2.22	1.52
Gan 2	River	Ca-Mg-HCO3-NO3-SO4	74	22.1	42.2	2.7	1.2	9.12	5.52	1.57	0.27	2.85	30.13	0	22	10.8
Gan 3	Spring	Ca-Mg-HCO3	97	22.7	63.2	3.8	0.5	13.68	4.6	0.102	0.33	3.8	57.95	0	5.4	1.04
Gan 4	BH	Ca-Mg-HCO3	123	24.3	77	6.1	0.4	15.2	4.6	0.075	0.63	1.9	74.18	0	14.3	0.381
Gan 5	River	Ca-Mg-HCO3	134	23.5	85.6	6.5	1.7	15.2	6.9	0.85	0.77	1.9	76.5	0	10.2	10.18
Gan 6	Flood	Ca-Mg-HCO3	138	23.1	86	5.8	2.9	16.72	5.98	0.26	0.45	2.85	78.81	0	11.09	2.67
Gan 7	Spring	Ca-Mg-HCO3	164	21.7	71	3	0.7	22.8	6.9	0.102	0.63	0.95	92.72	0	22.2	1.62
Gan 8	Spring	Mg-HCO3	164	17.4	100	7.8	2.7	7.6	15.8	0.102	0.46	5.7	92.72	0	23.3	1.43
Gan 9	Lake	Ca-Mg-HCO3	186	23.6	151	5.9	2	22.8	6.9	0.323	0.3	5.7	99.67	0	16.2	3.99
Gan 10	Spring	Ca-Mg-HCO3	190	18.3	88.3	6.1	1.4	24.3	6.9	0.182	0.19	1.9	104.31	0	16.48	1.71
Gan 11	River	Ca-Mg-HCO3	217	23.5	195	10.4	2.7	28.88	8.28	0.275	0.33	5.7	127.49	0	6.98	5.71
Gan 12	Spring	Ca-Mg-HCO3	208	20.5	132.8	5.4	1.6	24.32	10.12	0.084	0.41	3.8	127.49	0	20.1	0.95
Gan 13	BH	Ca-Mg-HCO3	231	24.5	144	8.9	2.4	30.4	6.9	0.08	0.19	1.9	129.81	0	35.6	0.95
Gan 14	BH	Ca-Na-Mg-HCO3	247	14.6	154	23	8.8	22.04	7.36	0.084	0.36	6.65	139.08	0	13.56	0.28
Gan 15	BH	Ca-Mg-HCO3	251	20.3	157.4	9.9	1.4	31.92	8.28	0.168	0.21	9.5	139.08	0	10.39	11.23

comon id	SOURCE OF SAMPLE	Water Type	El. Conductivity	Temperature	Total Dissolved Solids	Na	K	Ca	Mg	NH4	F	Cl	HCO3	CO3	NO3	SO4
Gan 16	River	Ca-Mg-HCO3	245	25.7	259	10.4	2.3	32.68	11.5	0.602	0.47	5.7	148.35	0	14.15	0.47
Gan 17	HDW	Ca-Na-Mg-HCO3-SO4	330	25	202	23.5	1.3	36.48	10.12	0.151	0.26	11.4	155.31	0	1.48	41.89
Gan 18	HDW	Ca-Na-HCO3	261	23.8	168.2	19	0.7	34.2	5.98	0.128	0.44	4.75	162.26	0	18.2	0.381
Gan 19	BH	Ca-Mg-HCO3	361	20.6	218	7.4	1.6	49.4	11.5	0.089	0.39	15.2	162.26	0	21.4	1.14
Gan 20	BH	Ca-Mg-Na-HCO3	269	24.1	151	17	0.8	29.64	9.66	0.133	0.27	0.95	169.2	0	0.7	2.8
Gan 21	HDW	Ca-HCO3	397	23	251	18.5	1.1	60.8	6.9	0.119	0.53	10.45	174.22	19.2	38.7	0.19
Gan 22	BH	Ca-Na-HCO3	284	20.6	173	29.5	1.5	34.2	5.98	0.119	0.43	2.85	176.17	0	21.88	0.11
Gan 23	Spring	Ca-Mg-HCO3	298	22.9	136.6	8.9	1.7	42.56	11.04	0.182	0.26	3.8	176.17	0	16.7	0.666
Gan 24	HDW	Ca-HCO3	318	25.3	191	8.3	1.8	49.4	5.06	0.093	0.55	7.6	185.44	0	18.86	1.71
Gan 25	Spring	Ca-HCO3	350	23.8	157	8.6	2.4	59.28	1.84	0.1	0.19	23.75	187.76	0	2.18	0.381
Gan 26	BH	Na-HCO3	318	24.3	203	72	0.9	3.8	9.2	0.044	0.62	5.7	206.3	0	9.7	1.43
Gan 27	River	Ca-Mg-HCO3	368	23.3	226	11.9	2.3	45.6	16.1	0.27	0.32	10.45	208.62	0	25.2	5.71
Gan 28	BH	Ca-Mg-HCO3	342	26.7	197.2	12.5	1.4	45.6	16.1	0.101	0.46	1.9	215.57	0	50.6	1.43
Gan 29	HDW	Ca-Mg-HCO3-Cl	833	25.3	493	23	2.4	104.28	25.76	0.221	0.51	68.4	238.75	0	128.6	49.41
Gan 30	BH	Na-HCO3	372	22.1	240	80	5.2	8.36	6.44	0.137	0.27	3.8	243.39	0	0.8	0.28
Gan 31	BH	Na-Ca-Mg-HCO3	427	27.5	256	47	0.7	38	11.96	0.112	0.33	5.7	271.21	0	8.71	0.12
Gan 32	HDW	Ca-Mg-HCO3	568	24	358	10.8	0.9	64.6	29.6	0.23	0.7	39.6	301.34	0	28.6	0.12
Gan 33	BH	Na-Ca-HCO3	859	20.8	506	93	2.1	76	12.42	0.29	0.63	53.2	306.09	21.6	82.6	23.61
Gan 34	HDW	Ca-Na-HCO3	562	24.6	315	36	6.4	82.08	12.42	0.195	0.61	20.9	312.93	0	36.6	0.85
Gan 35	BH	Na-Ca-HCO3	515	25.6	310	101	0.7	25.84	3.68	0.106	0.3	10.45	324.52	0	5.98	0.48
Gan 36	BH	Na-Ca-HCO3	533	25.6	330	72	7.3	53.2	6.9	0.244	0.87	8.55	331.5	0	15.3	0.76

comon id	SOURCE OF SAMPLE	Water Type	El. Conductivity	Temperature	Total Dissolved Solids	Na	K	Ca	Mg	NH4	F	Cl	HCO3	CO3	NO3	SO4
Gan 37	BH	Na-Ca-HCO3	536	24.2	328	84	13.4	30.4	11.96	0.093	0.39	13.3	336.11	0	1.8	3.14
Gan 38	BH	Na-Ca-HCO3	722	20.1	432	104	2	44.08	12.42	0.195	0.32	38.95	347.7	0	81.62	19.23
Gan 39	BH	Ca-Mg-Na-HCO3	513	24.1	314	34	2.2	64.6	22.54	0.159	0.58	5.7	354.65	0	1.7	0.286
Gan 40	HDW	Ca-Na-HCO3	560	22.5	542	32	0.5	102.6	4.6	0.363	0.68	7.6	361.61	0	15.39	5.99
Gan 41	BH	Ca-HCO3	662	24.1	397	27	1.5	125.4	6.9	0.312	0.32	10.45	394.06	0	50.9	0.286
Gan 42	HDW	Ca-Mg-HCO3	621	24.1	368	13.5	0.8	83.6	25.76	0.204	0.32	10.45	394.16	0	21.2	0.76
Gan 43	HDW	Ca-Na-Mg-HCO3	598	23.3	369	44	1.4	73.72	17.48	0.217	0.63	7.6	401.01	0	10.19	1.24
Gan 44	HDW	Ca-Mg-HCO3	655	27.4	388	31	1	79.8	27.8	0.208	0.18	11.4	417.24	0	14.3	0.19
Gan 45	HDW	Ca-HCO3	708	25.5	419	29	1.1	108.68	16.1	0.275	0.45	15.2	452.01	0	20.15	0.19
Gan 46	BH	Ca-Mg-HCO3	680	23.5	493	30	1	85.88	26.22	0.381	0.18	10.45	452.37	0	6.6	0.38
Gan 47	BH	Ca-Mg-HCO3	793	23	489	31	0.6	108.68	28.98	0.39	0.59	19.95	458.35	28.8	24.3	0.11
Gan 48	HDW	Na-Ca-HCO3	849	24.6	512	138	0.8	45.6	18.4	0.69	0.32	37.05	470.55	0	3.81	46.65
Gan 49	HDW	Ca-HCO3	757	24.1	446	27	0.3	138.32	8.28	0.766	0.48	8.55	516.91	0	2.1	22.85
Gan 50	BH	Na-HCO3	840	21.4	469	176	1.1	33.44	5.98	0.137	0.71	10.45	549.37	0	1.58	1.9
Gan 51	HDW	Ca-Na-Mg-HCO3	990	24.5	587	94	0.2	98.8	28.52	0.49	0.71	16.15	574.86	0	10.24	61.49
Gan 52	HDW	Na-Ca-HCO3-SO4	1440	23.5	822	218	0.5	82.08	34.96	1.24	0.3	55.1	637.45	0	2.7	184.69
Gan 53	HDW	Ca-Mg-HCO3	956	25.3	553	44	1.6	97.3	52.44	1.32	0.41	13.3	649.04	0	24.35	1.43
Gan 54	HDW	Na-Ca-HCO3	1032	24.6	606	126	0.5	98.8	19.78	0.56	0.46	8.55	679.17	0	5.74	0.381
Gan 55	HDW	Ca-Mg-HCO3	1094	24.1	649	48	4	123.12	56.58	2.1	0.6	29.45	718.58	0	5.5	32.65
Gan 56	HDW	Na-HCO3	1230	24.6	718	240	0.6	38	19.78	0.64	0.27	12.35	761.52	33.6	1.9	0.95
Gan 57	HDW	Ca-Na-Mg-HCO3-Cl	2490	25.3	1398	220	1.6	211.28	90.62	4.95	0.58	319.2	927.2	0	64.79	220.6
Gan 58	HDW	Na-Ca-HCO3	2210	24.2	1224	390	2.1	144.4	39.1	1.43	0.27	59.85	1390.8	0	6.38	14.08
Gan 59	holy Spring	Na-HCO3	13460	20.3	6410	3750	96	104.88	3.22	0.23	3.75	1007	6954	0	0.69	675.92

Table 11-First phase Geochemical data error checking calculation

Lat	Long	Elevation (m)	Ca(meq/l)	Mg (meq/l)	Na (meq/L)	K (meq/L)	HCO3 (meq/l)	CO3 (meq/l)	Cl (meq/l)	So4 (meq/l)	PO4 (meq/l)	NO3 (meq/l)	NO2 (meq/l)	F (meq/l)	cations	Anions	reaction error	Reaction error(%)
327039	1284101	1792	2.24	1.32	0.54	0.04	3.53	0.00	0.05	0.03	0.00	0.82	0.00	0.02	4.14	4.46	-0.04	-3.73
326297	1283157	1790	1.12	0.57	0.26	0.05	1.63	0.00	0.16	0.08	0.00	0.26	0.00	0.02	1.99	2.16	-0.04	-3.95
320519	1280556	1802	1.49	0.57	0.39	0.06	2.13	0.00	0.05	0.02	0.01	0.57	0.00	0.01	2.51	2.79	-0.05	-5.39
350880	1308449	1795	3.61	1.44	1.91	0.04	6.57	0.00	0.21	0.03	0.01	0.16	0.00	0.03	7.00	7.02	0.00	-0.14
351217	1308882	1792	0.75	0.57	0.28	0.04	1.25	0.00	0.05	0.21	0.01	0.16	0.00	0.04	1.64	1.73	-0.03	-2.71
350776	1312078	1787	0.82	0.49	0.25	0.07	1.29	0.00	0.08	0.06	0.00	0.18	0.00	0.02	1.64	1.63	0.00	0.17
359236	1319518	1745	1.49	0.98	3.65	0.34	5.51	0.00	0.38	0.07	0.00	0.03	0.00	0.02	6.47	6.00	0.04	3.78
359583	1325967	1791	1.42	0.68	0.45	0.07	2.09	0.00	0.16	0.12	0.01	0.11	0.00	0.02	2.62	2.51	0.02	2.20
359150	1326302	1792	4.77	4.31	1.91	0.04	10.64	0.00	0.38	0.03	0.00	0.39	0.00	0.02	11.04	11.46	-0.02	-1.86
367342	1318729	1889	2.42	0.42	0.36	0.05	3.04	0.00	0.21	0.04	0.00	0.30	0.00	0.03	3.24	3.63	-0.06	-5.56
359731	1321238	1803	4.02	1.02	1.57	0.16	5.13	0.00	0.59	0.02	0.00	0.59	0.00	0.03	6.77	6.36	0.03	3.17
356959	1316287	1805	2.91	0.15	0.37	0.06	3.08	0.00	0.67	0.01	0.00	0.04	0.00	0.01	3.49	3.80	-0.04	-4.22
350766	1312020	1790	1.79	0.83	1.02	0.03	2.55	0.00	0.32	0.87	0.00	0.02	0.00	0.01	3.68	3.78	-0.01	-1.38
341996	1301294	1955	0.75	0.38	0.27	0.01	1.22	0.00	0.05	0.01	0.00	0.23	0.00	0.03	1.40	1.54	-0.05	-4.85
350294	1292522	2066	1.45	0.79	0.74	0.02	2.77	0.00	0.03	0.06	0.00	0.01	0.00	0.01	3.01	2.89	0.02	2.04
378137	1316917	2031	3.17	2.44	0.47	0.02	4.94	0.00	1.12	0.00	0.01	0.46	0.00	0.04	6.09	6.56	-0.04	-3.69
389770	1311620	2603	1.68	0.49	1.28	0.04	2.89	0.00	0.08	0.00	0.01	0.35	0.00	0.02	3.49	3.35	0.02	1.99
407026	1304114		1.08	0.61	1.00	0.23	2.28	0.00	0.19	0.01	0.00	0.22	0.00	0.02	2.91	2.72	0.03	3.49
393601	1311601	2570	0.41	0.53	3.48	0.13	3.99	0.00	0.11	0.01	0.00	0.01	0.00	0.01	4.55	4.13	0.05	4.83
382080	1317523	2075	5.14	0.26	163.11	2.46	113.96	0.00	28.41	14.07	0.00	0.01	0.00	0.20	170.98	156.65	0.04	4.37
383954	1317915		2.98	0.57	0.80	0.03	2.86	0.16	0.29	0.00	0.00	0.62	0.00	0.03	4.38	3.97	0.05	4.92
362803	1334122	1827	5.33	1.32	1.26	0.03	7.41	0.00	0.43	0.00	0.01	0.32	0.00	0.02	7.94	8.20	-0.02	-1.58
362783	1334971	1927	6.78	0.68	1.17	0.01	8.47	0.00	0.24	0.48	0.01	0.03	0.00	0.03	8.64	9.25	-0.03	-3.41
359622	1334420	1819	1.27	0.30	4.39	0.02	5.32	0.00	0.29	0.01	0.00	0.10	0.00	0.01	5.98	5.74	0.02	2.07
367760	1344101	1959	1.86	0.98	2.04	0.02	4.44	0.00	0.16	0.00	0.01	0.14	0.00	0.02	4.91	4.77	0.01	1.42
364497	1336280	1849	3.91	2.29	1.35	0.03	6.84	0.00	0.32	0.00	0.00	0.23	0.00	0.01	7.57	7.41	0.01	1.10
373010	1340011	1970	4.10	2.12	0.59	0.02	6.46	0.00	0.29	0.02	0.01	0.34	0.00	0.02	6.83	7.13	-0.02	-2.22
348183	1347233	1797	3.17	1.85	1.48	0.06	5.81	0.00	0.16	0.01	0.01	0.03	0.00	0.03	6.56	6.05	0.04	4.04

Lat	Long	Elevation (m)	Ca(meq/l)	Mg (meq/l)	Na (meq/L)	K (meq/L)	HCO_3 (meq/l)	CO_3 (meq/l)	Cl (meq/l)	So_4 (meq/l)	PO_4 (meq/l)	NO_3 (meq/l)	NO_2 (meq/l)	F (meq/l)	cations	Anions	reaction error	Reaction error (%)
349594	1355006	1898	1.64	0.49	7.66	0.03	9.00	0.00	0.29	0.04	0.00	0.03	0.00	0.04	9.81	9.40	0.02	2.14
348924	1361256	2031	2.09	0.91	0.39	0.04	2.89	0.00	0.11	0.01	0.01	0.27	0.00	0.01	3.43	3.30	0.02	1.87
343168	1370231	1918	4.21	2.16	1.30	0.03	7.41	0.00	0.29	0.01	0.01	0.11	0.00	0.01	7.70	7.84	-0.01	-0.92
339243	1371808	1906	5.11	2.12	1.00	0.06	3.91	0.00	1.93	1.03	0.01	2.07	0.00	0.03	8.29	8.98	-0.04	-3.98
331192	1380758	1863	2.24	1.32	0.52	0.06	3.42	0.00	0.29	0.12	0.01	0.41	0.00	0.02	4.14	4.26	-0.02	-1.52
334541	1392929	2066	2.16	1.02	4.52	0.05	5.70	0.00	1.10	0.40	0.01	1.32	0.00	0.02	7.76	8.54	-0.05	-4.78
333851	1391781	2049	3.73	1.02	4.05	0.05	5.02	0.18	1.50	0.49	0.00	1.33	0.00	0.03	8.85	8.56	0.02	1.66
329878	1389685	2076	1.56	0.68	0.43	0.04	2.28	0.00	0.27	0.23	0.00	0.17	0.00	0.01	2.71	2.96	-0.04	-4.43
319025	1371679	1810	5.33	2.38	1.35	0.02	7.51	0.24	0.56	0.00	0.00	0.39	0.00	0.03	9.08	8.74	0.02	1.86
318351	1368918	1809	4.02	2.88	9.48	0.01	10.45	0.00	1.55	3.85	0.00	0.04	0.00	0.02	16.39	15.91	0.01	1.50
319520	1367241	1809	6.04	4.65	2.09	0.10	11.78	0.00	0.83	0.68	0.01	0.09	0.00	0.03	12.88	13.42	-0.02	-2.05
324264	1359992	1807	2.24	1.51	6.00	0.02	7.71	0.00	1.05	0.97	0.02	0.06	0.00	0.02	9.77	9.82	0.00	-0.25
320946	1360264	1795	1.86	1.63	10.44	0.02	12.48	0.28	0.35	0.02	0.05	0.03	0.00	0.01	13.94	13.22	0.03	2.67
318681	1360964	1793	7.08	3.22	16.96	0.05	22.79	0.00	1.69	0.29	0.09	0.10	0.00	0.01	27.31	24.98	0.04	4.46
324574	1362610	1812	10.36	7.46	9.57	0.04	15.20	0.00	9.00	4.59	0.01	1.04	0.00	0.03	27.42	29.88	-0.04	-4.29
323085	1364310	1804	4.84	1.63	5.48	0.01	11.13	0.00	0.24	0.01	0.01	0.09	0.00	0.02	11.96	11.50	0.02	1.96
307347	1364172	1902	6.15	0.57	1.17	0.04	6.46	0.00	0.29	0.01	0.00	0.82	0.00	0.02	7.93	7.60	0.02	2.12
312512	1354841	1811	2.61	0.57	3.13	0.19	5.43	0.00	0.24	0.02	0.00	0.25	0.00	0.05	6.49	5.99	0.04	4.07
296613	1370446	1862	1.60	0.95	0.45	0.06	2.43	0.00	0.16	0.01	0.01	0.23	0.00	0.02	3.06	2.86	0.03	3.36
300350	1367758	1850	5.03	0.38	1.39	0.01	5.93	0.00	0.21	0.12	0.01	0.25	0.00	0.04	6.81	6.55	0.02	1.93

Table 12-Second phase Geochemical Data error calculation

Lat	Long	Elevation (m)	Ca(meq/l)	Mg (meq/l)	Na (meq/L)	K (meq/L)	HCO3 (meq/l)	Cl (meq/l)	So4 (meq/l)	PO4 (meq/l)	NO3 (meq/l)	NO2 (meq/l)	F (meq/l)	Cations	Anions	reaction error	Reaction error (%)
355074	1316529	1850	5.59	2.27	4.96	0.10	10.92	0.28	0.00	0.01	0.95	0.00	0.02	12.92	12.18	0.03	2.96
351400	13323326	1801	4.71	4.52	7.05	0.05	14.70	0.95	0.03	0.02	0.10	0.00	0.03	16.33	15.83	0.02	1.55
348972	1325966	1799	4.25	0.87	1.61	0.06	5.71	0.67	0.12	0.02	0.13	0.00	0.03	6.78	6.68	0.01	0.81
346884	1323561	1797	5.59	1.48	4.26	0.05	5.71	4.23	0.21	0.03	0.47	0.00	0.02	11.38	10.67	0.03	3.21
347741	1323345	1790	2.12	1.25	0.74	0.03	2.73	1.01	0.02	0.01	0.07	0.00	0.03	4.14	3.87	0.03	3.32
349001	1329778	1792	3.05	0.79	1.78	0.18	4.83	0.31	0.33	0.01	0.04	0.00	0.03	5.81	5.54	0.02	2.33
352636	1323262	1800	5.96	0.95	3.78	0.15	9.91	0.45	0.03	0.00	0.89	0.00	0.02	10.84	11.30	-0.02	-2.10
359603	1325937	1800	3.32	0.23	1.48	0.16	4.45	0.31	0.02	0.00	0.01	0.00	0.02	5.18	4.81	0.04	3.64
359125	1324260	1798	3.35	2.61	3.52	0.03	8.19	0.17	0.76	0.01	0.01	0.00	0.02	9.52	9.16	0.02	1.91
357692	1324819	1801	4.21	2.99	3.48	0.04	9.27	0.45	1.72	0.00	0.01	0.00	0.01	10.72	11.46	-0.03	-3.36
359147	1326298	1798	4.66	5.26	1.78	0.05	11.08	0.28	0.01	0.00	0.02	0.00	0.02	11.75	11.42	0.01	1.44
331370	1381040	1864	2.98	0.76	0.65	0.07	4.20	0.31	0.03	0.00	0.06	0.00	0.03	4.46	4.63	-0.02	-1.83
318344	1368917	1807	1.68	5.68	7.57	0.01	10.37	1.88	3.77	0.00	0.01	0.00	0.03	14.93	16.06	-0.04	-3.63
319520	1367247	1802	3.53	6.50	2.17	0.11	10.70	0.62	0.02	0.00	0.02	0.00	0.02	12.32	11.38	0.04	3.95
320725	1368423	1811	4.99	3.07	2.83	0.02	10.50	0.31	0.19	0.00	0.01	0.00	0.01	10.91	11.02	-0.01	-0.53
316477	1362807	1793	8.94	1.51	5.22	0.03	12.60	2.32	0.03	0.01	0.12	0.00	0.01	15.70	15.10	0.02	1.97
316477	1361381	1793	26.08	4.92	7.83	0.14	8.39	31.37	2.71	0.02	0.78	0.00	0.02	38.96	43.28	-0.05	-5.25
315234	1360004	1795	16.76	1.89	7.39	0.07	14.70	7.00	0.07	0.03	2.49	0.00	0.02	26.12	24.31	0.04	3.58
323109	1363097	1794	7.45	1.89	6.61	0.01	13.86	1.23	0.79	0.01	0.01	0.00	0.01	15.97	15.91	0.00	0.17
324561	1363034	1796	2.70	0.26	0.57	0.09	3.02	0.28	0.03	0.01	0.05	0.00	0.01	3.62	3.39	0.03	3.17
324574	1362600	1799	6.03	7.98	9.35	0.05	10.71	9.38	3.46	0.01	1.38	0.00	0.01	23.41	24.95	-0.03	-3.19
321376	1359608	1792	9.71	9.87	8.70	0.06	14.28	7.28	7.86	0.02	0.04	0.00	0.01	28.33	29.49	-0.02	-2.00
322468	1365098	1795	7.45	3.78	7.92	0.01	3.77	12.89	2.43	0.01	0.01	0.00	0.01	19.16	19.12	0.00	0.11
326431	1283402	1785	1.42	0.08	0.35	0.06	1.68	0.06	0.03	0.00	0.01	0.00	0.02	1.91	1.79	0.03	3.05