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ADDIS ABABA UNIVERSITY

College of Natural and Computational Science

School of Earth Sciences

Identification of Water Supply Sources through Physico-Chemical and Environmental Stable Isotopes Characterization of Tap Waters in Addis Ababa

A Thesis
Submitted to
School of Graduate Studies of Addis Ababa University

In Partial Fulfillment of the Requirements for the Degree of Masters of Science (Hydrogeology)

Abdulhafiz Siraj

Addis Ababa, Ethiopia

June, 2021

IDENTIFICATION OF WATER SUPPLY SOURCES THROUGH PHYSICO-CHEMICAL AND ENVIRONMENTAL STABLE ISOTOPES CHARACTERIZATION OF TAP WATERS IN ADDIS ABABA

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June, 2021

STATEMENT OF THE AUTHOR

By my signature below, I declare and confirm that this thesis is my own work. I have followed all ethical and technical principles of research in the preparation, data collection, data analysis and compilation of this thesis. Any scholarly article that is included in the thesis has been given acknowledgment through reference.

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Abstract

This research evaluates the physical characteristics, and the isotopic signature of tap water and the physicochemical characterization of groundwater and surface water to link water users of Addis Ababa city to their respective water supply sources. As a result of the increase in city water demand caused by increasing populations in recent years, many groundwater water supply points (pocket areas) in the city have been drilled and injected into the previous main water supply pipe lines in various areas, resulting in a complicated and unclear distribution of water supply sources. Isotopic signatures (δD, $\delta^{18}O$) and Electrical Conductivity (EC) of tap water samples collected from ten Addis Ababa sub-cities were used to map the spatial distribution of water supply sources. The isotopic signatures and EC measurements indicated Bole, Gulele, Addis Ketema, and Arada sub-cities heavily rely on the surface. Sub-cities such as Akaki, Nifas Silk Lafto, Lideta, Kirkos, and Yeka, on the other hand, rely heavily on groundwater. Kolfe Keraniyo, Yeka, and Kirkos sub-cities get a measurable amount of water from mixed sources (surface and groundwater). Spatial distribution of water supply sources mapped using stable isotope ratios of hydrogen and oxygen (δ^2H and $\delta^{18}O$) and EC was overlaid on Addis Ababa city population distribution. The overlay map showed up to 1.9M people in the city depend on the surface water and nearly 1M people consume water abstracted from the groundwater sources. A noticeable number of the Addis Ababa city population (~800, 000) get water from both surface and groundwater supply sources. The results implied, about 50% of the Addis Ababa city population depends entirely on the surface water supply sources which are more sensitive to climate and demographic changes compared with the 25% depending on more climate-resilient groundwater supply sources. Given the current Addis Ababa city surface water supply production which only accounts the 40% of the total Addis Ababa city water supply, the dependence of a significant portion of the Addis Ababa city population may result in a continuous interruption of connectivity for part of the city which are highly dependent on the surface water supply sources. This study demonstrates applications of Physico-chemical and isotopic information to provide more sustainable and resilient urban water management perspectives which should be considered during the design and construction of water supply infrastructure.

Keywords: *isotopic signature; spatial distribution; tap water; surface water and groundwater sources; Physico-chemical.*

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Acronym

AAU: Addis Ababa University

AAWSA: Addis Ababa Water and Sewerage Authority

CSA: Central Statistics Agency

EC: Electric Conductivity

GSE: Geological Survey of Ethiopian

GMWL: Global Meteoric Water Line

LMWL: Local Meteoric Water Line

MER: Main Ethiopian Rift

MoWR: Ministry of Water Resources

TDS: Total Dissolved Substances

WWDSE: Water Works Design and Supervision Enterprise

V-SMOW: Vienna Standard Mean Oceanic Water

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Surface water and groundwater are both important sources for community water supply needs. Over the past few decades, ground water has become a fundamental resource for social, economic, and environmental sustainability. In the densely populated region of Addis Ababa, there are three surface water supply sources (-Gefersa, Legedadi, and Dire) and several ground water prospect sites (i.e., Akaki, Legedadi-Legetafo, Sebeta-Tefki, pocket areas) being used for drinking, irrigation, and industrial activities.

With population growth, urbanization and industrialization, Addis Ababa city water demand has been increasing dramatically. Associated with the increase in the city water demand, many groundwater water supply points have been drilled together with the surface water supply reservoirs and the drilled ground water point has been connected with the previous main water supply points (Legedadi, Gefersa, Dire and Akaki well field). The years since 2015 mark the highest groundwater exploration in the country (Mengistu et al., 2019). As a result, it has already become difficult to map which areas depend on the surface water and which on the groundwater resource. Not only distribution of reliance in space, but the extent of the inhabitants relying on either of the supply sources has never been plotted. Not to mention, a significant portion of the area gets water both from surface and groundwater supply sources.

Mapping the distribution of the water supply sources and linking the users to their respective water supply sources help to inform a sustainable use of urban water resources with the changing climatic conditions. For instance, groundwater is more climate-resilient than surface water where groundwater resources are relied upon to buffer the effects of greater climate variability. Besides, knowing which part of the city gets more uninterrupted water supply (from surface water reservoirs? From groundwater? From both?) Supports which water supply strategy better enhances water supply services in the city. However, in a big metropolitan city like Addis Ababa where there are multiple water supply sources, complicated water supply distribution systems, and a poor city master plan, mapping of water users properly linked with the supply sources is not an easy attempt. Water resource management is likely to become increasingly difficult in many contexts as a result of the predicted effects of climate change, urbanization, economic development, and increasingly complicated water resource supply systems and infrastructure (Jameel, Y. et al, 2018).

Understanding the fluctuation of stable hydrogen (H) and oxygen (O) isotopes in tap water has broad implications in a variety of industries (Bowen et.al, 2019). Understanding the source of tap water supply is important for sustainable water resource management, as the associated risks, including those due to climate change (Wang, S. et al, 2018). Stable isotopes in tap water also offer an approach to monitoring the dynamics and utilization of critical water resources at a national scale (Wet R. et al, 2020).

The primary aim of this study is to characterize the physical parameters and isotopic signature of Addis Ababa city tap waters combining the information of Physico-chemical properties of water sources to identify tap water supply sources. Successful disaggregation of groundwater and surface water sources would improve water resource management. It would allow for the identification of municipalities that may be vulnerable to predicted climate and demographic changes, the prioritization of adaptation interventions to increase the resilience of the water supply system, and the provision of a framework for directly and cost-effectively monitoring the water resources on which sub-cities rely.

1.2 Research problems

Many countries are struggling to keep stable water supplies, and this is predicted to worsen in the future years (Mulatu Kassa, 2017). Addis Ababa has very limited surface and ground water resources, which play a crucial role in meeting household needs in bulk condominium houses (Admasie, 2016). Akaki catchment area supports expanding urban and industrial areas, with increasing water demands. Many groundwater supply points (pocket areas) in the city have been drilled and injected into the previous main water supply pipe lines in various parts of the city in response to increased city water demand in recent years. As a result, the distribution of water supply sources has become more complicated and unclear. Even more groundwater level decline is observed In the Akaki catchment. Water resource management is likely to become increasingly difficult in many contexts as a result of the predicted effects of climate change, urbanization, economic development, and increasingly complicated water resource supply systems and infrastructure (Ruan F., 2020).

As a result, the application of physical parameters and stable isotope ratios of hydrogen and oxygen (δ^2H and δ^{18}O) in tap water is not well known. In the central parts of Ethiopia, water resource management issues like water sources salinity, pollution vulnerability, and climate change is a major concern for water resources development as well as for urban water supply services.

In the processes of designing an appropriate urban water management strategy, understanding the spatial variation of tap to source mapping (ground water and surface water, mixed source) should be the first task in the list.

No attempt has been made to identify the water supply sources through physicochemical characterization and isotopic signature of tap water as an indirect method of identifying sources in Addis Ababa city or the country. Therefore, this study aimed at the identification of water supply sources through stable isotope signature and Physico-chemical characterization of tap water of the Addis Ababa region. The research is believed to fill the stated gap and provide important information on the reliability of surface and groundwater sources for Addis Ababa city.

1.3 Research objectives

1.3.1 General objectives

This research aims to identify water supply sources (ground water and surface water) using Physico-chemical characterization and Isotopic signature of tap water for Addis Ababa city.

1.3.2 Specific objectives

- To analyze Physico-chemical parameters of surface water, groundwater, and tap water.
- To Map the distribution of the water supply sources.
- Determine the extent of population dependency on respective water supply sources.

1.3.3 Research questions

The study was guided by the following questions;

- How are the water supply sources distributions of tap water at the different locations in the study area?
- Do the Physico-chemical and stable isotopic signatures indicate the tap water sources?
- How much of Addis Ababa city population rely on surface and groundwater resources?
- Can applications of Physico-chemical and stable isotopic data be used to generate important information support to enhance urban water supply services?

1.4 Significance of the study

This study is important to apply physical parameters and isotopic signature of tap water to urban water supply services. Many groundwater supply points (pocket areas) in the city have been drilled and injected into the former major water supply pipe lines in various parts of the city in recent years, making it increasingly difficult and confusing to identify water supply sources. Understanding the spatial variation of tap to source mapping has important for sustainable water resource management and helps for designing appropriate urban water management strategies. Mapping the distribution of the water supply sources and linking the users to their respective water supply sources help to inform a sustainable use of urban water resources with the changing climatic conditions. It would enable to supports which water supply strategy better enhances water supply services in the city. It can help in designing appropriate urban water management strategies.

1.5 Activities and Materials

1.5.1 Identification of Tap water Measurement sites

Representative numbers of tap water samples have been taken from each sub-city depending on population number and areal coverage of the sub-cities. The measurements have been taken from private households, hotels, industries, and governmental institutions. Tap water physical measurements total of 510 samples and 200 isotopic data of tap water collected from ten sub-cities (Kolfe Keranyo, Gulele, Addis Ketema, Lideta, Nefassilk Lafto, Kirkos, Arada, Akaki Kality, Bole, and Yeka), and five measurements took from surface water body of the study sites.

Table 1-1:- Locality, population number, Area and number of primary Tap water data points

s/n	Locality	Population number	Area (sq.km)	Number of Measurement
1	Addis Ketema	343,807	7.33	41
2	Akaki Kality	244,042	127.3	85
3	Arada	284,836	9.2	14
4	Bole	416,127	127.9	83
5	Gulele	360,334	31.7	35
6	Kolfe Keranyo	577,467	65.7	62
7	Kirkos	297,949	14.42	24
8	Lideta	271,617	11	18
9	Nefassilk Lafto	425,935	58.3	68
10	Yeka	466,885	86.4	76

1.5.2 Collection of Water Quality Data

The Relevant secondary water quality and Physico-chemical data including location tables and maps of wells in Addis Ababa city have been collected and studied from concerned organizations and different technical reports. Literature review including published and unpublished reports on water quality data of Hydrochemistry, Hydrochemical, hydrogeological, and other important topics concerning the study sites and objectives have been revised from previous works.

1.5.3 Collection of Water samples

After setting the relevant objectives and identifying sampling sites proper field planning has been conducted for taking water samples. The water samples were collected from Private households and institutions Tap water once per site in two weeks. Environmental isotopes (Deuterium and Oxygen-18) samples had been collected from ten sub-cities and determined in the AAU water isotope laboratory.

1.5.4 In-situ measurements of some water quality variables

Five hundred ten Tap water physical (EC, pH, and temperature) measurements have been taken from ten Addis Ababa sub-cities. Tap water samples were measured in February-March, 2021, for EC, PH and Temperature (see Annex 2). Electrical conductivity (EC), Total dissolved solids (TDS), Temperature, and pH of water samples were measured in-situ with HANNA pH/EC/TDS instrument after the pH is calibrated with two buffers solutions of pH 4.01 and pH 7.01 in Addis Ababa University Water Isotope laboratory. Coordinates (X, Y) and altitudes (m.a.s.l) of sampling points have been measured with Garmin-12 channel GPS (Global Positioning System).

Table 1-2:- Methods used for Physico-chemical data and Environmental Isotope analysis.

physicochemical parameters/Isotopes	Method of measurement/ analysis
Electric conductivity(EC)	In-situ measured using Hanna instrument, pH/EC/TDS meter
Temperature	In-situ measured using Hanna instrument, pH/EC/TDS meter
PH	In-situ measured using Hanna instrument, pH/EC/TDS meter
Total dissolved solid (TDS)	In-situ measured using Hanna instrument, pH/EC/TDS meter

CHAPTER 2

LITERATURE REVIEW

2.1 General

Environmental isotopes are commonly used for the understanding of groundwater chemistry and evolution, rock-water interaction, water resources origin and mixing, source of salinity, and contaminants (Mazor, 1991; Mook, 2000). The isotopes of hydrogen and oxygen undergo large fractionations during these processes, providing a multiple isotopic tracer record of diverse phenomena (Clark and Fritz, 1997).

The stable isotope composition of tap water preserves information on the source of these waters and can provide information on tap water origin and evaporation losses from water supplies, as well as vulnerabilities to environmental change which are not obvious from traditional water management data (Bowen et al., 2007).

To devise methods for ensuring the sustainability of long-term water supply, understanding the relations between water consumers and climate (precipitation) sources is essential. Water's light stable isotope ratios (d^2H, $d^{18}O$) are parameters that can be easily and routinely measured for almost any water sample and which can preserve information on the climatological source (i.e., the location, time, and phase of precipitation) and post-precipitation history of water (Bowen et al., 2007).

Human societies face huge difficulty in planning for and conserving sustainable drinking water resources. This problem will worsen as human populations grow and have a more powerful and widespread influence on their environment, as a result of factors such as rising demand, increased contamination risk, and changes in the characteristics and distribution (both geographical and temporal) of supplies (Bowen et al., 2007).

2.2 Water supply sources

Groundwater and surface water resources are the foundation of socioeconomic activities and environmental functions. Surface water and groundwater are both important sources of water for communities. The fundamental interface between individuals and the hydrological system is tap water.

Most municipalities are supplied by a combination of local surface and groundwater, but they may also rely on non-local sources such as treated sewage effluent or desalinated seawater via inter-basin water transfer schemes Groundwater, surface water, and mixed sources are a common source for Addis Ababa city, three surface water supply sources (Gefersa, Legedadi, and Dire) and several ground water prospect sites (i.e., Akaki, Legedadi-Legetafo, Sebeta-Tefki, pocket areas) are water supply sources for Addis Ababa city. Although approximately 98 percent of liquid fresh water exists as groundwater, much of it occurs very deep. This makes pumping very expensive, preventing the full development and use of all groundwater resources.

Isotope hydrology is a very cost-effective means to assess the vulnerability of groundwater sources to pollution. By determining how rapidly the water is moving and where in the system is being recharged, isotopes provide critical information to guide decisions on where to extract water.

2.2.1 Ground water sources

Groundwater resource is commonly the most important water resource in semi-arid and arid areas that are often subject to water shortage. It is critical in delivering clean and safe water to competing applications in the home, industrial, and agricultural sectors, and greater attention is being devoted to its importance for ecological integrity. (Seyedmohammadi et al., 2016). Groundwater aquifer systems, on the other hand, are usually complex, nonlinear, multi-scale, and unpredictable as a result of frequent interactions between surface water and groundwater, as well as an acute human disturbance (Nourani et al., 2015; Han et al., 2016). The utility of an aquifer as a groundwater supply is determined by the porosity of the geologic stratum, or layer, from which it is produced. Water is extracted from an aquifer by pumping it from a well. Groundwater has a far more important function in mitigating seasonality and long-term trends.

Because meteoric processes change the stable isotopic composition of water, recharge waters in a certain environment will have a distinct isotopic signature. This characteristic is then used as a natural tracer to determine the source of groundwater.

According to Seifu Kebede (2013), the composition of Ethiopian ground waters is the result of three major processes. Specifically,

(a) Lithologic variation—Rock type is the ultimate control of water quality because it controls which minerals are accessible to interact with rock water and release ions into ground waters. In crystalline volcanic and basement rocks, the main kind of geochemical reaction is 'hydrolysis' in the presence of atmospheric or geogenic CO_2, and the ions formed include Ca, Mg, Na, K, and HCO_3.

(b) Evaporative enrichment before recharge—before recharge, incidental recharge water can acquire some ions because of evaporation. In arid and semiarid regions where evaporation is the dominant hydrologic process enrichment of ions such as Ca and SO_4 occurs. Dissolution of trace salts from the soil zone imparts ions such as SO_4, Cl, Ca, and Na, and this process are common also in arid areas where top soil is salinized because of evaporation of available soil moisture and accumulation of trace salt in the soil zone.

(c) Thermodynamic control-rock type or evaporation process alone may not be enough to explain the variation in groundwater geochemistry. The role of thermodynamics is to determine whether reactions are conceivable given a particular rock type, temperature, saturation indices, and ionic activity.

2.2.2 Surface water sources

A watershed, drainage basin, or catchment area is the total land area that produces surface runoff to a river or lake. The volume of water available for municipal delivery is primarily determined by the amount of rainfall. It is also affected by the size of the watershed, the ground's slope, the kind of soil and vegetation, and the type of land use. Surface waters are available seasonally and respond quickly to climate change.

Surface runoff is an important component of the terrestrial water cycle, and the interactions between surface water and other hydrological components (particularly precipitation and groundwater) can be studied using stable water isotopes (Zang and Wang, 2018).

Dansgaard (1964) demonstrated that temperature and precipitation amount are important meteorological factors controlling stable isotope composition in precipitation, which is commonly known as temperature effect and precipitation effect, respectively. Light isotopes evaporate preferentially to heavy isotopes, so heavy isotopes of evaporated water are more depleted than those of residual water. Hence, in some open water bodies (especially lakes), the heavy isotopes were more enriched, relative to precipitation, due to strong evaporation (Cappa, 2003).

2.3 Hydrochemical process

The chemical quality of water results from hydrogeochemical processes of solution or precipitation of solid minerals, reduction and oxidation compounds, solution or evolution of gases, sorption or ion exchange, pollution, leaching fertilizers or manure, and mixing of different waters (Appelo and Postma, 1996; Hounslow, 1995). These processes are dependent on water and rock interaction, atmospheric inputs, inputs of chemicals by human activities, precipitation, geological structure, mineralogy of aquifers (Freeze & Cherry, 1979; Hem, 1985; Jeong, 2001; Krishnaraj et al., 2011).

Nearly all groundwater originates as rain or snowmelt that infiltrates through the soil into flow systems in the underlying geologic materials. The soil zone has unique and powerful capabilities to alter the water chemistry, as infiltration occurs through this thin, biologically active zone. In recharge areas, the soil zone undergoes a net loss of mineral matter to the flowing water. As groundwater moves along flow lines from recharge to discharge areas, its chemistry is altered by the effects of a variety of geochemical processes (Freeze and Cherry, 1979).

As a result of chemical and biochemical interactions between groundwater and the geological materials through which it flows, and to a lesser extent because of contributions from the atmosphere and surface-water bodies, groundwater contains a wide variety of dissolved inorganic chemical constituents in various concentrations. Dissolved constituents in the water provide clues on its geologic history, its influence on the soil or rock masses through which it has passed the presence of hidden ore deposits, and its mode of origin within the hydrologic cycle (Freeze and Cherry, 1979).

2.4 Physical Parameters of water source

Water sample parameters are analyzed in a laboratory. Some parameters such as temperature, conductivity, alkalinity, dissolved oxygen, pH, cations and anions, hardness, TDS, sodium adsorption ratio, and saturation index are determined in the field (Hounslow, 1995).

2.4.1 Temperature

Temperature data are need for water-rock equilibrium calculations, as well as for the identification of water groups, and the determination of water end-member properties (Mazor, 1991).

2.4.2 Hydrogen Ion-Activity (PH)

The pH of a solution indicates an effective concentration of the hydrogen ion. The units of pH are the negative logarithm of hydrogen ion concentration, expressed in moles per litter.

$$PH= -\log (H^{+})$$

2.4.3 Electric Conductance (EC)

Conductivity, which is also called electrical conductivity (EC), is a reciprocal of the resistance in Ohms between the opposite faces of a 1 – cm cube of an aqueous solution at a specified temperature (usually 25^{0}C). It is temperature dependent and the international unit is Siemens/m that is numerically equivalent to the Mhos/m (Hounslow, 1995; Mazor, 1991).

It is well known that the electrical conductivity of a solution is a measure of its total dissolved salt contents (Hem, 1971).

Conductivity is a good estimator of TDS because TDS in mg/l is proportional to the conductivity in micromhos.

TDS (mg/l) = A * conductivity (µMhos/cm), where A = 0.54 -0.96 usually (0.55-0.76) Conductivity may also be estimated from the sum of cation expressed in meq/l. Conductivity (µMhos/cm) = sum cations (meq/l) * 100

2.4.4 Total Dissolved Solids (TDS)

A total dissolved solid (TDS) is a measurement of the total amount of organic and inorganic components in a liquid. This includes anything in the water that isn't pure $H_{2}0$ molecules. These solids, which largely consist of minerals, salts, and organic materials, can serve as a general indicator of water quality.

TDS (mg/l) = A * conductivity (µMhos/cm), where A = 0.54 -0.96 usually (0.55-0.76)

2.5 Isotope Basics

Isotopes are atoms of the same element that have the same number of a proton (atomic number) but a varying number of neutrons (or mass number). Therefore, isotopes have slightly varying masses of the same element. For light isotopes, the mass difference between isotopes of the same element is greater (or isotopes of lighter elements ex hydrogen, oxygen, sulfur, boron, nitrogen, carbon, helium, etc.). For example, the heavier stable isotope hydrogen ^{2}H is twice as heavy as the lighter isotope ^{1}H equivalent.

Because of the slight variation in mass, the molecules have different physical properties. Isotopes of the same element behave differently during hydrologic processes involving phase changes (e.g., evaporation, condensation, sublimation, freezing, etc.) and geochemical reactions, resulting in isotopic fractionations and, ultimately, different natural isotopic abundance in different hydrologic compartments (e.g. lakes, oceans, rivers, atmospheric water, groundwater, etc.).

The physical and chemical properties of isotopes of the same chemical element are nearly identical. However, due to the small mass differences, they exhibit differing reaction rates and abundances in two isotopically exchanged chemical compounds or phases. Physical processes such as diffusion, evaporation, condensation, melting, and so on also result in isotopic differentiation. Isotopic fractionation refers to all differences in isotopic composition caused by chemical or physical processes in compounds or phases existing in the same system (Mook, 2000).

The temperature at which the isotope fractionation occurs affects the isotopic fractionation. This property enables us to employ natural isotopic fluctuations as tracers of climate phenomena. Because meteoric processes change the stable isotopic composition of water, recharge waters in a certain environment will have a distinct isotopic signature. This signal is then used as a natural tracer to determine the source of groundwater.

Isotopes of hydrogen and oxygen are the most widely used in hydrologic studies. This is because these isotopes are an integral part of the water molecule and therefore can trace the history of water, its movements, its interactions, and mixing, etc. The determination of an isotopic concentration of a specific isotope in a given water system is very difficult. This is because the isotope concentrations/abundance of heavy isotopes is extremely small. It is therefore easier to express isotopic abundances using the isotopic ratio R ($R < 1$).

$$R = \frac{Abundance\ of\ rare\ (heavy)\ isotope}{Abundance\ of\ abundant\ (light)\ isotope}$$

The internationally accepted standard for reporting the hydrogen and oxygen isotopic ratios of water is Vienna Standard Mean Ocean Water, V-SMOW (Coplen, 1996). The absolute isotopic ratios 2H/1H and 18O/16O of V-SMOW were found to be equal to

$^{2}H/^{1}H = (155.95 \pm 0.08) * 10^{-6}$ (De Wit et al., 1980)

$^{18}O/^{16}O = (2005.20 \pm 0.45) * 10^{-6}$ (Baertschi, 1976)

These values are close to the average isotopic composition of ocean water given by (Craig, 1961a; b cited in Mook, 2001). Since the ocean represents about 97% of the total water inventory on the earth's surface and the observed variations of $^{2}H/^{1}H$ and $^{18}O/^{16}O$ within the water cycle are relatively small, the heavy isotope content of water samples is usually expressed in delta (δ) values defined as the relative deviation (in per mil- $‰_0$) from the adopted standard representing the mean isotopic composition of the global ocean (Mook, 2001).

$$\delta^{18}O(‰) = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample} - \left(\frac{^{18}O}{^{16}O}\right)_{standard}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} x\,1000 \qquad \delta^{2}H(‰) = \frac{\left(\frac{^{2}H}{^{1}H}\right)_{sample} - \left(\frac{^{2}H}{^{1}H}\right)_{standard}}{\left(\frac{^{2}H}{^{1}H}\right)_{standard}} x\,1000$$

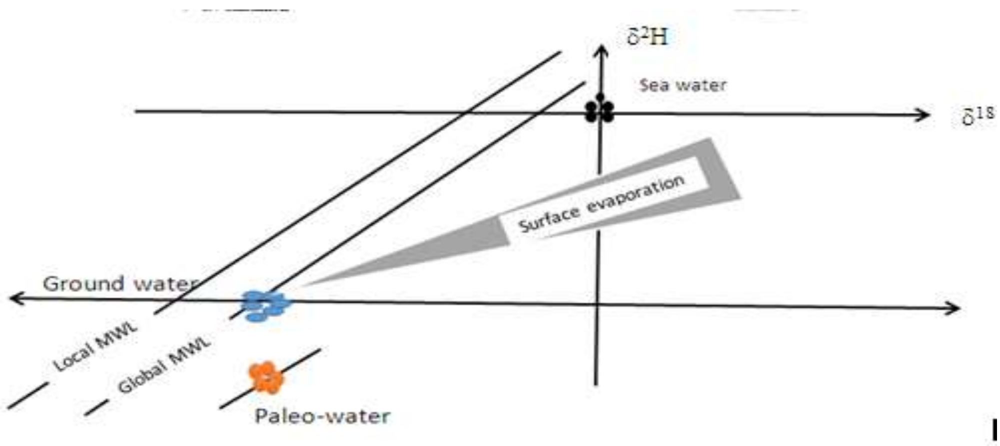

Fig 2.1:- Figure showing the LMWL, GMWL, and isotopic composition modifications accompanying hydrological exchanges in the hydrologic compartment. (Modified from; Seifu kebede, 2013)

2.5.1 Environmental Stable Isotope

Environmental isotopes have been extensively used during the past decades to address key aspects of the water cycle, such as for studying the origin, dynamics, and interconnections of groundwater, surface water, and atmosphere (Mook, 2000). In addition, stable isotopes are chemically conservative elements and can be used for hydrogeological investigations and to trace environmental phenomena (Krishnaraj et al., 2011).

Isotope hydrology is a well-established methodology for understanding hydrological processes such as recharge rate and mechanism, surface water groundwater interaction, the time scale of processes, pollution origin, and so on. When utilized to study the hydrology of arid and semi-arid environments, the tool becomes much more powerful.

Environmental isotopes have been widely used in recent decades to investigate essential components of the water cycle, such as the origin, dynamics, and linkages of groundwater, surface water, and atmosphere (Mook, 2000).

Among all isotopes used in hydrology, stable isotopes of water ($d^{18}O$ and $d^{2}H$) are the most widely used in Ethiopia. Two important concepts are useful to better understand the stable isotopes of water application in classical hydrologic studies. These are the meteoric water line and the isotope effects. As early as 1961 Craig and Gordon (1965) and Dansgaard (1964) found a relation between the $d^{2}H$ and $d^{18}O$ values of precipitation from various parts of the world. The plot of these isotopes on an x–y graph falls on a line defined by the following equation called the Global Meteoric Water Line or Craig Line.

$$d^{2}H = 8d^{18}O + 10$$

Depending on the humidity and temperature conditions locally the $d^{18}O$-$d^{2}H$ plot of local rains may deviate from the GMWL and form a local meteoric water Line (LMWL). This line is the reference against which comparison can be made to understand isotope effects that have taken place to understand the processes of recharge, evaporation, mixing, etc. During the hydrological cycle, the most frequent processes are condensation and evaporation. Water evaporation leads to enrichment (increase in heavy isotope content with respect to the light) in the stable isotope composition in the residual water fraction. Every precipitation event depletes the vapor remaining reservoir. Water with a heavier $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratio forms the initial water droplets of rains and as vapor mass continues to lose its heavy isotopes it becomes more light (Seifu Kebede, 2013).

2.5.2 Isotope Fractionation

Isotope fractionation refers to the physical phenomenon that causes fluctuations in the relative abundance of isotopes due to mass differences. This can occur as a result of an isotopic composition shift produced by a chemical transition from one state to another (example: liquid water to water vapor). Tracing groundwater with environmentally stable isotopes provides unique and supplementary information on the origin and movement of groundwater and its dissolved constituents, as well as a quantitative evaluation of mixing and other physical processes in geothermal systems such as evaporation and isotopic exchange (Mook, 2000).

A remarkable feature about the $\delta^{18}O$ and δD composition of the Ethiopian meteoric waters is their enrichment despite the high altitude location of the region. The $\delta^{18}O$ and δD composition of the rainfall at the IAEA station at Addis Ababa varies between -4 and 0‰ with d being the excess between 10 and 20 (IAEA 2006). The weighted mean $\delta^{18}O$ and δD composition of the summer (June to September) rainfall waters of the Addis Ababa IAEA station are -2.5‰ in $\delta^{18}O$, -5‰ in δD, and 15 in d-excess.

The spring (March and April) rainfalls have a weighted mean composition of +1‰ in $\delta^{18}O$, +20‰ in δD, and 10 in d-excess (Kebede et al., 2008). The spatial variations in $\delta^{18}O$ and δD with latitude, longitude, and altitude are small (Schoell and Faber, 1976; Seifu Kebede et al., 2005).

Isotope fractionation addresses tiny differences in the chemical as well as physical behavior of molecules (Mook, 2000). Fractionation of the isotopic composition of a water resource is caused by different physical environmental processes (Krishnaraj et al., 2011). Hence, chemical composition and isotropic gradients show differences between water resources and this can be quantified by comparing the signatures of the stable water isotopes ($\delta^{18}O$, $\delta^{2}H$) (Nies et al., 2011).

The $d^{18}O$ and $d^{2}H$ enrichment in lakes is the result of isotope fractionation that takes place during evaporation (Craig and Gordon, 1965). Other post-precipitation activities, including evaporation and chemical interaction with minerals in soils and rocks, have the ability to change stable isotope ratios of water and can be differentiated using paired $d^{2}H/d^{18}O$ data. (Bowen et al., 2007).

Evaporated water bodies and waters exposed to vapor loss such as lakes, wetland waters, running waters, reservoirs, and oceans tend to enrich in their heavy isotope content with respect to the vapor derived out of them. Another form of evaporation effect results from the evaporation of rainfall while the rain droplets are making their way to the ground. In arid and semi-arid environments significant evaporation of rain droplets in the dry atmosphere can take place resulting in enrichment of rainwaters and deviation from the global meteoric water line (Seifu Kebede, 2013).

2.6 Previous Studies

A comparatively large number of researchers have evaluated both surface and groundwater resources in terms of potential, flow models, and vulnerability in the study area. Environmental isotopes have also been explored for determining groundwater occurrence, recharge rate, recharging mechanism, pollutant origin, and dynamics. Previous research examined the degree of groundwater-surface water interaction in the country's central region.

The main reviewed publications, reports, and thesis which are relevant to the research are briefly summarized below:

Andarge Yitbarek (2010). Hydrogeological and Hydro-geochemical Framework of Complex Volcanic System in the Upper Awash River Basin, Central Ethiopia.

He pointed out the groundwater from the deep exploratory wells (>250m) tapping the lower basaltic aquifer and wells located in the south were found to be moderately mineralized (TDS: 400-600 mg/l), with a relatively depleted stable isotope composition. In contrast, the upper shallow aquifer has a lesser ionic concentration, more isotopically enriched.

Aynalem Ali (1999). Water quality and groundwater in Akaki river interaction in the sekelo basin (lower Akaki river sub-basin), central Ethiopia.

He mentioned that the geology of the area is characterized by volcanic of Late Pliocene and Plio-Pleistocene age of lower basalt flows and young basaltic scoria and lava which belong to the Bofa Basalts and the Bishoftu Basalts, respectively. The lower basalt flows comprise intercalations of basalt flow, scoria, scoriaceous basalt, and tuff. The young basaltic scoria and lava are commonly spattered cones consisting of scoria, scoriaceous basalt at the top of the cones, surge deposit, and volcanic breccia at the bottom of the cone. Alluvial sediments are localized along the Akaki river.

Berhane Melaku (1982). Investigating the General Hydrogeology of the Upper Awash Basin, EIGS. Ethiopia. Based on surface geological mapping and inventorying about 40 boreholes, 101 dug wells, 38 springs and 6 lakes water and water quality analysis characterized the Awash River, sub-basins, and major tributaries catchment hydrogeology. The study proposed qualitative aquifer classification i.e. very good, good, moderate, and poor aquifers. Very good aquifers are considered, quaternary scoriaceous and vesicular basalt distributed in the vicinity of the Debrezeyt area. Good aquifers are considered faulted upper Miocene ignimbrites and basalt in the Central Plains.

Moderate aquifers are considered Pleistocene to Pliocene basalts in the Central Plains. Poor aquifers are considered quaternary alluvial-lacustrine deposits and rhyolitic and trachytic rocks.

Berhanu Gizaw (2002). Hydrochemical and Environmental Investigation of Addis Ababa Region. The Ludwig Maximilian University of Munich. Germany.

He pointed out that the regional groundwater flow is north-south. Except the thermal and a few borehole $NaHCO_3$ types of waters, the groundwater of the Addis Ababa area is $CaMgHCO_3$ type. Most of the rivers which are being recharged are upstream by the groundwater is highly polluted inside Addis Ababa and at their downstream riches. He also pointed out that due to more than 40m vadose zone in Akaki well field area up to the Abasamuel power plant, the groundwater is not subjected to pollution from the river waters.

Tamiru Alemayehu *et al.* (2003) study ground water vulnerability mapping of the Addis Ababa water supply aquifers and they have been conducting the risk for groundwater pollution through DRASTIC mapping of water supply aquifers, and finally, they reported that main sources of pollutants that deteriorate the quality of water in the project area are wastes generated from industries, domestic activities, garages, health centers, and fuel stations.

Tilahun Azagegn (2008). Findings reveal the Hydro Geochemical Characterization of Aquifer systems in Upper Awash and Adjacent plateau using geochemical modeling and isotope hydrology.

He concluded that groundwater of low pH and TDS, CaHCO3 water type in shallow plateau and transition zone aquifer, through the processes of silicate hydrolysis, cation exchange followed by precipitation evolves rift ward to NaHCO3 water type with high TDS and pH.

The whole Plateau zone, permeable and locally faulted transition and rift zones are recharge areas for the aquifer systems in the study area.

Seifu Kebede et al. (2008). The $d^{18}O$ and $d^{2}H$ enrichment of Ethiopian lakes. The study concluded the low latitude lakes show similar enrichment behavior to that of other lakes in high latitude settings. Satisfactory agreement between the calculated and the measured local evaporation a line was obtained through adjusting the theta value which accounts for humidity build-up over the evaporating lake. All the investigated lakes are evaporation-dominated systems, with evaporative water losses exceeding 50% of total water loss.

Seifu Kebede et al. (2007). Groundwater origin and flow along selected transects in Ethiopian rift volcanic aquifers.

The research mentioned Up to 50% of recharge to the rift aquifers comes from the plateau as groundwater inflow where the rift is cross-cut by transverse fault zones. Recharge from the mountains is found to be insignificant where the rift is bounded by marginal grabens; channel loss and local precipitation are the principal sources of recharge to the rift aquifers in such cases. At a regional scale, there is a clear zonation in the geochemical compositions of ground waters, the result of aquifer matrix composition differences. The environmental isotope results show that the majority of the aquifers contain modern groundwater. In a few localities, particularly in thermal groundwater representing deeper circulation, paleo- groundwater has been identified.

Tenalem Ayenew et al. (2008). Application of Numerical Modeling for Groundwater

Flow System Analysis in the Akaki Catchment. Central Ethiopia.

The research result indicates that the groundwater flows regionally to the south converging to the major well field. Reservoirs and rivers play an important role in recharging the aquifer. Simulations made under different pumping rates indicate that an increase in pumping rate results in substantial regional groundwater level decline, which will lead to the drying of springs and shallow hand-dug wells. Also, it has implications of reversal of flow from contaminated rivers into productive aquifers close to main river courses.

Behailu Birhanu et al. (2021). Impact of Natural and Anthropogenic Stresses on Surface and Groundwater Supply Sources of the Upper Awash Sub-Basin, Central Ethiopia.

The research stated that considering the high population growth rate scenario for Addis Ababa city, the unmet domestic water demand may increase to 760 MCM in 2030. Water leakage through poor water supply distribution networks contributed about 23% of the unmet water demand. Though not significant compared with population and water loss stresses, climate change also affects the supply-demand condition in the basin. Planning for more groundwater abstraction without considering additional surface water reservoir schemes will noticeably impact the groundwater resource, with groundwater levels projected to decline by more than 20 m.

Belema Gemechu (2004). Natural Hydrochemical variations and anthropogenic influences on surface water and ground water systems in the selected urban centers in the upper Awash Basin.

He indicates On the basis of major chemical constituents, it can be indicated that the chemical composition of the waters are continuously enriched by calcium and magnesium cations and bicarbonate anion due to the effect of the interaction between waters and the geological formations through which they reside and move.

Molla Demlie et al. (2007). Groundwater recharge, flow and hydrogeochemical evolution in a complex volcanic aquifer system, central Ethiopia

The study reveals five spatial groundwater zones with defined hydrochemical facies, residence times, stable isotopic signals, and hydrochemical evolution. These zones are designated as the Intoto, central, Filwuha fault, south zones, and a highly polluted sub-sector identified within the central zone. It is mentioned that the central sub-sector as being in spite of differentially polluted by NO_3^-, Cl^- and $SO_4^{2-}$and its tritium content shows recent recharge. The main recharge source is precipitation, the hydrochemical and environmental isotope data indicated that the central and southern sectors are also recharged from domestic waste water and leakage from water mains and reservoirs.

Solomon Tale (2000). Assessed the extent of groundwater-surface water interaction in the central part of the city.

There is a definite zonation of total dissolved solids (TDS) following the route of groundwater movement from the highlands to the rift. This zonation corresponds to changes in recharge, climate, and geological setting. Almost all highland surface waters and ground waters are fresh with TDS ranging from 50 to 1200 mg/l.

Local exceptions with high TDS exist in the Akaki river catchment (Addis Ababa area) and few urban centers where the water is polluted by anthropogenic sources.

The previously detailed hydrogeological investigation has been also carried out by Anteneh Girma (1994) in his master's thesis "Hydrogeology of Akaki Area". As cited in a thesis, many geoscientists like Mohr (1967), Morton et al. (1966), Kazmin (1978), Morton et al. (1979), Zanettin and Justin Visitin (1974), Mohr P.A,(1983) have discussed the geology of Addis Ababa region in their studies.

Regarding the surface and ground water potential of the Addis Ababa region, AAWSA and SEURECA (1989) have conducted valuable works. Assessments to assure the feasibility of surface and groundwater as a source of water supply in the Akaki area have been carried out by AAWSA (2000).

In Addis Ababa and its surrounding areas, both surface and groundwater resources have been investigated in terms of potential, and vulnerability by a relatively good number of investigators such as Vernier (1993); AAWSA-SEURECA (1991); Anteneh Girma (1994); Eccleston (1997); Aynalem Ali (1999); AAWSA (2000); Gebrekidan (2000); Tamiru Alemayehu (2001); and Berehanu Gizaw (2002). EPA (1997) has surveyed pollutant load on three rivers of Addis Ababa city. These studies, although they vary in scope and degree of geological and geochemical information, have stressed that the quality of surface water is often affected by uncontrolled waste disposal of domestic and municipal wastes and industrial effluents. They further indicated that these would have a potential impact on the quality of groundwater in the region. Molla Demlie (2007) studied the recharge in the area and he stated that recharge takes place over the entire surface area, major recharge takes place within the Intoto sector of the catchment, serving as a so-called mountain block recharge. Moreover, hydrochemical and environmental isotope data indicated additional recharge sources from wastewater, leakage from mains and reservoirs. In addition to that, Tamiru Alemayehu et al., (2005) did aquifer vulnerability of the whole Akaki catchment and water quality assessment.

CHAPTER THREE

OVERVIEW OF THE STUDY AREA

3.1 Location

Addis Ababa city is geographically located at a longitude of 38° 44′ E and latitude of 9° 1′ N. Addis Ababa city divides into ten sub-cities those are Arada, Kolfe Keranyo, Kirkos, Lideta, Addis Ketema, Gulele, Bole, Akaki Kality, Nefassilk Lafto, and Yeka. The AAWSA in Addis Ababa is a public institution in the city, which is responsible for the supply of potable water. Currently, Addis Ababa gets its water supply from surface water (-Gefersa, Legedadi, and Dire), mixed sources, and several ground water prospect sites (i.e., Akaki, Legedadi-Legetafo, Sebeta-Tefki, pocket areas) being used for drinking, irrigation, and industrial activities. (**Figure 3.1**)

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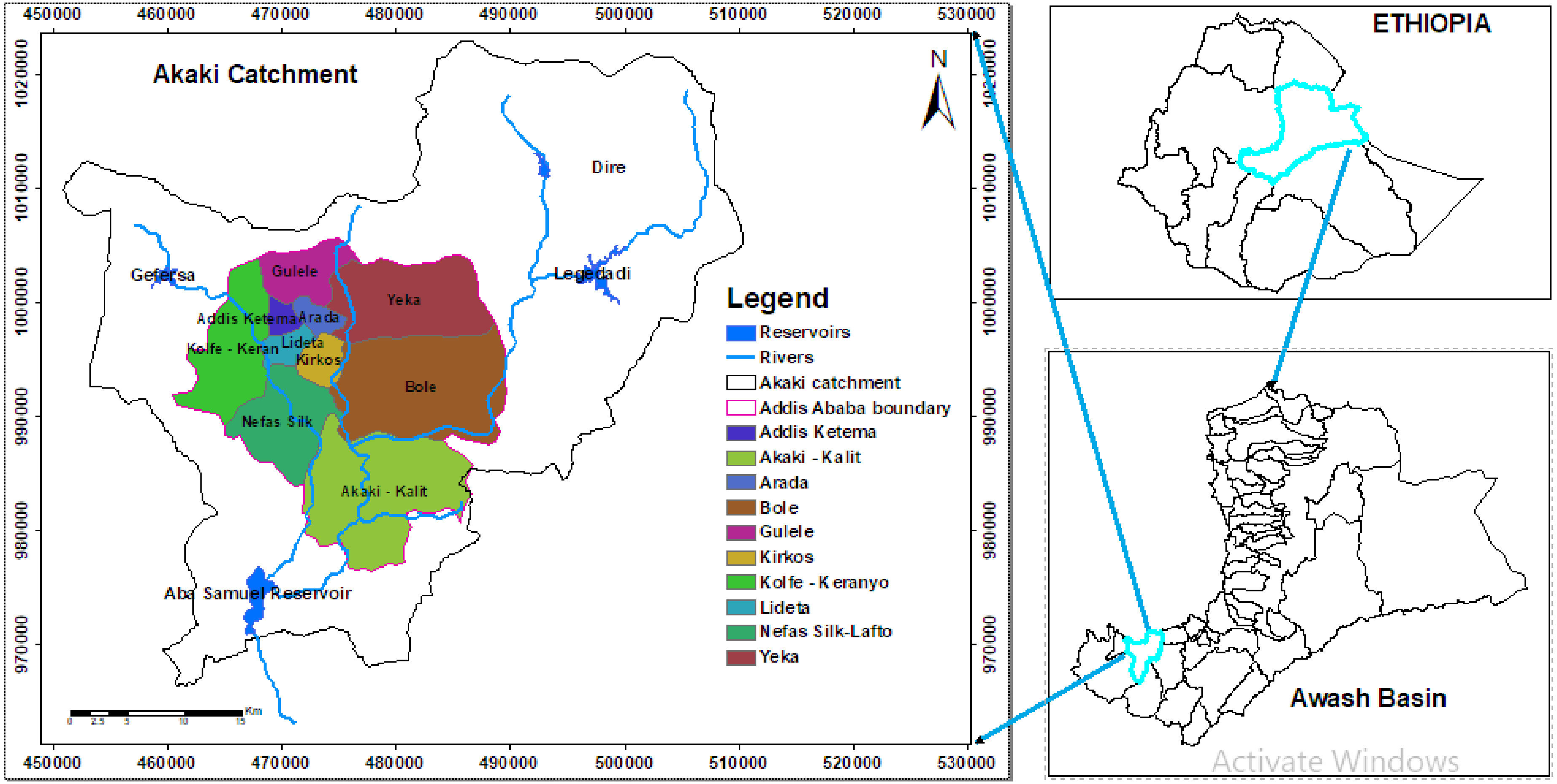


Fig 3.1:- Location map of the study area

3.2 Physiography

The study area is part of the western plateau margin of Ethiopia having an altitude ranging 1800m-3300m above sea level (**Figure 3.2**). The southeastern and the northwestern part of the study area are above 2000 meters above sea level. Addis Ababa is found in the Akaki River catchment. The northern boundary of the town is Entoto Mountain Range. The volcanic mountains; Mt. Furi located southwest of the town and Mt. Yerer located south-east of the town are high massive volcanic centers rising to elevations of 2,839 and 3,100 m, respectively. These two peaks heights form the western and eastern drainage divides of the Akaki River respectively.

The morphology of the Addis Ababa area is complex. Entoto Ridge, which constitutes the northern boundary of Addis Ababa, has rugged topography characterized by steep slopes rapids, and waterfalls. Towards the south, the morphology changes to quite gentle slopes though there are some hilly features.

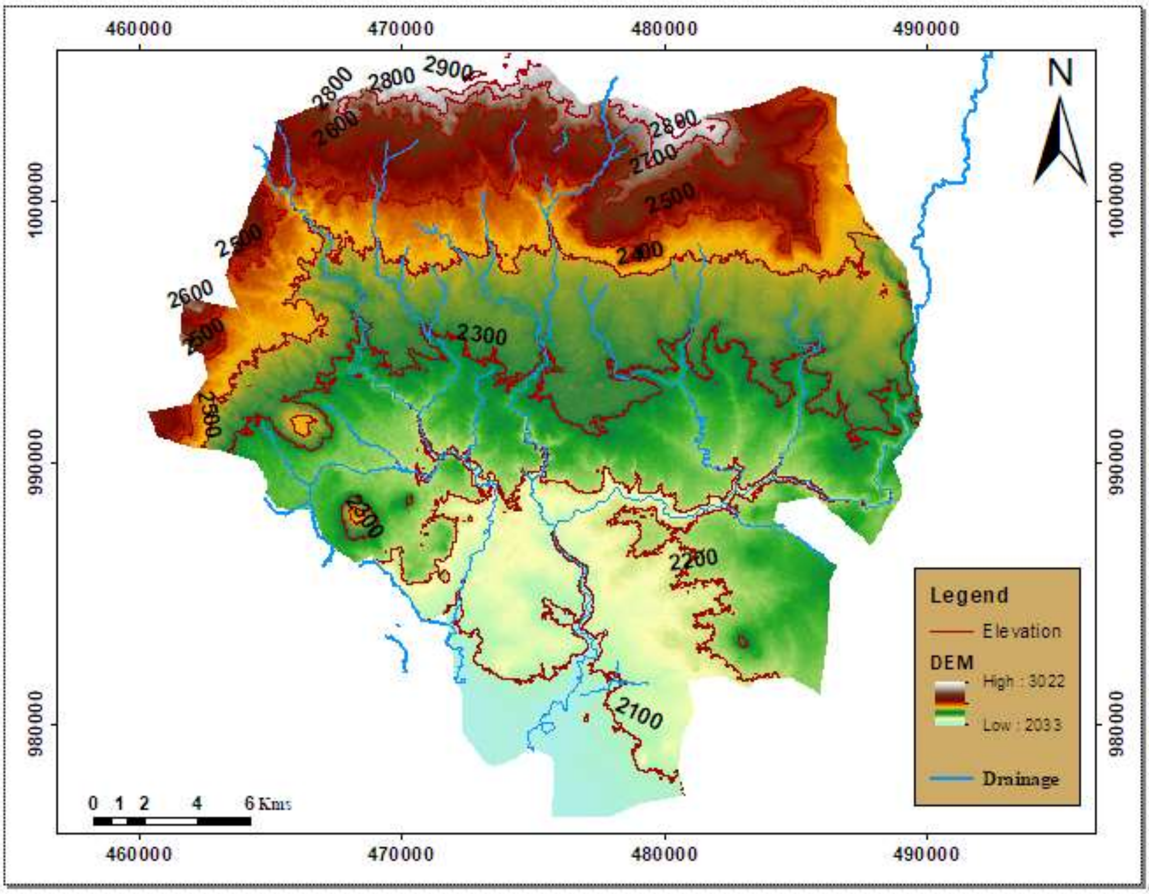


Fig 3.2:- Drainage pattern and Elevation of the study area of the study area

3.3 Drainage

The drainage in the study area shows a dendritic pattern (**Figure 3.2**). These drainages are denser to the southern part. These drainages are matured forming big rivers like Abasamuel etc. The major rivers are Kebena, Abasamuel, Akaki, etc. (GSE, 2007).

The Addis Ababa area is located in Akaki catchment's which consists of Akaki River catchments and numerous small rivers, streams, and canals. The dominant ones are the Big Akaki, which drains the Eastern part of the catchment's area, has many a tributary among which genfile, kebena, kechene, kurtume and yeka all are founded in the eastern part of the city boundaries and the Little Akaki that drains the Western part of the catchments and their respective tributaries.

The two rivers form one of the biggest tributaries of the Awash River called Akaki River that enters Abba Samuel Lake, leaves the lake, and pass through a gorge up to 100 m deep which extends for about 8 km before it joins the Awash River. Big Akaki River basin with a catchments area of 900 Km^2 and Little Akaki River with catchments area of 540 Km^2 with their tributaries drains the city of Addis Ababa from North to South (Feven Solomon, 2007).

3.4 Populations

According to the CSA's 2014 annual statistical abstract, the majority of Ethiopians reside in rural areas. However, Ethiopia's urban population more than doubled from 4.87 to 11.86 million between 1984 and 2007 and, growing at a rate of 3.8% annually, is expected to triple by 2037 (World Bank, 2015 as cited in UN-Habitat (2017)). According to UN-Habitat (2017) report, Addis Ababa is one of the fastest-growing cities on the continent. Its population has nearly doubled every decade the population of Addis Ababa has grown from 2 million to about 4 million in the last fifteen years with the administrative area expansion from 220 to 540 square kilometers.

This has resulted in heavy pressure on the Addis Ababa City Administration and the Addis Ababa Water and Sewerage Authority to extend safe drinking water supply and sanitation services.

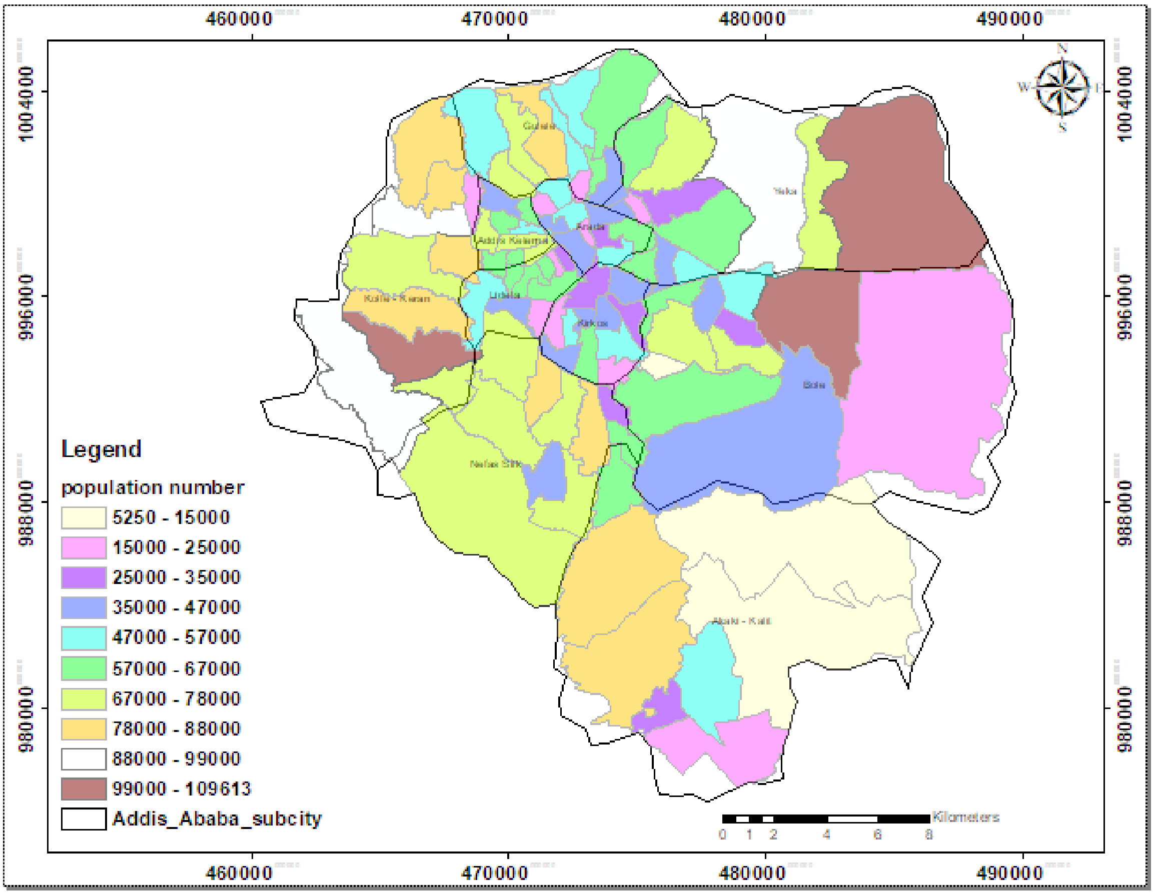


Fig 3.3:- Population map of Addis Ababa city

In 1984 the population was 1, 412, 575, in 1994 it was 2,112, 737, and this number will continue to rise, According to the city government of Addis Ababa's 2011/2012 report, the total population of Addis Ababa was estimated to 3,048,631 reaching 12 million in 2024. Lack of water scheme maintenance and lack of new facilities combined with rapid population growth has brought water shortage in Addis Ababa. A high volume of water wastage due to faulty piping (as high as 35 percent), and needs priority given to industries, also contribute to the shortage. In terms of the urban population, it currently accounts for at least 22.9% of the country's total urban population (CSA, 2012). The population of Addis Ababa in various sub-cities and kebeles is displayed in (Annex 4) for the years 2007 and 2020. (Source, CSA, 2021). Addis Ababa is divided into 10 sub-cities with the population of each sub-city as shown in (**Table 3-1**) below kolfe keranyo, yeka and Nefassilk Lafto sub-cities are highly populated.

Table 3-1:- Addis Ababa sub-cities population 2007 and 2020 (CSA, 2021).

Addis Ababa Sub-Cities	2007			2020		
	Both sex	Male	Female	Both sex	Male	Female
AKAKI KALITY	181,270	88,714	92,556	244,042	118,454	125,588
NEFAS SILK-LAFTO	316,283	148,984	167,299	425,935	198,929	227,006
KOLFE KERANIYO	428,895	207,641	221,254	577,467	277,250	300,217
GULELE	267,624	129,396	138,228	360,334	172,774	187,560
LIDETA	201,713	96,272	105,441	271,617	128,546	143,072
KIRKOS	221,234	103,500	117,734	297,949	138,197	159,752
ARADA	211,501	99,165	112,336	284,836	132,409	152,427
ADDIS KETEMA	255,372	124,898	130,474	343,807	166,768	177,039
YEKA	346,664	161,592	185,072	466,885	215,763	251,122
BOLE	308,995	145,225	163,770	416,127	193,910	222,218

3.5 Water services

Water commonly is not present at the locations and times where and when it is most needed. As a result, engineering works of all sizes have been constructed to distribute water from places of abundance to places of need. In Addis Ababa, water services coverage is almost universal (99.9%) with access to none-shared taps increasing from 20% in 2007 to 42% in 2011 (UN-Habitat, 2017).

However, a tap is only as good as the water it provides and despite the increased coverage in the water services network, the supply has increasingly become unreliable. The situation is worst for relocatees in peri-urban areas with more frequent supply interruption in the resettlement areas compared to relocatees' experience before their relocation (UN-Habitat, 2017). Knowing which part of the city gets more uninterrupted water supply (from surface water reservoirs? From ground water? From both sources?) Supports which water supply strategy better enhances water supply services in the city.

3.6 Hydrometeorology

3.6.1 Climate

Climate change will have an impact on water quality and even water ecosystems, with precise consequences varying among locations and water bodies (Xia, X.H. et al, 2014). Temperature, as well as the amount and distribution of precipitation, have a considerable influence on the processes of rock weathering. Climate change will have a minor impact on physicochemical characteristics. Dissolved oxygen and carbon dioxide will be greatly impacted, with long-term consequences for aquatic Flora and Fauna. Climate change will have an impact on water quality and even water ecosystems, with precise consequences varying among locations and water bodies. Climatic patterns tend to produce distinct plant communities and soil types, and the composition of water in streams draining such regions (which may subsequently percolate to join groundwater) could be viewed as a product of the ecological balance.

Certain of the key ionic elements of natural water are more significantly influenced by climate factors than others. In locations where the plant grows abundantly, bicarbonate, for example, tends to prevail in water. Some metals are deposited by vegetation and may reach peak concentrations when plant-decay cycles allow excess metals to enter the circulating water.

National Atlas of Ethiopia (1981) defined five climatic zones: "Kur" (Alpine), 3000m and above mean sea level; "Dega" (temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical), 1500 to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m. Having a maximum and minimum elevation range a little above 3000m and a little below 1500m respectively, most of Addis Ababa falls under the Weina Dega (Sub tropical) category. Accordingly, the climate of the Addis Ababa area is typically characterized by two distinct seasonal weather patterns: the wet season which extends from June to September, contributing about 70% of the annual rainfall, and the dry season which covers the period from October to May with a minor rainy season in March and April well known for its frequent failure. Such climates which are characterized by alternating wet and dry seasons may favor weathering and affects Physico-chemical parameters of ground water (Solomon waltenigus, 2007). The names and geographical locations of active hydrometeorological stations are as described in (**Table 3-2**).

Table 3-2:- Location of active meteorological stations in Addis Ababa

station name	Elevation (m)	Longitude (◦)	Latitude (◦)
Addis Ababa Bole	2354.0	38.8	9.0
Addis Ababa Obs	2386.0	38.7	9.0
Akaki	2057.0	38.8	8.9
Ayertena	2325.0	38.7	9.0
Intoto	2903.0	38.7	9.1
Kality	2186.0	38.8	8.9
Kolfe Keranio School	2382.0	38.7	9.0
Kotebe TTC	2462.0	38.8	9.0
Medhanalem/Sch	2539.0	38.7	9.1
Yekatit 23 School	2456.0	38.7	9.0

3.6.2 Precipitation

According to Daniel (1977) classification of Ethiopia's rainfall regions, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region, there are seven rainy months from March to September and the small rains occur from March to May. The big rains are from June to September. A high concentration of rainfall occurs in July and a very high concentration in August.

Climatic conditions appropriate for deep weathering, specifically precipitation exceeding evapotranspiration to provide rainfall-fed groundwater recharge, have existed in Western Ethiopia since the Miocene to maintain deep weathering, which has continued in the west but not in the east and north (Seifu Kebede, 2013).

In this study, monthly total rainfall records of four stations for the year between 1996 and 2019 are used to analyze monthly mean rainfall, annual mean rainfall, and rainfall coefficient. The mean monthly and annual mean rainfall of National Meteorological Services Agency (NMSA) stations at Intoto, Addis Ababa Bole, Addis Ababa Observatory, yekatit 23 schools, Ayertena, and Akaki are shown in (**Table 3-3**). All stations are located at different geographical coordinates rainfall affects the weathering of rocks.

Table 3-3:- Mean monthly rainfall (mm) at six stations in Addis Ababa (1996-2019)

station name	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Mean Annual RF (mm)
Addis Ababa Bole (mm)	11.7	15.1	49.1	63.5	79.4	106.3	223.2	251.7	123.9	31.5	5.2	7.1	967.7
Addis Ababa Obs (mm)	16.4	17.5	46.6	63.8	74.5	127.3	239.3	293.3	176.9	33.8	11.5	8.5	1109.6
Akaki (mm)	10.3	15.3	42.9	66.9	66.1	108.2	205.4	195.8	111.0	17.0	8.0	3.5	850.4
Ayertena (mm)	10.6	16.6	43.9	60.9	76.0	125.7	245.1	262.8	151.7	31.0	7.0	4.2	1035.5
Intoto (mm)	11.1	16.6	46.1	63.4	79.9	152.4	301.6	306.1	125.6	28.8	15.7	7.4	1154.6
Yekatit 23 School (mm)	8.9	13.1	41.7	56.2	81.3	144.7	259.6	250.0	137.4	27.5	10.1	5.6	1036.1

3.6.3 Temperature

The investigated Area is characterized generally by a warm climate with a mean annual temperature of 16.88^{0}c. The highest and lowest mean maximum temperature over the record periods is 28^{0}c in the dry season (May) and 23^{0}c in the wet season (July), while the variation of mean monthly temperature values falls in the range of 7^{0}c (December) to 12^{0}c (May) throughout the year. From these values, one can observe that daily variation in temperature in the area is more pronounced than the annual variation and the calculated mean annual temperature was around 16.88^{0}c. In general, one can classify the climate in this area as a warm temperate climate.

3.6.4 Evapotranspiration

Evapotranspiration is a term that refers to the combination of two independent processes by which water is lost from the ground surface and open water bodies by evaporation and plants via transpiration (ET).

Surface water is more enriched in isotope concentration due to evapoconcentration. Groundwater is comparatively lower with isotope concentration than surface water. Evaporated water bodies and waters exposed to vapor loss such as lakes, wetland waters, running waters, reservoirs, and oceans tend to enrich in their heavy isotope content with respect to the vapor derived out of them. Another form of evaporation effect results from the evaporation of rainfall while the rain droplets are making their way to the ground. In arid and semi-arid environments significant evaporation of rain droplets in the dry atmosphere can take place resulting in enrichment of rainwater and deviation from the global meteoric water line (Seifu Kebede, 2013).

Demlie (2007) estimated the mean annual potential evapotranspiration of the Akaki catchment to be around 1215mm using the FAO Penman-Monteith technique. In general, evapotranspiration is the most important factor in the loss of surface and subsurface waters in the study area.

CHAPTER FOUR

GEOLOGY, HYDROGEOLOGY, AND HYDROCHEMISTRY

4.1 Regional geology

Ethiopia is separated into four primary physiographic zones, which are commonly referred to as the western plateau, southeastern plateau, main rift, and Afar depression. The orogenic bands of the Arabian Nubian shield and the Mozambique belt are thought to be more dominant in Ethiopian outcrops than in any other horn of Africa country (Kazmin, 1972; Berhe, 1990). However, the rocks belonging to these orogenic belts are only exposed in a few areas, which have not been affected by Cenozoic volcanism and rifting, and where the Phanerozoic cover rocks have been eroded (Tefera et al., 1996).

The Ethiopian plateau is underlain at depth by Precambrian rocks of the Afro-Arabian Shield (Mohr, 1967). The Precambrian rocks are high-grade gneisses and migmatites. The Precambrian basement is covered for the most part by glacial and marine sediments of the Permian to Paleogene period and Tertiary volcanic rocks with related sediments. Crustal motion started at the beginning of the Mesozoic era, about 225 million years ago. During the late Triassic and early Jurassic periods, a regional epirogenic sinking of the crust commenced causing a progressive transgression of the ocean from the southeast that is, from the Indian Ocean coast of present-day Somalia in the general direction of Lake Tana in North West Ethiopia.

The great east African rift system started to develop in Miocene. Rifting began from the presently oceanic red sea and Gulf of Aden rifts, which joins with the younger and continental Main Ethiopian Rift (MER) at the complex proto-oceanic Afar triple junction (Afar Depression). According to Kazmin et al., (1980), initial sagging of the MER started at about 15ma and was followed by major episodes of rifting at 10ma, 5ma, 4ma, and 1.8 to 1.6ma. Each stage of rifting and down faulting was accompanied by bimodal (felsic-mafic) volcanism in the rift and formation of basaltic and trachytic shield volcano on the rift shoulder and margins. This rifting resulted in a physiographic setup that incorporates highlands, escarpment, and rift (low land). Eventually, Addis Ababa happens to fall on the western margin of the main Ethiopian rift.

Zanettin (1978) divided the tertiary volcanism of central Ethiopians into three stages of volcanism and tectonics. Where the first transitional (thiolettic) flood basalt is followed by alkali rhyolite and ending with alkali basalt. At first, the volcanism has occurred on a large elongated basin. The outer part of the basin was uplifted and deep eroded (peniplanation of Ashangi) during this stage the volcanism dies out on the uplifted area.

According to the general geological description of the Awash River basin (Tenalem Ayenew et al., 2007), most of the highlands are covered with early Cenozoic Trap Series volcanic (dominantly basalt, rhyolite, and ignimbrite) and the rift with acidic volcanic of the Nazreth Group and a relatively younger basic volcanic of the Afar Group (Zanettin et al., 1980). The rift floor plains are often covered with thick lacustrine and alluvial deposits.

Quaternary sediments of different origin (fluvial, lacustrine, eolian, alluvial marine) are widely spread all over Ethiopia, in the Main Ethiopian Rift the Quaternary sediments are mostly of lacustrine origin. Lacustrine beds are interbeded with Plio-Pleistocene pyroclastic in the lakes region and on the rift shoulder (Mohr, 1966: Lloyd, 1980). The lacustrine beds are mostly re-deposited volcanic sands tuff with calcareous material and diatomite. According to Mohr (1996) at the beginning of the quaternary and ancestral lake which was almost certainly continuous from the Abaya-Chamo lakes to the south of the Awash basin to the north existed. Until it shrunk to a smaller one by Late Pleistocene tectonic movement, Pleistocene- Holocene parts of afar is represented by several sheet flood terraces mainly composed of salts, sand, gravel, gypsiferous, fossiliferous limestone of lacustrine origin.

All the rocks are faulted in the rift and adjacent rift escarpments. The rift is distinctly separated from the plateaux by a series of step-faults. A major fault running E-W via Kesem river-Addis Ababa-Ambo cuts across the western rift escarpment and uplifted its northern block (Zanettin et al., 1978) about 8 My ago. This fault marks the outer boundary of the western Ethiopia rift margin immediately north of Addis Ababa - Ambo (Zanettin et al., 1974).

4.2 Local geology

The study area being part of the Main Ethiopian Rift (MER) its geological setup arises from the evolution and development history of the Ethiopian Plateau and the Rift system. Thus, the catchment is covered by a range of volcanic rocks overlain by fluvial and residual soils varying in thickness from a few cm to about 19 m in which black cotton soil is the predominant type. The volcanic formation includes mainly basalts, rhyolites, trachyte, scoria, trachybasalts, ignimbrites, and tuff belonging to a wide range of ages most of which are highly weathered and fractured (Molla Demlie et al., 2007).

The area that covers the city of Addis Ababa and/or the Akaki river catchment consists of various volcanic rock units of different compositions and ages. Following a traverse from North (Entoto Mountain) to South (Akaki-Kality area), the geological formations change from the oldest volcanic sequences to the youngest.

The geological formation of the Akaki catchment is categorized as Miocene–Pleistocene volcanic successions in which basaltic lava flows, acidic and intermediate lava flows, and pyroclastic flows interlayer and frequently intersected by Quaternary normal faults. Stating different sources, the summary made by (Ayenew et.al. 2008, as cited in Ruhama Kifle, 2016) about the lithostratigraphy of the study area was as follows:

Generally, the litho-stratigraphy was classified into four groups saying Alaji Formation, Addis Ababa basalts, younger volcanic, and recent deposits. The Alaji Formation group includes the rhyolites, trachyte, tuff, agglomerate, and aphanitic basalt dominating the northern and central parts. This was also further into Alaji rhyolites and Intoto Silicic in which the Intoto Silicics represents massive Oligocene fissure-basalt, rhyolites, and trachytes with minor welded tuff and obsidian.

The second group, the Addis Ababa basalts, overlay the Intoto Silicic and covers the central and southern part of Addis Ababa. Paleosol and scoriaceous horizons are common and Olivine porphyritic basalt outcrop in central Addis Ababa with a thickness varying from 1 m in the foothills of Intoto to more than 130 meters in central Addis Ababa.

The third ones, the Younger Volcanics, include the Nazareth Group and Bishoftu Formations. The Nazareth Group contains aphanitic basalts, welded tuffs, ignimbrites, trachytes, and rhyolites being aphanitic at the top and porphyritic at the bottom. These rocks were found dominantly south of the Filwuha Fault. On the other, the Bishoftu Formations consists of olivine porphyritic basalt, scoria, vesicular and scoriaceous basalt, and locally trachybasalt lava flows overlaid by scoria, tuff, sand, and gravel.

These are dominant in the southern part in which the Akaki well field is found forming the major aquifers. Their thickness varies from 20- 40 m in the Akaki well field. The last group, Recent Deposits, includes alluvial, residual, and lacustrine deposits.

Overlaid by dark younger black cotton clayey soils in some parts, the thicknesses of these deposits vary from 5 m to 50 m and are dominant in the southern part. Further, Alluvial deposits are found along the Little- and Big-Akaki rivers and in most flat plains

According to the studies conducted by different geologists on the city of Addis Ababa area (Kebede Tsehayu & Tadesse Hailemariam, 1990, Seureca, 1991, Morton and al, 1979, Antonio Vernier & Tesfaye Chernet, 1985, Gasparon and al, 1993 and BCEOM/Suereca 2000), the following rocks are exposed generally from the north to the south. The local geology of Addis Ababa is Trachytes, rhyolites, basalts, and pyroclastics of Entoto Mountain and northern and northeast Addis Ababa, Basalts of the central and southern Addis Ababa known as Addis Ababa Basalt; Ignimbrites of the eastern (Bole area) and central Addis Ababa (Ledeta area); Trachy-basalts, trachyte, ignimbrite, and tuff forming the volcanic mountains of Wechecha, Furi and Yerer; Basaltic lava, spatter and cinder cones and maars of Akaki and Lacustrine deposits, Alluvial and residual soils: Lacustrine soils occur around Bole, Lideta, Mekanisa, between Abasamuel Lake, Akaki town and small Akaki River and their thickness of this deposit varies between 5m and 50m.

Addis Ababa is located at the edge of the Ethiopian Rift, there are a number of fault systems having a general trend of the rift system (NE - SW) and some faults and lineaments oriented E-W, N-W, and NE - SE. The density of faults and lineaments increases to the southeast of the town towards the rift valley. Moreover, Akaki catchment being near the MER, rocks were subjected to rift tectonics that is manifested by a number of fault systems having a general trend of the rift system NE, and some are also oriented in EW, NW, and NS (Ebasa Oljira, 2006).

The geological map of the study area presented in (**Figure 4.1**) was adopted from the works on a hydrogeological map of Addis Ababa, Akaki, and Dukem Areas by AG consult (AG consult, 2004 as cited in Ebasa Oljira, 2006).

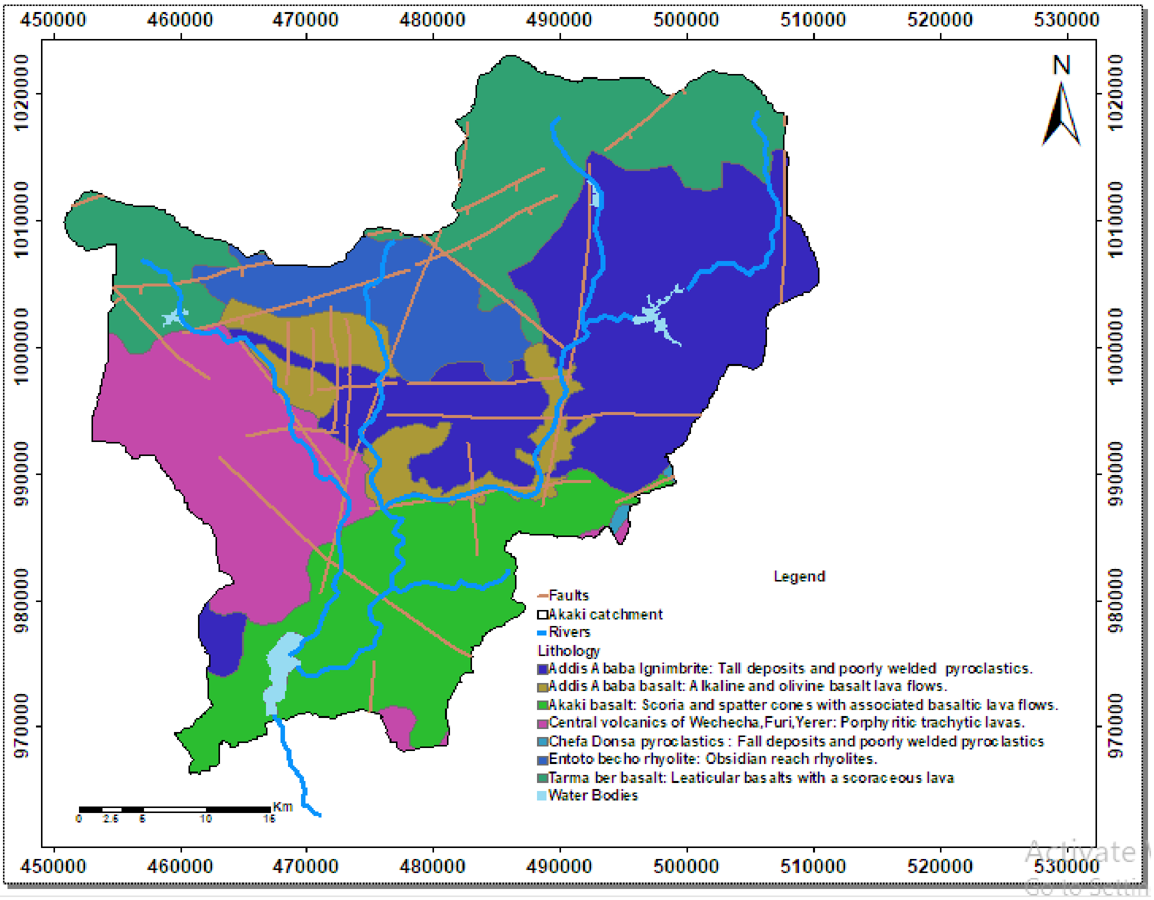


Fig 4.1:- Geological map of Akaki catchment (source; WWDSE, 2008)

4.3 Location of Reservoirs and Well fields with geochemical setup

As described earlier, the geology of the Akaki catchment is very complex. Several rock units of different composition and/or age can be encountered along a given transect. As a result, it happens that the reservoir generally falls in three different geological settings. Two of them (namely Dire and Legedadi reservoirs) that are located to the northeast (NE) part of Akaki catchment lie on the Addis Ababa basalts (porphyritic to aphanitic basalt), one of them (Gefersa reservoir) that is located to the North-Western part of Akaki catchment lie on the Chilalo formation (younger volcanic rocks comprising rhyolites, ignimbrite, trachyte, and trachybasalts) and Aba Samuel reservoir that is located further to the south lies on the Alluvial deposit and Lacustrine clays and silts generally 5-50m thick.

The Bishoftu Formations consists of olivine porphyritic basalt, scoria, vesicular and scoriaceous basalt, and locally trachybasalt lava flows overlaid by scoria, tuff, sand, and gravel. These are dominant in the southern part in which the Akaki well field is found forming the major aquifers. Their thickness varies from 20- 40 m in the well field (Tenalem Ayenew et al., 2008). The Akaki well field which contributes 25% domestic water supply for Addis Ababa city, and the DebreZeyt well field some 45 km south of Addis Ababa city both tap water from the young Quaternary basaltic aquifers (Seifu Kebede et al., 2008).

4.4 Hydrogeological Setting

Swaine and Schneider (1971) refer to the chemical composition of groundwater changing during circulation due to ion exchange. They further indicate that the composition of water is often modified during concentration, mainly by ion-exchange effects.

Volcanic rocks have been always considered very important from the hydrogeological point of view. Although they are very heterogeneous, they have been recognized as important groundwater-bearing formations. Notable is also the fact that the groundwater circulation in these units is normally not very deep so that frequent springs or geometrically well-defined productive aquifers occur (Tamiru Alemayehu, 1992).

Volcanic rocks, due to their complex Spatio-temporal distribution, their different reciprocal stratigraphic relationships, their changeable contacts with ancient and recent rocks, their great compositional, structural, and textural variability, and their different level of tectonization and weathering, have complex hydraulic characteristics (Davis and DeWiest, 1966; Vernier, 1993).

The hydrogeology of the Akaki catchment is not simple due to the extreme variations of lithology and structure (Molla Demlie, 2007). Scoria and scoriaceous basalt constitute highly productive aquifers with primary porosity and permeability. Highly weathered and fractured basalts, fractured tuff, ignimbrite, and other pyroclastics are highly productive aquifers of secondary porosity and permeability. Basalt with some fractures, vesicles and sparsely spaced joints, ignimbrites, and agglomerates form moderately productive aquifers in the area.

These units, which can be mapped as aquifers, have been grouped into an upper shallow phreatic aquifer, constituted by weathered and fractured volcanic rocks, and a confined or semi-confined volcanic aquifer of wide areal coverage (Girma A, 1994).

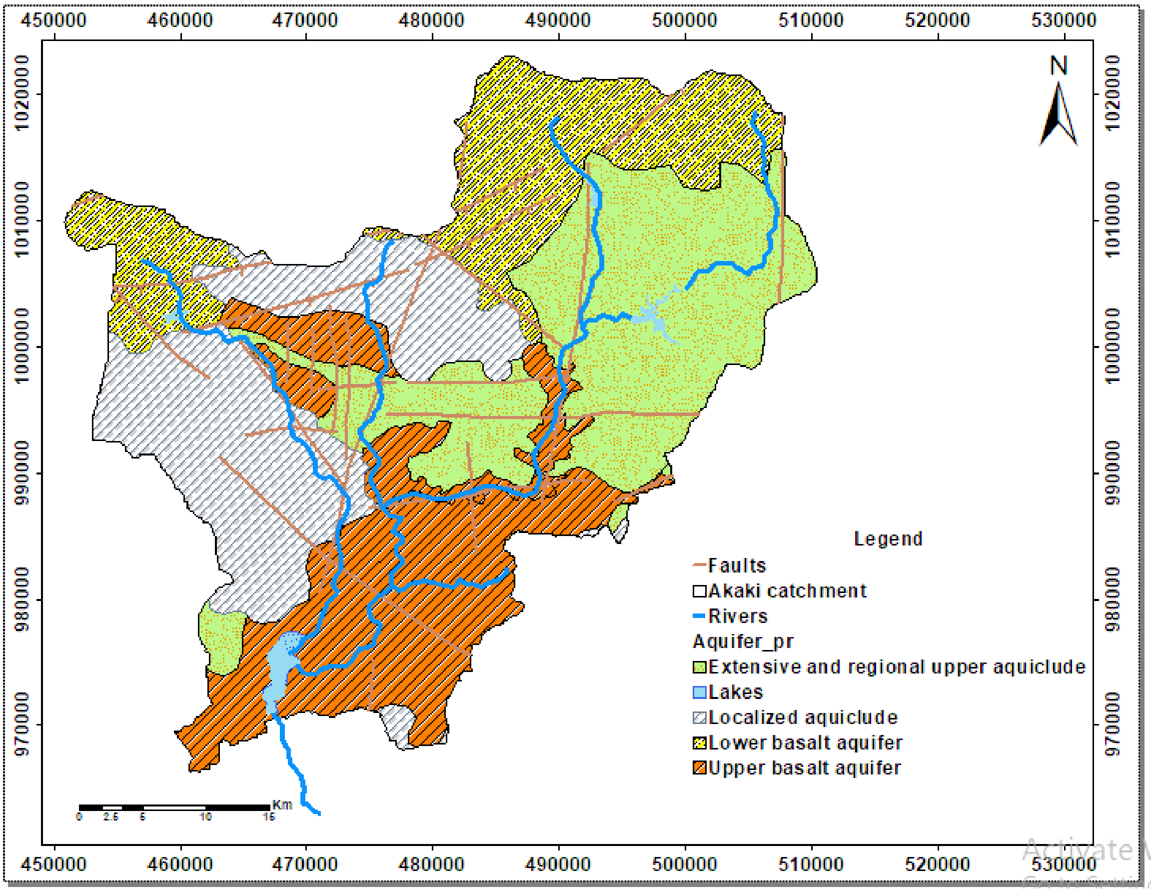


Fig 4.2:- Hydrogeological map of Akaki catchment (source; WWDSE, 2008)

The existence of highly conductive groundwater pockets is explained by the base exchange processes in areas where a higher grade of weathering takes place (sarma and krishnaiah, (1976) as cited in Sarma et al., (1979). The lithologies of most geological formations tend to vary significantly both laterally and vertically. The lithology, stratigraphy, and the geological structures that affect the rocks largely control the nature and distribution of aquifers in a geologic system.

The water in the fissures contains ions such as Na^{+}, Ca^{2+}, Cl^{-}, So_4^{2-} which reduce the resistivity of the rock and increases the conductivity of water. The highly weathered lithologies are found mostly in the southern part of the Akaki catchment. In the Akaki well field, there is existence of highly conductive groundwater it is considered that hydrogeological situation in areas of a higher grade of weathering takes place.

Aquifer transmissivities are observed as showing a gradual increase from the north towards the south where the main productive aquifers and the Akaki well-field are located.

Water-level observations from wells show that groundwater flows generally from north to south in the northern and central sector of the catchment, and southeastwards towards the Akaki well-field in the southern sector of the catchment following the topographic gradient (Molla Demlie et al., 2007).

4.5 Hydrochemistry

The composition and properties of surface water and groundwater resources are affected by many factors such as the water source, evaporation, catchment geology, contact times with reactive minerals, and the velocity and direction of water movement (Freeze and Cherry, 1979). Both surface water and groundwater composition are also highly vulnerable to anthropogenic impacts.

The chemical composition of natural waters and the number of its ionic species depend on several factors: type of soil and rock through which the water passes, the degree of weathering and solubility of the mineral components of the rocks and soils, the extent and duration of the contact with rocks and soils, the temperature conditions, the type of dissolved and suspended solutes that falls with precipitation (Tenalem Ayenew, 2005).

The chemical composition of natural water is derived from many different sources of solutes, including gases and aerosols from the atmosphere, weathering, and erosion of rocks and soil, solution or precipitation reactions occurring below the surface, and cultural effects resulting from human activities (Hem, 1992). The chemistry of groundwater in the saturated zone is controlled by chemical reaction rate, residence time within the saturated zone, and mineralogy of the rock matrix, where residence time and flow path are determined by factors such as aquifer thickness, permeability, and amount of recharge (Griffioen, 2004). These factors combine to different degrees to create diverse water types with compositions that vary with space and time. The objectives of the hydrochemical investigations are to determine the sources, concentration, and fate of dissolved constituents within the physical framework of flow and transport (Griffioen, 2004).

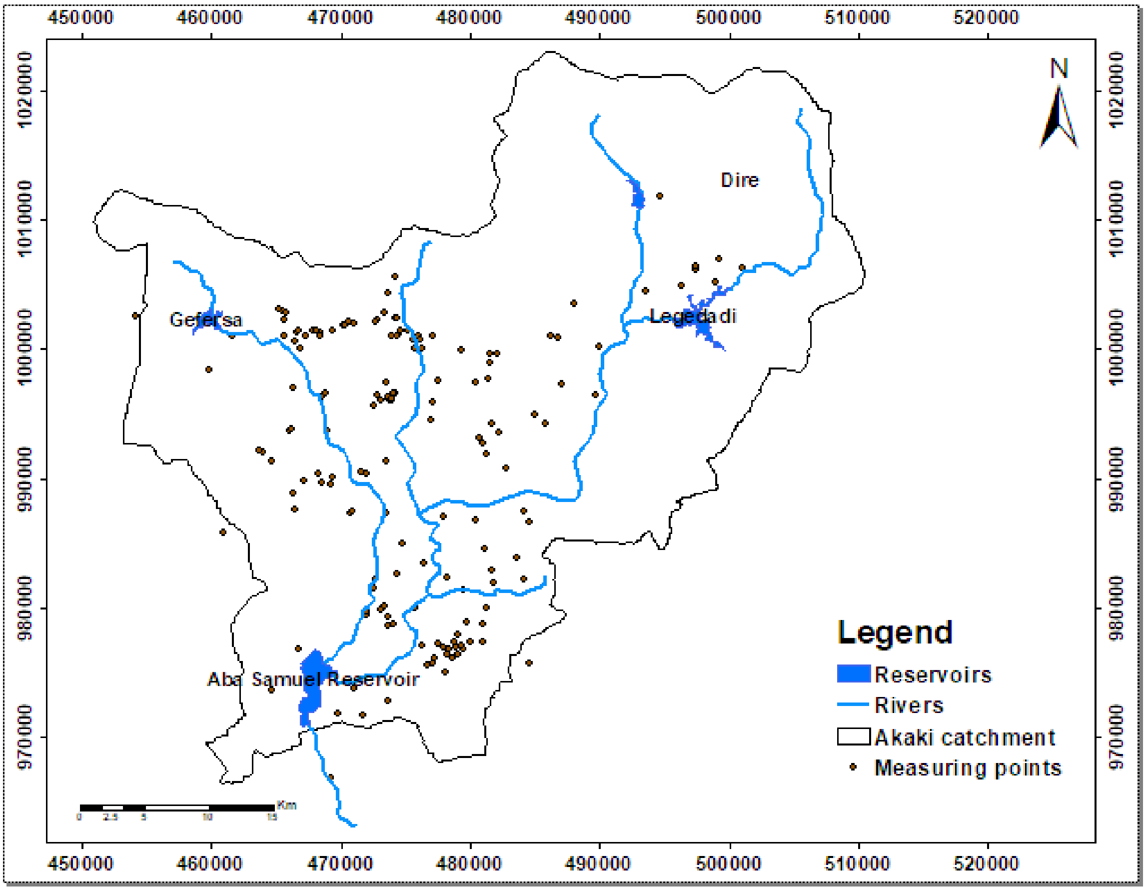


Fig 4.3:- Location of measuring points

The groundwater is dominated by alkali earth and bicarbonate ions, with comparatively slight salt concentrations. In terms of silica, all of the waters are saturated. Because of ion exchange, the chemical composition of groundwater changes during circulation (Swaine and Schneider, 1971).

Water chemistry data can be used to infer groundwater flow directions, identity sources and amounts of recharge, estimate groundwater flow rates, and define local, intermediate, and regional flow systems (Anderson and Woessner, 1992). For major cation and anion data to provide the greatest insight into the nature of groundwater flow systems, interpretations must include consideration of specific hydrochemical processes that can account for the observed concentrations (Freeze and Cherry, 1979).

To identify the water supply sources, the water chemistry of the area is used as a supplementary for the classification of water type. The secondary water chemistry data from different sources (boreholes, springs, and rivers) were collected from different organizations.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Results

Chemical analysis results for groundwater secondary data from prior research are given in (**Table 5-1**). Groundwater physicochemical characteristics are summarized in (Annex-1). According to (**Table 5-1**), the groundwater is dominated by alkali earth and bicarbonate ions, with comparatively high salt concentrations. In terms of silica, all of the waters are saturated.

Table 5-1:- Descriptive statistics of Physico-chemical parameters of groundwater

Parameters	SD	Max	Min	Average	Variance
EC (µs/cm)	978.3610156	4600	58.5	747.10847	957190.277
TDS	681.999591	3220	38.025	498.64137	465123.442
PH	0.427348706	8.67	6.2	7.4743605	0.18262692
NH4 (mg/l)	0.198499561	1.19	0	0.2802865	0.03940208
Na (mg/l)	228.8396445	1150	3	125.9468	52367.5829
K (mg/l)	8.121284139	72	0.9	8.0062209	65.9552561
Ca (mg/l)	20.8501744	96.8	2.46	32.095291	434.729773
Mg (mg/l)	7.281927315	29.2	0.24	8.7455233	53.0264654
Fe (mg/l)	0.125646732	1.23	0	0.0373235	0.0157871
Mn (mg/l)	0.036514837	0.1	0	0.0366667	0.00133333
Cl (mg/l)	12.27611485	69.3	0.96	16.491919	150.702996
NO2 (mg/l)	0.142092919	0.65	0	0.05695	0.0201904
NO3 (mg/l)	8.216921936	52.6	0	5.5274329	67.5178061
F (mg/l)	6.896288843	41.55	0	3.2288304	47.5587998
HCO3 (mg/l)	537.1017785	2269.2	29	430.04581	288478.32
CO3 (mg/l)	19.12753356	208.08	0	2.623125	365.86254
SO4 (mg/l)	21.95666705	203	0	14.358869	482.095228
PO4 (mg/l)	0.426777846	4.34	0	0.3001598	0.18213933

5.2 Plausibility control of analysis

The water quality variables data, which were collected from the different sources during the fieldwork and/or obtained from laboratory analysis, were checked for their accuracy using anion-cation balance. A solution must be electrically neutral i.e. the sum of cations in meq/l should equal the sum of the anions in meq/l (Hounslow, 1995).

$$\text{Electro neutrality } (\%) = \frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} * 100$$

According to Hounslow (1995), if the electrical balance calculated is less than 5% then the analysis is assumed to be good and if it is greater than 5% the analysis is supposed to be poor, or some missed constituents are not included in the calculation or the water is very acid. But sometimes up to 10% is acceptable in dilute and saline water due to some errors during measurement (Fetter, 2001). The hydro-geochemical data from the laboratory analysis work were almost less than 10%. But for the secondary data collected from different resources only 170 out of 172 water quality data fulfilled the acceptable requirement of < 10% (**Annex-1).**

5.3 Hydrogeochemical facies

Hydrogeochemical water classification was done using the major anions and cations having charge balance error less than 10% and by plotting on piper diagram using Grapher version 13.2.734. Eight variables (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, and NO_3^{-}) were included in the clustering of the 170 Hydrochemical data.

Water types were identified using the piper pilot shown in **Figure 5.1**.Ca-HCO_3, Ca–Na–HCO_3, Na–Ca–HCO_3, Ca-Mg-HCO_3, Na–HCO_3, and other water types were identified based on the dominant cations and anions in groundwater samples. The facies are a function of lithology, solution kinetics, and flow patterns of the aquifer (Back, 1960; 1966 as cited in Fetter, 2001).

Water Chemistry data has been collected from previous studies for analysis and interpretation based on major cations and anions. Accordingly, compiled data from previous studies by (WWDSE, 2000; AAWSA, 2000) is presented in (**Annex-1**) and the resulting piper plot and classification of water types is shown in (**Figure 5.1**).

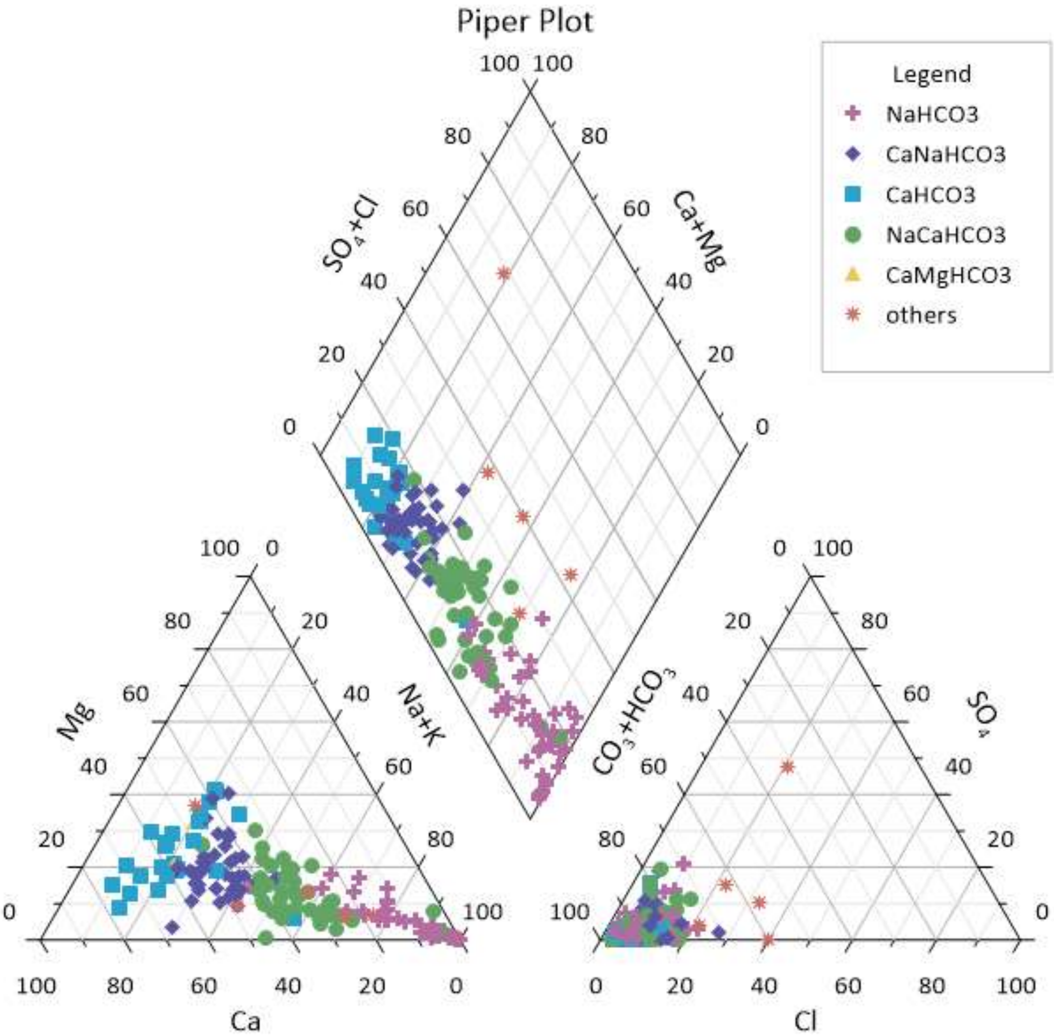


Fig 5.1:- piper plots of water samples

Piper plots were used to investigate chemical data clustering. Four major water types were discovered based on an assessment of the piper plot of chemical data from wells. These are the water types $CaHCO_3$, $CaNaHCO_3$, $NaCaHCO_3$, and $NaHCO_3$. Some of the data clustered around the $CaHCO_3$ water type, while others clustered around the $CaNaHCO_3$ and $NaCaHCO_3$ water types, and the remaining cluster is characterized by the $NaHCO_3$ water type. There have been a few situations where $MgHCO_3$ water types or their derived species have been seen, which for subsequent discussion have been regarded alongside $CaHCO_3$ water types.

The concentration of Na in groundwater boreholes in the northern and central research areas (summit, Ghion, National Palace, and Hilton) is higher than that of Ca and Mg. The Boreholes in the northern area are drilled on the Ambo-Filwuha fault line and the groundwater from deep water circulation has been more geochemically evolved.

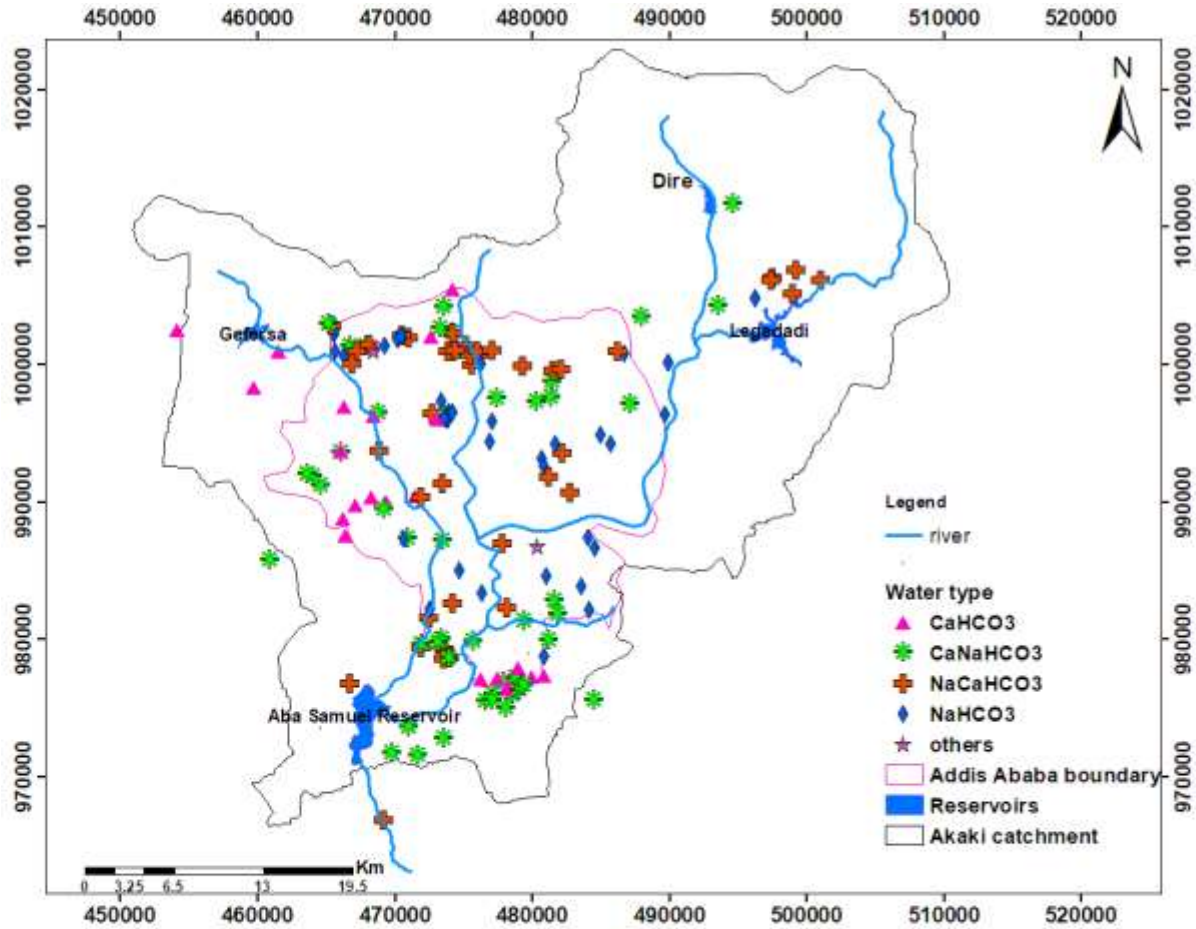


Fig 5.2:- Groundwater type variation along the Akaki catchment

Groundwater boreholes in the north tend to be dominated by Na-Ca-HCO3 water types, which is likely due to isolated patches generated by structures and faults that must be defined independently rather than as interconnected. The northern Na-Ca-HCO3 water type trends could be attributed to drilled wells on the Ambo-Filwuha fault line, and groundwater from deep water circulation that has been more geochemically changed, thermal influence, and higher residence time with rock contacts. As a result, the concentration of Na in groundwater boreholes in the northern section of the province is high.

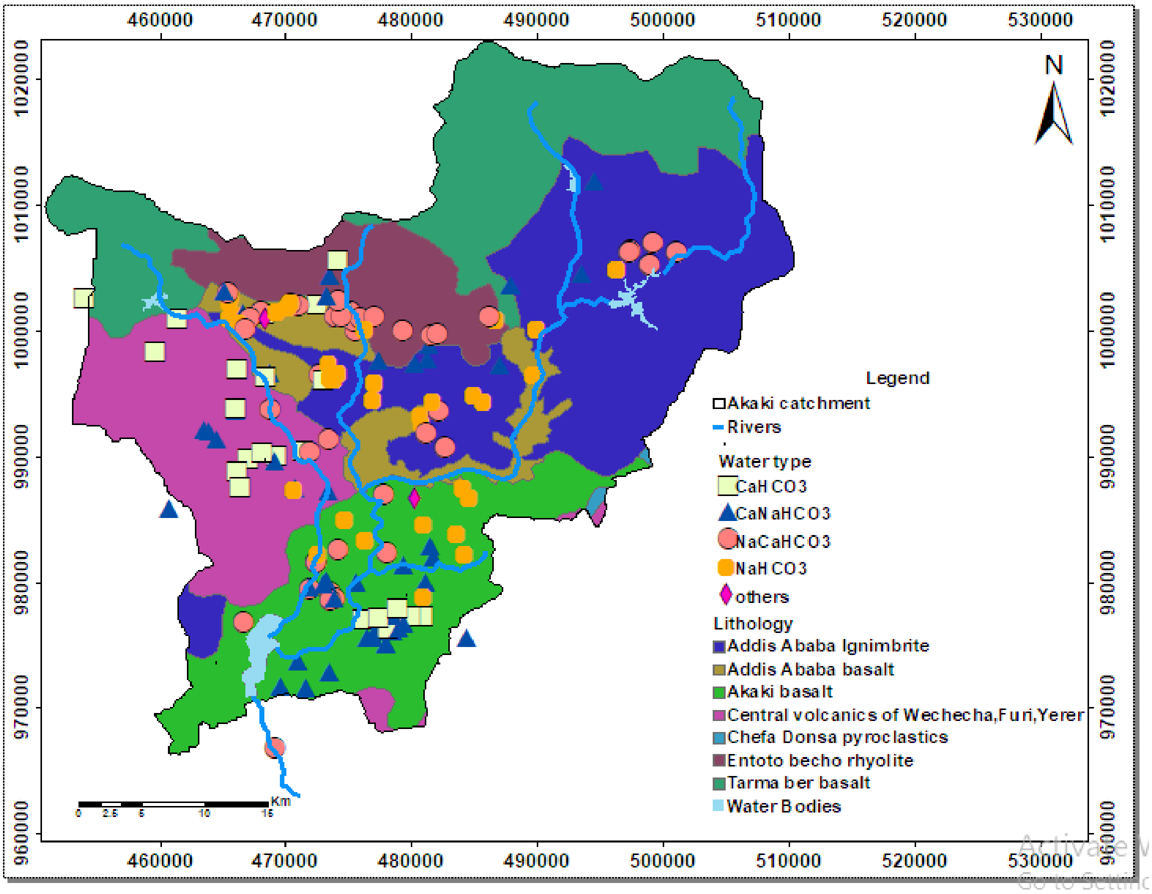


Fig 5.3:- Groundwater type and geology of Akaki catchment

The hydrochemical analysis revealed a high concentration of Na-Ca-HCO_3 and Na-HCO_3 type water draining the Entoto becho rhyolite in the north and Addis Ababa Ignimbrite (tall deposits and poorly welded pyroclastics) in the east as a result of drilled wells on the Ambo-Filwuha fault line indicating deep water circulation with thermal effect and long residence time; Ca-HCO_3 type water dominantly draining the central volcanic of Wechecha, Furi and Yerer (porphyritic trachyte lavas) in the western part and the Akaki basalt in the south; and Na-HCO_3 type water draining the 'Filwuha' thermal system While the Na-Ca-HCO_3-Cl type water cycling in the catchment's middle sector is a result of anthropogenic influences.

A limited number of chemical data show unique water type in the study area as shown by

(*) sign in the piper plot. These are $NaCaHCO_3Cl$, $CaNaHCO_3Cl$, NaClHCO3 and $NaHCO_3Cl$ water types.

For water samples evaluated from groundwater data in parts of the study area, the $CaHCO_3$ water type, which comprises $CaHCO_3$, $CaMgHCO_3$, and $MgCaHCO_3$, was observed in the Akaki watershed.

This groundwater type is distinguished by very low EC, frequently less than 400 mg/l, and thus represents an early stage of geochemical evolution in the recharge area and shallow depths of rapid circulation, as well as a relatively short residence time in the subsurface, with no significant water-rock interactions, corroborating similar observations earlier (Tilahun Azagegn, 2014). This group includes a few water samples taken from deep wells. This might be explained by a mixing effect, in which the measured section of the water is dominated by local recharges around the well. The aquifer material's mineralogy is responsible for the differentiation that can be detected between the $CaHCO_3$ and $CaMgHCO_3$ signatures in this water type. The latter is common in type water draining the Addis Ababa basalt in the central sector.

The second form of water is a mixture of $CaNaHCO_3$ and $NaCaHCO_3$. This category includes groundwater flowing in intermediate zones (depth and travel distance from recharge sites). The EC values of the waters in this category range from 100 to 600 mg/l. The low EC values from certain deep wells in this group might be explained by local recharging; nonetheless, the high EC values recorded in this group are attributable to comparatively extended residence time in the subsurface.

This water type indicates an intermediate stage of geochemical evolution, with a significant travel distance from the recharge location and/or at a somewhat deeper section of the aquifer, or a mixing influence of local recharge with the regional flow system. This, in turn, indicates that the groundwater in this group is in the transition zone between the recharge and discharge zones.

The third water type group in the area is $NaHCO_3$. This category's EC values range from 500 to 4600 mg/l. The 'Filwuha' thermal system is rock-dominated hydrochemistry of Na-HCO3 type water. The thermal features of the waters detected in the fault area could explain the high EC values in the research region's center. This shows a greater level of geochemical evolution, and the sampling sites are deep circulation fluid discharge zones. The high EC waters in this group are caused by thermal fluids cycling along the Fuloha fault zone. A high EC value in the lower Akaki watershed serves as a discharge point for circulating waters.

The fourth group consists of mixed-composition waters with high anion species concentrations (NO_3^-, Cl-, SO_4^{2-}). Anthropogenic factors such as animal waste and fertilizer use in the area may contribute to groundwater with a greater proportion of NO_3^-.

5.4 Physico-chemical parameters of groundwater sources

The groundwater Physico-chemical analysis is important in determining and characterizing the water supply sources. Physical and chemical parameters including statistical measures, such as minimum, maximum, Mean, Variance, and standard deviation are reported in (**Tables 5-1**). The following water quality parameters were selected and their respective maps were prepared: pH, EC, and TDS; using point data spatial analysis of Arc GIS 10.5.

5.4.1 Hydrogen ion concentration (pH)

Figure 5.3 shows interpolated spatial variation map of the pH of the groundwater in the Akaki catchment. When substances dissolve in water they produced charged molecules called ions. Hydrogen (H^+) ions are found more in acidic water whereas Hydroxyl (OH^-) ions are in basic water. The pH scale ranges from 0 to 14, with 7 being neutral for pure water. Acidic water has pH values less than 7, with 0 being the most acidic; likewise, the basic water has a value greater than 7, with 14 being the most basic. A change in pH from 7 to 6 indicates that there is a tenfold increase in hydrogen ion concentration. Similarly, a change in pH from 7 to 8 indicates a tenfold increase in the hydroxyl ion. In the area, the pH of water samples ranges from 6.2 to 8.67, indicating acidic to alkaline in nature (**Figure 5.4)** with an average of 7.47.

The highest pH values on average (7.73-7.86) appeared in the Eastern part of yeka sub-city. Other samples with relatively high values (7.47-7.73) have mainly occurred in Akaki Kality and the little northern part of Kolfe Keranyo sub-cities. Samples with medium values (7.3-7.47) refer to the location Nefassilk Lafto, the southern part of kolfe keranyo, and the Eastern part of Lideta. The location with the lowest values (7.2-7.3) is kirkos sub-city. Samples obtained from central Addis Ababa (Bole and Gulele sub-cities) also presented extremely low values (7.07-7.2). The high pH values in central parts of the study area are related to deep ground circulation through faults. A high pH value in groundwater shows that deep groundwater and slow groundwater recharge (Mahamat et al., 2017).

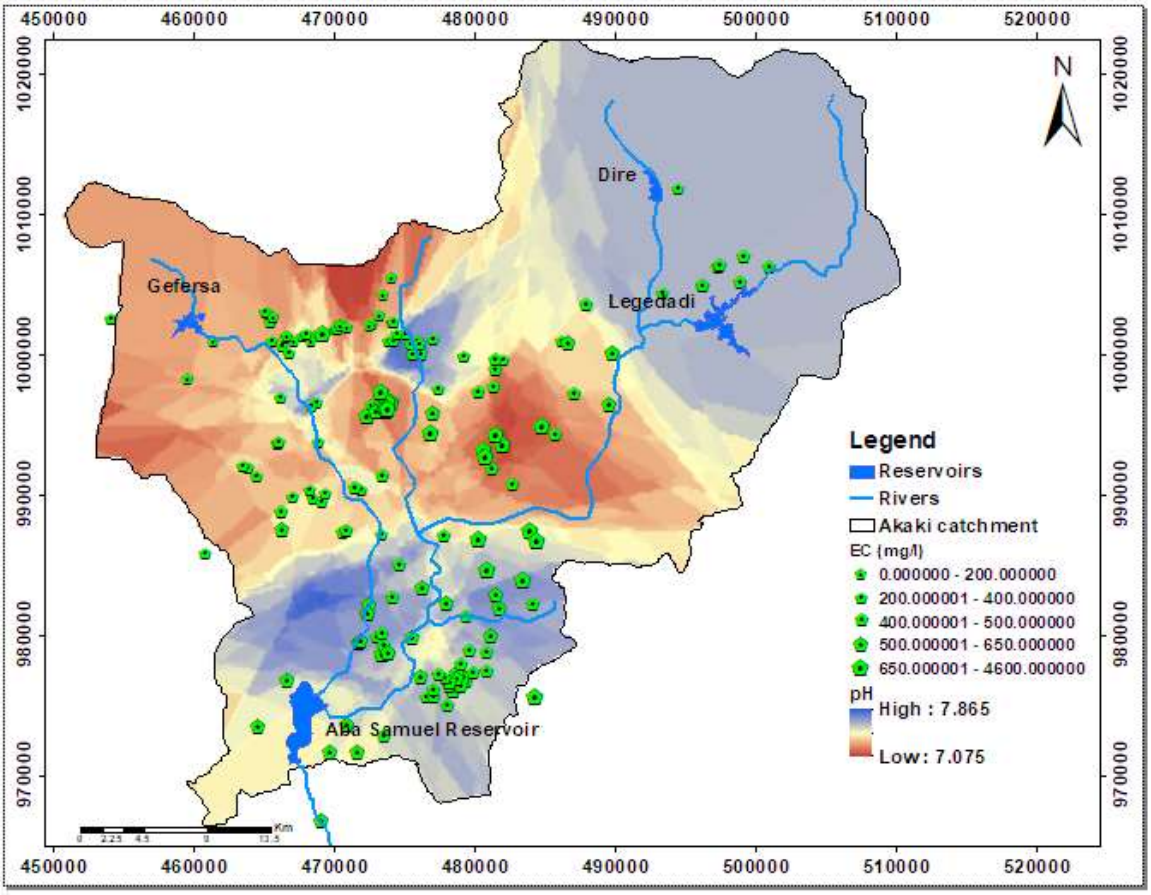


Fig 5.4:- spatial distribution map of groundwater pH

5.4.2 Electrical conductivity (EC)

The spatial variation of EC values is shown in (**Figure 5.5**). The interpolated spatial variation map of EC values shows that the low elevation and central part of the study area has a high value of EC concentration in groundwater. The low elevation area that found near the Akaki River and a lake that acts as a discharge area. The extreme values of EC on the central part of the study area could be due to the thermal properties of waters found in the fault area. The high values of EC near Akaki River and lakes could be due to surface-groundwater interaction based on hydraulic conductance and groundwater level. The low value of EC was observed in the highlands that act groundwater recharge (Fig. 5.5).

Electrical conductivity is a parameter related to total dissolved solids (TDS). EC is a measure of solution in terms of its capacity to transmit current. The importance of EC and TDS lies in their effect on the corrosion of a water sample and their effect on the solubility of slightly soluble compounds such as $CaCO_3$. In general, as TDS and EC increase, the corrosion of the water increases.

Therefore, the study of spatial variation of groundwater EC is necessary to identify the sources and for the optimized management of groundwater resources. The EC of groundwater sources in the study area varied from 58.5 to 4600µs/cm with a mean value of 747.1µs/cm.

The minimum EC was recorded 58.5µs/cm in Gebrechefie well northern part of Gulele sub-city. The maximum EC was recorded at 4600µs/cm in the central part of Addis Ababa's old national palace area. Lower groundwater EC values (200-400µs/cm) were detected on the northwestern Akaki catchment in kolfe keranyo, most of Nefassilk, Gulele, and north yeka sub-cities. Samples with medium values (400-600µs/cm) refer to the location Legedadi area and most of Akaki Kality. The location with higher values (400-600µs/cm) is the most of Akaki Kality, Legedadi area, and west yeka. The highest EC values on average (1000-3500µs/cm) appeared in Bole, Arada, kirkos, and Lideta sub-cities. In few area like FW-BH2 (4400µs/cm), GHION-DW (4300µs/cm), National palace old BH (4600µs/cm) and National palace new BH (4590µs/cm) which had extremely high Electric conductivity values. The extreme values in the Fuloha area are the case of thermal, brackish, and saline properties of the water.

The large variation in EC is mainly due to lithologic composition and anthropogenic activities prevailing in this region. It is observed that in some samples the EC values increase with the increasing amounts of sulfates, chloride, and bicarbonate.

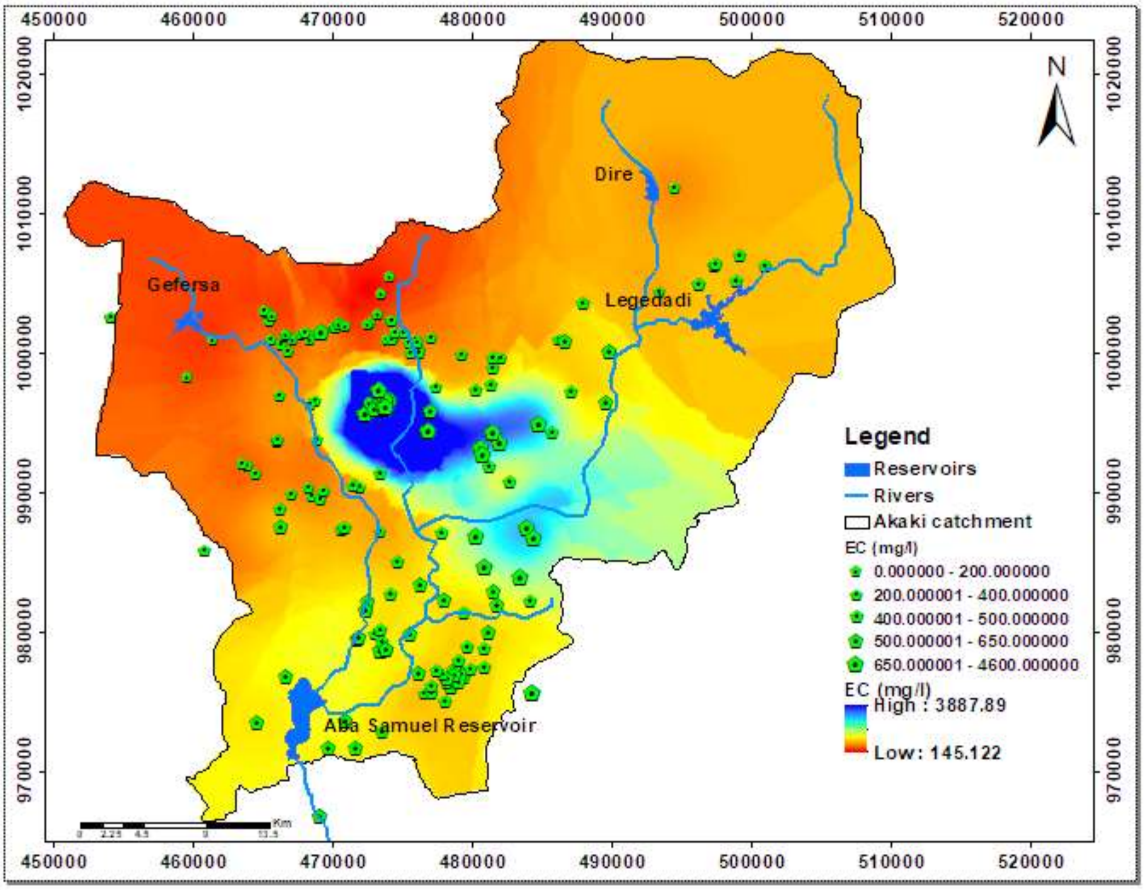


Fig 5.5:- spatial variation map of groundwater EC

The extreme EC values in the study area's center could be attributed to the thermal properties of the waters found in the fault zone. This fault is distinguished by the Filwuha thermal manifestations, which include hot springs and deep hot wells.

5.4.3 Total dissolved solids (TDS)

They originate from the dissolution or weathering of the rocks and soil, including dissolution of lime, gypsum, and other slowly dissolving soil minerals. A strong linear correlation of 0.99 is observed between EC and TDS. The relation is used to convert the conductivity value measured in the field to total dissolved solids to fill the data gap of laboratory analysis results (Annex1).

The general formula that can relate the specific conductance of natural water and dissolved solids is expressed as:-

KA=S, S= stands for dissolved solids in mg/l

K = conductance in micro semen

A= Conversion factor and for most groundwater, the specific conductance multiplied by a factor of 0.55 to 0.75 gives a reasonable estimate of the dissolved solids (Tenalem Ayenew and Tamiru Alemayehu, 2001).

In terms of total dissolved solids (TDS), there is a clear zonation following the direction of groundwater flow from the highlands to the rift. This zonation corresponds with the spatial variations of recharge, climate, and geological setting. Almost all highland surface waters and groundwater are fresh with TDS ranging from 50 to 1200 mg/l. Local exceptions with high TDS exist in the Akaki river catchment (Addis Ababa area) and few urban centers where the water is polluted by anthropogenic sources (Tale, 2000; Alemayehu et al., 2005; as cited in Tenalem Ayenew et al., 2008).

The spatial variation map of TDS is shown in **Figure 5.6**. The solubility of minerals resulted in high-value EC and TDS in groundwater. The majority of the study area has a TDS value less than 500 mg/l and falls in the freshwater group except for some areas found in the central part of the study area.

In addition, the TDS concentration of the area shows high dependency on the altitude. TDS of Water samples increase from the plateau area towards the river gorges and relatively low lands. Generally topographically high areas with high rainfall show low TDS than low topographic areas with low rainfall.

Groundwater Total Dissolved Solids is lowest along the North Akaki and highest in central Addis Ababa where values of up to the concentration of 3220 are recorded (**Table 5-1**). High TDS areas are observed at the central part greater than 1000mg/l (Filwuha area) and west of the city. These localized high TDS areas have a northeast-southwest direction following the main rift valley direction. The high TDS areas are mainly due to the thermal water effects and related either to thermal wells and springs along fault zones, very deep wells in discharge areas. Mean total dissolved solids concentrations are considerably higher from areas on the Central Addis Ababa than on the surrounding catchment area (**Figure 5.6**). The TDS in the area may be due to the influence of anthropogenic sources such as domestic sewage, industrial waste, septic tanks, agricultural activities, and the influence of rock–water interaction.

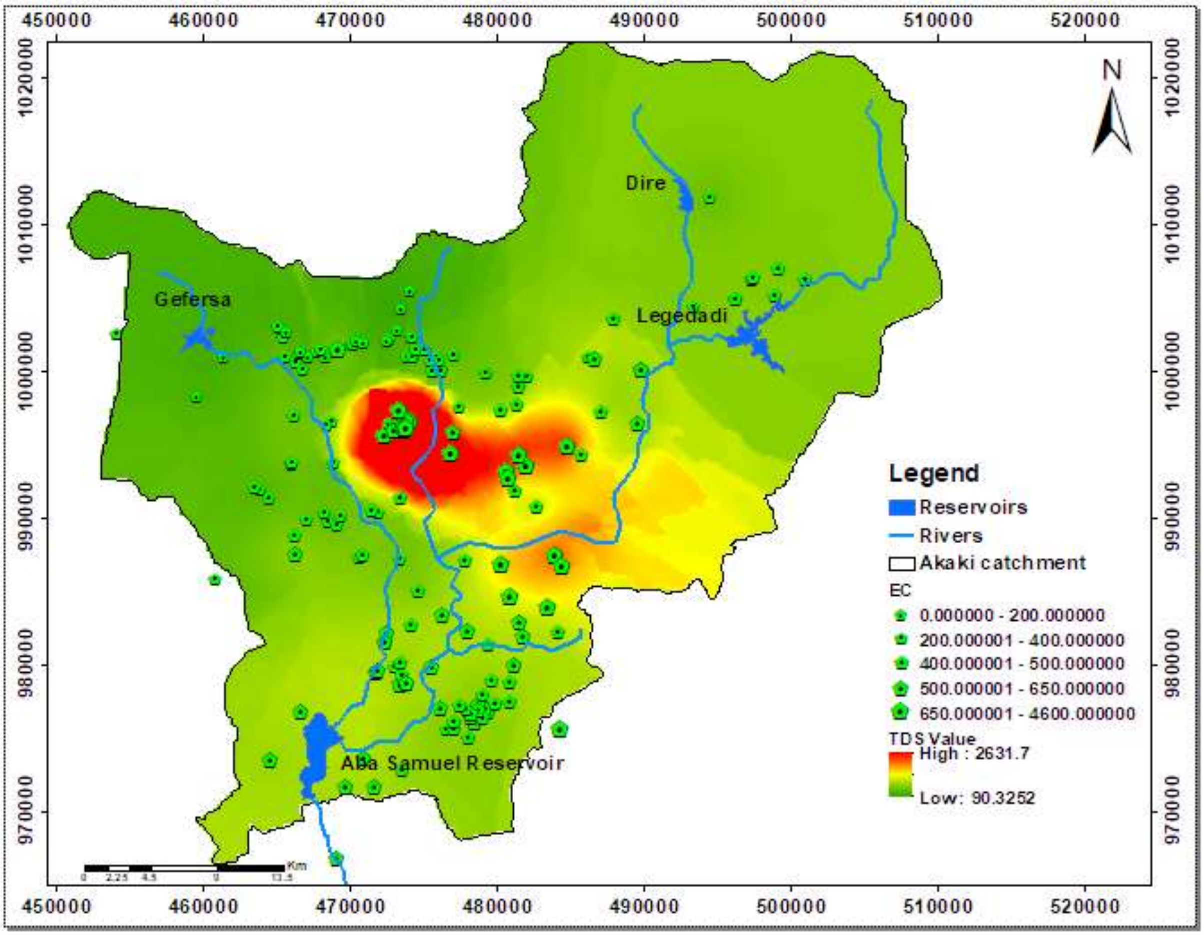


Fig 5.6:- spatial distribution map of groundwater TDS

5.5 Physical parameters of surface water sources

Addis Ababa gets its water supply from both surface water and groundwater sources. There had been four surface waters in the Akaki catchment those are Abasamuel, Legedadi, Dire, and Gefersa.

The physical analysis of surface water is represented by five samples; one sample is from the river the remaining four samples are from surface water dams which are taken from Legedadi, Dire, Gefersa, Abasamuel, and Akaki River to characterize surface waters (**Figure 5.7**).

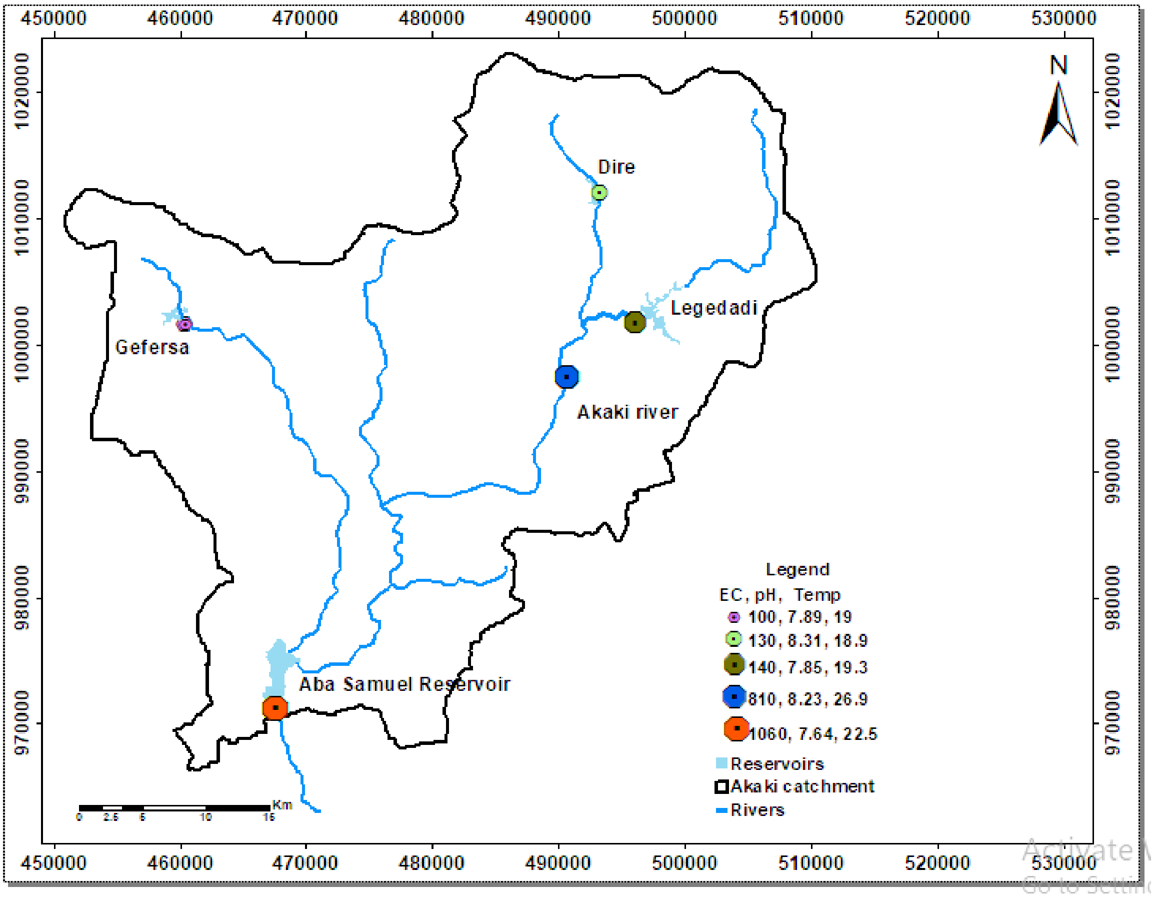


Fig 5.7:- EC, pH, and Temperature of Akaki catchment surface water sources

The city water supply sources will become from three surface water supply sources those are Gefersa, Legedadi and Dire found upstream of the study area and they are not polluted by anthropogenic effects.

The statistical analysis of EC, PH, Temperature, Total Dissolved Solids, and alkalinity values of surface water sources are described in (**Table 5-2**).

Table 5-2:- Descriptive statistics of physico-chemical parameters of surface water

No	UTME	UTMN	Elevation	Location	Sample ID	EC (µs/cm)	PH	Temp	TDS
1	493206	1012026	2552	Dire	LW-02	130	8.31	18.9	70
2	488282	997424	2309	Akaki	RW-01	810	8.23	26.9	400
3	460510	1001619	2589	Gefersa	LW-04	100	7.89	19	50
4	467537	971244	2043	Abasamuel	LW-03	1060	7.64	22.5	530
5	496071	1001758	2447	Legedadi	LW-01	140	7.85	19.3	70
6		Min				100	7.64	18.9	50
7		Max				1060	8.3	27	530
8		Average				448	8	21.3	224
9		SD				405.6	0.3	3	201
10		Variance				164536	0.06	9.6	40464

5.5.1 Electric conductivity of surface water

It is well known that the electrical conductivity of a solution is a measure of its total dissolved salt contents (Hem, 1992). Surface water is exposed for evapotranspiration as a result the conductivity of the water should increase because of the increasing concentration of the dissolved salts.

The EC of surface water sources in the study area varied from 100 to 1060µs/cm with a mean value of 448µs/cm. The lowest EC was recorded 100µs/cm in Gefersa surface water northeastern part of Akaki catchment. The maximum EC was recorded 1060µs/cm in the southern part of Akaki catchment Abasamuel reservoir. The surface water dire dam and Legedadi reservoirs have 130µs/cm and 140µs/cm respectively. In the Part of the big Akaki River at the location of Legetafo area 810µs/cm were measured.

The highest values in the Abasamuel reservoir are the case of discharge area and anthropogenic effect. Big and Little Akaki Rivers, with their tributaries drains the Addis Ababa city and they serve as natural sewerage line for domestic, agricultural chemicals and industrial wastes.

The two rivers with their pollutant loads flow into Aba Samuel artificial reservoir and Aba Samuel reservoir served as a sink for pollutant load from the two rivers and from other small tributaries which directly drain into the lake without joining the Akaki Rivers. The large variation in EC is mainly due to lithologic composition and anthropogenic activities prevailing in this region.

The high values of EC near Akaki River and lakes could be due to surface-groundwater interaction based on hydraulic conductance and groundwater level. Akaki River is highly contaminated by industrial and urban wastewater and agricultural runoff (Aynalem Ali, 1999).

5.5.2 PH of surface water

The spatial distribution of pH shows that the surface water of the study area is alkaline. In this study, the pH of sampled waters from surface water and river were found between the ranges7.64—8.31 log units (**Table 5-2**) with a mean and standard deviation values of 7.98± 0.25 (Table-9). The maximum and minimum values were 8.31 and 7.64 log units detected at the dire dam and Abasamuel reservoir respectively.

The average pH values showed little spatial variation across all the study sites showing a difference of about 0.344 to 0.326 log units between the lower and upper limits of the mean & average values.

5.5.3 Temperature of surface water

The temperature of sampled waters from surface water and rivers were found between the ranges 18.9^{0}C — 26.9^{0}C (**Table 5-2**) with a mean value of 21.32^{0}C (**Table 5-2**). The highest value was at Dire dam (26.9^{o}c) and the minimum value at Abasamuel reservoir (18.9^{o}c).

In (**Figure 5.8**) shows the relation between temperature and electric conductivity of surface water is high with a degree of correlation R^2=0.62. Surface water is exposed for evaporation as a result the conductivity of the water should increase because of the increasing concentration of the dissolved salts.

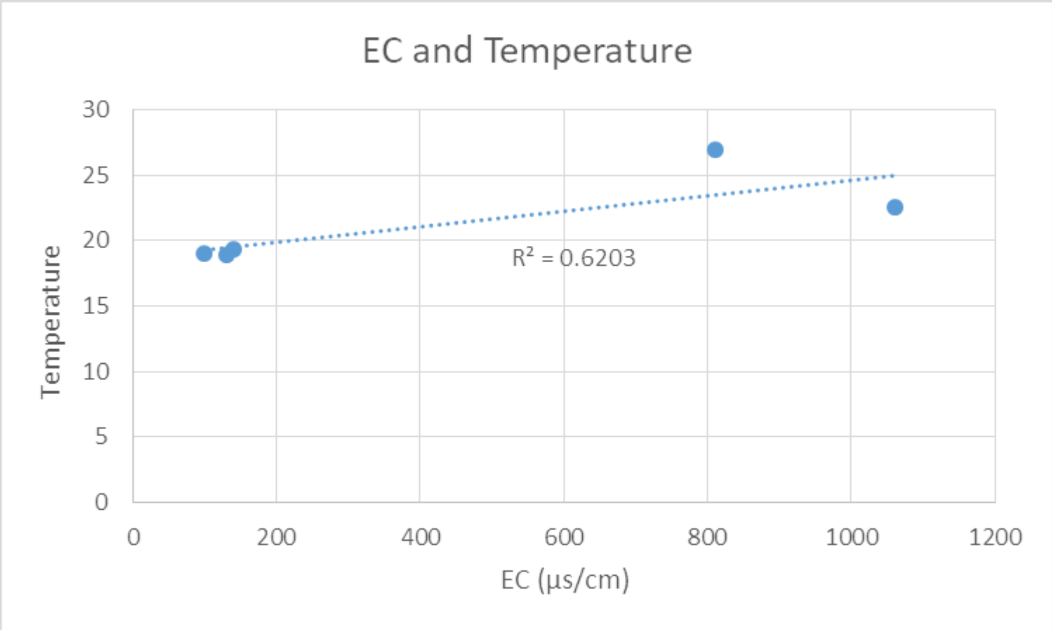


Fig 5.8:- correlation graph of EC and Temperature of surface water

5.6 Physical parameters of Tap water

The locations of Tap water samples were shown in **Figure 5.9** Temperature, pH, and electrical conductivity (EC) were determined in the field using portable pH and EC meters, respectively. Then, the determined EC of groundwater samples was multiplied by 0.64 to compute total dissolved solids (TDS) (Brown et al., 1970).

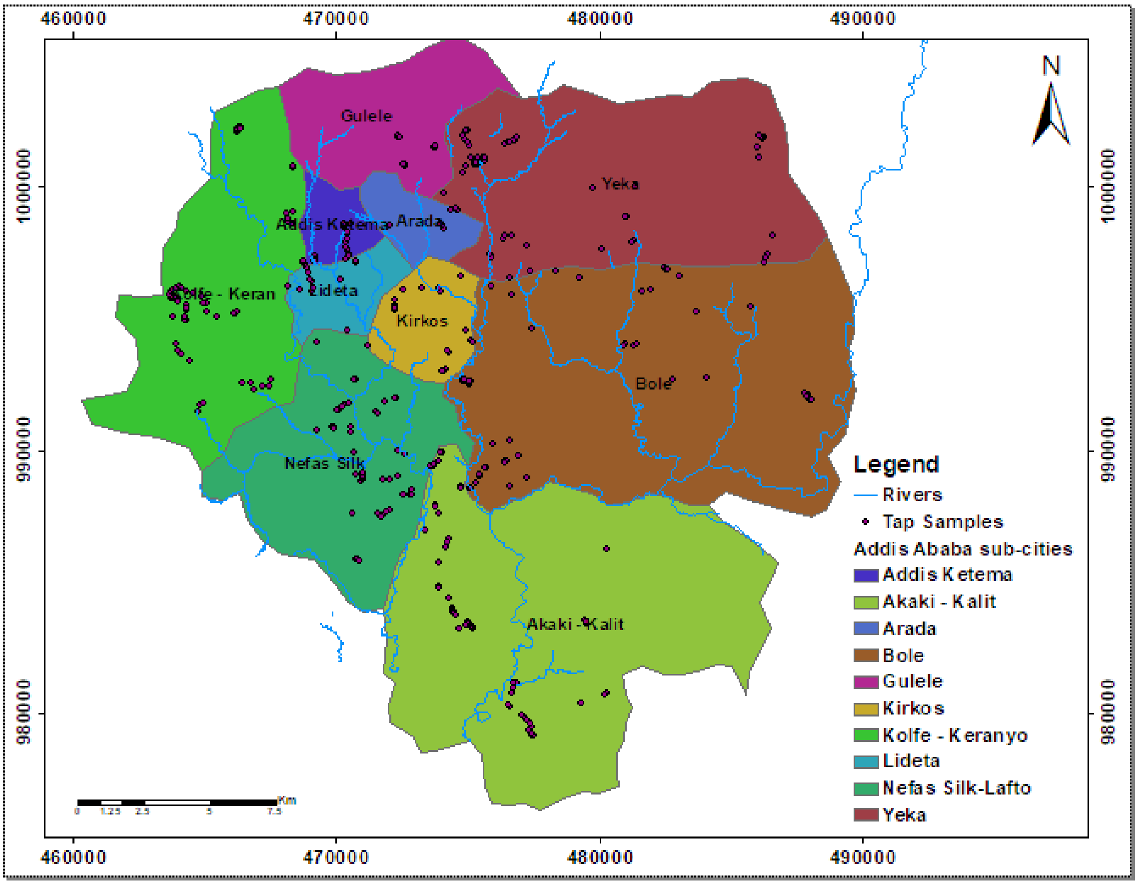


Fig 5.9:- sampling point of tap water

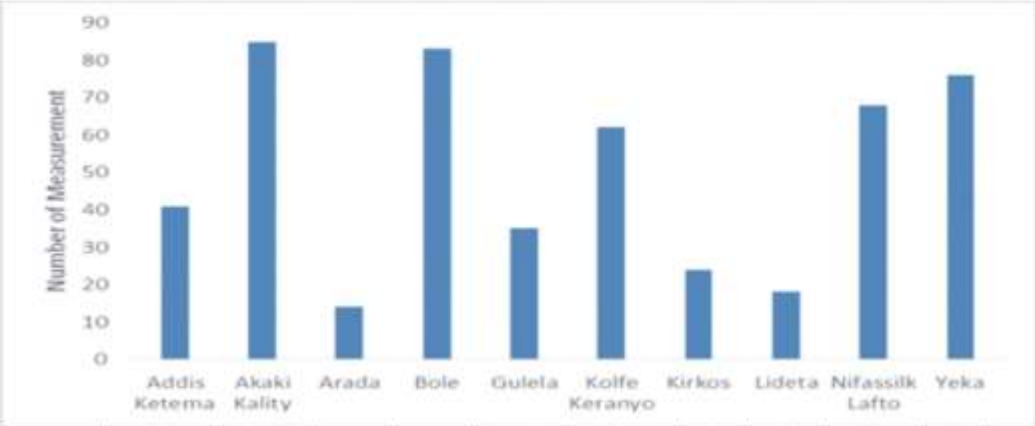
Tap water Physico-chemical measurements were collected from ten sub-cities (Kolfe Keranyo, Gulele, Addis Ketema, Lideta, Nefassilk Lafto, Kirkos, Arada, Akaki Kality, Bole, and Yeka) of the study site (**Figure 5.9**). Five hundred ten Physico-chemical measurements (EC, PH, and Temperature) were taken from each sub-city (**Annex 2, Figure 5.9**).

Results of physicochemical analysis for the Tap water measurements from private households, hotels, industries, and governmental institutions are reported in table 5-4. The major chemistry of the groundwater is summarised in Annex 1.

From Tables 5-1, it is apparent that the groundwater is dominated by alkali earth and bicarbonate ions and relatively high sodium concentrations.

All the waters are saturated with respect to silica. The areal coverage and number of sampling points in each sub-city are shown in table 5-3.

Table 5-3:- number of sampling points in each city with graphical distribution



	Addis Ketema	Akaki Kality	Arada	Bole	Gulela	Kolfe Keranyo	Kir kos	Lide ta	Nifass ilk Lafto	Ye ka	Total
Tap water samples number	41	85	14	83	35	62	28	18		76	510

Table 5-4:- Descriptive statistics of physico-chemical parameters of Tap water

Parameters	SD	MAX	MIN	AVERAGE	VARIANCE
EC (µs/cm)	204	670	100	359.3	41628.57
PH	0.19	8.55	7.14	7.85	0.037
Temperature (^oC)	2.9	33.3	15	21.5	8.5
TDS	130.58	428.8	64	230	17051.06

5.6.1 Electric conductivity of Tap water

Electrical conductivity is a parameter related to total dissolved solids (TDS). EC is a measure of solution in terms of its capacity to transmit current. The importance of EC and TDS lies in their spatial variation of electric conductivity in tap water used to identify sub-cities that are supplied by surface water sources that have low electric conductance values, groundwater sources that have high electric conductance values, and those supplied by both sources that have medium electric conductance values. Therefore, the study of spatial variation of tap water EC is necessary to identify the sources and for the optimized management of urban water resources.

The spatial variation of EC values is shown in **Figure 5.10**. The interpolated spatial variation map of EC values shows that low elevation, southwest (Nefassilk Lafto), and southern part (Akaki Kality sub-city) of the study area has a high value of EC concentration in tap water.

The high elevation area that found the northern and central part of the study area has a low value of EC concentration in tap water. The remaining part (East yeka, southern part of Bole, southern part of kirkos, southern part of kolfe keranyo, and Northern part of Nefassilk Lafto) of study areas have a medium value of EC concentration in tap water (**Figure 5.10**). The EC of Tap water sources in the study area varied from 100 to 670µs/cm with a mean value of 359.3µs/cm.

The minimum EC was recorded 100µs/cm in the Gulele sub-city northern part of the city and it's near to Gefersa surface water sources. The maximum EC was recorded 670µs/cm in the southern part of Addis Ababa Akaki Kality sub-city and it's near to the Akaki well field. Lower groundwater EC values (100-270µs/cm) were detected on the north and northeastern part of Addis Ababa in Gulele, most of Yeka, north to central Bole, Arada, north Addis Ketema, and north Kirkos area. Samples with medium values (270-460µs/cm) refer to the location east Yeka, south to east Bole, central Kirkos, west Kolfe Keranyo, and north Nefassilk area. The location with higher values (460-670µs/cm) is Akaki Kality, south Nefassilk, east Kolfe Keranyo, and central Lideta areas.

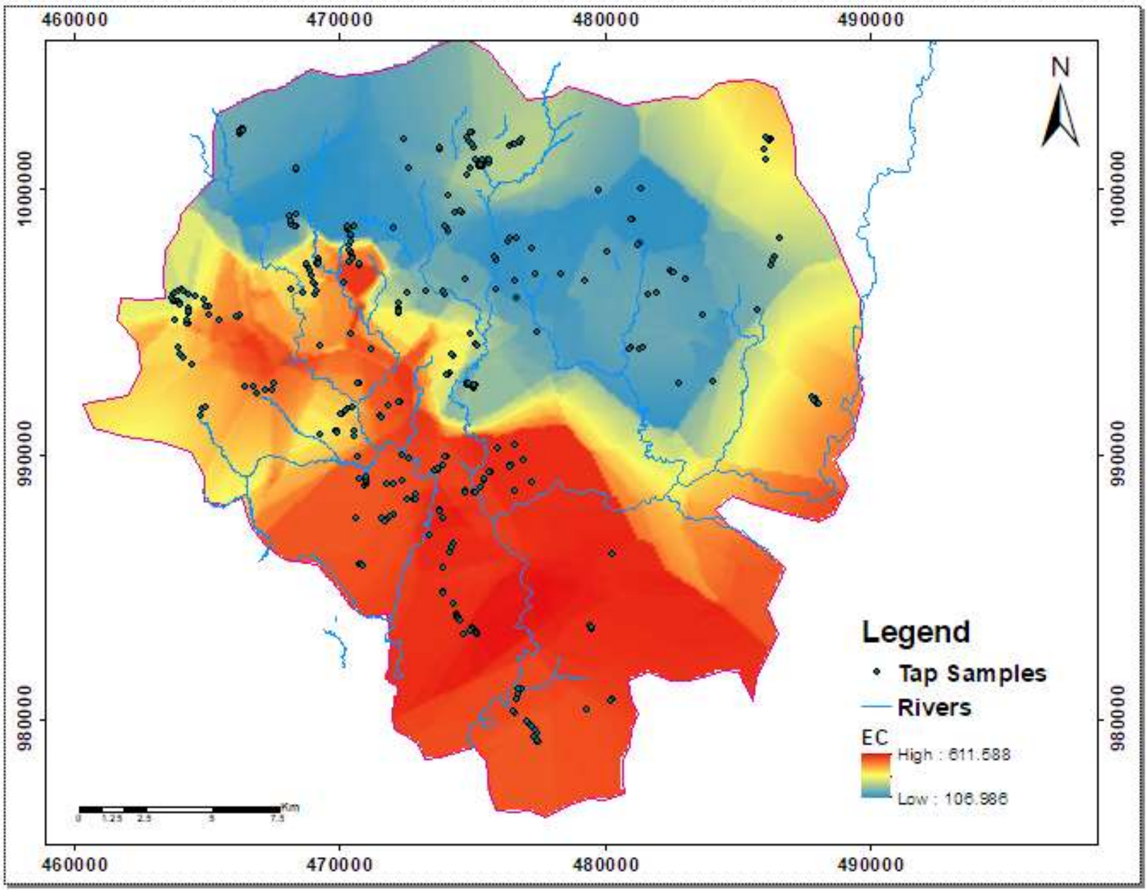


Fig 5.10:- spatial variation of Tap water EC

5.6.2 PH of tap water

Fig.34 shows spatial variation of pH of the surface water in Addis Ababa. The spatial distribution of pH shows that the surface water of the study area is slightly alkaline.

In this study the pH measurements of sampled waters from tap water found between the ranges 7.14—8.5 log units (**Table 5-4 & Figure 5.11**) with a mean and standard deviation values of 7.85 ± 0.19 (**Table 5-4**). The maximum and minimum values were 8.55 and 7.14 log units detected at Bole and Kolfe Keranyo sub-city respectively. The average pH values showed some spatial variation across all the study sites showing a difference of about 0.71 to 1.41 log units between the lower and upper limits of the average values. The pH values also show a little spatial variation of tap to the source distribution. The higher pH value of tap shows the sources from recharge area or surface water and low pH value indicate sources at discharge point or groundwater.

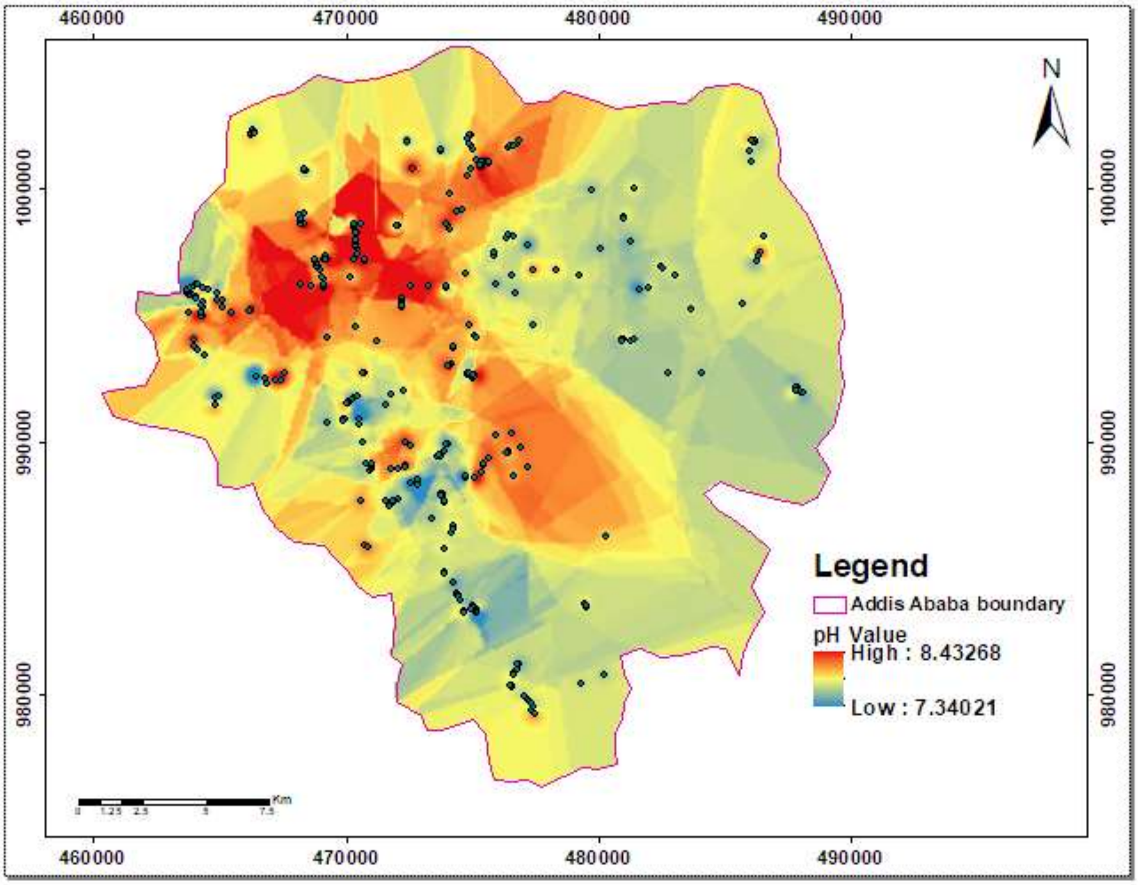


Fig 5.11:- spatial distribution of PH of tap water

5.6.3 Temperature of tap water

The temperatures of sampled waters measured from tap water were found between the ranges 15^0C — 33.3^0C with the mean value of 21.5^0C (**Table 5-4**). The highest value was recorded at 33.3^oc at yeka sub-city in the afternoon and the minimum value at Kolfe Keranyo (15^oc) in the morning. The temperature of tap water is depending on the atmospheric or surface temperature. The temperature and Electric conductivity correlation graph show a slightly positive correlation (R-squared value=0.2) between the two parameters (**Figure 5.12**). These results show that the effect of temperature when evaporating the tap water the EC will be increased in addition to the source value of electric conductivity concentration.

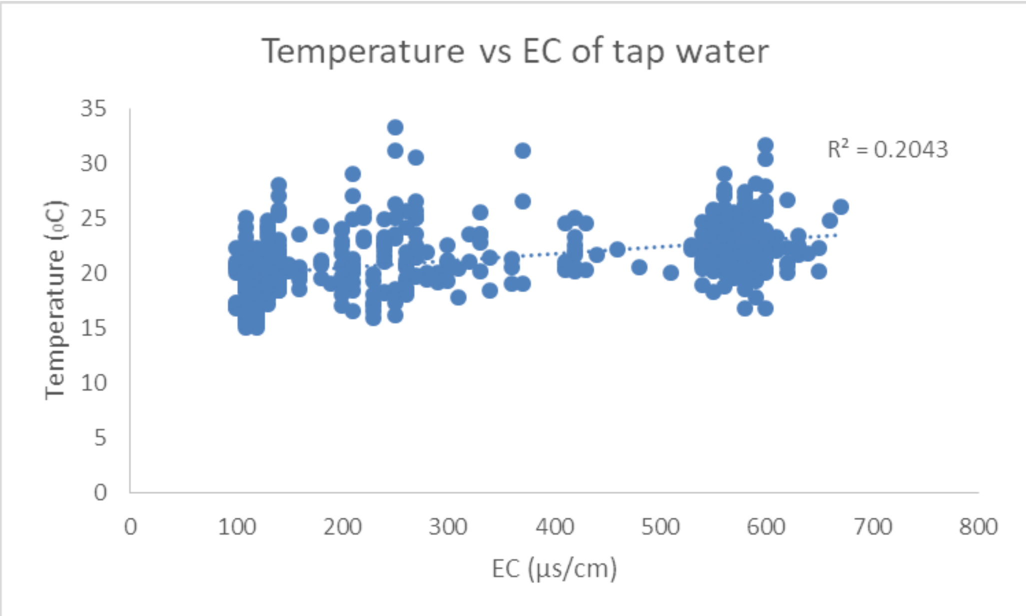


Fig 5.12:- correlation between Temperature and EC of tap water

5.7 Isotope Hydrology

5.7.1 General

Isotopes are atoms of the same elements with the same number of a proton (atomic number), but with a different number of neutron (or mass number). Isotopes of the same element, therefore, have slightly different masses. Stable isotopes are those isotopes that do not undergo radioactive decay; so their nuclei are stable and their masses remain the same. However, they may themselves be the product of the decay of radioactive isotopes.

Isotopes of hydrogen and oxygen are the most widely used in hydrologic studies. This is because these isotopes are an integral part of the water molecule and therefore can trace the history of water, its movements, its interactions, and mixing, etc.

The stable isotopes of ^{18}O (oxygen-18) and ^{2}H (deuterium) are used to provide information on hydrological processes, including groundwater-surface water interactions. Environmental isotopes are commonly used for the understanding of groundwater chemistry and evolution, rock-water interaction, water resources origin and mixing, source of salinity, and contaminants (Mazor, 1991; Mook, 2000).

Water undergoes phase transitions, interacts with minerals and the atmosphere, and participates in complex metabolic processes essential to life.

The isotopes of hydrogen and oxygen undergo large fractionations during these processes, providing a multiple isotopic tracer record of diverse phenomena (Clark and Fritz, 1997).

Isotopes are applied in hydrology either as tracers or as age indicators. An ideal tracer is defined as a substance that behaves in the studied system exactly as the material to be traced as far as the sought parameters are concerned, but that has at least one property that distinguishes it from the traced material (Zuber, 1986 cited in Mook, 2001). In the hydrologic cycle, hydrogen and oxygen ratios provide conservative tracers, uniquely intrinsic to the water molecule that elucidates the origin, phase transitions, and transport of H_2O (Dansgaard,1964). Isotope techniques in water management provide important and sometimes unique tools for obtaining critical information. Isotopes could be used to get information on the identification of water sources (groundwater and surface water).

The isotopic composition of water can be determined by mass spectrometry and compared to the isotopic composition of ocean water (SMOW) and expressed in per mil ($^0/_{00}$) deviations from the SMOW standards (Mazor, 1991; Mook, 2000). The standard material, VSMOW, prepared by H. Craig has been decided by an IAEA panel in 1976 to replace the original SMOW in fixing the zero point of the $^{18}\delta$ scale. All water samples are to be referred to this standard (Mook, 2000).

$$\delta = \frac{\text{Rsample} - \text{Rreference}}{\text{Rreference}} * 1000 \left[\text{in } ^0/_{00}\right]$$

Where water with less δ than VSMOW has negative δ and vice versa.

5.7.2 Environmental Isotopes Fractionation

The tiny difference in chemical and physical behaviour between isotopes is called isotopic fractionation (Mook, 2000). Isotopic fractionation or separation occurred due to a physical process in which energy-loaded water molecules move from the water phase into the vapor phase (evaporation) (Mazor, 1991; Mook, 2000).

Isotopically light water molecules evaporate more efficiently than heavy ones because heaver isotopes have a lower velocity and higher binding energies (Mazor, 1991; Mook, 2000), as a resulting vapor has light molecules of water (negative δD and $\delta^{18}O$). In contrast, the residual water phase becomes relatively enriched in the heavy isotopes (positive δD and $\delta^{18}O$) (Mazor, 1991).

According to Mook (2000), we have to consider two main processes such as evaporation of surface ocean water and the progressive raining out of vapor masses as they move towards lower temperature regions to better understand the variation in δD and $\delta^{18}O$.

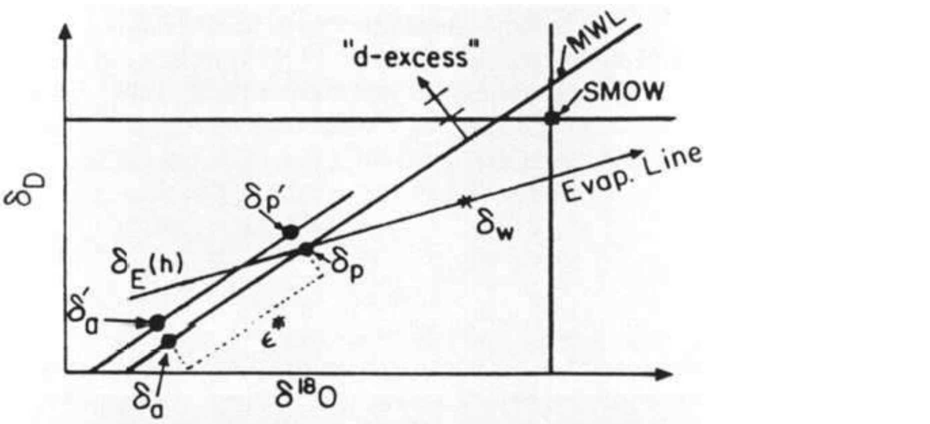


Fig 5.13:- The isotopic compositions of evaporated surface water (δ_w), the original precipitation prior to evaporation (δ_p), and the evaporated vapor (δ_E) all plot along the same evaporation line. Both the precipitation (δ_p) and the atmospheric vapor (δ_a) in equilibrium with it plot along the MWL, separated by the enrichment factor for the environmental temperature (ϵ^*). When the evaporate (δ_E) mixes with the local atmospheric vapor (δ_a), a new vapor (δ'_a) is formed that plots above the MWL. If rain later condenses from this vapor, it would plot along a new line parallel to the MWL but with a higher *d-excess* value. **(Source; Gat et al., 1994)**

As the evaporation process continues, the isotopic composition of an evaporating water body and the net evaporation flux define a relation that is called the evaporation line. The initial isotopic composition of the water, the evaporated moisture, and the residual water must all plot on the same straight line because of mass balance considerations. The slope of the evaporation line is determined by the air humidity and the equilibrium and kinetic fractionations, both depending on temperature and boundary conditions (Mook, 2001).

5.7.3 Environmental stable isotope composition of precipitation in the study area

The relation between natural variations of $^{18}\delta$ and $^{2}\delta$ ocean water, atmospheric vapor, and precipitation has become known as the Meteoric Water Line (MWL). MWL characterized by a slope of 8 and a certain intercept with the ^{2}H axis (= the $^{2}\delta$ value at $^{18}\delta$ = 0‰) is Global Meteoric Water Line (GMWL) (Mook, 2000). MWL is used as a convenient reference line for understanding and tracing local groundwater origins and movements.

Hence, a local meteoric line has to be established for hydrogeochemical investigations from individual rain events or monthly means of precipitation (Mazor, 1991).

From the long-term $\delta^{18}O$ and $\delta^{2}H$ measurements of precipitation at the Addis Ababa GNIP station of IAEA (Data from 1961-2005), the mean isotopic composition of precipitation is δ18O = -0.32‰ and δ 2H = 9.7‰, $\delta^{2}H$ is positively correlated with $\delta^{18}O$ measurements. The line of best fit through data points representing $\delta^{2}H$ vs. $\delta^{18}O$ values (Fig 5.14) is given by:

$$\delta^{2}H = 7.13\delta^{18}O + 11.98, \ (R^{2}=0.96)$$

This is comparable to the global meteoric water line (GMWL) of (Craig, 1961), which is given by $\delta^{2}H = 8\ \delta^{18}O + 10‰$ SMOW, and later modified by Rozanski et al. (1993) using the regression line of IAEA GNIP stations as δ2H = 8.17 (±0.07) δ18O + 11.27 (± 0.65) ‰ VSMOW.

The isotope value of precipitation is controlled by, isotope value of the source, rate of evaporation of the source, isotopic evolution of air mass, relative humidity during precipitation (Gat, 1996). As an air mass leaves its source it cools as it rises above the continents. This cooling induces precipitation that distills the heavy isotopes from the water vapor in the air mass. The remaining vapor becomes progressively depleted in 18O and 2H. Precipitation with relatively high isotope values (compared to the air mass vapor) falls from the clouds. This results in the so-called continental effects and orographic effect that produces precipitation with very low values at high altitudes (Dansgaard, 1964).

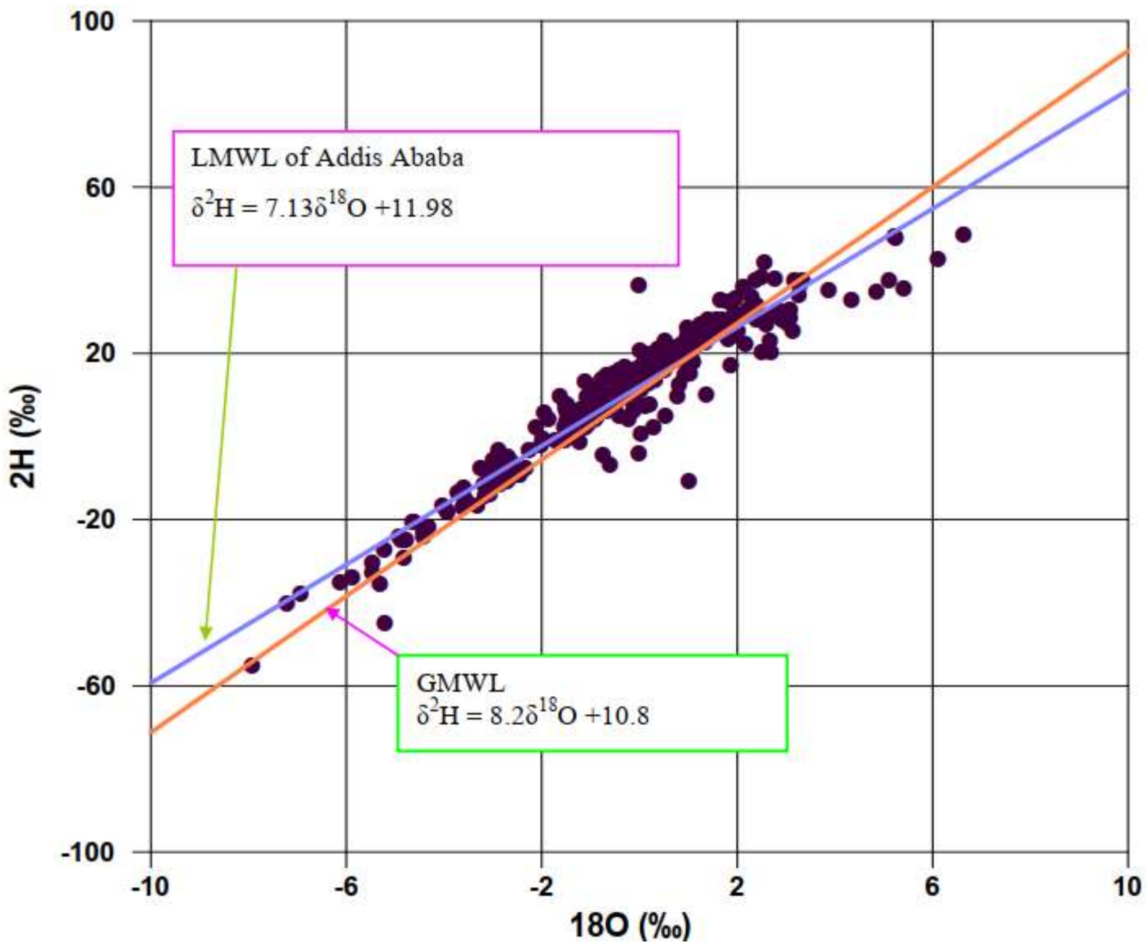


Fig 5.14:- Plot of δ18O‰ versus δ2H‰ of precipitation at Addis Ababa GNIP station (Data 1961-2005, IAEA), the blue regression line through data points represents the local meteoric water line (LMWL) for Addis Ababa and the red line represents the global meteoric water line (GMWL). (Source; Andarge Yitbarek, 2009).

5.7.4 Environmental Stable Isotope of water sources

Understanding the variation of stable hydrogen (H) and oxygen (O) isotopes in tap water has global application for several diverse fields (Bowen et al., 2019).In many contexts, the management of water resources is expected to become increasingly challenging given the predicted impacts of climate change, urbanization, economic development, and increasingly complex water resource supply systems and infrastructure (Jameel et al., 2018).

Municipal tap water is a primary interface between people and the hydrological system. Most municipalities are supplied by some combination of local surface and groundwater but may also rely on non-local sources through inter-basin water transfer schemes and processed water such as treated sewage effluent or desalinated seawater.

A theoretical understanding of the variability of stable isotopes in precipitation, surface water, and groundwater (**Figure 5.13**) provides the foundation from which informed inferences can be made about the variability of stable isotopes in tap water (Ruan et al., 2020).

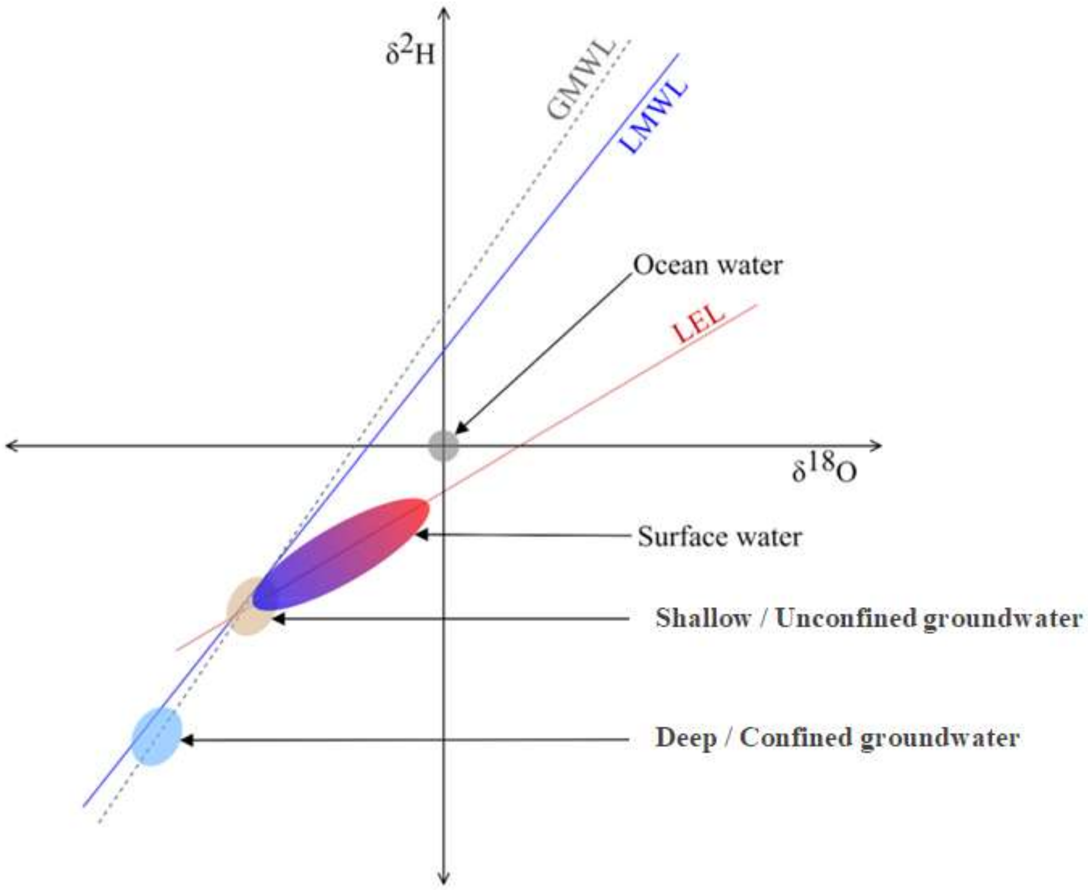


Fig 5.15:- Hypothetical δ2H and δ18O values for surface water, confined and unconfined groundwater, and ocean water relative to the global and local meteoric water lines (GMWL and LMWL), and local evaporation line (LEL) (modified from Ruan F.et al., 2020).

Surface water is more enriched in isotope concentration due to evapoconcentration. In unconfined or shallow groundwater reflecting that of mean annual precipitation and confined or deep groundwater differing from the local mean annual precipitation but rather reflecting that of the spatially or temporally distant recharge source (such as paleo-recharge). The δ^2H and δ^{18}O values in ocean water, by definition, approximate the origin.

5.7.5 Isotopic signature of Tap water

The rainfall water at Addis Ababa IAEA/WMO station shows the highest ^{18}O and ^{2}H enrichment compared to any station in the region and the globe. This is regardless of the high altitude and low mean annual temperature of Addis Ababa. The weighted mean $d^{18}O$ and $d^{2}H$ composition of the summer rainfall waters of the Addis Ababa IAEA station is -1.56 % in $\delta\ ^{18}O$, +1.48 % in $\delta^{2}H$.

The spring rainfalls have a weighted mean composition of +0.47 % in $\delta\ ^{18}O$ and +17.36 % in $\delta^{2}H$. In the $\delta\ ^{2}H$ $\delta\ ^{18}O$ plot (**Figure 5.14**) the monthly rains of Addis Ababa plot defines a local meteoric Waterline (LMWL) defined by: $\delta^{2}H = 7.2\ \delta^{18}O+11.9$ (Seifu Kebede and Travi, 2012).

The result Plotted in the conventional $\delta^{18}O$ versus $\delta^{2}H$ diagram together with the Local Meteoric Water Line (LMWL) with the equation is $\delta^{2}H = 7.2\delta^{18}O+ 11.9$ and Global Meteoric Water Line of Craig (1961) with the equation is $\delta^{2}H = 8\delta^{18}O+ 10.8$.

The Tap Water data set of Addis Ababa based on the 200 tap water sample analyses and the plot was shown in (**Figure 5.14**). The tap water data clustered near Global Meteoric Water Line (GMWL: $\delta^{2}H = 8\ \delta\ ^{18}O + 10$) and below Local Meteoric Water Line ($\delta^{2}H = 7.2\delta^{18}O+ 11.9$). The tap water data were clustered lower than those in LMWL, which may reflect the effects of evaporation in tap water sources (Groundwater and Surface water).

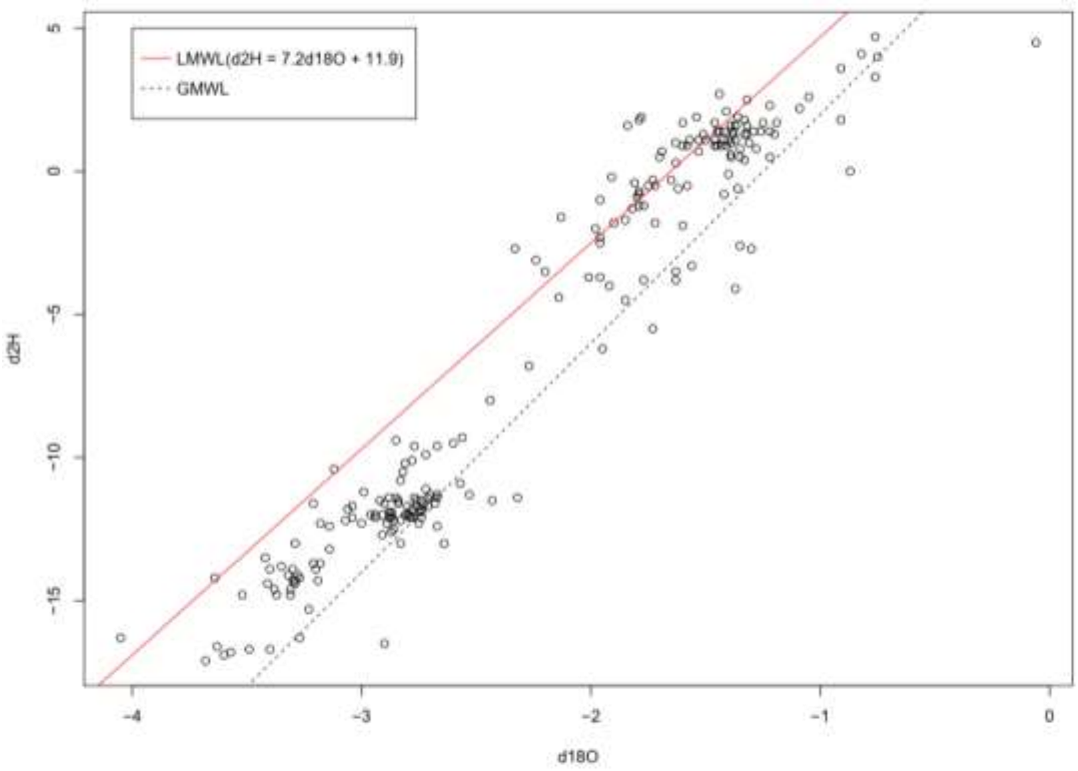


Fig 5.16:- Relationship between δ^2H and δ^{18}O in tap water in Addis Ababa. There were 200 tap water samples used in this chart, which were collected from private households. (GMWL: Global Meteoric Water Line, LMWL: Local Meteoric Water Line).

5.7.6 Spatial variation of ^{18}O and ^{2}H isotopes in the Tap waters of Addis Ababa city.

Spatial variation of ^{18}O and ^{2}H isotopes in the Tap waters of Addis Ababa city indicate tap water sources (**Figure 5.15**). An interpretation is made on a data set of stable hydrogen (H) and oxygen (O) isotope, as far as the original Tap water data is concerned. The spatial distribution of the stable isotope data points in the study area is presented in Figure 5.18. The use of stable water isotopes helps to clarify the sources of tap water (sources from surface water or groundwater) and the mixed sources.

According to Andarge Yitbarek (2009), the comparison of stable isotope data from tap water sources (surface water and groundwater) samples to global or local meteoric water lines can provide information on water sources. Isotopically light water molecules, for example, evaporate faster than isotopically heavy water molecules. Because of the diversity in isotopic vapor pressures, evaporation results in residual water that is enriched in heavier isotopes relative to the initial isotopic composition.

Therefore water that has undergone evaporation lies to the right of the local meteoric water line due to this enrichment (Coplen, 1993).

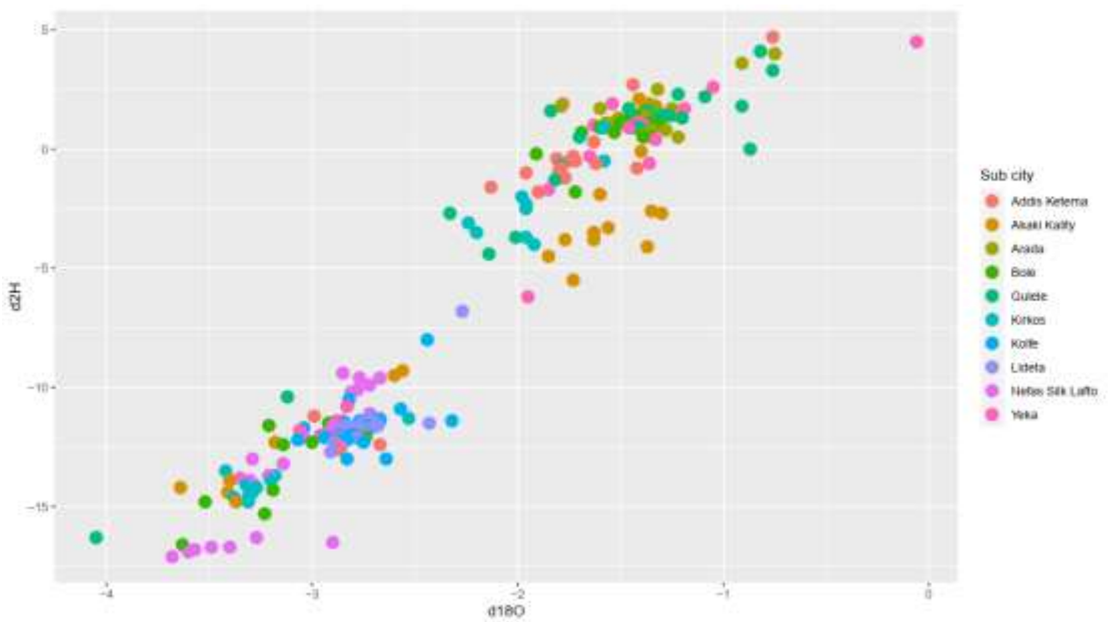


Fig 5.17:- Spatial variation of ^{18}O and ^{2}H isotopes in the Tap waters of Addis Ababa city.

Evaporated water bodies and waters exposed to vapor loss such as lakes, wetland waters, running waters, reservoirs, and oceans tend to enrich in their heavy isotope content concerning the vapor derived out of them. Another form of evaporation effect results from the evaporation of rainfall while the rain droplets are making their way to the ground. In arid and semi-arid environments significant evaporation of rain droplets in the dry atmosphere can take place resulting in enrichment of rainwaters and deviation from the global meteoric water line (Seifu Kebede, 2013).

The enrichment of $\delta\ ^{18}O$ and $\delta\ ^{2}H$ in lakes is caused by isotope fractionation during evaporation (Craig and Gordon, 1965). However, the intensity of enrichment, the absolute isotopic content, and the slope of the Local Evaporation Line (LEL) are the result of an interplay of processes involving the isotopic composition of inflow waters, ambient vapors, and humidity. Because of the abundance of d18O and d2H in evaporating surface water, the resulting isotopic signature differs from that of groundwater and serves as an appropriate conservative tracer for determining the extent of mixing of surface water and groundwater (Gonfiantini, 1986).

The $\delta^{18}O$ versus $\delta^{2}H$ plot of waters from different Tap water in the study area revealed certain trends and indicate tap water sources. The water samples all plots on and close to the local meteoric water line (LMWL) Figure 5.17 suggesting that Tap water sources originate from local precipitation.

Most of the samples except some of Lideta, Kolfe, Kirkos, and yeka sample points scatter on the right (below) of the LMWL signifying the source is from surface water and on the Left (below) of the LMWL signifying the source is from groundwater (**Figure 5.14**).some of the samples from the Kirkos, Kolfe, Lideta and Yeka area scatter on the center (below) of the LMWL signifying the source is from mixing of surface water and groundwater.

From the plot, it is possible to observe at a glance that there are three major groups of waters, group i, ii, and iii (Fig.39). Group i comprises the relatively depleted samples plotted in the lower corner of the $\delta^{18}O\_H_2O$ vs. $\delta^{2}H\_H_2O$ (**Figure 5.16**) are tap water samples in which the sources are from Deeper groundwater which are isotopically depleted that has experienced rain out with the loss of heavier isotopes during precipitation so this deep groundwater originated from rains of the different regime, therefore, the hypothesis of the recharge of deep groundwater is from locally heavy rainfalls or high altitude recharges. Groundwater from the lower aquifer system of the area generally have lower values of $\delta^{2}H$, $\delta^{18}O$ indicating a colder climatic signal during recharge (Andarge Yitbarek, 2009).

Tap waters samples in group ii are relatively enriched in their heavy stable isotope composition. The tap water plotted at the Upper corner go large isotopic fractionation (enriched) since most of the urban tap waters are supplied directly from surface water that undergoes large isotope fractionation (enrichment) due to evaporation. The water supply source is directly from surface water (Legedadi, Dire, and Gefersa).

Tap water samples are plotted on a mixed source line between the composition of groundwater and surface water in the center of the graph (Figure 5.16). The tap water samples depicted in the graph's center show little enrichment due to the combination of groundwater and surface water.

Tap water in Addis Ababa is supplied by three sources: surface water, groundwater, and a combination of the two sources. Bole sub-city is heavily reliant on surface water, moderately reliant on mixed sources, and less on groundwater. Akaki sub-city is reliant on groundwater, whereas the rest of the city is reliant on a combination of sources. Nifas Silk-Lafto sub-city is reliant on groundwater and has a scarcity of mixed sources. Kolfe Keranyo is reliant on surface water, groundwater, and a combination of the two. Gulele sub-city is mostly supplied by surface water and receives less from mixed sources. Addis Ketema sub-city is increasingly reliant on surface water from a variety of sources. Arada is reliant on surface water sources, while Lideta is reliant on groundwater.

Kirkos sub-city is mostly dependent on surface water and has a slight reliance on mixed sources. Yeka sub-city is mostly dependent on surface water and, to a lesser extent, on mixed sources.

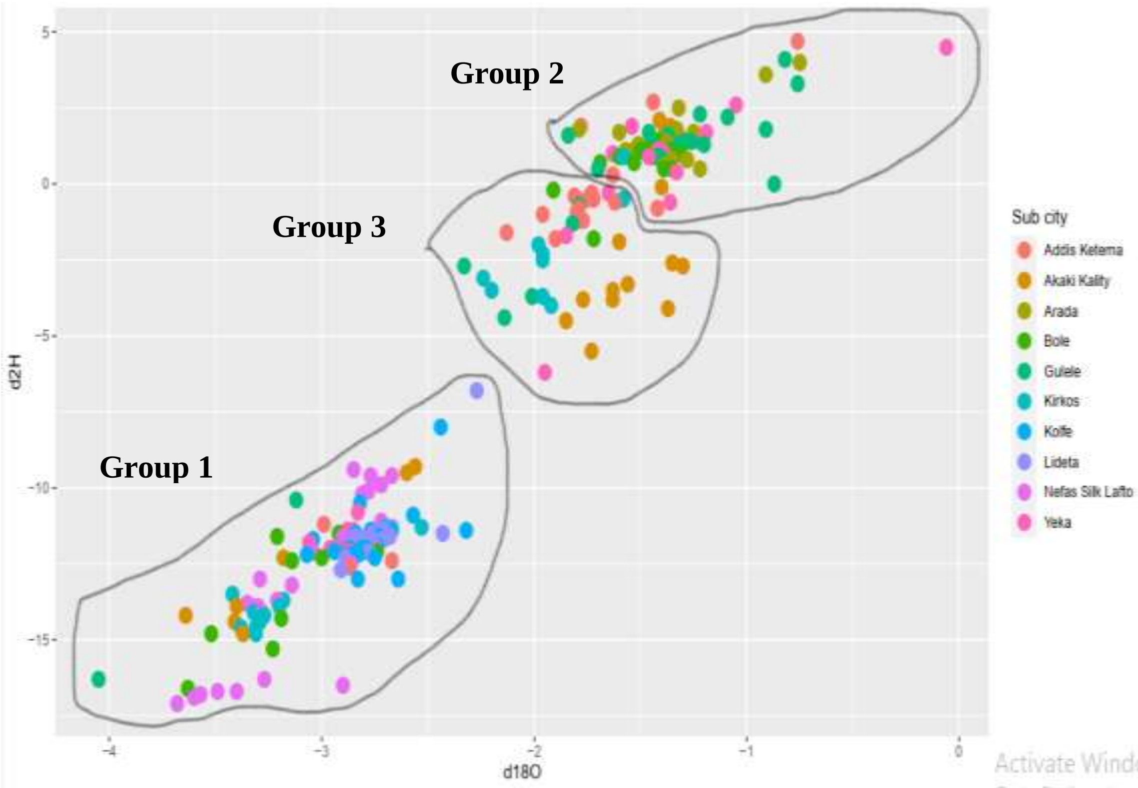


Fig 5.18:- plot of ^{2}H versus ^{18}O of Tap waters in Addis Ababa with their groups.

5.8 Identification of water supply sources

Physico-chemical and isotopic signatures indicate the tap water sources. Through a comparison of the isotopic signature and electrical conductivity of the Tap water samples collected in different parts of the city, varying water source types with varying isotopic signatures and distribution of reliance in space can be plotted as described below:

Three regions were identified based on spatial variation of isotopic signature and electric conductivity (**Figure 5.17**).

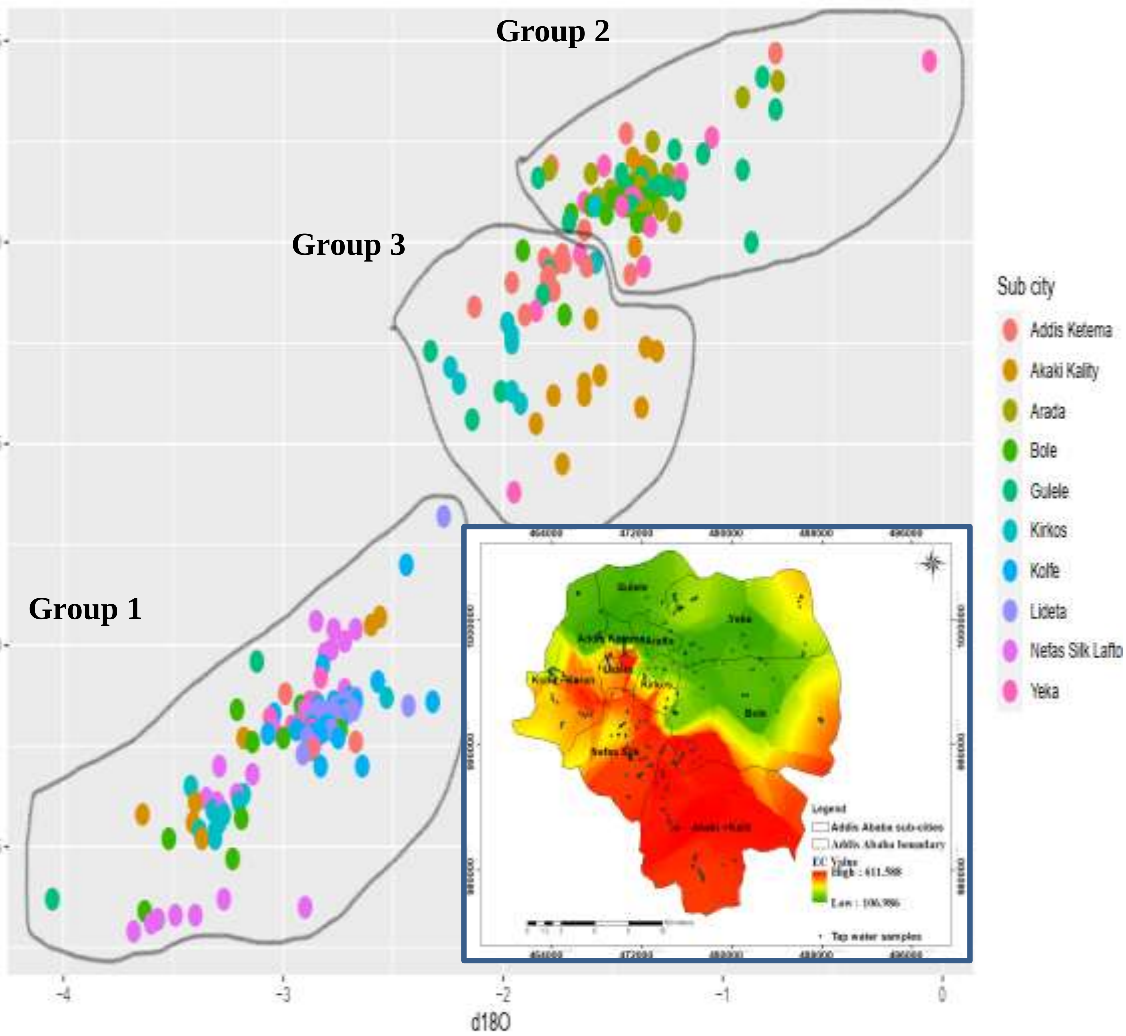


Fig 5.19:-The spatial distribution of isotopic signature of tap water with EC distribution

5.8.1 Enriched Isotopic Signature

In some of these areas, most notably the upper elevated North and Northeastern area of the city (Gulele, West and south of Yeka, North to central Bole, Arada, North of Kolfe Keranyo, Northern part of Addis Ketema, and North Kirkos) tap water isotope ratios are also much higher than those for the lower area tap water. Enriched isotopic signatures for δD and δ18O and Lower electrical conductivity of 100µs/cm to 270µs/cm exist in this region.

Evaporation leads to an increase in the d^2H and $d^{18}O$ values of the residual water, in places, enriched stable isotope ratios of tap waters can be taken to indicate that a substantial degree of evaporation is typical of water sources consumed in these areas.

Addis Ababa city, located in the Akaki catchment abstracts water from both surface water sources (Gefersa, Legedadi-Dire) and groundwater. Groundwater accounts for about 60% of the total Addis Ababa city water supply (Kidanewold et al., 2014 as cited in Behailu et al., 2021). The 40% left is provided from the four open reservoirs (Legedadi, Dire dam, Gefersa dams I and III), and monitoring and planning for the stability of these water sources represent a major challenge for water managers. Evaporative water loss from reservoirs can significantly impact water storage, and its effects on water resource stability, particularly under changing climatic conditions, can be difficult to incorporate in reservoir planning models (Adeloye et al., 1999; Montaseri and Adeloye, 2004 cited in Bowen, 2007).

Network-based stable isotope data provide a means of monitoring rates of water loss and regional water resource sensitivity to evaporation. Although the isotopic evidence for evaporation does not in itself provide a warning signal of water resource sensitivity, data collected over time and analyzed in combination with information on regional climate and hydrology could be used to characterize and monitor surface water resources susceptibility to climate change.

5.8.2 Depleted Isotopic Signature

Stable hydrogen and oxygen isotope ratios of tap water are much low across most of the southern part of the Addis Ababa Akaki Kality, along the Nefassilk Lafto, East of Kolfe and Lideta sub-city. Higher electrical conductivity and depleted isotopic signatures for δD and exists in this region. The most depleted samples plotted in the lower corner of the $\delta^{18}O\_H_2O$ vs. $\delta^{2}H\_H_2O$ (**Figure 5.17**) are sources from deeper groundwater which is isotopically depleted that has experienced rain out with the loss of heavier isotopes during precipitation so this deep groundwater originated from rains of the different regime, therefore, the hypothesis of the recharge of deep groundwater is from locally heavy rainfalls or high altitude recharges.

Depleted tap water isotopic signature in these areas can be attributed to the groundwater sources from Akaki, Legedadi-Legetafo, and Sebeta-Tefki and pocket water in the city. The effect of evaporation on the groundwater is very low. These groundwater sources were most isotopically depleted because of two factors. First, the stable isotope ratios of H and O in precipitation are strongly correlated with altitude (Bowen and Wilkinson, 2002), and tap water derived from sources recharged with high-elevation water could have lower isotope ratios than those characteristics of precipitation at the site of water use (Bowen et al., 2007). Second, in regions characterized by temperate, continental climates, the stable isotope ratios of precipitation exhibit strong seasonality (Rozanski et al., 1993), and tap water derived from sources recharged primarily with winter season water might have isotope ratios that reflect the relatively low $d^{2}H$ and $d^{18}O$ values of winter precipitation.

Addis Ababa city, located in the Akaki catchment abstracts water from both surfaces water sources (Gefersa, Legedadi-Dire) and groundwater. Groundwater accounts for about 60% of the total Addis Ababa city water supply (Kidanewold et al., 2014 as cited in Behailu et al., 2021).

5.8.3 Medium Isotopic Signature

Natural or artificial mixing of waters from various sources and ages, as well as overland or subsurface movement, will mix and spread the isotopic ‘‘signatures" of source water, keeping an integrated signal of the precipitation sources contributing to water supplies (Bowen et al., 2007).

The tap water samples shown in the graph are in-between (East part of Yeka, Central part of Kirkos, minor part of Akaki, South-East of Bole, South Addis Ketema, West of Kolfe, and Northern Nefassilk Lafto sub-city) demonstrate low enrichment due to the mixing of groundwater and surface water sources. This region has a slight enrichment of isotopic signatures for D and 18O, as well as medium electrical conductivity ranging from 270s/cm to 460s/cm. Tap water samples (**Figure 5.17**) are plotted on a mixing space between the compositions of groundwater and surface water resources.

5.9 Water users linked with water supply sources

Addis Ababa has three surface water supply sources (Gefersa, Legedadi, and Dire) and groundwater prospect sites (Akaki, Legedadi-Legetafo, Sebeta-Tefki, pocket regions) for drinking, agricultural, and industrial activity. Water is supplied to Addis Ababa's population from three sources: surface water, groundwater, and a mix of the two. The percentage of residents who rely on either supply source (groundwater, surface water, or a mixture of the two) is depicted below. Mapping the distribution of water supply sources and connecting customers to their respective water supply sources help to guide the sustainable use of urban water resources in the face of changing climatic circumstances.

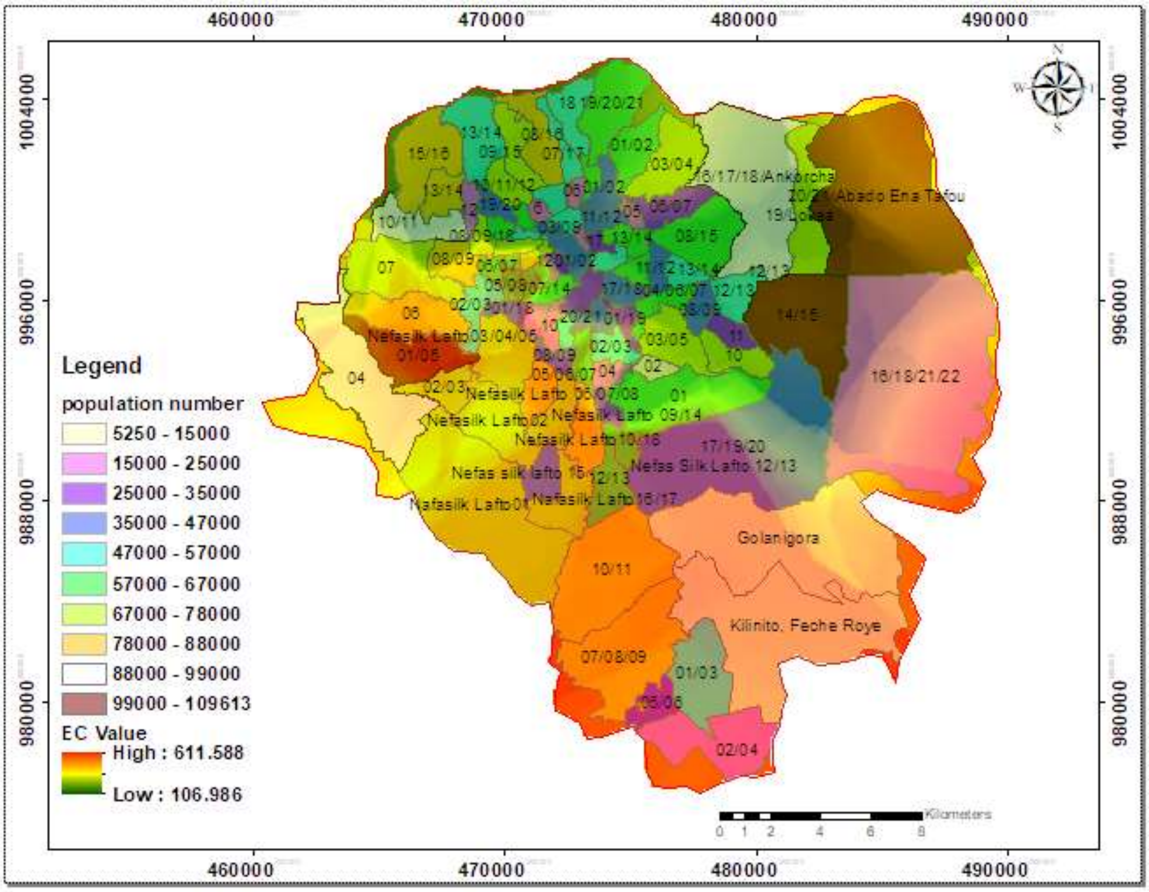


Fig 5.20:- EC map overlaid by population map of Addis Ababa

Figure 5.18 depicts the distribution of water supply sources and the extent to which the population relies on either of the supply sources. The following is a description of the spatial variation map of water supply sources with the number of residents in 10 sub-cities divided by kebeles boundaries: Kebele 01 (35-47K), Kebele 16/18/21/22 (15-25K), and middle Kebele 17/19/20 (8-12K) in Bole sub-city inhabitants rely on a mix of water supply sources. Surface water sources are used by the populations of Kebele 14/15 (99-109K), Kebele 12/13 (25-35K), Kebele 08/09 (25-35K), Kebele 11 (15-25K), Kebele 02 (5-15K), Kebele 03/05, 10 (35-47K), and 04/06/07. (35-47K). Residents in Lower Kebele 17/19/20 (8-12K) rely on groundwater resources.

The Akaki Kality sub-city east Golanigora Kebele (5250 people) relies on a combination of sources, while the rest of the kebeles (239K people) rely on groundwater. Kebele 02 (35-47K peoples), Kebele 01 (17.5-23.5 K peoples), and Kebele 11 (15-25K peoples) in the Nefas-Silk Lafto sub-city rely on mixed water sources.

Kebele 03/04/05 (35-47K peoples), Kebele 06/07/08 (47-57K peoples), Kebele 09/14 (35-47K peoples), lower Kebele 01 (17.5-23.5K peoples), Kebele 10/18 (47-57K peoples), 12/13 (35-47K peoples), and Kebele 15 (25-35K peoples) utilize groundwater sources.

Populations in Kolfe Keranyo sub-city Kebele 04 (67-78K), 07 (47-57K), and 08 (23-28K) rely on a mix of sources. The populations of Kebele 01/05 (15-25K), 02/03 (35-47K), and 06 (47-57K) rely on groundwater supplies. Surface water sources are important to the populations of Kebele 10/11 (67-78K), 15/16 (57-67K), 13/14 (47-57K), 12 (15-25K), and 09 (23-28K).

Keble 21 (13K) residents in Gulele sub-city rely on mixed sources, while the remaining Kebeles (347K) rely on surface water sources. Addis Ketema sub-city Kebele 06/07 (35-47K), 04/05 (35-47K), 01/02/03 (35-47K), and lower Kebele 08/09/18 (18-24K) populations rely on a variety of sources. The populations of Kebele 19/20 (25-35K), 14/21 (35K-47K), 16/17 (35-47K), 13/15 (25-35K), 10/11/12 (35-47K), and upper Kebele 08/09/18 consume surface water resources.

The Arada (285K) sub-city population is nearly dependent on surface water, whereas the Lideta (272K) sub-city population is depending on subsurface water supplies. Kirkos sub-city populations rely on a combination of sources in Kebele 08/09 (25-35K), 05/06/07 (35-47K), 04 (15-25K), 02/03 (25-35K), 11/12 (25-35K), 10 (5-15K), 20/01 (13-18K), and 13/14 (13-18K). (13-18K). Surface water resources are used by the people of Kebele 15/16 (15-25K), 17/18 (25-35K), upper Kebele 20/21 (13-18K), and upper Kebele 13/14 (13-18K).

Mixed water sources are used by residents of Yeka sub-city Kebele 20/21 Abbado and Tafou (78-88K) and Kebele 03/04 (35-47K). The residents of Kebele 09/10 (35-47K), 11/12 (25-35K), 13/14 (25-35K), 08/15 (35-47K), 16/17/18 (67-78K), 19 Lokea (35-47K), and 01/02 (35-47K) rely on surface water sources.

Surface water is used by 274-360K people in the Bole sub-city, groundwater by 8-12K people, and mixed water by 58-84K people. The residents of Akaki Kality (239K) rely on groundwater; while around 5250 rely on a mixture of water sources.

Arada population nearly totally relies on surface water, whereas Lideta inhabitant relies on groundwater. In the Nefas Silk-Lafto sub-city, groundwater is used by 241-313K people, while 67-95K people rely on a mixture of sources. Gulele sub-city has 348K residents who rely on surface water and 130K who rely on a combination of sources.

Surface water is used by 173-235K people in Addis Ketema, whereas 123-165K people rely on a variety of sources. Surface water is used by residents of the Kirkos sub-city of 66-96K, while residents of the 156-228K rely on a mixture of sources. In the Yeka sub-city, 257-336K people use surface water, while 113-135K people rely on a mixture of sources (**Table 5-5; Figure 5.19**).

Table 5-5:- Extent of the population that is dependent on three water supply sources in ten sub-cities.

s/n	Sub-city	Population		
		Surface water dependent	Groundwater dependent	Mixed sources
1	Bole	274000-360000	8000-12000	58000-84000
2	Akaki Kality	-	238792	5250
3	Nefassilk-Lafto	-	241500-313500	67500-95500
4	Kolfe Keranyo	209500-255500	97000-129000	137500-163500
5	Gulele	347334	-	13000
6	Addis Ketema	173000-235000	-	123000-165000
7	Arada	284836	-	-
8	Lideta	-	271617	-
9	Kirkos	66000-96000	-	156250-228000
10	Yeka	257000-336000	-	113000-135000

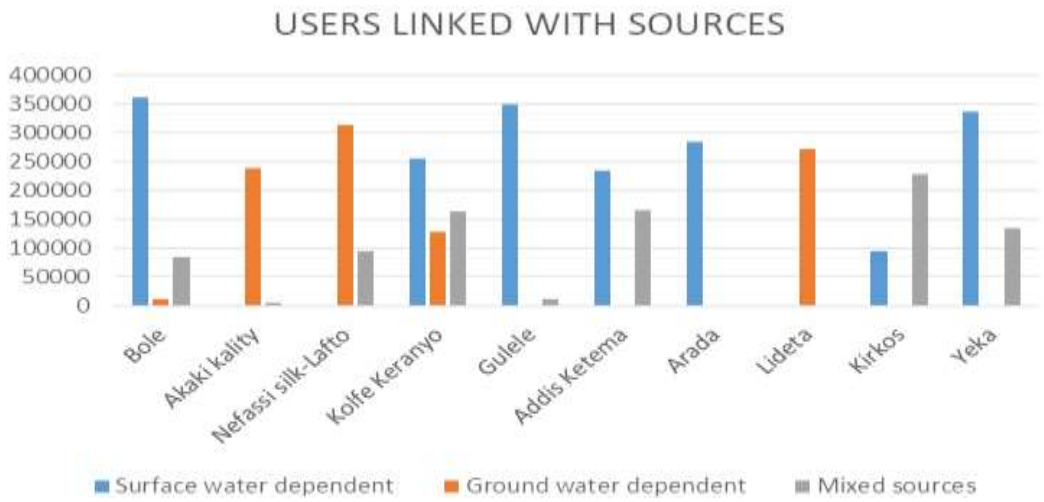


Fig 5.21:- spatial variation of population number linked with water supply sources.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

The physical parameters and stable isotope composition of tap waters are useful for the studies of climate, urban water management, and water source. In this study Mapping, the distribution of water supply sources, and linking the users to their respective water supply sources are done. A new urban tap water isotope signature with the spatial distribution of electric conductivity of tap water was established in this study.

The distribution of water source reliance in space and the extent of the inhabitants relying on either of the supply sources plotted. The spatial characteristics of electric conductance and isotopes in tap water, their proper connection with water sources, and extent of the inhabitants dependent on three water supply sources and the application of isotopes data in urban water supply services are discussed in detail, combining the information of Physico-chemical parameters of a groundwater source.

The spatial distribution of the isotopic signature and electrical conductivity of the water samples indicates the spatial variability of the water type sources (groundwater, surface water, and mixed sources). In Surface water sources the isotope concentration was more enriched, relative to groundwater, due to strong evaporation. Groundwater was mainly recharged by the precipitation water at a higher altitude and had a low evaporation rate as a result they were more depleted in isotope concentration. Electric conductance of groundwater is much higher than surface water due to weathering effect and rock water interaction.

The spatial variability (isotope concentration variability and electric conductance) of tap water isotopic signature is potentially an efficient and cost-effective method of identifying and characterizing groundwater and surface water-dependent tap water sources. Spatial variability in electric conductivity and stable water isotope concentration, as defined by the distribution of reliance in space and the extent of the inhabitants relying on either of the supply sources, provides a powerful diagnostic tool help to inform a sustainable use of urban water resources and identify the source of tap water supply.

Sampling locations that exhibited a high electric conductance (460µs/cm-670µs/cm) and a depleted isotopic signature (Group 1; $\delta^2H < -8.75‰$ and $\delta^{18}O < -2.5‰$) are consistent with the expectations for groundwater. Sampling locations that exhibited a low electric conductance (100µs/cm-270µs/cm) and enriched stable isotopes that approximate local evaporation (Group 2; $\delta^2H > -2‰$ and $\delta^{18}O > -1.75‰$) are consistent with the expectations for surface water. Sampling locations that exhibited a medium electric conductance (270µs/cm-460µs/cm) and slightly enriched stable isotopes (Group 3; δ^2H and $\delta^{18}O$ isotope ratio between the above) are consistent with the expectations for the mixture of groundwater and surface water.

In general, the total Addis Ababa city population (1.6-1.9M) is dependent on surface water resources; Second Addis Ababa population (857-965K) is dependent on groundwater and third, the population (673-889K) is dependent on mixed sources from groundwater and surface water.

Tap water in Addis Ababa is supplied by three sources: surface water, groundwater, and a combination of the two. Bole sub-city is heavily reliant on surface water, moderately on mixed sources, and less on groundwater. Akaki Kality sub-city is reliant on groundwater and is less reliant on mixed sources. The Nefas silk-Lafto sub-city is reliant on groundwater and is less reliant on mixed sources. Kolfe Keranyo is reliant on surface water, groundwater, and a combination of the two. Gulele sub-city is mostly supplied by surface water and receives minor supply from mixed sources. Addis Ketema sub-city is highly reliant on surface water from a variety of sources. Arada is reliant on surface water sources, while Lideta is reliant on groundwater. Kirkos sub-city is mostly dependent on surface water and has a slight reliance on mixed sources. Yeka sub-city is mostly dependent on surface water and, to a lesser extent, on mixed sources.

After disaggregating between surface and groundwater-reliant sub-cities linked with the extent of the population dependent on either of water sources, considerable distinctions are noted in the spatial variability of δ^2H and $\delta^{18}O$ in space. This has direct implications on the application and utility of stable isotopes in tap water for water resource management. Addis Ababa populations are more dependent on surface water than groundwater. However, groundwater is more climate-resilient than surface water where groundwater resources are relied upon to buffer the effects of greater climate variability.

Surface water is exposed to risks that are distinct from that of groundwater; for example, they are more impacted by silting up due to upstream erosion processes. They are also at greater risk of increased evaporative losses due to climate change. Groundwater sources, by contrast, are more at risk of saltwater intrusion and from dissolving fluoride from the rift.

Groundwater accounts for approximately 60% of the total Addis Ababa municipal water supply, while surface water supply sources provide for 40% of total water output. However, surface water consumption exceeds groundwater usage. Surface water is more vulnerable to climate change than groundwater. Surface waters are available only during certain seasons and respond fast to climate change.

Groundwater has a far stronger impact on mitigating seasonality and long-term tendencies. Aside from its significance as a climate change buffer, groundwater also plays an essential strategic role as a tool for rural poverty alleviation, economic growth, and ensuring metropolitan water supply services. High groundwater production is preferable for more sustainable and resilient urban water supply services. Furthermore, this has implications for providing more sustainable and resilient urban water management views that should be considered throughout the design and building of water supply infrastructure employing physicochemical and isotopic information applications.

6.2 RECOMMENDATION

The use of physical parameters and the isotopic signature of tap water for identifying water supply sources are not used on urban water supply services in the study area. The results of this study reveal that the physicochemical and stable isotopic signatures reveal tap water sources and those applications of physicochemical and stable isotopic data can be utilized to provide vital information that helps to improve urban water supply services.

Stable isotope ratios of hydrogen and oxygen (δ^2H and $\delta^{18}O$) in tap water provide an important understanding of how the sources vary through space and inhabitant allows for the management of these resources to be improved. So application of isotopic signature in urban water supply systems should be adopted.

Finally, I advocate for the use of physicochemical and stable isotopic signatures on urban water supply services to provide vital information to support and improve urban water supply services.

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Annexes

Annex 1: chemical data of groundwater in Akaki catchment

No.	Well Inde	Locality	UTME	UTMN	EC	TDS	PH	NH4	Na	K	Ca	Mg	Fe	Cl	NO3	F	HCO3	SO4	PO4	Error
1	KDPW-01	Kotebe De	479316	999941	339	216	7.22	0.01	38	3.6	30.4	11.52	0.02	8.19	0.16	1.53	204.96	8.09	0.12	5.749463
2	KDPW-02	Kotebe De	479310	999940	391	242	7.66	0.43	42	3.7	33.46	8.32	Trace	18.89	0.07	1.15	195.2	22.57	0.13	0.897121
3	DCPW-01	Deginet co	463973	991974	226	134	6.99	0.47	17.5	0.9	28.22	4.23	0.03	7.52	1.12	0.64	134.2	0.1	0.33	2.25675
4	DCPW-02	Deginet co	463590	992116	236	148	7.2	0.27	24.5	3.5	21.6	5.28	0.005	4.7	1.63	0.71	148.44	3.94	0.41	-0.02132
5	MKPW-01	Mekanisa	470682	987316	405	266	8.01	0.43	94	3.8	12	3.67	0.03	18.2	0.38	3.67	219.6	4.93	0.26	9.243294
6	MCPW-01	Mikililand	466336	1000658	388	234	8.21	0.01	74	1.3	8	2.4	0.02	10.93	0	1.84	177.51	3.74	0	7.698614
7	KHPW-01	Kotebe Ha	482076	999660	360	274	7.03	0.62	63	2.3	48	0.24	0.24	6.56	0.37	2.18	234.24	36.36	1.36	4.268243
8	MCPW-02	Mikililand	466841	1000105	268	176	7.53	0.25	34.5	1.6	27.2	7.2	0.08	9.04	3.92	1.19	170.8	3.74	0.34	4.50115
9	APW-01	Awelia	467840	1001410	280	160	6.8	0.19	27	2.1	28	6.72	0.08	27.18	0.26	3.49	122	2.46	0.29	5.909594
10	TBH-01	Tsion-1	470158	1001882	235	136	7.31	-	45	2.2	6.4	3.36	0.51	5.46	0.09	0.66	141.52	0.79	1.44	2.330639
11	TBH-02	Tsion-2	470503	1002189	176	118	6.85	0.31	29	3.3	9.12	1.82	0.51	4.55	0.21	0.64	113.58	2.17	0.42	-2.18872
12	KPW-01	Kidanemil	474203	1002351	332	190	7.34	0.41	38.5	3.2	25.6	2.4	0.51	5.46	0.12	2.82	158.6	31.93	0.31	-2.81088
13	SBH-01	Shegole	469302	1001458	845	548	8.1	0.63	212	1.2	12.8	0.96	0.25	16.92	0.59	7.19	517.28	29.96	4.34	1.896468
14	KMPW-01	Kechene	472720	1002256	215	144	6.25	0.89	16	3.4	84	5.76	1.23	16.87	0.66	0.66	102.48	3.35	0.85	41.79471
15	AASPW-0	Asko Addi	465635	1001021	345	232	7.45	0.39	81	1.4	13.06	2.94	0.14	13.62	0.005	5.44	212.28	7.76	0.04	5.00495
16	AMPW-01	Asko Mem	465517	1002276	304	202	6.84	0.29	46	12.1	18.4	3.36	0.12	22.66	0	2.56	179.34	0	0.02	-1.08729
17	GKPW-01-	Gurara Kid	477067	1001053	248	158	7.67	0.27	33.5	4.5	22.4	2.88	0.02	11.33	0	0.77	156.16	0	0.27	0.828666
18	IEPW-2	Italy Emba	476287	1000116	588	370	8.02	0.05	98	7.6	19	3.65	0.03	5.54	0.03	2.68	368	0	0	-4.04697
19	SMPW-01-	Shiromed	473314	1002774	146	94	6.2	0.46	12.8	5.1	15.2	5.28	0.29	14.43	0	0	97.6	0	0	-3.20534
20	F1PW-01-	Ferensay I	475466	1000729	292	188	7.75	0.15	40.5	18.5	21.6	1.92	0.03	15	0.82	1.21	154.6	11.56	0.33	3.857752
21	F2PW-01-	Ferensay I	475976	1001005	263	160	7.33	0.41	43.5	5.8	14.54	2.42	0.05	10.69	0	0.51	129.81	11.04	1.99	5.41938
22	SGPW-01-	Salo Giorg	472585	982237	589	378	7.89	0.3	138	18.5	8.8	1.92	0.1	31.2	0.73	4.96	301	20.5	1.7	6.069738
23	SPW-01-1	Serti	476370	983392	546	368	7.7	0.34	116	30.5	6.4	0.96	0.05	30.89	0.47	2.24	314.76	18.97	0.53	-1.73493
24	H19PW-01	Hamle-19	474402	1001122	283	178	7.27	0.28	38.5	18.5	16.8	4.32	0.08	11.3	0.37	1.13	151	9.93	0.02	5.301809
25	KGPW-01-	Kality Geb	474716	985017	443	248	7.36	0.28	60	6.3	20	10.1	Trace	11.25	0.91	4.84	253.64	6.77	0.13	-0.25175
26	GPW-01-1	Gofa Meb	471925	990400	377	250	7.12	0.55	58	7.2	23.2	3.36	0.06	11.67	0.02	0.8	228.1	9.07	0.14	-1.37599
27	LPW-01-1	Leghare	472456	995639	3630	2528	8.67	0.65	1150	36	2.46	0.98	0.11	47.94		41.55	1941.26	85.76	0.48	18.75252
28	24KPW-01	24 Kebele	477052	995894	610	406	8.1	0.49	136	6.8	3.36	2.02	0.08	26.03	0.02	2.91	340.99	25.76	0.48	-3.36207
29	BHSPW-01	Bole High	476933	994457	2570	1778	7.1	1.03	710	72	15.2	2.88	0.28	69.3	0	8.58	1419	203	0.57	6.716959
30	NSPTCPW	Nifas Silk	473446	991371	438	284	7.71	0.35	66	2.4	36.12	5.54	0.02	21.02	0	1.89	266.57	8.04	0.7	0.58721
31	BH-14R	Gelan	478583	976061	514	300	7.64	0.13	37	4.8	46	19.2	0.29	16.4	4.1	0.7	297	5.54	0.17	1.011619
32	LLA-2	Gawasa si	489927	1000153	507	332	7.89	0.09	93	3.3	19.3	12.75	0.02	16.48	9.14	1.29	297.2	1.76	0.15	5.37993
33	LLA-PW7	Legedadi I	499253	1006931	447	260	7.21	0.55	44	7.4	38.4	7.68	0.07	14.56	0.35	0.76	263	1.77	0.86	-1.13655
34	LLA-5	Berech wo	497374	1006185	419	260	7.52	0.32	45	7.7	38	5.9	0.09	15.47	7.07	0.66	246	10.2	0.28	-2.7356
35	LLA-3	Bereh wor	496269	1004908	485	286	8.2	1.19	87	9.6	12.9	6.38	0.18	18.2	0.47	0.66	281	1.97	0.06	0.291404

36	BH1R	Akaki	478074	975053	472	302	7.56	0.47	34	1.9	54.4	15.36	0.02	11.72	3.9	0.45	281	1.87	0.33	4.576075
37	BH14R	Gelan tow	478558	976061	514	300	7.64	0.13	37	4.8	46.4	19.2	0.29	16.38	4.1	0	297	5.54	0.17	1.194023
38	LLA-2	Berehe w	489927	1000153	507	332	7.89	0.09	93	3.3	19.3	12.75	0.02	16.48	9.14	0.7	297	5.54	0.17	4.703534
39	BHT1030	AA-Mekar	467135	989840	344	226	7.05	0.35	17	6.8	46.64	9.18	0	5.96	4.56	0.58	234.97	0.11	0.15	-1.08038
40	BHT1058	AA-Shego	468295	1001339	311	174	7.04	0.144	8.4	1.8	42	12.75	0	7.94	1	1.29	197	0	0.162	1.438711
41	BHT75	Alem Gen	464607	973547	507	312	7.8	0.13	20	6.1	68.7	17.5	0	3.8	8.5	1.24	316.1	0.55	0.123	4.22784
42	BHT1560	Alem Gen	466690	976790	588	376	7.36	0.188	67	9.5	41.8	13.8	0	20.2	32.5	0.8	266.3	17.3	0.143	4.657299
43	BHT1511	Tatek Mili	459689	998340	196	132	6.91	0.06	8.6	4.8	30.3	3.8	0	0.96	7.5	0.15	122.98	0.53	0.41	3.400258
44	BHT598	AA-Ameri	473900	1001050	227	139	8.6	0.32	28.9	5.3	24.1	10.7	0	14.2	2.1	0.15	170.8	0	0.2	3.708022
45	BHT1512	AA-French	474300	1001005	310	189	7.9	0.05	26.55	5.53	27.81	6.89	0	11.42	2.13	0.1	158	6.79	0.2	2.652993
46	BHT615	AA-Glass a	467200	1001017	188	115	7.4	0.3	43.4	3	16	3.9	0	7.1	0.1	1.97	146.4	18	0.02	1.802954
47	BHT616	AA-Anbes	468400	1001016	176	107	8.6	0.3	38	5	8	2	0	14.2	0.3	0.6	98	14.3	0.09	0.68679
48	BHT1578	Ministry o	472700	996500	174	106	7.2	0.13	23.8	1.3	11.2	3	0	28.4	0.2	0.3	73.2	0	0.23	-3.50749
49	BHT770	AA-Kality	474225	982650	470	356	8	0.05	54.4	11.6	35.3	15.6	0	28.4	0.7	1.12	317	0	0.02	-2.48391
50	BHT900	Sebeta Ag	460850	985850	244	159	6.65	0.3	16	3.1	28.8	4.84	0	3.88	14	0.5	141.5	1.8	0.23	-1.41865
51	BHT909	Netherlan	468800	996600	375	253	7.9	0.3	23.8	2.8	40.1	6.8	0	11.3	15.1	0.2	195.2	0	0.03	-1.18422
52	BHT912	Korea Emb	468425	996350	395	246	7.34	0.3	19	5	42	14	0	5	2.83	0.23	242	3	0.23	0.032507
53	BHT914	AA-Hagbe	468875	993750	251	163	7.2	0.3	29	3	16	5	0	6	7.4	0.35	134	0	0.23	1.327947
54	BHT920	Hillton Ho	474175	996550	3359	2049	7.48	0.3	840	15	6	2	0	43	0.04	21.1	2198	55	0.23	-1.36554
55	BHT1571	TW2 Test	473576	972821	498	305	7.8	0.3	45	7.7	60	7.3	0	7.2	8.8	0.8	302.6	4.5	0.23	3.22666
56	BHT1572	TW3 test	484475	975622	672	408	7.5	0.3	40	3.5	96.8	18	0	7	9.7	0.3	444	0.5	0.23	3.309112
57	BHT965	AA-Ato Ta	465410	1002944	135	89	6.83	0.3	11.5	4.6	9.6	3.4	0	1.99	1.5	1.68	76.86	1.6	0.23	0.250322
58	BHT968	AA-Burayu	465161	1003103	201	130	7.8	0.3	18	4.9	21.6	4	0	8	0.5	0.9	136.6	3.2	0.23	-4.54468
59	BHT970	AA-Repi E	464538	991302	248	168	7.36	0.3	14	4.3	30.4	6.32	0	4.4	5	0.52	153.7	1	0.2	0.340206
60	BHT1574	Akaki Bev	480895	977403	489	298	7.52	0.3	23	3.4	39	26	0	9	0.33	0.33	315	2.5	0.23	-2.57095
61	BHT-997	AA-Batu T	473466	987247	337	206	7	0	34	4.6	56.1	14.6	0	11.4	1.8	0.5	317	2.5	0.08	0.127658
62	BHT1025	Militatry F	466050	993650	459	280	7.1	0.3	36	4.9	45.7	20	0	14	0.03	0.5	317.2	6	0.23	-0.72976
63	BHT802	AA-Water	486200	1001042	239.85	369	7.5	0.3	65.5	2.7	36.9	14.6	0	25.5	0.5	0.67	292.8	15	0.23	1.095613
64	BHT805	AA-Water	473566	978610	652.3077	424	7.65	0.3	33.6	5.1	60.1	19.95	0	26.8	0.5	0.67	317.2	4.7	0.23	1.520119
65	BHT808	AA-Water	461500	1001023	170.7692	111	7.3	0.3	4.1	1.3	14	4	0	7.1	3	0.3	61	4.7	0.23	-4.01811
66	BHT809	AA-Water	466200	988800	429.2308	279	7.5	0.3	16.1	6.9	26.4	6.3	0	7.1	0.02	0.74	152.5	4.7	0.23	-1.43352
67	BHT810	AA-Water	466400	987600	540	351	7.9	0.46	20.4	4	56.1	9.7	0	7.1	0.5	0.67	268.4	4.7	0.23	-1.13819
68	BHT811	AA-Water	481200	980000	530	385	7.6	0.03	40.8	5.3	67.3	15.6	0	14.2	11.7	1	366	4.7	0.23	-0.88587
69	BHT812	AA-Water	481600	982900	540	380	7.4	0.3	44.2	4	56.1	20.4	0	14.2	9.6	0.7	341.6	15	0.23	0.432616
70	BHT814	AA-Water	480900	978800	500	330	8.4	0.3	78.9	3.4	9.6	8	0	28.4	2.7	0.6	158.6	42.4	0.23	3.620854

71	BHT815	AA-Water	479400	981400	430	362	7.4	0.3	44.2	4	91.4	2.9	0	20	0.1	0.67	366	5	0.23	1.174866
72	BHT820	AA-Watet	473108	979851	397	258.05	7.6	0.3	37.4	5.3	54.5	22.4	0	14.2	18.9	0.65	317.2	24.7	0.23	-0.55941
73	BHT851	AA-Water	479405	976735	493	301	7.3	0.3	26	4.2	45.7	27.2	0	9	18.6	0.35	307.4	6.6	0.03	0.484274
74	BHT1564	AA-Water	479246	977104	512	312	7.3	0.3	27.2	3.63	44.9	29.2	0	17	25.7	0.24	305	6	0.06	-0.59446
75	BHT1569	AA-Water	478780	977307	516	315	7.4	0.05	30.6	3.96	40	28.2	0	14.2	3.9	0.39	329.4	6.58	0.23	-1.89798
76	BHT1566	AA-Water	478199	976361	486	300	7.99	0.3	27.73	5.3	56.1	24.4	0	14.2	3.9	0.39	329.4	5.35	0.23	1.643156
77	BHT849	Akaki Wat	479942	977322	480	310	7.78	0.05	24.47	3.96	49.7	23.35	0	12	12.3	0.55	292.8	7.4	0.23	0.909455
78	BHT853	Akaki Wat	478998	977937	496	303	7.8	0.3	36.6	3.3	39.7	23.6	0	9.2	16.4	0.45	302.6	7.9	0.04	-0.22186
79	BHT119	Mekanisa-	468515	989719	295	194	7.71	0.3	14.5	5.7	42.24	9.18	0	1.99	3.08	1.13	197.64	0.74	0.14	4.15702
80	BHT1069	Lebu mek	469191	989547	309	200	7.28	0.3	22	8.3	36.96	11.22	0	5.96	5	0.94	221.8	1.24	0.104	0.502373
81	BHT976	Yeka-Ank	477446	997611	367	240	7.52	0.3	27.5	6.3	34.4	10.21	0	6.95	0.52	1.31	215.2	17.56	0.072	-2.15025
82	BHT-659	Lafto BH 1	471500	990500	438	280	7	0.3	13.8	5.2	65.63	10.26	0	9.93	6.2	0.75	245.95	2.75	0.183	4.247762
83	BHT1046	MIKILILAN	466601	1001250	147	98	6.87	0.24	12.7	4.1	13.2	2.7	0	1.8	0.52	1.4	87.84	4.65	0.129	-1.73268
84	BHT1037	Mekanisa	469360	990078	344	226	7.05	0.3	17	6.8	46.64	9.18	0	5.96	4.56	0.58	234.97	0.11	0.15	-1.08038
85	BHT1082	Mekanisa-	468261	990357	295	194	7.71	0.3	14.5	5.7	42.24	9.18	0	1.99	3.08	1.13	197.64	0.74	0.14	4.15702
86	BHT-122	Ayat old	489669	996423	524	344	7.42	0.39	77	22	16.63	3.24	0	32.77	5	1.72	225.46	29.73	0.02	-3.08282
87	BHT117	Belay Zele	470218	1001886	209	138	7.61	0.3	38	4.3	9.24	2.04	0	5.96	1.2	1.2	129.32	6	0.23	-0.83267
88	BHT1086	Ankorcha-	481462	998906	414	272	7.24	0.3	30.5	3.2	53.76	10.71	0	7.94	0.16	2.48	258.6	6.38	0.09	4.034681
89	BHT1121	Summit Sl	484971	994879	1904	1394	6.5	0.3	495	24.5	25.2	5.61	0	47.66	0.3	6.4	1434.72	48.6	0.39	-4.06137
90	BHT1088	Ketchene	472608	1002066	194	128	6.88	0.3	9	4.3	25.2	5.1	0	6.95	1.49	0.62	129.3	2.28	0.18	-4.44056
91	BHT1089	Sheromed	474238	1002370	234	154	7.74	0.3	19	7.4	22.68	4.08	0	7.94	10	1.7	134.2	4.95	0.08	-3.88801
92	BHT116	Total Bela	470504	1002135	181	128	7.34	0.3	24	5.5	12.6	2.04	0	1.99	5.4	0.8	117.12	0.8	0.6	-2.36442
93	BHT1096	Selam Tec	481519	999648	422	282	7.39	0.3	55	4.6	35.28	8.16	0	10.9	8.5	1.62	263.5	11.3	0.2	-0.50579
94	BHT1100	Egzeabher	471026	1002023	189	126	7.42	0.26	22.5	10.5	10.4	2.04	0	4.97	0.4	0.94	112.24	3.86	0.12	-3.2792
95	BHT1514	New Kara	480321	997370	440	286	7.05	0.3	41	3.2	54.6	9.18	0	10.92	0.4	3.2	278.16	11.42	0.14	2.322366
96	BHT730	French Em	475638	999991	333	216	7.89	0.3	48.5	9.8	18.48	3.06	0	24.83	0.2	1.6	173.24	8.85	0.12	-2.72198
97	BHT1128	Summit Sl	482163	993603	750	492	6.89	0.3	123	12.9	38.64	6.63	0	11.9	0.4	0.67	490.44	5.62	0.23	-2.04264
98	BHT1130	Hana Mari	465729	1002755	192	128	7.44	0.3	30.5	7.1	8.4	3.57	0	8.24	0.214	0.79	120.41	2.86	0.241	-1.03956
99	BHT1131	New Kara	481368	997713	445	292	7.5	0.177	42	5.9	50.4	7.14	0	14.89	0.3	2.2	239.12	23.1	0.06	2.628524
100	BHT1132	Hana Mari	468094	1001478	220	140	7.25	0.3	30	4.6	17.64	4.08	0	7.21	0.5	0.55	128.1	5.05	0.047	4.443974
101	BHT1133	East Bole	481213	991853	498	332	7.1	0.3	80	7.4	33.6	5.61	0	8.94	1.7	0.87	314.76	0.76	0.48	3.164958
102	BHT1134	Summit,M	481681	994296	1908	1246	6.96	0.64	465	22	15.12	6.12	0	23.82	4.1	1.92	1307.84	30.1	1.05	-1.70813
103	BHT1109	Summit,Sl	485733	994302	490	318	7.19	0.3	102	8.2	5.4	2.04	0	23.83	0.36	3.02	256.2	3.5	0.6	1.249015
104	BHT1114	Legetafo	486723	1000881	625	410	7.89	0.3	132	2.4	21	7.14	0	12.36	0.18	0.85	389.42	2.28	0.04	4.624334
105	BHT1115	Abo Churc	476078	1000763	267	182	8.17	0.18	41.5	7	19.32	2.55	0	8.94	7.48	2.8	169.99	5.99	0.1	-1.94191

106	BHT1104	East bole,	480717	993193	1742	1132	7.44	0.3	380	35.5	17.64	8.94	0	23.8	0.24	2.5	1176.08	40.84	0.23	-4.40317
107	BHT1118	Akaki	478130	982300	532	344	7.66	0.22	66	9.3	45.36	8.16	0	20.8	3.8	0.9	285.48	15.61	0.23	3.373293
108	BHT764	Akaki	470888	987426	492	296	7.82	0.3	43	3.3	57.12	9.69	0	21.8	5	3.75	280.6	8.85	0.05	1.168814
109	BHT1120	East Bole,	480863	992647	735	477	7.32	0.3	128	12.1	31.08	7.65	0	11.92	1	1.1	492.88	14.09	0.23	-3.94868
110	BHT1124	Ferensay,	475165	1001449	319	210	7.72	0.3	35	9.1	24.36	3.06	0	17.87	4.8	1.78	148.8	18.1	0.2	-2.65882
111	BHT991	Fanta vall	481828	981943	558	364	8.01	0.3	53	3.9	58.08	18.36	0	11.92	0.41	0.7	358.68	18.49	0.15	1.679872
112	BHT1126	Bole Lemi	482757	990710	478	314	7.11	0.19	58	6.6	47.04	6.63	0	9.93	1.02	0.83	309.88	3.43	0.29	1.302113
113	BHT1140	Akaki BH5	476574	975607	385	250.25	8.1	0	25.5	4.3	44.9	11.6	0	14.2	3.2	0.6	244	0	0.07	-0.3005
114	BHT1141	AkakiBH0	479714	978929	485	315.25	7.5	0	24.5	4.2	45.7	27.2	0	9	18.6	0.35	307.4	6.6	0.03	-0.08213
115	BHT1561	AkakiBH-9	476246	977104	512	332.8	7.3	0	27.2	3.6	48.5	27.7	0	8.7	16.7	0.42	327	7	0.04	-0.13435
116	BHT1567	Akaki BH0	479061	976370	464	301.6	7.3	0	27.2	3.63	44.9	29.2	0	17	25.7	0.24	305	0	0.06	0.453749
117	BHT1145	Akaki BH1	478808	976897	508.2	330.33	8	0	27.2	3.96	59.3	24.32	0	11.96	9.8	0.52	341.6	6.5	0.03	0.324661
118	BHT1563	Akaki BH1	478347	976752	542.4	352.56	7.5	0	27.2	5.3	56.1	24.4	0	14.2	3.9	0.39	329.4	5.35	0	1.456413
119	BHT1137	Akaki BH2	477945	976985	398	258.7	7.5	0	23.8	4.6	43.3	13.6	0	14.2	4.9	0.6	244	0	0.03	-0.37693
120	BHT842	Akaki BH2	477477	977216	462.8	300.82	7.5	0.04	18.7	4.64	59.3	19.5	0	14.2	1.33	0.5	305	0	0.04	0.866292
121	BHT1587	Akaki BH2	477086	975624	476.4	309.66	7.8	0	27.2	3.96	49.7	23.35	0	12	12.3	0.55	292.8	7.4	0	1.958625
122	BHT1562	Akaki BH 2	477162	976038	494.2	321.23	7.3	0	27.2	4.3	49.7	23.4	0	14.2	9.4	0.4	292.8	8.85	0	1.651908
123	BHT208	Legadadi	493518	1004421	382	244	7.43	0.22	33	6.7	37.4	8.64	0	5.73	0.14	0.5	225.86	16.2	0.41	-0.11327
124	BHT1341	Akaki city	475697	979915	595	390	6.89	0.28	46	8.6	64.68	15.3	0	14.42	7.2	1.4	348.4	5	0.09	2.950611
125	BHT1353	Akaki	471909	979461	582	360	8.2	0.25	69	6.9	29.6	14.4	0	29.12	0.42	2.96	284.38	21.87	0.05	-0.84179
126	BHT1349	Akaki	473583	979260	488	320	7.86	0.2	79	11.9	30.4	1.84	0	9.5	28.6	1.19	281.8	6.6	0.253	-0.70298
127	BHT1357	Akaki	473944	978722	539	314	7.6	0.1	59	6.5	43.3	5	0	21.8	28.6	0.7	266.6	7	0.4	-2.62893
128	BHT1358	Akaki	473386	980122	479	302	8	0.11	50	10.1	35.72	10.49	0	14.56	10.77	0.88	266.57	16.94	0.36	-2.11012
129	BHT1363	Akaki	471677	971640	540	350	7.09	0.3	54	8.8	60.8	9.12	0	6.37	14.9	0.65	353.56	14.76	0.17	-1.18162
130	BHT1365	Akaki	469738	971752	573	344	7.07	0.22	37	15	53.2	12.31	0	14.56	3.99	0.7	310	24.85	0.15	-3.40913
131	BHT1367	SANFTW1	477819	987018	484	308	7.34	0.14	82	9.1	24.32	3.65	0	15.47	0.4	0.97	281.82	8.57	0.57	0.678838
132	BHT1368	SANFTW 2	484094	987465	1571	1026	7.52	0.78	360	9.8	29	12.53	0	40.7	0.27	0.8	1049.2	29.58	0.24	-1.56721
133	BHT1369	SANFTW3	481012	984597	711	460	7.55	0.13	154	17	13.68	1.82	0	35.49	0.55	1.63	405.04	14.63	0.27	-0.0028
134	BHT1516	legedadi	498961	1005177	438	278	7.34	0.63	54	7.7	30.4	11.86	0	17.29	0.17	0.65	241.07	8.36	0.04	4.451204
135	BHT1375	legedadi	501033	1006222	425	260	7.64	0.67	43	7.9	34.2	8.21	0	16.38	0.95	0.73	239.12	10.36	0.25	-1.68247
136	BHT1376	legedadi	497455	1006373	458	298	7.62	0.56	62	8.9	34.2	7.75	0	19.11	7.07	0.67	270	7.32	0.52	0.389115
137	BHT121	LLA3	496269	1004908	473	286	7.5	0.2	85	9.6	15.2	3.19	0	19.11	28.9	0.76	225.46	14.18	0.22	-0.36076
138	BHT1598	Country C	487920	1003552	474	308.1	7.87	0.3	33	3.4	58	10	0	4	0.44	0.85	316	4	0.23	-1.2194
139	BHT1595	Addis mer	487089	997218	401	260.65	7.71	0.3	35	4	40	7	0	4	0.44	0.98	261	4	0.23	-3.17301
140	BHT1513	Hamele 19	474510	1001445	273	177.45	7.85	0.3	33	5.3	20	2	0	5	0.44	1.13	151	8	0.23	-0.98897

141	BHT1576	Mikililand	466727	1001399	183	118.95	7.67	0.3	15.4	3.8	18	3	0	4	0.44	1.54	101	7	0.23	-0.15501
142	BHT1594	Ayer tena	466082	993808	308	200.2	7.74	0.3	12	3.4	40	8	0	3	6.65	0.68	193	3	0.23	-2.1482
143	BHT1592	Abyssinia	494578	1011816	269	174.85	7.68	0.3	15	3.1	26	6	0	2	1.77	0.68	154	4	0.23	-3.09943
144	SPT502	Gefersa Et	454124	1002590	240	148	7.01	0.25	5.3	1.1	40.9	4.9	0	4.8	8.5	0.41	148.6	0.53	0.14	-0.17252
145	SPT425	Abasamue	469142	966835	571	371	7	0.1	46	6	40	22	0	9	6	1	304	6	0.1	4.582266
146	SPT546	Entotoma	474208	1005540	196	127.4	7.57	0.3	4	1.4	28	5	0	4	8.4	0.07	107	4	0.23	-1.47615
147	SPT259	Gebreche	473540	1004307	58.5	38.025	6.65	0.3	3	2.1	7	0.8	0	1	3.1	1	29	3	0.23	-1.27594
148	SPT548	yeshy deb	466260	996974	362	235.3	7.59	0.3	13	3	44	12	0	3	7.53	0.64	227	4	0.23	-2.16032
149	BHT1599	FW-BH2	473713	996131	4400	3080	7.1	0.12	800	19.5	4.8	0.97	0	34.74	0	28.6	2171.6	39	0.24	-2.4677
150	SPT553	FW-SP1	473710	996129	4400	3080	7.25	0.04	800	18.5	4.8	0.97	0	34.7	1.3	23	2196	46.96	0.15	-3.27984
151	SPT554	FW-SP2	473633	996163	4280	2782	7.19	0.03	800	18	5.6	0.49	0	29.7	0.44	25.4	2196	43.04	0.26	-2.98341
152	BHT1600	FW-BH1	473678	996200	3890	2723	7.05	0.08	800	18	6.4	0.97	0	43.7	0.88	27	2208.2	53.48	0.5	-3.95025
153	BHT1601	GHION-DV	473799	996041	4300	3010	7.23	0.15	800	20.5	4	0.97	0	29.78	1.32	34.4	2220.4	80.87	0.32	-4.51782
154	BHT1602	GHION-SV	473846	996042	3450	2415	7.06	0.15	900	28.5	4.8	1.46	0	29.78	0.44	25.4	2110.6	65.22	0.28	4.421321
155	BHT1603	GHION-SV	473849	996100	3030	2121	7.04	0.14	750	28.5	8.8	1.96	0	29.78	0	23.6	1903.2	60.2	0.31	0.948394
156	BHT1604	Z-HOSPITA	473605	996364	790	553	7.17	0.97	80	7.5	84	9.73	0	62.7	14.91	1.21	329.4	65.22	0.12	-0.62534
157	BHT1605	HILTON-N	473955	996585	3150	2205	7.11	0.2	750	15	5.6	1.46	0	37.4	10	21.6	1903.2	27	0.45	0.606465
158	BHT1606	HILTON-O	473950	996583	3140	2198	7.14	0.1	750	16	5.6	1.46	0	39.4	8	21.4	1939.8	39	0.46	-0.66376
159	BHT1607	RAS-HOTE	473069	996040	596	417.2	7.08	0.17	20	3.5	92	9.73	0	18.7	33	0.43	244	37	0.04	4.364237
160	BHT1608	National F	473818	996216	4600	3220	7.24	0.05	900	22	6.4	0.97	0	48.4	15	17.2	2257	61	0.59	0.249709
161	BHT1609	National F	473822	996091	4590	3213	7.15	0.28	900	20	6.4	0.97	0	46.2	5	27.4	2269.2	51	0.3	0.477928
162	BHT1610	GHANDI-H	473413	997389	1092	764.4	7.39	0.94	250	7	4	1.46	0	17.6	8.8	3.4	610	26	0.41	0.816856
163	BHT1612	ST.JOSEPH	473890	996131	3197	2237.9	8.27	0.19	700	8.9	6.4	2.92	0	39.6	11	11.6	1878.8	40	0.23	-2.67399
164	BHT114	WF01-PW	472460	981553	581	346	8.27	0	118	8.8	2.88	5.6	0	29.93	2.67	3.02	285	1.58	0.1	3.141637
165	BHT114	WF01-PW	472460	981553	590	340	8.42	0	112	8.6	3.04	0.91	0	26.39	0.87	3.74	243.39	18.12	0.27	1.74468
166	SANF-PW	North fant	480385	986784	1045	696	8.03	0.62	255	6.6	10.4	1.9	0.03	49	0.33	2.7	629	18.6	0.6	-0.70626
167	WFO1-PW	Roge villa	471027	973709	624	410	7.61	0.19	51	9.6	60.8	13.8	0.06	21.6	52.6	1.4	273	1.8	0.18	5.344412
168	WFO1-PW	Dukem	473944	978720	589	368	7.28	0.19	39	6.9	74	15.3	0.15	17.38	36.7	0.72	309	19.1	0.42	2.205876
169	WFO1-PW	Akaki kali	471918	979657	636	420	7.18	0.23	35	7.1	87	18.2	0.01	15.5	18.7	0.68	392	14.63	0.24	0.631172
170	SANF-PW	North fant	484553	986685	974	638	7.46	0.54	198	19	15.2	5.28	0.03	35	0.47	1.12	517	10.8	0.76	2.938855
171	SANF-PW	North fant	483560	983856	984	468	7.44	0.33	126	4.9	48	16.1	0.07	32.5	7.7	0.71	439	9.2	1.49	5.08478
172	SANF-PW	Woreda 0	484142	982196	484	326	8.16	0.25	105	5.9	16	6.2	0.04	23.5	0.22	2	292	16.3	0.42	1.95799

Annex 2: physical data of tap water

s/n	subcity	sample code	X(m)	Y(m)	Z(m)	EC(µs/cm)	T (°C)	PH	TDS
1	Addis Ketema	AK01	468352	1000722	2548	100	20.4	7.7	64
2	Addis Ketema	AK02	468395	1000684	2547	100	20.6	7.68	64
3	Addis Ketema	AK03	468367	1000718	2548	110	19.2	7.66	70.4
4	Addis Ketema	AK04	468360	1000808	2546	100	21.1	7.8	64
5	Addis Ketema	AK05	469193	997349	2398	570	22.1	7.84	364.8
6	Addis Ketema	AK06	469160	997198	2392	460	22.2	8.05	294.4
7	Addis Ketema	AK07	469157	997192	2390	580	20.1	8.02	371.2
8	Addis Ketema	AK08	469172	997205	2390	430	24.6	8.08	275.2
9	Addis Ketema	AK09	469195	997202	2394	560	23	8.14	358.4
10	Addis Ketema	AK10	469191	997210	2398	550	23.4	8.06	352
11	Addis Ketema	AK11	469221	997224	2395	560	21.1	8.13	358.4
12	Addis Ketema	AK12	469215	997205	2396	540	20.4	8.12	345.6
13	Addis Ketema	AK13	469243	997182	2397	570	19.6	8.08	364.8
14	Addis Ketema	AK14	469224	997187	2396	110	21.7	8.27	70.4
15	Addis Ketema	AK15	469219	997183	2401	100	20.1	8.11	64
16	Addis Ketema	AK16	470350	997221	2433	590	24.7	8.14	377.6
17	Addis Ketema	AK17	470473	997404	2424	550	22.3	8.22	352
18	Addis Ketema	AK18	470486	997406	2424	580	27.4	8.06	371.2
19	Addis Ketema	AK19	470474	997396	2433	570	20.5	8.24	364.8
20	Addis Ketema	AK20	470427	997590	2446	580	23.6	8.1	371.2
21	Addis Ketema	AK21	470426	997594	2446	590	20.7	8.05	377.6
22	Addis Ketema	AK22	470409	997650	2445	580	21.9	8.21	371.2
23	Addis Ketema	AK23	470390	997719	2442	580	20.8	8.14	371.2
24	Addis Ketema	AK24	470401	997876	2452	110	19.2	8.5	70.4
25	Addis Ketema	AK25	470411	997987	2454	110	24.2	8.16	70.4
26	Addis Ketema	AK26	470464	998222	2468	110	20.8	8.15	70.4
27	Addis Ketema	AK27	470424	998219	2458	110	22.7	7.91	70.4
28	Addis Ketema	AK28	470411	998253	2454	110	25	7.76	70.4
29	Addis Ketema	AK29	470325	998455	2467	120	17.7	8.39	76.8
30	Addis Ketema	AK30	470332	998457	2467	110	17.6	8.1	70.4
31	Addis Ketema	AK31	470328	998465	2464	120	17.4	7.95	76.8
32	Addis Ketema	AK32	470308	998523	2473	120	17	7.92	76.8
33	Addis Ketema	AK33	470309	998527	2472	110	16.8	7.95	70.4
34	Addis Ketema	AK34	470302	998522	2468	110	15.3	7.82	70.4
35	Addis Ketema	AK35	470296	998526	2470	110	16.2	7.86	70.4
36	Addis Ketema	AK36	470329	998538	2468	110	16.2	7.82	70.4
37	Addis Ketema	AK37	470329	998538	2468	110	16.2	7.82	70.4
38	Addis Ketema	AK38	470343	998543	2472	120	15.4	7.81	76.8
39	Addis Ketema	AK39	470294	998599	2475	120	16.9	7.79	76.8
40	Addis Ketema	AK40	470291	998595	2473	120	16.1	7.82	76.8
41	Addis Ketema	AK41	470577	998576	2466	130	18	8.51	83.2

42	Akaki Kality	AKK01	475169	983239	2196	600	25.7	7.34	384
43	Akaki Kality	AKK02	475171	983253	2168	580	22.7	7.54	371.2
44	Akaki Kality	AKK03	475176	983283	2169	580	22.1	7.64	371.2
45	Akaki Kality	AKK04	475186	983327	2165	650	22.3	7.82	416
46	Akaki Kality	AKK05	475177	983319	2166	630	22.6	7.83	403.2
47	Akaki Kality	AKK06	475165	983321	2164	630	23.47	7.81	403.2
48	Akaki Kality	AKK07	475156	983307	2167	570	24.3	7.6	364.8
49	Akaki Kality	AKK08	475126	983340	2166	650	20.2	7.86	416
50	Akaki Kality	AKK09	475106	983327	2171	570	20.8	7.8	364.8
51	Akaki Kality	AKK10	475074	983369	2173	630	21.7	7.77	403.2
52	Akaki Kality	AKK11	475078	983420	2171	580	24.4	7.71	371.2
53	Akaki Kality	AKK12	475081	983450	2159	640	21.8	7.83	409.6
54	Akaki Kality	AKK13	475012	983475	2163	570	25.5	7.61	364.8
55	Akaki Kality	AKK14	474990	983437	2165	580	25.6	7.66	371.2
56	Akaki Kality	AKK15	474954	983369	2169	590	23.5	7.63	377.6
57	Akaki Kality	AKK16	473923	987600	2202	660	24.8	7.89	422.4
58	Akaki Kality	AKK17	473925	987611	2201	600	23.9	7.79	384
59	Akaki Kality	AKK18	473912	987616	2211	620	20.9	7.86	396.8
60	Akaki Kality	AKK19	473893	987624	2220	600	23.5	7.65	384
61	Akaki Kality	AKK20	473797	987942	2216	620	22.3	7.82	396.8
62	Akaki Kality	AKK21	473795	987947	2215	620	26.7	7.74	396.8
63	Akaki Kality	AKK22	473779	987944	2213	590	24.9	7.79	377.6
64	Akaki Kality	AKK23	473778	987948	2212	570	20.4	7.64	364.8
65	Akaki Kality	AKK24	473793	987925	2211	580	24.1	7.68	371.2
66	Akaki Kality	AKK25	473792	987918	2211	590	21	7.75	377.6
67	Akaki Kality	AKK26	473803	987913	2207	670	26	7.71	428.8
68	Akaki Kality	AKK27	473785	987896	2207	590	24.7	7.61	377.6
69	Akaki Kality	AKK28	473800	987869	2200	580	23	7.66	371.2
70	Akaki Kality	AKK29	473800	987867	2207	580	22.5	7.65	371.2
71	Akaki Kality	AKK30	473781	987861	2209	580	20.9	7.72	371.2
72	Akaki Kality	AKK31	473780	987875	2206	580	23.4	7.65	371.2
73	Akaki Kality	AKK32	473787	987856	2203	590	22.4	7.71	377.6
74	Akaki Kality	AKK33	474681	983253	2160	590	22.4	7.9	377.6
75	Akaki Kality	AKK34	474702	983238	2159	600	23	7.88	384
76	Akaki Kality	AKK35	473390	986961	2194	590	23.2	7.68	377.6
77	Akaki Kality	AKK36	474266	986635	2223	580	23.5	7.85	371.2
78	Akaki Kality	AKK37	474167	986349	2239	580	23.6	7.76	371.2
79	Akaki Kality	AKK38	473898	985765	2246	590	22.89	7.85	377.6
80	Akaki Kality	AKK39	473907	989595	2253	580	23.3	7.64	371.2
81	Akaki Kality	AKK40	473740	989427	2239	560	24.7	7.82	358.4
82	Akaki Kality	AKK41	473602	989371	2240	580	23.6	7.72	371.2

83	Akaki Kality	AKK42	473916	984842	2225	590	23.8	7.77	377.6
84	Akaki Kality	AKK43	473926	984764	2218	590	22.9	7.86	377.6
85	Akaki Kality	AKK44	474018	989897	2253	600	27.9	7.67	384
86	Akaki Kality	AKK45	474232	986539	2255	580	26.9	7.88	371.2
87	Akaki Kality	AKK46	474277	984388	2254	590	25.6	7.59	377.6
88	Akaki Kality	AKK47	474402	984005	2256	580	23.68	7.62	371.2
89	Akaki Kality	AKK48	474418	983941	2255	590	25.6	7.81	377.6
90	Akaki Kality	AKK49	474433	983902	2258	590	25.3	7.8	377.6
91	Akaki Kality	AKK50	474456	983849	2253	590	25.9	7.69	377.6
92	Akaki Kality	AKK51	474465	983826	2259	580	26.3	7.75	371.2
93	Akaki Kality	AKK52	474539	983722	2256	590	24.1	7.69	377.6
94	Akaki Kality	AKK53	473991	989897	2256	600	26.5	7.5	384
95	Akaki Kality	AKK54	476589	980251	2081	570	23.9	7.8	364.8
96	Akaki Kality	AKK55	476574	980253	2075	550	23.3	7.78	352
97	Akaki Kality	AKK56	476751	980958	2078	560	23.1	7.68	358.4
98	Akaki Kality	AKK57	476874	981171	2080	550	23.1	7.61	352
99	Akaki Kality	AKK58	476762	981170	2079	560	22.9	7.69	358.4
100	Akaki Kality	AKK59	476576	980251	2075	560	21.6	7.84	358.4
101	Akaki Kality	AKK60	476534	980325	2080	550	23.3	7.82	352
102	Akaki Kality	AKK61	476529	980327	2078	550	24.9	7.76	352
103	Akaki Kality	AKK62	476531	980327	2077	560	29	7.82	358.4
104	Akaki Kality	AKK63	476528	980323	2075	560	21.8	7.9	358.4
105	Akaki Kality	AKK64	477470	979197	2093	560	20	8	358.4
106	Akaki Kality	AKK65	477475	979200	2092	540	20.8	7.9	345.6
107	Akaki Kality	AKK66	477467	979238	2088	560	22	7.86	358.4
108	Akaki Kality	AKK67	477331	979359	2088	550	24.5	7.86	352
109	Akaki Kality	AKK68	477430	979519	2090	550	22.3	7.69	352
110	Akaki Kality	AKK69	477355	979606	2087	540	20.8	7.81	345.6
111	Akaki Kality	AKK70	477227	979741	2089	550	23.6	7.74	352
112	Akaki Kality	AKK71	477101	979870	2090	560	22.9	7.88	358.4
113	Akaki Kality	AKK72	477050	979935	2089	550	23.1	7.69	352
114	Akaki Kality	AKK73	480253	980759	2180	560	25	7.74	358.4
115	Akaki Kality	AKK74	480228	980751	2164	570	24.4	7.7	364.8
116	Akaki Kality	AKK75	479440	983540	2156	600	22.8	7.81	384
117	Akaki Kality	AKK76	479333	980415	2151	600	26.2	7.74	384
118	Akaki Kality	AKK77	479487	983457	2195	610	23.3	7.73	390.4
119	Akaki Kality	AKK78	479502	983484	2199	610	22.1	7.82	390.4
120	Akaki Kality	AKK79	476652	980806	2070	600	30.4	7.72	384
121	Akaki Kality	AKK80	476651	980804	2072	590	22.7	7.91	377.6
122	Akaki Kality	AKK81	476661	980786	2071	580	24.7	7.8	371.2
123	Akaki Kality	AKK82	474763	988601	2182	600	22	7.62	384

124	Akaki Kality	AKK83	474762	988586	2194	590	20	7.53	377.6
125	Akaki Kality	AKK84	474743	988596	2189	420	22.6	7.41	268.8
126	Akaki Kality	AKK85	480274	986238	2195	600	23.2	7.86	384
127	Arada	AR01	472034	998506	2445	120	17.6	7.78	76.8
128	Arada	AR02	472044	998522	2452	120	16.5	7.81	76.8
129	Arada	AR03	472055	998520	2457	120	16.9	7.78	76.8
130	Arada	AR04	472028	998530	2459	120	17	7.78	76.8
131	Arada	AR05	472020	998531	2461	120	17	7.78	76.8
132	Arada	AR06	472016	998531	2466	120	16.4	7.73	76.8
133	Arada	AR07	472028	998542	2464	120	16	7.73	76.8
134	Arada	AR08	472025	998536	2461	120	15.7	7.8	76.8
135	Arada	AR09	472017	998514	2460	130	17.2	7.78	83.2
136	Arada	AR10	472016	998513	2455	130	17.7	7.78	83.2
137	Arada	AR11	472022	998511	2416	120	19	7.75	76.8
138	Arada	AR12	474119	998372	2450	130	18.6	7.86	83.2
139	Arada	AR13	474018	998504	2458	130	19.5	8.13	83.2
140	Arada	AR14	474386	999086	2450	140	25.5	8.08	89.6
141	Bole	BO01	475033	992517	2300	160	18.6	8.1	102.4
142	Bole	BO02	475033	992552	2325	160	20.5	7.85	102.4
143	Bole	BO03	475019	992547	2329	140	18.4	7.76	89.6
144	Bole	BO04	474940	992607	2321	310	20.4	7.68	198.4
145	Bole	BO05	474974	992598	2319	240	18.2	7.86	153.6
146	Bole	BO06	474975	992608	2319	280	19.4	7.78	179.2
147	Bole	BO07	474977	992614	2316	210	18.4	7.89	134.4
148	Bole	BO08	474966	992617	2312	290	19.2	7.79	185.6
149	Bole	BO09	474968	992623	2313	300	19.3	7.84	192
150	Bole	BO10	474964	992629	2310	290	20	7.84	185.6
151	Bole	BO11	474860	992639	2312	160	20.1	7.91	102.4
152	Bole	BO12	474853	992628	2308	120	19.6	7.96	76.8
153	Bole	BO13	474851	992648	2308	130	19.6	7.84	83.2
154	Bole	BO14	474827	992611	2314	300	21.2	7.65	192
155	Bole	BO15	474834	992618	2310	280	20	7.8	179.2
156	Bole	BO16	474833	992623	2305	300	22.6	7.75	192
157	Bole	BO17	474824	992643	2304	300	20.3	7.82	192
158	Bole	BO18	474840	992670	2305	140	20.1	7.9	89.6
159	Bole	BO19	474842	992667	2306	180	20.8	7.82	115.2
160	Bole	BO20	474841	992669	2306	130	23.7	7.75	83.2
161	Bole	BO21	474822	992704	2311	110	19.6	7.87	70.4
162	Bole	BO22	474840	992701	2311	210	27	7.58	134.4
163	Bole	BO23	474838	992698	2312	140	27	7.68	89.6
164	Bole	BO24	474851	992699	2313	210	20.4	7.91	134.4

165	Bole	BO25	474865	992690	2314	270	21.6	7.71	172.8
166	Bole	BO26	474868	992691	2312	140	20.7	7.78	89.6
167	Bole	BO27	474867	992695	2312	180	24.3	7.63	115.2
168	Bole	BO28	474866	992698	2312	210	20.8	7.66	134.4
169	Bole	BO29	483043	996585	2377	130	23.3	7.8	83.2
170	Bole	BO30	482472	996930	2398	120	19.3	7.83	76.8
171	Bole	BO31	482525	996847	2394	110	19.4	7.76	70.4
172	Bole	BO32	482545	996845	2397	110	21.1	7.76	70.4
173	Bole	BO33	482552	996841	2397	110	19.5	7.79	70.4
174	Bole	BO34	482568	996846	2389	110	20.8	7.77	70.4
175	Bole	BO35	482572	996826	2391	130	21.3	7.8	83.2
176	Bole	BO36	475062	988587	2175	590	19.7	8.1	377.6
177	Bole	BO37	475683	989340	2207	620	20.7	8.03	396.8
178	Bole	BO38	475671	989352	2215	600	20.4	8.04	384
179	Bole	BO39	475119	988565	2162	590	21.1	8.2	377.6
180	Bole	BO40	475342	988766	2159	590	20.6	8.01	377.6
181	Bole	BO41	475459	989013	2171	580	21.01	7.98	371.2
182	Bole	BO42	475445	989105	2182	590	20.4	8.02	377.6
183	Bole	BO43	476399	989593	2222	580	19.8	7.97	371.2
184	Bole	BO44	476447	989564	2221	600	21.3	7.82	384
185	Bole	BO45	476385	989547	2221	600	21.7	7.9	384
186	Bole	BO46	476581	990337	2254	590	21.2	8.03	377.6
187	Bole	BO47	476936	989777	2243	580	20.1	8.01	371.2
188	Bole	BO48	477230	988940	2211	590	21.2	7.98	377.6
189	Bole	BO49	476603	988641	2191	590	20.3	7.89	377.6
190	Bole	BO50	475939	990227	2260	590	20.2	7.92	377.6
191	Bole	BO51	475102	992599	2304	150	20.2	8.18	96
192	Bole	BO52	475093	992574	2303	200	18.1	8.03	128
193	Bole	BO53	475055	992604	2301	200	20.7	7.94	128
194	Bole	BO54	476583	996538	2364	130	18.9	7.76	83.2
195	Bole	BO55	477406	996762	2369	150	20.8	7.99	96
196	Bole	BO56	478315	996764	2361	140	23	7.93	89.6
197	Bole	BO57	480970	994027	2305	140	22.5	7.91	89.6
198	Bole	BO58	480966	994012	2307	130	24.8	7.72	83.2
199	Bole	BO59	480951	994020	2321	130	21.2	7.78	83.2
200	Bole	BO60	480922	993972	2302	140	25.8	7.7	89.6
201	Bole	BO61	480915	993981	2302	130	24.3	7.67	83.2
202	Bole	BO62	481287	993970	2303	130	20.4	7.8	83.2
203	Bole	BO63	481403	994035	2305	140	25.3	7.71	89.6
204	Bole	BO64	483692	995260	2352	130	24.1	7.77	83.2
205	Bole	BO65	486233	997111	2399	120	22.1	7.62	76.8

206	Bole	BO66	479263	996547	2367	130	19.4	7.85	83.2
207	Bole	BO67	481635	996021	2352	540	22.4	7.48	345.6
208	Bole	BO68	485706	995462	2344	140	21.3	7.75	89.6
209	Bole	BO69	481944	996086	2370	130	22.5	7.78	83.2
210	Bole	BO70	484051	992715	2298	140	22.1	7.7	89.6
211	Bole	BO71	482778	992704	2271	140	19.8	7.72	89.6
212	Bole	BO72	488001	991926	2333	540	22.2	7.46	345.6
213	Bole	BO73	488057	991936	2330	420	25.1	7.81	268.8
214	Bole	BO74	487944	992027	2328	480	20.6	7.8	307.2
215	Bole	BO75	487888	992132	2349	530	22.5	7.78	339.2
216	Bole	BO76	487880	992130	2352	530	22.2	7.69	339.2
217	Bole	BO77	487790	992140	2339	540	22.2	7.61	345.6
218	Bole	BO78	487831	992020	2359	420	20.6	8.07	268.8
219	Bole	BO79	470577	998576	2466	130	18	8.51	83.2
220	Bole	BO80	474751	996601	2363	110	18.5	7.92	70.4
221	Bole	BO81	477434	994603	2331	130	19.8	7.71	83.2
222	Bole	BO82	476688	995866	2359	130	20.1	7.67	83.2
223	Bole	BO83	475909	996207	2359	120	18.7	7.62	76.8
224	Gulela	GL01	472618	1000806	2559	120	17.7	8.2	76.8
225	Gulela	GL02	472621	1000804	2543	120	17.2	8.12	76.8
226	Gulela	GL03	472614	1000808	2537	120	18.1	7.94	76.8
227	Gulela	GL04	472608	1000810	2537	100	16.9	7.89	64
228	Gulela	GL05	472610	1000811	2540	110	16.9	7.88	70.4
229	Gulela	GL06	472604	1000812	2541	110	17.1	7.89	70.4
230	Gulela	GL07	472598	1000818	2543	100	17.1	7.83	64
231	Gulela	GL08	472597	1000813	2545	110	15.5	7.86	70.4
232	Gulela	GL09	472597	1000835	2546	110	18.5	7.82	70.4
233	Gulela	GL10	472581	1000842	2544	100	16.9	7.8	64
234	Gulela	GL11	472582	1000847	2544	100	17.3	7.8	64
235	Gulela	GL12	472597	1000836	2546	110	19.3	7.76	70.4
236	Gulela	GL13	472597	1000842	2544	100	16.9	7.8	64
237	Gulela	GL14	472582	1000847	2544	100	17.3	7.8	64
238	Gulela	GL15	472597	1000836	2546	110	19.3	7.76	70.4
239	Gulela	GL16	472535	1000849	2540	110	19.6	7.69	70.4
240	Gulela	GL17	472406	1001857	2618	120	19.9	7.74	76.8
241	Gulela	GL18	472404	1001856	2614	120	16.3	7.85	76.8
242	Gulela	GL19	472406	1001859	2613	120	17	7.8	76.8
243	Gulela	GL20	472392	1001908	2621	130	18.5	7.81	83.2
244	Gulela	GL21	472395	1001898	2631	130	19.4	7.79	83.2
245	Gulela	GL22	472383	1001904	2623	130	20.7	7.74	83.2
246	Gulela	GL23	472385	1001909	2619	120	18.5	7.8	76.8

247	Gulela	GL24	472458	1001865	2615	130	18.8	7.75	83.2
248	Gulela	GL25	472458	1001859	2605	130	20.1	7.7	83.2
249	Gulela	GL26	473735	1001489	2585	130	18.6	7.7	83.2
250	Gulela	GL27	473745	1001490	2584	140	18.4	7.73	89.6
251	Gulela	GL28	473779	1001513	2587	130	21.4	7.67	83.2
252	Gulela	GL29	473765	1001493	2579	130	19.6	7.73	83.2
253	Gulela	GL30	473757	1001503	2574	130	20.6	7.71	83.2
254	Gulela	GL31	473783	1001490	2579	140	19.7	7.72	89.6
255	Gulela	GL32	473777	1001485	2573	140	19.9	7.69	89.6
256	Gulela	GL33	473788	1001497	2573	140	20.4	7.66	89.6
257	Gulela	GL34	473779	1001517	2570	130	19.6	7.7	83.2
258	Gulela	GL35	473778	1001524	2562	140	21.9	7.67	89.6
259	Kolfe Keranyo	KK01	463947	995781	2447	240	18.3	7.98	153.6
260	Kolfe Keranyo	KK02	464319	994919	2463	580	20.9	8.05	371.2
261	Kolfe Keranyo	KK03	464264	994956	2454	580	16.8	8.19	371.2
262	Kolfe Keranyo	KK04	464263	995052	2455	580	19.4	8.31	371.2
263	Kolfe Keranyo	KK05	464314	995299	2444	250	18.6	7.81	160
264	Kolfe Keranyo	KK06	463894	995767	2482	200	19.7	7.77	128
265	Kolfe Keranyo	KK07	463772	995785	2485	210	19.2	7.41	134.4
266	Kolfe Keranyo	KK08	463729	995833	2501	600	16.8	7.66	384
267	Kolfe Keranyo	KK09	463723	995835	2491	590	19.3	7.93	377.6
268	Kolfe Keranyo	KK10	463709	995917	2490	230	18	7.86	147.2
269	Kolfe Keranyo	KK11	463724	996005	2487	230	19.3	7.38	147.2
270	Kolfe Keranyo	KK12	463828	996057	2483	230	19.9	7.28	147.2
271	Kolfe Keranyo	KK13	463962	996151	2476	230	16.6	7.58	147.2
272	Kolfe Keranyo	KK14	464098	996202	2478	370	19.1	7.53	236.8
273	Kolfe Keranyo	KK15	464124	996179	2478	230	17.1	7.73	147.2
274	Kolfe Keranyo	KK16	464336	996052	2487	230	15.9	8.01	147.2
275	Kolfe Keranyo	KK17	464562	995987	2476	580	20.7	7.79	371.2
276	Kolfe Keranyo	KK18	464903	995840	2462	260	18.6	7.69	166.4
277	Kolfe Keranyo	KK19	465096	995598	2469	590	20.9	7.95	377.6
278	Kolfe Keranyo	KK20	464943	995580	2460	620	20	8.18	396.8
279	Kolfe Keranyo	KK21	463800	995085	2526	590	20.8	7.96	377.6
280	Kolfe Keranyo	KK22	463972	994029	2460	590	17.8	8.11	377.6
281	Kolfe Keranyo	KK23	464024	993749	2426	340	18.4	8.03	217.6
282	Kolfe Keranyo	KK24	464107	993615	2425	270	23.5	7.8	172.8
283	Kolfe Keranyo	KK25	464451	993386	2426	270	21.4	7.74	172.8
284	Kolfe Keranyo	KK26	464805	991457	2356	270	25.1	7.91	172.8
285	Kolfe Keranyo	KK27	464844	991728	2333	370	31.2	7.44	236.8
286	Kolfe Keranyo	KK28	464975	991782	2327	370	26.6	7.66	236.8
287	Kolfe Keranyo	KK29	466456	992579	2334	570	22.6	7.14	364.8
288	Kolfe Keranyo	KK30	466781	992521	2314	590	23.6	7.89	377.6
289	Kolfe Keranyo	KK31	466904	992279	2299	600	31.7	7.89	384
290	Kolfe Keranyo	KK32	467211	992415	2303	580	21.5	8.18	371.2

291	Kolfe Keranyo	KK33	467464	992411	2302	590	20.8	8.19	377.6
292	Kolfe Keranyo	KK34	467559	992705	2304	580	23.2	8.1	371.2
293	Kolfe Keranyo	KK35	464036	995714	2457	360	19	7.78	230.4
294	Kolfe Keranyo	KK36	464035	995635	2463	220	25.1	7.66	140.8
295	Kolfe Keranyo	KK37	464312	995479	2471	210	21.3	7.76	134.4
296	Kolfe Keranyo	KK38	465131	995268	2468	540	20.8	7.9	345.6
297	Kolfe Keranyo	KK39	465477	995051	2459	580	18.5	8.12	371.2
298	Kolfe Keranyo	KK40	466224	995161	2455	580	22.2	8.06	371.2
299	Kolfe Keranyo	KK41	466242	995225	2447	580	20.2	8.1	371.2
300	Kolfe Keranyo	KK42	466157	995184	2440	580	26.1	7.99	371.2
301	Kolfe Keranyo	KK43	468217	996222	2346	230	17.3	8.55	147.2
302	Kolfe Keranyo	KK44	468647	996109	2359	590	24.2	7.9	377.6
303	Kolfe Keranyo	KK45	469090	996042	2371	110	15	8.43	70.4
304	Kolfe Keranyo	KK46	469156	996141	2367	110	15.5	8.26	70.4
305	Kolfe Keranyo	KK47	469123	996179	2364	250	16.2	7.96	160
306	Kolfe Keranyo	KK48	468367	998596	2461	120	15.1	8.16	76.8
307	Kolfe Keranyo	KK49	468318	998593	2456	110	16.7	8.09	70.4
308	Kolfe Keranyo	KK50	468206	998625	2441	100	16.8	8.04	64
309	Kolfe Keranyo	KK51	468209	998759	2455	110	15.7	8.01	70.4
310	Kolfe Keranyo	KK52	468202	998789	2459	110	16	7.97	70.4
311	Kolfe Keranyo	KK53	468145	998980	2470	110	17.2	7.95	70.4
312	Kolfe Keranyo	KK54	468363	999028	2472	120	19.3	7.83	76.8
313	Kolfe Keranyo	KK55	466258	1002092	2579	160	19.8	7.88	102.4
314	Kolfe Keranyo	KK56	466254	1002153	2584	160	19.4	7.85	102.4
315	Kolfe Keranyo	KK57	466270	1002171	2588	160	23.6	7.85	102.4
316	Kolfe Keranyo	KK58	466301	1002280	2590	210	16.5	7.8	134.4
317	Kolfe Keranyo	KK59	466301	1002287	2594	200	17.1	7.79	128
318	Kolfe Keranyo	KK60	466394	1002240	2592	210	20.1	7.75	134.4
319	Kolfe Keranyo	KK61	466388	1002178	2586	180	21.2	7.89	115.2
320	Kolfe Keranyo	KK62	464311	995368	2458	210	20.2	7.4	134.4
321	Kirkos	KR01	472245	995675	2358	140	19.9	8.18	89.6
322	Kirkos	KR02	472236	995477	2352	140	19	7.96	89.6
323	Kirkos	KR03	472233	995467	2353	140	20.5	7.88	89.6
324	Kirkos	KR04	472238	995457	2351	130	22.4	7.85	83.2
325	Kirkos	KR05	472236	995461	2350	100	22.3	7.91	64
326	Kirkos	KR06	472239	995448	2350	130	21.7	7.94	83.2
327	Kirkos	KR07	472240	995441	2359	300	20.8	7.81	192
328	Kirkos	KR08	472236	995424	2364	140	20.2	8.08	89.6
329	Kirkos	KR09	472232	995329	2353	130	20.5	8.01	83.2
330	Kirkos	KR10	472216	995346	2350	570	24.6	7.73	364.8
331	Kirkos	KR11	472220	995339	2357	580	22.1	8	371.2
332	Kirkos	KR12	472218	995370	2356	590	21.2	8.04	377.6
333	Kirkos	KR13	472211	995357	2356	580	24.9	7.95	371.2
334	Kirkos	KR14	472206	995353	2355	580	24.5	8	371.2
335	Kirkos	KR15	472210	995366	2355	580	24.6	7.99	371.2

336	Kirkos	KR16	472545	996115	2354	140	19.6	8.4	89.6
337	Kirkos	KR17	473250	996173	2356	140	21.4	8.13	89.6
338	Kirkos	KR18	473989	996034	2341	580	22.2	7.56	371.2
339	Kirkos	KR19	474916	994564	2345	140	21.1	8.01	89.6
340	Kirkos	KR20	475123	994152	2305	340	21.4	7.68	217.6
341	Kirkos	KR21	475169	994110	2329	150	20.7	7.97	96
342	Kirkos	KR22	474167	993043	2294	580	20.7	7.97	371.2
343	Kirkos	KR23	474077	992987	2302	570	21.3	8.16	364.8
344	Kirkos	KR24	474058	992977	2297	580	21.6	8.03	371.2
345	Kirkos	KR25	474259	993705	2313	590	22.2	7.93	377.6
346	Kirkos	KR26	474246	993744	2338	590	21.2	7.96	377.6
347	Kirkos	KR27	473936	996125	2341	140	28	7.99	89.6
348	Kirkos	KR28	473995	998592	2438	130	20.4	8.08	83.2
349	Lideta	LD01	469111	996415	2316	580	19.2	7.87	371.2
350	Lideta	LD02	469027	996475	2362	580	24	7.92	371.2
351	Lideta	LD03	468969	996751	2388	580	23.7	7.9	371.2
352	Lideta	LD04	468971	996755	2388	580	21.7	7.98	371.2
353	Lideta	LD05	468879	996899	2395	580	23.1	7.99	371.2
354	Lideta	LD06	468876	996944	2400	590	28.2	7.86	377.6
355	Lideta	LD07	468822	997042	2393	180	19.5	8.08	115.2
356	Lideta	LD08	468826	997058	2395	100	20.7	8.1	64
357	Lideta	LD09	468794	997137	2392	100	20.8	8.01	64
358	Lideta	LD10	468746	997192	2400	110	21.45	7.92	70.4
359	Lideta	LD11	470190	996493	2372	590	26	7.77	377.6
360	Lideta	LD12	470183	996495	2371	590	23.6	7.88	377.6
361	Lideta	LD13	470176	996494	2374	580	21.4	7.94	371.2
362	Lideta	LD14	470179	996496	2377	580	24.1	7.84	371.2
363	Lideta	LD15	470156	996482	2374	580	19.9	7.96	371.2
364	Lideta	LD16	470181	996493	2374	580	22.6	7.8	371.2
365	Lideta	LD17	470730	997145	2446	600	23.6	8.16	384
366	Lideta	LD18	470765	997168	2448	590	21.7	8.1	377.6
367	Nifassilk Lafto	NL01	470935	988846	2242	540	22.3	7.68	345.6
368	Nifassilk Lafto	NL02	471003	988895	2230	550	20.2	7.84	352
369	Nifassilk Lafto	NL03	471015	988898	2228	550	21.8	7.86	352
370	Nifassilk Lafto	NL04	471042	988911	2240	550	18.3	7.96	352
371	Nifassilk Lafto	NL05	471026	988928	2230	560	27.7	7.75	358.4
372	Nifassilk Lafto	NL06	471012	988933	2228	550	22.5	7.82	352
373	Nifassilk Lafto	NL07	471005	988949	2232	550	22.1	7.84	352
374	Nifassilk Lafto	NL08	470984	988941	2237	550	21.1	7.86	352
375	Nifassilk Lafto	NL09	471004	988996	2235	540	18.9	7.9	345.6
376	Nifassilk Lafto	NL10	471018	988994	2230	550	25.7	7.8	352
377	Nifassilk Lafto	NL11	471028	989000	2236	560	21.2	7.89	358.4
378	Nifassilk Lafto	NL12	471015	988980	2238	540	24.7	7.83	345.6
379	Nifassilk Lafto	NL13	471025	989011	2242	550	25.1	7.78	352
380	Nifassilk Lafto	NL14	471037	989029	2239	550	22.5	7.85	352

381	Nifassilk Lafto	NL15	471020	989146	2227	550	21	8.02	352
382	Nifassilk Lafto	NL16	470282	991705	2255	330	23.6	7.84	211.2
383	Nifassilk Lafto	NL17	470249	991670	2244	570	20.7	7.34	364.8
384	Nifassilk Lafto	NL18	470224	991643	2242	570	20	7.48	364.8
385	Nifassilk Lafto	NL19	470124	991550	2251	410	20.3	7.71	262.4
386	Nifassilk Lafto	NL20	470111	991544	2251	360	21.3	7.86	230.4
387	Nifassilk Lafto	NL21	470103	991530	2243	410	20.4	7.67	262.4
388	Nifassilk Lafto	NL22	470082	991528	2243	410	24.6	7.7	262.4
389	Nifassilk Lafto	NL23	470073	991522	2243	440	21.7	7.65	281.6
390	Nifassilk Lafto	NL24	470065	991514	2243	360	20.6	8	230.4
391	Nifassilk Lafto	NL25	470045	991506	2247	330	20.2	7.88	211.2
392	Nifassilk Lafto	NL26	469871	990851	2235	330	25.6	7.85	211.2
393	Nifassilk Lafto	NL27	469266	990756	2226	320	23.5	7.65	204.8
394	Nifassilk Lafto	NL28	469938	990865	2239	330	23.6	7.81	211.2
395	Nifassilk Lafto	NL29	469890	990817	2245	320	21	7.93	204.8
396	Nifassilk Lafto	NL30	470605	987618	2230	560	23.6	7.99	358.4
397	Nifassilk Lafto	NL31	470554	990858	2226	560	22.1	7.31	358.4
398	Nifassilk Lafto	NL32	470670	989933	2220	550	25.8	7.78	352
399	Nifassilk Lafto	NL33	470726	992691	2277	580	23.9	7.88	371.2
400	Nifassilk Lafto	NL34	470480	991770	2220	330	22.8	7.67	211.2
401	Nifassilk Lafto	NL35	470744	985851	2236	550	21.1	8.01	352
402	Nifassilk Lafto	NL36	470788	989090	2228	540	21.3	7.67	345.6
403	Nifassilk Lafto	NL37	470561	990694	2227	560	24.9	7.83	358.4
404	Nifassilk Lafto	NL38	470693	992688	2278	580	24.8	7.87	371.2
405	Nifassilk Lafto	NL39	470683	992687	2280	580	21.4	8	371.2
406	Nifassilk Lafto	NL40	471557	991430	2262	600	22.9	7.63	384
407	Nifassilk Lafto	NL41	471575	987624	2256	540	23.6	7.78	345.6
408	Nifassilk Lafto	NL42	471594	991402	2262	590	21.1	7.78	377.6
409	Nifassilk Lafto	NL43	472276	991984	2296	590	21.3	7.75	377.6
410	Nifassilk Lafto	NL44	472252	991983	2290	600	20.1	7.79	384
411	Nifassilk Lafto	NL45	472361	989015	2246	560	27.2	7.99	358.4
412	Nifassilk Lafto	NL46	471825	991862	2274	580	22.6	7.79	371.2
413	Nifassilk Lafto	NL47	472374	989991	2213	560	22.1	8.1	358.4
414	Nifassilk Lafto	NL48	472038	987725	2201	560	24.2	7.81	358.4
415	Nifassilk Lafto	NL49	471830	987594	2219	550	24.3	7.82	352
416	Nifassilk Lafto	NL50	472351	989008	2251	560	21.8	8.11	358.4
417	Nifassilk Lafto	NL51	471759	988886	2232	560	25.9	8	358.4
418	Nifassilk Lafto	NL52	472060	988890	2233	560	23.3	7.89	358.4
419	Nifassilk Lafto	NL53	472834	988313	2214	570	25.1	7.38	364.8
420	Nifassilk Lafto	NL54	472853	988290	2212	560	24.8	7.33	358.4
421	Nifassilk Lafto	NL55	472872	988483	2220	560	24.1	7.56	358.4
422	Nifassilk Lafto	NL56	472543	988308	2225	570	23.1	7.42	364.8
423	Nifassilk Lafto	NL57	472595	989831	2219	560	20.8	8.01	358.4
424	Nifassilk Lafto	NL58	471908	987659	2222	560	24.8	7.33	358.4
425	Nifassilk Lafto	NL59	471889	987674	2222	550	24.3	7.77	352

426	Nifassilk Lafto	NL60	470848	985838	2238	560	27	7.8	358.4
427	Nifassilk Lafto	NL61	470865	985827	2237	560	20.2	8.18	358.4
428	Nifassilk Lafto	NL62	471707	987451	2242	560	25.6	7.88	358.4
429	Nifassilk Lafto	NL63	469292	994082	2309	580	24.3	7.89	371.2
430	Nifassilk Lafto	NL64	470419	994515	2320	580	23.86	7.88	371.2
431	Nifassilk Lafto	NL65	471205	993944	2307	570	24.3	7.91	364.8
432	Nifassilk Lafto	NL66	473715	989480	2238	560	23.7	7.73	358.4
433	Nifassilk Lafto	NL67	473714	989478	2238	560	18.8	8	358.4
434	Nifassilk Lafto	NL68	474751	996601	2363	110	18.5	7.92	70.4
435	Yeka	YK01	475620	1000999	2539	250	17.3	8	160
436	Yeka	YK02	475608	1001073	2539	260	18	8.02	166.4
437	Yeka	YK03	475622	1001090	2541	260	18.6	8.06	166.4
438	Yeka	YK04	475443	1000994	2538	270	19.8	8.14	172.8
439	Yeka	YK05	475436	1000998	2537	310	17.8	8.17	198.4
440	Yeka	YK06	475429	1001019	2537	270	21.4	8.15	172.8
441	Yeka	YK07	475447	1001026	2538	260	19.3	8.16	166.4
442	Yeka	YK08	475431	1001033	2538	260	19.5	8.16	166.4
443	Yeka	YK09	475415	1001051	2538	270	25.7	8.1	172.8
444	Yeka	YK10	475402	1001070	2543	190	19	8.18	121.6
445	Yeka	YK11	475356	1000880	2528	250	23.5	8.06	160
446	Yeka	YK12	475348	1000876	2528	270	30.6	7.91	172.8
447	Yeka	YK13	475362	1000869	2528	260	25.7	8.07	166.4
448	Yeka	YK14	475355	1000853	2527	240	21.1	8.16	153.6
449	Yeka	YK15	475327	1000858	2536	240	24.9	8.08	153.6
450	Yeka	YK16	475303	1000890	2533	250	25.1	8.06	160
451	Yeka	YK17	475314	1000893	2534	240	23.3	8.07	153.6
452	Yeka	YK18	475321	1000903	2536	250	33.3	7.91	160
453	Yeka	YK19	475310	1000904	2532	220	22.9	8.17	140.8
454	Yeka	YK20	475315	1000890	2531	220	25.6	8.06	140.8
455	Yeka	YK21	475304	1000863	2526	240	21.6	8.1	153.6
456	Yeka	YK22	475287	1000862	2531	240	22.6	8.1	153.6
457	Yeka	YK23	475278	1000863	2531	240	22.7	8.1	153.6
458	Yeka	YK24	475270	1000864	2533	250	23.2	8.09	160
459	Yeka	YK25	475270	1000870	2530	250	26.3	8.03	160
460	Yeka	YK26	475273	1000884	2534	240	23.1	8.08	153.6
461	Yeka	YK27	475275	1000894	2530	240	22.6	8.08	153.6
462	Yeka	YK28	475280	1000894	2530	250	31.2	7.91	160
463	Yeka	YK29	475281	1000880	2532	280	21.9	8.1	179.2
464	Yeka	YK30	475294	1000900	2533	240	22.1	8.06	153.6
465	Yeka	YK31	475897	997345	2368	130	19.5	7.82	83.2
466	Yeka	YK32	475883	997350	2366	110	18.3	7.78	70.4
467	Yeka	YK33	475876	997333	2374	110	18.5	7.76	70.4
468	Yeka	YK34	475851	997460	2391	110	18.9	7.79	70.4
469	Yeka	YK35	476657	998113	2414	110	19.2	7.83	70.4
470	Yeka	YK36	477225	997767	2399	110	20.9	7.52	70.4

471	Yeka	YK37	476326	998022	2410	110	18.5	7.8	70.4
472	Yeka	YK38	476399	998149	2419	110	18.4	7.76	70.4
473	Yeka	YK39	481267	997919	2415	110	23.3	7.65	70.4
474	Yeka	YK40	481244	997891	2413	110	21.5	7.62	70.4
475	Yeka	YK41	481023	998865	2468	110	21.7	7.89	70.4
476	Yeka	YK42	480984	998827	2473	110	22.6	7.69	70.4
477	Yeka	YK43	480060	997608	2421	110	21.8	7.66	70.4
478	Yeka	YK44	486195	1001833	2533	420	20.2	7.63	268.8
479	Yeka	YK45	486218	1001887	2474	410	21.1	7.68	262.4
480	Yeka	YK46	486165	1001889	2481	430	20.3	7.86	275.2
481	Yeka	YK47	486142	1001855	2488	420	22.1	7.98	268.8
482	Yeka	YK48	486082	1001905	2483	420	23.3	7.88	268.8
483	Yeka	YK49	486405	997467	2407	220	23.3	8.01	140.8
484	Yeka	YK50	486340	997302	2398	510	20.1	8.02	326.4
485	Yeka	YK51	485980	1001493	2474	420	21.7	7.72	268.8
486	Yeka	YK52	486546	998117	2426	130	19.8	7.81	83.2
487	Yeka	YK53	486055	1001088	2486	410	20.8	7.75	262.4
488	Yeka	YK54	476771	1001726	2593	260	21.9	8.08	166.4
489	Yeka	YK55	476762	1001771	2600	270	26.6	7.96	172.8
490	Yeka	YK56	476747	1001767	2593	270	25.1	7.95	172.8
491	Yeka	YK57	476870	1001895	2611	270	19.7	7.97	172.8
492	Yeka	YK58	474982	1002123	2570	260	20.6	7.92	166.4
493	Yeka	YK59	474104	999775	2473	260	21.2	7.93	166.4
494	Yeka	YK60	474807	1000516	2475	260	20.8	7.96	166.4
495	Yeka	YK61	474948	1000765	2494	260	20.5	7.89	166.4
496	Yeka	YK62	476417	1001636	2556	270	22.6	7.9	172.8
497	Yeka	YK63	476516	1001669	2566	270	25.2	7.78	172.8
498	Yeka	YK64	476626	1001706	2574	260	24.2	7.99	166.4
499	Yeka	YK65	475152	1001099	2531	200	22.9	7.92	128
500	Yeka	YK66	475154	1001120	2525	200	22.6	7.9	128
501	Yeka	YK67	474940	1002131	2588	210	29	7.78	134.4
502	Yeka	YK68	474912	1002110	2580	200	21.8	7.91	128
503	Yeka	YK69	474589	999137	2445	140	19.6	8.01	89.6
504	Yeka	YK70	475032	1001548	2544	200	18.9	7.89	128
505	Yeka	YK71	474974	1001670	2544	210	24.9	7.8	134.4
506	Yeka	YK72	474882	1001778	2544	200	23.9	7.82	128
507	Yeka	YK73	474793	1001939	2549	200	24	7.79	128
508	Yeka	YK74	474568	999185	2452	140	18.9	7.95	89.6
509	Yeka	YK75	479723	999952	2605	120	20.8	7.66	76.8
510	Yeka	YK76	481382	1000007	2546	120	22.3	7.84	76.8

Annex 3: summarized meteorological data

Month	RF (mm) Bole	RF (mm) OBS	RF (mm) Akaki	RF (mm) Ayertena	RF (mm) Intoto	RF (mm) Yekatit 23	RF (mm) AA	Mean Max Temp (Celsius)	Mean Min Temp (Celsius)
JAN	11.7	16.4	10.3	10.6	11.1	8.9	17.2	25.215	8.6
FEB	15.1	17.5	15.3	16.6	16.6	13.1	43.2	24.23	8.7
MAR	49.1	46.6	42.9	43.9	46.1	41.7	67.6	25.765	11.1
APR	63.5	63.8	66.9	60.9	63.4	56.2	86.4	24.24	11.4
MAY	79.4	74.5	66.1	76.0	79.9	81.3	88.6	28.025	12.1
JUN	106.3	127.3	108.2	125.7	152.4	144.7	109.8	25.02	12.2
JUL	223.2	239.3	205.4	245.1	301.6	259.6	246.8	23.615	12.3
AUG	251.7	293.3	195.8	262.8	306.1	250.0	262	24.315	12.3
SEP	123.9	176.9	111.0	151.7	125.6	137.4	155.8	25.51	12.3
OCT	31.5	33.8	17.0	31.0	28.8	27.5	37.6	25.785	10.0
NOV	5.2	11.5	8.0	7.0	15.7	10.1	7.6	23.415	7.5
DEC	7.1	8.5	3.5	4.2	7.4	5.6	12.2	23.265	7.4

Annex 4; Population number of Addis Ababa sub-cities in years 2007 and 2020.

	2007			2020		
	Both sex	Male	Female	Both sex	Male	Female
ADDIS ABABA CITY ADMINISTRATION						
AKAKI KALITY-SUB CITY	181,270	88,714	92,556	244,042	118,454	125,588
KEBELE 01/03	25,468	12,555	12,913	34,285	16,764	17,521
KEBELE 02/04	13,973	6,838	7,135	18,812	9,130	9,681
KEBELE 05/06	17,580	8,376	9,204	23,673	11,184	12,489
KEBELE 07/08/09	42,311	20,263	22,048	56,973	27,056	29,917
KEBELE 10/11	45,831	22,931	22,900	61,691	30,618	31,073
KEBELE 12/13	27,082	13,027	14,055	36,465	17,394	19,071
KILINITO,FECHE KOYE	5,122	2,615	2,507	6,893	3,492	3,402
GELANGORA	3,903	2,109	1,794	5,250	2,816	2,434
NEFAS SILK-LAFTO-SUB CITY	316,283	148,984	167,299	425,935	198,929	227,006
KEBELE 03/04/05	34,846	16,089	18,757	46,934	21,483	25,451
KEBELE 06/07/08	40,364	19,140	21,224	54,355	25,556	28,799
KEBELE 09/14	33,529	15,698	17,831	45,155	20,961	24,195
KEBELE 10/18	41,299	19,560	21,739	55,615	26,117	29,497
KEBELE 12/13	28,023	12,806	15,217	37,747	17,099	20,648
KEBELE 16/17	36,081	17,447	18,634	48,580	23,296	25,284
KEBELE 01(HANA,LEBU	31,627	15,323	16,304	42,583	20,460	22,123
KEBELE 02	32,224	15,096	17,128	43,398	20,157	23,241
KEBELE 11	16,010	7,722	8,288	21,557	10,311	11,246
KEBELE 15	22,280	10,103	12,177	30,013	13,490	16,523
KOLFE KERANIYO-SUB CITY	428,895	207,641	221,254	577,467	277,250	300,217
KEBELE 02/03	32,866	15,731	17,135	44,255	21,005	23,250
KEBELE 01/05	76,076	35,088	40,988	102,467	46,851	55,616
KEBELE 08/09	40,714	20,752	19,962	54,795	27,709	27,086
KEBELE 10/11	51,498	26,246	25,252	69,309	35,045	34,264
KEBELE 13/14	37,962	18,557	19,405	51,108	24,778	26,330
KEBELE 15/16	43,999	20,983	23,016	59,247	28,017	31,230
KEBELE 06	41,751	19,000	22,751	56,240	25,369	30,871
KEBELE 07	35,621	17,844	17,777	47,947	23,826	24,121
KEBELE 12	13,034	6,497	6,537	17,545	8,675	8,870
KEBELE 04	55,374	26,943	28,431	74,553	35,975	38,578
GULELE-SUB CITY	267,624	129,396	138,228	360,334	172,774	187,560
KEBELE 01/02	20,932	10,361	10,571	28,178	13,834	14,344
KEBELE 03/04/05	28,124	13,247	14,877	37,874	17,688	20,186
KEBELE 07/17	24,495	12,208	12,287	32,973	16,301	16,672
KEBELE 08/16	37,066	17,605	19,461	49,913	23,507	26,406
KEBELE 09/15	31,954	14,877	17,077	43,036	19,864	23,172

KEBELE 10/11/12	32,704	15,481	17,223	44,040	20,671	23,370
KEBELE 13/14	23,727	11,335	12,392	31,949	15,135	16,815
KEBELE 19/20/21	29,235	14,045	15,190	39,365	18,753	20,611
KEBELE 06	13,264	6,106	7,158	17,866	8,153	9,713
KEBELE 10/18	26,123	14,131	11,992	35,140	18,868	16,272
LIDETA-SUB CITY	201,713	96,272	105,441	271,617	128,546	143,072
KEBELE 01/18	21,427	9,969	11,458	28,858	13,311	15,547
KEBELE 02/03	24,577	11,760	12,817	33,094	15,702	17,391
KEBELE 04/06	26,810	13,088	13,722	36,095	17,476	18,619
KEBELE 05/08	28,166	13,315	14,851	37,930	17,779	20,151
KEBELE 09/10	29,171	14,283	14,888	39,273	19,071	20,201
KEBELE 07/14	26,387	12,465	13,922	35,534	16,644	18,891
KEBELE 15/16/17	14,355	6,794	7,561	19,331	9,072	10,259
KEBELE 11	13,365	6,364	7,001	17,997	8,497	9,500
KEBELE 12	17,455	8,234	9,221	23,506	10,994	12,512
KIRKOS-SUB CITY	221,234	103,500	117,734	297,949	138,197	159,752
KEBELE 01/19	18,236	8,495	9,741	24,560	11,343	13,217
KEBELE 02/03	24,997	11,478	13,519	33,670	15,326	18,344
KEBELE 05/06/07	28,467	13,065	15,402	38,344	17,445	20,899
KEBELE 08/09	20,935	9,873	11,062	28,193	13,183	15,010
KEBELE 11/12	22,870	10,636	12,234	30,802	14,202	16,600
KEBELE 13/14	22,694	10,745	11,949	30,561	14,347	16,213
KEBELE 15/16	17,132	8,498	8,634	23,062	11,347	11,715
KEBELE 17/18	21,506	9,762	11,744	28,970	13,035	15,935
KEBELE 20/21	20,558	9,462	11,096	27,690	12,634	15,056
KEBELE 04	12,792	6,269	6,523	17,222	8,371	8,851
KEBELE 10	11,047	5,217	5,830	14,877	6,966	7,911
ARADA-SUB CITY	211,501	99,165	112,336	284,836	132,409	152,427
KEBELE 01/02	21,436	10,289	11,147	28,863	13,738	15,125
KEBELE 03/09	24,725	11,571	13,154	33,299	15,450	17,849
KEBELE 04/05	22,010	10,709	11,301	29,633	14,299	15,334
KEBELE 07/08	25,303	11,524	13,779	34,084	15,387	18,697
KEBELE 11/12	19,861	9,238	10,623	26,749	12,335	14,414
KEBELE 13/14	28,157	12,852	15,305	37,928	17,160	20,767
KEBELE 15/16	24,627	11,601	13,026	33,165	15,490	17,675
KEBELE 06	13,669	6,373	7,296	18,409	8,509	9,900
KEBELE 10	13,521	6,337	7,184	18,209	8,461	9,748
KEBELE 17	18,192	8,671	9,521	24,497	11,578	12,919
ADDIS KETEMA-SUB CITY	255,372	124,898	130,474	343,807	166,768	177,039
KEBELE 01/02/03	33,259	16,574	16,685	44,770	22,130	22,640
KEBELE 04/05	27,143	13,047	14,096	36,548	17,421	19,127
KEBELE 06/07	29,058	14,535	14,523	39,114	19,408	19,706
KEBELE 08/09/18	33,076	16,834	16,242	44,516	22,477	22,039

KEBELE 10/11/12	32,656	15,742	16,914	43,970	21,019	22,950
KEBELE 13/15	23,199	11,062	12,137	31,239	14,770	16,469
KEBELE 16/17	28,542	13,524	15,018	38,435	18,058	20,378
KEBELE 19/20	19,800	9,541	10,259	26,660	12,739	13,920
KEBELE 14/21	28,639	14,039	14,600	38,556	18,745	19,811
YEKA-SUB CITY	346,664	161,592	185,072	466,885	215,763	251,122
KEBELE 01/02	27,163	12,519	14,644	36,586	16,716	19,870
KEBELE 03/04	32,346	15,110	17,236	43,563	20,175	23,387
KEBELE 06/07	18,843	8,542	10,301	25,383	11,406	13,977
KEBELE 08/15	30,422	14,247	16,175	40,971	19,023	21,948
KEBELE 16/17/18	55,035	26,241	28,794	74,108	35,038	39,070
KEBELE 19	31,854	14,864	16,990	42,900	19,847	23,054
KEBELE 20/21	65,127	31,515	33,612	87,688	42,080	45,608
KEBELE 13/14	23,860	10,837	13,023	32,141	14,470	17,671
KEBELE 11/12	21,292	9,582	11,710	28,683	12,794	15,889
KEBELE 09/10	27,025	12,110	14,915	36,408	16,170	20,238
KEBELE 05	13,697	6,025	7,672	18,455	8,045	10,410
BOLE-SUB CITY	308,995	145,225	163,770	416,127	193,910	222,218
KEBELE 03/05	31,757	14,849	16,908	42,769	19,827	22,942
KEBELE 04/06/07	29,029	13,339	15,690	39,100	17,811	21,290
KEBELE 08/09	20,228	9,645	10,583	27,238	12,878	14,360
KEBELE 12/13	24,361	11,129	13,232	32,814	14,860	17,954
KEBELE 14/15	81,405	39,025	42,380	109,613	52,108	57,505
KEBELE 16/18/21/22	13,531	6,846	6,685	18,212	9,141	9,071
KEBELE 17/19/20	21,623	10,792	10,831	29,106	14,410	14,696
KEBELE 01	28,203	13,120	15,083	37,984	17,518	20,466
KEBELE 02	8,155	3,699	4,456	10,985	4,939	6,046
KEBELE 10	32,262	14,822	17,440	43,455	19,791	23,664
KEBELE 11	18,441	7,959	10,482	24,850	10,627	14,223