ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

IDENTIFICATION OF THERMAL GROUNDWATER ZONES USING HYDRO-GEOCHEMICAL APPROACH: IN CASE OF AKAKI RIVER CATCHMENT

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

By: Behailu Girma Mamo

Advisor: Tilahun Azagegn (Ph.D.)

Addis Ababa, Ethiopia

December 2022

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Thesis approval form and declaration of originality

I CERTIFY THAT THE RESEARCH WORK ENTITLED AS "IDENTIFICATION OF THERMAL GROUNDWATER ZONES USING HYDRO-GEOCHEMICAL APPROACH: IN CASE OF AKAKI RIVER CATCHMENT'' IS MY OWN WORK. THE WORK HAS NOT BEEN PRESENTED ELSEWHERE FOR ASSESSMENT. WHERE MATERIAL HAS BEEN USED FROM OTHER SOURCES HAS BEEN PROPERLY ACKNOWLEDGED. HERE I HAVE PROVIDED IT FOR THE APPROVAL BY THE BOARD EXAMINERS.

Candidate: Behailu Girma Mamo

Name SignatureDate

Advisor: Tilahun Azagegn (Ph.D.)

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Internal Examiner: ____________ ______ ________

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External Examiner: ____________ ______ ________

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Abstract

Ethiopia is gifted with many different thermal groundwaters and hot spring resources which are located in various physiographic, climatical, and geologic settings. The filwoha springs had been served as the source of thermal waters for many decades. An attempt was made to zone and identify thermal groundwater in the akaki river catchment through assement of thermal wells and distinguishing the geological and structural setup of the area. The study area is located in the awash river basin. Adminstratively, the area is situated within addis ababa city and finfinne specila zone of oromia regional state. Fourty four (44) boreholes were inventoried to delineate thermal groundwater areas of akaki river catchment. Temperature of the inventoried wells ranges from 37°c to 86°c. The tds measurement range between 230 to 2528mg/l. The thermal boreholes depth varies from 56.4 to 583.50 meter. Geologically, the area is characterized by secondary structures which are mainly related to extensional tectonics responsible for rift formation and volcanic activity. The thermal groundwater in the study area is characterized by higher TDS, EC, Na^+, and F^-; and lower concentration of ca concentration. Both the tds and ec concentrations decrease in all directions away from the epicenter of the filwoha zone. The lowest concentration of TDS and EC in thermal water is recorded in southern area thermal groundwater with tds and ec values range from 280 mg/l to 378mg/l and 467 mg/l to 589 mg/l respectively. The thermal water in north western part of the study area around filwoha is substantially hot and it can reach up to 86 ^oC as it is observed at legahare well. In the eastern part of the study area, the thermal groundwater varies from 38 ^oC to 50 ^oC. The thermal groundwater in southern part of the study area is comparatively lower than the two areas and has a maximum value of 48 ^oC. The groundwater temperature versus depth of well plot show that the temperature of thermal water has a positive linear correlation with the depth of the boreholes.

Key words: Thermal Groundwater, Temperature, Akaki River Cacthment

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Above all, my gratitude and thanks goes to God, for being with me from the beginning to the end of this study.

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Acronyms, Abbreviations and symbols

AAU	Addis Ababa University
AAWSA	Addis Ababa Water and Seweradge Authority
ABGPEP	Adaa-Becho Groundwater Resource Evaluation Project
°C	Degree Celcius
EC	Electrical Conductivity
MER	Main Ethiopian Rift
TDS	Total Disolved Substances
UTM	Universal Transverse Mercator
WWDSE	Water Works Design and Supervion Enterprise

CHAPTER-1 INTRODUCTION

1.1. Background

Thermal groundwater had been used for generating heat, personal hygiene, curative and recreational purposes which are deeply integrated with the history of civilization. Such groundwater resources had also played a significant role in religious, cultural, scientific, and economic development in ancient kingdoms. The development of thermal groundwater for its purpose is very slow as compared to the normal cold-water resource. However, at the current time, thermal groundwater is developed throughout the world and many new watering places (SPA) are established as fashionable centers of resorts for the upper classes of the community.

Ethiopia is endowed with many different thermal groundwaters and hot spring resources which are located in various physiographic, climatic, and geologic settings. The hot springs of Sodere, Woliso, Filwoha, Wondogenet, Gidabo, and the lakeside of Shalla are some of the well-known thermal groundwater resources serving the country's communities for bathing and therapeutic purposes.

The Filwoha springs and pumped boreholes had been served as the source of thermal waters for more than 100 years for public bathing and therapeutic purposes for the Addis Ababa City dwellers. Currently, the source of thermal water is completely dependent on the development of artesian deep boreholes and pumped wells; and several thermal boreholes are drilled in study area to meet the public demand of the city. The interest in the use of thermal water for bathing (SPA) and therapeutic services is growing with the rapidly increasing numbers of customers living in the city. To address the demand of the city inhabitants, this recerch work encompasses thermal groundwater zoning in the Akaki River Catchment.

This work mainly focuses on hydrogeological, geological, hydrogeochemical, structural assessments of Akaki River Catchment in order to delineate thermal groundwater zoning.

1.2. Statements of the Problem

The Filwoha springs and pumped boreholes had been served as the source of thermal waters for more than 100 years for public bathing and therapeutic purposes for the Addis Ababa City dwellers. Currently, the source of thermal water is completely dependent on the development of artesian deep boreholes and pumped wells; and several thermal boreholes are drilled in its study area and developed to meet the public demand of the city. To address the demand of thermal water, knowing location and distribution of thermal groundwater is cruicial. This work mainly focuses delineating thermal groundwater areas by using integrated approaches such as, geological mapping, structural mapping, hydrochemical investigation, water point inventory and analyses techniques in the Akaki River Catchment.

1.3. Objectives

1.3.1. General objective

The general objective of this research is to identify thermal groundwater zones in the Akaki River Catchment of upper Awash Basin.

1.3.2. Specific objective

The specific objectives of the research are to address the following ideas:

- Geological and structural characterization of the area by harmonization of existing geological maps in different scales together with ground verification and calibration with existing boreholes lithological logs to make geological/hydrogeological framework
- Determining the general hydrochemistry in the study area as water chemistry parameters are critical to optimize the possible physico-chemical changes.
- Integration of data from temperature variation perspective in relation with geology, geological structures, hydrochemistry, hydrogeology and thermal localities.

1.4. Description of the study area

1.4.1. Location and accessibility

The Akaki River catchment is located in the Western Ethiopian highlands of the Shewan plateau, and partly in the western margin of the Ethiopian Rift Valley floor. The capital city, Addis Ababa and other small towns such as Akaki, Sendafa, Burayu and smaller peasant association villages are found in this catchment.

The Intoto Mountain forms the northern drainage boundary of the Akaki River Catchment and other volcanic mountains bound it from the eastern, western and southwestern boundaries; these are Mt. Yerer, Mt. Wechecha and Mt. Furi, respectively.

The study area, the Akaki River catchment, has an approximate surface area of around 1462 km^2 and boundary length of 216 km, and approximately bounded between the geographic coordinates 8^0 45’20’’ to 9^0 13’17’’ N latitude and 38^0 34’ 3’’to 39^0 4’10’’ E longitude. All maps in this work are given in UTM coordinates (zone 37).

As Addis Ababa is found in the northern central heart of the catchment, the study area is accessed in every direction by highways from the capital that is, by the major roads stretching to Jimma, Wollega, Harar/Sidamo, Wallo and Gojjem. In fact, other minor roads are found in the catchment and these are used for traverses between villages and sites.

1.4.2. Topography

The project area lies in the upper part of the Awash River Drainage Basin. It is drained from almost north to south by rivers such as Lege Tafo and Lege Dadi and their tributaries Lege Beri and Secoru into Akaki river and finally into Awash River outside the project area. The Akaki River flows from northeast to southwest and eventually towards south dividing the area in to two halves, the northwest-northeast and south east halves. Only the main rivers (Lege Tafo and Lege Dadi) whose water shades drain the high land margin carry water throughout the year. The tributaries that head in the intervening elevated plains are seasonal.The surface water reservoir, Lega Dadi and Dera, found in this chachement and they are the major water supply to Addis Ababa.

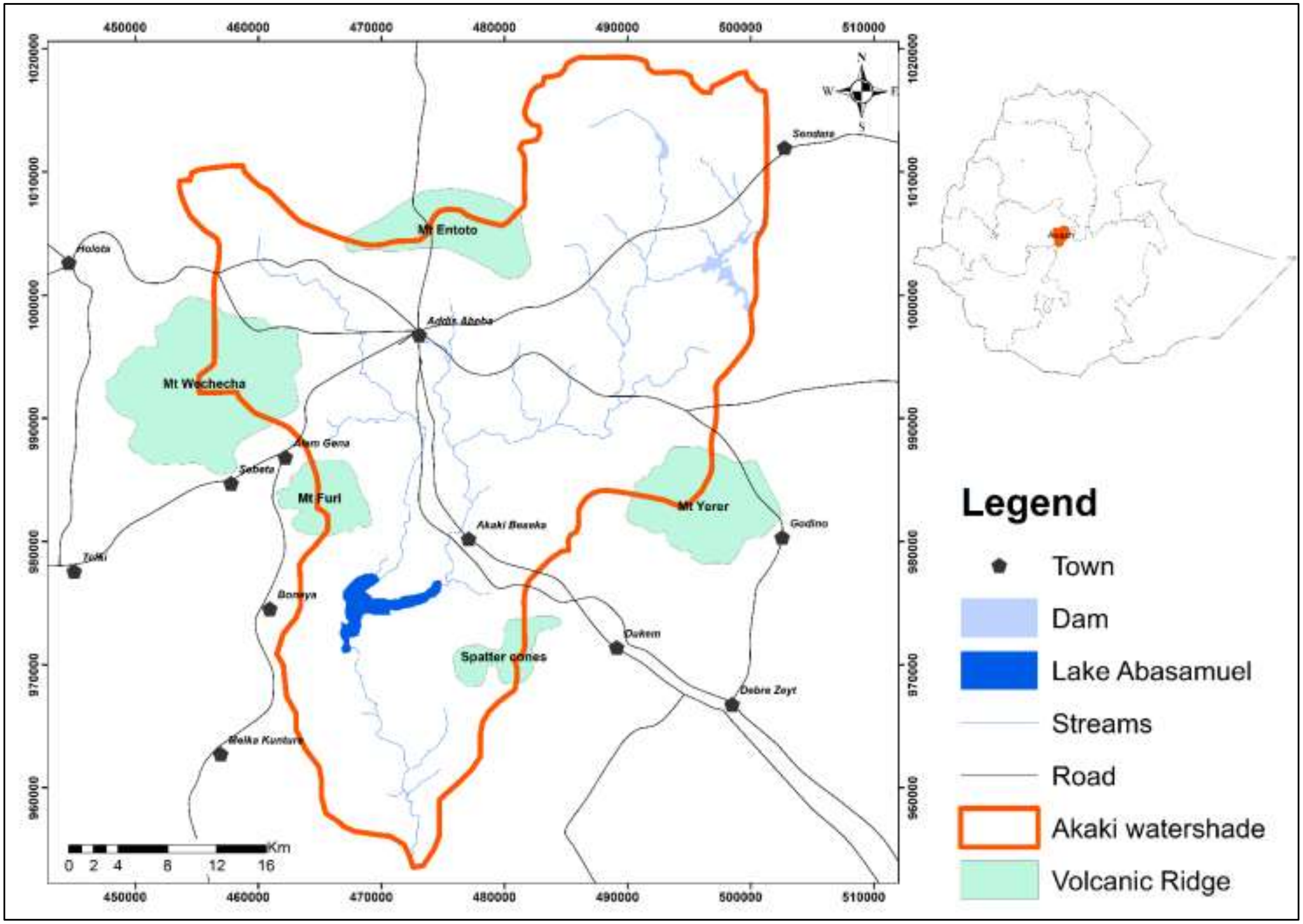

Figure 1: Location of Study Area

Northern part of the study area: the elevation of the Northern part of the study area ranges generally between 2280 meters above sea level in the most extreme southern corner to over 2700 meters above sea level in the north western and north eastern parts of the area.

The study area can be divided into four major physiographic divisions. These are the northern, the southern, the south central and the eastern physiographic regions

The northwestern, northern and northeastern (the north physiographic region) lies between 2600 to 2800 meters mountain range the southern extension of the highland terrain from north. It is built by relatively more resistant to erosion central origin basalt flows.

The southern part of the study area (southern physiographic terrain) is dominantly underlain by an extensive sheet of ignimbrite intercalated with various pyroclastic rocks. These successions form flat-topped extensive topographic feature. The most top part is mainly blanketed by horizontal to semi horizontal monotonous ignimbrite sheet, generally inclined towards south. The flat- topped form of the terrain is a function of the horizontal attitude of the underlying Tertiary volcanic flows. These physiographic region lies between 2400 to 2600 meters.

In the south-central part of the study area (southcentral physiographic terrain), once continuous flat-topped terrain is now intermittently deeply cut into gorges by lower reaches rivers like Lege Tafo, Lege Dadi and Akaki river itself. The elevation ranges from 2280 to 2400 meters. In the gorges up to something like 120 meters thick dominantly salic rocks have been exposed. In these sections intercalations of more resistant and less resistant rocks forming steep cliffs and less steeper cliffs respectively can be observed. The steeper vertical cliffs are usually built of ignimbrite and lesser ones are commonly built of softer materials like tuffaceous material and ash.

The eastern corner of the site area is underlain by Quaternary basalt lava flows. This basalt flow represents relatively little modified topographic feature of recent origin.

Nourth western part of the study area around Filwoha: theis area located in the nourth western study area around Filwuha and it is bounded in the north by the Entoto mountain range.

The Filwuha area has elevations in the range of 2300m to 2400m. The northern part of the Filwuha area has rugged topography characterized by steep slopes. Towards the south, there is a part which is relatively flat and with gentle slopes. It is drained from northwest directions into Akaki river drainage system.

Eastern part of the study area: theis area is deeply dissected almost in to two equal north and south parts by Akaki river flowing east-west and finally North-South in the south western part. It is drained from north, northeast and northwest directions into Akaki river drainage system.

It ranges in elevation from about 2060 meters in the southwestern corner to 2300 meters in the northwestern corner. It can broadly be divided into two physiographic features, northern and southern physiographic regions

The northern physiographic region, just north of Akaki is underlain by Termaber basalt the oldest rock unit exposed all along the course of Akaki River in the site area. In the physiographic region the salic flows and pyroclastic successions have been largely stripped off of the underlying basalt flows and only minor cover reminants occur at the most extreme northern corner. It is drained from north to south in to Akaki River by major rivers such as Kebena, Kotebe and Hanku. The elevation ranges between about 2080 meters in the southwestern corner and 2300 meters in the north western corner.

In south central and southeastern sector (southern Physiographic region), the underlying successions–basalt flows, silicic flows and pyroclastics have been overlapped by Quaternary age basalt lava flows making up relatively younger topographic features. The Quaternary volcanism has given rise to little modified volcanic cones and associated basalt flows. The elevation ranges between about 2060 meters to 2260 meters. There are scattered both cinder and basalt cones sticking out of the flow surface forming prominent topographic features in the study area. The cones rise to about 20 to 60 meters above the surrounding surface. It is drained generally from the southeast to northwest into Akaki River, almost all the streams that drain the site area are seasonal and shallow.

Southern part of the study area: The southrn study area ranges in elevation from 2060 meters in south central part to 2140 meters in the northeastern corner. It Is drained from north west, north, northeast, southeast ward across the site area into Akaki River, in places losing itself among extensive seasonal swamps, but eventually discharging into the Awash River.

The area can be divided into three major Physiographic regions. These are: (1) The Furi Ridge, (2) The eastern and (3) Akaki plain physiographic regions. The Furi ridge physiographic region, the south eastern part of the Furi volcano, is drained from Northwest to southeast into the Akaki plain, part of the radial drainage of the Furi volcano. The creeks finally lose themselves into the extensive Akaki seasonal swamp area. It rises from the surrounding area by about 700 meters. It is built of mainly trachytic flows and minor associated pyroclastics.

The northwestern, northeastern and southeastern areas are underlain by Quaternary age basalt flows. It gradually slopes due west into south central part. This is a large and relatively little modified basalt shield of recent origin. This large mound has been built by voluminous out pouring of basalt flows from east–northeast trending central fissures, now marked by speckles of numerous well-preserved cinder and basalt cones. There are scattered cinder and basalt cones sticking out of the surrounding surface forming conspicuous topographic features in the site area.

The south-central part of the site is a sediment depositional site, a northeast –southwest trending sort of graben structure now filled with recent alluvial sediments. It presents a flat lying not yet modified topography the feature less alluvial plain, completely devoid of bed rock exposure, lies between 2060 and 2080 meters. Akaki river meanders southeastward across the plain, in places losing itself among extensive seasonal swamps, but eventually discharging into Awash River outside the site area. The river meanders through the alluvial sediment eroding its own depositions.

The Akaki river chachement is bounded by the ridges of Intoto and Wechecha in the north and west direction and the volcanic cones of Yerer are in the southeast directions. The long-term mean annual rainfall of Addis Ababa and its suburbs is 1108mm. Its rainfall distribution is characterized by a type-I rainfall regime (mono-modal type). The area has seven rainy months from March to September where the big rains in the area are from June to September. The maximum temperature varies on average between 20° C in the wet season and 25° C in the dry season, while the variation of minimum temperature falls in the range of 7° C to 12° C throughout the year.

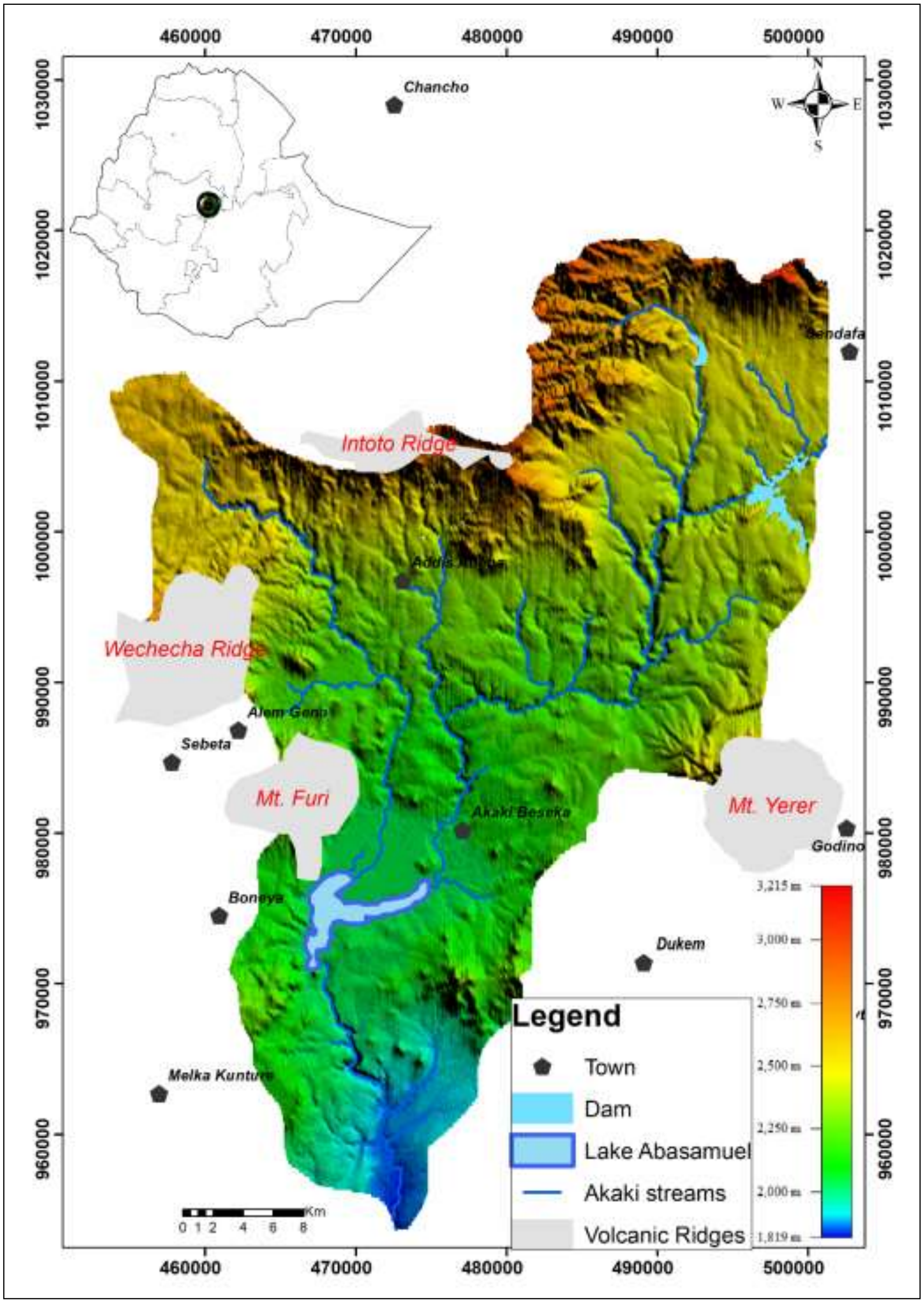

Figure 2: Topographic set up of the study area

1.4.3. Drainage

The Akaki River catchment comprises of numerous small rivers. The dominant ones are the Big Akaki, which drains the eastern part of the catchment area, and the Little Akaki that drains the western part of the catchment; 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 passes through a gorge up to 100m deep which extends for about 8km before it joins the Awash River. Almost all the streams in the catchment originate from the northern part of the catchment.

The Big Akaki suffers a total drop of about 600m in a river length of 95km from its origin to its confluence with the Awash River near Dodota, 1800m above sea level (AAWSA 2000).

The Intoto Mountain range in the northern forms the surface water divide between the Blue Nile and Awash River basins. The drainage of an area is affected by numerous factors among which, rainfall, slope, vegetation, rock type and tectonic activity, infiltration capacity, soil types and thicknesses, are some. In the northern part of the catchment the drainage forms steep narrow gorges (facilitates runoff) which can be attributed to high rainfall, dense vegetation cover and high topographic elevation (>2800m). Where there are volcanic ridges /domes, drainage radiates in all directions forming radial or parallel drainage system. It is clear that areas with higher permeability have lower drainage density that in turn may decrease the surface runoff. These can be observed from the topographic map of the area in that areas with high elevation and that are not covered with vegetation have higher drainage density compared to flat lying areas and areas that are covered with vegetation (increases permeability). Generally, the drainage in the catchment is oriented nearly from north to south following the regional slope.

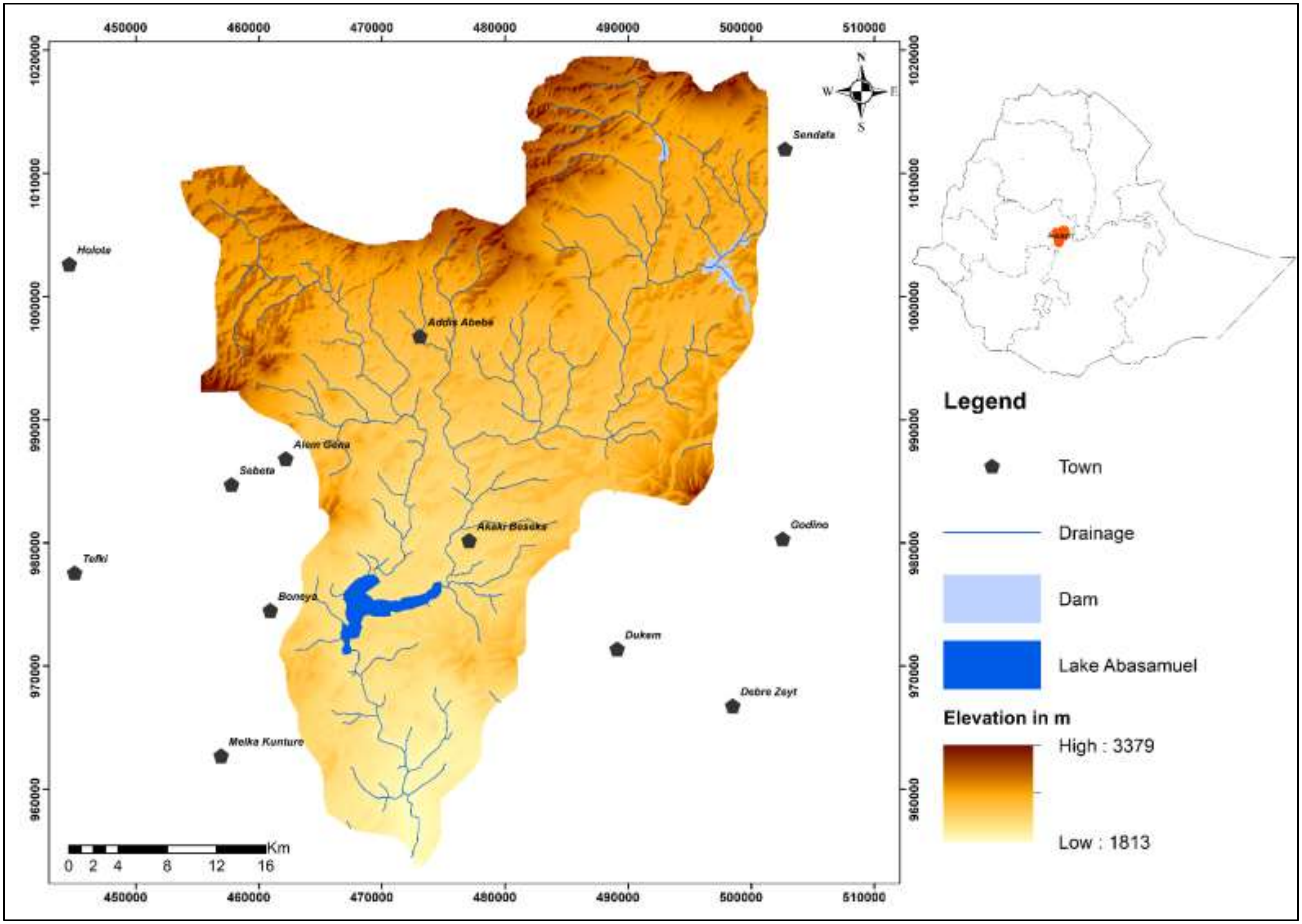

Figure 3: Drainage pattern of study area

1.5. Methodology

In order to achieve the objectives of this work, several well-integrated and reliable methodologies and approaches have been used. The study was commenced by defining the boundary of the anticipated the study area, review of previous studies, and collecting pertinent secondary data. Large scale topographical map, high-level resolution Digital elevation model, and large-scale geological maps were used to prepare a preliminary hydrogeological map of the study area. All the input data sets were georeferenced into the Adindan UTM zone 37N coordinate system. Detailed interpretation of Satellite imageries that embrace delineating major regional lineaments, understanding the geomorphologic and drainage pattern of the area, and defining possible thermal groundwater localization zones have also been carried out during the desk study phase.

Primary data have been collected systematically during fieldwork observations along with the preliminary thermal and cold groundwater sites of the area. Classification of all the outcropped rock units and identification of major geologic structures defining the vertical and lateral extents in relation to lithostratigraphic units were carried out, Measurements of static and dynamic water levels of the existing wells and boreholes, the actual discharge of wells was conducted during a field survey at places where measurement is possible. In-situ measurements such as electrical conductivity (EC), temperature and pH) were carried out at the site as well.

Data compilation, processing, analysis, and interpretation have been conducted in the post fieldwork phase. Both the primary and secondary data obtained from different sources were processed and analyzed thoroughly and the subsurface hydrogeological conditions in relation to aquifer properties, depth to groundwater, and groundwater flow direction along the defined thermal groundwater zone were determined.

Materials like Garmin GPS, Electrical Conductivity meter, and Deep meter were used during field work and the analysis and interpretations were supported by the application of different software like Arc GIS 10.5, surfer 10, Global Mapper 20, and Auto CAD 16.

1.6. Previous works and related literatures

Several previous works on thermal groundwater potential assessment have been conducted in the study area at different times. The most important works related to thermal groundwater development in the study area were carried out by (Kondo, 1958), A geological and Geoelectrical investigation of the Filwoha hot spring, Elias Lew, 1999 Resistivity Survey to locate hot water reserves at Filwoha, (WWDSE, 2002)Thermal and Cold groundwater potential assessment of Filwoha area, ECDSW-WEDSWS, Hydrogeological survey for water well sitting and drilling supervision at Filwuha compound and Ada'a-Becho-Evaluation of Groundwater Potential (WWDSE, 2008, 2011, ECDSWC 2019).

I. According to (Kondo, 1958), a geological and Geoelectrical investigation of the Filwoha hot spring

Four major structural lines which have a strong relation to the Filwoha hot spring are identified. These include NE-SW, WNW-ESE, NNW-SSE, and N-S trends. The two structural lines NNW-SSE and N-S seem to be intimately related to the yielding of hot springs and the hot springs are erupting the junction of the two structural lines.

II. The sub-surface electrical properties of the Filwoha area are characterized by (Lew, 1999) Resistivity Survey to locate hot water reserves at Filwoha.

The result showed that two low resistivity zones in the Filwoha area were indistinguishable at shallow depth and emerged as two distinct zones at higher depth in the first zone near the ministry of foreign affairs between the national palace and Ethiopian mapping agency and the second stadium zone.

III. WWDSE, Dec 2002 Thermal and Cold groundwater potential assessment of Filwoha area (WWDSE, 2002)

The thermal groundwater basin around Filwoha area is controlled by NE-SW, N-S, NNE-SSW, NW-SE, and E-W trending faults and lineaments forms graben. Both the established and inferred faults of the thermal basin of Filwuha could be responsible for transporting heat flux to the surface of the earth and heats the local groundwater along the faults. Moreover, the tectonic structure that controls the thermal groundwater determines the recharge, discharge, and thermal conditions of the area. The NE-SW (Filwuha fault) trending fault extends for a long distance and drains the groundwater of the area traversed by the fault to the Filwuha discharge area. The study also showed that the groundwater of the Filwuha area is categorized into two groups: the shallow cold groundwater found within 100 meters depth while the thermal groundwater can be found greater than 100 meters depth and both the temperature and yield increase proportionally with depth.

IV. (ECDSW-WEDSWS, 2017), Hydrogeological survey for water well sitting and drilling supervision at Filwuha compound

The main aquifers of thermal groundwater in Filwuha area are acidic roks of ignimbrite and Rhyolite intercalated with Basalt. The relationship between the groundwater temperature and the depth of the boreholes is linearly related where boreholes with higher depth show increased temperature.

V. According to (Kondo, 1975), Hydrogeological studies on the thermal springs of Ethiopia

Division on thermal and cold waters in Ethiopia the lower limit of the thermal water should be from 25ᵒC to 32ᵒC his decided consideration of altitude

VI. Ada'a-Becho Evaluation of Groundwater Potential (WWDSE, 2008, 2011)

Detail hydrogeological, geological and geophysical investigation of this project shows that, major recharge zone of Ada'a-Becho catchment is tectonically impacted area of Abay Plateau in addition to recharge induced within the area. As stated in these studies, high yield artesian wells close to water divide of the Awash and Abay basins indicate the inter-basin groundwater transfer. In addition, this study reveals five principal hydrogeologic units within the vicinity of Addis Ababa and adjacent areas. Moreover, estimated recharge of Ada'a-Becho plains groundwater system is about 965Mm3/year or 2,643,835m3/day (WWDSE, 2008) and groundwater flow is almost in North-south direction within the study area.

VII. Evaluation of Groundwater Resources of South Ayat North Fanta and Lega Dadi Lega Tafo Area Well Fields (ECDSWC, 2019)

According to this work, three principal hydrogeological units are recognized in the eastern study area.

•Alluvial & Clay confining layer

•Basalt aquifer (UBA)

•Confining layers – Ignimbrite, Rhyolite and Tuff

In addition, aquifer of eastern study area is composed of fractured basalt and scoria interbedded with different acidic rocks such as Ignimbrite, trachyte and rhyolite. These rocks are impacted by geologic structure and interconnected by conduits formed by faulting. The geological structures of eastern area are N-S, NNE-SSW, NNW-SSE and E-W trending. Moreover, localized barrier, Yerer Mountain composed of rhyolite; tuff, Ignimbrite and trachyte also govern groundwater movement by acting as barrier.

In most of SANF area groundwater prospective site, depth to groundwater level is less than 40 meters. The groundwater depth is shallow on the north-eastern, center and southwestern part of the well field and it ranges from artesian condition to 25m deep. In the north-western direction of SANF well field the groundwater depth increases to more than 60 meters deep.

This study shows that, regional groundwater flow direction extending from Abay plateau to northeast direction flow out in south west direction to Akaki well field

VIII. Well Completion report of 32 (thirty Tow) Wells in Poket areas of Addis Abeba

The main aquifer of Central part of the study areas varies from place to place. Fractured Ignimbrite is the main aquifer of boreholes drilled in north Eastern and Western part of the central study area. Whereas the main aquifers of boreholes located in south part of the central study area are Basalt and Ignimbrite.

As observed from boreholes data, yield of the wells drilled in the vicinity of dislocation related to Ambo Filwuha fault and penetrated structurally affected basalt and ignimbrite is high. Whereas boreholes drilled in intermediate rocks such as trachyte have low yield.

Groundwater data collected from 32 deep wells drilled in poket areas of Addis Abeba shows that, The chemical quality analysis result of water sample collected during pumping test shows that most of the water qualifies the standard that is set by W.H.O for domestic uses. But, wells drilled in acidic rocks such as Trachyte and Rhyolite exhibits high Fluoride than recommended

Table 1 Summary of Poket area of Addis Abeba water supply wells

	Well Depth, m	SWL, m	Q, l/s	DD, m	TDS, mg/l	F, mg/l
Min	236	Artesian	6.00	2.77	94.00	0.51
Max	550	225.00	103.00	141.22	2528.00	41.55

1.7. Water Points Inventory

Water points within the study area, boreholes drilled by AAWSA, Industries, private companies and others are inventoried cold and hot water points (Figure 4, Appendix I) and gathered from review of various well completion reports. Data from inventoried boreholes shows that, most boreholes of study area penetrated multilayered aquifers of basaltic, ignimbrite, Scoria, rhyolite, tirackite, and welded tuff aquifers. These hydrolithologic units are fractured and impacted by tectonic structures as observed from lithologic description of inventoried boreholes. According to Chuzo kondo water division, inventoried hot water point's data temperature above 30^{o}C, depth of inventoried boreholes ranges between 56 to 623 meters below ground level. The static water level of these boreholes ranges between artesian to 153.25 meters and drawdown between 1.31 to 183.3m. In terms of yield, discharge of boreholes ranges between 0.83L/S to 142L/S. Moreover, discharge of deep (>250meter) boreholes are higher than that of shallow boreholes (<250 meter) where as cold-water point's data, tempratue below 30^{o}C, depth of inventoried boreholes ranges between 120 to 602 meters below ground level. The static water level of these boreholes ranges between artesian to 193.67 meters and drawdown between 0.45m to 201m. In terms of yield, discharge of boreholes ranges between 5L/S to 152L/.

As observed from inventoried data, groundwater temperature of the area varies both spatially and depth wise. Groundwater from most of boreholes within the study area is very hot around centeral part; eastern part and some southern part of the study area whereas as distance from these area increases, most of inventoried water points are cold.

In terms of water quality, most of inventoried water points groundwater can be categorized into potable except high fluoride detected in some of water points inventoried from centeral and eastern part of study area. Groundwater of the area exhibit Fluoride that ranges between 0.1mg/l to 41.55 mg/l, TDS that ranges between 50mg/l to 2528 mg/l and Temprature that ranges between 21degree centgrade to 84.4degree centgrade Show Figure.4 Distribution of hot and cold water points.

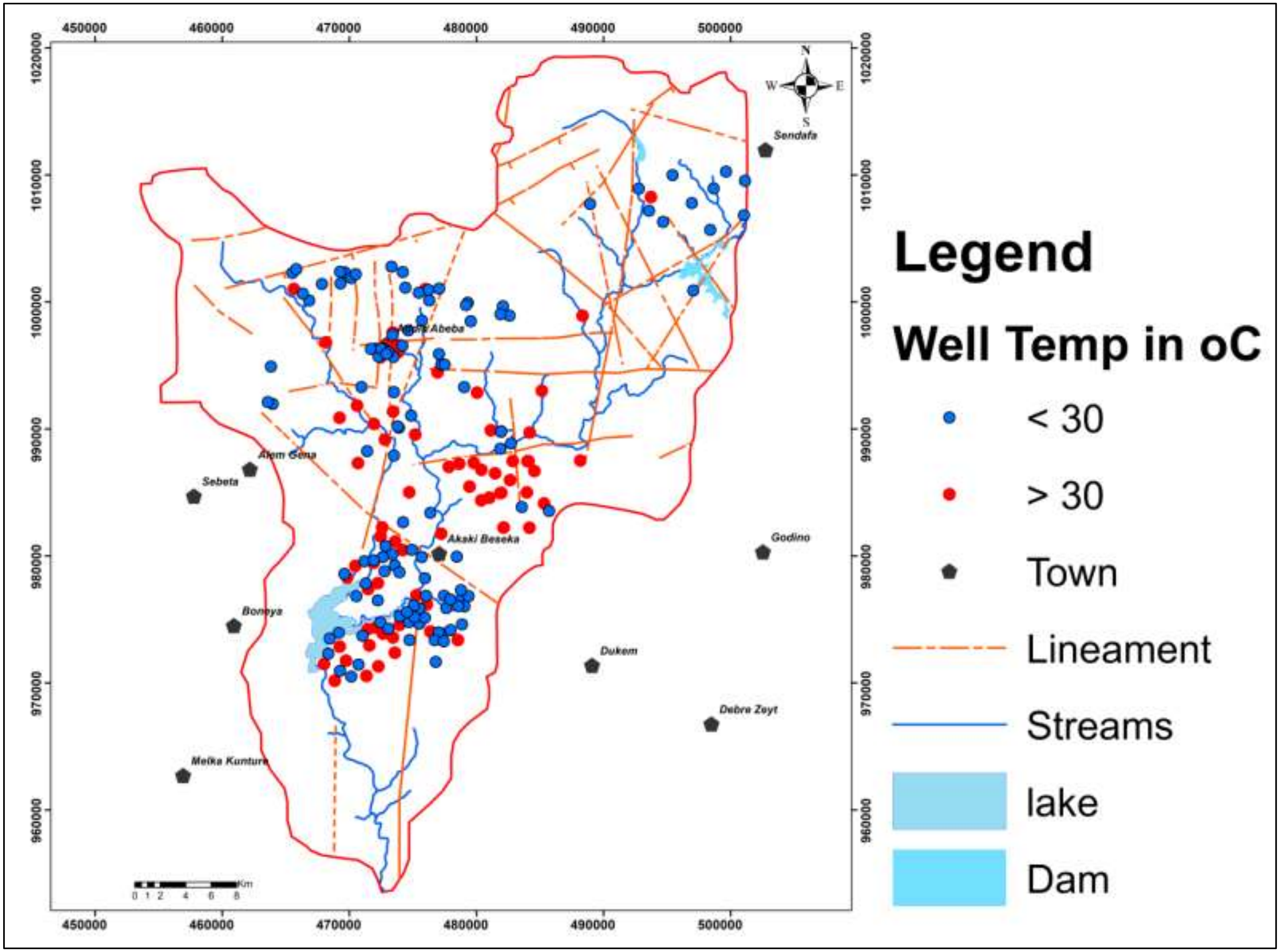

Figure 4: Distribution of hot and cold-water points

CHAPTER-2 GEOLOGY OF THE STUDY AREA

Surface geology of study area Knows geologic formations and structures of the study area is crucial inorder to identify potential sites of both thermal and cold groundwatwer. For this reason, both regional and local geology of the study area has been studied and geological map of scale 1:50000 is prepared for the study area. The geological mapping includes lithology, structures and lineaments (Figure 5).

2.1. Regional Geology

Ethiopia can be divided in to four major phsiographic regions, widely known as the western plateau, southeastern plateau, the Main Ethiopian Rift (MER) and the Afar Depression (AD). The Ethiopian plateau is underlain at depth by Precambrian rocks of the Afro-Arabian Shield. The Precambrian basement is covered for the most part by glacial and marine sediments of Permian to Paleogene period and Tertiary volcanic rocks with related sediments. The Precambrian basement exposures are found in the north (Tigray), in the west along the Sudan border (Gojam, Wollega, Illubabor, and Kefa), in the south (Sidamo and Bale) and in the east (Harerghe). The Precambrian rocks of Ethiopia are consisting of high-grade gneiss, metamorphosed volcano sedimentary rocks and associated ultramafic bodies and intrusives ranging from mafic to granitic composition.

The outline of the geological history of the Afro-Arabian countries – Ethiopia is believed to be in the group – was sketched by (Gouin, 1979) as follows:

At the end of the Precambrian era, the crystalline basement complex of the present Afro-Arabian swell had been above sea level for a long time and remained for another 370 million years until the end of Paleozoic era. Such a long period of erosion and denudation left the earth’s surface almost completely peneplained.

Crustal motion started in the beginning of Mesozoic era. During the late Triassic and early Jurassic periods, a regional epi-orogenic sinking of the crust commenced causing a progressive transgression of the ocean from the south east that is, from the Indian Ocean coast of present-day Somalia in the general direction of Lake Tana in the North West Ethiopia.This downward crystal movement, concomitant with a sedimentation process, started a cycle of marine transgression and recession of Mesozoic Sea. Within this large epi-continental sea, extensive layers of sediments were deposited to form hundreds of meters of rocks consisting of sandstone, shale, gypsum, limestone and other varieties of sedimentary rocks.

The crustal movement was reversed into the upward motion during the late Jurassic period, which brought the crust's surface up to sea level by marine regression in late Cretaceous period.

The regional uplift resulted in wide spread crustal fracturing during the early Tertiary period. The crystalline and sedimentary rock layers were fissured mostly along or in the vicinity of the zone of maximum uplift, thus allowing outpouring of molten lava to cover the older rock layers.

Major fault displacement along the Rift Valley was initiated during middle Tertiary period. Subsidence of large crystal blocks along steeply inclined fault zones created grabben type depressions along the rift valley and at Lake Tana. Significant volcanic activity was associated with the formation of grabben and young volcanic rocks cover the old Tertiary volcanics in many depressions.

Present day tectonic activity occurs along the Rift Valley as evidenced by numerous earthquakes. More recent volcanism, associated with tectonic activity, had been concentrated within this structure along the edge of the adjoining plateau. The geological setting of the study area and its vicinity is representative of: The Mesozoic era transgression and regression event depositions of sediments, like Adigrat sandstone, which rests unconformably on the crystalline basement rock, Abay beds composed of gypsum and shale units, Antalo Limestone which conformably overly the Abay beds, Amba Aradam sandstone.

Tertiary and Quaternary volcanic units include: - the Blue Nile basalts, Amba Aiba basalt, Alaji rhyolites, Tarmaber basalt, Rift volcanic;

The Tectonic events of the rift system gave rise to the volcanic phenomenon of the area (mainly the eruption of basaltic lava flows and acidic fall deposits), the fault escarpments and the different physiographic units (the plateau, the escarpment and the depression area). Lacustrine and alluvial deposits and basaltic lava flows characterize the depression area.

2.2. Local Geology

Various geologic units ranging from Tertiary and Quaternary age groups of acidic and basic volcanic rocks and Quaternary lacustrine and alluvial deposits are mapped in the project area.

2.2.1. Tertiary volcanic rocks

A. Tarma Ber Basalt (PNtbB)

The Tarma Ber Basalt which is the dominant unit exposed and in the northern plateau parts and watershed divide of the Awash and Abbay river basins. In the rift valley part of the study area this unit is downthrown by the regional east west running Ambo fault and overlain by thick (282m) younger ignimbrite (Lega Dadi area exploration boreholes data). This unit was originally assumed to be the regional aquifer and the main water bearing formation in the study area. It is consisting of mainly scoraceous lava flows and at places it is columnar olivine bearing basalt as pockets within the scoraceous components. It is highly weathered, fractured and pinkish to grayish in color. The age of this unit is Miocene, 27-5Ma.

B. Addis Ababa Basalt (NadB)

This unit is mapped by (Kebede, 1990) at 1:25,000 scales and the basalts area classified in to different units based on their texture and compositions. For the purpose of the present mapping scale, they are mapped as one unit. This unit is fine to coarse grained basalt composed of olivine and plagioclase phenocrysts. In most part of the outcropped area northern and centeral part of the study area it is relatively thin (20m) lava flow overlying the ignimbrite. The age of the Addis Ababa basalt is 7.5-4.5 Ma ((Chernet et al, 1998) and (Morton et al , 1979)).

C. Addis Ababa Ignimbrite (NadI)

This Ignimbrite is outcropped in most part of the area around NE part, centeral part, some SW and southern part of the study area. It is composed of welded tuff (ignimbrite) and non-welded pyroclastic fall (Ash and tuff). It is grayish to white color and when welded it exhibits flame textures, elongated rock fragments of various color. Around the Lega dadi plane the age of this unit is 5.11-3.26 Ma (Morton et al , 1979).

D. Akaki Basalt (NakB)

This unit is outcropped at southern part, Abasamuel Dam, Akaki area. It is coarse grained porphyritic olivine basalt. It is highly vesicular basalt and at places the vesicles were filled by carbonate minerals. It is consisting of scoria and spatter cones with associated lava flows. Both the basalt and scoria are quarried for construction around Akaki area. The thickness of this unit around Akaki is 202m (exploration drilling data). The age of the Akaki basalt is 2.9-2.0 Ma ((Chernet et al, 1998) and (Morton et al , 1979)).

2.2.2. Central Volcanoes Unit

A. Wecheca, Furi and Yerer Trachyte (NcvTy)

The Central Volcanoes units are mainly trachytic lavas exposed at Wechecha, Furi, Yerer, Western and Southwestern ridges of the project area forming an elevated ridges or mountain picks. The Yere trachyte is eleveted about 1000 m from the surrounding plane area. It is grayish color fine to medium grained trachyte with subordinate ash falls and ignimbrite. The age of this unit is 10-3 Ma (Kazmin, 1979).

It is porphyritic in texture with phenocrysts of feldspar up to 1cm across. In fresh hand specimen it is grayish in color. Petrographic studies conducted by (Abebe et al, 1999) indicates that Trachytes of Wecheca and Furi are composed of plagioclase and sanadine phenocrysts predominating the trachyte, alkaline pyroxene and rare olivine. The groundmass varies from glassy to microcrystalline and is constituted mainly by alkali feldspar, pyroxene and amphiboles and opaque. The ages of the trachytes are different with Wecheca 4.6-3.7 Ma, Furi 4.0-3.7 Ma (Chernet et al, 1998), Yerer 3.9-3.3 Ma (Morton et al , 1979).

B.* Entoto ridge and Becho area Rhyolites *(NebRy)

The Entoto ridge forms watershed divides of Abay and Awash River basins in the northern part of the study area. The ridge forms steep slope towards the Abay basin steep to gentle slope towards the Awash basin. In fresh hand specimen it is grayish pink and reddish brown to yellowish grey color when weathered. Data on the ages of the rhyolites are not available; however, from the cross-cutting relationship they can be younger than the adjacent ignimbrite.

C. Chefa Donsa Unit (NQcdPc)

The Chefa Donsa volcanic rocks units are outcropped at the southern part of the study area and central part to wards the east direction Yerer Mountain They are consisting of fall deposits (ash, tuff and pumice) and poorly welded ignimbrites of rhyolitic composition. The age of this unit ranges 2.24 to 1.71Ma (Morton et al , 1979).

2.3. Geological Structure

Akaki river chachement is characterized by secondary structures which are mainly related to extensional tectonics responsible for rift formation and volcanic activity. The main secondary structures of the area include fracture systems –lineaments and Joints and minor faults encountered and observed during the course of the field survey and can be recognized and traced from the landsat imageries and topographic maps that cover the site area. A few numbers of faults were encountered during the field work or identified from the landsat imageries studies. This is a primarily because extensional normal faults are concentrated and affected those of the rift complex and to some minor degree the rift margin complex. The project area is located on the western rift margin. The project area is intersected on all scales by prominent linear features and Joints. Only few exposed rock types that underlie the study area entirely free of joints.

2.3.1. Lineaments

The lineaments of the area reflect the subsurface phenomena related to structural fabric elements such as faults, joint/fracture, and other none-tectonic elements. Conspicuous linear features can be recognized from the landsat imageries and topographic maps that cover the site area. The features are commonly marked by drainage systems of the site area. It is obvious that the drainage system is mainly controlled by these weak fracture zones. The lineaments range in size from a few kilometers to several kilometers.

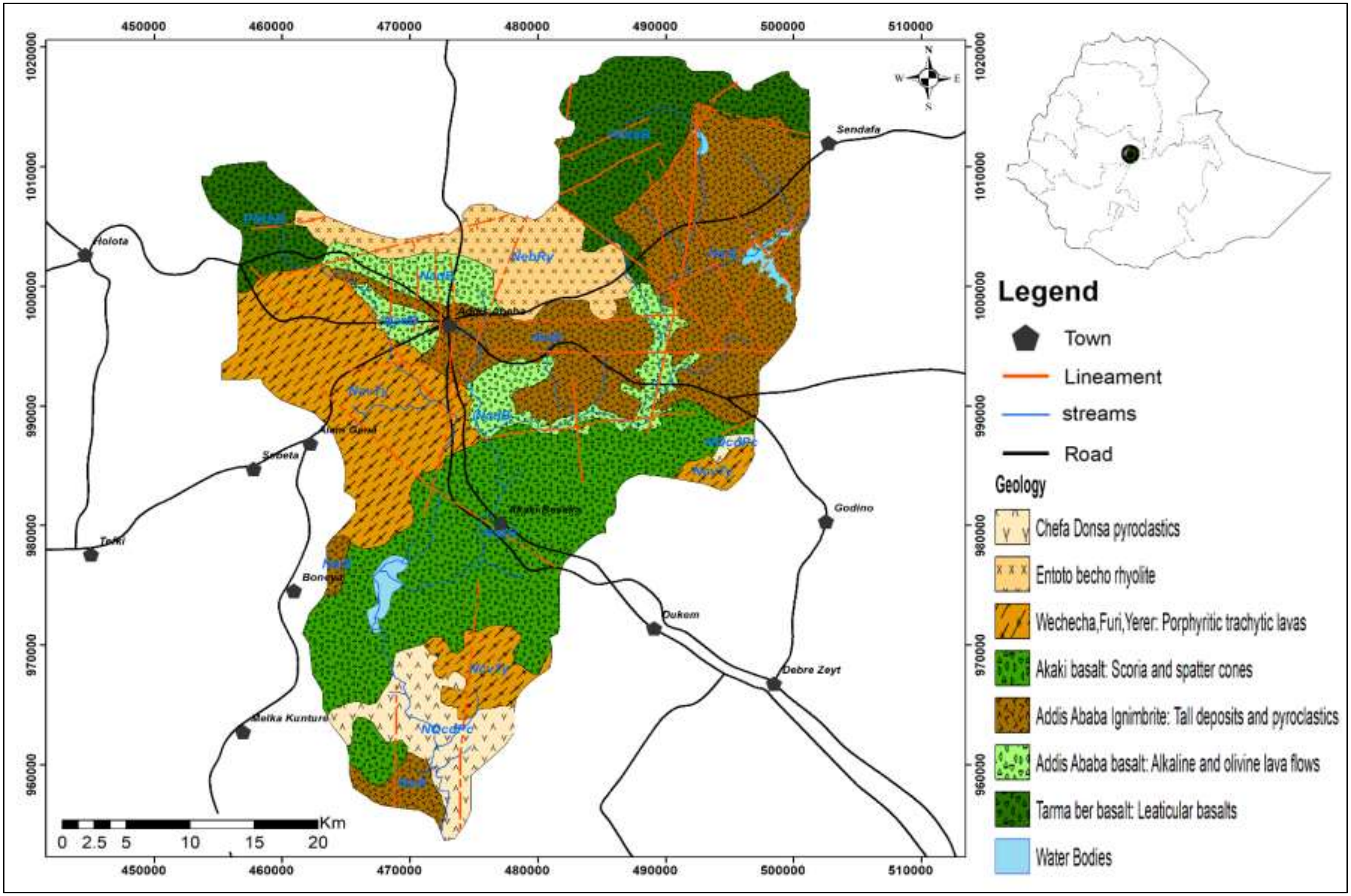

Figure 5: Geological map of Akaki Area

These lineaments can be group into four main systems based on their orientation. These are: NE-SW, NW-SE, N-S/NNE-SSW and E-W trending fracture systems. The NE-SW and NW-SE systems are the major prominent and widespread ones affecting the site area. The orientation of the lineaments corresponds to the regional trend of the Main Ethiopian Rift and Afar Depression respectively. The N-S/NNE-SSW trending lineament system are less wide spread throughout the entire site area and can be correlated to the Wonji Fault Belt of (Mohr, 1967) along the axial part of the Main Ethiopian Rift System. Only few E-W oriented lineaments occur in the study area. These lineaments can be ascribed to the Yerer–Wechacha–Ambo-Tulu Wolele mega lineament system.

2.3.2. Joint

The joints /fractures affected the hard rock units and resulted in blocky outcrops in many places. The joint pattern varies from one to the other lithology depending upon the composition, texture, and mechanism of fracture propagation/ formation. The volcanic rocks are affected by joints trending NW-SE, NE-SW, and E-W either closed or open with variable persistence, at places irregular closed joints are noted in the basalt. In addition to this, columnar joints are widespread in flood basalt, ignimbrite, and trachyte. Columnar jointing with both vertical and inclined orientation is a common feature in massive basalt formations, Ignimbrite, and rhyolite which are traversed by minute horizontal fractures. Except for the tuff layers and agglomerates, other volcanic sequences show irregular fracturing. The spacing and opening of the fractures are variable from place to place.

The orientation of the joint systems is analogous to the linear features (lineaments) mentioned before. The major ones generally trend NE-SW, NW-SE and subordinate one's trend N-S/NNE-SSW and steeply dipping or vertical.

2.3.3. Faults

The area has been affected by different faulting systems that resulted in the different structural development of the area. Four types of fault features are recognized during the interpretation of satellite imagery lineaments data. The widespread brittle deformation consisting of fractures and dislocations are also observed during the field survey.

a. Northwest Southeast Fault System

The NW-SE fault system, the oldest fault system have extended history affects all the rock type in the western escarpment. They are crustal scale served as a conduit for the extensive volcanic formation in the area and their age may go up to early Paleozoic, but becomes reactivated latter with the main tectonic event in the region. The trend of the Bede Gebaba - Wecheca volcanic belt can be associated with this NW fault system and the afar depression can be associated with this SE fault system.

b. East West Fault System

The EW fault system, which is the upper boundary of the Ethiopian rift margin, is running approximately E-W north of the Addis Ababa Ambo Road. They are major fault on the western plateau part and densely affected the Tarma Ber basalt in the area.

c. Northeast Southwest Fault System

The NE-SW fault system runs parallel to the principal system of fissures in rift floor north east of Debrezeit and Modjo and extending to Nazeret. This fault system is densely affecting the volcanic rocks and served as a conduit to younger eruption (Tulu Rie basalt). The fault system of the rift margin exhibit step like block faults.

d. North South Fault System

The NS fault system is the recent fault system which serves as a conduit for young volcanic (Addis Ababa basalt).

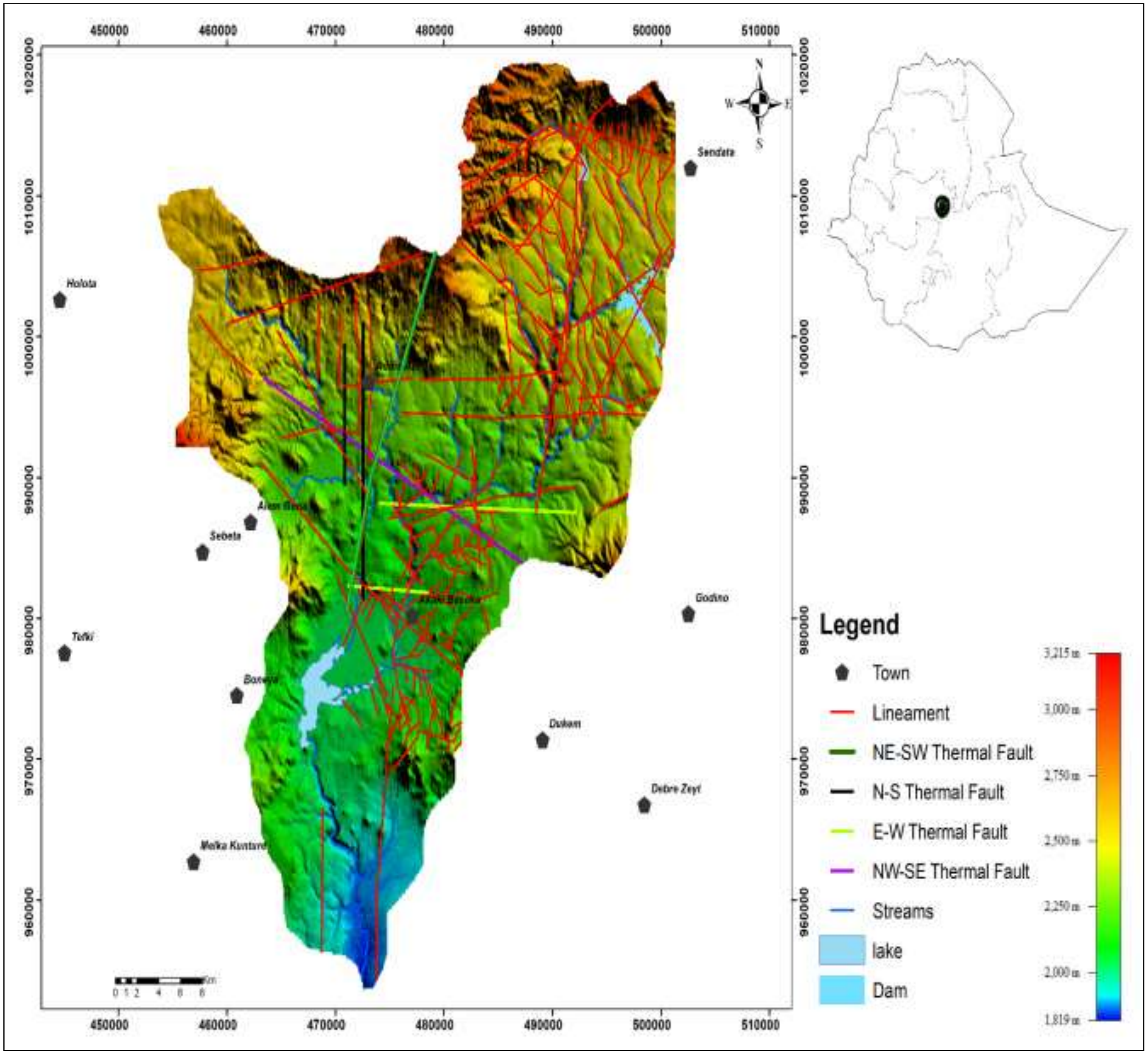

Figure 6: Structural map of the study area

CHAPTER-3 HYDROGEOLOGY

3.1. General

Hydrogeology can be defined as the study of ground water with particular emphasis given to its chemistry, mode of circulation and relation to geology environment (Davis & DeWiest, 1996). The occurrence of groundwater in hydrostratigraphic units (water-bearing formations or aquifers) is mainly controlled by the type of geology, degree of geological weathering or density and intensity of geological structures, and geomorphological features of the area. In the study area, different types of hydrostratigraphic units are defined to their water storage and transmissivity capacities. The number of interconnected porosities in any hydrostratigraphic unit has a significant role in increasing the storage and transmissivity capacity of the units. Both the primary porosity and secondary porosity formed as a result of fracturing, jointing, and faulting can form different hydrostratigraphic units.

The majority of productive aquifers are characterized by their high degree of weathering and intense fracturing. Fractured volcanic rocks are the major potential rock units for storage and movement of ground water. In addition, the intergranular pour spaces of alluvium also have significant role in occurrence of ground water. The main recharge for ground water of the area is precipitation, although surface water and Perennial River and streams are also act as local recharges.

3.2. Hydro stratigrahic units

The occurrence of groundwater in hydrostratigraphic units (water-bearing formations or aquifers) is mainly controlled by the type of geology, degree of geological weathering or density and intensity of geological structures, and geomorphological features of the area. In the study area, different types of hydrostratigraphic units are defined to their water storage and transmissivity capacities. The number of interconnected porosities in any hydrostratigraphic unit has a significant role in increasing the storage and transmissivity capacity of the units. Both the primary porosity and secondary porosity formed as a result of fracturing, jointing, and faulting can form different hydrostratigraphic units. The different types of hydrostratigraphic units defined in the study area are:

3.2.1. Upper Basaltic aquifer

This hydrogeologic unit/aquifer comprise the quaternary and some tertiary basalt and cover the northern and eastern part of the study area forming flow layering and small ridges with some vesicles on their surfaces. They are characterized by the presence of primary porosities and secondary porosities formed as the result of tectonic activities as they are part of the active rift zone. They are moderately fractured units that favor moderate groundwater storage and circulation system. Subsurface information shows that the thickness of the aquifer unit is variable from place to place. The thickness of the aquifer is variable and increases from the west to the east direction. However, in some cases very thick aquifer units may be encountered and give appreciable groundwater to the wells to have high potentiality.

The geological formation is highly variable from place to place i.e., massive basalts, scoraceous basalt and scoria. The basalts when is faulted and fractured the yield of bore holes increases. In addition, when the formation is scoria the yield of bore holes is very high due to its high storage coefficient and transmissivity. Southern part of the earea supposed to be part of this aquifer system.

3.2.2. Ignimbrite and Pyroclastic aquifer

The Ignimbrite units form regional and local volcanic aquifers interlayered by pyroclastic and tuff deposits. The aquifer units are entirely distributed in the central and the eastern part of the study area. Originally, this unit has none or low primary porosities and its aquifer productivitis are completely dependent on the secondary porosities. Most of the central and eastern part of the unit is located along the rift margin close to the regional fault system where the fault system is active and responsible to form secondary porosities through fracturing the intact rocks. The effect of regional tectonic effect produces highly fracture rock and the aquifer unit is believed to be a moderate potential aquifer.

3.2.3. Trachytes/Rhyolite aquifers

These hydrogeologic units are mainly found in the western, southwestern, and northern parts of the study area.They are characterized by poor primary porosity and are considered as poor aquifer productivity. However, if these units are affected by tectonic activity and forms fractured rock, it can store and circulate satisfactory groundwater and can produce a good aquifer. The rock unit found at rift margin close to active regional fault system can produce fractured rocks with the moderate productive aquifer. Such conditions are encountered in some places at the exposure of these rock units.

3.2.4. Lower basalt /Scoriaceous basalts aquifer

These are the lower tertiary volcanic aquifer composed of tarmaber scoriaceous basalt and amba Aiba basalts. These units are found in the southern and southeastern margins of the study area. Subsurface information shows that the rocks are underlying both the upper volcanic aquifer and ignimbrite units. They are characterized by the presence of primary porosities and secondary porosities formed as the result of tectonic activities as they are part of the active rift zone. They are highly fractured units that favor very great groundwater storage and circulation system. Subsurface information shows that the thickness of these aquifer unit is very thick and more than 300 meters. This aquifer unit is considered a highly productive aquifer unit where many wells were drilled in and appreciable groundwater was developed supplying the water demand of Addis Ababa city.

3.3. Groundwater flow characterstics

The major sources of groundwater recharge for the aquifer in the study area are inflow from the regional groundwater flow due to the infiltration of precipitation in the highlands and some percolation through local fractures. Different studies show that sufficient recharge is available in the area.

Previous groundwater resource evaluation studies conducted by WWDSE office, 2014 had identified regional groundwater flow direction extending from the Abay plateau to the southern direction of Addis Ababa through the project sites. The current study also shows that groundwater flow is from north to south through the study area except at local highs, domes, and eruption centers. The groundwater most commonly flows along preferential paths dominantly through faulted zones. The pattern of local groundwater flows through the study areas is similar to regional groundwater flow direction N-S direction along preferential flow paths.Depth to groundwater level for the deep regional aquifer varies between artesian flowing conditions close to weak zones along with river courses and up to 190m, at elevated parts of the area depending on the topographic setup. Depth to the groundwater for the shallow aquifer is within a range of 5 to 40m.

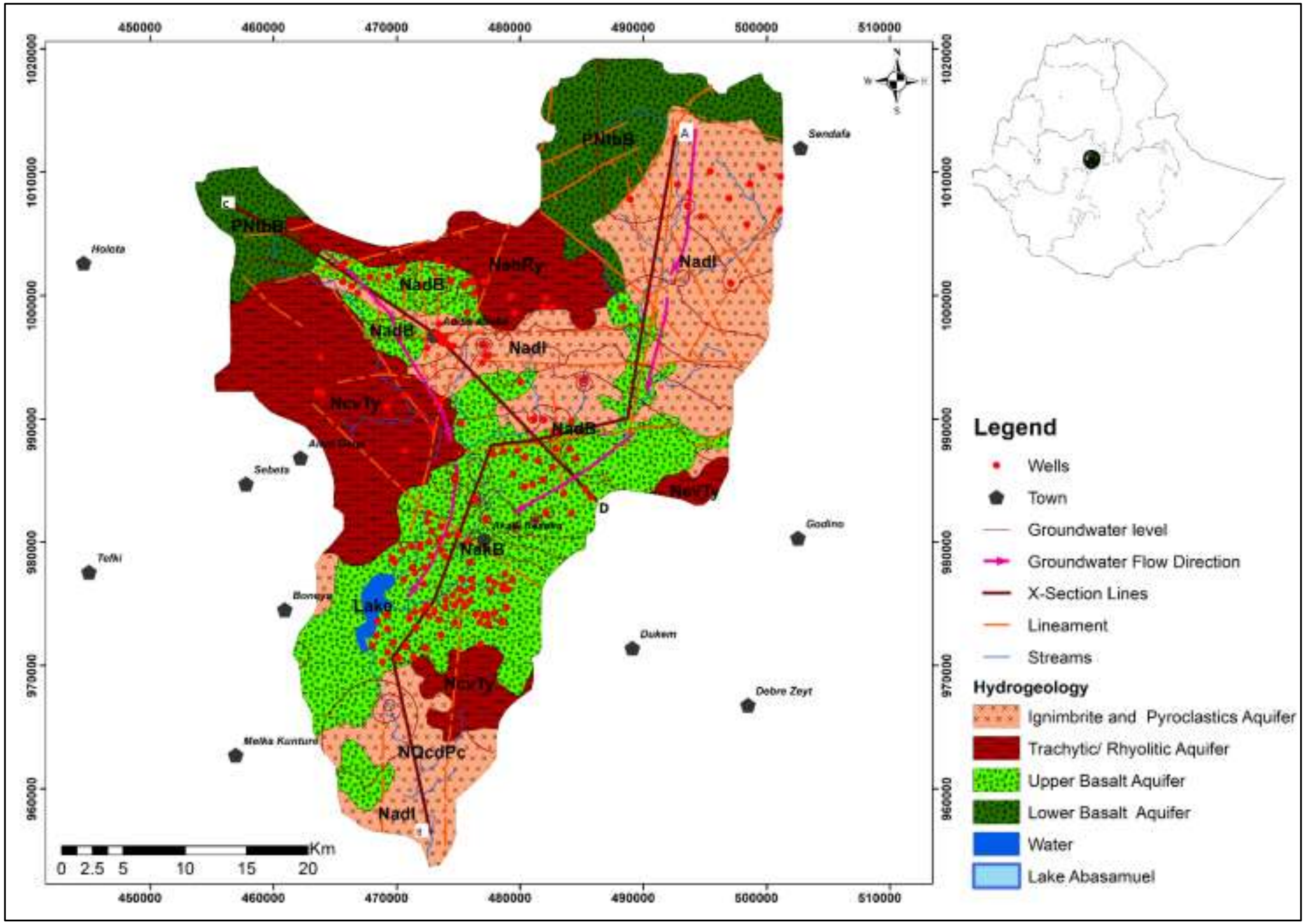

Figure 7: Hydrogeological map of the Study area

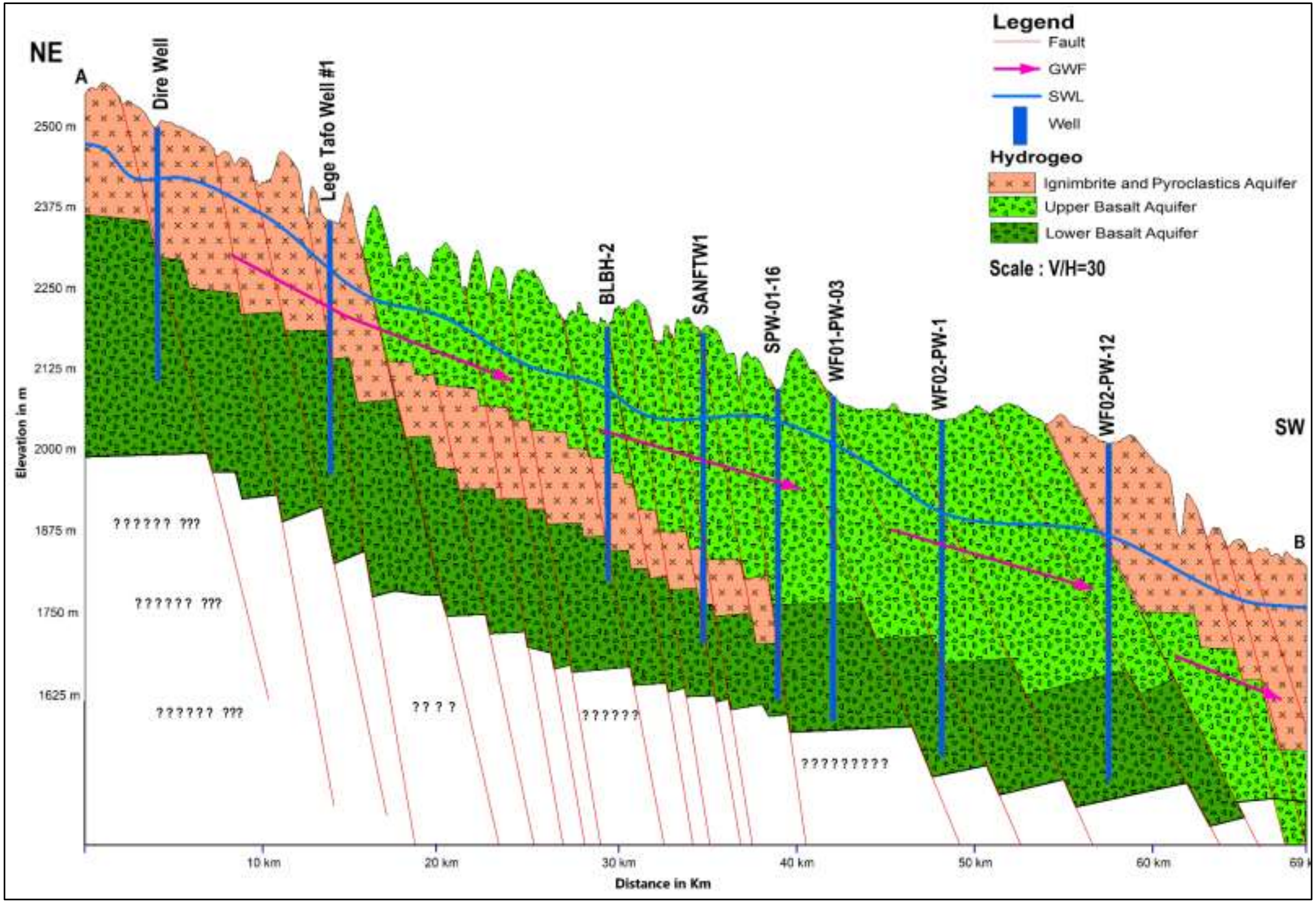

Figure 8: Hydrogeological cross-section map along NE-SW direction

CHAPTER-4 HYDROCHEMISTRY

4.1. General

The objectives of chemical hydro geological investigations are to determine the sources, concentration and fat of dissolved constituents within the physical frame work of flow and transport. The term “water chemistry” (or water quality) refers to the quantities of these various substances (commonly called solutes) that are present in a particular water sample, making up its chemical composition water acquires very small quantities of some solutes from dust and gases when it falls through the atmosphere as precipitation, but it typically acquires the majority of its solvents once it reaches the land surface. Solutes that were already present in the water increases in concentration because of the processes of evaporation and transpiration, for the most part, remove water while leaving the solutes behind.

The main environmental factors that control the number of solutes present in the natural water climate, structure and position of the rock strata and biochemical effects associated with life cycle of plants and animals are considered by (Hem, 1971). So those, accurse of basic and acidic volcanic rocks, major tectonic discontinuity and topography are the major water quality controlling factors. Urbanization and associated development features for more than a century in in Addis Ababa city significantly change the chemical and biological constituents of surface and ground water. Standardization of water quality based on world health organizations can also be generated on the basis of hydro chemical data.

4.2. Groundwater Quality

According to analysis of water samples collected from deep wells and shallow wells of the study areas and for Floride analaysis, water samples are taken from thirteen deep wells and seven shallow wells collected from the study aera.most analysed chemical elements, including fluoride, are within the acceptable level of WHO recommended standard for domestic uses except high fluoride concentration observed in water samples of boreholes located in central part and eastern part of study area. According to analysis made using Aquachem 4, groundwater of the study areas is classified as

Na – HCO3 (sodium bicarbonate) type

Na- HCO3 type waters are found central part and eastern part of the study area, also found to have this facies which could be an outcome of groundwater evolution along the regional flow path.

The other systems with this facies are the highly mineralized (TDS>1600mg/l) thermal wells which are located Central part and eastern part of the study area. From their association to acidic volcanics in place, these waters might have evolved from Ca-Na-HCO3 and Ca-HCO3 type water-silicic rock interaction at elevated temperatures where Ca is lost through CaCO3 precipitation. The other process could be deep circulation and longer residence time which leads to further hydrolysis of silicate minerals in the Ca-Mg-HCO3 type waters whereby the concentration of Na, K and HCO3 increase. Similar conclusions were made by previous researchers (Kebede et al. 2005 and Demlie et al 2008). Na – HCO3 (sodium bicarbonate) type. The Na – HCO3 water type of study area indicates that groundwater of the area deemed to be from deeper aquifer, undergoes cation exchange due to long residence time and enriched with fluoride due to fluorite precipitation facilitated by high groundwater temperature.

Na-Ca-HCO3

The other facies groups are the Na-Ca-HCO3 type waters and are mainly encountered in central part, eastern part and southern part of the study area. In the central part of the study area these waters are associated with deep wells having a diluted chemistry (TDS<250mg/l). In many groundwater circulation systems strata of high permeability may be separated by clay or shale layer of much less permeable rocks. These layers can act as semi permeable membranes and thus give rise to anomalous effects on the concentration of dissolved ions. Sodium is retained by adsorption on mineral surface, especially by minerals having high cation-exchange capacities such as clays. Cation exchange process in fresh water systems tend to extract divalent ions such as Ca^{2+} from solution and to replace them with monovalent ions such as Na^+ (Hem, 1992). The Na^+ dominance in some of the borehole samples, therefore, might indicate the exchange of Ca by Na^+. In the eastern part and southern part of the study area this type facies is associated with wells having a moderate mineralization (TDS<500mg/l). The reason for this could be groundwater evolution along its flow path.

Ca-Na-HCO3

Ca-Na-HCO3 are associated with moderately mineralized waters (TDS< 400mg/l) and are mainly distributed to the central part and southern part of the study area. This part of the area is characterized by intercalations of acidic volcanics (rhyolites, ignimbrites, tuff, trachytes and Pyroclastics), where water systems are tapping the weathered and fractured rocks rich in Ca- and Na- plagioclases which could be responsible to have such water chemistry.

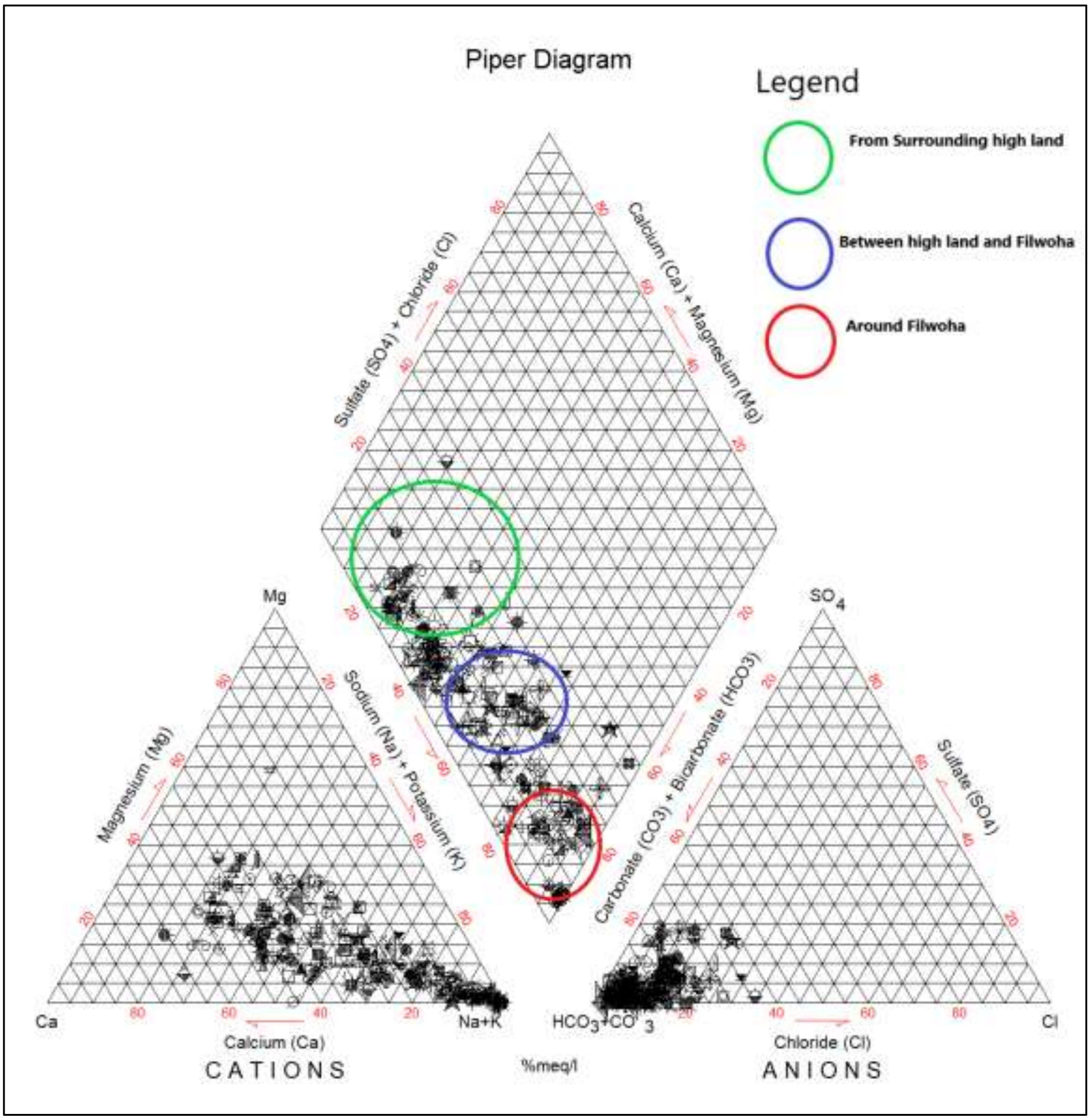

Figure 9: Piper plot of the study areas groundwater

The main hydrochemistry of water characteristics of the study area can be expressed by some physical parameter like TDS (Total desolved substance), Tempratue, and Flouride have been used.

4.3. Physical Parameters

4.3.1. Total Dissolved Solids

TDS: Total Dissolved Solids include all the solid substance in solution. The amount of dissolved solids can be determined from the weight of the dry residue remaining after evaporation of the volatile portion of the water sample (usually at 180 ^{o}C) or may be calculated if the concentration of major ions is known (Hem, 1971).TDS can have important effects on the taste of drinking water. The field measured value ranges from 90m to 2200m in mg/l. The total dissolved solid (TDS) of different samples from different geological unit ranges from 62m to 2528mg/l which shows a big variation indicating the impact of different rock types to water chemistry.

TDS of the study areas aquifer is less than 1000µS/cm in most part of study area, except at central part of study area where both groundwater temperature and is more than 40^{o}C and it exceeds 2528µS/cm. Dissolution of minerals by groundwater facilitated by an increase in temperature is deemed to be the main reason for an increase in TDS in central part of the study area.

In general, the concentration of alkaline earth metals, Ca and Mg gradually decreases when the ground water becomes rich in TDS. In the contrary, the concentration of the alkaline metals, Na and K increases with the increase of TDS.Very low value of the Ca/Na ratio is the characteristics of the thermal aquifers and those aquifers the groundwater from basaltic or if acidic, they are located on the fault line that could serve as a conduit for the water to come from the deep lower basaltic aquifer that underlay the penetrated acidic unit.

4.3.2. Fluoride

Fluoride concentration of the study areas groundwater is beyond the limit of WHO in central part, eastern part some southern part of the study area. In these areas, most of the boreholes penetrated aquifers of trachyte, rhyolite and ignimbrite. In addition, an increase in temperature is believed to facilitate dissolution of fluorite that led to an increase in fluoride and sodium. Some boreholes which are associated with fault Zones show higher fluoride concentration than the normal drinking water standard. The higher concentration of fluoride in the study area is associated with recent acidic volcanic (Gizaw, 1996). High Fluoride concentration, up to 41.55mg/l in central part of the study area associated with thermal waters whereas, in most part of the study area, fluoride concentration is within the limit of WHO.

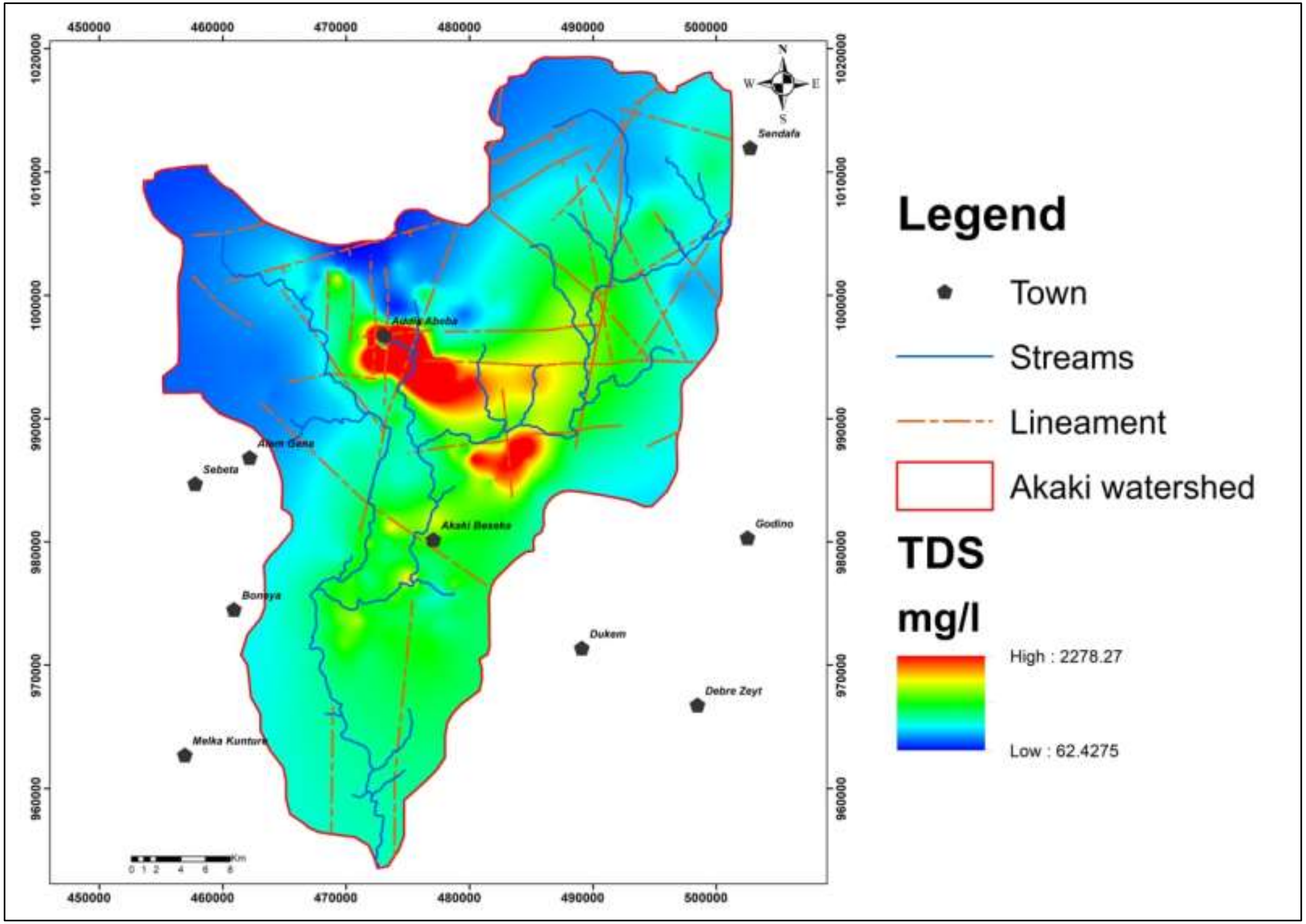

Figure 10: TDS map of study area

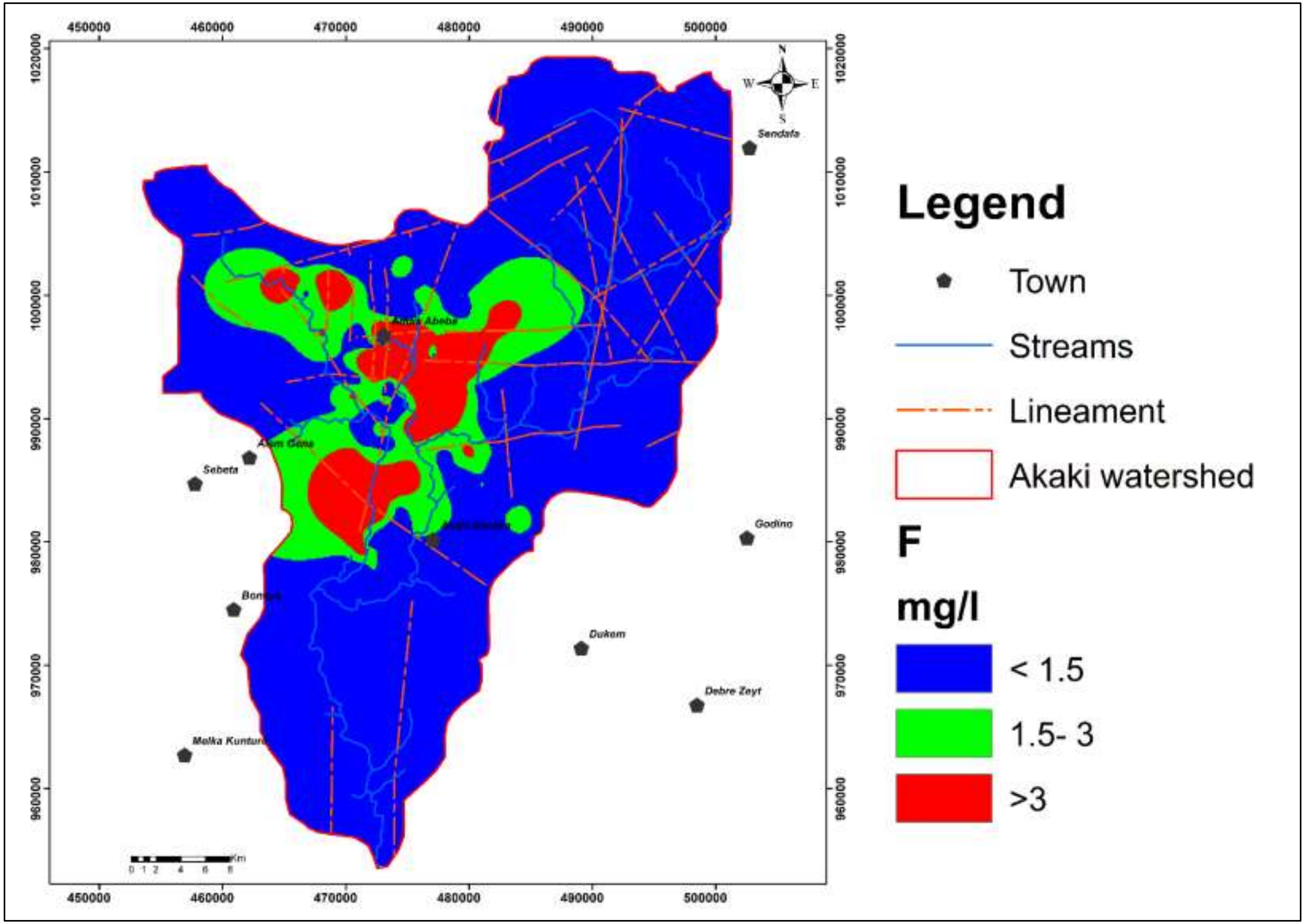

Figure 11: Fluoride map of study area

4.3.3. Temperature

In-situ temperature record central part of the study area wells located at both the structural line and junction exhibiting higher thermal groundwater ranging from 65 ^{O}C to 86 ^{O}C are FWDW-01, GHDW-01-18, LPW-01-17, and WGPW-01-18.

On the course of LPW-01-17 well drilling showed that, temperature of LPW-01-17 drilling fluid exceeds 30 degree Celsius at depth of 150 meter below ground level depth of drilling increase and temperature increase.

In addition, as observed from pumping test of Sheraton hotel borehole, the temperature of groundwater gradually increased from 39^{o}C to 45^{o}C when the dynamic water level reached 244.28 meter. Similar increment in temperature is also observed during pump test of NPPW-02-19 (National Palace Borehole), Gihon Hotel and Filwuha spa deep boreholes when the dynamic water level increases. This shows that, hot of the area exist at below 240 meter .This fact is alsosupported by in-situ electrical conductivity record of LPW-01-17 drilling fluid that has an increasing trend from 126 meter depth and exceeds 1000µS/cm at a depth of 268 meter. Moreover, as distance from N-S trending faults (Graben) and Filwuha area increases depth to thermal groundwater aquifer increases.

In-situ temperature record Eastern part of the study area in situ measurement of water temperature from boreholes, groundwater temperature of the study area ranges between 37degree Celsius to 50degree Celsius high groundwater temperature is observed close to N-S and E-W trending faults of the area. These structures are responsible for heat flux dissipation that increases groundwater temperature.

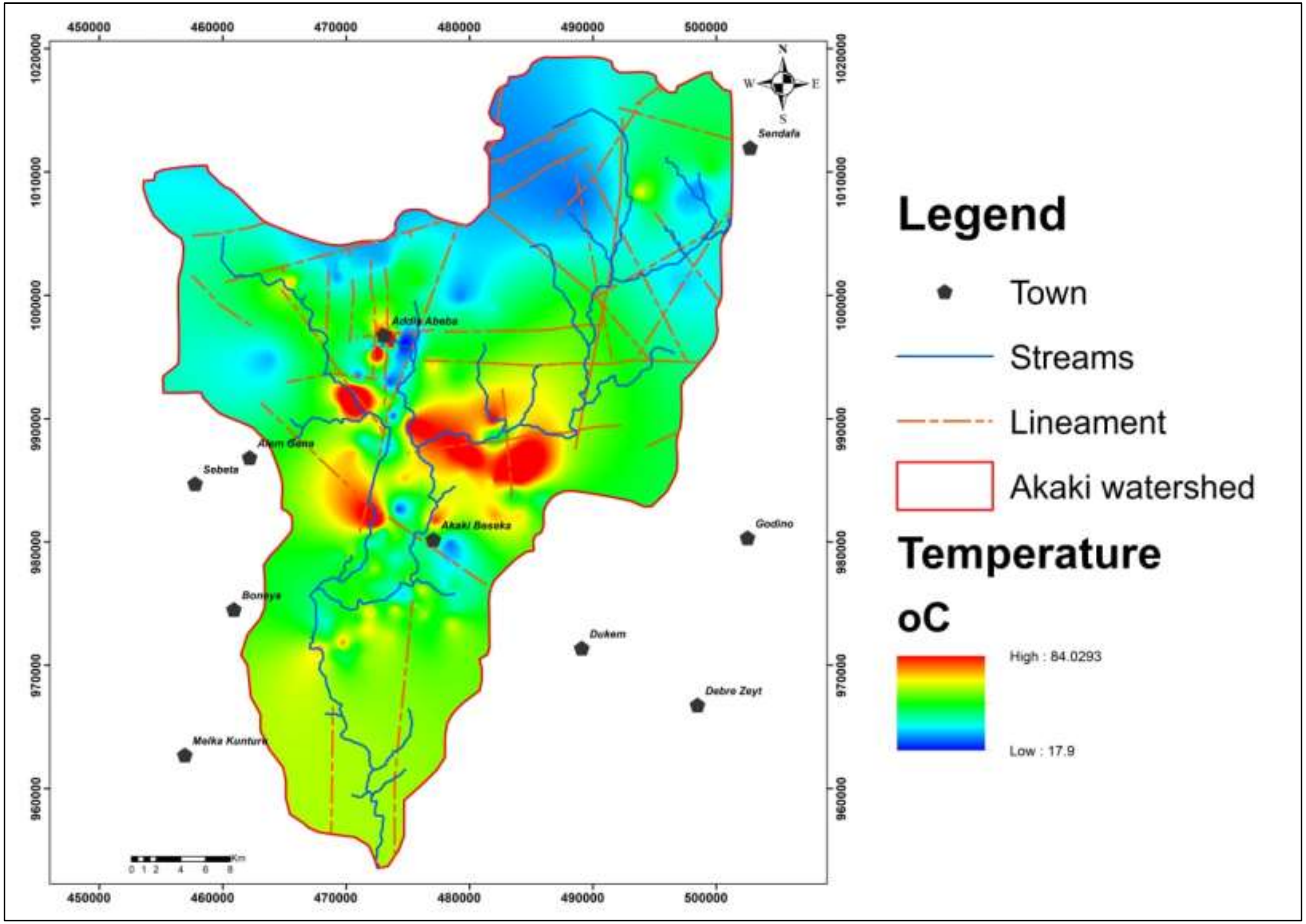

Figure 12: Groundwater temperature

CHAPTER-5 THERMAL WATER SYSTEMS

5.1. *Heat production and heat flow*

The temperature of groundwater is influenced by air temperature to depths of about 50 m.Below this, additional heat is obtained from the rocks with which the water is in contact. The main source of heat is the earth's mantle, Rock and water temperatures increase gradually with depth in the earth's crust this temperature gradient, usually referred to as the geothermal gradient, results in the flow of heat from the earth's surface (M. Albu, 1997).

The highest heat flows are associated with seismically active belts intercontinental rifts such as the Red Sea and East African rifts, where the earth's crust is relatively thin and where there is upwards convection in the mantle. Many of these belts mark theboundariesofcrustalplateswhichmoverelativeto each otheroften giving rise to volcanism. Elsewhere a significant thermal potential may be found where the sub crustal or intracrustal heat flow is high, often in areas of crustal thinning,or where aquifers are deep enough for the water to be heated under a'normal'geothermal gradient (M. Albu, 1997)

The study area have highest heat flow associated with SW extension of the Aden gulf grabber forms the median hot spring zone about 100km long in breadth the zone extends straightly beneath the Ethiopian plateau a part from the rift valley many thermal springs are known on the zone such as in order from the east Haulle 94^{o}C, Chillelu 94.3^{o}C, Uarf 45^{o}C, Aretu 85^{o}C, East Errer 41.5^{o}C, Donka pool 37^{o}C, Palm 40^{o}C, Sodere 59^{o}C, Filwoha 78^{o}C, Weliso 43^{o}C, Ambo 39^{o}C, Abelti 57^{o}C. On the other hand; the red sea structure having traversed the median zone are N50^W in the east, but deviate to N40^W in the west. And in the western half of the median zone N30^W is found in the Filwoha region Addis Ababa and Ambo-Weliso stand in the west the red sea structure seem approach from N50^W to the north-south, alike there may be a center of radial fracture in the north.

The Aden gulf structure of N60^-&75^E forming median zone appeared at first in O-ligocene, then the N30^E structure of rift valley forming both the lower awash belt and the lake zone belt occurred in L Pliocene.

The Red Sea structure of NW forming the Eretria belt and its parallel line appeared at last U Pliocene. All are results of tensional forces pulling apart (Kondo, 1975).

5.1.1. Heat transport

Heat is transported in thermal water systems by conduction and convection. Conduction is thetransfer of heat through asubstance without any detect-able motion of the substance taking place, while convection is the transfer of heat by the motion of fluids. Heat transfer by conduction is the product of the thermal conductivity of the medium and the temperature gradient. Since fluids are generally poor conductor's conduction is often only significant in the rock matrix and is roughly approximated by the measured heat flow. However, the temperature gradient and hence the heat flow is affected by convection. Convection plays an important part in heat transport in aquifers of any extent and may be caused both by density variations due to temperature gradients (freeconvection) and by groundwater movement according to Darcy's law (forced convection or advection) (M. Albu, 1997).

5.1.2. Classification of thermal water system

a. **High enthalpy thermal water system:** High enthalpy (i.e., high temperature) systems may produce saturated steam (steam with water), dry steam or superheated steam. The dominant phase in any system depends on the temperature and pressure. Vapour-dominated systems often contain hot liquid at depth, where pressures are greatest, and steam at shallower depths.The hot liquid is generally accepted to be boiling brine, from which steam moves upwards along fractures.

b. **Low enthalpy thermal water systems:** Low enthalpy systems are widespread compared tothoseof highenthalpy becausetheiroccurrenceonlyrequiresthepresenceof aquifersatagreat enough depth, or at asmall enough distancefromasource of geothermal energy, to be heated bythe local heat flux (M. Albu, 1997).

5.2. Thermal Groundwater

The nomenclature of thermal groundwater varies from place to place depending on geographical locations. However, for this recerch paper, groundwater with a temperature greater or equal to average human body temperature (i.e., ≥ 37°C) is considered as thermal waters and also according to (Maraver, et al., 2003) geothermal classification their temperature above 37°C is hyperthermal water more than 50% of resorts have hyperthermal water.

The hydrogeological conceptual model for encountering thermal groundwater could be associated with the existence of a heat source originated from deep sub-surface magma.

The magma could transfer its heat to the conductive materials through the conduction process. The deep groundwater flowing and circulating in the aquifer will be heated by conductive rocks through a mechanism of conduction. Depending on the degree of permeability of the aquifer, the groundwater could get sufficient time to be heated by the conductive rocks which ultimately form thermal groundwater in the aquifers. Generally, the lower permeability of the aquifer corresponds to the slow groundwater movement and the longer time for the water to be heated by the conductive rocks which eventually result in increasing the thermal environment of the groundwater.

The thermal ground water encountered in the study area is central part of Filwoha, in the Eastren part and small parts of the southern of study area. The structural and hydrogeological settings related to thermal groundwater in the Akaki watershed are discussed as follows.

5.3. Structural Setting of Thermal Groundwater Occurance in the Akaki Watershed

Groundwater with a temperature greater than or equal to 37^{o}C is encountered in the different parts of the study area. The study area is characterized by secondary structures which are mainly related to extensional tectonics responsible for rift formation and volcanic activity. The main secondary structures of the area include Joints/fractures, lineaments, and faults.

The joints /fractures affected the hard rock units and resulted in blocky outcrops in many places. The joint pattern varies from one to the other lithology depending upon the composition, texture, and mechanism of fracture propagation/ formation. The volcanic rocks are affected by joints trending NW-SE, NE-SW, and E-W either closed or open with variable persistence, at places irregular closed joints are noted in the basalt. In addition to this, columnar joints are widespread in flood basalt, ignimbrite, and trachyte. Columnar jointing with both vertical and inclined orientation is a common feature in massive basalt formations, Ignimbrite, and rhyolite which are traversed by minute horizontal fractures. Except for the tuff layers and agglomerates, other volcanic sequences show irregular fracturing. The spacing and opening of the fractures are variable from place to place.

The lineaments of the area reflect the subsurface phenomena related to structural fabric elements such as faults, joint/fracture, and other none-tectonic elements. Field data showed that lineaments of the area trending NE, NNE, NW, and W trending lineament.

The area has been affected by different faulting systems that resulted in the different structural development of the area. The major faults identified in the area encompass W-E, N-S, NNE-SSW, NE-SW, and NW-SE trends.

5.4. Thermal Groundwater Hydrogeological Setting of the Akakai Watershed

5.4.1. Central part of the study area around Filwoha

Filwuha thermal groundwater is found in the center of study area, at the edge of the Main Ethiopian Rift Valley. The thermal groundwater is localized in the escarpment of the rift, where the geomorphology of the area forms a small-localized intermountain basin (Kondo, 1958).

Geologically except the intermountain Filwuha thermal groundwater basin, which is partly filled by alluvial sediment, the area is generally composed of volcanic rocks of Ignimbrites and trachytes, rhyolitic flow, aphanitic and porphyritic basalts. Drilled boreholes in the area show that the subsurface lithology of the filwoha area is exclusively composed of acidic volcanic rocks mainly ignimbrite and trachytes with thin layer intercalation of tuff and basalts. In the southwestern part of filowha near legahare, the subsurface lithology is characterized by a thick layer of basalts underlain by the ignimbrite unit. To the southwestern part near mekanisa, the basaltic unit is overlain by a thin layer of acidic rocks of ignimbrite and trachyte. The thermal groundwater static water level of the filwoha area and its southwestern parts varies from flowing to 13.13m below ground surface. The thermal groundwater becomes deeper away from the filwoha area in the southeast direction.

The thermal groundwater in the central part of the study area around Filwoha is controlled by NW-SE, W-E, and N-S trends trending faults and lineaments. The established and inferred faults of the thermal basin could be responsible for transporting heat flux to the surface of the earth and heats the local groundwater along the faults. This assumption can be proofed by the maximum observed temperatures from drilled wells at the structural line and junction of NW-SE and N-S trending faults. The wells located at both the structural line and junction exhibiting higher thermal groundwater ranging from 65 ^{O}C to 86 ^{O}C are

FWDW-01, GHDW-01-18, LPW-1, and WGPW-01-18. And also, according to (Kondo, 1975) very hot spring over 90ºC such as Halle and Chillelu are found close to the intersecting area of the extended Eretria belt and median zone near NE boarder of the country

5.4.2. Eastern part of the study area

The Eastern part of the study area is extending towards the foot of Yerer Mountain.Eluvium deposits, Ignimbrite and Tuffs, scoriaceous basalt, and Basalt & Aglomerates are some of the out-cropped rocks distributed all over in the study area. The Eluvium deposits mainly clay silt covers almost the whole parts of the study area, the ignimbrites and Tuffs are mainly distributed in the northeastern part of the study area, the scoriaceous basalts and Basalt & Aglomerates are distributed as mall patches in the southeastern and northeastern part of the study area respectively. Existing data from drilled boreholes show that the subsurface geology of the study area is composed of both basalt and ignimbrite with minor tuffs. Rock formation with series of layers of basalt, ignimbrite, and with thin layers of tuffs is common in sub-surface lithology throughout the study area. The static water level of the thermal groundwater around the study area varies from flowing to 41m below the ground surface.

Both the NW-SE and E-W trending faults control the occurrence of thermal groundwater in the study area. Wells found in the eastern margin of the study area near Yerer Mountain have relatively higher groundwater temperatures than the westeastern part of the study area. The thermal groundwater in the eastern part of the study area varies from 37 ºC to 50 ºC.

5.4.3. Southern part of the study area

Southern part of the study area is Eluvium deposits, scoriaceous basalts, and Basalt & Agloromerate rock units are exposed in the study area. The silty clay eluvium deposits cover the major part of the study area while the scoriaceous basalt is distributed irregularly as small patches in the central, southern, and eastern part of the the study area. Basalt and agglomerate are distributed only in the northern part with small areal coverage. The subsurface lithology of thermal groundwater of the study area is characterized by trachyte and tuffs rock units overlain by basalt and scoriaceous basalt unit. The thermal groundwater level in the study area is relatively deeper and can reach up to 58m below ground surface. But there is an exceptional case where the thermal groundwater is flowing as it is encountered at the WF01-PW17 well.

Both the NW-SE and E-W trending faults are the main controlling structures that control the thermal groundwater in the part of the study area. The maximum observed temperatures from wells are recorded at the junction of NW-SE and E-W trending faults (WF01-PW17). The groundwater temperature is relatively higher near the foot escarpment of Furi Mountain than the remaining parts of the study area. The thermal groundwater in the part of the study area varies from $37^{O}C$ to 48 ^{O}C.

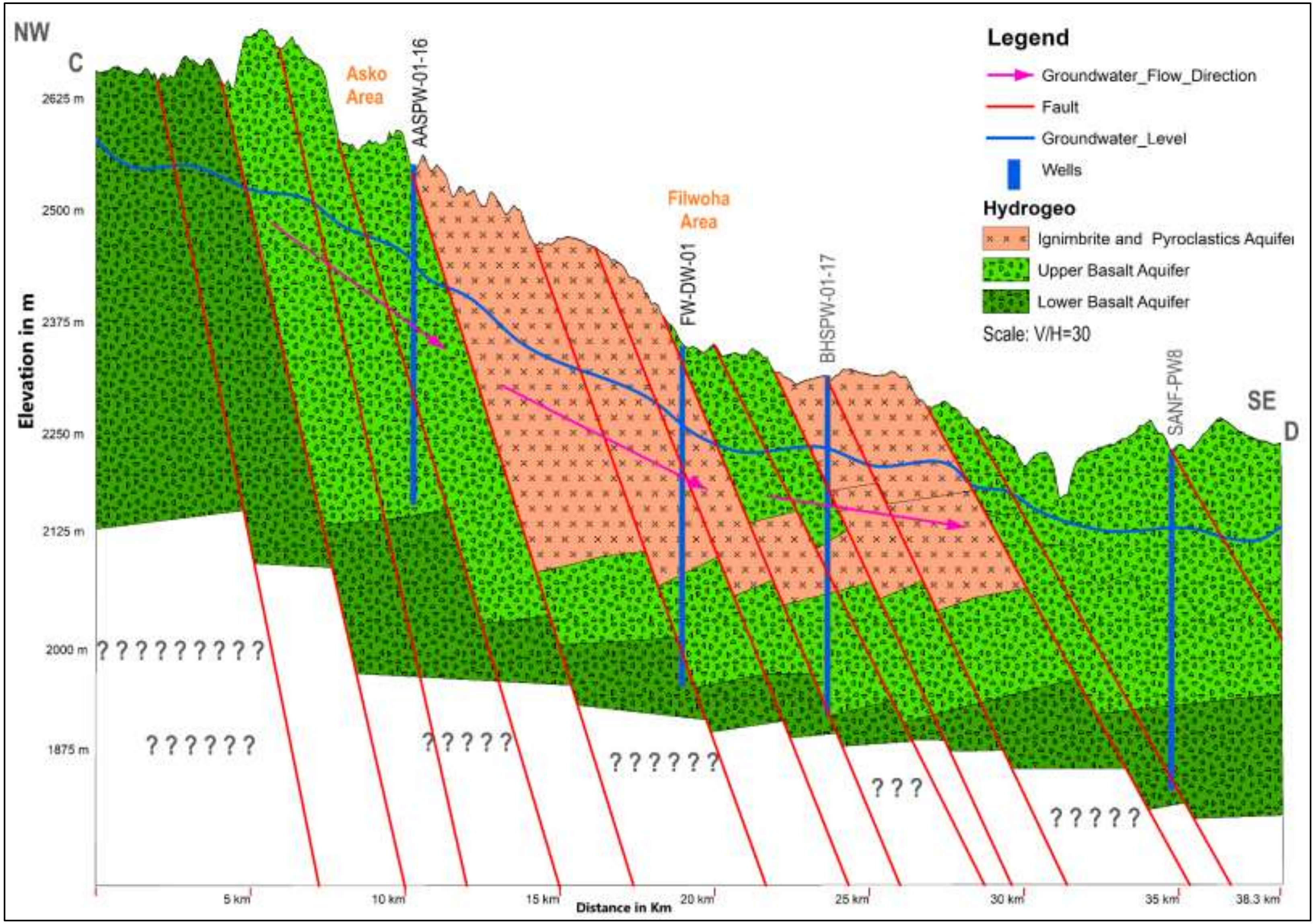

Figure 13: Thermal cross secton along NW-SE direction

5.5. Hydrochemistry of thermal ground water in the Akaki Watershed

Hydrogeochemistry are an important way within the geothermal resources assessment to obtain information, such as geothermal fluid origin, circulation paths, residence time, mixing processes, water–rock interactions, reservoir rock characteristics, and reservoir temperature

5.5.1. Distribution of thermal groundwater on the study area

Identigication of thermal groundwater areas of Akaki River catchment of upper Awash River basin, 40 boreholes are inventoried Annex-II and gathered from review of well completion reports. According to inventoried water points data, 24, 10 and 6 of thermal water points are inventoried from central part around Filwuha area, eastern part and Southurn part of Akaki river catchment.

According to inventoried thermal groundwater points from borehole is detected in central part around Filwuha, eastern part and southern part of study area. Thermal groundwater boreholes have a depth varies from 56.4 to 583.50 meter and static water level of Filwuha area thermal groundwater boreholes ranges between artesian to 62.8 meters and also their yield varies between 0.83 & 75l/s.

Groundwater temperature of central part around Filwuha area ranges between 37 to 86 degrees Celsius varies both spatially and depth wise and their TDS also ranges between 230 to 2528mg/l.Groundwater from most of shallow boreholes is cold whereas deep boreholes yield hot water. Moreover, as distance from Filwuha area increases, the depth of thermal groundwater aquifer increases.

In eastern part of study area, 10 water points are inventoried these water points exhibit temperature that ranges between 37.0°C to 50.20°C and depth varies between 411m to 550m. TDS of these water points are in the range of 308mg/l to 1026 mg/l.
Among inventoried water points, Akaki area water points exhibit groundwater temperature of 37°C to-48.1°C and 319m to 537.37m deep. These water points have low TDS relative to the others thermal groundwater observed with in the study area.

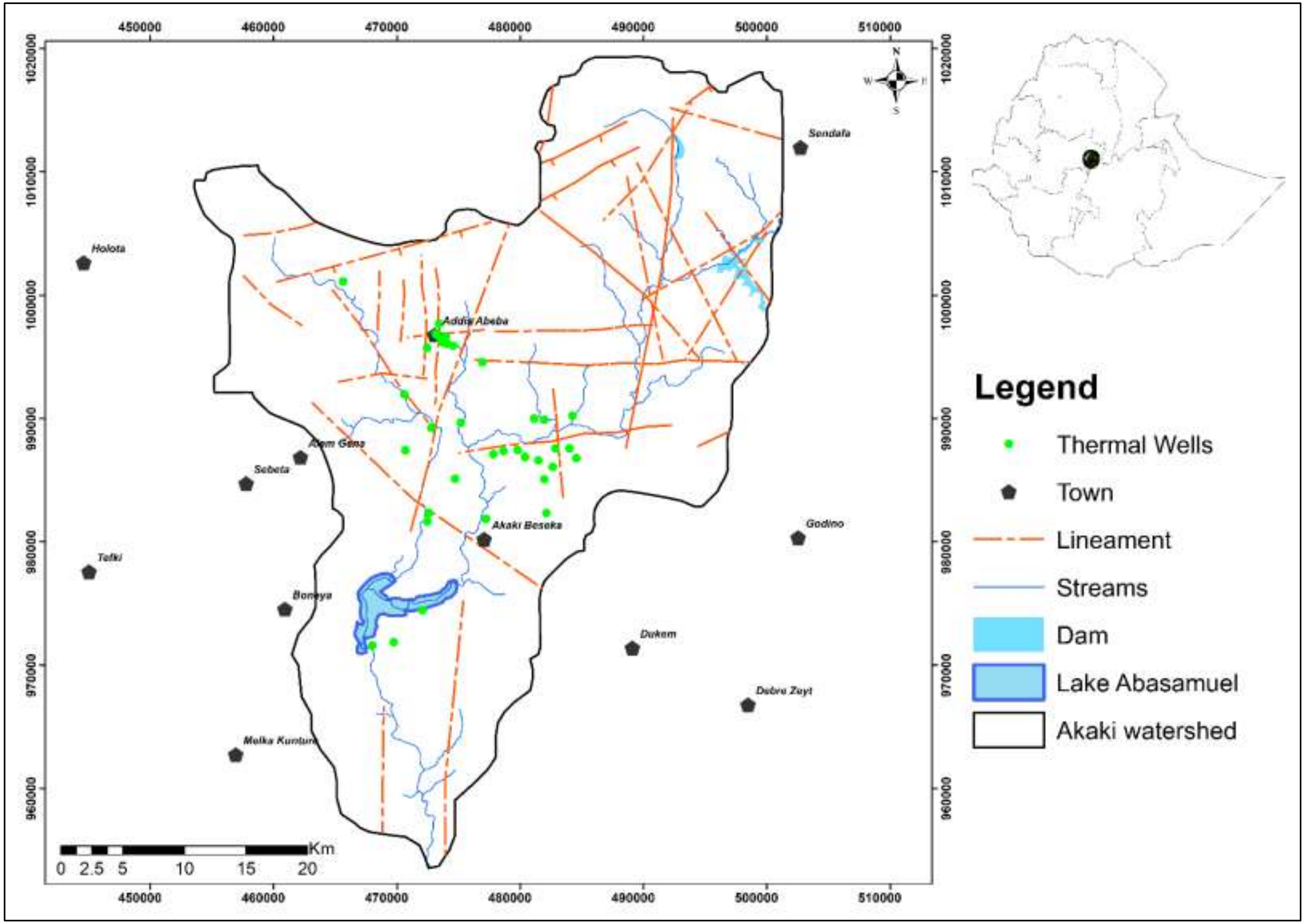

Figure 14: **Distribution of thermal water points**

5.5.2. Thermal groundwater chemical characrerstics in the Study Area

The main objectives of the hydrochemical study of the area thermal groundwater system are:

- To characterize the water quality of different thermal water sources in the system
- To establish the interrelationships between the temperature, fluoride of thermal water concerning the depth of the well.
- To estimate the reservoir of the temperature of the different thermal water sources by applying the suitable geothermometry method.
- To determine thermal groundwater sources
- To determaine filud circulation depth

The thermal groundwater in centeral part of the study area around filwoha is characterized by higher TDS, EC, Na, and F; and lower concentration of Ca. The maximum values of TDS and Ec in the central part around Filwoha are 2578 mg/l and 4600 mg/l while the minimum values are 248mg/l and 443 mg/l. Both the TDS and EC concentrations decrease in all directions away from the epicenter of the filwoha zone. The thermal groundwater in the Eastern area is relatively non-saline as compared to the Central area and its TDS concentration varies from 308 mg/l to 1026 mg/l and the EC also varies from 484mg/l to 1571 mg/l. The lowest concentration of TDS and EC in thermal water is recorded in Southern area thermal groundwater with TDS and EC values range from 280 mg/l to 378mg/l and 467 mg/l to 589 mg/l respectively.

The concentration of Na in thermal groundwater of the Central part around Filwoha area is much higher than Ca. The Na concentration varies from 1150 mg/l to 54.5mg/l while the Ca varies from 26.34 mg/l to 0.09 mg/l.Similarly, in the Eastern part of the area, Na concentration in thermal water is higher than Ca. The Na values vary from 360 mg/l to 82mg/l whereas the Ca one varies from 32 mg/l to 3.2 mg/l. the same trend with relatively lower values was also observed in Southern part of the area, thermal water where the Na varies from 138mg/l to 38mg/l while the Ca values vary from 46.4 mg/l to 5.6 mg/l.

The fluoride concentration in Central part around Filwoha is substantially high in thermal groundwater with maximum and minimum values are 41.55 mg/l and 4.84mg/l. However, its concentration is lower in both Eastern part and Southern part thermal groundwater. Its values in Eastern part and Southern part of the areas vary from 3.5 mg/l to 0.64 mg/l and 4.96 mg/l to 0.72 mg/l respectively.

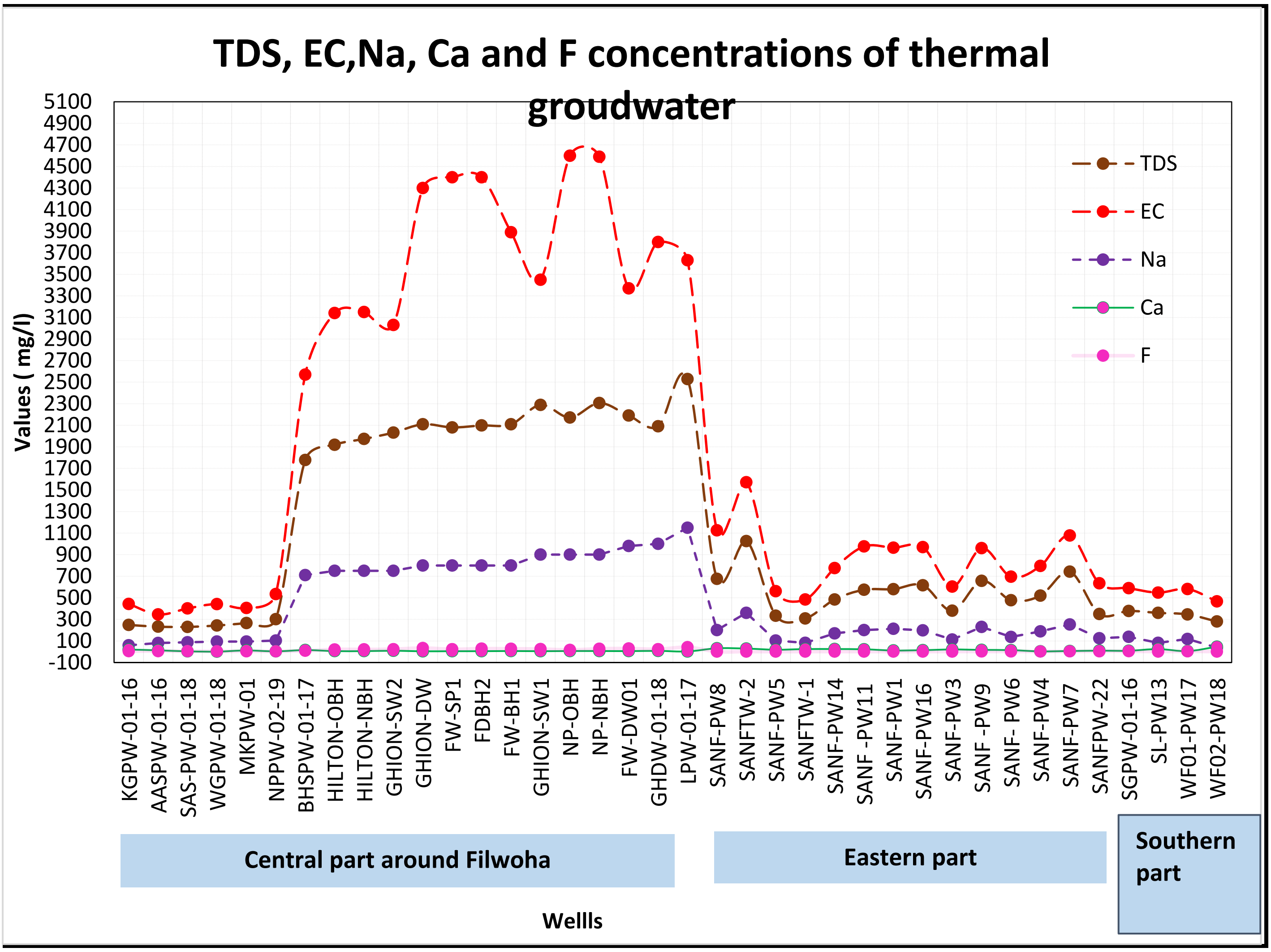

Figure 15: EC, TDS, and Na, Ca, and F concentration in thermal groundwater

The study attempted to evaluate the interrelationships between the temperature and fluoride of thermal water concerning the depth of the well. The thermal groundwater is highly distributed around the central part of filwoha area extending to the southwest direction up to Mekanisa kotari, eastern part, and to some extent in the Southern area near Salo Giorgis locality. The thermal water in Central part of the study area around Filwoha is substantially hot and it can reach up to 86 ^{O}C as it is observed at Legahare well. In the Eastern part of the study area, the thermal groundwater varies from 38 ^{O}C to 50 ^{O}C. The thermal groundwater Southern area is comparatively lower than the two areas and has a maximum value of 48 ^{O}C. To assess the linear variation of thermal groundwater with respect to depth of boreholes in both Central part around Filowha and Eastern study areas, groundwater temperature versus depth of well have been plotted. The results show that the temperature of thermal water has a positive linear correlation with the depth of the boreholes. Thus, the temperature in the thermal groundwater increases with increasing depth of penetration of the borehole throughout the Central part around Filwoha and Eastern part of the areas.

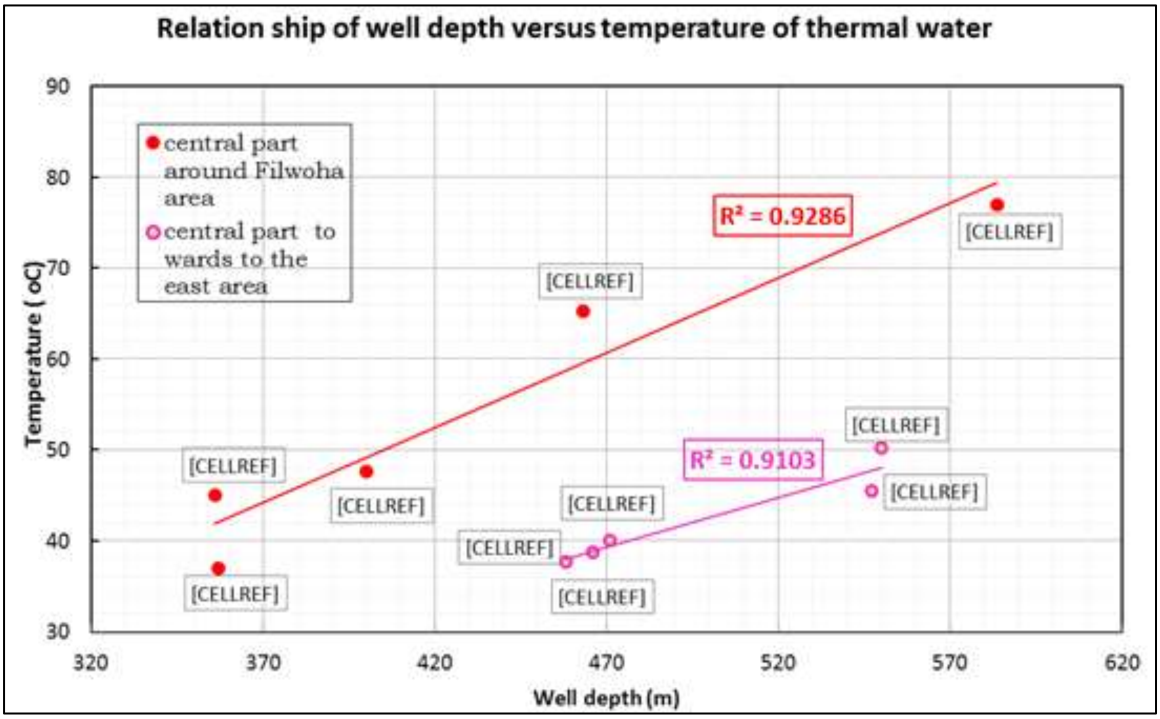

Figure 16: Relationship of well-depth versus temperature of thermal waters

The thermal groundwater in Central part around Filwoha area is characterized by higher fluoride concentrations ranging from 4.8 mg/l to 41.55 mg/l. The maximum values of fluoride in Eastern and Southern part of the areas are 3.5 mg/l and 5 mg/l respectively. However, fluoride concentrations in thermal water under the permissible limit of the WHO water quality guideline are observed in several boreholes found in both Eastern and Southern areas. To evaluate the linear variation of fluoride in thermal water with respect to the depth of boreholes in both Central parts around Filowha and Eastern part of the areas, fluoride versus depth of well has also been plotted. The results show that the flouide of thermal water has a positive linear correlation with the depth of the boreholes. Thus, the fluoride concentration in the thermal groundwater increases with increasing depth of penetration of the borehole throughout the Central part of the study area around Filwoha and Eastern part of the study areas.

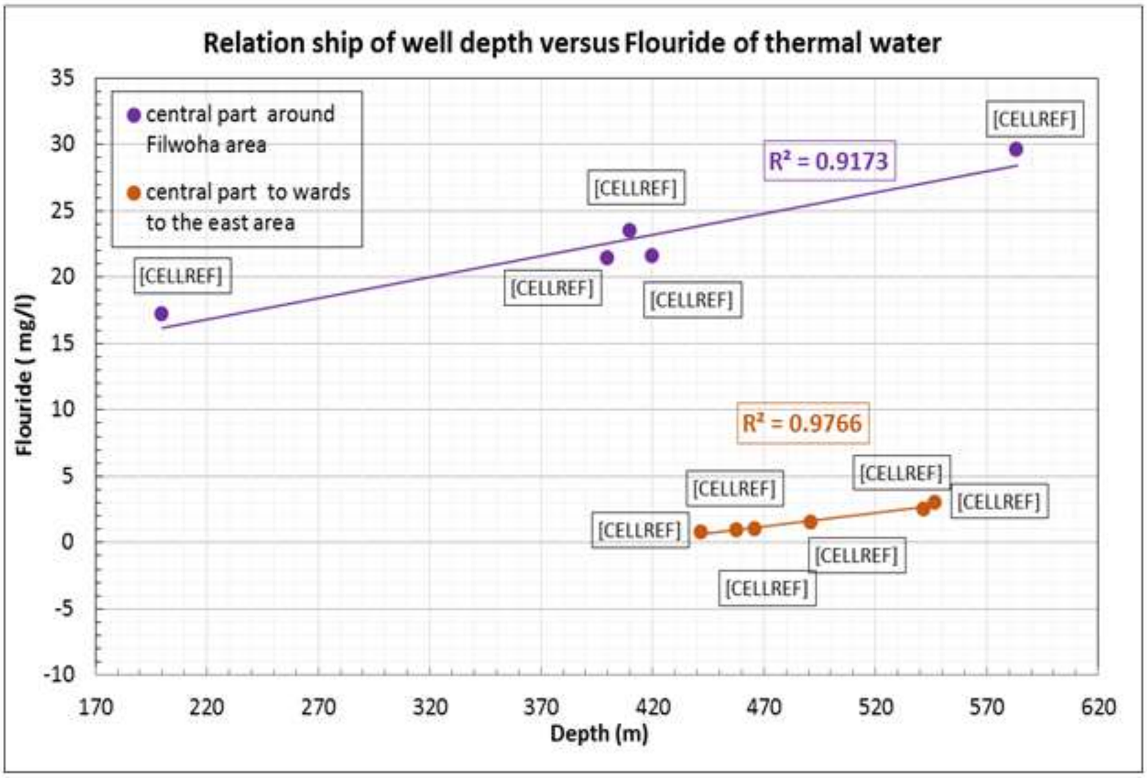

Figure 17: Relationship of well-depth versus fluoride of thermal waters

The linear correlation of temperature with respect to fluoride concentration of thermal water in both Central parts around Filowha and Eastern area is evaluated.The result shows that fluoride has a perfect positive linear correlation with the temperature of thermal waters or vice versa.The higher temperature is characterized by the higher fluoride concentration of thermal water in both Central part of the study area around Filwoha and eastern areas.

Generally, the deep boreholes located around Central part of the study area and Eastern part has relatively higher fluoride concentration and thermal water than shallow boreholes.

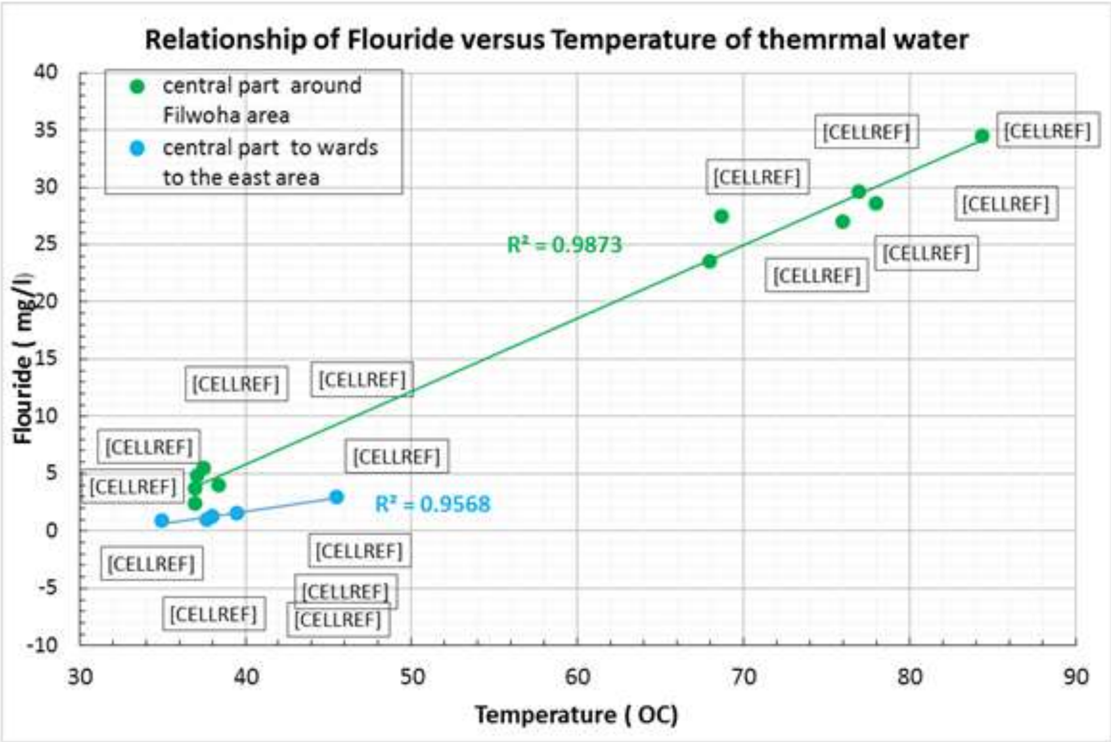

Figure 18: Relationship of fluride versus temprature of thermal waters

5.5.3. Classification of thermal groundwater in the Study Area

Classification of thermal water was carried out based on relative content of the three major anions and cations ie Cl-SO4- HCO3 and Na-Ca - Mg. Accordingly, two types of thermal waters are distinguished such as Peripheral or carbonate and Sulphate waters. Except for one well found in Southern area (WF02-PW18), all thermal waters have sodium dominant cation while Ca is dominant in the former well.

Almost all thermal water samples are located within the region of high bicarbonate concentration and they can be classified as peripheral water that may have mixed with cold groundwater. The dominant cation is Na and only one sample has Ca dominant cation. The thermal waters can be categorized as Na-HCO3 water type except the remaining sample has Ca-HCO3 water type.

One water sample is located within volcanic water where the dominant anions are both bicarbonate and sulphate. This thermal water could be originated from a volcanic high-temperature system. The water is classified as Na-HCO3-SO4 water type.

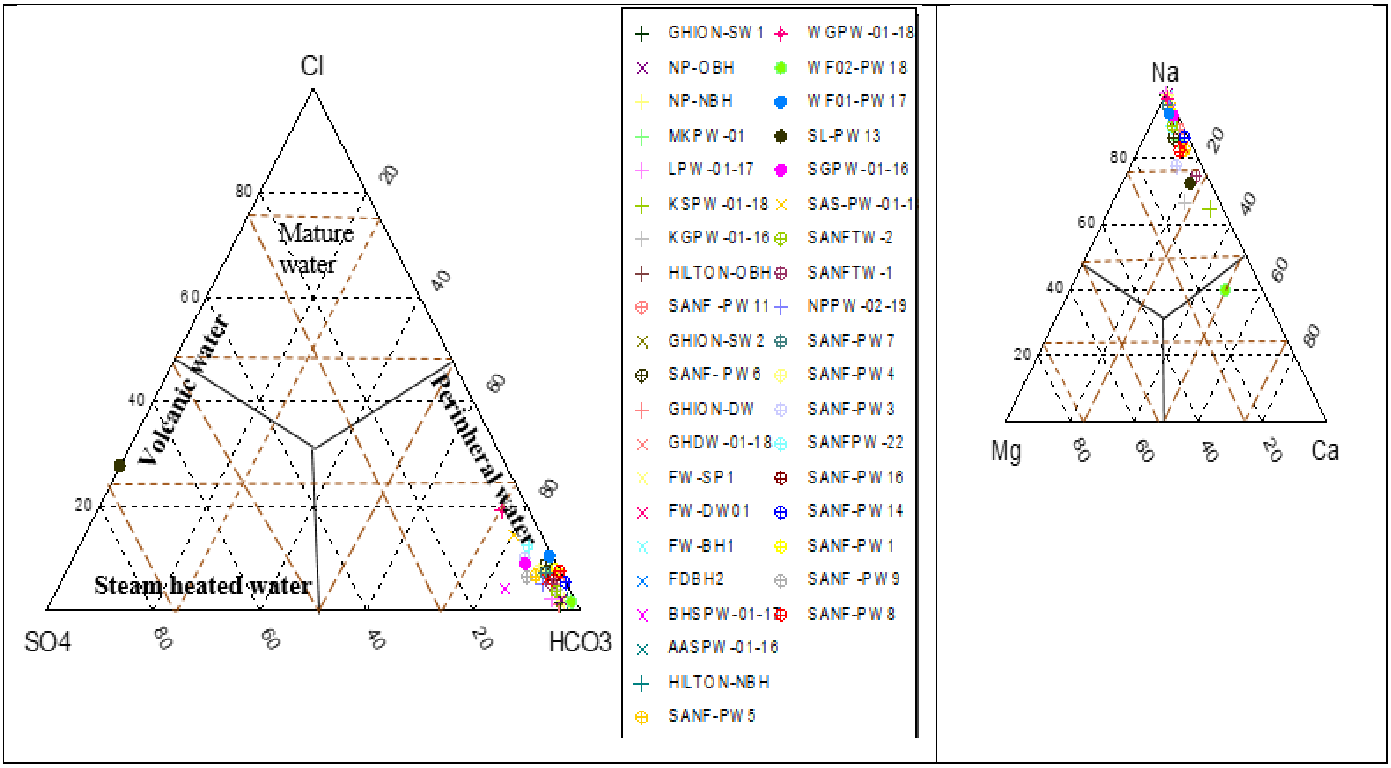

Figure 19: Thermal Water Type Classification Relative to Cl-So4-HCO3 and Na-Ca-Mg

5.6. Geothermometry

Where the effective permeability is relatively high and water residence times are long, water and rock reach chemical equilibrium quite fast, in the order of months to years, especially where temperatures exceed 200°C chemical reaction rates are generally slower at lower temperatures and the concentrations of dissolved silica, sodium, potassium and calcium and some isotopes stay relatively constant as the water cools on its way to the surface, and can be used to estimate the temperature of the system (Fournier R. O., 1973).

5.6.1. Geothermometry method

Conventional SiO_2, Na-K, Na-K-Ca, and K-Mg geoindicators (geothermometers) were utilized to estimate subsurface reservoir temperatures for each thermal system. These reservoir temperatures are empirical calculations based on the assumption of water-rock chemical equilibrium at depth, and the preservation of equilibrium during migration to the surface ((Fournier, 1977) and (Giggenbach, 1988)). Silica geothermometers are based on the solubility of silica species (i.e. quartz, chalcedony) in water, as a function of temperature and pressure (Fournier, 1977). Thus, silica precipitation along flow paths can cause problems in the confidence of this geothermometer. The quartz geothermometer is best suited for reservoir temperatures >150°C and the chalcedony geothermometer is a better approximation for temperatures <150°C. The Na-K cation geothermometer is based on the equilibrium between hydrothermal fluids and feldspars, and Na-K-Ca reflects equilibrium for feldspars and calcite (Giggenbach, 1988). The advantage to the Na-K geothermometer is that it re-equilibrates more slowly than the silica geothermometer, and can reveal temperatures from the deepest section of the reservoir (Giggenbach, 1988). The Na-K geothermometer is most applicable to waters with reservoir temperatures >100°C and minimal Ca (log [Ca^0.5/Na] + 2.06 <1) content (Fournier R. O., 1973). The Na-K-Ca geothermometer is designed for higher concentrations of Ca and assumes the total conversion of Ca-plagioclase to calcite (Fournier R. O., 1973). Unlike the Na-K and Na-K-Ca geothermometers, the K-Mg geothermometer re-equilibrates rapidly at cooler temperatures, thereby preserving a cooler and likely shallower reservoir signal (Giggenbach, 1988). The K-Mg geothermometer is also more influenced by mixing with shallow ground waters containing dissolved Mg. Differences and similarities between geothermometry temperatures can provide valuable information about the circulation depth and degree of fluid-rock interaction in thermal fluids.

The Na-K-Ca geothermometer has been used to estimate the subsurface or aquifer temperatures of the study area its main advantage over the other geothermometers is that it doesn’t give high and misleading results for cold and slightly thermal, non –equilibrated waters. It is represented by the equation:

$$\boldsymbol{T}\ (°\mathrm{C}) = \frac{\mathbf{1647}}{\log\left(\frac{\boldsymbol{Na}}{\boldsymbol{K}}\right) + \boldsymbol{\beta}\log\left(\frac{\boldsymbol{Ca}^{0.5}}{\boldsymbol{Na}}\right) + \mathbf{2.24}} - \mathbf{273.15}$$

Where: β= 4/3 for t < 100 °C and 1/3 for t > 100 °C and for log ($Ca^{0.5}$/Na) <0

The subsurface or aquifer temperatures of Central study area around Filwoha, Eastern, and Southern study areas are estimated using the above geothermometer. Accordingly, the observed and the estimated temperature distributions of the Central part around Filwoha, Eastern and Southern areas were presented in table 1. The maximum estimated subsurface reservoir temperature of Central around Filwoha, Eastern, and Southern are 294.5^{O}C, 168.8 ^{O}C, and 152.8 ^{O}C respectively. Both the maximum observed temperature and estimated subsurface temperature correspond at Central around Filwoha, Eastern, and Southern areas, the observed and estimated sub-surface temperatures do not coincide with each other which showed slight variations.

Table 2: Observed and Estimated Temperatures of Thermal waters

	Central part around Filwoha			**Eastern Area**		
No	**Well_Index**	**ToC (Observed)**	**ToC (Na-K-Ca)**	**Well_Index**	**ToC (Observed)**	**ToC (Na-K-Ca)**
1	AASPW-01-16	37.5	44.9	SANF -PW11	38.8	110.8
2	BHSPW-01-17	37.1	241.9	SANF- PW6	42.5	91.8
3	FDBH2	78.0	209.3	SANF -PW9	39.5	113.9
4	FW-BH1	76.0	193.2	SANF-PW1	41.0	168.8
5	FW-DW01	77.0	208.5	SANF-PW14	37.7	103.4
6	FW-SP1	79.6	206.1	SANF-PW16	50.2	143.1
7	GHDW-01-18	68.0	217.7	SANFPW-22	40.0	99.3
8	GHION-DW	84.4	220.1	SANF-PW3	38.0	92.9
9	GHION-SW1	42.2	236.5	SANF-PW4	41.0	143.1
10	GHION-SW2	39.7	187.3	SANF-PW7	45.5	124.1
11	HILTON-NBH	43.3	186.7	SANF-PW8	42.6	91.7
12	HILTON-OBH	47.6	190.3	SANFTW-1	38.9	89.3
13	LPW-01-17	86.0	294.5	SANFTW-2	43.0	105.6
14	MKPW-01	37.0	77.3	**Southern part around Akaki**		
15	NP-NBH	68.7	201.6	**Well_Index**	**ToC (Observed)**	**ToC (Na-K-Ca)**
16	NP-OBH	74.7	207.4	SGPW-01-16	44.0	152.8
17	NPPW-02-19	38.4	125.2	SL-PW13	37.0	107.5
18	WGPW-01-18	65.3	118.5	WF01-PW17	48.1	130.4
19	KSPW-01-18	37.0	70.0	WF02-PW18	37.5	69.2
20	KGPW-01-16	37.1	77.8			
21	SAS-PW-01-18	45.0	87.2			

Based on the geothermometer result, the subsurface reservoir temperature curve to gether with the observed temperature for each thermal water well is constructed, the boreholes where the maximum estimated sub-surface temperature LPW-01-17 near Legahare central part is 294.5 ^{O}C, SANF-PW1 in eastern part is 168.8 ^{O}C and SGPW-01-16 near Salo Giorgis locality southernpart is 152.8^{O}C.

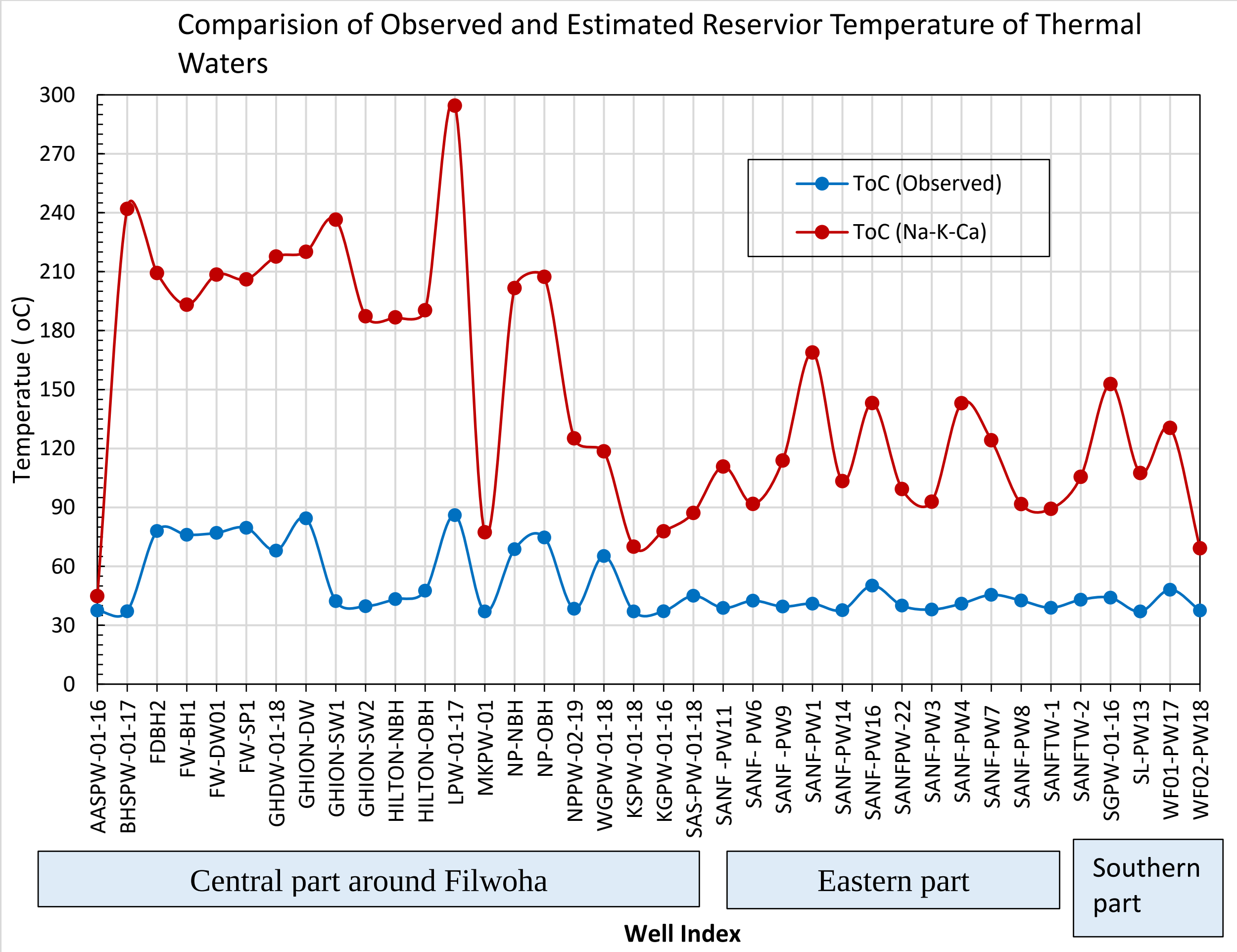

Figure 20: Observed temperatures and estimated subsurface temperature curves of thermal wells

5.6.2. Geothermometry and fluid depths

Reservoir temperature estimates (RTE) provided by geothermometry are useful for evaluating temperatures at depth, fluid-rock interaction along flow-paths, and estimates of fluid circulation depth. Processes such as boiling, mineral precipitation during ascent, re-equilibration with rocks along flow-paths, and mixing with shallowly circulated meteoric waters can promote disequilibrium and alter/overprint RTE ((Fournier R. O., 1973); (Fournier R. O., 1977); (Giggenbach, 1988);). We suggest the Na-K-Ca geothermometry data are most reliable for detecting the deepest fluid circulation depths. The chalcedony geothermometer is susceptible to disequilibrium by silica precipitation during fluid ascent. The loss of dissolved silica to precipitation results in anomalously low RTE (Fournier R. O., 1977).RTE from the Na-K geothermometer are commonly influenced by dissolved Ca, and are applicable when "log [Ca^0.5/Na] + 2.06 <1 (Fournier R. O., 1973). Baños (Olleros, Monterrey, Huanacarhuaz, and Recuay) all thermal wells that meet the criteria for high Ca (log [Ca^0.5/Na] + 2.06 >1), making the Na-K-Ca geothermometer ideal for this study. According to (Bekele, 2012) ssuming the average geothermal gradient based on the present estimation is 108°C/km and an average surface temperature of 0°C, RTE (Na-K-Ca) central part around Filwoha study area (125.2–294.5°C) correspond to circulation depths that range from 1.21km to 2.72km, Eastern part of the study area(110.8 – 168.8 °C) correspond to circulation depths that range from 1.01km to 1.56km and Southern part of the study area (107.5 – 152.8 °C) correspond to circulation depths that range from 1km to 1.41km.

(Fournier R. , 1979) If the calculated temperature is significantly higher than the measured temperature for these unmixed or re-equilibrated waters, some heat has probably been lost conductively as the water moves through the aquifer.

In contrast, RTE central part (44.9 – 118.5°C), Eastern part (89.3-105.6°C) and Southern part (69.2°C) correspond to circulation depths that ranges from 0.41km-1.0km, 0.82km-0.97km and 0.64km respectively, correspond to substantially lower circulation depths (< 1.0km km).

If the calculated temperature is not significantly higher than the measured temperature for these mixing with type water without sufficient time to equilibrate with the surrounding rock. Waters emanating from lower depth are shallowly circulating, compared to the deeper flow-paths interpreted for the deep depth. Additionally, if fluids from lower circulation depth have a prolonged residence time in the shallow crust, then they are also likely subjected to mixing with near-surface waters. For the distribution of these wells (lower circulation depth) far from the fault zone (around Filwoha) and reservoir temperature sufficiently low so that water- rock reaction occurs very slowly.

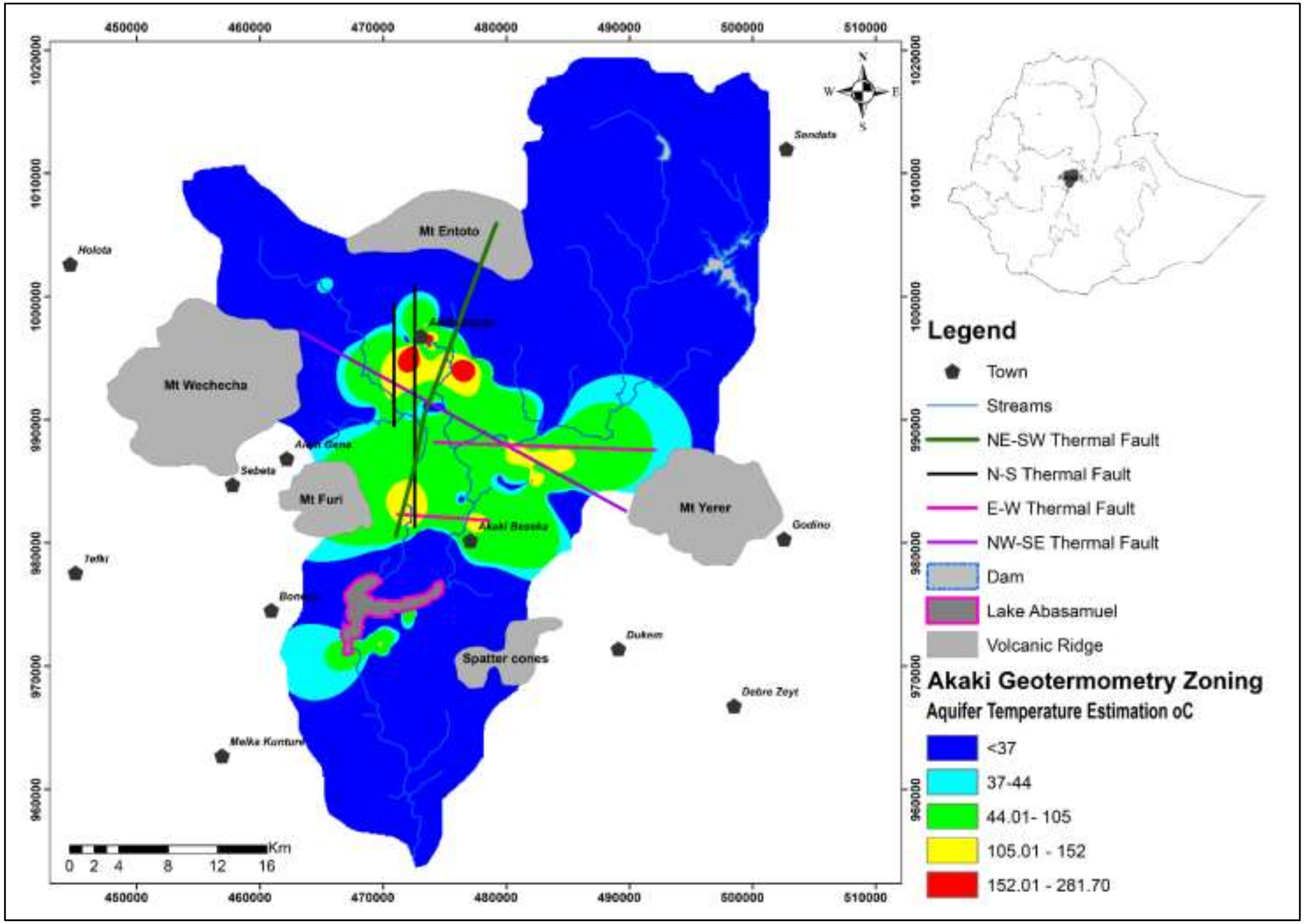

Figure 21 Thermal Groundwater Zoning of Akaki Watershed Using Geotermometry method (Na-K-Ca)

5.7. Thermal Groundwater Zoning in the Akaki Watershed

A detailed inventory survey of the thermal groundwater manifestations has been carried out and used as a basis for producing an isothermal map for future thermal water development and utilization within the study area. Accordingly, three thermal groups of waters have been identified and categorized as:

a) Hot groundwater zone (> 60 ^{O}C)

This zone is completely localized in the central part of the study area around Filwoha and that extends from legahare to the southwest direction up to Lideta and Africa union areas. Both the conductive nature of the sub-surface acidic rocks and the exiting major faults trending NW-SE and N-S directions are believed to be the main controlling factor for the manifestation of this local thermal anomaly in the area. The temperature of the groundwater decreases in all directions from the epicenter of the Filwoha zone. Moreover, the general heat flow from the Filwoha zone is along with the NW-SE and N-S directions.

b) Moderate Hot groundwater zone (42 ^{O}C - 60 ^{O}C)

It comprises areas SW part of the central study area, some parts of the eastern area, and some small patches of southern near Salo Giorgis locality. It is highly confined in the NW-SE part of Addis Ababa running from Kolfe - Keraniyo to the eastern margins of the study area. Both the NW-SE and W-E trending faults could be played a significant role in the encountering of such zone.

c) Thermal groundwater zone (37 ^{O}C - 40 ^{O}C)

It covers most central part to wards south around Mekanisa Kotari and Eastern part of the study area. The NW-SE and W-E trending faults can be considered as the major structured responsible for the occurrence of the thermal zone.

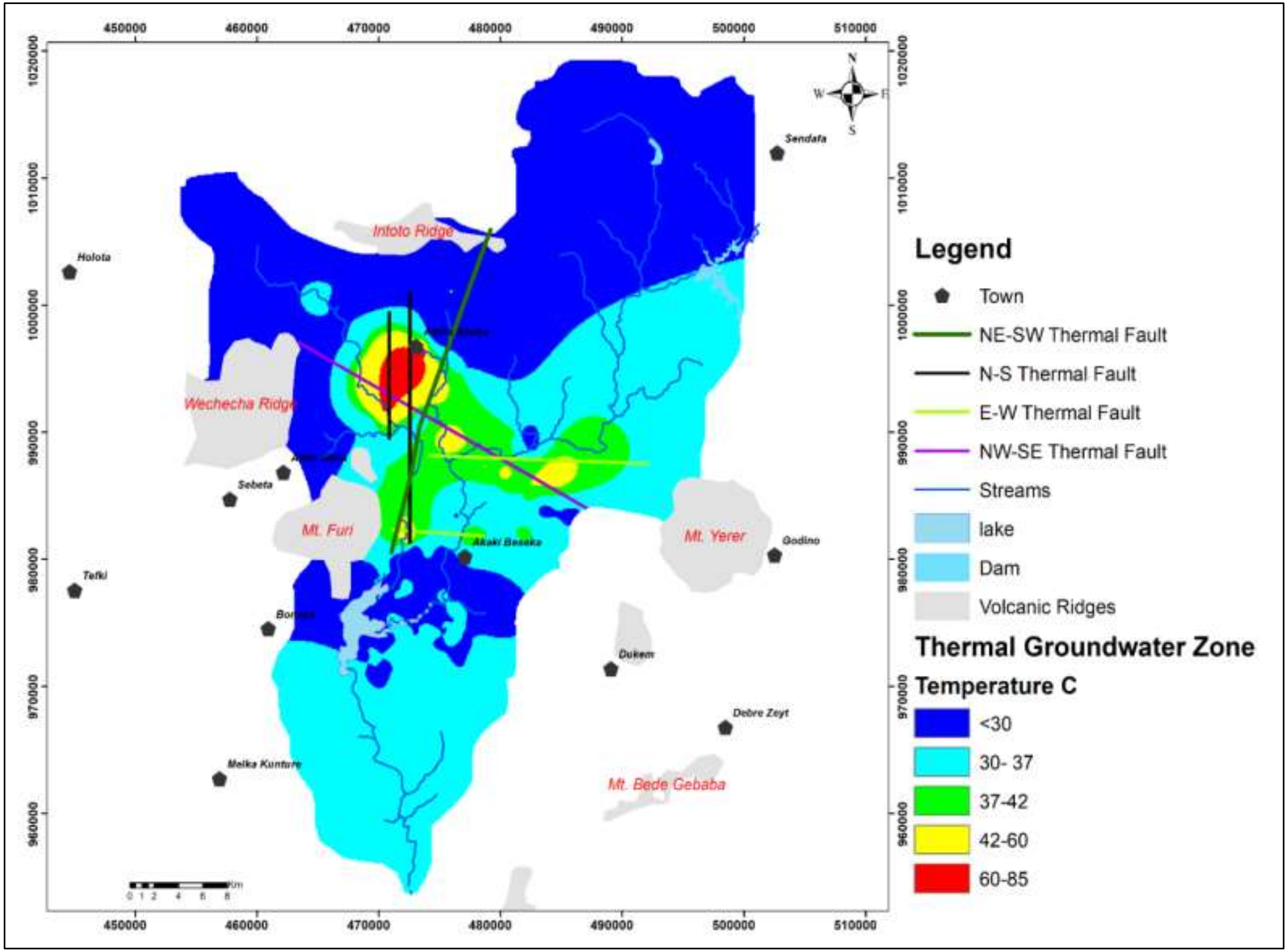

Figure 22: Thermal Growndwater Zone of Akaki River Catchement

CHAPTER-6 CONCLUSION AND RECOMMEDATION

6.1. Conclusion

Systematic and well-Integrated hydrogeological investigations and hydrochemical characterstics have been carried out around the study area all the existing pertinent data and data generated from the field survey are profoundly used for the development of the following conclusions:

- High TDS, Flouride and Temprature associated with regional structure in this case associated with NW-SE foults.
- The NW-SE and E-W trending major faults are the main controlling structures for the occurrence of thermal groundwater potential in the Akaki river cachement. These structures are responsible for heat flux transport and heating groundwater of the area.
- The thermal groundwater throughout the study area is highly rich in fluoride concentration above the permissible limit of the WHO water quality guideline and its concentration increases with increasing temperature of groundwater and depth.
- The water type in the study area is predominantly bicarbonate type (Na-Ca-HCO3, Ca-Na-HCO3, and Na-HCO3).
- The thermal groundwater in central part of the study area around Filwoha is characterized by higher TDS, EC, Na, and F; and lower concentration of Ca. Both the TDS and EC concentrations decrease in all directions away from the epicenter of the Filwoha zone. In the Eastern area is relatively non-saline as compared to the Central area. The lowest concentration of TDS and EC in thermal water is recorded in Southern area.
- The temperature in the thermal groundwater increases with increasing depth of penetration of the borehole throughout the Central part around Filwoha and Eastern part of the areas.

- The fluoride concentration in the thermal groundwater increases with increasing depth of penetration of the borehole throughout the Central part of the study area around Filwoha and Eastern part of the study areas.

- The higher temperature is characterized by the higher fluoride concentration of thermal water in both Central part of the study area around Filwoha and eastern areas. Generally, the deep boreholes located around Central part of the study area and Eastern part has relatively higher fluoride concentration and thermal water than shallow boreholes.

- Two types of thermal waters are distinguished such as Peripheral or carbonate and Sulphate waters. Except for one well found in Southern area (WF02-PW18), all thermal waters have sodium dominant cation while Ca is dominant in the former well.

- Used to Na-K-Ca Geothermometry method to estimate subsurface reservoir temperature of the study area; central part around Filwoha study area (152.2–281.7°C) correspond to circulation depths that range from 1.21km to 2.72km, Eastern part of the study area (105.01 – 152.2°C) correspond to circulation depths that range from 1.01km to 1.56km.

- In contrast, RTE central part, Eastern part and Southern part of the study area is (44.9 – 105°C) correspond to circulation depths that range from 0.41km-0.97km.

- Three thermal groups of waters have been identified and categorized as:

    1. Hot Groundwater zone (>60^0C)
    2. Moderate hot Groundwater zone (42^0C-60^0C)
    3. Thermal Groundwater zone (37^0C)

6.2. Recommendations

Based on the findings of the study the following recommendations are made:

- Thermal groundwater potential is available within the Akaki river cachement for future utilization and development. Three areas named central part around Filwuha, eastern part and southern part of the study area are delinated as thermal groundwater zones.

- Thermal groundwater can be used both for recreational and related purpose. For these reasons, developing and using thermal groundwater is important.
- Chemistry of boreholes drilled within delienated zones of thermal groundwaters are poor and beyond the limit seted by WHO for domestic uses. Due to this fact, future groundwater development for water supply purpose shall overlook areas of thermal groundwater.

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Annex-I: Inventoried Water Points

No	Locality	Well_Index	Easting	Northing	Well_ Depth (m)	SWL (m)	DWL (m)	DD (m)	Q(l/s)	T(O c)	TDS	Cond	PH	Na	K	Ca	Mg	F	Cl	HCO 3	SO4
1	Lafto-Kosta sefer area	KSPW-01-18	472792	989152	500	11.2	119.94	108.74	50	37	240	436	7.1	54.5	6.1	26.3	3.4	2.4	17.1	225.1	8.8
2	AA	SL-PW13	472078	974359	319.2	51.65	57.57	5.92	105.12	37	360	548	7.4	82	15	24.3	7.3	0.8	33.1	Nil	86.8
3	Mekanisa kotari*	MKPW-01	470682	987316	357	Artesian	141.22	141.22	50	37	266	405	8	94	3.8	12	3.7	3.7	18.2	219.6	4.9
4	Bole High School	BHSPW-01-17	476933	994457	500	62.8	145.2	82.4	37.5	37.1	1778	2570	7.1	710	72	15.2	2.9	8.6	69.3	1419	203
5	Kality Gebriel	KGPW-01-16	474716	985017	394	Artesian	15.85	15.85	69	37.1	248	443	7.4	60	6.3	20	10.1	4.8	11.3	253.6	6.8
6	Asko Addis Sefer	AASPW-01-16	465635	1001021	473.5	35.42	72.9	37.48	60	37.5	232	345	7.5	81	1.4	13.1	2.9	5.4	13.6	212.3	7.8
7	Akaki	WF02-PW18	468006	971498	496	57.8	102.05	44.25	77	37.5	280	467	7.1	38	9.8	46.4	11	0.7	4.6	292.8	2.4
8	SouthAyat Fanta	SANF-PW3	482119	982234	523	32.2	136.15	103.95	40	38	380	604	8	112	8.2	20.8	11.5	1.3	35.5	300.1	19
9	Near Sheraton Addis Hotel	NPPW-02-19	473413	997587	517.76	49.31	143.72	94.41	50	38.4	302	535	7.9	103	5.6	3.2	1	4	15.3	268.8	13
10	SouthAyat Fanta	SANF -PW11	482852	987470	466	20.6	146.34	125.74	52	38.8	574	976	7.6	200	11.5	22.4	3.4	1.1	38.6	585.6	4.3
11	SouthAyat Fanta	SANFTW-1	477819	987018	411	8.2	80.5	72.31	35	38.9	308	484	7.4	82	9.1	24.3	3.7	1	15.5	281.8	8.6
12	Akaki	WF02-PW11	469737	971752	337	109.88	146.23	36.5	60	39.1	425	654	7.2	72	25.5	28.9	9.2	1	22.2	306.1	31
13	SouthAyat Fanta	SANF -PW9	481467	986506	491	35.36	115.72	80.36	78.58	39.5	656.6	960	7.8	230	9.8	16.8	3.4	1.6	44.6	614.9	47.8
14	Ghion Hotel	GHION-SW2	473847	996100	60	59			0.83	39.7	2032	3030	7	750	20.5	8.8	2	23.6	29.8	1903. 2	60.2
15	SANF	SANFPW-22	479787	987337	471.05	42.14	108.44	66.3	40.8	40	349	634	8.5	124	5.7	9.7	4.9	3.5	39.3	266.3	11.3
16	Bole Lemi-6	BLBH-6	484233	990120	-	Artesian	-	-	--	40	-	-	-	-	-	-	-	-	-	-	-
17	SouthAyat Fanta	SANF-PW4	477224	981760	542	5.95	132.17	126	30	41	520	795	8	188	6.9	3.2	1	2.5	35.5	417.2	17.8
18	SouthAyat Fanta	SANF-PW1	481952	984973	528	16.54	137.84	113	35	41	580	965	8	212	26	11.2	3.4	1.1	45.5	539.2	3.6
19	Greek Club	Greek Club	474568	995813	250	47.68	-	-	5.8	42	-	-	-	-	-	-	-	-	-	-	-

No	Locality	Well_Index	Easting	Northing	Well_ Depth (m)	SWL (m)	DWL (m)	DD (m)	Q(l/s)	T(O c)	TDS	Cond	PH	Na	K	Ca	Mg	F	Cl	HCO 3	SO4
20	Ghion Hotel	GHION-SW1	473846	996042	56.4	7.6	-	-	4.15	42.2	2289	3450	7.1	900	28.5	4.8	1.5	25.4	29.8	2110.6	65.2
21	SouthAyat Fanta	SANF- PW6	478634	987263	530	4.85	90.65	85.8	86	42.5	478	695	8	136	5.9	14.7	7.3	1.6	38.3	392.8	8.8
22	SouthAyat Fanta	SANF-PW8	482636	985971	542	30.48	172.43	141.95	34.93	42.6	676	1125	7.5	200	8.7	32	11.5	0.6	50.7	634.4	0.2
23	SouthAyat Fanta	SANFTW-2	484001	987465	442	0.35	41.52	41.7	52	43	1026	1571	7.5	360	9.8	29	12.5	0.8	40.7	1049.2	29.6
24	Bole Lemi-3	BLBH-3	481934	989797	328	Artesian	95.76	95.76	37.5	43	466	740	6.8	105	4.4	41.2	17.3	0.6	19.2	456.3	
25	Hilton Hotel	HILTON-NBH	473955	996585	420	35.25	-	-	4.24	43.3	1973	3150	7.1	750	15	5.6	1.5	21.6	37.4	1903.2	27
26	Salo Giorgis	SGPW-01-16	472585	982237	537.37	41.4	188.4	147	15.5	44	378	589	7.9	138	18.5	8.8	1.9	5	31.2	301	20.5
27	Sheraton Hotel	Sheraton Hotel	473147	996795	356	4.19	-	-	2.56	45	-	-	-	-	-	-	-	-	-	-	-
28	Saris Addis Sefer compound	SAS-PW-01-18	475182	989553	475	7.9	69.32	61.42	75	45	230	401	8.7	87	2.2	3.3	1	4.5	22.1	122.6	8.1
29	SouthAyat Fanta	SANF-PW7	480385	986784	547	14.2	115.22	101.02	100	45.5	742	1077	8	252.5	6.5	6.5	3.8	3	49.1	626.4	20.2
30	Hilton Hotel	HILTON-OBH	473950	996583	400	9.8	-	-	3.15	47.6	1919	3140	7.1	750	16	5.6	1.5	21.4	39.4	1939.8	39
31	Sologora	WF01-PW17	472460	981553	500	Artesian	85.7	85.7	48.75	48.1	346	581	8.3	118	8.8	5.6	2.9	3	29.9	258.6	1.6
32	Hyatt Hotel	Hyatt Hotel	474089	995970	300	13.13	-	-	10.5	50	-	-	-	-	-	-	-	-	-	-	-
33	SouthAyat Fanta	SANF-PW16	484553	986685	550	7.1	130.7	123.6	80	50.2	616	970	7.4	198	18.5	14.4	3.8	1.3	34.2	531.9	12.3
34	Mekanisa-Wolde Glocery area	WGPW-01-18	470610	991840	463	8.06	54.3	46.24	40	65.3	243	442	9.4	94	2.2	1	0.6	3.5	24.1	95.2	6.2

No	Locality	Well_Index	Easting	Northing	Well_ Depth (m)	SWL (m)	DWL (m)	DD (m)	Q(l/s)	T(O c)	TDS	Cond	PH	Na	K	Ca	Mg	F	Cl	HCO3	SO4
35	Ghion Hotel	GHDW-01-18	473543	996296	410	6.3	182	183.3	5	68	2090	3800	7.2	1000	28.5	7.8	0.9	23.5	50.6	-	73.8
36	National Palace	NP-NBH	473822	996091	109	Flowing	-	-	5	68.7	2306	4590	7.2	900	20	6.4	1	27.4	46.2	2269.2	51
37	National Palace	NP-OBH	473818	996216	200	Flowing	-	-	5	74.7	2172	4600	7.2	900	22	6.4	1	17.2	48.4	2257	61
38	Filwoha compound	FW-BH1	473633	996163	249	Flowing	-	-	7.3	76	2109	3890	7.1	800	18	6.4	1	27	43.7	2208.2	53.5
39	Filwoha compound	FW-DW01	473238	996706	583.5	8.3	127.26	118.96	18.6	77	2190	3370	7.5	980	20	5.6	4.3	29.6	41	2334.5	21.1
49	Filwoha compound	FDBH2	473713	961310	300	Flowing	-	-	-	78	2098	4400	7.1	800	19.5	4.8	1	28.6	34.7	2171.6	39
41	Filwoha compound	FW-SP1	473710	996129	100	Flowing	-	-	-	79.6	2080	4400	7.3	800	18.5	4.8	1	23	34.7	2196	47
41	Ghion Hotel	GHION-DW	473799	996041	77.7	Flowing	-	-	4.15	84.4	2109	4300	7.2	800	20.5	4	1	34.4	29.8	2220	80.9
43	Leghare	LPW-01-17	472456	995639	500	Artesian	-	-	-	-	2528	3630	8.7	1150	36	2.5	1	41.6	47.9	1941.3	85.8
44	SouthAyat Fanta	SANF-PW14	481129	989896	458	1	123.32	122.32	72.4	37.7	484	775	7.3	170	10.7	24.8	1.9	1	28	495.3	0.3