The Role of Structures and Geomorphology On The Occurrence of Groundwater In The Northern Main Ethiopian Rift System

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Abstract

The Northern Main Ethiopian Rift system is known by its active geological and tectonic processes. This study used integrated field survey, RS and GIS, geological, structural, geomorphological, hydrogeological and hydrogeochemical methods to analyze the role of geological structures and geomorphology for the occurrence of groundwater in Northern Main Ethiopian Rift system. The Hydrogeology of the area is characterized by complex bimodal composition of geology and geological structures of NE-SW border faults and NNE-SSEW WFB, E-W trending transverse fault system, calderas, silicic centers and spatter cones along the Rift floor.

The highly productive aquifer is observed in the Akaki and Adaa plain with the yield (50-60L/S) and Mojo well field (15-30L/S). This is influenced by YTVL that cross-cut the NMER structure formed both shallow and deep aquifer system and due to local and regional recharge and high rainfall from the plateau sector. The Wonji basin is yielding up to 10L/S from shallow aquifer system of alluvial deposits recharged from Koka reservoir and Awash River flow. Whereas, in Kereyu, and Wolenchiti basin, the yield is very low to be 1.5L/S and in Lake Beseka region from 3 to 12L/S due to deep circulated regional aquifer system from Plateau and adjacent escarpment and low local recharge and recharge from Fantale and Abadir farm to Beseka lake. In the rift axis, due to the intense structures and deep sub surface circulation thermal springs and steams are emerged in Sodere, Geregedi and Boku thermal spring.

The Eastern Plain of Dera and Iteya have a yield between 3 to 5 L/S associated to deep seated fault system that makes groundwater flow along the rift sector to undergo a deep circulation except in Gonde and Huruta high discharge springs that are associated with local aquifer. The hydrogeochemical data shows that Ca-Mg-HCO3 of shallow fresh groundwater to NaHCO3 and high TDS (>2,000 mg/l) and EC (>3,000ms/m) highly deeply evolved and undergone strong water-rock interaction in the subsurface and intermixing of waters in the Beseka lake region.

Key Words: Northern Main Ethiopian Rift, Geological structures, Geomorphology, Aquifers, Yield, Groundwater flow.

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Table of Contents

List of Figures

Acronyms

ERS= East African Rift System

HCA= Heirarchical Cluster Analysis

MER = Main Ethiopian Rift

NMER= Northern Main Ethiopian Rift

WFB= Wonji Fault Belt

YTVL= Yerer Tullu Welel Volcano tectonic lineament

1. Introduction

1.1. Background

The Main Ethiopian Rift (MER) is the northern segment of the East African Rift System (EARS) with a symmetrical graben with steep border faults dividing the thousands of kilometers wide uplifted Ethiopian volcanic province asymmetrically into the northwest and southeast plateaus (Woldegabriel et al., 1990). The Northern MER (Fig.1), the current study area, is characterized by recent intensive volcanic activities, geologic structures and geomorphological features. The MER boundary faults are active from late Miocene (Wolde Gebriel et al., 1990), Striking between NNE-SSW in the south and NE-SW in the north (Korme et al., 2004) and the youngest part of the MER is the axial zone (Wonji Fault Belt, WFB), mainly formed during the quaternary (Mohr et al., 1962, 1967) is characterized by active NNE-SSW trending extension fractures and normal faults with en-echelon arrangement that are associated with volcanic activity. The geomorphological and geological studies, Abbate et al., 2015, the northern MER funnels from the Afar depression, where it is about 100 km wide, to the 80-km long to the north of Ziway lake. The rift floor is occupied by recent volcanic edifices rising some hundreds of meters above the plain (e.g., Fantale, Boset Gudda and Aluto) and calderas (e.g., Gademsa, Lake Shala O’a caldera) and irregular morphology with narrow uplifted blocks, valleys, lava fields, spatter cones, and swampy depressions.

The MER is associated with bimodal two quaternary magmatic episodes of basaltic flows followed by ignimbrites and silicic centers in the rift floor and axial silicic volcanoes and basalts (Abebe et al., 2007). Wonji magmatic segments in the Northern MER represent well-developed magmatic system that allow magmas to rise quickly through existing conduits from melt generation zones to shallow levels (Rooney et al., 2007); geochemical analysis indicate that Quaternary magmas are generated at ~15–25 kbar (~50–90 km; Rooney et al., 2005; Furman et al., 2006) reference there in. A temporal evolution from silicic volcanism from the shallow magma chambers to basaltic activity within the Wonji segments has also been suggested (Abebe et al., 2007).

In the Northern Main Ethiopian Rift (NMER) system, groundwater resource is one of the important supplies of drinking water for millions of people living in the area. The NMER is characterized by semi-arid to arid climate conditions where water scarcity is often associated with quality problems. In this tectonically active areas of the NMER, active deep faults tap steam from high thermal anomaly, hot springs are generally non-gravity type and fractures of various extents play a very important role in groundwater circulation and storage, increasing also the permeability of rocks (Tamiru et al., 1997).The hydrogeology of the rifted volcanic terrain is controlled by complex cross-cutting faults that disrupted the lithologies of the area and the rift valley aquifers depends on the nature of the bounding faults by marginal grabens, local precipitation as well as up to 50% of recharge to the rift aquifer comes from the groundwater inflow continuity between the high rainfall plateau bounding the rift where the rift is cross cut by transverse fault zones (Kebede et. al., 2007).

In mountain-bounded lowland aquifers in arid regions, the relative importance of the recharge component coming from the mountains as groundwater inflow, compared to recharge from precipitation in the valley or from stream loss, must depend on the hydrogeology (nature and depth of bounding faults, the presence of transverse faults connecting the mountains with the valleys, the permeability of the mountain mass, etc.) of the interface between the mountains and the valleys. To understand the potential, occurrence, flow and distribution of ground waters in the Northern Main Ethiopian Rift, the detail study of geological structures from the plateau margins and rift floor and geomorphology that play a major role as a conduit to the recharge of groundwater for both vertical and horizontal sub-surface flow are crucial works to be done in the present study.

1.2. Statement of the Problem

Globally, it is recognized that groundwater plays a vital role in day to day activities of the human being to be used for domestic, industrial and agricultural purposes. The Northern Main Ethiopian rift is one of the areas that use ground water for a vital purpose in many localities for different activities. In the study area, there are many large cities, towns, Villages and pastoral residences, Large scale Agricultures and industries. Since the area comprises many towns (Mojo, Olen-Chiti, Metahara, Iteya and Others) and Adama City with water scarcity and many activities and large scale agricultural activities such as Wonji Suger Plantation, Metahara(Abadir Farm) and Nura-Hera; the demand for groundwater use for all activities is clearly understandable. Hence, the current study focuses on the assessment of groundwater potential, flow, recharge and discharge zone, hydrostratgraphic occurrence based on the special emphasis of the geomorphological and geological structures that are used as a conduit for the recharge, circulation and distribution of ground water through the sub-surface.

1.3. Objectives

1.3.1. General Objective

The general objective of this study is to assess the role of structures and geomorphology on the occurrence and groundwater flow in the Northern Main Ethiopian Rift.

1.3.1. Specific Object

- To study the occurrence and distribution of groundwater
- To assess the role of structures and geomorphology for the occurrence of ground water
- To identify the orientation of geological structures that can be the conduits for the aquifer
- To determine the recharge and discharge zone of groundwater
- To identify hydrostratigraphy and geologic formations of the study area
- To analyze the pump tests of different groundwater wells
- To determine the groundwater potential zone from the study area

1.4. Significance of the Study

Now a days, groundwater resource is one of the major supply source for the domestic, industrial and agricultural purpose in many countries of the world as well as in Ethiopia. In the NMER, there is a significant scarcity of water resources due to the complex tectonic effects, lithostratigraphic formation, limited annual precipitation and climatic conditions. Due to this reasons, there are few groundwater boreholes that are effectively supplying water for this demanding areas with a huge industrial, agricultural, pastoralist communities and population growth. Thus, this study plays a vital role to contribute to the developmental activities of the region in the agricultural and Industrial activities, Cities, towns, pastoralists' water supply and the scientific communities.

2. Literature review

2.1. Location and Physiography of the Study Area

The study are, the NMER is situated in the Northern sector of the Main Ethiopian Rift in the East African Rift System. The NMER contains different physiographic land forms like drainage systems of the Awash basin (Middle Awash), volcano-tectonic Lakes, calderas, horst and graben, volcanic shields and plateau margins. The physiography of the study area (Fig: 2.1) is characterized by high plateau margins in the Eastern and Western escarpments that rise high up to 4,000m to the low the low lying areas 780m. The drainage system is characterized by topographic features from the two sides of the plateau sectors to the axis of the rift following the general volcano-tectonic land forms. Most of the drainage systems drains towards the Awash River system from different directions and within the sub-basin water sheds. There are a lot of sub-basins situated in the NMER like Kereyu-Olenchiti, Adama, Wonji, Modjo and Chefe-Donsa, Iteya Plain and marginal systems that are generally comprised under the Middle Awash basin. The area is accessible from different asphalt and all weather roads along Addis-Harar, Adama-Asela,Asela-Meki, Iteya-Huruta and Dera-Sire.

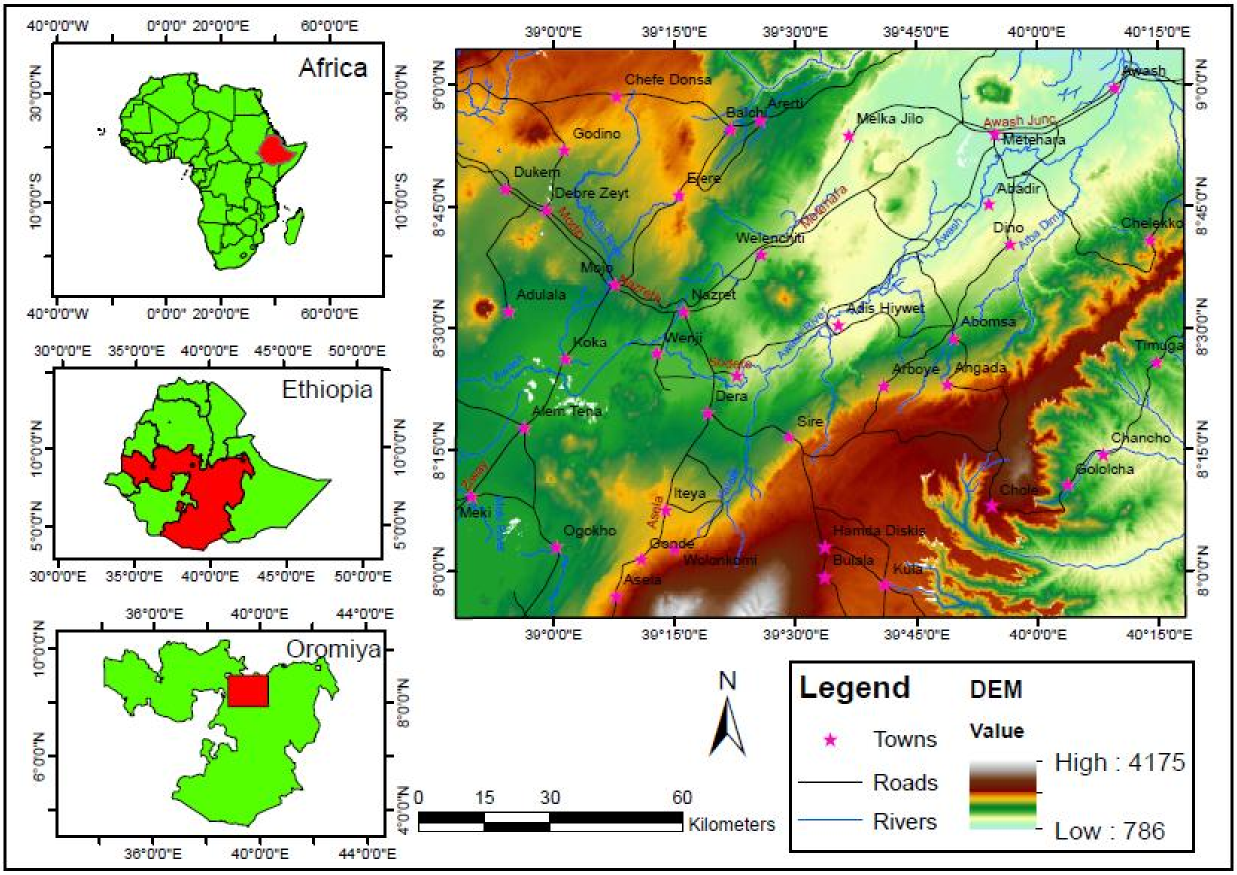


Figure 2.1: Physiographic Map of the Northern Main Ethiopian Rift System

2.2. Geology

The geology of the study area has been studied by numerous authors ((Mohr et., 1960, Mohr et a., l 19 67, Di Paola et al., 1972; Barberi et al., 1975, Morbidelli et al.,1975;Morton et al., 1979; Meyer et al., 1975Kazmin et al., 1978, Kazimin et al.1980, Bigazzi et al., 1981 Mohr 1986,WoldeGebrial et al., 1990, Alula Damte 1992, Abebeetal., 2005, Abebe et al, 2007). The NMER is distinguished by its two volcanic units of the Nazreth group(ignimbrite, rhyolite, trachyte and pumice) and Wonji group dated as 5 – 2 million years and Pleistocene –Holocene age respectively (Meyer, 1975) that are separated by Nazreth faulting phase initiated from 1.6 to 1.8 million years.

The detailed geological study for the dominant rock types has been conducted by Damte et al., 1992, are classified as Dera-Sodere-Nazreth group, Keleta group,Boku group, Gedemsa group,Melkassa Group, Boseti Group, Wonji unit, Lacustrine deposits, soil and reworked volcanics, talus and recent alluvial deposits. The Dera-Sodere-Nazreth group comprises acidic lava domes and flows that are exposed at Dera-Sodere and Dibibisa,Jogo, Didimtu and Garmama areas composed of rhyolite light trachyte and interlayered obsidian with clear flow structures and columnar joints. In this group the Bofa basalt with subaphyric, scoraceous and vesicles exposed at the rift floor round Golba area and the Aphyric flood basalt with vesicular dark fine grains is outcropped at the Kimimbiti at the base of Tedecha cone, Melka Oba near Sodere.

The Keleta group contains pyroclastic flow deposits with grey ash flow covered by glassy ignimbrite and thick ignimbrite, fragments of pumice and thin sandy coarse grained paleo-soils with various thickness and grain size are highly exposed at Keleta River, Dera domes, Awash Melkassa, SE of Gedemsa Caldera and Feyisso River. The Boku group is associated with large central volcanoes and collapsed calderas of alkaline and peralkaline rhyolite lava domes, pyroclastic flows and falls which covers the floor complex ignimbrite deposits. The boku group is exposed at Wagillo, Boku, Adama city dump, Kibimbiti, Tede Mariam and along the Koka-NazretRoad. The Gedemsa Groups are the intra-rift event that comprises the pumice and surge deposits associated with large central volcanoes. It comprises several elongated domes at the floor of the Caldera. The Melkassa group is composed of basaltic units, spatter cones and associated lava flows that are exposed at Tedecha area. The Boseti unit is characterized by prphyritic lava flows and pentellerite composition that are related to the central volcanic complex exposed at NE of Melkassa around Tatecha. The Wonji unit is composed of rhyolite, trachyte, obsidian associated with recent fissuralbasaltic lava flows, spatters and cinder cones that are situated around Wonji, Tede, Gedemsa caldera rim and Dera. The Lacustrine deposits consist of clay, silt, welded travertine, ashes,diatomites with intercalation of pumice cover the large flat areas of Wonji. These deposits were believed to be in the lake during Holocene (Di Paola, 1972) and are not disturbed by tectonic activities. The soil and reworked materials are the weathering products of the volcanic rocks covered the central and western part of Adama. Whereas, the talus covers the flanks of Dibibisa ridge East of

Adama and the escarps of the NW part of Adama. The recent alluvial deposits covered the banks of Awash and Wonji plains, overlying tuff, ignimbrite and volcanic ash.

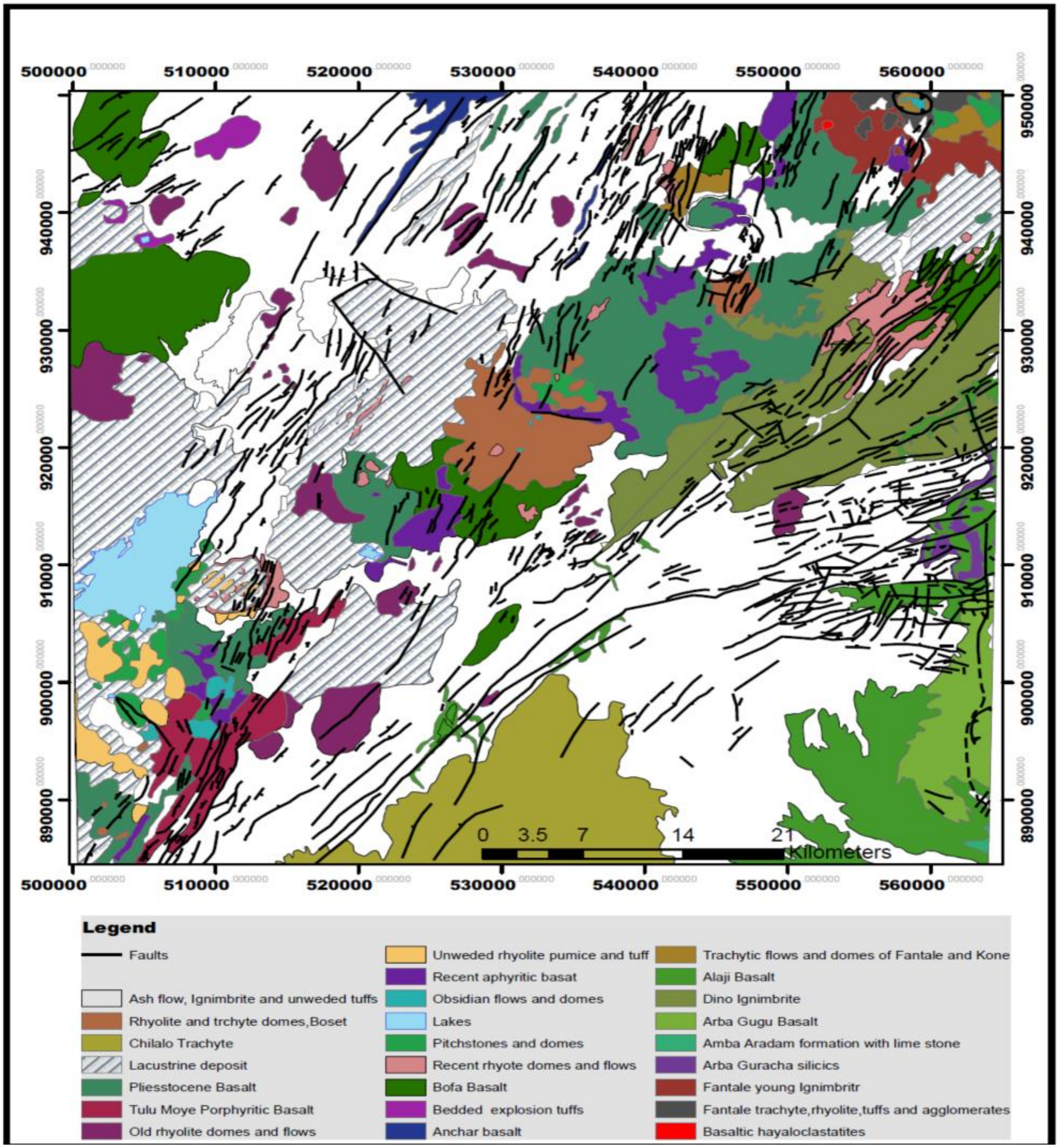


Figure 2.2: Geological map of the study area modified from Tsegaye Abebe et al., 2005.

2.3. Geological Structures and Volcano-Tectonics

In the MER two distinct fault systems are recognizable as a NNE-NE trending border fault system which is well developed, especially along the eastern margin separating the rift zone from the Somalian Plateau; and a NNE-SSW to N-S trending, right stepping en echelon fault system(the Wonji Fault Belt: WFB) as observed in(Fig.2.2) affecting the youngest volcanic rocks(Boccaletti, 2000). The WFB is located between the rift borders and affects the rift floor branching off from the eastern border. Meckenze et al., 1970, Francheteau et al., 1978, Mohr, 1983, Ebinger et al., 1993), suggested that the tectonic evolution of the MER has been commonly related to a pure extension mechanism.

The oblique extension resulted in a left lateral component of motion along the rift floor, which caused the WFB system to develop and this quaternary oblique faulting is also coherent with the locally complex structural pattern as graben in graben, rhomb-shaped and pull-apart structures, which are kinematically compatible with the left-lateral component of motion along the rift axis (Boccaletti, 1992, 1998). WoldeGebriel et al., 1990, suggested that the WFB is composed of right-stepping, offset fault segments, which further support the occurrence of a sinistral component of displacement along the rift structure. Continuing the oblique extension up to recent times, the WFB faults reached the upper mantle allowing the uprising of the basaltic magmas (Bofa, Galo-Salen and Melkassa Units), while the felsic products eruptions persisted along this MER sector (Aluto-Bericha and Gedemsa Units), giving rise once more to bimodal volcanism.

In the NMER, the orientation of the boundary faults are ~N40°E, whereas, the major boundary fault systems of Arboye and Sire separated by a right-lateral offset of about 35 km at latitude ~8°20′ N; similarly, the Sire Fault System dies out to the southwest at latitude ~8°N and is separated by a right lateral offset of about 15 km from the Asela fault escarpment (Wolfenden, 2004). The Wonji faults of the NMER are oriented ~N20°, forming an angle of ~20° with the roughly N40°-trending boundary faults.

The Gedemsa, Boseti and Kone WFB segments are axial ridges, whereas the Fantale–Dofen magmatic segment is marked by a graben that lies 550 m below the Boseti and Kone segments (Ebinger and Casey, 2001; Casey et al., 2006). The dimensions of individual segments range between 40 and 70 km in length and between 10 and 15 km in width; they are separated by areas devoid of magmatism and brittle deformation (Casey et al., 2006; Kurz et al.,2007), where the distances between segments in an E–W direction vary from 2 km (Boseti segment–Kone segment) to 18 km (Gedemsa segment–Boseti segment).

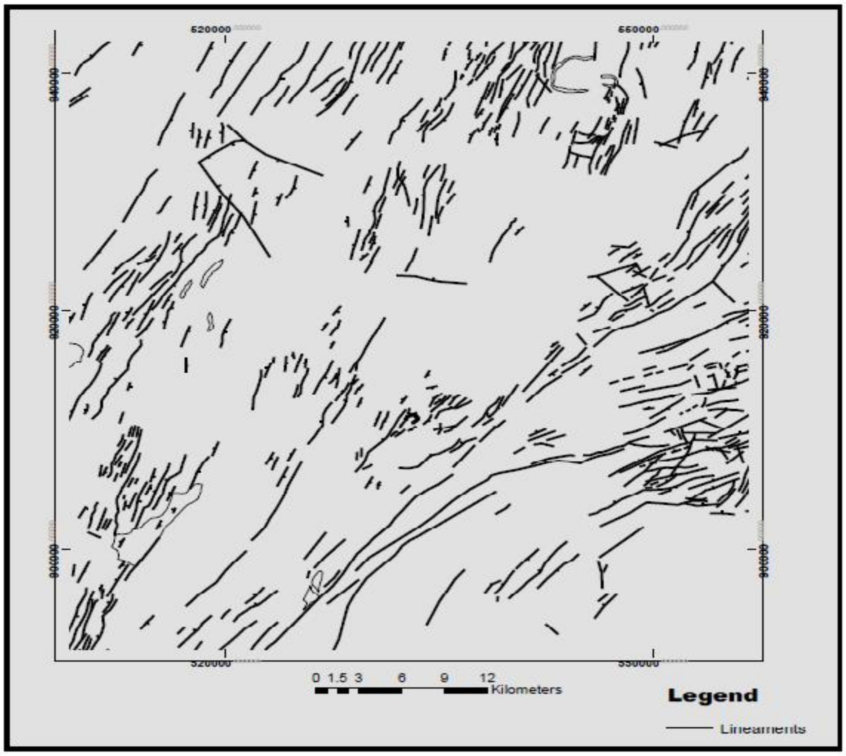


Figure 2.3: Lineament and structural map of the study area modified after Tsegaye Abebe et al., 2005.

2.4. Geomorphology

The present day morphology of Ethiopia, results from interaction of the continental fragmentation of Gondwana and Afro-Arabian plates and connected basin development, Paleozoic glaciation and mantle plume activity. The geo dynamic process due to the plume action gave rise to extrusion of huge amounts of magma, uplift, and fragmentation of the continental crust and contributed to the birth of the Red Sea, Gulf of Aden, East Africa Rift valley, and the adjoining Afar depression. According to Abbate et al., 2015, the morphological response due to the Cenozoic geodynamic events in to three main physiographic provinces like the highlands of the northern western and south eastern

Ethiopian plateau, the Afar depression and the MER. The uplift of the Ethiopian plateus are supposed to be due to the domal uplift started in the Oligocene (Merla , 1079). Ebinger et al, 1998, determined that the regional high structure was due to the combined effects of the Afar plume impingement and associated large basalt effusions.

The morpho-tectonic history of the Northern Ethiopian Plateau started from a broad dome with slow rate of uplift from 29 to 10 Ma, a rapid rate of increase in the uplift occurred at 10 Ma, followed by a dramatic plateau rise to 6 Ma. The MER, from morphological and geological point of view, has been subdivided in to three main segments of the Northern(100km to 80km wide), Central(80km wide) that extends to E-W trending Goba-Bonga lineament and the southern MER narrows up to 60km wide bifurcates in to two branches(lake Chamo and Galana river rifts) separated by Amaro Horst(Mohr, 1967). The rift floor is not uniformly flat but it is occupied by recent volcanic edifices rising some hundreds of meters above the plain (Fantale, Boseti Gudda, Aluto, Tosa Sucha) and Calderas. The Wonji fault belt is characterized by rough and irregular morphology with narrow uplifted bock, valleys, lava fields, spatter cones and swampy depressions. Hayward et al., 1996, Wolfenden et al., 2004 and 2995, suggested that there are four major WFB segments (Gedemsa, Boseti, Kone and Fantale-Dofen); the en-echelon segmentation continues northeast ward in to the Afar depression.

2.5. Hydrogeology

The groundwater flow continuity between the high rainfall plateau bounding the rift and the rift valley aquifers depends principally on the nature of the bounding faults (kebede et al 2007). Up to 50% of the recharge to the rift aquifers comes from the plateau as groundwater inflow where the rift is cross cut by transverse fault zones. Recharge from the mountains is found to be insignificant where the rift is bounded by marginal grabens; channel loss and in such cases local precipitation are the principal source of recharge to the rift aquifers.

Groundwaters in the Main Ethiopian Rift valley are controlled by the complexity of the stratigraphic settings, hydrography and hydrogeology of the rift floor. Previous studies from Kebede et al, 2007, reveals that the intersection of Rift faults with an older, E-W trending structure (the Yere-Tullu-Welel volcanic lineaments, YTVL has formed transverse faults orthogonal to the rift faults, creating a ``hydrgeologic window`` that enables groundwater flow from the escarpment to the rift in this area. Whereas, in Akaki and Bishoftu area, the younger quaternary scoraceous basalts and associated ashes with a thick cover of the alluvial material form highly productive aquifers (Kebede et al. 2007; Demlie et al. 2007).

In the Adama Graben, Rift Aquifers of Adama and Wolenchiti area are characterized by complex inter-layering of the alluvial/lacustrine sediments, pumice, fractured basalts and ignimbrites in highly faulted terrain, in which the bore hole depth often exceeds 200m (Kebede et al, 2007). While the very young fractured basalts and scoraceous basalts as well as pyroclastic deposits such as pumice, tuff and volcanic breccia are identified as the water baering formations in the Lake Beseka region (Ayalew, 2008).

The groundwater in the Asella transect from the Eastern escarpment and the Guragie mountains in the western margin in the Butajira area is characterized by low productivity aquifers with low yield. In the western margin a single prominent fault and minor marginal graben filled with sediments (e.g. Meki and Waja valley) and the eastern margin is characterized by a series of step normal faults running parallel to the rift. At the shoulder of the western escarpment, the geology is characterized by course grained (alluvial) deposits at the base of the scarp (pediment) plain with shallow groundwaters and springs.

The hydrogeology of the NMER (Fig: 2.4) is modified from Nazreth Hydrogeological map, is characterized by the high productivity aquifer in some areas around Mojo, Chefe Donsa, Platue sector of the Arsi, Wonji basin and Akaki area; Moderate productivity in Nura Hera, Abadir Farm, Koka lake region; Low productivity in some volcanic domes, shields and central volcano areas and Very low productivity in Fantale volcano area, Boku ridge and near to the Iteya-Dera Plain.

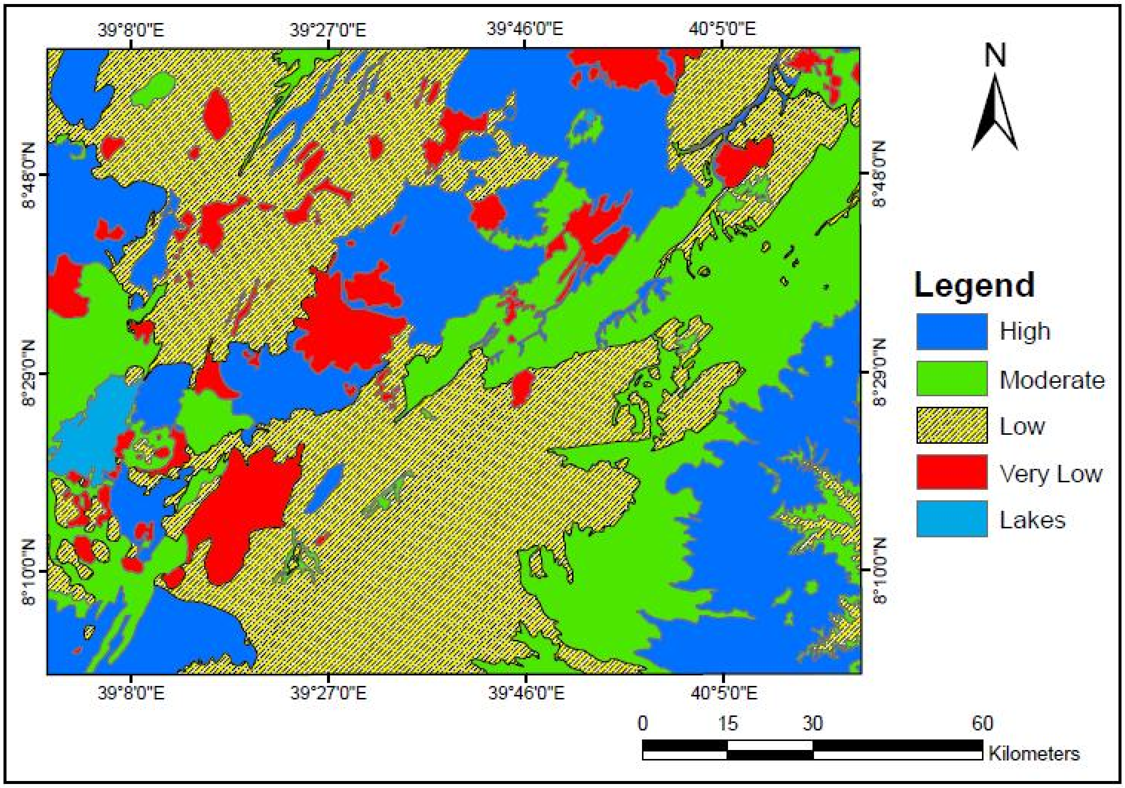


Figure 2.4: Hydrogeological map of the NMER modified after the Nareth hydrogeological map compiled by Getahun Kebede, 1985.

3. Methods and Materials

The current study comprises an integrated multidisciplinary approach that utilized the geological structures, geomorphology, geology, hydrogeology and hydrogeochemistry. Field Work was conducted to identify the geomorphologic, geological structures, geologic and hydrogeological setting of the NMER. Geomorphological features situated within the region are observed to characterize its role for groundwater occurrence and flow system. During the field work, topographic maps (1: 50, 000) and geologic and hydrogeologic maps (1: 250,000) and Satellite images were used as for navigation.

GIS and Remote Sensing of various data sets used in this research were carried out using ESRI ArcGIS v.10.3, ERDSA IMAGINE (ver. 9.3), Global Mapper (ver.15) and Surfer 9. Thematic maps of the drainage, geomorphology, geology, hydrogeology, groundwater contour maps, hydrogeochemistry spatial maps and structural lineaments map were prepared in ArcGIS v.10.3. Structural data (strike and dip) of some selected sites from the margins and rift floors are collected to analyze the major structural orientation of local and regional geological structures. Major lineaments and small local faults extracted from previous geological structural maps and analyzed using Arc GIS V.10.3 tools.

Existing groundwater wells (shallow and deep), Hand dug wells, springs and surface waters data were collected from different sector offices in the NMER. The water points inventory of depth of groundwater wells (static and dynamic water level), Pump test and well completion reports are collected to analyze aquifer productivity and aquifer properties(hydraulic conductivity, transmissivity and storativity).

A total of 96 water samples were collected with field tests like electrical conductivity, PH, TDS and EC measured and described representing the hydrogeochemistry of the flow system within the basin. Data of major cations and anions are analyzed using hydrogeochemical demonstration of the piper plot in Aquachem software and identified the water types to investigate the evolution of ground water flow. HCA is conducted using STATISCA 10 software to classify dendrogram of the waters in to distinct objective groups and subgroups to characterize the subsurface circulation and water-rock interaction and residence time.

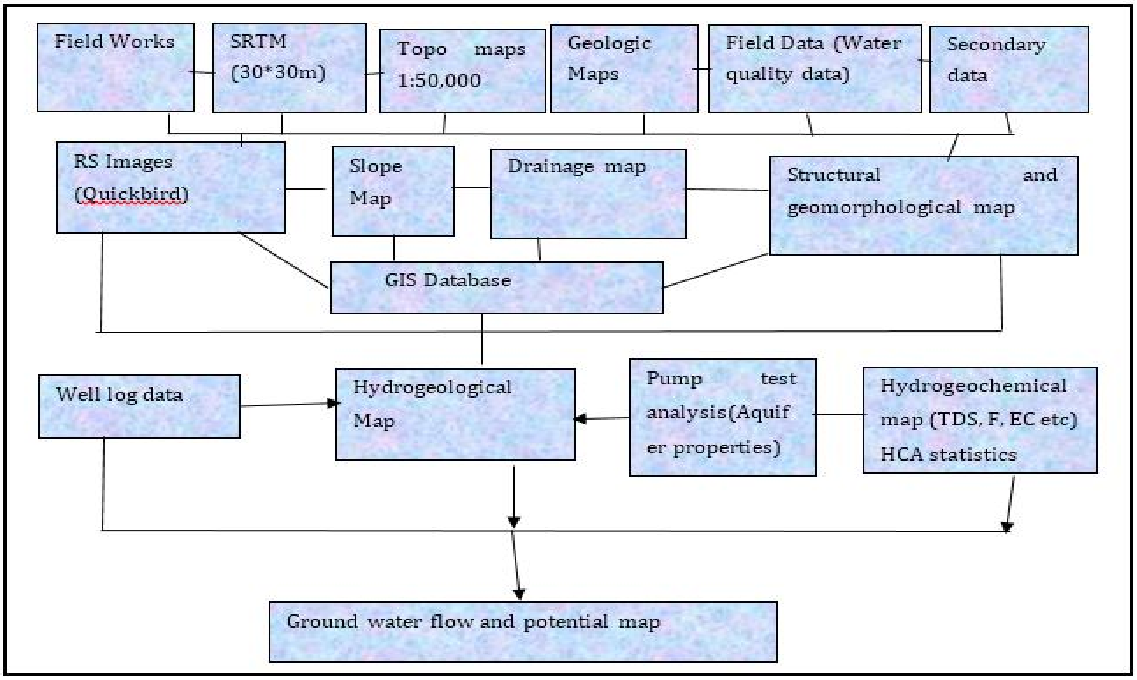


Figure: 3.1. Methodology Flow Chart

4. Results and Discussion

4.1. Analysis of Geological structures

Field observations and satellite image analysis shows that faults situated in the NMER have different kinematic nature and orientation in different sectors of the rift floor, in Eastern and Western escarpment of the Rift. In the Eastern escarpment of the NMER, like in Asella- Sire and Sire-Arboye (Fig.4.1.) there are various step normal faults that formed a lot of half and full grabens.

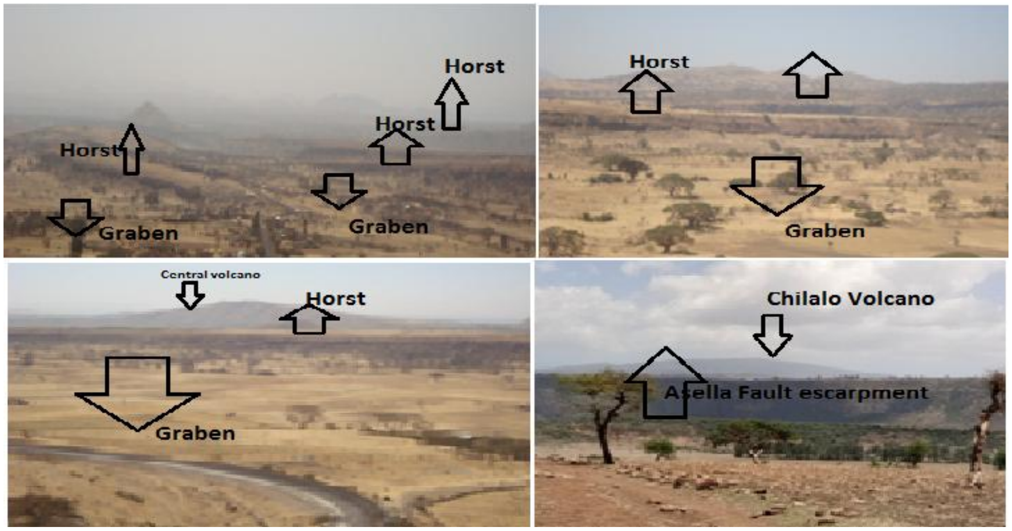


Figure 4.1: Horst and Graben, central volcanoes in the rift floor, Marginal faults and Shield volcanoes.

The down thrown blocks and the fault plane decrease in length from the two marginal faults in both Eastern and Western escarpments of the rift towards the rift floor like in Wonji Fault Belts. In the western escarpments of the NMER, step normal faults are not developed well rather than marginal structures with very high marginal blocks. There are a lot of scoria cone alignments emerged following the Bishoftu-Butajira alignment. While in the Northern part of Bishoftu, the E-W trending Yerer-Tullu Welel volcano tectonic lineament cross-cut the western part of the NMER that formed the hydrogeological window for groundwater flow from the western transects to the MER. Some horst and grabens are situated along the express way from Mojo to the western part of Adama city near the Oromia Police College. Most of these faults formed small grabens and horsts that are not interconnected as in the case of the Eastern escarpment they rather pinch out with only few kilometers lateral distance.

In the rift floor along, there are volcano-magmatic segments that formed the Calderas, central volcanoes and small scoria cones. The systematic alignment of these are controlled by the kinematic structures of the oblique transverse faults that are oriented NNE following the right stepping en-echelon arrangements. The orientations of these transverse faults are E-W like the YTVL; situated in Dera area between Gedemsa and Boku caldera and near Wolenchiti area. The rift floor also comprises a lot of opening fissures, deep cracks and blister caves (Figure: 4.2) mainly in the Northern part near Kone caldera and Beseka Lake. Deep and extended ground cracks are commonly observed in the rift floor along Adama-Asella highway and Ziway area that are emerged following heavy rainfall and runoff.

Figure 4.2: Deep fracture openings of ignimbritic rocks in the flanks of Beseka lake N-S oriented to the Fantale volcano.

Figure 4.3: Deep fractures in ignimbrite near the Beseka Lake oriented N-S trending structure indicating the subsurface groundwater flow hydraulically interconnected with Beseka lake.

Regional and Local groundwater flow in the study area is controlled by the complex structures formed in the region with different orientations. Previous studies (kebede et al., 2007) reported that the E-W trending Yerer Tullu-Welel that cross cut the western part of the NMER created the hydrogeological windows like Akaki well field and interrelated Adaa plain of the Bishoftu and Akaki well field. It also controls the surface flow of Awash basin to flow from the western escarpment to the rift floor. Local recharge in the vicinity of the plateau sector and the adjacent escarpment is commonly from rainfall contribution for shallow ground water flow. The role of geological structures in facilitating the recharge of groundwater in the vicinity of the Eastern margin and escarpments are relatively different from that of the western escarpment of the NMER.

In the eastern escarpment of Asella-Sire Border faults there are high discharge springs (Gudelcha Spring East of Huruta) that contributes water supply share for the towns like Iteya, Dera and Awash. In Sire Area, there are some productive boreholes and springs along structures of step-Normal faults. But, along geological structures near the rift floor many drilled borehole are not productive and abandoned. This indicates that deep seated geological structures in the vicinity of the Eastern escarpment of the NMER in Asella-Sire and Sire-Arboye controls the recharge from the Eastern plateau sector to flow into deep rather that shallow groundwater circulation. This can be observed from the wells drilled adjacent to the escarpment that shows no shallow groundwater discharge. This also influences the occurrence of groundwater in the rift floor at the side of the eastern escarpments. Some transverse faults around Dera area also blocks the flow of some shallow groundwater flow to the Dera-Iteya plain. Although some deep boreholes are drilled in this plain they have very low discharge that shows the influence of this structural block of groundwater flow from Wonji basin to the Dera-Iteya plain.

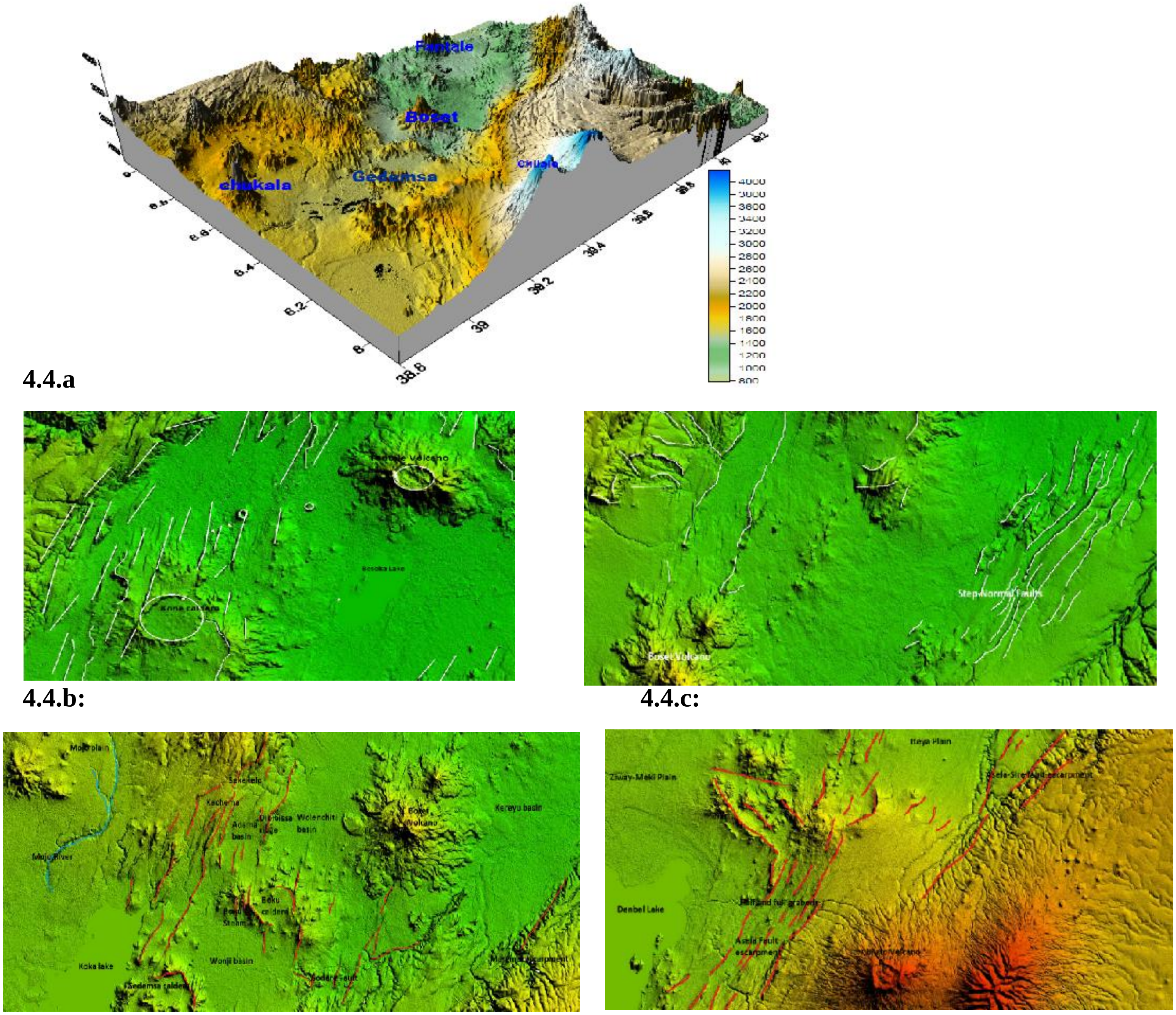
Structures in the southern part of the NMER has less contribution to the hydraulic connection to groundwater since the flow from the plateau and adjacent escarpment is very deep circulation. Shallow groundwater flow as observed from Melka Hida and Wonji area bore holes in Wonji basin, at the bank of the Awash River and Koka reservoir is controlled by thick alluvial deposits and surface water of Awash river recharge and irrigation return flow from Sugar plantation.

In Boku caldera, an elongated N-S trending deep ground cracks are commonly emerged following heavy rain falls. This shows that there is high infiltration of runoff from the southern side of the ridge in to some quarry mine holes for pumice and local sand mines that makes the subsurface of the loose alluvial deposits to be very saturated and followed by collapse of the surface. This type of ground crack is observed in Adama-Asella asphalt road in Hate Haroreti village. In the Adama basin, surrounded by ridges like Kechema in the west, Dibibissa in the East, Sekekelo in the North and Dabe in the South east, comprises a lot of water wells in the Adama City, Dhaka Adi and Wonji area with hand dug wells, shallow and deep wells with varying discharges.

4.2. Geomorphological analysis

The NMER is characterized by volcano-tectonic magmatic activities, rift evolution, extension and continuous eruptions that formed different land forms like calderas, craters, volcano-tectonic lakes, fissural and central eruptions, silicic centers, cinder cones, half and full grabens and large basins. In the NMER, Calderas like Gedemsa, Boku, Kone, Boset and Fantale, volcano-tectonic lake of Beseka, Kereyu and Adama basin and cinder cones aligned following systematic structures of the WFB.

Geomorphological interpretation is used to identify recharge to groundwater from landforms that are associated with soils, superficial deposits and denudational history affecting the nature of hydrogeological properties of the near surface materials. The significance of geomorphology on groundwater occurrence is controlled by the proportion of rainfall available for recharge of groundwater depends not only on the permeability of soils and rocks, but also on the residence time of rainwater over groundwater intake areas. Little water for recharge can be due to soils nature, integrated dense drainage networks, sloping areas can cause rapid runoff. Relief plays a role for the development of drainage lines and level of erosion is governed by tectonics and geomorphologic history. This type high runoff generation is common in areas with steep slope in ridges surrounding the Adama City(Figure:4.4.d) like Kechema ridge, Sekekelo, Dabe and GolbaTegene. Much water can be retained and potentially conducive for recharge in areas where the soil is permeable and less dense drainage network and mild slop nature runoff generation will be less and infiltration capacity will be high. This is also observed in areas surrounding the Wonji basin, Modjo and Chefe Donsa area Batu and Meki plain surrounding the Lake Denbel. The geomorphic signature in the Eastern plateau margin is characterized by step-normal faults that facilitates the infiltration of groundwater to flow into the deep sub-surface aquifer. In areas around Sire step-normal faults(Figure: 4.4.c), Asella fault scarps and Iteya-Dera plain (Figure:4.4.e); although there is a less drainage density and some areas the slope is also mild, the effect of faults make the recharge of ground water to be deep in to sub-surface. Thick alluvial deposits are considered as highly permeable formation in the banks of the Awash and wonji basin due to landscapes and low drainage densities. In the NMER (arid regions), during the heavy rain fall, the drainage density is not related to the permeability of the soil and rock complex. It rather develops high runoff generation due to the less infiltration capacity that exceeded by overland flow.



4.4.e:

4.4.d:

Figure 4.4.a: Geomorphologic land forms of the NMER, 3D view of geological structures and volcanic land forms, 4.4.b: Fantale volcano, Kone caldera and Beseka lakes region 4.4.c:Sire step-normal faults 4.4.d: Boset volcano, Kereyu, Adama, Wolenchiti and Wonji basin, Boku Caldera and Kechema ridge 4.4.e:Asela Fault escarps, Chilalo volcano, Iteya plain, Batu and Meki plain and Denbel Lake

Very low drainage pattern is observed in the plateau regions flood basalt outcrops due to the low permeability and vegetation cover. While in the recent age lava flows with rough surfaces that can be used to store rain water in some surface depressions apart from its permeability nature. Low drainage density in some rift floor regions of young volcanic eruptions is due to the high permeability of some pyroclastic materials (tuffs and conglomerates).

4.3. Hydrogeological and Aquifer Characterization

Hydrogeological interpretation of the study area is conducted by integrating the aspects of previous subsurface data and surface features that influence and show evidence of groundwater recharge and discharge. Geological maps and cross-section, water well drilling logs, extrapolating surface geological features from image to the subsurface data. Evidences from images showing permeable conditions like non-eroded thick soil, colluvial deposits over a dipping rock sequence with good transmissivity in non-deep rooted and dense vegetation shows that recharge can be high. In areas where direct runoff of large outcrop areas where the flowing out of the area through incised drainage networks provides very low recharge to groundwater. Few of the generated runoff in the weathered part of the area contribute to the recharge.

Some signatures observed from satellite image showing lineament structures dipping with dike and associated to the vegetated having tensional fractures contains groundwater. The artesian conditions that shows the confined aquifer is not observed in the study area. Alluvial deposits and buried escarpments and buried channels in a fairly straight area shows that due to the up-bringing of rocks with low permeability. Most of the rivers in the study area, the base flow in the river beds is not observed, this shows that the water loss is due to infiltration in permeable river bed deposits and ground water level will be below the river beds in the alluvial deposits and deep infiltration through rock formation and large fractures.

Regionally the groundwater movement is strongly controlled by geological structures; mainly faults. According to some previous research and technical works, the groundwater flow direction is parallel to the rift axis along major faults against the regional topographic slope. The groundwater occurs at different elevations based on the extent orientation of the normal step faults in the escarpment and rift zones. At places where rift faulted volcanics is covered with thick sediments shallow and highly productive aquifers is formed. At places where deeply fractured volcanics occur very deep aquifers exists.

The hand dung wells around Mojo town due to the occurrence of alluvium and lacustrine deposits that are suitable for the target layers of hand dug well. Whereas, the hand dug well are very few around Lake Beseka area due to the lack of suitable layers for hand dug well. The distribution of alluvium clay or slit layers, 12 m to 17 m depth from surface and also of rock layer without the alluvium affect the drilling of hand dug well.

Groundwater wells yield and depth of bore holes in the East Shewa, Arsi and Beseka Lake and surrounding areas in the following figures are analyzed for the productivity of the bore holes. It shows that there is a very slight correlation of increasing depth with an increased yield of the bore holes. This indicates that there are very deep-seated structures that serves as a conduit to make the water to flow in to a very deep aquifer system. Well log information from bore holes in the Beseka region shows that the yield of bore holes varies from 3 to 12L/s based on the increasing depth of drilling that shows an increasing of yield. Wells with a depth of less than 100m shows less than 10L/S yield. However, wells with depth of more than 350 m has more than 10 L/sec, and 2 to 6 L/sec yield is recognized in wells of less than 100 m depth in Eastern escarpments of the NMER. Between Kone Caldera and Adama, the well depth of 100-205 m and yield of 1 to 1.5 L/sec among which only one point is 5 L/sec yield. In northern part of the study area, North Shoa zone having well depth between 100 m to less than 200 m characterized by a yield with less than or equal to 3 L/sec and 5 L/sec and two wells are more than 300 m depth and its yield is 25 to 30 L/sec.

In the Wonji basin, most of the wells are shallow with a depth of 30-67 m, the deepest one in this area being 200 m and ten wells are 100 m to less than 200 m depth have the yield of 3 to less than 10 L/sec. Whereas, around Mojo area, data of 38 existing wells shows that the shallow depth wells are 15-30 m have 1 to 3 L/sec yield, and deep wells depth are 100-280 m have 200 m depth well has 15 L/sec, and an average for all wells of 1 to 5

L/sec. Some boreholes in the Adda-Becho are deep up to 350m to 370 m depth have more than 30 L/sec yield except one well, and other two wells yield is 50 to 60 L/sec. Groundwater wells data collected from eastern escarpment in Arsi zone shows that the drilling depth is between 200 to 300 m and yield is 3 to 5 L/sec. groundwater well around Dera town shows that the well of 420 m depth has 3.4 L/sec yield around Dera town in Arsi zone.

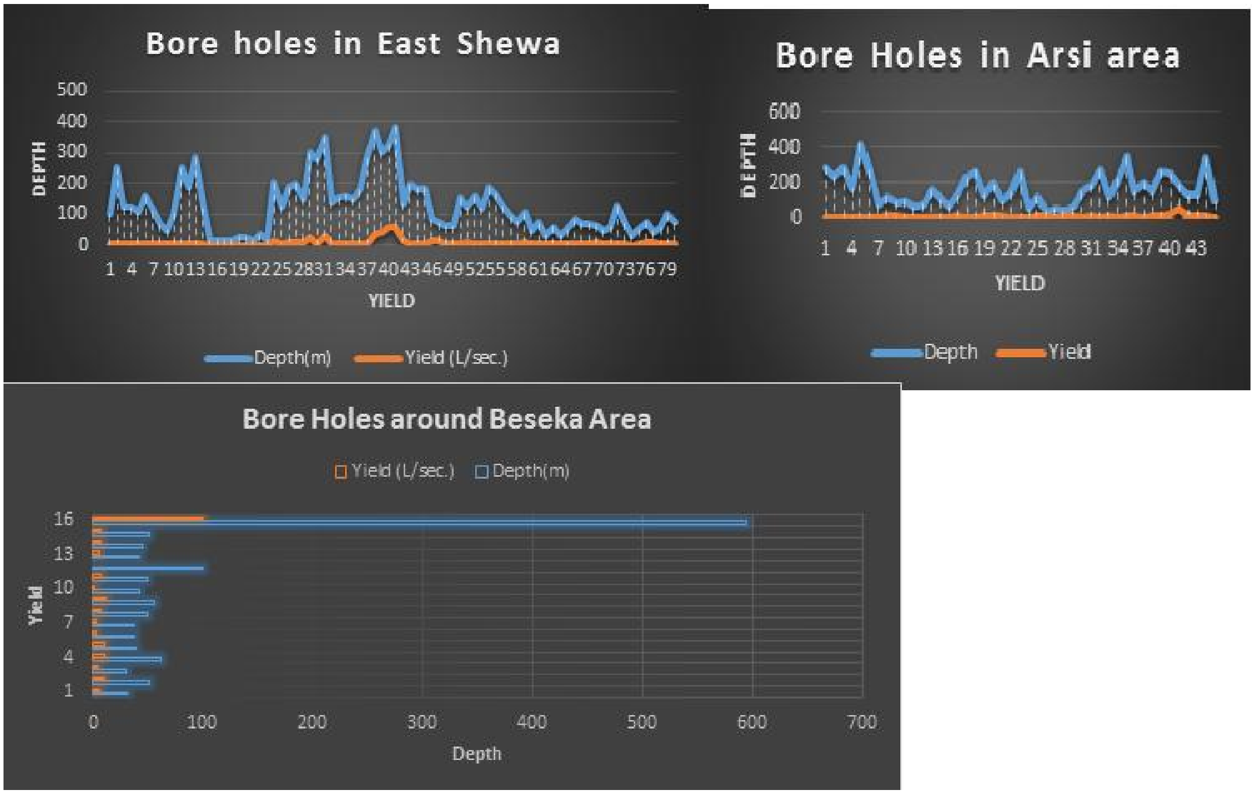


Figure 4.5: Depth Vs yield of bore holes in the East Shewa, Arsi and Beseka lakes Region

Groundwater level in the study area as investigated from some boreholes shows that in the Wonji basin shallow groundwater is commonly occurred with the yield of up to 10 L/S and in the Adaa Plain, around Bishoftu, deep aquifer system is characterized by the yield from 30 to 60L/S. Whereas, In Mojo area, shallow hand dug wells are commonly found in alluvium and lacustrine deposits, deep aquifer system is characterized by the yield of up to 15L/s. In Wolenchiti and kereyu basin, deep aquifer system is investigated with low yield of 1 to 1.5L/s. In eastern escarpment, ground wells of the depth up to 300m shows that the yield between 3 to 5 L/s. in Northern Part of the study area, groundwater wells of up to 100 to 200m and greater that 300m depth shows the yield of 3 to 5 l/s and 25 to 30l/s respectively.

From yield analysis of boreholes in the study area, groundwater potential and aquifer system of the region varies from all sub-basin. This can be due to variation in hydrostratigraphic formation and complex geological strucures. In the Adaa plain and mojo area, due to the cross-cutting of the YTVL and NMER structures and the nature of hydrostratigraphy, both shallow and deep groundwater is found with very good potential as compared to the other parts of the study area. In Wonji plain, thick alluvial deposits near the bank of Awash river, hydraulic interconnection of Awash with groundwater and koka reservoir, shallow ground water with good potential is for both shallow water wells and hand dug wells are highly observed.

In the Adama basin, deep groundwater wells are common from deep hydrostratigraphic unit of the fractured basalt and ignimbrite, with moderate potential aquifer system. Whereas, in Wolenchiti and Kereyu basin, the water bearing formations are found rarely in to a deep aquifer with very low yield. This might be due to the deep-seated structures and volcano-magmatic segments that make groundwater flow to be very deep and the weathering effect that makes hydrostartigraphic unit to be permeable is very rare due to scarcity of rainfall in these region. In Beseka Lake Region, due to the intense fractures and geological structures connected to Fanatale volcano, there is interconnection of groundwater with Beseka Lake. Some hand dug wells and springs shows that there is some shallow groundwater due the structures connected that make it to be discharged in to the banks of the lake. Whereas, groundwater wells in deep aquifer system shows that deep seated geological structures are highly intense in this region as observed from high temperature of springs and water wells.

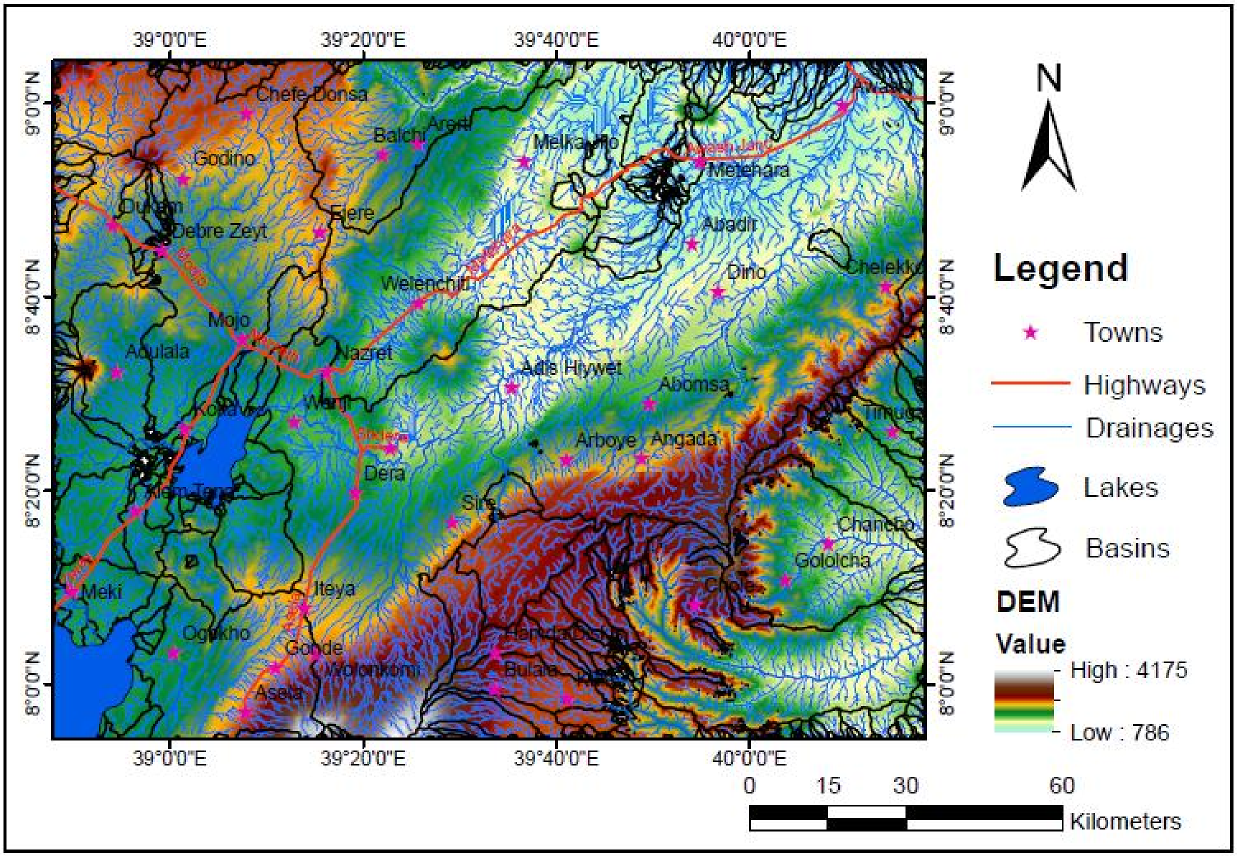


Figure 4.6: Drainage Patterns and sub-basins in the Middle Awash area

From the drainage patterns in the basin(Figure:4.6) as classified in different sub-basins, it shows that there are very dense drainage networks that are interconnected to different tributary rivers and all finally drains to Awash River. The density of these drainage networks shows that during rainfall, over land flow that cause runoff to flooding hazard is common in Adama and Wonji basins of the study area. Local recharge from rainfall is mostly affected by overland flow than being infiltrated due to the slope and drainage network of the region.

4.4. Hydrogeochemical analysis

The hydrogeochemical characteristics of waters were obtained from analysis of water samples of which from ground water (wells and springs) surface water (rivers and lakes). Groundwater geochemistry indicates that the waters collected from around Beseka Lake, Metahara Fentale, Merti and Awash Fentale areas as indicated in the following figures is characterized by high TDS (Fgure:4.7), EC (Fgure:4.8) and Fluoride (Fgure:4.9). Highland ground waters are generally characterized by low TDS, salinity and fluoride content. The increment of TDS and EC towards the rift sector is attributed to the groundwater evolution along its flow patterns from highland to the rifts. The increment of TDS, EC and F shows similar trend in the following figures(Figures 4.7(TDS), 4.8(EC) and 4.9(F)), that are observed in the NE part of the study area around Metahara,Awash Fentale,Abadir, Nura Hera, Bole areas. It also shows similar trends in Wonji, koka, Dire, Denkaka and AlemTena areas. The F ion is increased in the water instead of forming fluorite compound or mineral form of calcium fluoride. A high concentration of F in the rift could also be due to the occurrence of dominant obsidian, Micas, amphiboles and pyroxenes, which may contain appreciable amounts of F.

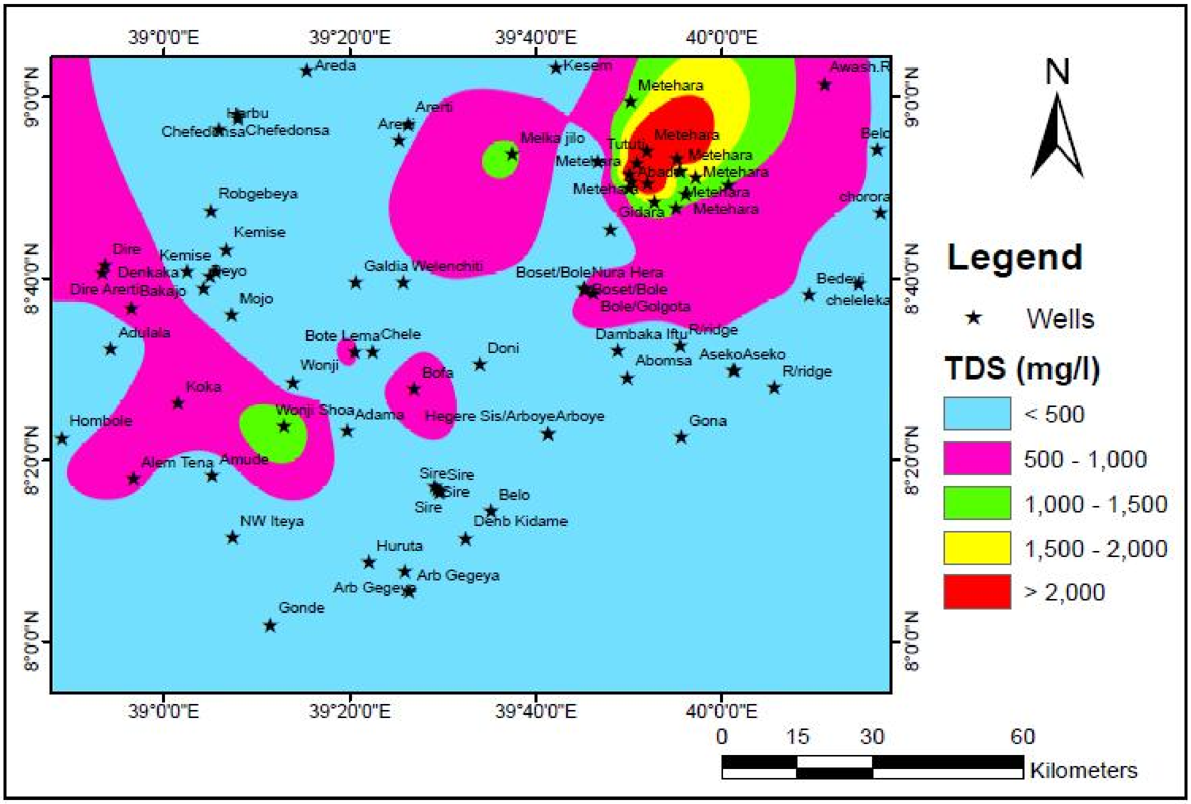


Figure 4.7: TDS Map of chemical data of water samples in the study area

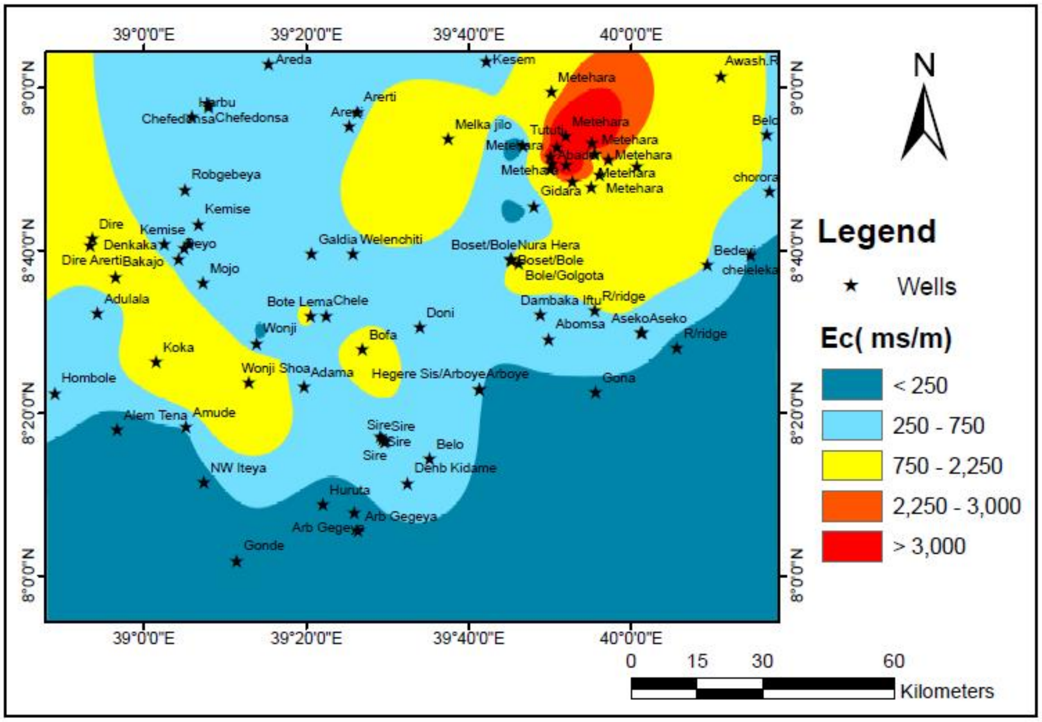


Figure 4.8: EC Map of chemical data of water samples in the study area

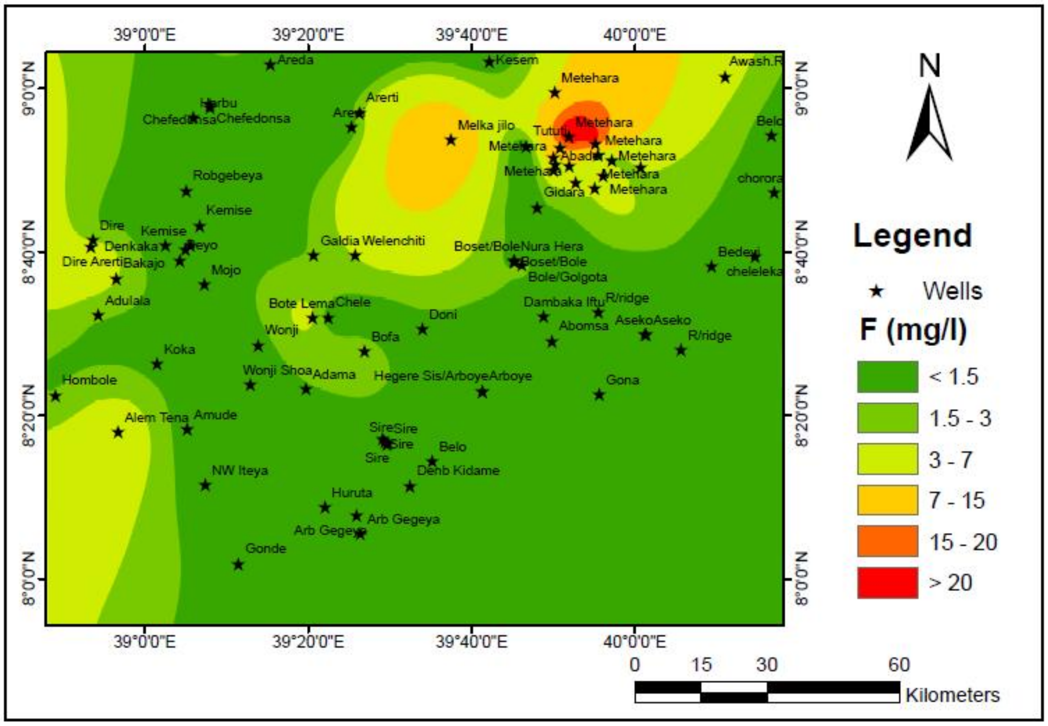


Figure 4.9: Fluoride Map of chemical data of water samples in the study area

The hydrochemical facies of the study area (Figure 4.10), varies from Ca-Mg-HCO3 to Na-HCO3 water types. Most of groundwater samples from spring and bore holes were categorized to Ca-Mg-HCO3 type, groundwater samples from some borehole of the rift region and lakes are grouped in to Na-HCO3 water types that shows water in the rift regions are mostly geochemically highly evolved from highland plain via escarpments to the rift sector; from recharge to discharge areas with long residence time.

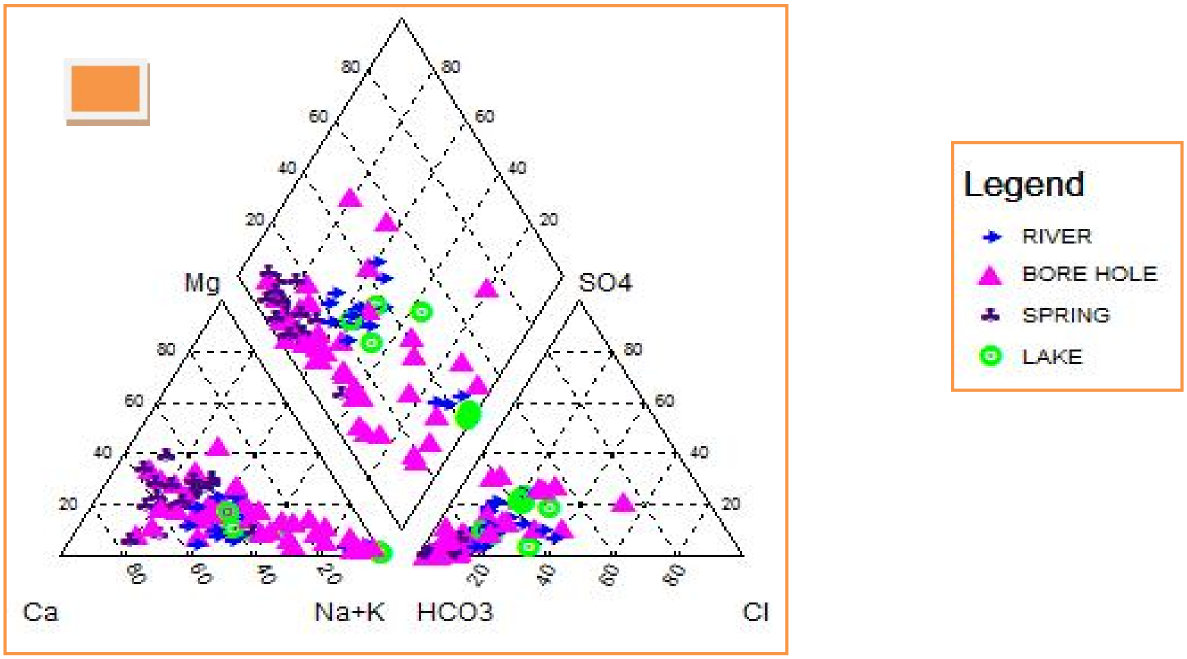


Figure 4.10: Piper plot of chemical data of water samples in the study area all water source type.

4.5. Hierarchical Cluster Analysis (HCA)

HCA is used to classify waters into objective groups that are classified in to dendrograms for the total of 90 water samples shows that there are two major groups and nine subgroups of waters. The two major groups are classified based on their TDS value. Group 1 waters are observed as high TDS waters >2240mg/l deep groundwaters of Metahara areas and Lake Beseka while group II are classified by low TDS < 2240mg/l from medium and shallow groundwaters, rivers and springs of the rift escarpments and shallow ground waters of the Rift area. HCA is used for ten variables (pH, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, $HCO3^{-}$, Cl^{-}, $SO4^{2-}$, EC and TDS) were considered to classify the 90 groundwater samples. From the dendrogram shown in figure 4.11, two major groups and nine subgroups were selected visually.

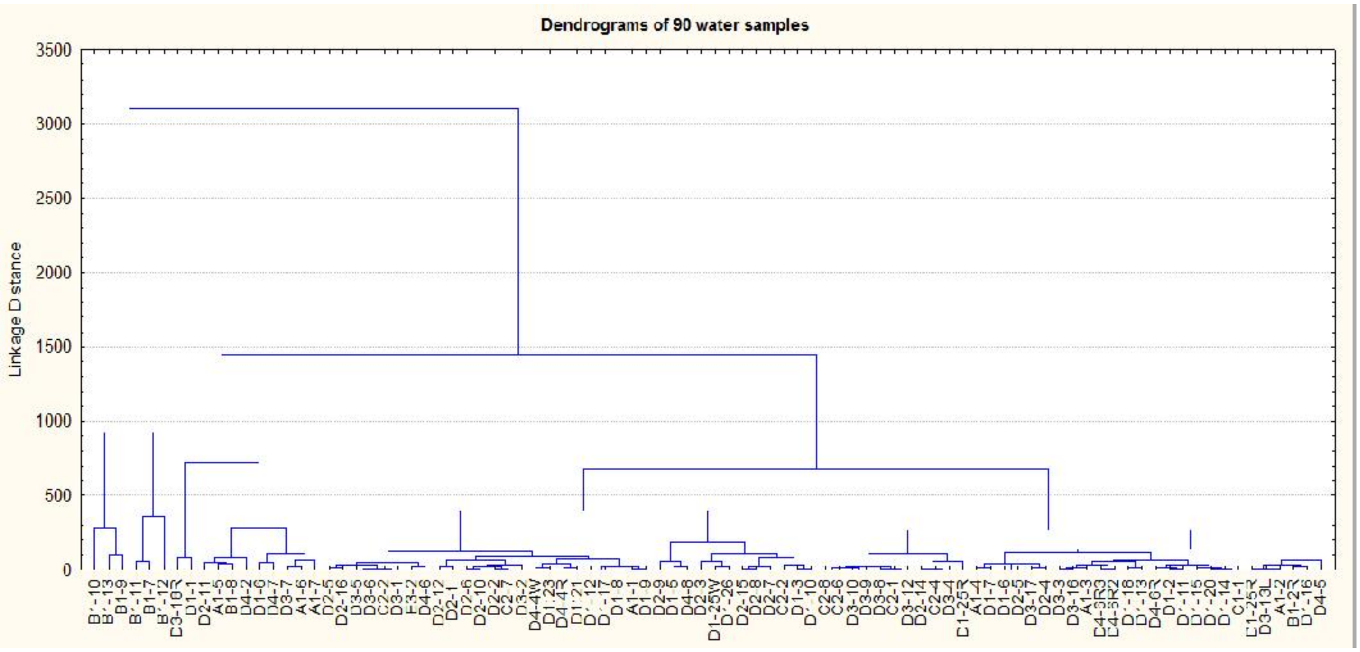


Figure 4.11: Dendrogram for 90 water samples

Table 4-1: The mean chemical composition of waters resulting in subgroups from HCA

Catagory	EC	Na+	K+	Ca	Mg	F	Cl	SO42	HCO3	PH	TDS
Sub group I	4480	1110	52.33	8.3	4.8	17.31	246.83	486.23	819.03	9.36	3033.3
Sub group II	3640	926.7	43.33	6.4	2.88	9.18	288.2	365.09	978.44	9.36	2460
Sub group III	2255	324.5	37.75	130	30	2.305	192.94	263.705	692.96	7.77	1460
Sub group IV	1263.6	226.3	14.66	53.2	11.18	2.96	93.1	114.31	496.54	7.87	884
Sub group V	583.71	39.43	6.64	65.14	18.79	0.62	18.07	5.17	342.64	7.72	356
Sub group VI	684.75	70.65	12.64	65.54	14.95	0.99	28.95	20.56	376.52	7.61	434.375
Sub group VII	908.94	147	14.81	67	11.72	2.08	63.40	33.16	484.54	7.74	539.14
Sub group VIII	161.18	10.7	3.72	17.67	5.45	0.58	6.20	1.5	95.60	7.20	102.18
Sub group IX	426.19	36.66	7.48	45.48	10.92	0.86	13.44	9.47	248.45	7.6	272

Sub-group I waters has a member of The Metahara bore holes that are represented by the deep circulation of ground water with high TDS and Na-Ca-SO4 and NaHCO3 water types indicating the pyrite oxidation and sulfide and affected by ion exchange during groundwater circulation and significant evaporation.

Sub-group II has a member of Metahara Bore holes, spring and Lake Beseka characterized by high TDS and Na-HCO3-CO3 and Na-HCO3-CO3-Cl water types indicating of saline water of Lake Beseka and Bore holes and spring water by deep circulation and affected by ion exchange.

Sub-group III has a member of Abadir 04 and Wonji Shoa are characterized by TDS > 1420 mg/l and Na-HCO3-SO4-Cl and Ca-Na-HCO3 affected by mixing of fresh and saline water that shows the reverse ion exchange and significant evaporation and Wonji Shoa is significantly affected by evolution of groundwater cation exchange, dissolution and water-rock interaction.

Sub-group IV has a member of Kora, Awash fall, Melka Jilo, Boset/Bole, Bole/Golgota, Awash and Koka are characterized by TDS > 800mg/l and Ca-HCO3-Cl, Na-HCO3, Na-HCO3-SO4, Ca-Na-HCO3, Na-Ca-HCO3-SO4, Na-Ca-HCO3-Cl and Na-HCO3-SO4 indicate that there is a mixing of fresh and saline waters , affected by evaporation, dissolution of pyrite and mixing of groundwaters and by deep circulation and pyrite oxidation and significant evaporation.

Sub-group V has a member of Dallo, two Sire waters, Meti and Metahara Bela are characterized by TDS between 280 -380 mg/l and Ca-Na-HCO3, Ca-Mg-Na-HCO3, Ca-Mg-HCO3 and Ca-Na-Mg-HCO3 water types of shallow regional aquifer with ion exchange effect and influence of reverse exchange.

Sub-group VI has a member of Arerti and Welenchiti are characterized by TDS between 390 to 460 mg/l and Ca-Na-HCO3, Mg-Ca-Na-HCO3, Na-Cl-HCO3, Ca-Mg-HCO3, Na-Ca-HCO3, NaHCO3 and Na-Ca-HCO3-Cl indicating the shallow portion of regional confined aquifer affected by ionic exchange, dissolution and deep circulation and highly saline ground water.

Sub-group VII has a member of Sire and Rift floor with TDS value between 560 – 740 mg/l. Bofa, Bote Lema and Alem Tena water samples are Na-HCO3 water. Two water samples from Sire area are characterized by Ca-Na-Mg-HCO3 showing the slight evolution and ion exchange of the water and dissolution of minerals. This is the characteristics of shallow portion of regional groundwater which is affected by ionic exchange.

Sub-group VIII has a member of Eastern escarpments of Asella-Arboye characterized by low TDS value between 58- 118 mg/l and Ca-Mg-HCO3 water type indicating shallow and fresh recharge area ground waters. Whereas, Guna, Gonde, NW of Iteya, Huruta and Arboye are characterized by Ca-Mg-Na-HCO3 show slight evolution and dissolution of minerals and ionic exchange effect. While Arboye spring shows the Ca-Na-HCO3 that indicates the ionic exchange and water-rock interaction.

Sub-group IX has a member of Western escarps(Chefe Donsa, Kessem, Amude) and Rift floor that are characterized by low TDS values between 210- 360 mg/l and Ca-Na-HCO3 water type are collected from the Rift which indicates the effect of ionic exchange, precipitation and dissolution of minerals along the flow path.

4.6. Groundwater Potential and Flow

Groundwater flow system in the NMER is controlled by the nature of geomorphological, geological and geological structures. Groundwater flow in the NMER is characterized by the complex geological structures that controls both regional and local aquifer systems. The NMER major structural orientations vary from the plateau, rift escarpment and rift floor in both eastern and western side of the study area.

Groundwater flow from this eastern plateau to the rift system in to the Dera-Iteya plain, Lakes region (Ziway area) and Kereyu basin is characterized by deep sub-surface regional flow than being discharged to the surface in the nearest distance adjacent to the escarpment. This is observed from the deep groundwater well in Dera-Iteya plain that shows deep aquifer system and hot springs in Sodere area. Shallow groundwater is not observed along this eastern escarpment due to the deep-seated structures that infiltrate groundwater into deep aquifer system. While in the escarpments very adjacent is characterized by springs with high discharge like the Gudelcha spring South East of Huruta is currently serving as a water supply source for Huruta, Iteya, Dera and Awash Melkassa towns. Similar high discharge spring is situated at foot hill of the Chilalo volcano near Gonde town also serving as the water supply source for some villages around Anole Massacare Museum and Tero area. This shows that there is a high recharge source in the Plateau region that locally discharged in the nearby adjacent escarpments and regionally flow in to a very deep through structures that can be discharged at the rift floor. But the discharge zone at the axis of the rift floor is not well observed due to the deep subsurface flow except hot springs that emerges to the surface through faults situated in Sodera, Boku and Geragadi.

Shallow groundwater flow system is common in the Wonji basin due to the aquifer system formed by deep alluvial deposits and local recharge from Awash River. Whereas, in Adama, Wolenchiti and Kereyu basin shallow groundwater flow is not observed due to the lack of local recharge and rare contribution of rainfall and deep ground water flow system. While in the Beseka lake region, there are a lot of springs that are discharged and shallow hand dug wells are observed at the banks of the lake. This shows that the groundwater flow is from the Fantale Volcano that serves as a recharge source to the Beseka Lake region that are interconnected due to the deep intensive fractures oriented N-S and Jigsaw puzzle structure and deep seated faults.

Groundwater flow system from the western Plateau and adjacent escarpment to the rift floor is controlled by cross-cutting structures of NE-SW marginal fault of the MER and the E-W trending YTVL. Local and regional groundwater flow system from the western escarpment to the rift floor is characterized by both shallow and deep flow systems. The E-W trending structure that creates the `hydrogeological window` as reported by previous authors formed large plains and well fields like the Akaki, Adaa-Becho plain, Chefe Donsa and Mojo fields. These areas are characterized by shallow and deep ground waters from local flow and recharge from rainfall that are observed by hand dug wells. Geological structures in these regions are characterized by faults with short length escarps and lateral distances that die out and followed by flat plains.

In some areas with horsts and full and half grabens are observed in the western part of Adama city across the express way up to the Mojo Fields. In this small grabens, unlike the Eastern escarpments of the NMER, shallow groundwaters and hand dug wells are commonly observed. This shows that there is a shallow ground water circulation and enough recharge from rainfall and deep sub-surface regional flow.

Geomorphological set up of the NMER system has also a great role in controlling groundwater flow system in the region. The tectono-magmatic evolution created different landscapes of the NMER with different topographic features. There are different volcanic land forms like shield volcanoes, composite volcanoes, cinder cones, calderas, craters, Maars, basaltic and rhyolitic lava flows and recent lake sediments covered the NMER system. The drainage networks and topographic features in the study area is also controlled by the geological and structural set up following the weak zones.

The influence of runoff after heavy rainfall is common in the study area in Adama, Kereyu and Wolenchiti basins due the loose volcanic ash and pyroclastic materials and reworked materials that can be easily eroded forming the gorgy flow networks and drainage systems. There are a lot of deep gorgy drainage canals formed by the influence of this heavy erosion influence that facilitates high overland flow than infiltration to recharge groundwater. It is also observed that there are improper sand mining from every gorgy drainage networks in the study area that makes the beds of the flow channel and from some agricultural fields to be impermeable and facilitate the runoff water to be high than to be infiltrated to the groundwater. Some quarry sites situated at the NW part of the Adama city facilitates the runoff from Kechema ridge to make the adjacent nearby agricultural fields to form gorgy drainage that makes a high and disastrous flooding in the inner part of Adama city.

Groundwater contour map (Fig.4.12) of the study area shows that the depth of groundwater is controlled by deep seated structures and geomorphological set up formed by the evolution of the rift system and volcanic land forms initiated during extension, dike swarms, fissural and central eruptions. Groundwater flow as observed from contour map shows that the Beseka lake region is observed as the discharge zone due to the sub-surface flow from Fantale volcano that serves as a water divide (recharge zone) and intensive structures hydraulically connected to the lake. The Kereyu, Wolenchiti and Eastern part of Melka Jilo and Dire Arerti have rare groundwater wells that shows these regions are categorized as discharge zone. In these regions groundwater potential is very rarely explored and exploited and therefore the area is highly water scarcity. This scarcity of groundwater resource is due to the aridity and lack of rainfall as well as the regional groundwater flow system from the two plateau sectors circulated deep in to the subsurface rather than being shallow and discharged to the surface.

The Adama basin is also characterized as the discharge zone relatively as compared to the Wolenchiti and Kereyu basin. A lot of groundwater wells drilled in Adama basin up to the depth of between 200 to 400m have a potential of yielding groundwater in many bore holes in the vicinity between the Kechema Ridge in the west, Dibibisa and Dabe Soloke in the Eastern region. Whereas, in the Akaki, Adaa plain, Mojo and Chefe Donsa are also categorized as a potential zone that get sufficient recharge from the regional flow of western plateau and adjacent escarpments and local recharge from rainfall. Therefore, these regions contains both shallow and deep aquifers systems with good potential.

The Wonji basin is characterized as a discharge zone that comprises a lot of groundwater wells that are currently serving for water supply. The shallow aquifer of the Wonji basin contains hydrostratigraphy of deep alluvial deposits and reworked pyroclastic materials that gets recharge from Koka reservoir and Awash River hydraulic interconnection with this aquifer system. There is a structural influence on groundwater flow between the Wonji basin and Dera Iteya plain. As observed from structural analysis the E-W trending fault formed the flow block from Wonji basin and Awash River to the Dera Iteya plain.

Groundwater flow in the Dera-Iteya plain, flat plain between Keleta and Sire, Tulu Moye and horsts and graben areas between at the eastern part of Ziway Meki area shows that scarcity of groundwater potential due the deep seated faults that makes regional groundwater flow the eastern escarpment to flow deeply in to the subsurface. Shallow groundwater circulation is rarely observed in the region due to the scarcity of rain fall and local ground water circulation. Groundwater recharge from Chilalo volcano discharged at Gonde high discharge spring near Kulumsa flows further deeply in the complex structure of the Asella Fault rather than being discharged at the adjacent escarpment. Further North at Huruta, similar high discharge spring of Gudelcha is emerged east of Huruta town that is currently serving as water supply source of the area. Whereas, in the Sire border fault system there are very spring and bore holes and in flat plain along the road to Keleta-Dera groundwater flow system is changed in to deep aquifer system as observed from very deep bore holes up to 250m with very low discharge. Similar scenario is commonly observed in Iteya plain up to rift axis up to Anole historical Museum.

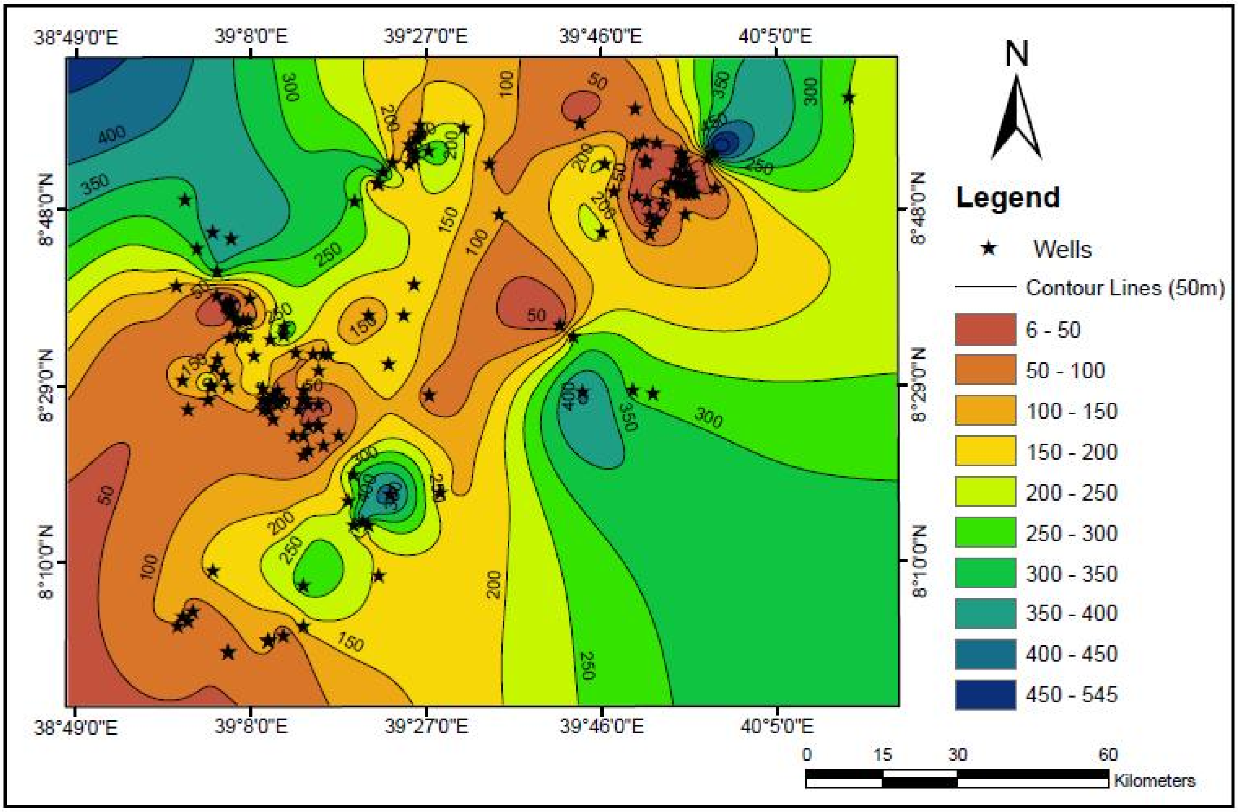


Figure 4.12: Groundwater Table and bore boles map

The conceptual model (Fig.4.13) is used to summarize the systematic groundwater flow system in the NMER. The rift extension is subjected to the thinning of the crustal system and shallowing of the magma chamber that makes the deep regional groundwater flow system to have a very high temperature and it also created a lot of hot springs and geothermal steams in the region like Sedere hot spring, Boku steam and Geregedi hot spring.

Groundwater flow system from the western escarpment to the rift floor is characterized by both regional and local flow of both shallow and deep aquifers along the E-W and NE-SW of the YTVL and NMER that makes groundwater to flow deeply to the rift sector and locally in the Akaki, Adaa, Chefe Donsa and Mojo plain. Whereas, in the Eastern escarpment, the local ground water flow is restricted to very adjacent escarpment and most of the flow system from plateau is characterized by deep regional ground water flow system to the rift sector. In the axis of the rift floor the flow system is affected by WFB and the tectono-magmatic activities of the Fantal-Dofan, Boset-Kone, Gedemsa-Boku calderas and central eruptions and small scoria cones that followed the same orientation with WFB system. Groundwater flow in this axial center is characterized by deep, highly evolved and transported, geothermally influenced with high Temperature except in some pocket areas with shallow groundwater flow system from local recharge that stored in alluvial grabens like Wonji basin. Thermal spring observed in rift floor are also related to the deep seated structures and are horizontal and vertical highly evolved groundwater flow system.

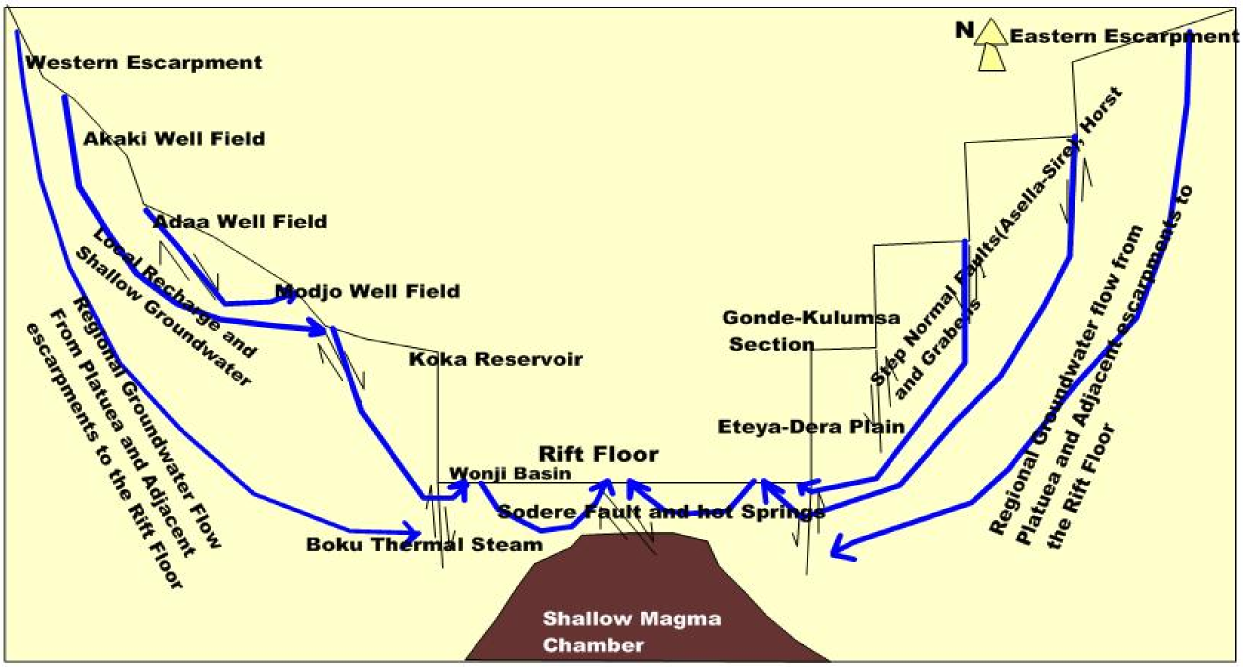


Figure 4.13: Conceptual groundwater flow model of regional and local groundwater flow pattern and geological structures of the NMER, not to scale.

5. Conclusions and Recommendations

5.1. Conclusion

The Northern Main Ethiopian Rift System is characterized by recent geological, structural and tectono-magmatic activities. The major fault systems are the NE-SW border faults and NNE-SSW right stepping en-echelon arrangement of the WFB system with the E-W extensional direction. The topographic features and drainage networks are formed along the ridges like Dabe Soloke, Kechema, Dibibissa, Golba Tegene, Chokonu, Abba Geda and Boku areas. The geological structures and geomorphology is used by integrating with hydrogeological and hydrogeochemical methods to investigate the occurrence and flow of groundwater in the NMER.

Groundwater flow from the Western escarpment is influenced by YTVL that cross-cut the NMER structure which is characterized by both shallow and deep productive aquifer systems in Akaki, Adaa plain, and Modjo well field. This is due to local and regional recharge from the plateau sector and good potential of rainfall. The Aquifer productivity in the Beseka Lake region, Dire Arerti, Melka Jilo, Kerayu and Wolenchiti basin is characterized by the low yield that shows low productivity except in some deep aquifers. This is due to low local recharge and deep circulated regional ground water flow from Plateau and adjacent escarpments. The Wonji basin shallow aquifer system of alluvial deposits is interconnected with the recharge from Koka reservoir and Awash River flow. The Dera and Iteya plain is characterized by deep seated structures that facilitate a deep circulation of groundwater flow system. In the Rift axis groundwater flow is associated to the intense structures and deep circulation as observed from thermal springs and steams in Sodere, Geregedi and Boku thermal spring.

Hydrogeochemistry shows that Ca-Mg-HCO3 of shallow fresh groundwater at the two plateau, Ca-Mg-Na-HCO3 to Ca-Na-HCO3 in the adjacent escarpments and to the Rift sector NaHCO3 water type as deep and highly evolved groundwater that undergone strong water rock interaction in the subsurface. The TDS and EC values also show very high values that are associated to the role structures and gromorphology in the Beseka Lake region.

5.2 Recommendation

It is recommended that the detail hydrogeological map of the whole Rift system in general and NMER in particular is not conducted well to solve the strong water scarcity problem of the area. Further studies should also be conducted by integrating the hydrogeophysics with detail RS and GIS, geological and structural mapping to identify the surface and subsurface structures for detail groundwater potential zonation and data base establishment. Detail study at the sub-basin level within the NMER sector should be conducted for each Adama, Wolenchiti, Kereyu and Beseka lake regions.

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Annexes

Annex I: Existing Well Data around Lake Beseka								**Annex II: Wells existing in the East Shewa zone and Amhara Regions**							
Well ID	**Easting (m)**	**Northing(m)**	**Elevation(m)**	**Depth(m)**	**SWL(m)**	**DWL(m)**	**Yield (L/sec.)**	**Well ID**	**Easting (m)**	**Northing(m)**	**Elevation(m)**	**Depth(m)**	**SWL(m)**	**DWL (m)**	**Yield (L/sec.)**
Be1	601152	980062	953.14	-	4.5	-	-	LO-1	510038	937615	1633	130	4.12		
	603938	979874	949.5	-	4	-	-	LO-2	506730	937464	1651	100			2.22
Be3	600941	979443	953.36	-	5.62	-	-	LO-3	506569	938054	1661	250			4.44
Be4	592664	986463	981.29	53.3	30.94	-	-	LO-4	509134	939939	1682	120			3.76
Be5	602168	979920	950.24	-	4.5	-	-	LO-5	508030	943076	1711	120			2.9
Be6	601259	977156	957. 62	6.4	-	8	-	LO-6	507296	941463	1694	105			2.96
Be7	600867	976796	951. 32	4.76	-	6.5	-	LO-7	515176	943875	1750	160			3.9
Be8	601097	976963	964	65.5	15.26	-	-	LO-8	510372	947373	1754	110			5.55
Be9	600767	976710	947	32	12.65	-	6	LO-9	510614	952023	1804	68			5.12
Be10	602298	979030	950 42	6.27	-	23.2	-	LO-10	507728	955897	1842	48			3.97
Be11	602192	976337	968.31	52	15.9	-	10	LO-11	514334	954970	1880	101			3.8
Be12	600048	976634	959. 48	15.32	-	6.5	-	LO-12	521272	949734	1898	252			3.3
Be13	600885	972384	990	-	42.7	-	-	LO-13	518460	946916	1849	185			2.5
Be14	603967	980053	-	-	-	-	-	LO-14	521115	948060	1904	283			3
Be15	605405	982881	949.8	30	6.15	-	4	LO-15	523525	944293	1736	120			3.8
Be16	600186	976837	960	62	13.2	-	10	LO-16	509597	958520	1844				0.33
Be17	594785	969889	987.96	40	33.43	-	10	LO-17	508823	957924	1850				0.3
Be18	595371	971036	975.74	37	25.65	-	3	LO-18	508994	955227	1831				
Be19	596616	973698	965.23	37	14.68	-	3	LO-19	509913	952151	1795				0.2
Be20	602009	979970	950.95	32	2.8	-	-	LO-20	509891	952058	1797				0.2
Be21	588477	988474	1005	-	52.8	-	-	LO-21	509800	952640	1798				0.25
Be22	584990	982082	1120	200	159.5	-	-	LO-22	508447	952941	1814				0.33
Be23	591516	993908	994.6	-	43.47	-	-	LO-23	508194	952954	1814				0.3
Be24	589343	992721	985.1	-	32.95	-	-	LO-24	508165	953217	1815				0.33
Be25	586845	976572	1050	116	90.7	-	-	LO-25	509619	953910	1815	15			0.42
Be26	604599	986801	958.1	-	7.71	-	-	LO-26	509531	954026	1816	15			0.2
Be27	604682	978812	952	-	10.18	-	-	LO-27	513568	957880	1841				
Be28	592939	984497	964.01	-	2.23	-	-	LO-28	510565	954590	1814	15			0.25
Be29	600250	984000	960.16	56	13.6	-	-	LO-29	510679	954123	1817	32			

Be30	584500	968500	1200	205	177	-	-	LO-30	510365	954125	1810	15			0.25
Be32	600646	980333	953.39	-	4.04	-	-	LO-31	509917	953997	1810	25			0.33
Be33	594409	984369	955	-	-	-	-	LO-32	509961	953356	1802	25.5			0.2
Be34	595426	984300	952.6	-	1.75	-	-	LO-33	509806	953792	1819	15			0.25
Be35	601116	979750	963.36	-	5.14	-	-	LO-34	510245	953283	1800				0.22
Be36	593879	971578	967.37	20.4	-	-	-	LO-35	509677	953088	1807				0.3
Be37	600517	982590	953	21.55	3.71	-	-	LO-36	510599	952248	1806	38			
Be38	600305	982301	953.21	-	3.7	-	-	LO-37	510895	952183	1800	35			0.25
Be39	599903	979853	953.93	50.65	4.43	-	-	LO-38	511654	950667	1780	16			0.33
Be40	598914	980723	953.02	30.24	3.24	-	-	ES-3	513615	947586	1779	203	50.12	103.72	16.68
Be41	593282	982350	953.24	16.3	2.3	-	-	ES-4	480885	931783		125	79.2	81.51	5
Be42	593035	982691	958.32	73 8.18	-	-	-	ES-14	471568	924324	1771	186	58	62.95	9.2
Be43	595362	986153	973.83	59	23.16	-	-	ES-15	516888	937379	1616	200	16.1	21.95	9.2
Be44	600252	984352	958.93	50.5	8.62	-	-	ES-16	499760	957578	1910	152	54.85	56.2	9.2
Be45	596921	976889	955.14	71.45	4.2	-	-	AM-1	547301	984124	1771	300	141.3		25
Be46	593389	974555	955.53	46.3	4.54	-	-	AM-2	549970	984541	1754	280	190		1
Be47	591413	975520	959.35	29.45	7.7	-	-	AM-3	540905	980439	1847	351	120		30
Be48	598043	978183	965.16	50.45	14.25	-	-	AM-4	547674	987202	1753	140	133		2.8
Be49	599940	977965	963	23.5	4.62	-	-	AM-5	547621	986845	1750	155	128.4		3.7
Be50	599118	977968	958.64	42.45	8.08	-	-	AM-6	548417	988083	1745	162	115.7	116.33	4.5
Be51	590483	970777	1020	-	57.62	-	-	AM-7	546500	984583	1745	186			
Be52	600331	981811	953.42	44.45	3.65	-	-	AM-8	548235	989763	1256	150	127		1.5
Be53	600207	981559	952.84	-	3.85	-	-	AM-9	542651	982173	1791	151	91		
Be54	599916	977954	964	-	7.9	-	-	AM-10	539660	977988	1887	144			
Be55	591853	994109	994.6	-	43.47	-	-	AM-11	547292	982768	1766	180	147	149	2.53
Be56	591843	993329	1001	-	48.28	-	-	AM-12	535224	974501	1978	285	187	188.55	5.5
Be57	589634	992954	985.1	-	32.95	-	-	AdTw1	507013	968324	1877	370	21.05	37.69	37
Be58	609923	985407	967	-	63.29	-	-	AdTw2	503928	965114	1885	303	24.95	66	43
Be59	596854	974753	973	-	15.57	-	-	AdTw3	507887	960487	1848	324	6.91	14.31	60
Be60	605069	983266	952	-	6.09	-	-	AdTw4	501470	974992	1911	336	20.3		
Be61	602707	975416	963	-	23.02	-	-	AdTw5	510700	967019	1908	384	51.12	69.06	57
7Be31	580000	990000	1000	50.6	25	-	6.7	1	527000	967000	2200				
10	601000	983000	1000	56	13.6	14.98	12	2	546000	986000	1720	134	129	134.8	12
12	602000	979000	950	42.6	8.8	-	2	3	557000	989000	1750	198.1	188.9		1
14	601000	980000	950	49.6	11.19	14.43	7	4	540000	978000	1900	184.4	115.8		0.76
16	612000	977000	-	100	-	-	-	5	546000	982000	1800	184.4	115.8	135.8	0.75
136	601000	976000	960	42	20.6	30.1	6	6	562000	982000	1150	102			

140	600000	976000	960	45	25.6	30.6	8
142	602000	976000	966	52	42.8	49.3	8
ALPW3512	606822	984277	938	595	46.65	62.10	100

Annex III: Existing Well Data in Arsi and West Hararge Zone

ID	Easting	Northing	Elevation	Depth	SWL	DWL	Yield
AR-1	590639	936870	1530	288	120.22	136.57	4.4
AR-2	578805	947750	1200	236	132.25	138.57	3.4
AR-3	580609	936751	1618	400			
AR-4	594564	936407	1719	285	154.35	199	4.2
AR-5	552351	916424	1795	170	61.85	120.6	4
AR-7	542260	916154	1664	420	295.45	297.68	3.4
AR-8	536828	910778	1752	400	Dry		
105	535000	920000	1650	268	256		0.3
107	510000	885000	1700	60	16.5		
110	534000	915000	1840	200			
111	525000	898000	2110	266	245		
112	535000	910000	1750	200			
113	538000	910000	2110	200			
114	521000	888000	2360	75			1.8
116	518000	887000	2400	126			5.8
118	500000	890000	1650	91	42.7	43.4	5
119	501000	892000	1650	102	83		1.5
120	502000	891000	1650	63.5	42.8		1.4
121	503000	893000	1680	78	52.8		1.8
122	507000	901000	1770	160	128		1.3
124	518000	887000	2150	105	80	80.25	1.1

8	564000	972000	1320	102.7			
9	591000	986000	1020	83.2	34.54		12
11	591000	993000	1000	71	46.2		11.76
15	617000	993000	950				
18	512000	948000	1780	104	39		
21	514000	951000	1780	61.9	12.2		2.52
22	513000	951000	1780	61.9	36.6	57.9	1.3
25	512000	951000	1780	152.4			5.3
26	529000	944000	1650	120	100		8
28	530000	944000	1600	158.6	31.2	43.4	2.75
31	528000	941000	1600	117.3	103.6	106.6	2.5
32	527000	944000	1650	105	95		
34	547000	958000	1495	185			1.1
35	552000	959000	1400				
36	545000	952000	1495	167.6	136.1	160.5	1.36
37	538000	952000	1580	125			5
38	562000	942000	1230				
39	506000	935000	1650	93	24		2
42	502000	933000	1600	70	45		
43	525000	924000	1600	76	56.6		3.5
44	520000	937000	1546	60.7	15		
45	520000	935000	1578	60.5	32		
46	517000	935000	1532	96.3	19		
47	517000	933000	1577	90	17		
48	518000	933000	1603	60	46		
49	518000	933000	1584	81.4	23		

125	525000	890000	2230	170				50	519000	936000	1595	100.2	45		
126	510000	885000	1750	70	22.6		2.66	52	517000	935000	1600	80	50		
127	540000	900000	2000	193				53	518000	935000	1574	100.1	27		
WH-1	685360	1017109	1412	129.4	91.42		5.1	54	521000	935000	1560	107.5	29		
WH-3	668811	1001717	1220	228	60.8	88	1	55	520000	934000	1577	73.8	31		
WH-4	677655	1014917	1402	267.4	153	188.23	4.4	56	519000	931000	1613	92	62		
WH-6	650764	972995	1320	132	39.2	58.1	6	57	519000	935000	1555	42.4	11		
WH-7	685854	1009744	1528	196	86.61	170.67	5.6	64	525000	937000	1540	103.6	14.9	17.56	9.2
WH-8	691053	1020494	1341	95	53.16	58.57	6	68	525000	935000	1540	47	14	17.2	3.2
WH-9	681157	1014332	1466	148	90		3.1	69	525000	935000	1540	24.5	8.6		
WH-10	677652	1014917	1402	264			2.2	76	524000	933000	1540	73			5
WH-11	695877	1015842	1418	51			4	77	528000	934000	1540	33	8.6		3
WH-12	696722	1018866	1382	122.7	66.6	67.45	8	78	528000	930000	1540	59	13.7		5
WH-13	669175	1006477	1282	37	6	14.72	5.2	79	526000	930000	1540	31	11		1.2
WH-14	695477	1016353	1389	57	16.5		3.3	83	528000	930000	1540	50	12.4		3
WH-15	695667	1016299	1405	42	14.5	21.2	5.6	84	525000	928000	1540	84	7.05	26.68	2
WH-16	695608	1016170	1407	62	7.2	25.1	6.6	87	528000	930000	1540	82			
WH-21	669069	993048	1597	177	Artesian			89	526000	925000	1540	69	7.2		5.5
WH-22	676209	1005803	1353	150	67.05	88	1.3	91	529000	926000	1540	70.4	6		5.5
WH-23	655718	975718	1605	78	18			93	532000	928000	1540	63			6
WH-24	684940	1016759	1423	188	99.23	99.3	6.5	96	526000	934000	1540	49	8.9		5.4
WH-26	668144	1011413	1327	272	162	256.63	0.51	99	523000	928000	1540	58	10.9	16.8	5.8
WH-30	695873	1015826	1413	120				108	518000	887000	2130	120	90	102	
WH-31	696719	1018863	1387	105				116	518000	887000	2400	126			5.8
WH-32	684294	1011906	1459	200				126	510000	885000	1750	70	22.6		2.66
WH-33	687372	1018853	1378					128	501000	939000	1600	120			
WH-34	686247	1017940	1387	250				129	525000	935000	1540	32			0.27

WH-35	677356	1011149	1434	150				132	523000	935000	1560		24.4		
WH-36	680652	1014328	1455					133	550000	936000	1450	80			
WH-37	694125	1019865	1327	120	78		6	134	542000	942000	1500	200	190		
WH-38	671235	1012743	1341	226	156		4	135	502000	980000	950				
WH-39	660737	1004315	1140	127				137	603000	976000	960	51	85.9	90.4	5
WH-40	657745	1005906	1144					139	601000	977000	960	74	14	16	8
WH-41	652511	996025	1106	350	53.28	120.83	5	141	602000	977000	960	42			8
WH-42	650907	997415	1046					143	607000	977000	1000	55	26	30	5.5
WH-43	668149	1011415	1335	272				144	605000	974000	980		69.1	70.1	6.5
WH-44	681409	1009313	1400	151	53	57.97	5.6	145	601000	972000	980	100	83	88	4.5
WH-45	687371	1018850	1376					146	594000	968000	1000	73	50		5.5
WH-46	693001	1021056	1316				4.4	147	602000	979000	950		14.9		8
WH-47	694136	1019853	1329					169	576000	950000	1238	31.26			
WH-48	674163	1025893	2266					174	560000	968000		205			1.5
WH-49	653270	998630	1072	200	39.45	83.25	4.5								
WH-50	653928	976613	1561	186	19										
WH-51	669172	1006468	1412	150.7	53.4	58.35	5.6								
WH-52	652464	996002	962	266	62.27	120.83	6								
WH-53	641424	1007510	892	257	72.95										
WH-54	633631	995259	962	252	101.17	138.81	20								
WH-55	627464	1015684	823	192	75.66	76.78	50								
WH-56	685362	1011710	1366	130	92.5		12								
WH-57	669172	1006468	1412	130	91.42	91.5	8.5								
WH-60	695124	1018271	1373	341			10								
WH-61	695550	18517	1362	350											
WH-64	692995	1021060	1321	94			2.3								

Annex IV: Water Quality Data

SN	Sample Number	Source of sample	Turbidity	Total Dissolved Solids	Suspended Solids	pH	EC	Total Hardness ($CaCO_3$)	Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Iron (Fe)	Manganese (Mn)	Chloride (Cl)	Sulfate (SO_4)	Nitrate (NO_3)	Nitrite (NO_2)	Alkalinity (CO_3^{2-}, HCO_3^-)	Fluoride (F)	Total Phosphorus (TP)	Ammonium ($NH_3 + NH_4$)
			NTU	mg/l	mg/l		ms/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	D4-5	spring	Trace	180	8	7.3	302	150	40	12	1.7	11.6	Trace	Trace	9.1	0.67	5.97	0.006	144	0.56	0.32	0.23
2	C1-1	spring	0.365	280	12	7.64	426	172	49.6	11.52	7.7	32	0.13	Trace	10.92	2.66	2.93	0.003	220	0.63	0.24	0.09
3	D1-14	spring	16.8	280	0	7.6	428	170	41.6	15.84	9	31.5	0.05	Trace	8.19	4.47	4.02	0.024	222	0.66	0.21	0.23
4	D1-15	well	Trace	268	12	7.42	446	204	52	17.76	4.3	23.5	0.03	Trace	7.28	1.05	2.29	0.003	240	0.79	0.33	0.08
5	D1-16	spring	Trace	240	12	7.84	388	176	50.4	12	3.6	16.5	0.04	Trace	8.19	0.1	4.26	0.004	210	0.53	0.76	0.25
6	D1-13	spring	Trace	300	12	6.91	482	202	52	17.28	6	34	Trace	Trace	10.01	2.76	2.6	0.01	250	0.54	0.34	0.08
7	D1-20	spring	Trace	280	16	7.83	444	112	36	5.28	7	60	Trace	Trace	10.92	1.71	3.87	0.001	230	0.65	0.25	0.16
8	D1-10	well	Trace	612	12	7.72	1036	216	56	18.24	17.5	150	0.01	Trace	42.77	7.89	3.42	0.01	498	3.14	0.34	0.12
9	D1-18	well	Trace	320	12	7.44	492	172	56	7.68	8.4	53	Trace	Trace	11.83	3.14	2.37	0.01	244	1.79	0.34	0.08
10	D1-3	well	Trace	600	8	7.7	959	188	60	9.12	17	170	Trace	Trace	22.75	3.52	4.99	0.006	486	4.49	0.31	0.11
11	D1-4	well	Trace	632	8	7.83	952	172	59.2	5.76	18	176	Trace	Trace	23.66	4.37	1.07	0.01	480	2.44	0.55	0.12
12	D1-9	Hand Pump	Trace	460	12	7.49	719	260	76	16.8	10.5	70	0.01	Trace	19.11	9.88	10.79	0.01	360	1.07	0.3	0.22
13	D1-8	Hand Dug	Trace	440	8	7.37	676	250	88	7.2	11.3	68	0.27	Trace	19.11	7.7	6.78	0.01	336	0.71	0.29	0.23
14	D1-17	Hand Dug	0.365	440	12	7.55	704	250	73.6	15.84	16	65	0.01	Trace	19.11	8.27	7.44	0.01	340	0.69	0.31	0.29
15	D1-12	Mojo River	34.31	440	60	7.94	687	218	51.2	21.6	11.6	75	0.06	Trace	23.66	25.65	7.37	0.52	310	0.82	0.32	0.42

16	D1-11	spring	Trace	280	8	7.82	449	196	69.6	5.28	7	29.5	Trace	Trace	6.37	2.76	4.64	0.004	230	0.52	0.33	0.11
17	D1:21	well	Trace	410	10	7.75	615	188	52	13.92	18.5	82	0.13	Trace	11.83	25.15	2.2	0.058	316	0.74	0.29	0.23
18	D4-4R	well	Trace	390	8	8.01	583	146	45.6	7.68	18	83	0.06	Trace	9.1	34.9	5.36	0.038	286	0.63	0.39	0.27
19	A1-7	Mojo River	134.32	800	120	7.73	1278	228	62.4	17.28	23.5	172	0.16	Trace	131.05	100.38	41.94	Trace	356	0.92	0.51	0.52
20	D1-26	well	Trace	560	12	8.21	9.29	50	16	2.4	12.1	190	0.08	Trace	41.86	21.16	0.68	Trace	424	4.78	0.33	0.26
21	A1-1	Awash	167.54	460	180	7.32	692	192	68	5.28	18	82	0.29	Trace	55.52	33.02	22.25	0.054	220	1.63	2.75	0.34
22	D1-2	well	Trace	280	8	7.44	463	106	32	6.24	19.5	63	0.08	Trace	9.1	11.97	0.99	0.03	214	1.69	0.31	0.25
23	A1-2	Awash	65.7	214	106	8.2	327	110	36	4.8	7	35.5	0.24	Trace	14.56	14.96	2	Trace	140	0.94	0.28	0.33
24	D1-1	Hand Dug	0.73	1420	20	7.44	2230	720	224	38.4	49.5	154	0.1	Trace	192.03	243.21	71.23	0.016	486	0.54	1.16	2.01
25	D3-13L	Koka Lake	39.06	210	70	7.65	332	106	29.6	7.68	7.7	33	0.34	Trace	17.29	14.4	2.27	0.05	140	0.72	0.26	0.32
26	D1-25R	River /Cana	77.38	220	120	7.98	342	108	29.6	8.16	7.2	39	0.32	Trace	14.56	11.74	3.01	0.109	152	1.06	0.42	0.41
27	B1-3	Pond	417.93	118	502	6.85	169	50	16	2.4	12.5	14	4.64	Trace	21.84	2.66	0.19	1.6	72	0.48	0.73	1.96
28	B1-12	Lake Besek	13.87	2240	30	9.28	3260	30	6.4	3.36	41	840	Trace	Trace	258.47	351.79	0.8	0.08	1156	12.72	0.85	0.65
29	B1-7	Lake Besek	14.6	2600	40	9.25	3840	26	6.4	2.4	43	940	Trace	Trace	313.98	383.37	0.35	Trace	1324	11.34	1.11	0.11
30	B1-9	Lake Besek	20.81	3060	40	9.41	4470	28	5.6	3.36	51	1120	Trace	Trace	346.74	483.09	0.16	Trace	1648	23.91	1.28	0.3
31	D4-6R	kesem River	Trace	270	8	8.44	442	146	35.2	13.92	5.2	48	0.02	Trace	23.66	21.83	1.3	0.012	180	0.68	0.21	0.23
32	D4-2	well	Trace	1060	12	8.25	1582	42	4.8	7.2	24.5	390	0.02	Trace	140.15	182.16	17.59	0.01	430	11.46	0.17	0.14
33	B1-2R	River /Cana	21.17	240	30	7.76	357	100	34.4	3.36	7.3	43.5	0.39	Trace	18.2	31.02	1.22	0.023	160	1.07	0.58	0.59
34	B1-11	Lake Besek	14.6	2540	20	9.54	3820	28	6.4	2.88	46	1000	0.15	Trace	292.14	360.1	3.61	0.076	1290	3.49	1.69	0.62
35	B1-8	spring	Trace	980	10	8.02	1450	64	12.8	7.68	26.5	350	0.09	Trace	105.57	169.08	3.32	0.023	480	5	0.66	0.54
36	D3-18R	well	Trace	1500	8	8.11	2280	180	36	21.6	26	495	0.05	Trace	193.85	284.2	10.38	0.01	650	4.07	0.59	0.45

37	B1-13	Lake Besek	25.92	3160	50	9.34	4630	44	9.6	4.8	54	1130	Trace	Trace	360.4	485.3	0.25	Trace	1698	22.68	1.24	0.28
38	D4-7	Hand Pump	Trace	870	10	8.44	1337	50	12.8	4.32	5.5	276	0.01	Trace	77.36	49.97	9.35	0.002	544	0.73	0.45	0.19
39	A1-5	Awash	19.71	1020	30	8.5	1530	86	29.6	2.88	21	345	0.18	Trace	102.84	146.48	0.78	0.012	572	3.55	0.84	0.79
40	B1-10	Lake Besek	17.52	2880	24	9.33	4340	50	9.6	6.24	52	1080	0.04	Trace	330.36	490.29	0.21	0.002	1490	5.37	1.76	0.57
41	D1-23	well	Trace	420	10	7.85	625	96	24.6	8.16	20	121	0.02	Trace	14.56	16.07	1.42	0.01	316	3.08	0.28	0.21
42	D1-25W	well	Trace	560	10	7.98	813	40	11.2	2.88	22.5	188	0.03	Trace	27.3	32.46	1.55	0.01	392	3.24	0.07	0.2
43	D4-6	River	Trace	340	8	7.82	568	192	48.8	16.8	4.9	50.5	0.01	Trace	31.85	8.75	0.25	Trace	272	0.6	0.09	0.4
44	D4-6R2	River	3.29	280	14	8.43	429	170	56	7.2	3.7	38.5	Trace	Trace	28.21	16.91	0.02	Trace	190	0.64	0.16	0.2
45	D4-6R3	River	2.92	290	16	8.23	473	174	50.4	11.52	5.1	37	0.03	Trace	29.12	6.56	1.69	0.019	202	0.56	0.26	0.27
46	D4-4W	well	Trace	400	12	8.32	611	172	42.4	15.84	21	77	0.05	Trace	15.47	18.28	12.22	0.03	304	2.42	0.14	0.32
47	A1-3	River	58.035	300	80	7.78	411	130	37.6	8.64	12.3	51.5	0.31	Trace	20.93	42.55	0.86	Trace	168	1.4	0.22	0.34
48	D3-2	Spring	Trace	460	10	7.74	755	344	128	5.76	8.1	33.5	0.14	Trace	22.75	20.05	15.33	Trace	324	0.6	0.19	0.19
49	D3-12	Well	Trace	80	12	7.03	123	54	12	5.76	3.6	6.7	0.3	Trace	4.55	0.22	9.76	Trace	54	0.47	0.28	0.33
50	D3-8	Spring	Trace	74	6	6.89	123	50	12	4.8	3.4	6.6	0.25	0.01	3.64	0.78	8.84	Trace	54	0.53	0.21	0.59
51	C2-1	Spring	Trace	80	6	7.5	125	50	11.2	5.28	2.8	9.2	0.05	0.03	1.82	0.11	0.99	Trace	66	0.57	0.19	0.24
52	D3-9	Spring	Trace	58	10	7.11	99	46	12	3.84	1.5	4.6	0.03	Trace	0.91	0.11	0.95	Trace	50	0.49	0.3	0.4
53	D3-10	Spring	Trace	60	40	6.98	98	50	14.4	3.36	1.5	4.6	0.06	0.02	2.73	0.11	0.99	Trace	52	0.65	0.31	0.29
54	E3-2	New Well	Trace	360	14	7.65	567	200	58.4	12.96	11.1	50.5	0.06	0.02	12.74	13.19	1.87	Trace	290	0.54	0.18	0.33
55	D3-1	Well	Trace	380	8	7.6	608	250	68	19.2	10.8	38	0.05	0.03	10.01	2.22	10.55	0.002	310	0.7	0.21	0.25
56	C2-2	Spring	Trace	380	10	7.47	610	256	68.8	20.16	10.8	41.5	0.04	0.1	10.92	1.99	11.06	0.001	306	0.66	0.19	0.31
57	D3-16	Well	Trace	310	14	7.57	501	230	70.4	12.96	5.8	27.5	0.12	0.06	5.46	3.1	0.91	0.058	262	0.58	0.17	0.34

58	D3-3	Well	Trace	300	10	7.6	487	202	60.8	12	9	30.5	0.03	Trace	4.55	0.11	0.56	Trace	266	0.73	0.17	0.25
59	D3-4	Spring	Trace	160	8	7.55	264	116	32.8	8.16	4	18	0.06	0.04	3.64	0.11	2.35	Trace	148	0.82	0.2	0.37
60	C2-4	Spring	Trace	160	10	7.62	263	110	33.6	6.24	4.1	16	0.03	0.01	2.73	0.11	1.81	Trace	134	0.72	0.21	0.33
61	D2-4	Spring	0.365	250	10	7.01	421	176	52.8	10.56	3.4	22	Trace	Trace	10.01	0.46	3.09	Trace	220	0.52	0.23	0.25
62	D3-17	Well	Trace	270	10	7.16	445	160	48	9.6	10.7	32	0.05	0.01	9.1	1	3.61	Trace	218	0.99	0.24	0.3
63	C2-6	Spring	Trace	60	8	6.08	96	38	8.8	3.84	2.5	7.1	0.03	Trace	4.55	0.11	2.45	0.001	44	0.47	0.43	0.12
64	D3-6	Spring	Trace	380	10	7.4	598	308	76.8	27.84	1.6	14	0.01	Trace	18.2	0.22	42.13	0.001	276	0.47	0.35	0.23
65	D3-5	Spring	Trace	380	12	7.61	613	320	70.4	34.56	1.4	23	0.01	Trace	9.1	0.11	9.97	0.009	332	0.48	0.31	0.17
66	C2-8	Spring	0.37	60	14	7.59	88	50	12.8	4.32	1.3	2.9	0.01	Trace	3.64	0.11	2.88	0.011	50	0.48	0.94	0.09
67	C2-7	Spring	25.92	450	70	6.96	735	348	106.4	19.68	7.3	28	0.02	Trace	19.11	1.66	2.93	0.025	398	0.61	0.97	0.26
68	D2-2	Well	1.83	440	16	7.43	745	354	91.2	30.24	7.9	28	0.01	Trace	14.56	6.43	13.02	0.009	388	0.5	0.48	0.28
69	D2-14	Well	1.83	154	16	7.62	247	130	32	12	0.5	7	0.01	Trace	7.28	0.44	0.49	0.006	134	0.44	0.21	0.2
70	D2-1	Well	Trace	400	12	7.66	639	272	44	38.88	11.3	41	0.02	Trace	23.66	19.17	2.16	0.021	320	0.54	0.36	0.35
71	D2-7	Well	Trace	620	12	7.68	923	290	72	26.4	23	108	Trace	Trace	62.8	55.29	5.52	0.013	352	0.84	0.25	0.26
72	A1-6	River	31.39	800	80	8.46	1233	92	28	5.28	17.2	256	0.25	Trace	87.37	83.79	3.75	0.25	458	4.07	0.34	0.43
73	D4-8	Well	1.095	680	14	7.85	1012	60	16	4.8	13	220	0.04	Trace	73.72	56.43	0.82	0.04	380	1.83	0.17	0.29
74	D2-10	Well	2.19	460	20	7.28	716	78	23.2	4.8	5.3	134	Trace	Trace	121.95	64.79	2.22	0.02	100	0.65	0.33	0.21
75	D2-3	Well	2.6	560	20	7.34	911	400	136	14.4	4.5	53	Trace	Trace	45.5	17.5	10.57	0.01	410	0.71	0.3	0.28
76	D2-11	Well	0.37	1000	14	7.17	1492	656	236	15.84	5	72	Trace	Trace	200.22	71.73	38.98	0.02	430	0.5	0.15	0.47
77	D2-9	River	15.7	740	30	7.55	1213	400	148	7.2	12.5	118	0.03	Trace	160.18	36.48	1.65	0.09	380	0.52	0.36	0.67
78	D2-8	River	3.65	644	16	7.43	997	310	108	9.6	12.2	111	0.03	Trace	112.85	44.56	2.47	0.13	320	0.47	0.37	0.75

79	D2-6	River	158.05	460	210	7.83	752	230	76	9.8	6.2	77	0.02	Trace	50.97	29.26	0.16	0.01	300	0.64	0.32	1.56
80	D2-12	Well	4.38	420	20	7.26	702	220	58.4	17.76	11.3	66	0.17	0.09	22.75	8.65	0.25	0.01	360	0.57	0.17	0.13
81	D2-16	Well	Trace	376	10	7.66	648	290	86.4	17.76	6.5	33.5	Trace	Trace	14.56	0.22	11.08	Trace	320	0.56	0.25	0.34
82	D2-15	Well	Trace	640	10	7.79	1036	340	94.4	24.96	6.4	96	Trace	Trace	98.29	44.54	34.24	Trace	310	0.55	0.22	0.32
83	D2-5	Well	Trace	356	4	7.43	610	210	57.6	15.84	8.4	51	Trace	Trace	21.84	5.98	17.04	Trace	280	0.69	0.23	0.32
84	A2-1	River	145.27	280	36	7.75	376	98	31.2	4.8	7.7	49	0.03	Trace	26.39	14.85	2.76	0.118	170	0.96	0.36	0.56
85	D3-7	Well	2.19	780	20	7.57	1152	182	38.4	20.64	10	188	0.04	Trace	32.76	159.11	18.13	0.013	410	1.63	0.4	0.26
86	E1-5	Well	1.83	280	14	7.45	445	154	32.8	17.28	12	42	0.02	Trace	10.01	2.44	0.78	0.008	240	0.65	0.22	0.18
87	D1-6	Well	2.19	880	20	7.56	1161	220	54.4	20.16	10	192	0.02	Trace	43.68	179.94	37.8	0.027	422	1.26	0.24	0.19
88	D1-7	River	134.32	260	260	7.3	383	124	32.8	10.08	7.3	46	0.07	Trace	27.3	15.73	0.33	0.017	172	1.83	0.45	0.43
89	A1-4	River	40.6	240	20	6.89	353	120	36	7.2	6.6	40.5	0.49	0.3	16.38	32.8	0.27	0.001	150	1.05	0.81	3.32
90	D1-5	Well	Trace	700	12	7.86	1046	130	27.2	14.88	19	184	0.18	0.1	49.14	73.79	37.1	0.367	414	1.96	0.31	1.09
91	L-11	well	Trace	1700	Trace	7.48	2442	364	79.2	39.84	23	470	0.03	Trace	180.2	481.98	0.21	0.01	610	2.56	0.41	0.4
92	R-28	well	Trace	1240	Trace	7.52	1997	130	28	14.4	11.8	470	0.02	Trace	74.63	85.87	0.11	0.02	844	7.72	0.25	0.14
93	M-21	well	Trace	1100	Trace	7.54	1735	160	29.6	20.64	12.9	390	0.04	Trace	52.79	146.26	0.06	0.01	698	3.89	0.38	0.32
94	ABR-well	well	Trace	1120	Trace	8.37	1744	26	4	3.84	28.5	400	0.06	Trace	116.49	76.45	0.04	0.01	624	7.21	0.2	0.1
95	AWBH-5	well	Trace	1220	Trace	8.07	1903	88	18.4	10.08	12.1	450	0.07	Trace	182.93	157.89	0.04	0.01	556	1.87	0.29	0.16