Hydrogeological Investigation and Groundwater Potential Assessment in Haromaya Watershed, Eastern Ethiopia

Nata Tadesse[1]*, Bheemalingeswara[1], K and Abdulaziz[2], M

[1]Department of Earth Science, College of Natural and Computational Sciences, Mekelle University, Mekelle, Ethiopia (*tafesse24603@yahoo.com)
[2]Harari National Regional State Agricultural and Rural Development Bureau, Harar, Ethiopia

ABSTRACT

The paper assesses groundwater quality and productivity in Haromaya watershed, eastern Ethiopia. Continuous pumping test data, collected from seven boreholes was used to determine productivity of the aquifers. 14 water samples were tested for water quality. The aquifers on the basis of permeability, potential and extent of aquifers, are categorized into i) extended and shallow aquifers with intergranular porosity and permeability, and with moderate to high potential (alluvial and lacustrine sediments); ii) limited and shallow aquifers with fracture and/or karstic porosity and permeability, and with moderate potential (sandstone and limestone); and iii) limited and shallow aquifers with intergranular and fracture porosity and permeability, and with low potential (granite).

On the basis of chemical data, the water is fresh except in lacustrine and swampy areas. HCO_3^-, Ca^{2+}, Na^+ and Mg^{2+} are the dominating ions in water from granite, sandstone and alluvium; and Cl and SO_4 dominate in water from lacustrine sediments apart from HCO_3^-, Ca^{2+}, Na^+ and Mg^{2+}. Areas suitable for groundwater development in the area are discussed.

Keywords: Aquifer, Ethiopia, Groundwater potential, Haromaya, Hydrogeochemistry.

1. INTRODUCTION

The study area, Haromaya watershed in eastern Ethiopia, is currently serving as a source of groundwater supply for the three major towns: Harar, Alemaya, Awaday and Haromaya University main campus, besides the rural areas where the farmers are also extracting groundwater for different purposes. Sixteen functional boreholes and more than 160 hand-dug wells are found drilled in the watershed. In principle, the development of groundwater in an area should be preceded by an investigation of the groundwater resources. Continued development thereafter will increase the importance of the groundwater as contributor for the socio-economic development of the area. However, this is not the case in the study area. Besides in the area there is no regulation for the abstraction of water from these wells. Also there is no predetermined prioritisation between different water uses and water users. All these practices expose the groundwater resources of the area to mismanagement and risk.

1.1 Description of the Study Area

The study area, Haromaya watershed, is located in Oromiya Regional State, eastern part of Ethiopia, about 505 km east of Addis Ababa. Geographically, the study area is bounded between latitudes 42° 05' 16" N and 43° 55' 12" N; and longitudes 9° 21' 40" E and 9° 27' 13" E with areal extent of about 50.3 sq. km (Fig. 1). The area is located in the Harerghe plateau in the south-eastern highlands and lowlands physiographic unit of the country. The Harerghe highlands lying in the eastern part of the country are generally known for their rugged topography, mountainous landscapes which govern the variations in regional geomorphology, soil sequences, ecological zones, quantity and quality of plant and animal life (Tamire H., 1981). Steep to very steep slopes, hilly and mountainous area, which covers 18% of the total area of the watershed, characterize the eastern and northeastern parts of the watershed. Flat to gentle slopes, which cover 82% of the total area of the watershed and has a slope ranging 0-15%, characterize the remaining parts of the watershed. This physiographic unit includes a swampy area that lies in the southwestern part of the watershed. The slope of the watershed rises slowly in all directions away from the swampy area.

The slope, landform and the configuration of the hills and peaks surrounding the study area have created a drainage network, which takes the surface flow towards the swampy area. The major streams are: Lega-Hidha, Lega-Ambo, Lega-Burqa and Lega-Bati and all the flows are intermittent. These streams are supplied by gullies, ephemeral streams, road channels and sometimes directly from overland flows of adjacent farmlands. The drainage pattern of the area is sparse dendritic type. The monthly air temperature of the watershed range from 3.8°C at December to 25.2°C in March, and the mean annual is 16.7°C (Nata et al., 2006). The highest value of the minimum temperature is 13.6°C and the lowest value of the minimum temperature is 3.8°C, whereas the highest and lowest values of maximum mean temperatures are 25.2^0C and 22.5°C, respectively. The minimum mean and maximum mean temperatures are 9.6°C and 23.8°C, respectively.

Present research work was proposed to conduct hydrogeological investigation and assess groundwater potential of the Haromaya watershed with following objectives.

- Identification of the major water bearing formations;
- Characterization of different aquifers;
- Determination of aquifer productivity: transmissivity and hydraulic conductivity; and

- Determination of chemical-type and quality of water.

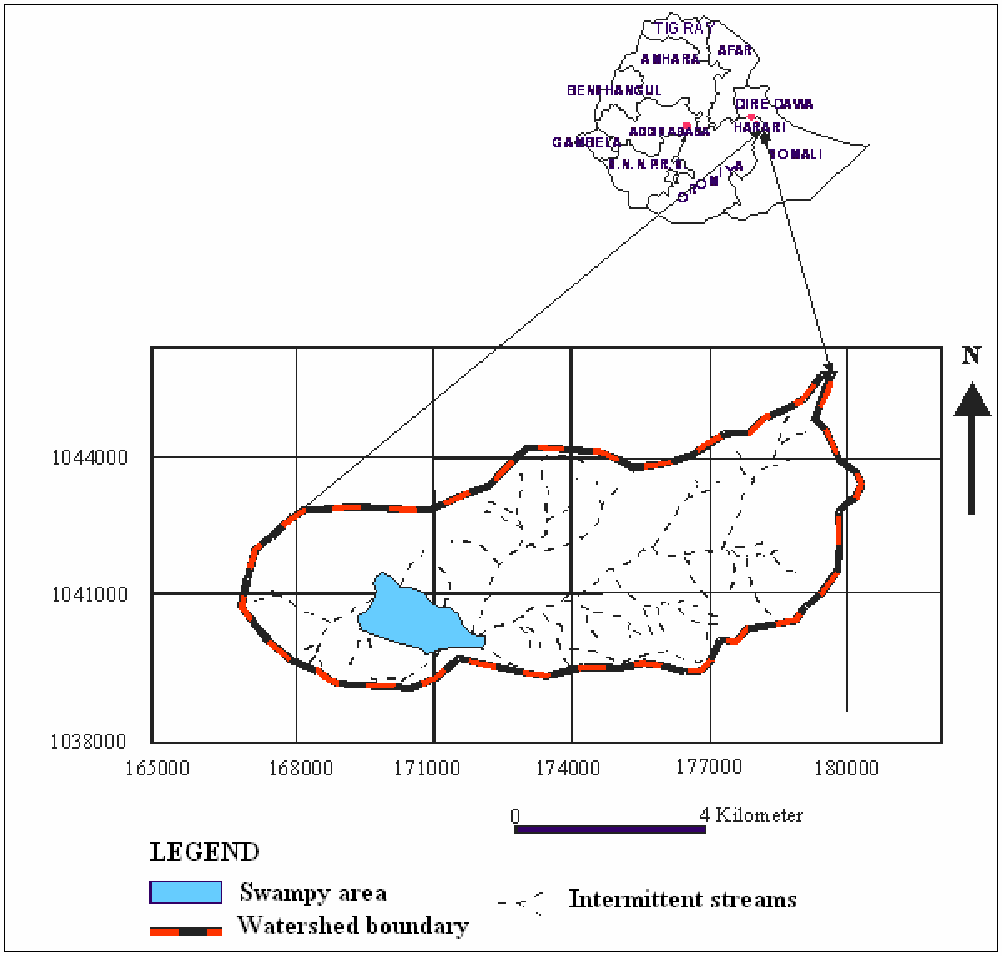

Figure 1. Location map of the Haromaya watershed.

2. METHODOLOGY

The methods used in this study include literature review, field investigation, laboratory analysis and data analysis using different software. Aerial photographs and topographic maps at a scale of 1:50,000 *(Karsa and Harar:* with reference numbers 0941 D2 and 0942 C1, respectively) were studied carefully. The aerial photographs were used to identify the geological structures and trace them on to the topographic sheet of 1:50,000 scale. The topographic sheet was used as base map in the field to mark the lithologies, their contacts and trends and to develop detailed geological and hydrogeological maps of the area.

Primary geological and hydrogeolgical data were collected in the field after having the secondary data. Hydrogeological field investigation was concentrated more on differentiating the rock units of groundwater significance (such as the degree of fracturing of the rock units, the extent of weathering, the type and degree of cementation, the thickness of the formations, the grain size, shape and sorting, and the clay proportion) and in collecting hydrogeological information, i.e., locating of water points, collection of water samples, and measurement of discharge of wells.

For determining the productivity of the aquifers within the study area continuous pumping test data from seven boreholes drilled in unconsolidated aquifer were used. In the watershed, due to the unavailability of the piezometer and recovery data, the analyses have been performed only for constant rate pumping test by using the pumping borehole data. The drawdown data of all boreholes have been analyzed using Neuman method (Neuman, 1975; cited in Krešić, 1997): drawdown versus time. Analyses of all data have been carried out using AquiferTest software. The program contains analytical solutions for pumping and slug tests for confined, unconfined, and leaky confined aquifers. The classification of the aquifer productivity was carried according to Sen (1995) based on transmissivity values.

For hydrogeochemical investigation, 14 water samples (4 springs, 7 hand dug wells, and 3 boreholes) were collected for laboratory analyses. In-situ measurements of electrical conductivity (EC), temperature, pH, and total dissolved solids (TDS) were made. The water samples were collected into properly cleaned and labeled one liter plastic bottles. The samples were again tested for EC, pH, temperature and TDS in the laboratory to cross check the data. All the water samples were analyzed for major cations (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, total iron, Mn^{+2}, NH_4^{+},) and anions (HCO_3^{-}, Cl^{-}, SO_4^{-2}, CO_3^{-2}, F^{-}, NO_2^{-}, NO_3^{-}, PO_4^{-3}) in the Water Works Design and Supervision Enterprise laboratory service, Addis Ababa. Interpretation of all water chemistry data have been carried out using AquaChem software. AquaChem is a fully-integrated software package developed specifically for graphical and numerical analyses and interpretation of aqueous geochemical data sets. Piper diagram was used for representing and comparing water quality analyses in the watershed.

3. GEOLOGY

The geology of the watershed is constituted by the rocks ranging in age from Precambrian to Recent. Stratigraphically, from bottom to top, they are granite (Precambrian), sandstone and limestone (Mesozoic sedimentary rocks) and recent sediments (Quaternary) (Fig. 2). Detailed description of these units is given below.

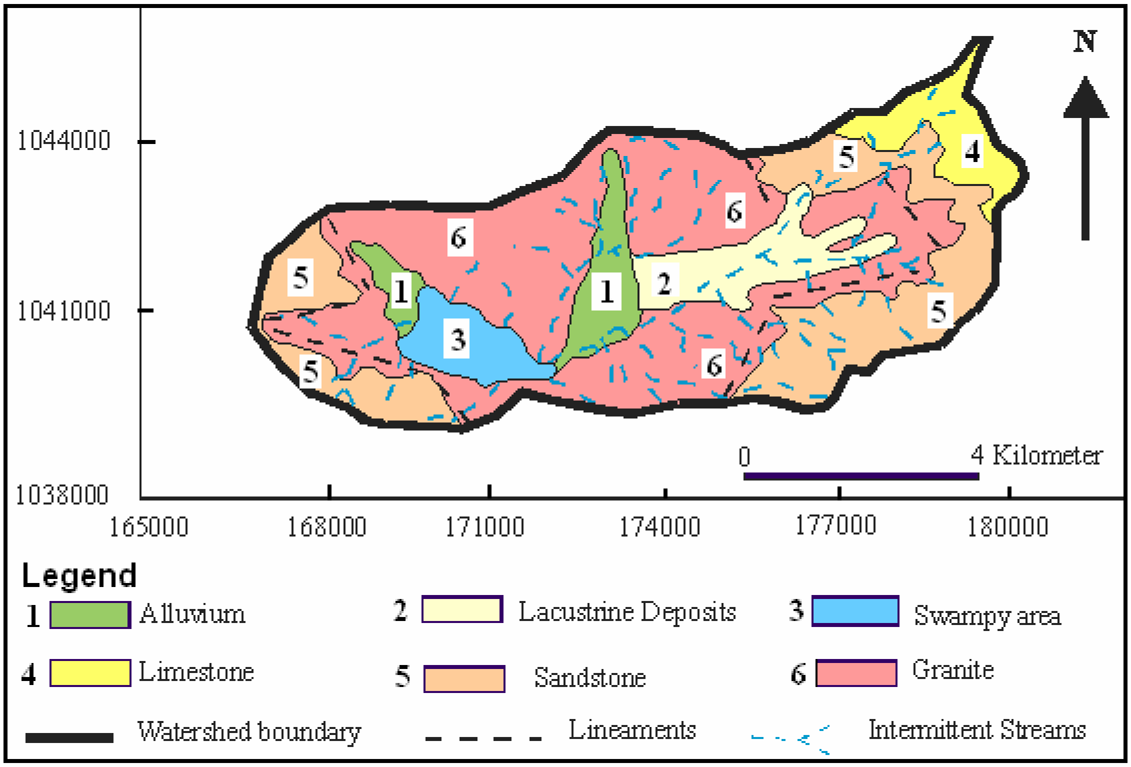

Figure 2. Geologic map of the Haromaya watershed.

3.1 Granite

This rock forms part of the Precambrian stratigraphy of Ethiopian geology. It is an intrusive pluton present within the basement gneissic rocks. It is mainly exposed in the north, northeastern, eastern, southeastern, southern and central parts of the watershed. This unit covers about 46.3% of the total area of watershed. The granite (batholith) rock is massive and shows light pink color. It is characterized by well developed medium grained quartz and orthoclase crystals. It is cut across and intersected by a number of quartz veins having thickness of about 3 to 10 centimeters and with predominantly north-south orientation. The length of the veins ranges from few cm to 1.5 m. Granite, with the exception of the northern ridges, is highly weathered in other parts of the watershed and shows light gray color. Maximum thickness of the weathered granite is about 25 m which is found in a river cut exposure in western parts of the watershed.

3.2 Sandstone

The Mesozoic sedimentary successions of the watershed consist of two formations, the sandstone and limestone. Both together cover about 19.4 % of the total area of the watershed. Sandstone unit is outcropping in the eastern, northeastern, northwestern, western, and southwestern parts of the watershed and overlie the basement granite, and occupies 14.3% of the mapped area. It shows yellowish to pink color and predominantly consists of fine to medium grained quartz. The rock shows well sorted, rounded grains, cross bedding and red color on the surface due to weathering. It is non-calcareous except at the top near the contact with the overlying limestone, where thin beds of limestone have developed. In the southwestern part, reddish brown massive mudstone intercalations are found in sandstone varying in thickness from 20 cm to 1 m. Average thickness of the sandstone unit ranges from 20 to 200 m, and shows well developed vertical joints (Nata et al., 2006). Generally the sandstone is highly weathered and fractured, and found forming hills and ridges in the area. In all parts where it is exposed, it is found covered with shallow soil. The age of the sandstone is Triassic (Garland, 1972).

3.3 Limestone

The outcrops of this unit are present in the northeastern part of the watershed. It overlies the sandstone unit and cover about 5.1% of the mapped area having a maximum thickness of about 180 m (Nata et al., 2006). The limestone is fossiliferous and micritic having very fine grained calcite crystals. It shows intercalations of thin beds of light brownish color marl varying in thickness from 3 to 5 m. It shows gray and light yellowish to black colors due to weathering. At places the unit is highly weathered and shows well developed karst topography. The rock occupies high elevations in the topography and forms steep cliffs in the area. This unit is regionally correlated with the Upper Hamanlei Formation of the Ogaden basin and the Antalo Formation of northern Ethiopia, which is considered to be Upper Jurassic (Mohr, 1963).

3.4 Alluvial Deposits

The alluvial deposits are mainly found in the central part of the watershed as thin strips along the margins of the major rivers and their tributaries. These sediments constitute about 16.7% of the total area and show E-W alignment. They stretch from the eastern and northeastern parts from the bottom of the mountain to the swampy area. The relative abundance and stratigraphic relation of the sediments, however, are generally not uniform throughout the area. Towards the mountain front, which is in the northeastern and eastern parts of the watershed, where steep topographic slopes exist and the gradient of the rivers is high, the alluvial sediments, in general, are dominated by sub-angular to sub-rounded coarse grained fragments with variable content of coarse grained sand. In the central parts of the watershed, where the gradient of the rivers decreases down slope, the dominant alluvial deposit is medium to fine grained sand with variable content of silt and clay.

3.5 Lacustrine Deposits

The lake sediments are found occupying the dried Haromaya lake and also in the current swampy area of the watershed. It covers about 17.7% of the total area. Compositionally the deposits are comprised of clay and silt in different proportions. The sediments are characterized by well developed hexagonal cracks having an opening space ranging from 1 to 5 cm.

4. RESULTS AND DISCUSSIONS

4.1 Hydrogeology

4.1.1 Aquifer Types

Different rocks and unconsolidated sediments in the study area which behave as aquifers have been classified on the basis of permeability which they exhibit and the extent of the aquifer. They are:

1. Extended and shallow aquifers with intergranular porosity and permeability (unconsolidated sediments: alluvial and lacustrine sediments);
2. Limited and shallow aquifers with fracture and/or karstic porosity and permeability (sandstone and limestone); and
3. Limited and shallow aquifers with intergranular and fractured porosity and permeability (Granite).

4.1.2 Aquifer Characteristics

Groundwater occurrence and its reservoirs are mainly controlled by the type of geology, degree of geological weathering or geological structures, and geomorphology of the area. In this section the hydrogeological characteristics of the different rocks and unconsolidated sediments of the watershed have been discussed with particular reference to their water storage and transmission capacities.

4.1.2.1 Unconsolidated Sediments

The recent sediments, which cover about 34.4% of the total mapped area in the form of lacustrine and alluvium serve as one of the major storage volumes for water flowing from the nearby highlands. Alluvial deposits in the central part of the watershed and as thin strips along the margins of the major rivers and their tributaries are the most common shallow aquifers which can be tapped by large diameter hand dug wells. Their permeability and productivity vary from place to place depending on their grain size, sorting and thickness. Lacustrine sediments on the other hand are dominantly fine grained with clay, and their thickness range from 3 to 18 m, most being between 10 to 18 m (Fig. 3). Being rich in clay, the sediments have a very low permeability and productivity and serve as confining or semi-confining layers. The poor drainage characteristics of these sediments lead to water logging.

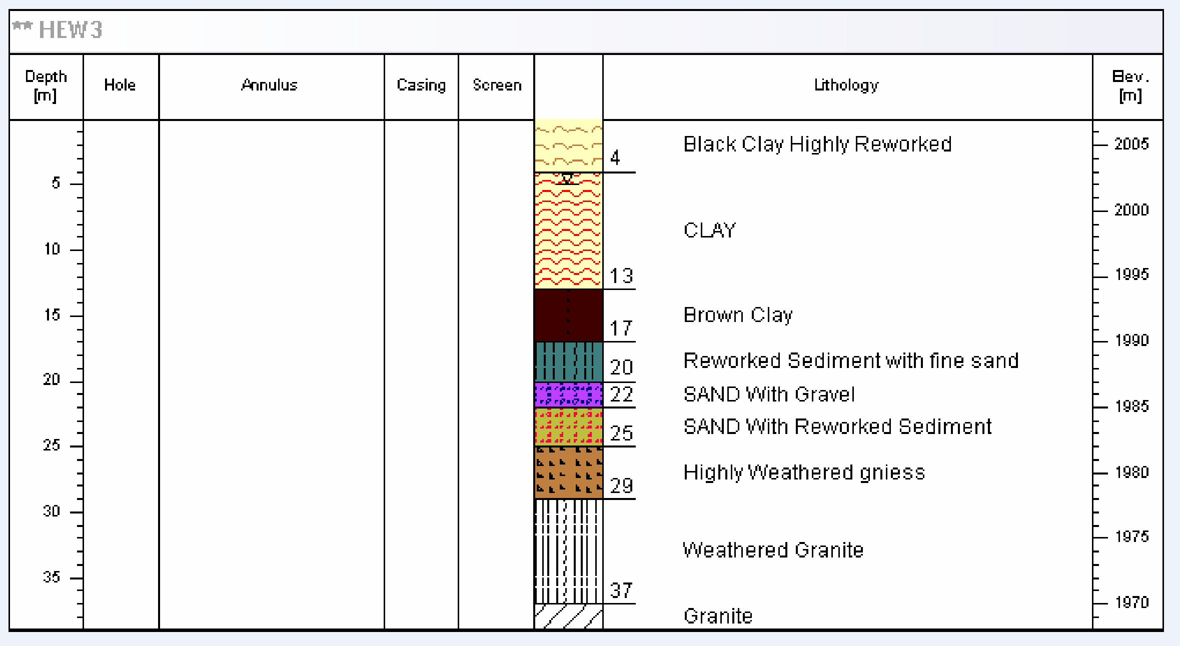

Figure 3. Borehole log of the Haromaya watershed (after Abdulaziz and Nata, 2006).

4.1.2.2 Sandstone

In the watershed there is no borehole that was drilled and found in this unit. However, five hand dug wells are found drilled on it. The assessment of permeability and productivity of the sandstone was carried out based on field observation and limited lithological logs due to lack of pumping test data from boreholes in the watershed. Accordingly, the sandstone has moderate permeability and productivity. Its moderate permeability and productivity is resulting from the limited shale intercalation, bedding planes and the deep vertical jointing. Infiltration and recharge occur mainly through these joints and bedding planes. Its lack of high degree of permeability and productivity is due to the varying medium to fine grain size and degree of cementation. Generally, in the sandstone, intergranular permeabilities are low but secondary porosities and permeabilities due to fracturing are significant.

In the watershed, in most places sandstone forms hills and ridges. These landforms act as runoff zones. Even though limited infiltration can take place along fractures and joints, these landforms make the exploitation of groundwater resource of the formation quite limited because the groundwater availability in these types of landforms, in general, is very poor. However, a large number of high discharge springs characteristically emerge at the contact of the sandstone with the underlying basement rock.

Outside the watershed in the nearby area, the permeability and productivity of the sandstone were evaluated based on pumping test data of boreholes. Accordingly, the sandstone has a moderate permeability and productivity.

4.1.2.3 Limestone

In the watershed, the limestone has appreciable secondary porosity and permeability as a result of fractures, solution structures and openings along bedding planes. However, the degree of permeability and productivity of this formation is highly controlled by the landforms that it constitutes. The rock forms steep mountains and cliffs. These landforms act as runoff zones. Even though limited infiltration can take place along fractures and joints, these landforms make the exploitability of groundwater resource of the formation quite limited because the groundwater availability in these types of landforms in general is very poor. However, a few number of high discharge springs characteristically emerge at the contact of the limestone with the underlying sandstone. In the watershed there is no hand dug wells and boreholes that were drilled and found in this unit. Due to this, the assessment of the productivity of this unit as a whole was carried out based on field observation. Accordingly, this unit as a whole may be taken as an aquifer of poor productivity. This degree of productivity is associated mainly with the topography that it constitutes and to a lesser degree to the nature of the intercalated thin beds of marl.

4.1.2.4 Granite

The granite occurs as crosscutting intrusive bodies in the north, northeastern, eastern, southeastern, southern and central parts of the watershed, and is found covering 46.3% of the total area of watershed, having a maximum thickness of more than 100 m in the southeastern parts. The granite forms round shaped bodies and is affected by strong exfoliation due to the weathering processes. However, the weathering processes affected only the shallow upper parts of the rock. Following are the important features of granite which enhances its usefulness to the water supply:

- Occurrence of weathering zone;
- Occurrence of tectonic fractures;
- Contact with the surrounding metamorphic rocks; and
- Wide differences in composition, structure and texture and corresponding variability of the hydraulic parameters of the same rock.

In the watershed there is no borehole that was drilled and found in this unit. However, more than ten hand dug wells are found in it. The weathered layers and fractures are the main sources of groundwater supply in granitic rock of the watershed. As a result, the extent of weathering and fracture characteristics decide its hydraulic conductivity and other properties. In all the hand dug wells the main aquifer is found to be weathered and fractured granite. The depth of the hand dug wells range from 3.7 to 25.0 m. The static water level ranges from 3 to 19 m. The discharge of the hand dug wells ranges from 0.7 to 3 l/s. Most of the hand dug wells are dried within 15 minutes when they were discharged with dewatering pump of 5 l/s discharge, indicating the low productivity nature of the rock. Assessment of the productivity of the weathered layers and fractured zones was carried out based on field observation and limited lithological logs due to lack of pumping test data from boreholes in the watershed. Accordingly, the weathered layers and fractured zones as a whole are estimated to have low permeability and productivity. This degree of permeability and productivity is due to the presence of medium to coarse grain sized particles and absence of secondary minerals in the weathered layers and limited infiltration that can take place along the fractures and joints. Their lack of moderate and high degree of productivity is mainly due to the limited thickness of fractured zones and weathered layers, the presence of fine grained materials both in the weathered layers and the overlying alluvium and the landforms which they form.

4.2 Aquifer Productivity

4.2.1 Hydraulic Characteristics of Unconsolidated Sediment Aquifers

All the boreholes (20 boreholes) and 158 of hand dug wells are found drilled in the sediments. Out of the twenty boreholes, four are abandoned and the rest are functional. The depths of the boreholes range from 13 to 66 m and the yields vary from 2 to 15 l/s. The depths of static water level also vary from 2.2 to 14.0 m. Among the boreholes and hand dug wells in the sediments of the watershed, only the performance of 16 boreholes have been checked by pumping test. However, pumping test data are available only for the seven boreholes of Hare Town Water Supply and Sewerage Authority. Pumping test and recovery test data were not obtained for the other nine boreholes and for all the 158 hand dug wells, and quantitative estimates of the performance of these boreholes and hand dug wells have not been determined. The following is the result of the analyses of the pumping test data obtained from the seven boreholes.

The Harer Emergency Well 1 borehole was drilled at elevation of 2018 m above seal level with a total depth of 47 m. The static water level is 2.2 m. The pumping test was conducted for 72 hours at a constant rate of 10.30 l/s. After a continuous 72 hours pumping, a volume of 2669.76 m^3 water was pumped out and a drawdown of 10.3 m was measured. According to the Neuman drawdown versus time method (Fig. 4), a transmissivity of 5.23×10^{-4} m^2/s and a hydraulic conductivity of 2.17×10^{-5} m/s have been computed.

The Harer Emergency Well 2 borehole was drilled at elevation of 2023 m above sea level with a total depth of 65 m. The static water level is 13.9 m. The pumping test was conducted for 24 hours at a constant rate of 4.46 l/s. After a continuous 24 hours pumping, a volume of 285.344 m^3 water was pumped out and a drawdown of 4 m was measured. In this borehole the recovery was fast. According to Harer Town Water Supply and Sewerage Authority (2003) cited in Abdulaziz and Nata, 2006) report, the borehole recovered 92% of the total drawdown within 5 minutes. The computed transmissivity and hydraulic conductivity values, by the Neuman drawdown versus time method (Fig. 5), are 1.4×10^{-3} m^2/s and 5.2×10^{-5} m/s, respectively.

The Harer Emergency Well 3 borehole was drilled at elevation of 2015 m above sea level with a total depth of 39 m. The static water level is 3.78 m. The pumping test was conducted for 10 hours at a constant rate of 10 l/s. After a continuous 10 hours pumping, a volume of 360 m^3 water was pumped out and a drawdown of 10.63 m was measured. According to the Neuman drawdown versus time method (Fig. 6), a transmissivity of 5.2×10^{-4} m^2/s and a hydraulic conductivity of 2.88×10^{-5} m/s have been computed.

The Harer Emergency Well 4 borehole was drilled at elevation of 2013 m above sea level with a total depth of 52.3 m. The static water level is 3.95 m. The pumping test was conducted for 21 hours at a constant rate of 18 l/s. After a continuous 21 hours pumping, a volume of 1360.8 m^3 water was pumped out and a drawdown of 9.3m was measured. According to the Neuman drawdown versus time method (Fig. 7), a transmissivity of 5.62 x 10^{-4} m^2/s and a hydraulic conductivity of 3.11 x 10^{-5} m/s have been computed.

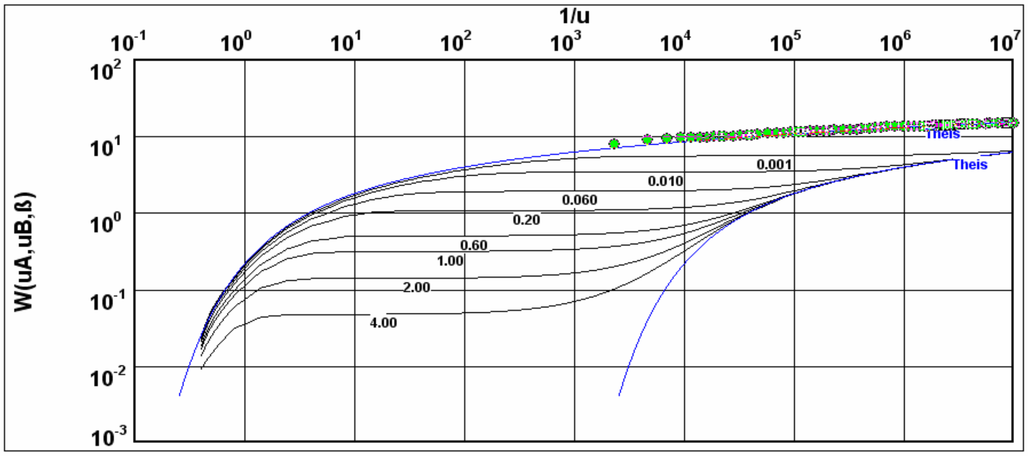

Figure 4. Neuman plot of drawdown versus time at the pumping borehole well 1.

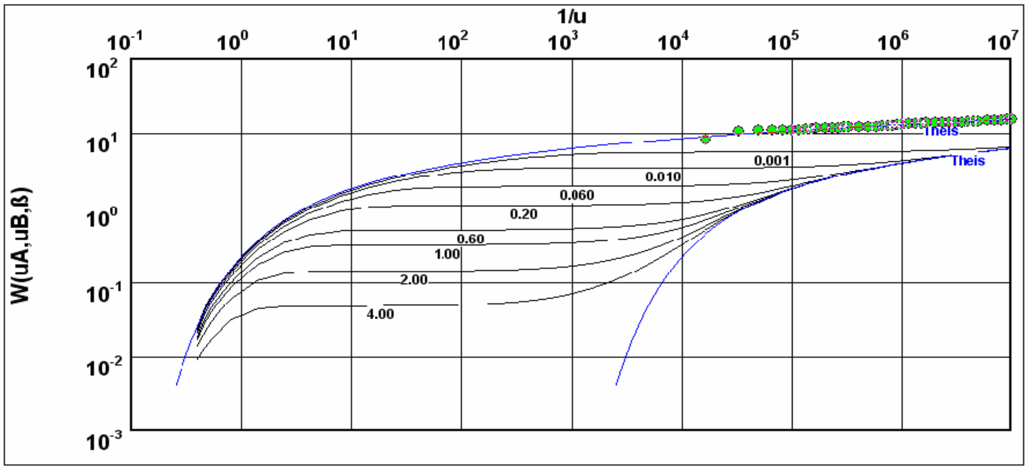

Figure 5. Neuman plot of drawdown versus time at the pumping borehole well 2.

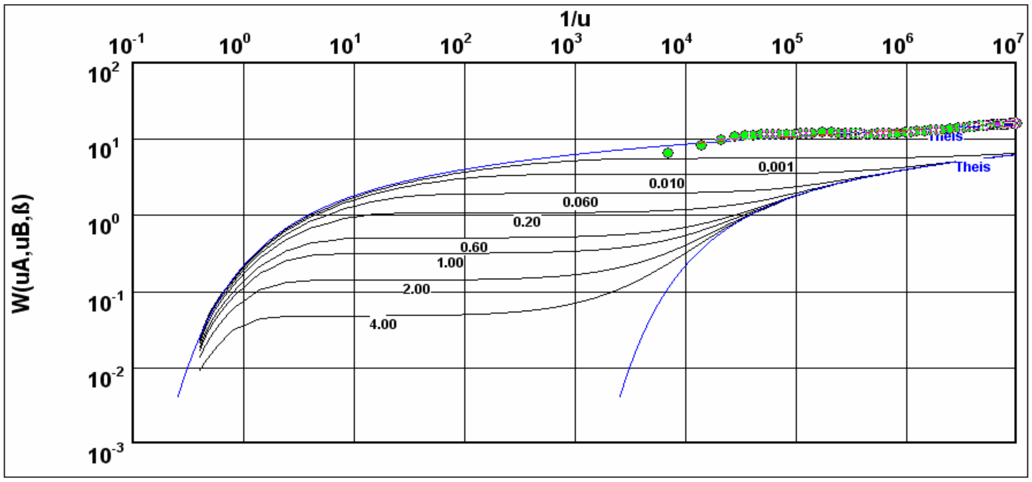

Figure 6. Neuman plot of drawdown versus time at the pumping borehole well 3.

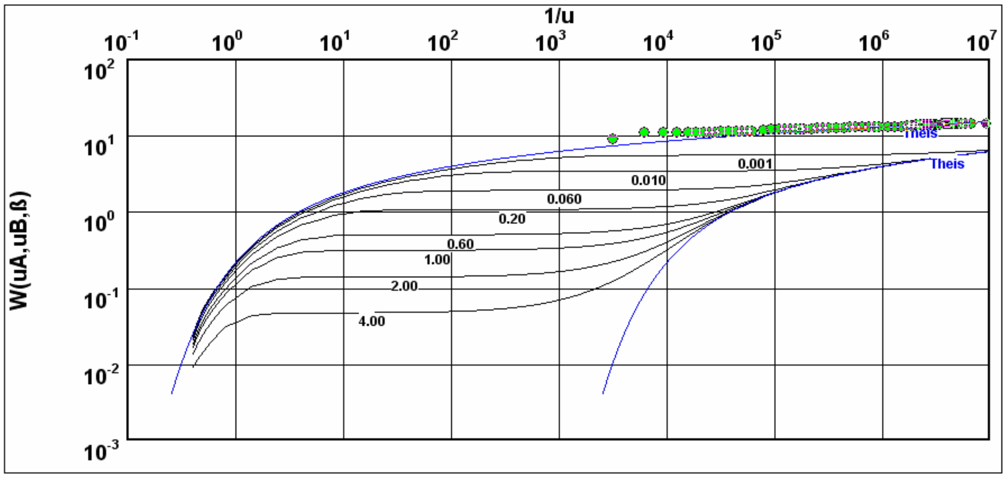

Figure 7. Neuman plot of drawdown versus time at the pumping borehole well 4.

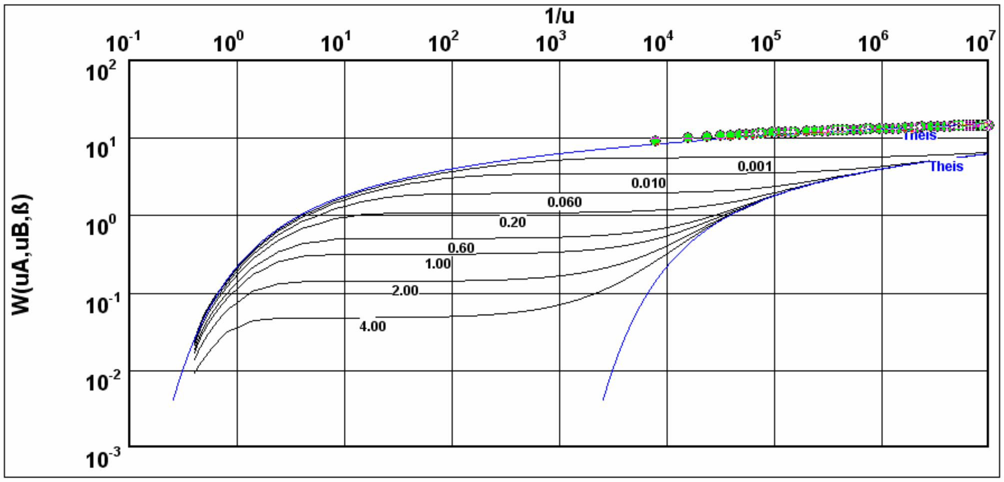

Figure 8. Neuman plot of drawdown versus time at the pumping borehole well 5.

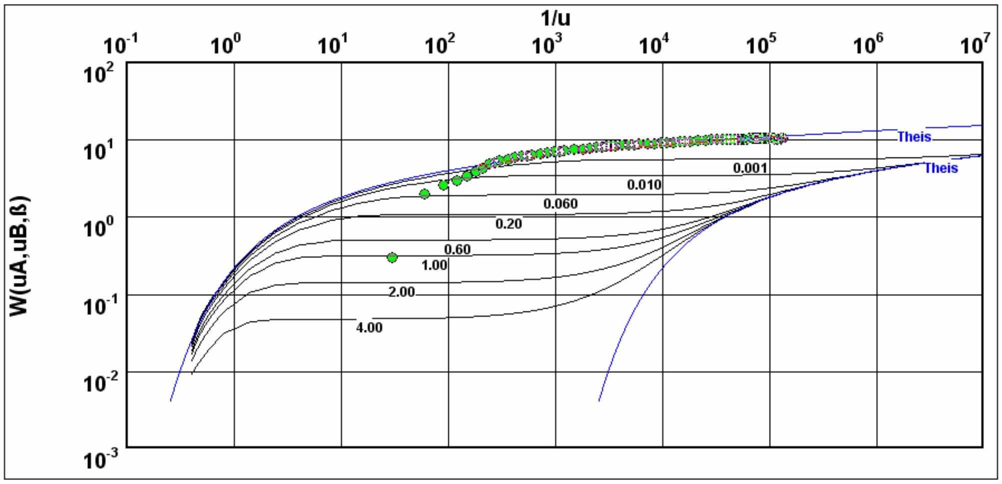

Figure 9. Neuman plot of drawdown versus time at the pumping borehole well 6.

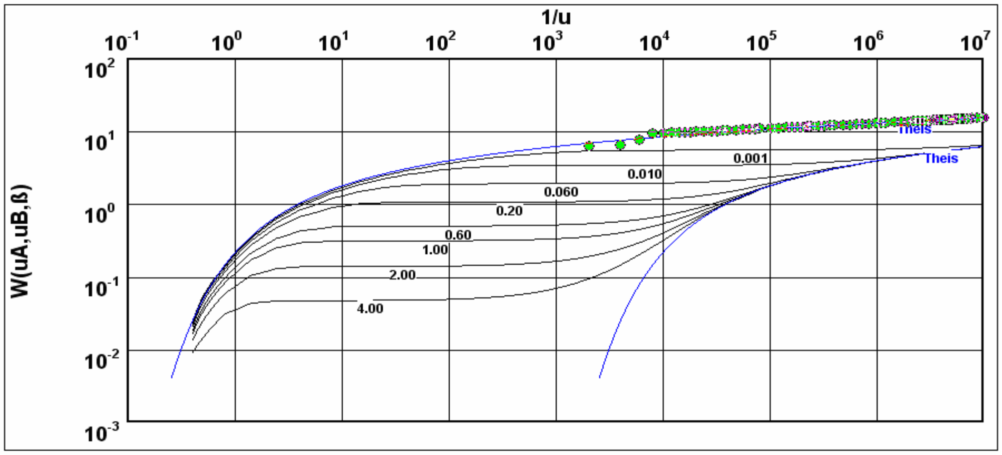

Figure 10. Neuman plot of drawdown versus time at the pumping borehole well 7.

The Harer Emergency Well 5 borehole was drilled at elevation of 2014 m above sea level with a total depth of 53 m. The static water level is 2.89 m. The constant rate pumping test was conducted for 48 hours at discharge rate of 18 l/s. After a continuous 48 hours pumping, a volume of 3110.4 m^3 water was pumped out and a drawdown of 8.91 m was measured. According to the Neuman drawdown versus time method (Fig. 8), a transmissivity of 5.78×10^{-4} m^2/s and a hydraulic conductivity of 2.4 x 10^{-5} m/s have been computed.

The Harer Emergency Well 6 borehole was drilled at elevation of 2011m above seal level with a total depth of 44m. The static water level is 4.86m. The constant rate pumping test was conducted for 37 hours at a constant discharge of 16 l/s. After a continuous 37 hours pumping, a volume of 2131.2 m^3 water was pumped out and a drawdown of 11.76m was measured. According to the Neuman drawdown versus time method (Fig. 9), a transmissivity of 5.3 x 10^{-4} m^2/s and a hydraulic conductivity of 1.6 x 10^{-5} m/s have been computed.

The Harer Emergency Well 7 borehole was drilled at elevation of 2020 m above sea level with a total depth of 44 m. The static water level is 5.65 m. The constant rate pumping test was conducted for 41 hours at an average discharge rate of 22 l/s. After a continuous 41 hours pumping, a volume of 3247.2 m^3 water was pumped out and a drawdown of 13.72 m was measured. According to the Neuman drawdown versus time method (Fig. 10), a transmissivity of 6.83 x 10^{-4} m^2/s and a hydraulic conductivity of 2.62 x 10^{-5} m/s have been computed.

Generally, according to Sen (1995) classification, the aquifer potential of unconsolidated sediment aquifers ranges from moderate to high.

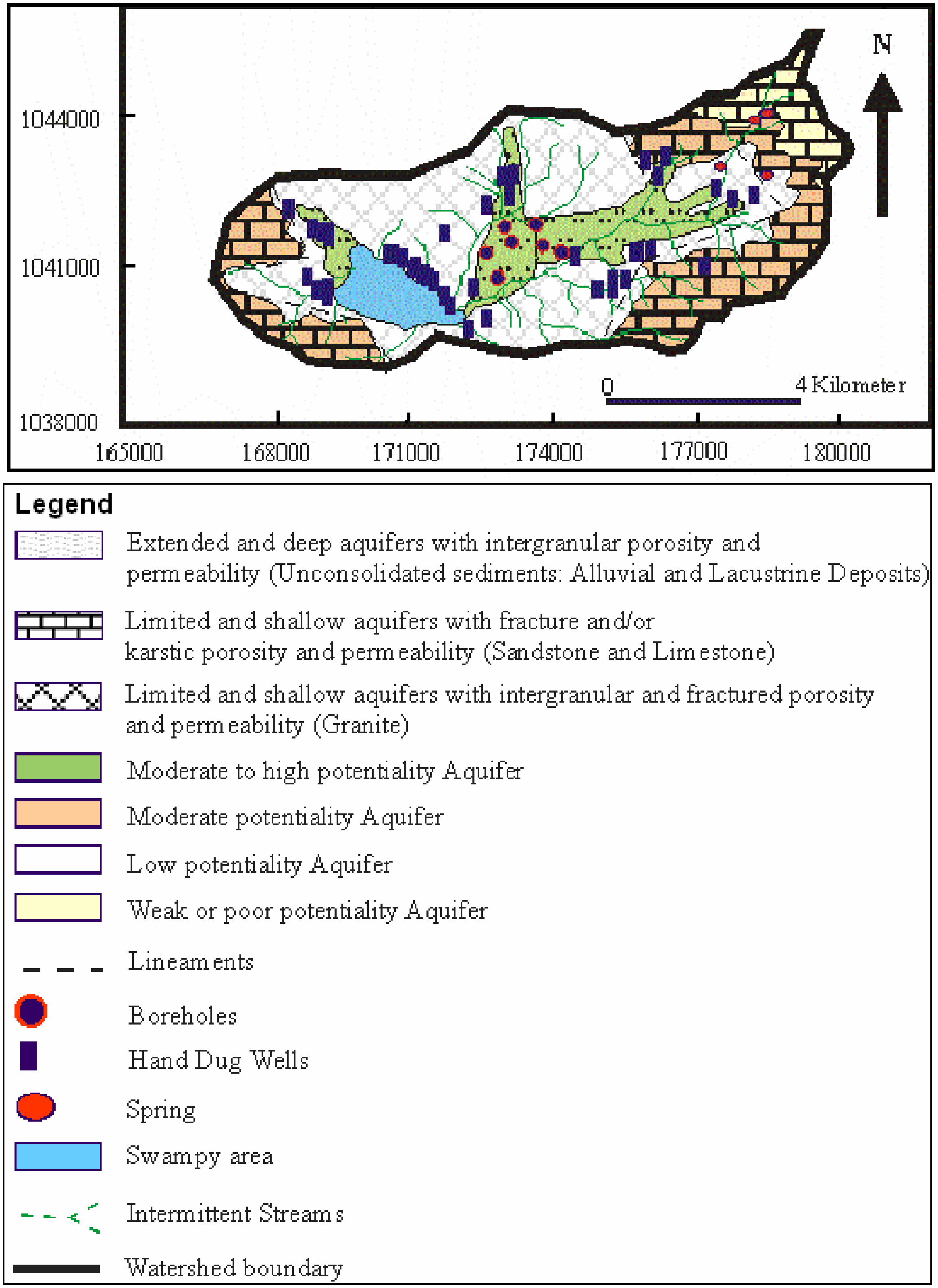

Figure 11. Hydrogeological map of the Haromaya watershed.

4.3 Hydrogeochemistry

The results of the geochemical analyses are shown in the Tables 1 and 2 and in figures 12 - 15, and are discussed below.

4.3.1 Granite

Five groundwater samples were analyzed from the granitic rock terrains of the watershed show slightly alkaline character. They are fresh (TDS less than 1000 mg/l), neutral to slightly basic and very hard (Figs. 12A & 13A). Alkalinity of the groundwater ranges from 193.8 to 354.9 mg/l $CaCO_3$. Except in one, other samples show above 300 mg/l CaCO3 alkalinity values (Fig. 13A). In terms of temperature the groundwater samples show variation from 19.7ºC to 25.8ºC. Among the anions, HCO^-_3 is dominant over Cl^- and SO_4^{2-}. The measured bicarbonate (HCO^-_3) concentrations range from 236.4 mg/l to 433.0 mg/l (Table.2; Fig.14A). The anions Cl^- and SO_4^{2-} occur in only minor concentrations. The highest measured chloride concentration is 46.6 mg/l and the lowest is 12.4 mg/l. The highest measured sulfate concentration is 49.4 mg/l and the lowest is 17.33 mg/l. The bicarbonate concentration in granitic rock can be accounted for by the dissociation of water under the presence of carbon dioxide. The prevailing pH (6.8 - 8.5) (Table.1) is also one of the factors for the existence of the bicarbonate as major dissolved inorganic constituents in the groundwater. Over most of the normal pH range of groundwater (6 - 9), bicarbonate is the dominant carbonate species. The anions Cl^- and SO_4^{2-} are not significant constituents in silicate rocks. Since their occurrence is normally be attributed to atmospheric sources, to the decomposition of organic matter in soil, and to the trace impurities in rocks and minerals, there is no such condition exists in granite. Any possible increase of SO_4^{2-} and Cl^- is also restricted because of limited movement of groundwater.

Among cations, alkaline earths elements are relatively higher in concentration (Ca^{2+} and Mg^{2+}) compared to alkalis (Na^+ and K^+) (Table.2; Fig 14B). Without exception, Ca^{2+} is dominant over Mg^{2+}. There is a dominance of Na^+ over K^+, as sodium is more soluble than potassium, and the latter is generally more easily fixed on clay minerals in the rock matrix. Hence K^+ is the least abundant among cations. Chemical character of water varies from Ca - HCO_3, Ca - Na - HCO_3, and Ca - Mg - HCO_3 types (Fig.15). Though bicarbonate and alkaline earth elements are expected to be contributed from the rock but slightly higher amounts of Na compared to K is contributed from the overlying sediments.

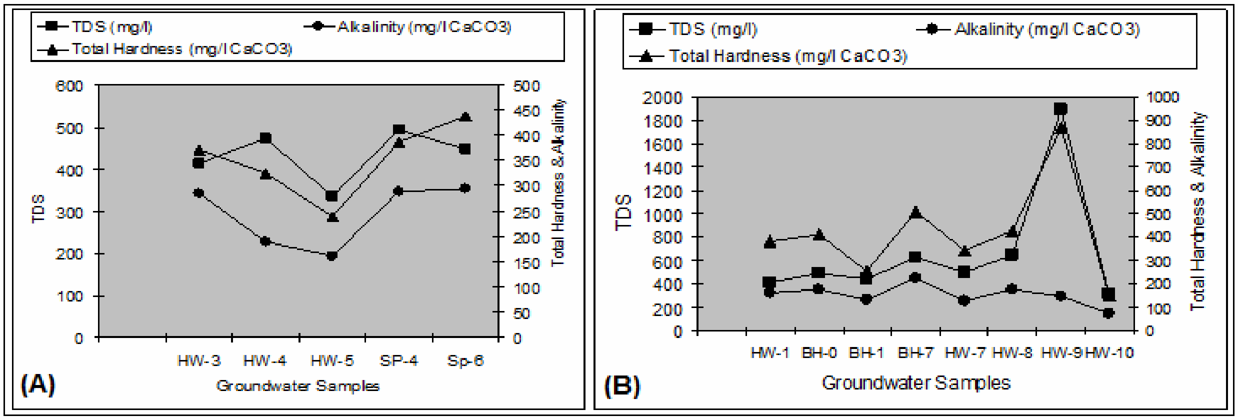

Figure 12. pH of the groundwater samples in (A) granite; (B) in sediment.

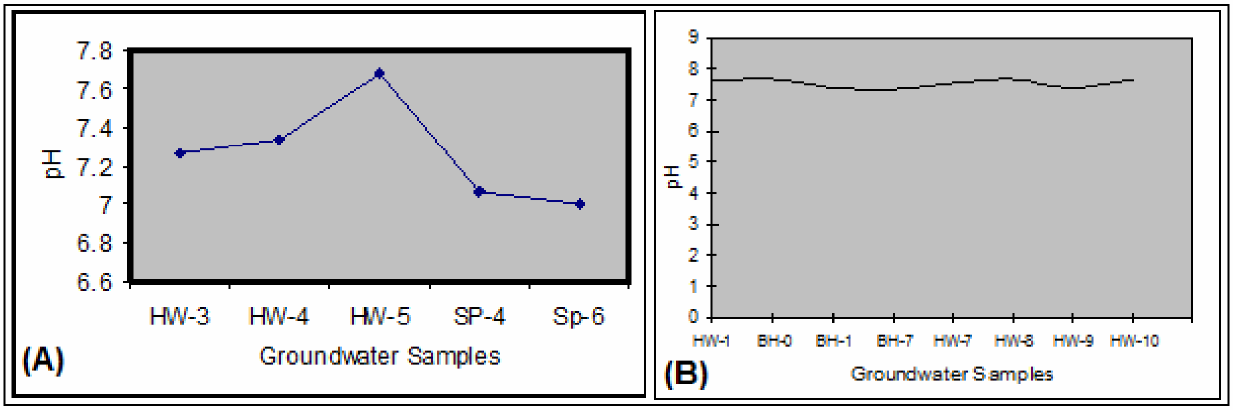

Figure 13. TDS, Alkalinity and Total hardness for groundwater (A) granite; (B) sediment.

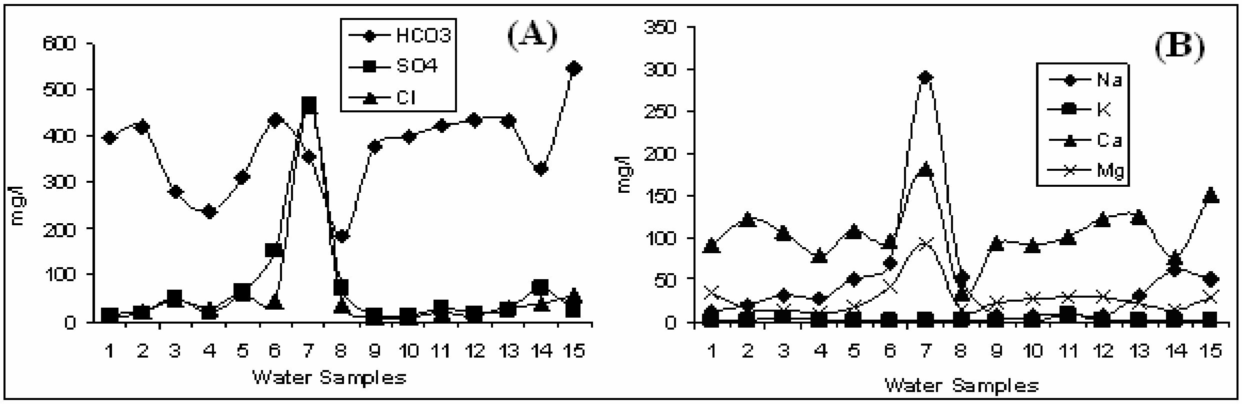

Figure 14. Variation in anion (A) and cation (B) concentrations in water (Note: water sample no. 1=HW alluvial; 2-4 = HW granite; 5-8=HW lacustrine; 9-10=SP sandstone; 11-12=SP granite; 13-15=SP alluvial).

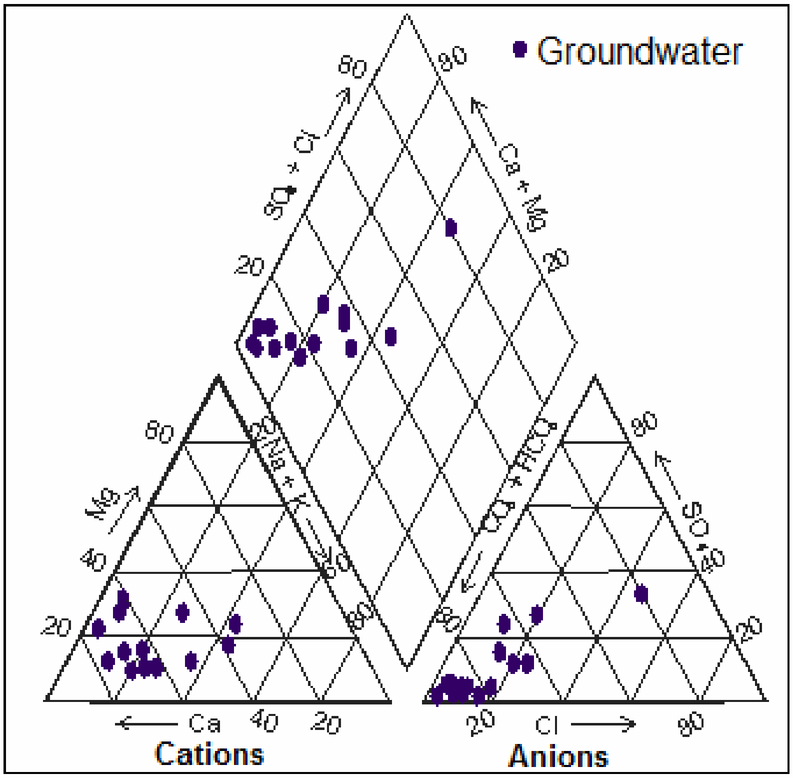

Figure 15. Piper diagram of hydrochemical data in the Haromaya watershed.

The fluoride content which ranges from trace to 0.5 mg/l (Table.2) is generally contributed from the fluoride-bearing minerals like apatite, fluorite and biotite in the rocks. Possible presence of minor amounts of biotite is expected to be the source for fluoride in the present case. Among secondary and minor constituents or trace elements total iron and manganese, both show very low concentrations below 0.5 mg/l (Table.2). These concentrations are low because of constraints imposed on the solubility of iron and manganese –bearing minerals or forming hydrous oxides of iron and manganese in the soil environment. Nitrite and ammonia concentrations in water samples are insignificant compared to the other nitrate nitrogen species. In all the analyzed samples the concentrations of nitrite is nil, but nitrate concentrations range from 7 to 21.5 mg/l. The most abundant nutrient in water from all the samples is nitrogen in the form of nitrate. Unlike most other elements in groundwater, nitrate is not derived primarily from the minerals in rocks that make up the groundwater reservoir. Nitrate in groundwater generally originates from nitrate sources on the land surface, in the soil zone, or in shallow subsoil zones where nitrogen-rich wastes are buried. Natural nitrate concentrations in groundwater range from 0.1 to 10 mg/l (Davis and DeWiest, 1966). As shown in table 2, only in one hand dug well, the nitrate concentration is below 5 mg/l. In the remaining four samples nitrate occurs at concentrations well above 10 mg/l. Here the presence of nitrate is mostly attributed to the open pit latrines as there are no proper sewerage systems in the watershed. Ammonia concentrations are also very low ranging from 0.15 to 0.25 mg/l and generally contributed from anthropogenic or the overlying organic rich sediments.

Phosphate (PO_4^{3-}) values are ranging from 0.041 to 0.123 mg/l. In general phosphate concentration of groundwater in granitic rock terrains of the watershed is low, due to the presence of high concentration of calcium. The phosphate may be due to the presence of phosphorus-bearing minerals like hydroxylapatite ($Ca_5(OH)(PO_4)_3$), strengite ($FePO_4.2H_2O$) and varisite ($AlPO_4.2H_2O$) in the rocks. The dominant control on phosphorus in the groundwater zone is the solubility of these slightly soluble phosphate minerals.

4.3.2 Sandstone

The chemistry of spring water in sandstone is slightly alkaline, fresh and very hard (Tables. 1&2). Ca^{2+} is dominant among cations and HCO_3^- among anions (Fig.14 A&B). Alkalinity values ranges from 310.1 to 326.4 mg/l $CaCO_3$ (Table. 1) and temperature from 18.5 ºC to 24.5 ºC. In the sandstone aquifer the major ions in the groundwater calcium and bicarbonate assumed to be from calcite dissolution. Other cations magnesium, sodium and potassium are very low in water. Similarly, among anions, chloride and sulfate are also found in very small concentration. Chemical type of water is mainly Ca - Mg - HCO_3 type (Fig.15).

The measured fluoride concentrations are below 0.5 mg/l. Natural concentrations of F^- in groundwater mainly depends on the availability of F^- in the rocks or minerals encountered by the water during its transport and on solubility constraints imposed on fluorite (CaF_2) or fluorapatite ($Ca_5F(PO_4)_3$). The fact that nearly all groundwaters are undersaturated with respect to fluorite and fluorapatite suggests that the F^- content of groundwater is generally limited due to non-availability of F^- in the rocks and sediments through which the groundwater moves rather than by the solubility these minerals (Freeze and Cherry, 1979).

Other anions like nitrite and ammonia show very low concentrations. Though, nitrite values are almost nil, the highest concentration recorded for ammonia is 0.188 mg/l. On the other hand, the highest measured nitrate concentration is 19.5 mg/l. This amount of concentration is mostly attributed to the open pit latrines as there are no proper sewerage systems in the watershed. The phosphate (PO_4^{3-}) concentrations are also insignificant. As shown in the table 2, among trace elements, both total iron and manganese show very low concentrations and insignificant.

4.3.3 Sediments

Eight groundwater and spring water samples analysed from the sediments of the watershed indicate that they are slightly alkaline, fresh (except HW9), neutral pH and very hard (Table.1; Figs. 12B and 13B). In the case of the sample HW9, the water is brackish in character. Alkalinity values ranges from 148.9 to 446.8 mg/l $CaCO_3$. Temperature values are ranging from 20.1 ºC to 24 ºC. Ca^{2+} is the dominant cation, followed by sodium (Na^+), magnesium (Mg^{2+}) and potassium (K^+) ions in both the groundwater of the alluvial and lacustrine aquifers (Fig.14B). HCO_3^- is the dominant anion and Cl^- the second most abundant anion followed by SO_4^{2-} in the groundwater from alluvial aquifer (Fig.14A). Here, the anions Cl^- and SO_4^{2-} occur in only minor concentrations. However, in the groundwater from lacustrine aquifers HCO_3^-, Cl^- and SO_4^{2-} ions show variation in concentration in all the samples. With the exception of sample HW9, in all other samples HCO_3^- is the dominant anion followed by SO_4^{2-} as a second abundant anion in samples HW-8 and HW-10 and Cl^- in sample HW-7. In the case of sample HW-9, Cl^- is the dominant anion and SO_4^{2-} the second most abundant anion followed by HCO_3^-. Water samples from lacustrine sediments in general show high concentrations for the anions Cl^- and SO_4^{2-}. This high concentration of Cl^- and SO_4^{2-} in the groundwater is mostly attributed to the dissolution of chloride and sulfate from lacustrine marl and evaporites, which can contribute salinity to the groundwater in this aquifer system. Fluoride concentrations are less than 1.2 mg/l in water from both the alluvial and lacustrine aquifers. The highest measured fluoride concentration is 1.1 mg/l. Chemical types of groundwater from the alluvial aquifer are Ca – Mg - HCO_3 and Ca – Na - HCO_3 types; and from the lacustrine sediment are Ca – Na - HCO_3 – Cl, Ca – Mg – Na - HCO_3 – SO_4, Na – Ca – Mg – Cl – SO_4 and Na - Ca – Mg - HCO_3 – SO_4 types (Fig.15).

Nitrite and ammonia concentrations in groundwater from both alluvial and lacustrine aquifers are insignificant. Though groundwater is free from nitrite, it indicates presence of nitrate whose concentration is around 17.5 mg/l. In the case of ammonia, the highest value recorded is 0.65 mg/l. Nitrate concentration is mostly attributed to the open pit latrines as there are no proper sewerage systems in the watershed. Other analysed parameters like phosphate (PO_4^{3-}), Mn and Fe (total) are insignificant in the groundwater from both the alluvial and lacustrine aquifers.

5. CONCLUSION

- As part of hydrogeological investigation different types of aquifers are noted and demarcated.
- On the basis of the relationship between hydraulic properties and geology in the area, the aquifer rocks have been classified in to low, medium and high potential for groundwater.
- Among different aquifers, the one associated with unconsolidated sediments have moderate to high potential; followed by the sandstone having moderate potential and granite with low potential; and limestone characterized by weak and poor potential aquifers.
- Hydrogeochemical data indicate that the water in general is fresh except the water in lacustrine sediments and swampy areas as indicated by EC and TDS.
- Hydrogen ion concentrations though vary between 7 and 8; neutral values are observed in water from granite and sandstone; and slightly basic in lacustrine and swampy areas. Bicarbonate values that are closely related to pH though broadly follow the same trend show variations in the rocks and sediment.
- High concentrations of sulphate and chloride in lacustrine and swampy areas though are assumed to be due to increased residence time and they do not show any relation with hydrogen ion concentration.
- Among cations Ca^{2+} and among anions HCO_3^- are the dominating ions.
- Nitrate, ammonia and fluoride though low concentration, nitrate may increase with time from anthropogenic sources. Iron and manganese as expected are very low in concentration.
- Water from the rocks and sediment clearly indicate variation in their chemical character. HCO_3^-, Ca^{2+}, Na^+ and Mg^{2+} are the dominating ions in water from granite, sandstone; and Cl and SO_4 dominate in water from lacustrine sediments apart from HCO_3^-, Ca^{2+}, Na^+ and Mg^{2+}.
- Any future development of groundwater should be concentrated on the moderate to high degree potential aquifers.
- Further investigations are to be done to establish lateral extent and vertical thickness of the moderate to high degree potential aquifers; and to know the presence of additional multilayer aquifers, their respective thickness and productivity.

6. ACKNOWLEDGMENTS

The Hare Town Water Supply and Sewerage Authority is duly acknowledged for funding this research project and also providing the necessary data. Thanks are also due to all those friends who helped during the field and laboratory work and for going through the manuscript many times and providing many constructive comments.

7. REFERENCES

Abdulaziz, M & Nata, T. 2006. Optimum groundwater utilization and management in Lake Alemaya watershed, Eastern Ethiopia. Mekelle University, Mekelle, Ethiopia.

Davis, S.N & DeWiest, R.J.M. 1966. Hydrogeology. John Wiley and Sons, New York, 463 pp.

Freeze, R.A & Cherry, I.A. 1979. Groundwater, Prentice Hall, Inc., New Jersey.

Garland, C.R. 1972. Explanation of the Geological Map of Adigrat Sheet (ND 37-7), 1:250,000 Scale. Ethiopian Institutes of Geological Survey (E.I.G.S.), Addis Ababa.

Krešić, N. 1997. Quantitative solutions in hydrogeology and groundwater modeling, Lewis Publishers, Boca Raton.

Mohr, P.A. 1963. Geological Map of the Horn Africa, 1:2,000,000 Scale. Philip and Jacey, London.

Nata, T., Dubey, N., Mintesnot, K & Shami, M. 2006. Water Balance of Haromaya basin, Oromiya, eastern Ethiopia. B.Sc thesis, Mekelle University, Mekelle, Ethiopia.

Şen, Z. 1995. Applied Hydrogeology, CRC Press, Boca Raton.

Tamire, H. 1981. Soil, water and forest conditions in Hararghe high lands, Alemaya. Unpublished report, Alemaya University, Alemaya, Ethiopia.

Table 1. Location and some important parameters of the analyzed water samples.

Sample ID	***Easting (m)***	***Northing (m)***	***Altitude (m)***	***pH***	***EC (µS/cm)***	***TDS (mg/l)***	***Alkalinity (mg/l $CaCO_3$)***	***Total Hardness (mg/l $CaCO_3$)***	***Water Type***	***Water-bearing Formation***
HW-1	176750	1043171	2101	7.62	664	408	324.4	384.1	Ca-Mg-HCO_3	Alluvial
HW-3	175571	1041113	2051	7.27	693	414	342.7	371	Ca-HCO_3	Granite
HW-4	828104	1040460	2043	7.34	708	474	228.5	325.5	Ca-HCO_3	Granite
HW-5	828272	1041936	2031	7.68	528	336	193.8	238.7	Ca-Na-HCO_3	Granite
HW-7	170767	1041348	2018	7.54	793	500	255	345	Ca-Na-HCO_3-Cl	Lacustrine
HW-8	172611	1040355	2014	7.65	966	648	354.96	427.5	Ca-Mg-Na-HCO_3-SO_4	Lacustrine
HW-9	171799	1040751	2011	7.38	2920	1890	291.7	868	Na-Ca-Mg-Cl-SO_4	Lacustrine
HW-10	173319	1042855	2020	7.68	484	318	148.9	151.9	Na-Ca-Mg-HCO_3-SO_4	Lacustrine
SP-1	178675	1044507	2203	7.09	628	404	310.1	332.01	Ca-Mg-HCO_3	Sandstone
SP-2	178049	1044093	2181	7.15	669	418	326.4	349.4	Ca-Mg-HCO_3	Sandstone
SP-4	177517	1043059	2113	7.06	780	494	346.8	386.3	Ca-Mg-HCO_3	Granite
Sp-6	178840	1042810	2126	7	736	448	354.9	438.3	Ca-Mg-HCO_3	Granite
BH-0	174135	1041428	2028	7.66	804	494	352.9	412.3	Ca-Mg-HCO_3	Alluvial
BH-1	173975	1041732	2028	7.36	702	444	269.3	256.1	Ca-Na-HCO_3	Alluvial
BH-7	173925	1042432	2028	7.35	1033	632	446.8	509.9	Ca-Mg-HCO_3	Alluvial

Table 2. Anion and cation concentrations (mg/l) in groundwater and spring water samples.

	HW-1	***HW-3***	***HW-4***	***HW-5***	***HW-7***	***HW-8***	***HW-9***	***HW-10***	***SP-1***	***SP-2***	***SP-4***	***SP-6***	***BH-0***	***BH-1***	***BH-7***
Na^+	11.7	19	32	28	51	70	290	52	6.3	7.3	10.7	6.5	31	61	51
K^+	1.4	1	4.6	1.8	2	1.3	2.3	2.6	0.6	0.8	8	1.3	1.4	2.4	1.7
Ca^{+2}	91.4	121.8	106.1	78.3	108.8	96.6	182.7	35.7	93.1	91.35	101.8	122.7	126.2	76.6	152.3
Mg^{+2}	35.3	15.2	13.7	9.8	16.7	42.14	93.1	14.2	22.54	27.44	29.9	29.9	22.1	14.7	29.4
Fe_{Tot}	0.03	Trace	Trace	Trace	Trace	Trace	Trace	0.02	Trace	Trace	Trace	Trace	Trace	Trace	Trace
Mn^{+2}	Trace	Trace	Trace	Trace	0.05	0.02	0.05	Trace	Trace	Trace	Trace	Trace	Trace	0.02	Trace
F^-	0.15	0.5	0.45	Trace	0.5	0.8	0.5	1.1	Trace	0.5	0.15	Trace	Trace	0.96	0.45
Cl^-	14.3	19.95	46.6	28.5	63.7	42.8	461.7	35.2	9.5	8.6	19	12.4	31.4	37.1	57
NO_3^-	12.5	7	14.25	21.5	5	5	17.5	8.5	19.5	19.5	14.3	14.25	8	10	8
CO_3^{-2}	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace
HCO_3^-	395.7	418.1	278.7	236.4	311.1	433	355.9	181.7	378.3	398.2	423.1	433	430.6	328.5	545
SO_4^{-2}	11.28	17.33	49.5	19.3	66	151.3	467.5	71.5	11.5	11	26.95	17.33	24.75	71.5	24.7
PO_4^{-3}	0.08	0.103	0.123	0.062	0.041	0.08	0.041	0.062	0.041	0.062	0.062	0.041	0.246	0.08	0.062
NH_4^+	0.275	0.15	0.15	0.25	0.22	0.26	0.65	0.39	0.13	0.188	0.188	0.4	0.15	0.13	0.65