CHARACTERIZATION OF GROUNDWATER AQUIFERS IN A STRUCTURALLY COMPLEX REGION: - A CASE STUDY OF WEST OF LAKE NAIVASHA AREA

BY

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DECLARATION

I declare that the dissertation is my original work and has not been submitted elsewhere for examination, award of degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced to University of Nairobi's requirements.

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Abstract

Climate change, groundwater abstraction, horticulture and geothermal activities have influenced the volcanic aquifers within and around Lake Naivasha area. In the previous studies, the effects of faults on varying groundwater quality in different areas and the relationship between surface and groundwater has not been well established within the study area. The main objective of this study was to characterize groundwater aquifers west of Lake Naivasha based on aquifer properties, structural controls on groundwater flow, as well as understanding the relationship between surface and groundwater interactions in context of water quality. In order to achieve this, hydraulic conductivity of groundwater system and aquifer transmissivity were determined to provide an understanding on the extent of localized aquifers. The aquifer transmissivity values are high in the northern parts of Lake Naivasha (1447-2652 m^2/day) due to high rates of groundwater abstraction, moderate within Ndabibi Plain (138-1042 m^2/day) and low in the southern and Kiambogo areas (<138 m^2/day). Four out of nine faults identified influences groundwater flow while the rest of the faults are permeable to groundwater flow. The general flow of groundwater is toward southwest. From the piezometric heads, there exist a water divide between Lake Sonachi and Lake Naivasha hence the two waters are not hydraulically connected. From electrical resistivity measurements, the aquifers in Ndabibi Plain occur in pools within weathered tuffs/pyroclastics and lake bed sediments. Shallow aquifers occur between 20-60m bgl around Lake Naivasha within lake sediments while deeper aquifers penetrated by the current boreholes range from 167 to 297 bgl. Electrical resistivity measurements identified deeper aquifers around Lake Naivasha between 180 and 240 m bgl which are not penetrated by the current boreholes. The concentration of ions follows the same pattern as the groundwater flow gradient, the northern parts of the study area are less saturated with respect to sodium, calcium and lithium ions compared to the southern parts, where the groundwater gradient is small hence more time of residence. Using lithium ion, two flow direction are realized; one is toward Lake Oloiden and the other around Lake Sonachi in Ndabibi plain. The ratios of Na and Cl of Lake Sonachi (6.7) resembles borehole waters around it (5.97), while River Marmanet, has an average value of 2.79 resembling that of Lake Naivasha (2.91) and possibly may indicate lake water-river water-groundwater interactions. The upgraded groundwater flow map will be useful in tracing the pollutants within the study area while delineated zones of fresh and saline water will enhance sustainable abstraction of fresh water while avoiding areas with deplorable quality.

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1 INTRODUCTION

1.1 Background Information

Groundwater occurrence and transmission is mainly controlled by geology (rock type) and geological structures (fractures, joints and cavities) in response to hydraulic gradient. The relationship between groundwater circulation, volcanic bedrock aquifers and watershed suggest that source of fracturing namely tectonic and volcanism affects the water quality (Frisbee et al., 2017).

In a detailed study on effects of fractures in relation to conduction of water, Fridrich et al., (1994) and Wu et al., (2002) showed that it depends on the geological matrix. Their study at Yucca Mountain, Nevada, showed that, fractures become active when the inhibition capacity of the walls is less compared to the inflow and low in the impermeable matrix an aspect supported by Krasny and Sharp, (2003). They further noted that in the volcanic rocks, groundwater has low Cl, SO_4 and other solutes. The principle of water quality applies to high chemical reactivity in the cases of leaching and the presence of CO_2 in the soil.

Groundwater transmissivity depends on the thickness of the aquifer penetrated and hydraulic conductivity. Hydraulic conductivity of the subsurface materials depends on the size and distributions of pores as well as viscosity of the water and temperature of the soils (Oosterbaan and Nijland, 1994). The flow of water changes directions depending on the properties of the rocks.

Lake Naivasha is located within Kenyan Great Rift Valley, in Nakuru County and lies North West of Nairobi, Kenya. The volcanic rocks that resulted during the formation of Great Rift Valley and characterized by different structural systems cover the region. The area surrounding the lake has highly variable groundwater potential zones with also varying salinity (Olago et al, 2009). Climate change, abstraction, horticulture, structural instances and geothermal activities have influenced the volcanic aquifers and surface water flow in this area (Odongo, 1993).

The spatial changes in groundwater quality within the area of study are attributed to geology, groundwater abstraction, climate change and tectonic movements in the previous studies (e.g. Olaka et al., 2016; Olago et al., 2009; Morgan, 1998). However, the relationship with respect to water salinity has not been well established between surface and groundwater system. The main economic activity in the study area is farming, primarily done through irrigation using groundwater. Due to the groundwater abstraction, this has affected aquifers in the northern parts of the lake where large irrigation takes place (Olago et al., 2009).

Climate history has suggested that the level of the lake has changed over periods of time and as suggested by Olago et al. (2009), 9000 years BP the lake level was three times larger and a depth of 150 m compared to current level of 9 m (Bergner et al., 2003). The effects of climate change on the surrounding groundwater clearly indicate alternate dry and wet periods. The lake water recharges aquifers during the wet periods and low recharges takes place during dry periods. The wet periods as suggested by Olago et al. (2009) occur after 10 years and lasts for three years and dry periods corresponding to low recharge periods last for six to ten years.

The study will be useful in providing ways of managing the available groundwater and avoiding polluted groundwater. In addition, it will provide also an understanding on the hydraulic connection between surface and groundwater systems, as well as the influence of geological structures in influencing groundwater occurrence and distribution.

1.2 Scope of the Research

The scope of the research work comprised the following: -

1) Collecting and collating of the existing data and information within the study area. The data included existing borehole completion records, hydrogeological maps, geophysical data of previous documented surveys, water quality data and topographical map. Most of the data were found in the previous studies carried out and published by different research urgencies, stakeholders, government entities and private consultants.
2) Analyzing both surface and groundwater quality data to establish the various spatial changes and gain a proper understanding of the interactions between surface and groundwater. The water quality was used to trace the groundwater flow directions together with the known aquifer properties.
3) Carrying out geophysical surveys on the anomalous areas based on the analyzed water quality data and targeted areas of low and high transmissivity values. The general idea was to map shallow fractures and faults and finally determine the hydrostratigraphy of the study area. The geophysical data was collected using PQWT-TC300 equipment, which measures the natural electric fields of the sub-surface materials. The electrical

resistivity results were in form of profile curves and profile maps auto-generated and presented. The analysis of the data was done in comparison with the borehole logs within the selected areas.

1.3 Overview of the Methodological Approach

The main objective of this study is to characterize groundwater aquifers within the study area based on water quality and hydrostratigraphic units. To achieve this, the study was undertaken under the following phased methodology: - Desktop study, data collection, field data collection, collation, data analysis, report writing, presentation of draft report, filling of data gaps, submission of the final report. During field data collection, physical and geochemical parameters such as EC, TDS, salinity, pH, temperatures were measured in-situ. Further, resistivity measurements by use of PQWT-TC300 equipment were carried out in pre-selected sites to reveal the thickness and lateral extent of the aquifers.

The piezometric maps, geological maps and hydrogeological maps were reviewed and re-evaluated in order to have a comprehensive study at the end of the project. This was done during the desktop study before carrying out the geophysical measurements. Geochemical data was obtained from the ongoing studies within the study area and others obtained from the borehole completion records held by the government.

1.4 Problem Statement

The reported low and high ranges of fluoride (0.2-75 mg/L) and E.C values (800 - 1560 µS/cm) for the groundwater in the study area from the previous studies are not properly characterized to know the boundaries. The impacts of the influent rivers in Ndabibi plain from Eburru and Mau Forest on groundwater resources have not been well established (Becht et al. 2005a). These rivers recharge the shallow aquifers and deeper groundwater in the areas depending on the local geology and structural properties. The effects of faults instances within Ndabibi plain on surface and groundwater require detailed investigation to understand the hydraulic heads and relationships between different aquifers as well as the relationship between surface and groundwater system.

1.5 Aim and Objectives

The main aim of this study was to characterize the groundwater resources west of Lake Naivasha.

The specific objectives were as follows: -

1) To determine the hydraulic conductivity and transmissivity of the aquifers within the study area
2) To determine structural control on groundwater flow
3) To define the surface and groundwater interactions in relation to water quality

1.6 Justification and Significance of the Research

The varying surface and groundwater with respect to fluoride and salinity levels, impacts of the influent rivers on groundwater resources called for a new approach in the study of both surface and groundwater resources. It was also important to understand how nitrates introduced into the ground in the northern parts where intense agricultural activities takes place will influence groundwater quality within the study and the southern parts. The above dynamics therefore called for a change in approach to groundwater characterization, identify ways of managing the available aquifers and provide detailed updated groundwater flow map in the study area from Clarke et al. (1990) using additional data. The understanding of hydraulic gradient and aquifer transmissivity within the study area guides the in-depth knowledge of spatial distribution of groundwater quality.

2 LITERATURE REVIEW

2.1 Geology and Stratigraphy

The geology is composed of different volcanic units overlain by recent sediments and these differ in extent. The older formations are made up of flood basalts of Miocene origin, Phonolites of Pleistocene overlie these older formations. The youngest formation comprises Trachytes of Quaternary, volcaniclastic and recent deposits according to Thompson and Dodson, (1963) and McCall, (1967). The gentle sloping trend of sediments toward Lake Naivasha is contrary to the general lithology of the area, which is characterized by steep and extensive promontories into the lake (Sikes, 1936). The four main rocks within the area are as follows: - phonolites of Miocene and volcanics of Pleistocene origin that include a mixture of trachytes, rhyolites, phonolites commendites and pyroclastics (Olaka et al., 2016). The general rock units from oldest to youngest in Naivasha area are basalts, tephrites, phonolites, trachytes, rhyolites, commendites and pyroclastics (Thompson and Dodson, 1963).

Volcanoes in the vicinity of the study area have distinct rock formations for example Mt. Longonot comprise mainly peralkaline trachytic lavas and pyroclastics Scott (1980) while Olkaria and Eburru volcanic complexes comprises rhyolite formations. The rift floor comprises of a mixture of rhyolites, commendites, phonolites, pyroclastics, basalts of Pleistocene, which underlies volcanics, fluviatile, and lacustrine sediments of Holocene confined around the Lake (Thompson and Dodson, 1963). These volcanic rocks are overlain by recent sediments and in some places by pyroclastic materials (McCall, 1967).

Stratigraphic units in the study area consist of three main formations as shown in **Figure 2.1**, which include Pyroclastics (Middle Lower Pleistocene) trachyte (Middle Pleistocene) and sedimentary rocks (Thompson and Dodson, 1963). The rocks are step-faulted with block structures detached from the bounding faults (Olago et al., 2009).

The sediments are laterally variable and comprise of lacustrine and fluvial sediments while volcanic units consist of reworked and weathered surfaces, which vary both laterally and vertically (Nabide, 2002; Yihdego, 2005; and Hogeboom, 2015). However, the best way to analyze the hydrostartigraphic units is by analyzing the well logs from different boreholes sampled within the study area and characterizing them in order to affirm the lithostratigraphic thickness, and to understand the well and aquifer properties. Due to different volcanic complexes from different volcanic centers (Legese, 2011), it is therefore misleading to conclude a hydro-stratigraphy of the area based on the general studies done in large scale. To understand the possible connections between surface and groundwater systems, small scale and detailed analysis of both borehole logs and geophysical data could possibly yield a better result.

Summary of the Stratigraphy

In terms of deposition of volcanic rocks in the area, the summary is made in **Table 2.1** for the stratigraphic units from the recent deposits. Sediments overlie most rock deposits in the area and few outcrops can be identified in the rift floor especially within Ndabibi plains. The table is modified after Thompson and Dodson (1963).

Table 2.1: Summary of the Stratigraphic Units (Modified After Thompson and Dodson, 1998)

Age	Rock Type	Description
Holocene	Trachytes and ashes	Mostly from Longonot and south of Eburru area. These are Recent formations
Upper Middle Pleistocene Deposits	Basalts as cones Rhyolites Trachytes Commendites Phonolites Trachytes	Pyroclastics intercalated within these formations with different thickness
Lower Middle Pleistocene Volcanics (?) deposits	Pyroclastics and sediments, welded tuffs	
Lower Pleistocene Volcanics (?)	Basalts	Identified around Kinangop at Mahindu Valley

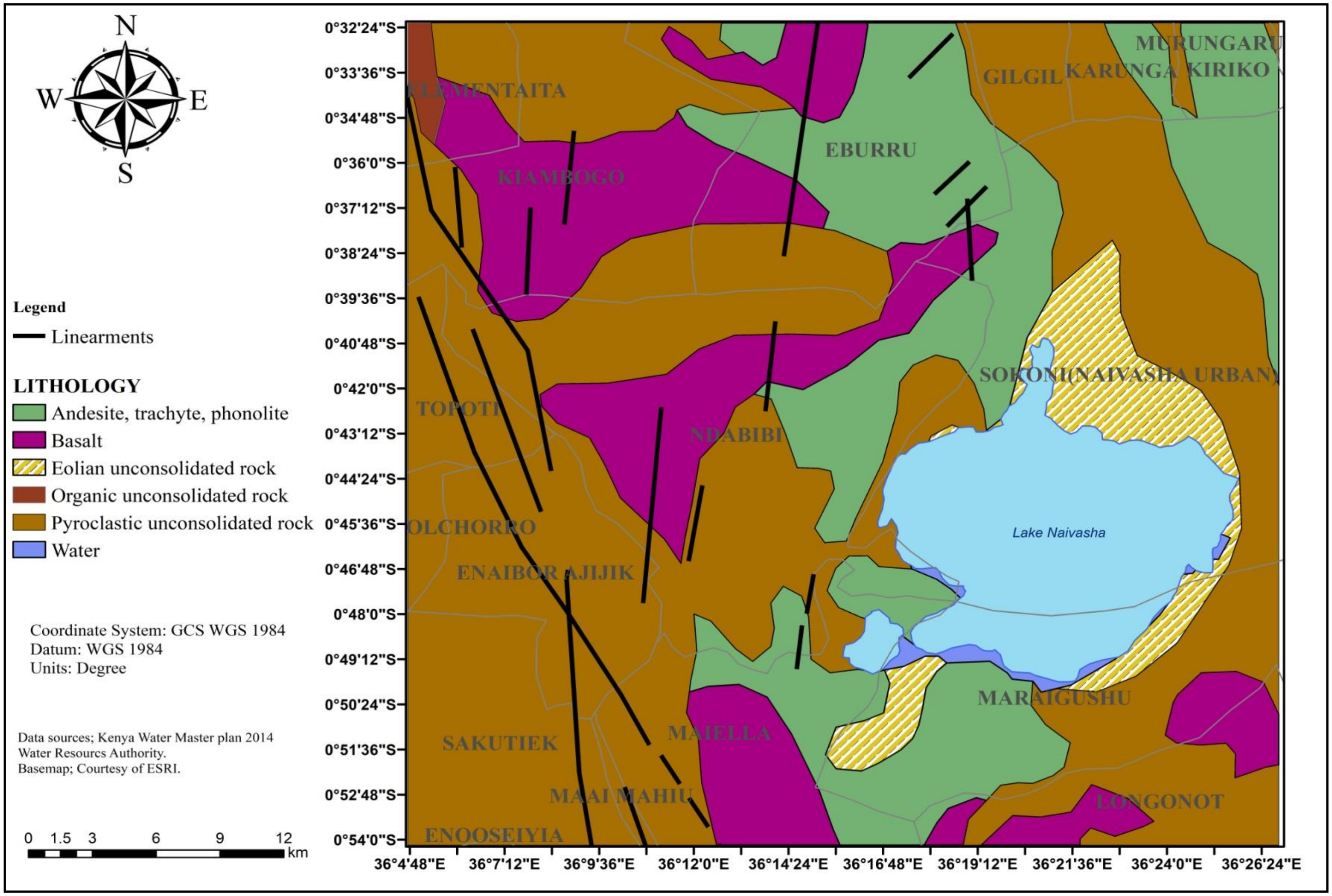


Figure 2.1: Geological and Structural Map of the Study Area (Modified after Government of Kenya, Ministry of Energy, 1988)

2.2 Geological Structures

The structures comprise faults on the sides and within Rift Valley and a slight folding near Hell's Gate Gorge. Slight unconformities in the lakebeds are present especially along Malewa River. Faults which are the main features in the older rift boundary trend NW-SE but the younger faults within the floor of the Rift are oriented in N-S direction (Omenda, 1998; and Simiyu and Keller, 2000). The faults regionally act as conduits for groundwater flow and an example is N-S oriented fault from Maji Moto spring SE part of the lake between Lake Naivasha and Lake Elementaita (Odongo, 1993). **Figure 2.2** shows these faults and their orientations.

The major tectonic structure is Gregory Rift while younger faults of upper Pleistocene age cuts through Gamblian Sediments at faulted craters and single instances in Ndabibi plains west of the lake (Odongo, 1993; and Sikes, 1936). The role of minor faults within Ndabibi plain with respect to groundwater flow is less understood but it can be attributed to the influent rivers.

The most conspicuous fault is Olkaria fault and a second one from the hill eastward ending at the Gorge below the younger lava flow (Odongo, 1993). These two major faults are the main structures controlling the bulk fluid movement, as they are permeable hence useful reservoirs rocks to both geothermal systems and groundwater systems (Odongo, 1993, Mwaura, 2016). Odongo later gave examples of major production wells in the northeast, which are probably tapping from these faults namely OW-701, OW-709, OW-714, OW-718 and OW-717 and OW-30 and OW-32 in the east. He further noted that there is comparatively marked inflow at shallow depths of cooler waters, attributed to the feeder fissures and dense network of minor faults.

Odongo (1993) and Morgan (1998) alluded that faulting within the study area is majorly extensional resulting in hot fissures; however, the previous studies have not provided any similarity in age comparisons between Olkaria and Eburru faults except in the general appearance. The two sets of faults are distinct and aligned in NNW-SSE direction while the younger faults are oriented in N-S direction (Odongo, 1993 and Clarke et al., 1990). The influence of these network of shallow faults on groundwater is not distinct and therefore need to be investigated. These faults are mostly found around Eburru area and some instances within Ndabibi area.

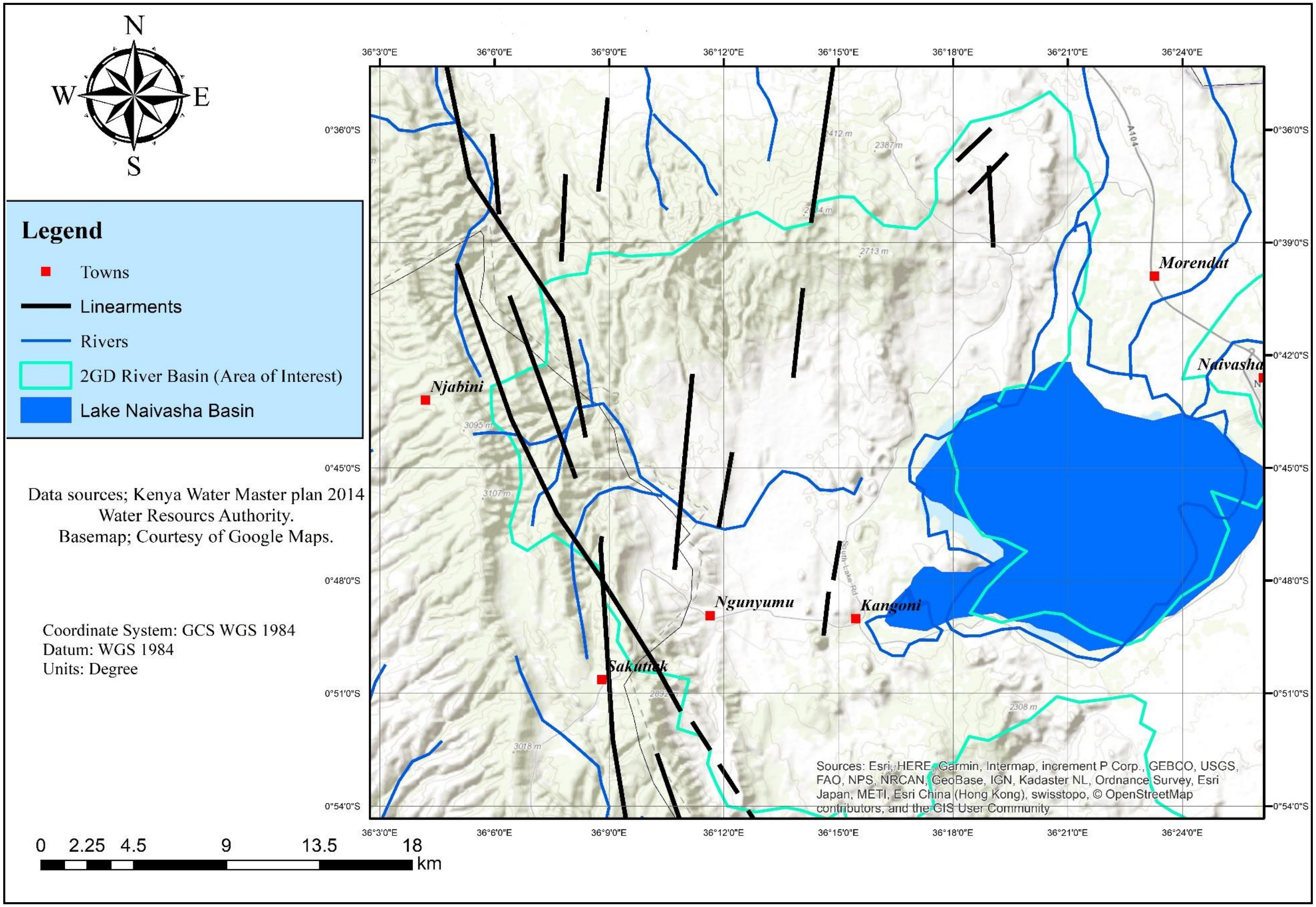


Figure 2.2: Structural Map of the Study Area (Modified after Government of Kenya, Ministry of Energy, 1988)

2.3 Groundwater Flow

The regional links between the groundwater flows can possibly be inferred from the properties of the lakes within Rift Valley, in which the lakes have inflow of dissolved solids that accumulate with time. This is evidenced in Lake Magadi containing deposits of soda and which, acts as a final sink in the southern rift in a large drainage system (Clarke et al., 1990; Becht et al., 2005; and Olago et al., 2009). The case is different for freshwater lakes, which are flushed by surface outflow discharge through groundwater seepages.

The top of geothermal aquifers is approximated to be about 1500 m asl while in the Kedong valley that is situated south of the lake, no borehole has been successfully drilled at elevation of 1400 m asl (Becht et al., 2005b). This is a suggestion that the outflow of water from Lake Naivasha southwards is via deep aquifers. Nevertheless, this does not dispute the possible leakage from the lake via shallow aquifers as seen in the work of Clarke et al. (1990) who hinted a possible flow using both hydraulic and isotope analysis in their study of shallow groundwater aquifers in the southern parts of the lake. The type of the existing fractures, which creates several aquifers within the regional aquifer (Clarke et al., 1990), majorly controls the flow and distribution of the groundwater and while Olago et al., (2009) confirmed the same situation by doing geo-electric measurements North of Lake Nakuru.

There is a general understanding in the Rift Valley Catchment area and significantly for Naivasha catchment area that the groundwater flow is towards the lake from west and east that is Mau and Aberdare Escarpment respectively, but diverted by the presence of faults depending on the permeability of the fault system (Mcann, 1974 and Olago et al., 2009). This brings two types of groundwater movement i.e. lateral toward the basin and axial movement along the Rift floor. The faults allow the longer flow paths and deeper groundwater aligned along the axis of the rift system.

The composition of water in the geothermal water around Naivasha area indicates a large distribution of water from Lake Naivasha. Usually unmodified groundwater has a mean cluster of isotope composition of about -4.6% 18O and -28% 2H but the water from the surrounding aquifers have 70% unmodified and 30% modified from lake water which can also be attributed by fumaroles and rain water (Arusei, 1991). The stable isotopes of natural 18O and 2H are all present in natural waters.

The sediments in relation to their hydraulic properties can be seen as highly fractured rocks or well sorted sand and gravel (Freeze and Cherry, 1979). The Ndabibi plain west of Lake Naivasha is mainly made up of sediments and is basically recharged laterally from Mau escarpment, while the aquifers around Olkaria is recharged via the deeper aquifers. It is also not clearly understood whether the aquifer west of Lake Naivasha directly recharges it or being recharged by the lake. Hydrogeology of the surrounding lake is considered complex system with respect to lake levels in which the rise of the lake level causes it to recharge the surrounding aquifers and during the low level the surrounding aquifers recharges the lake (Becht and Nyaoro, 2006). Olago et al. (2009) found out that the depth to the groundwater level varies and piezometric levels also changes widely, the best yields occurs at contact zones or within fractured/weathered zones.

In his Model development, Everard et al. (2002) considered the disappearing rivers emanating from Mau Forest assuming that all drains their waters into Lake Naivasha, however, faults within the area might form compartments that act as barriers rather than conduits to groundwater flow. In addition, Hogeboom (2013), illustrates the same effect together with the influence of groundwater abstraction to the lake. It is suggested in the previous studies that the interactions depend on the lake level (Becht et al., 2005b; Ayenew & Becht 2007; Becht and Nyaoro, 2006).

Groundwater flow from the lake greatly influences the surrounding groundwater system. Lake Naivasha and its surrounding consist of high yielding boreholes mostly used for irrigation. In the study done by Becht et al., (2006) considered the lake as a groundwater outcrop that recharges Lake Elmenteita and Lake Magadi on the south. The lake discharges water in the north and southern directions based on the dynamic groundwater level and isotopic composition in the previous studies (Olago et al., 2009; Becht et al., 2005a; Ojiambo, 1992).

The groundwater has patches of different water qualities which changes spatially within Ndabibi location. There is a general believe, that the lake loses water in all the directions except from the Ndabibi plains that recharges the lake. However, that is not clearly defined whether aquifers are connected to the lake level and hydraulic gradient allows the recharge to take place (Everard et al., 2002; Ojiambo, 1992; and Clarke et al., 1990).

2.4 Surface Water

Lake Naivasha basin consists of the following surface water resources; Lake Naivasha, which is a freshwater lake, other small lakes include Oloiden, Sonachi (crater and alkaline lake) and Crescent Island lake as well as three main rivers namely Malewa, Gilgil and Karati. These lakes may be connected through groundwater or surface flow (Olago et al., 2009; and Becht et al., 2005). Surface water dynamics is a factor of climate, volcanic barriers and faults, water table changes and finally the tectonic controlled morphologies.

The basin is entirely drained by two main rivers Malewa and Gilgil accounting for 80% and 20% respectively (Becht et al., 2005). River Karati is an ephemeral discharging into the lake. The volume contributed by these two major inflows is 153 Million m^3 and 24 Million m^3 for Malewa and Gilgil rivers respectively (Everard et al., 2002 and Morgan, 1998). The rivers from Mau forest and Eburru hill infiltrates into the soils and disappear in Ndabibi plain before reaching Lake Naivasha. The Marmanet River that loses its water on the Ndabibi plain is an example of a tapering stream (Thompson and Dodson, 1963; Becht et al., 2006 and Olaka et al., 2016). Topographically, these areas are of higher elevations and hydraulically they should be recharging the lake.

2.5 Aquifers

In the volcanic regions, the most productive zones are found at the contact zones and within the fractured/weathered zones. This is the regional perspective within the rift but the depth and piezometric levels varies both regionally and locally (Olago et al., 2009). Groundwater generally follows the elevation of the topography and these changes in the piezometric levels are possible due to the elevation changes and presence of dense faults within the rift system.

In the volcanic regions, hydraulic properties cannot be up-scaled or downscaled directly to specific formation, in some cases, permeability vary depending on fracturing and alteration of the rock as noted in the study of Canary Island aquifers (Krasny and Sharp, 2003). In zones affected by hydrothermal fluids, their hydraulic conductivity decreases. In some cases where pre-existing formations are overlain by volcanics like in Etna Sicily (D'Alessandro et al., 2004), the formation possibly in most cases acts as low or high permeability areas hence the volcanic units may be seen as recharge collectors, conductive or storage units (Krasny and Sharp, 2003). According to Hinds et al. (1999), faults are noted to be conductive especially when they are formed at cross-welded tuffs.

According to Water Resources Authority (WRA), the study area is classified under Lake Naivasha Strategic Aquifer with average depths of 125m bgl and average yield of about 7.5 m^3/hr (Pavelic et al., 2012). Using resistivity, magnetic and gravity methods done in the past studies, the area around the lake has two main aquifers at depths of 20-40 m and 50-80m bgl (Tsiboah, 2002). The main aquifers comprise sediments covering the floor of the rift with relatively high permeability and specific yield. From the piezometric maps and isotope analysis, it is agreed from the past studies that groundwater from Lake Naivasha discharge to the south and north of Lake Naivasha (Hogeboom, 2015; Legese, 2011; Clarke and Allen, 1990; Odongo, 1993 and Becht et al., 2005).

The transmissivity ranges from 1 to 500 m^3/day) while storativity is in the order of 0.01 for the aquifers around the Lake Naivasha (Kibona, 2000). Later works by Legese (2011) using Cooper-Jacob method noted the values of transmissivity and storativity are 462 m^2/day and 1.46 x 10^3 respectively. The inventory boreholes used by (Clarke et al., 1990) drilled around Lake Naivasha had an estimation of 12-148 m/d permeability in NW and NE parts. Notably, there is a significant disparity of the transmissivity and storativity values reported for Naivasha area. Therefore, this study endeavored to confirm the aquifer hydraulic and storage properties that reflect the area west of Lake Naivasha.

The regional aquifers in the Kenya Rift composed of volcanic units occur at different depths and vary litho-stratigraphically in thickness and number of layers encountered. An observation that was made by IEA, (2006) and Olago et al., (2009) through studies of varying piezometric levels. Most of the aquifers have average yields of 7.5 m^3/hr and average depth of about 94m below sea level (IEA, 2006). Therefore, in the detailed studies of groundwater system in the volcanic environment with hydrogeological complexes, the area should be divided into volcanic units and further classified by stratigraphy, structural characteristics and permeability of the formations. This will help to understand the groundwater circulation with the surface water interactions (Manca et al., 2017).

Aquifer Transmissivity

Transmissivity is defined as the flow of water under a unit hydraulic gradient through a cross-section area of unit width within the entire saturated aquifer. From the well test data, the formula below is used to determine transmissivity from Theis Equation (Thiem, 1906).

$$T= QW(u)/4\pi s$$

Where T is transmissivity, s is the drawdown and W(u) is well function of (u) equals to $u= (r^2S)/(4Tt)$.

One of the ways to solve the equation above, Theis used graphical method by drawing drawdown verses time and then substituted in the equation. Transmissivity can also be determined from the hydraulic gradient from Darcy's law. A more convenient formula derived from the Theis Equation by Logan (1964) is used to calculate transmissivity values. Logan developed a formula relating specific capacity and transmissivity after reworking Thiem's Equation. The formula is as follows:

$$T= 1.22 \times Q/s$$

The equation depends on two parameters only of the well test data, that is the amount of water discharged (Q) and drawdown (s).

The properties of rocks to transmit water are dependent on their hydraulic characteristics on the water bearing materials and the aquifer penetrated (Heath, 1983). For layered formations, hydraulic conductivity, K, is determined in respect with the flow direction of the subsurface water. In the case where groundwater flow parallel to the flow direction, which is possible in the case of volcanic rocks, the value of hydraulic transmissivity can be found from the summation of all the layers calculated while when dealing with perpendicular layers, hydraulic resistance is used instead (Oosterbaan, 1990a). There are three major types of flow, that is change from vertical direction to horizontal and finally an intermediate flow (Boumans, 1976).

The simplified formula above is used to calculate transmissivity values. The yield estimated from the well test and pumping well analysis could not be used in the Jacobs formula to find transmissivity values. This is due to lack of the observatory well during the test and improper recording of the data analyzed. Most companies in the country do not perform standard aquifer tests since there is usually no observatory boreholes monitored during such tests.

2.6 Groundwater and Surface Water Quality

The regional water quality challenges with excess of fluoride concentrations is a result of alkaline rock formations, weathering, hydrothermal, volcanic terrain interactions, leaching and cations exchange in groundwater (Edmunds, 1996; Olago et al., 2009; Olaka et al., 2016). The chemistry of the water definitely will derive its chemical components from the rock it interacts with (Arusei, 1991 and Muchemi, 1985). The horticulture farming with use of fertilizers also introduces more nitrate content into the aquifers through infiltration and other elements such as chlorine, potassium, calcium, magnesium, sulphur and other minor elements (Olago et al, 2009).

The boreholes and river waters have similar water properties. However, groundwater flow patterns, lithology and solution kinetics control the hydrochemical facies and enrichment of borehole water. In particular, the concentration of Na, F and SO_4 is mainly through leaching of pyroclastics and soda-rich volcanic rocks (Olago et al., 2009 and Arusei, 1991). In addition, Arusei (1991) noted that the boreholes in the northern parts of Lake Naivasha, generally contains elevated values of of fluoride compared to the ones in the southern parts, while there are no comparisons made to the borehole on the western parts of the lake in relation to the major hydrostratigraphic units.

The general range of fluoride concentration is between 0.02 -75 mg/l and highest fluoride concentration occurs around Lake Oloiden with a range of 13.3 - 72 mg/l, the level decreases towards Lake Naivasha (Morgan, 1998 and Olaka et al., 2016). Fluoride concentration is low in river waters with a range of 0.2-9.2 mg/L. Regional and complex groundwater models developed by Owor (2000), Legese (2011) and Yihdego and Becht (2013) with multilayered systems may not be practical in the field situations due to sparse data used as illustrated by Hogeboom (2015).

Lake Sonachi, which is a major surface water resource, is highly alkaline while toward Lake Naivasha the groundwater is of good quality. The general water quality tends to vary with the properties of the existing rock unit and geochemical processes within the area. In the south of the study area around Olkaria, basalts, trachytes/ryholites, tuffs, commendites and Pyroclastics are the main rocks while around Eburru contains mostly pyroclastics, obsidian lavas, basalts, trachytes/rhyolites and phonolites (Muchemi, 1985; Scott, 1980; Naylor, 1972; Thompson and Dodson, 1963). The decline and deterioration of water quality around Lake Naivasha basin especially on the north and western parts of the lake is due to horticulture industry (Becht et al., 2005) and effects of cones of depression (Becht and Nyaoro, 2006; Olago et al., 2009). This study did not account for water mixing between the different aquifers and aquifers with poor water quality were not also defined. It is therefore necessary to characterize the possible aquifers with deteriorating water quality and their interactions with other aquifers both laterally and vertically.

Gap in Knowledge

The study on aquifers in Naivasha area has defined a regional volcanic aquifer system. However, the cause of localized aquifers within the Central Kenya Rift depths has not been defined as well as their lateral extent. The spatial variations in groundwater with respect to major elements, fluoride, electrical conductivity (EC) and Total Dissolved Solids (TDS) between Mau Forest and Lake Naivasha may result due to the effect of borehole abstractions, farming activities, tectonic events and climatic evolution in the region. The influence of inferred faults on groundwater flow and quality within Ndabibi plains is ambiguous (Becht et al., 2005b). There is a need for detailed geophysical method together with analysis of boreholes logs and borehole water samples in order to understand detailed interactions between surface and groundwater, geology and subsurface structures. The study is important for sustainable management of groundwater resources and avoiding areas of deplorable water quality.

2.7 Research Questions

1. How do the faults within Ndabibi plain influence surface and groundwater flow?
2. What is the cause of localized aquifers within the rift (ITC-WRAP Phase V, 1996) with patches of different groundwater quality west of Lake Naivasha?
3. If the lateral flow of both surface and groundwater from Mau Forest does not directly recharge the lake, then what is the possible hydraulic head from Eburru to Olkaria via Ndabibi plain?

3 MATERIALS AND METHODS

3.1 Study Area

3.1.1 Introduction

This section describes the general location of the study area in terms of climate, soil, vegetation, physiography, drainage land use and land resources

3.1.2 Location and Description

The study area is located west of Lake Naivasha and is sandwiched between Mau forest and Lake Naivasha. It is within Nakuru County and some parts on the western side borders Narok County. The area borders Eburru to the north and Olkaria to the south and bounded by Mau Forest on the west and Lake Naivasha on the eastern part. The area lies between longitudes 36° 06´ 0´´ and 36° 24´ 0´´ and latitudes 0° 54´ 0´´ and 0° 39´ 0´´ (**Figure 3.1**). The main economic activity in the study area is horticulture done primarily through irrigation; crop production is practiced through subsistence farming (Becht et al., 2005a). Groundwater is abstracted from both shallow wells and boreholes due to prevalence of shallow aquifers. Surface water is harvested from pans and dams. Some mineral resources also exist in the county and a potential to solar and wind energy (CIDP, 2013).

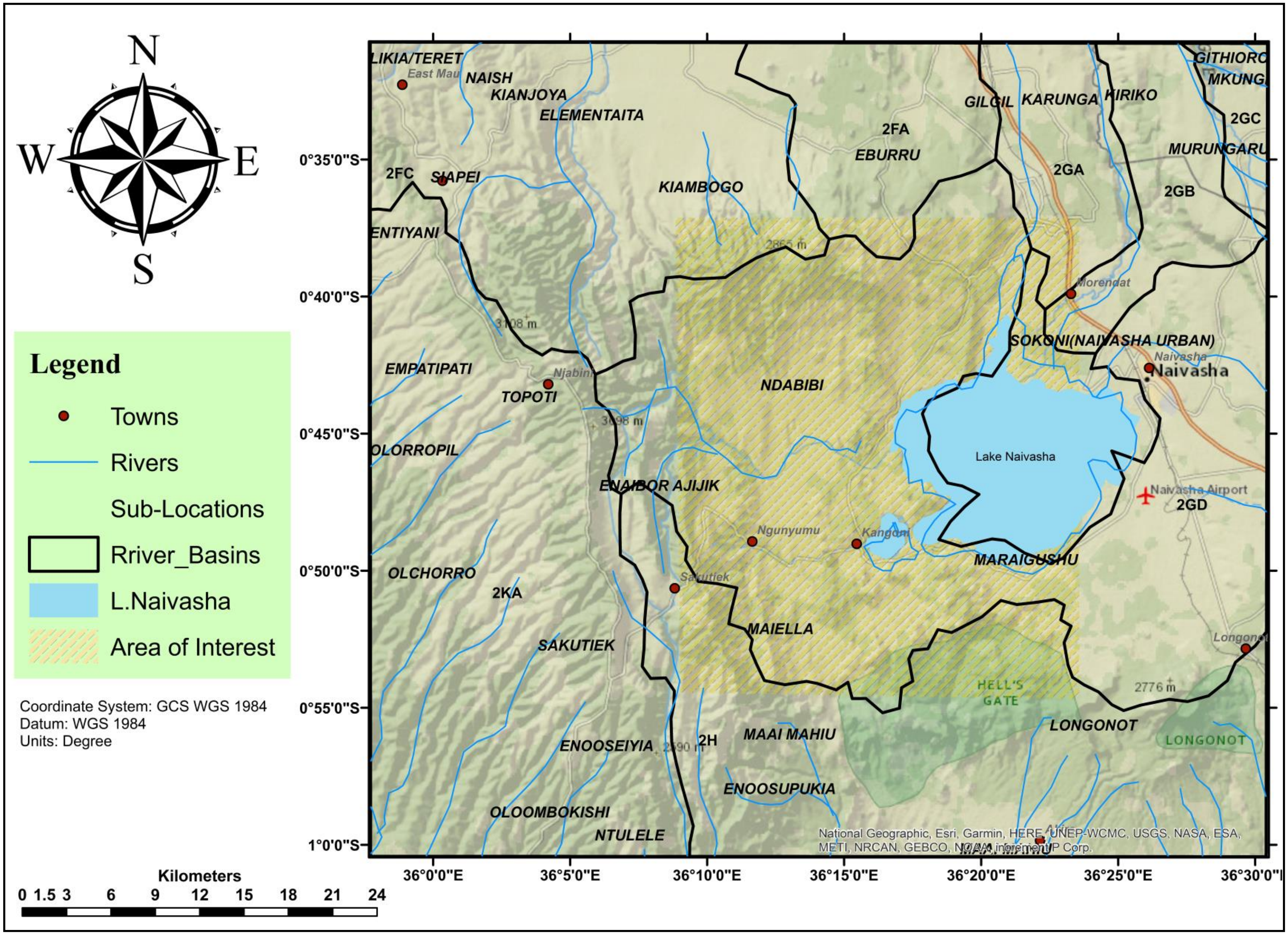


Figure 3.1: Study Area Location Map

3.1.3 Climate

The regional climate of the area can be described as warm, temperate, and locally influenced by the lake itself. East Africa normally receives rains between April and May and short rains between October and November. The variation within is caused by the seasonal changes in the land mass and sea breezes effects (Olago et al., 2009). The Köppen-Geiger system classifies the climate of the area around Naivasha as Warm-summer Mediterranean climate (Csb) with an average temperature of 17.1 °C and annual rainfall of 677 mm (**Figure 3.2**). The hottest month is March with a mean temperature of 18.4 °C and July with the lowest temperature of a mean of 15.7 °C (Nakuru CIDP, 2013).

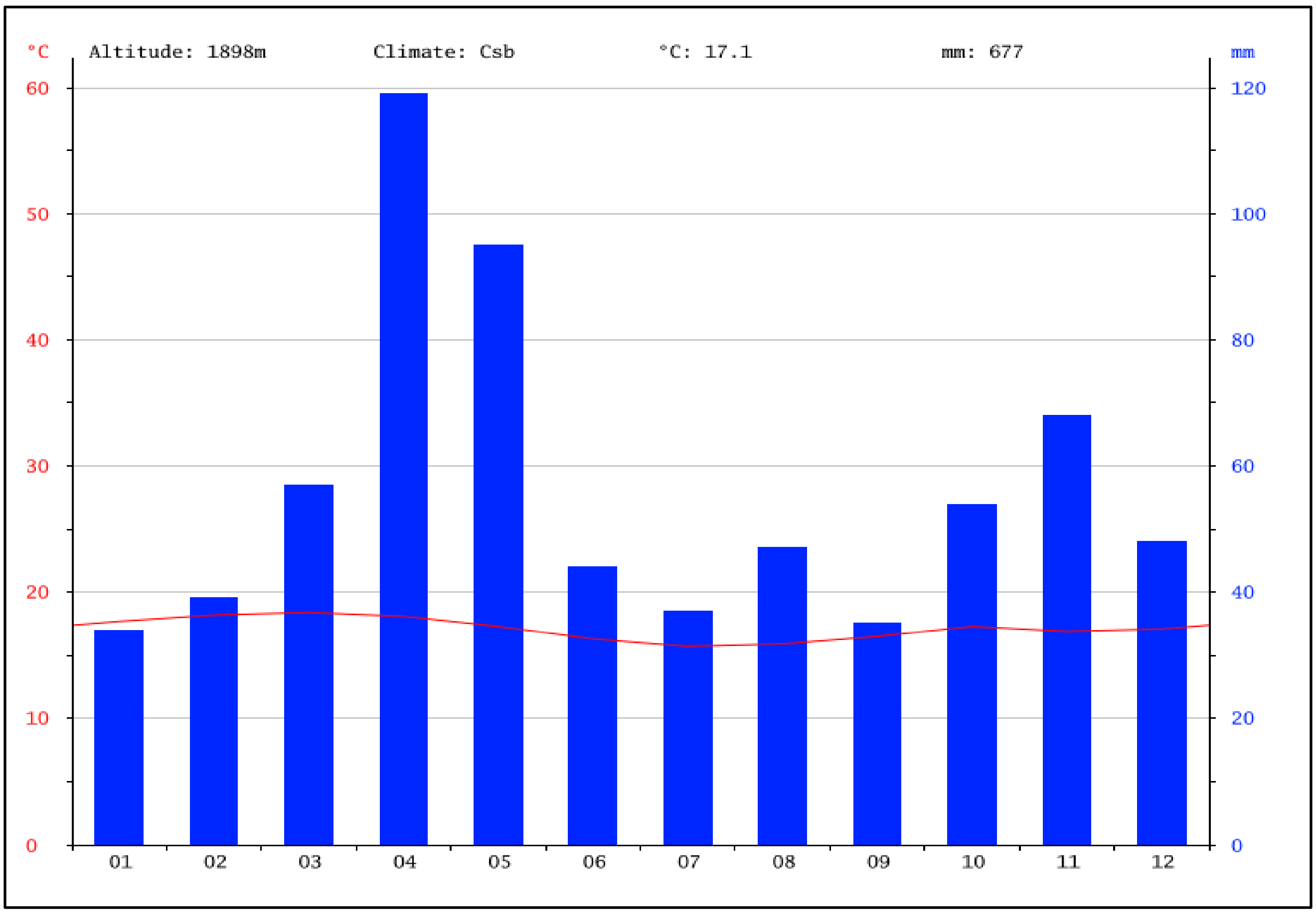


Figure 3.2: Rainfall and Temperature Distribution Graph of the study area

(Source website: https://en.climate-data.org/africa/kenya/nakuru/naivasha-11126/)

Temperature differences are a factor controlled by the season, altitude and topography of the surrounding features varying from freezing points at the mountain peaks and lowlands around the lake. The difference is about 85 mm between the hottest and wettest moths. In the area, the long rains are usually in the period of March-May while short rains in the months of September-October. The lake acts as a major influence to the eco-climate that is located in the rain shadow position with respect to eastern highlands that acts as major catchments (Legese, 2011).

3.1.4 Vegetation

The vegetation consists of Afromontane flora of uniform belt at altitudes of 2200 -3600 m above sea level. This is followed by moorland plateau with grassland above 3600m mostly on the mountain areas. The areas toward the top of Mau Forest, there exist a thick forest cover at a range of 2500 m to 3000m above sea level and mainly are occupied by bamboo while rosewood occupies the boundary at about 3600 m above sea level (Nakuru CIDP 2013; Clarke et al., 1990; and Morgan, 1998). Finally, at the top there exist bare rocks and scattered grassland.

3.1.5 Land Use and Land Resources

Generally, around the lake, there is horticulture farming, which began in early 1980s due to the presence of fertile soil, reliable rainfall, available groundwater for irrigation and cheap work force (Becht et al., 2006). The farms for flowers have increased over the years since then. Initially Maasai community used the land as a grazing ground. During the colonial period, large tract of land was used as ranches and lake water were mainly sources of small irrigation surfaces and grow vegetables and water for cattle (Becht et al., 2006; and Becht et al., 2005a).

These developments of horticulture farming caused a shift in both land ownership and population since people came and buy land due to booming business around. Five-land uses activities are agriculture (both horticulture and floriculture), settlement, game reserves, natural vegetation and rangeland for dairy (Becht et al., 2005a).

3.1.6 Physiography and Drainage

The regional landscape is described from the geological history that led to the formation of mountains, hills, ranges that are the high-altitude points. Aberdare National Park situated on eastern part is the highest altitudes and forest reserves on both sides with altitude of about 3000 m above sea level.

Mau forest to the west is a conspicuous feature within the escarpment, which forms a wall to the Rift Valley floor of Ndabibi Plains. Parts of Mau Escarpment is Eburru ridge which is about 2580 m (Thompson and Dodson, 1963). It is the major drainage divide feature separating Lake Naivasha and Lake Nakuru. At the lower areas of forest zones are the lost bamboo forests, which are subsequently followed by the grasslands at lower altitudes of 2000 m., which were the interest of colonial settlement but now mostly farming takes place by small-holdings (Becht et al., 2005a).

Lake Naivasha is a major drainage feature on the east of the study area whose riparian zone changes dramatically over time. Kinangop Plateau in the eastern part of the area forms a broad and flat plain of about 2440 m asl with down faulted rocks in a series of steps. Rivers forms deep valleys incised due to the presence softer formations e.g. Mahindu Valley while River Malewa at the northern edge flows in a Graben at the foot of the Plateau.

The study area is within Naivasha Basin, which is a raised part of the eastern branch of the Great Rift Valley, by high mountains ranges composed of volcanic rocks having conspicuous topography and high elevations. It is a steep landscape with fertile soils and a great variety of geological features, which relate to the diversity of landforms as well as of forms of life. The rivers from the west are intermittent and does not directly recharge to Lake Naivasha. An example is Marmanet River which terminates in Ndabibi Plain. Some rivers from Eburru area do not show direct connection with the lake where they presumptuously empty their waters (**Figure 3.3**).

3.1.7 Soils

The rift floor is mainly covered with sediments of volcanic origin. Generally, the volcanic rocks within the rift valley have high sodium content. The soils therefore are made of ashes with pumice grains and therefore pumice layers are abundant (Becht et al., 2006). These soils are highly permeable causing a larger percentage of irrigation water to be lost to the groundwater.

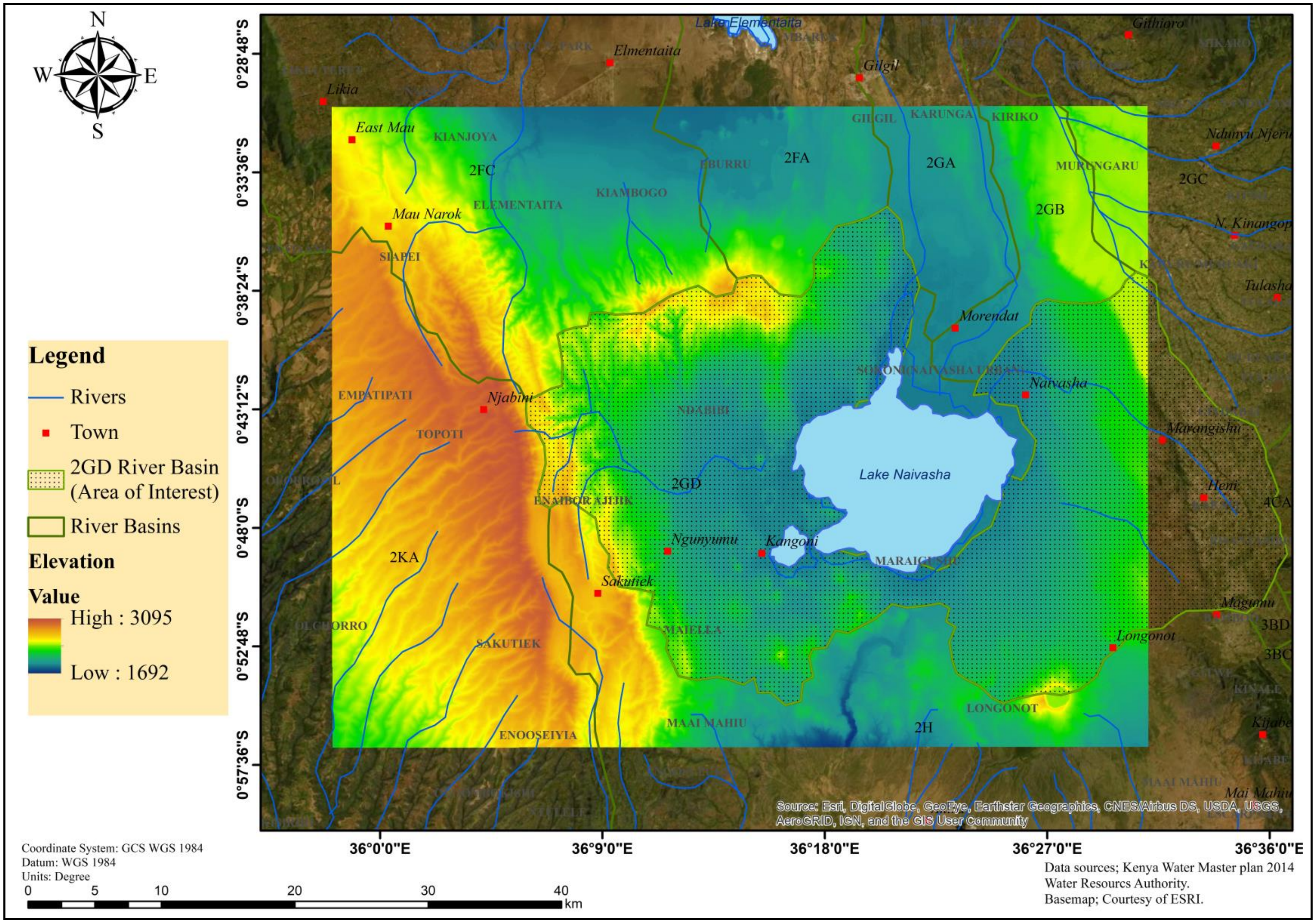


Figure 3.3: Drainage Map of the Area

3.2 Data

3.2.1 Introduction

The borehole data was obtained from the records kept by the Ministry of Water and Sanitation in the sub-regional office in Naivasha and some from the on-going study covering the Central Kenya Rift. Fifty-eight boreholes were used in analyzing the aquifer characteristics. Borehole data was analyzed to determine the groundwater flow direction and find the effects of faults and other structures on the flow. For water quality analysis, 21 number samples constituting of twenty (20) groundwater sources and one surface water source from a cave were used. Water analysis comprised of major elements Na, K, Ca, Mg, SO_4, Cl, HCO_3, F, NH_4, NO_3, NO_2, trace elements: Li, As, Cd, Se, Ba, Cu, Al, Hg, Co, Ni.

3.2.2 Data Analysis and Interpretation

Borehole Data

Borehole data were analyzed to understand different properties of the aquifers within the study area. These properties included depths of the aquifers, water struck levels, static water levels, drawdowns. From these properties, specific capacities of each borehole were calculated and their corresponding transmissivities. Most of the boreholes analyzed did not report aquifers depth hence it was not possible to directly find the hydraulic conductivities. The differences between static water and altitude of the borehole was determined to get the piezometric level, which helped in generating the groundwater flow paths map within the study area.

Water Quality Analysis

The water samples were collected during the field campaign in 2017, the surface and groundwater were sampled and analyzed for major and minor elements. The surface water bodies targeted were the Crater Lake, Lake Oloiden, Lake Naivasha, springs and rivers. For groundwater, a total of total of twenty (20) borehole data and one surface water from the cave were sampled and analyzed. Water quality sampled were analyzed in UFZ-Leibniz Institute Laboratory in Halle, Germany. The parameters analyzed are presented in results section.

The analysis and interpretation of water quality was analyzed based on the major and minor elements used in tracing groundwater flow and interactions between surface and groundwater. Spatial analysis was carried out to determine the distribution of various parameters. Concentration and distribution of elements were plotted to produce spatial distribution maps and to reveal the correlation of surface water quality and groundwater signatures. Major cation elements analyzed includes Na, K, Ca, Mg, Li, B while anions analyzed for this study were Cl, SO_4, NO_3.

The geochemical processes were analyzed by comparing the ratios of Na and Cl, Na and SO_4 to understand the interaction and relationships between the groundwater and surface water. Descriptive analysis and correlation matrix were determined using Excel for different elements, this enabled determination of major processes accompanying groundwater flow and also indicating the closely related elements. Various maps were produced using ArcGIS 10.5 showing distribution and concentration gradients of selected elements. The box-plots were drawn for Na, Ca, Cl and SO_4 to show the interaction between groundwater and different surface water bodies.

Geophysical Data

All data accrued from geophysical measurement were analyzed upon formatting and validation. Verification of trends in aquifer characteristics with the known borehole parameters was established using borehole logs and chemical parameters.

The geophysical data was analyzed by comparing the curve graphs and the sub-surface geology from the borehole logs. The single curves from the raw data were compared with the profile curve graphs which gave out the 2D profile of the investigated area. The PQWT-TC300 gives both the profiling and Soundings within the location for a maximum depth of 300m bgl. It was therefore possible to note the fractured and/or weathered zones in the sub-surface geology. The data was then analyzed by noting the shape of processed 2D curves in comparison with the 2D profile map. Further, by other multi-criterion decision analysis considering the lithology, structures, drainage, overburden thickness and aquifer layer resistivity assisted delineating groundwater.

The results of the profile measurements reflected lateral changes in resistivity, corresponding to variations in lithology, salinity, thickness of formations and water content at a fixed depth along the profile. Electrical Resistivity profile data is normally interpreted qualitatively.

3.3 Methods

3.3.1 Introduction

The study used a guided method to meet the set objectives, which included literature review, analysis of borehole data from the Borehole Completion Records (BCR), water quality data analysis and geophysical (resistivity) method. From the Borehole Completing Records, borehole logs were used to identify the weathered and fractured zones and guided the calibration of the geophysical layers. The electrical resistivity profiles using PQWT-TC300 equipment were performed targeting all the aquifers established from the data. This was performed to reveal the layout of the stratigraphy to a maximum depth of 300 m bgl.

3.3.2 Materials

The following resources were needed for the completion of this study at different stages. During the desk study, hydrogeological maps, piezometric maps, geological maps, topographical maps and water quality maps. At the second phase during the fieldwork, for resistivity survey, PQWT-TC300 with a complete set up, GPS, data sheets and EC meter for measuring physical qualities of water were used.

3.3.3 Fieldwork Activities

The fieldwork was conducted in two major phases. The first phase involved collecting of water samples for laboratory measurements of elements and measuring in-situ the physical characteristics such as pH, temperature, electrical conductivity and Total Dissolved Solids. The second phase involved taking of electrical resistivity data from the pre-selected areas.

Determination of Hydraulic Conductivity and Transmissivity of the Aquifers

A total of 58 boreholes were analyzed and plotted in ArcGIS 10.5 to get the spatial maps showing groundwater flow and transmissivity. Out of that, 16 boreholes had complete data, which were used to calculate transmissivity values using Theim's method. It was not possible to accurately calculate the hydraulic conductivities using the current borehole data since most of them did not report depths of the aquifers penetrated. In that case, aquifer transmissivity values were used for the analysis and characterization of the different zones. The available borehole data included total depths, water rest levels, water strike levels, yield and drawdown.

How the Aquifers were Classified

The aquifers classification was developed by considering the distribution of the transmissivity values within the study area, struck water levels from the boreholes used and total depths drilled. Aquifers surrounding lake Naivasha are struck at depths less 50 m bgl and therefore classified as shallow while northern parts, around Eburru area, the aquifers are struck at intermediate depths. On the other hand, deeper penetrated aquifers of depths greater than 167m bgl are encountered at the east of Mau Escarpments, southern parts of the study area at Maiella area. This classification was based on the current borehole data analyzed the depths to water struck levels varies with the geology of the sub-surface at each aquifer struck. Around the lakes, the subsurface is mainly composed of lake sediments while the surrounding high elevation surfaces, the sub-surface changes to phonolites, trachytes and basalts.

Determination of Structural Control on Groundwater Flow

All the 58 number boreholes were used to get the piezometric levels by getting the difference between the elevation and water rest level of each borehole. Google Earth was used to validate the elevation of each borehole used before piezometric levels were calculated. Later, the data was plotted in Surfer 17 to establish flow patterns within the area. The existing structures were then overlayed in ArcGIS 10.5 in order to see their influence on the groundwater flow.

Determination of Surface and Groundwater Interactions

The major ions were first plotted to show their general distribution in the study area and then major cations i.e. Na and Ca ions are used to indicate the flow direction due to ion exchange during horizontal movement of the groundwater. Cl, NO_3 and B ions were used to show the vertical interaction between the surface and groundwater. Lithium as one of the trace elements in water was also analyzed to establish the flow patterns correlated with major ions above.

Subsequently, additional data on the surface water was added by measuring physical properties; Total Dissolved Solids (TDS), Electrical Conductivity (EC), pH, salinity and temperature in-situ, which were helpful in determination the interactions with the groundwater and geochemical processes.

Box-plots were drawn from four major ions (Na, Ca, Cl and SO_4) analyzed from the borehole data, Lake Naivasha, Lake Oloiden and Sonachi (saline lakes) and river waters. The grouping was necessary in order to identify the ones with similar chemistry and clearly show the possible relationships between surface and groundwater. They were drawn from Microsoft Excel by selecting first, second, third and fourth quartile values from the data and getting the top and bottom whisker values that showed largest and smallest data set respectively.

Geophysical Measurement

The geophysical measurement was carried out in the month of June 2020. The sites were selected based on a combination of factors such as water quality, borehole logs present, targeted aquifers and physical manifestations on the ground, in areas revealing faulting zones from Google Earth. A total of 11 profiles were investigated using PQWT-TC300 Series equipment. The method was able to give a 2D scan of the surface and at the same time maintain the depth of investigation, this was able to give the sub-surface layers in form of profile curves and maps. These curves were correlated with borehole logs to get the stratigraphic sequence of the areas investigate. The shallow and deeper aquifers less than 300 m bgl were revealed.

Working Principle of PQWT-TC Series Equipment

The equipment uses the natural electric field source as a main principle contrasting with the subsurface resistivity of different rocks, groundwater and minerals. The method is measures naturally occurring electric fields within the sub-surface of N different frequency electric field component, to study the changes in the sub-surface geology, geological problems are therefore resolved. This is one of the latest geophysical exploration equipment developed by Hunan Puqi Geologic Exploration Equipment Institute by use of a number of patented technologies. The equipment is classified under electrical equipment due to its design and production; measuring natural electric field for geological exploration work.

PQWT-TC300 series was used, with a frequency of 40, this usually gives accuracy of 0.001 mV and probes to a depth of 300 m bgl (PQWT-TC300 Manual, 2017). The interval between the measuring points was kept at 4m for all the profiles investigated. The machine measures and stores the data automatically, curve graphs and drawing the profile maps is thereafter auto-generated.

The collected data is for the midpoint between the two electrodes while the point O is the first set of data. The illustration is given in **Figure 3.4** below.

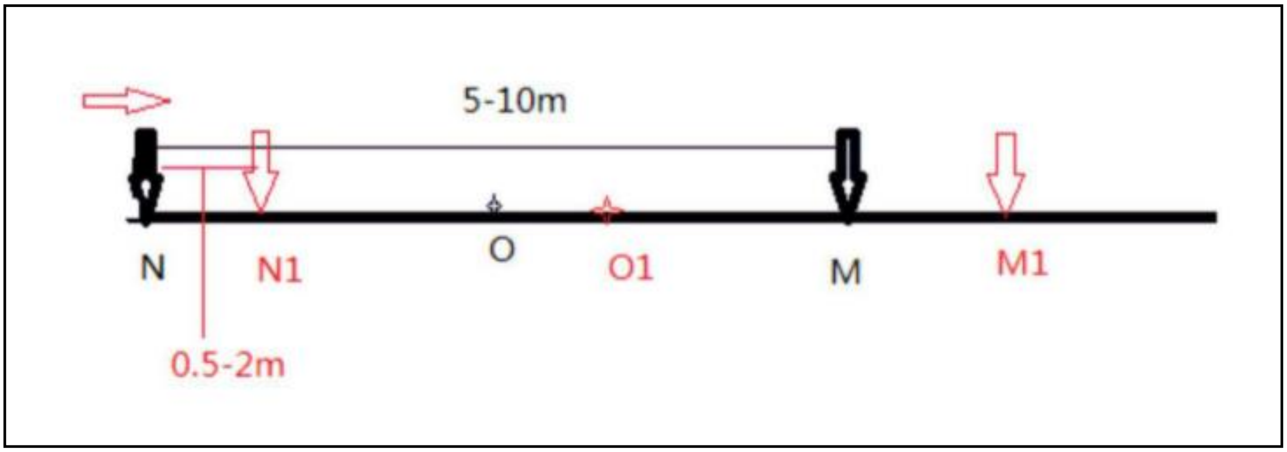


Figure 3.4: Illustration of Equipment Arrangement (*After PQWT-TC300 Manual, 2017*)

Profiling

PQWT uses Wenner electrode array capitalizing on measuring electromagnetic field strengths in voltage per meter. The machine sends electromagnetic impulse signals inform of bulk frequencies that penetrates 300m depths. PQWT uses Frequency Domain passive electromagnetic based on natural field strength of earth material. Horizontal resistivity profiling using the Wenner array was executed. The results of the profile measurements reflect lateral changes in resistivity, corresponding to variations in lithology, salinity, thickness of formations and water content at a fixed depth along the profile. Resistivity profile data is normally interpreted qualitatively.

4 RESULTS

4.1 Introduction

This chapter presents the findings in different sections to meet the set objectives. The section is sub-divided according to the objectives of this study in order to achieve the overall goal. The aquifer transmissivity is presented as a spatial map plotted from the borehole data in Table 3. The groundwater flow direction maps and the influence of the faults follow this. Finally, water quality as shown in **Table 4.4** and **Table 4.6** for groundwater and surface water quality data respectively, indicating major elements used in studying the interaction between surface and groundwater. The general distributions of these elements are presented in form of maps. In order to understand the interactions, the elements are further divided according to their chemical properties and changes they undergo to monitor horizontal and vertical groundwater flow. Finally, the elements used to indicate surface and groundwater interactions are discussed.

4.2 Aquifer Transmissivity

Transmissivity values ranges from 3 to 2650 m^2/day with an average value of 1325 m^2/day. Lower transmissivity values between 3 and 388 m^2/day occur within Eburru and southern parts of the study area while aquifers with higher transmissivities (1042-2650 m^2/day) exist north of Lake Naivasha, attributed to porous sediments. Ndabibi Area bounded on the west by Mau Forest and Lake Naivasha to the east have an average transmissivity of 544 m^2/day and increases toward Lake Naivasha.

Most boreholes drilled to depths ranging between 12 to 75 m below the ground level have higher yields and small drawdowns. It clearly indicates that shallow aquifers are penetrated as shown by the water struck levels and the results of transmissivity in

Table *4.1*. The data plotted to produce a transmissivity map in **Figure 4.1**.

Shallow aquifers with depths ranging from 20-42 m below ground level, moderate aquifers ranging from 62-130 m below ground level and deep aquifers between 167-297 m below ground level are established. The grouping of aquifers was based on the transmissivity values and their distribution in the study area together with the position of the aquifers struck as recorded and reported during the drilling works (see **Figure 4.1**).

Table 4.1: Borehole Data

BH Owner	Alt (m)	TD (m)	M-WSL (m)	WRL (m)	Q (m^3/hr)	Drawdown (s) (m)	Sp. Capacity (m^2/day	Transmissivity (m^2/day)
M. Estate BH	2133	229	216	196	4.98	7	17.07	20.83
N. Estate BH	2484	75	55	19	5.4	2.7	48	58.56
K. Farm BH	1890	27	48	7	31	4.6	161.73	197.32
Y. BH	1890	24	9	8	27	3	216	263.52
C.T G.W.	1890	33	30	23	13.68	1.8	182.4	222.53
Y 2 BH	1890	33	20	21	31.86	2.4	318.6	388.69
N. F BH	2438	107	95	93	3	7	10.28	12.54
L. Ltd	1905	12	5	5	9.06	3	72.48	88.42
W.C.C BH	1890	32	18	12	9.06	2	108.72	132.63
O. BH	1890	78	76	46	4.02	18	5.36	6.53
L. Estate	1920	62	39	39	27.18	0.3	2174.4	2652.76
C. P BH	1920	139	101	45	9	80	2.7	3.294
N. Estate BH 2	2255	167	161	125	8.1	9.1	21.36	26.06
K. Farm	1935	42	8	5	49.5	2.1	565.71	690.17
Mirera M. C BH	1950	130	100	71	7.2	0.1	1728	2108.16
	2103	297	267	213	39	6	156	190.32

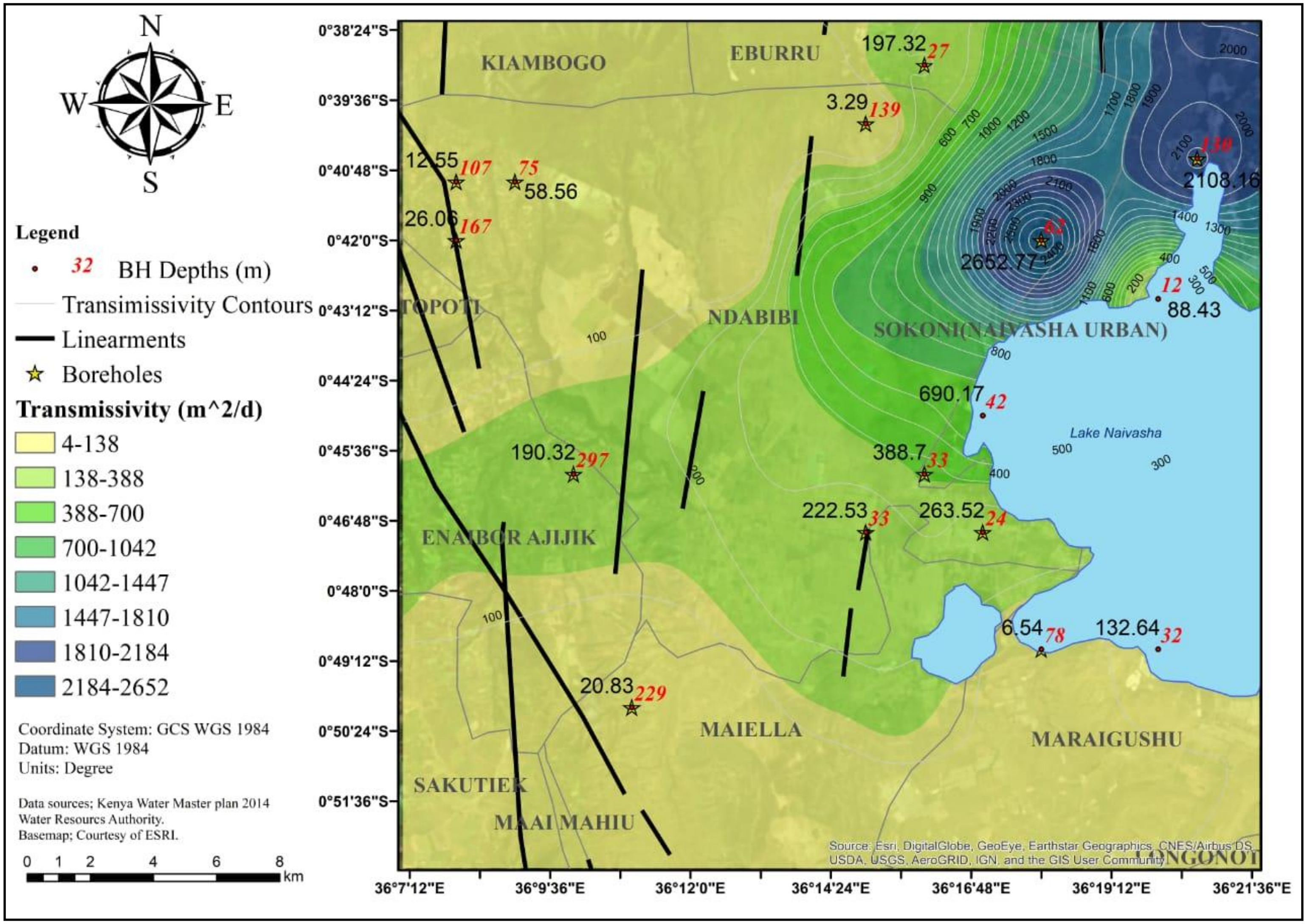


Figure 4.1: Transmissivity Map and Faults of the Study Area

The driller's log below shows the subsurface geology of the borehole drilled southern parts of the study in Mariagushi area where transmissivity is low. The borehole was logged to maximum depth of 286 m below ground level within Ndabibi area.

Table 4.2: Driller's Log

From (m)	To (m)	Description of Formation
0	6	Brownish clay
6	15	Dark brownish rock
15	16	Wet dark grayish sand
16	20	Wet fractured gray rock
20	55	Wet fractured gray soft rock
55	80	Hard grayish rock
80	90	Brownish clay materials
90	120	Dark grayish rock
120	130	Fractured dark grayish rock
130	150	Dark grayish rock
150	155	Hard dark grayish rock
155	180	Grayish clay formation mixed with a rock
180	286	Basement rock

The reported main water struck level for the borehole above is 195 m with aquifer thickness of 5m. The yield measured during the test pumping was 5.8 m^3/hr having a drawdown of 12.63m. This translates to a transmissivity of 13.6 m^2/day. From the transmissivity map, the area is classified as low transmissivity area. The aquiferous materials penetrated is made up of clay, which generally has low hydraulic conductivity ranging from 30m/day to 0.05m/day (Bressler and Bressler, 2013).

4.3 Groundwater Flow

The piezometric level was determined by finding the difference between elevation and water rest level of 58 number boreholes. Google earth was used to correct the elevation of some boreholes that differed in the previous data. The plot is as shown in **Figure 4.2**, effects of faults on groundwater flow direction are plotted together to determine how structures affect the flow. The faults in the area are named A-G and their influence on the groundwater flow determined. The groundwater flow follows the fault B orientation, covering the flow within Ndabibi plain while fault A1 and A2 diverts flow toward the saline lakes.

Table 4.3: Piezometric Levels

LOCALITY	Alt (m)	TD (m)	M_WSL (m)	WSL1 (m)	WRL (m)	Piezometric Level (m)
South Lake Rd.	1903	52	21	21	20	1883
Rondiani	1933	147	134	0	77	1856
Njoro	1911	112	90	0	50	1861
Ndabibi Estate	1911	61	42	0	15	1896
Ndabibi	1885	61	48	0	9	1876
Ndabibi	1973	148	121	0	107	1866
Navahsa	1913	46	33	27	27	1886
Naivasha.LR.1856/R	1955	104	100	0	75	1880
Naivasha.LR.1380	2190	229	216	201	196	1994
Naivasha.LR.9005	1945	57	24	0	22	1923
Naivasha.LR.7281	2375	75	55	0	19	2356
Naivasha.LR.7276	2542	27	48	15	7	2535
Naivasha.LR.7246	1925	72	37	27	27	1898
Naivasha.LR.6854/9	1925	24	9	0	8	1917
Naivasha.LR.6525	1905	33	30	0	23	1882
Naivasha.LR.6524/8	1906	33	20	0	21	1885
Naivasha.LR.6233	2380	107	95	0	93	2287
Naivasha.LR.6233	2366	229	42	0	40	2326
Naivasha.LR.4333/7	1890	18	16	0	12	1878
Naivasha.LR.420/4	1924	31	6	0	6	1918
Naivasha.LR.419	1905	10	5	0	5	1900
Naivasha.LR.419	1895	13	7	0	7	1888
Naivasha.LR.418	1890	16	8	0	3	1887
Naivasha.LR.418	1902	14	12	0	10	1892
Naivasha.LR.416/2	1925	52	51	0	46	1879

Naivasha.LR.416/2	1915	57	53	32	30	1885
Naivasha.LR.410	1890	31	3	0	3	1887
Naivasha.Lr.404/4	1890	32	18	0	12	1878
Naivasha.LR.1340/R	1890	78	76	54	46	1844
Naivasha.	1885	31	11	0	8	1877
Naivasha L.R.418	1950	62	39	0	39	1911
Naivasha L.R. 471	1905	63	63	46	41	1864
Naivasha 404/2	1890	33	20	0	20	1870
Naivasha	1945	105	85	0	59	1886
Naivasha	1915	31	21	0	7	1908
Naivasha	1935	79	53	0	50	1885
Naivasha	1955	114	119	104	99.4	1856
Naivasha	1890	43	27	0	22	1868
Naivasha	1890	31	27	0	23	1867
Naivasha	1921	61	42	0	15	1906
Naivasha	1921	130	35	0	11	1910
Naivasha	2365	139	101	0	45	2320
Naivasha	1915	18	15	0	15	1900
Naivasha	2368	167	161	131	125	2243
Naivasha	1905	31	19	0	17	1888
Naivasha	1890	42	8	0	5	1885
Naivasha	2000	113	113	0	101	1899
Migaa	1875	130	100	70	71	1804
Eburu	2543	152	0	0	0	2543
Eburu	2543	103	0	0	0	2543
	1976	92	23	0	0	1976
	1897	34	18	0	16	1881
	2178	297	267	0	213	1965

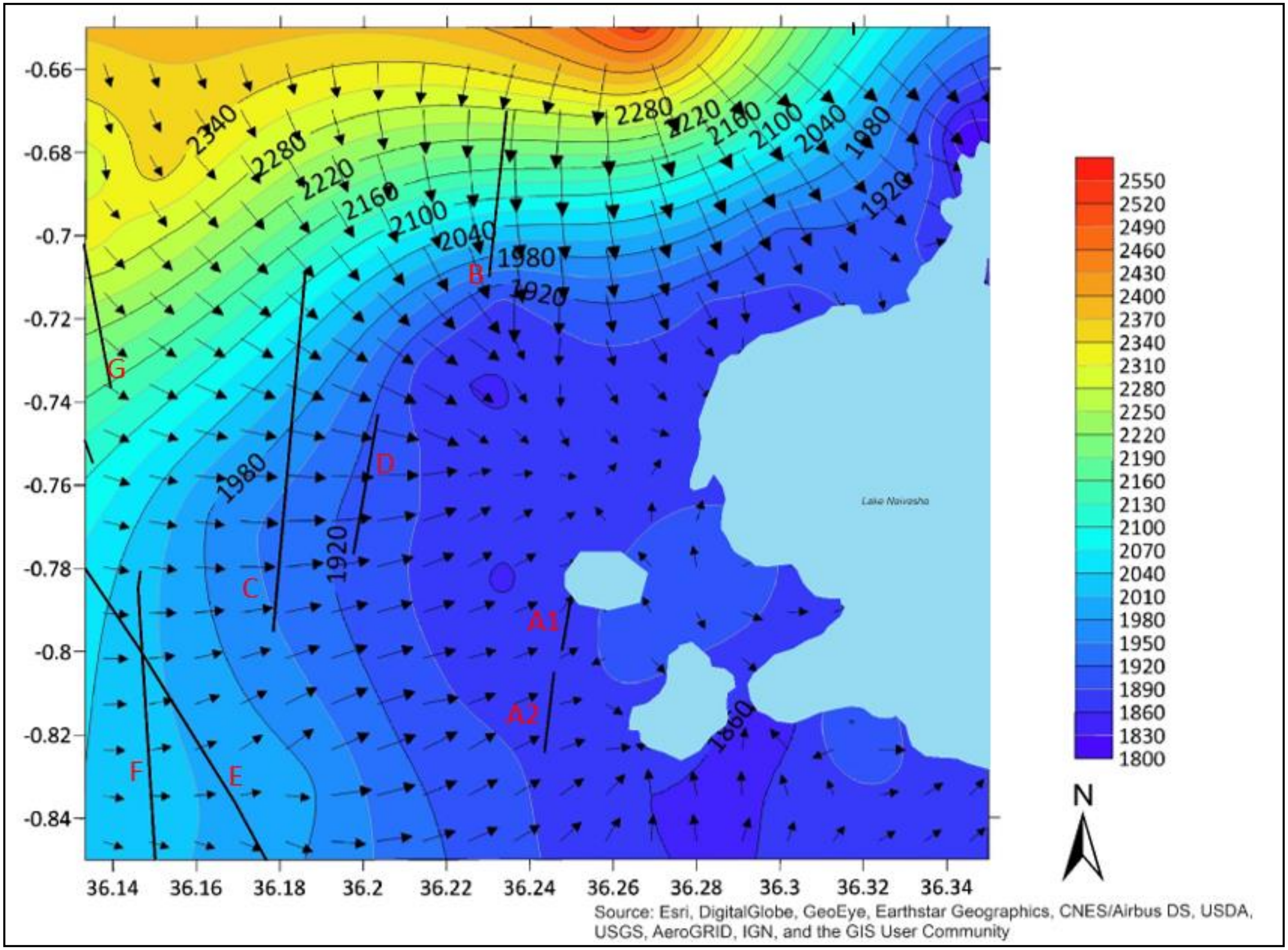


Figure 4.2: Piezometric Map and Effects of Faults on Groundwater Flow

4.4 Geological Logs Along Different Profiles

The geological logs are constructed to cover the whole area and penetrating three main aquifers from the section above. For proper analysis, the logs are grouped in three profiles with the elevation and distance between each other considered after interpolation from ArcGIS 10.5 and drawn using Microsoft Word. Th hydrogeological sections/profiles are presented separately. The boreholes and profiles are shown in the map in **Figure 4.3**.

Profile 1

The profile covers the western side of lake Naivasha where the aquifers are shallow and drilled to maximum depths of 63 m below ground level. A total of 7 number borehole logs are considered (**Figure 4.4**). The pumice layer has a thickness ranging from 10 and 30 m overlying pyroclastics in most cases which extend to more than 120m. A fault divides Indu Farm borehole and M.S Lake borehole. It is likely that M.S Lake borehole and K.S borehole are within this fault. The hydrogeological section for this profile is shown in **Figure 4.7**, indicating that the aquifers are semi-confined.

Profile 2

Profile 2 targeted the deeper aquifers on the western areas and some boreholes are situated at high altitudes around Kiambogo area. The profile contained five logged boreholes (**Figure 4.5**) and **Figure 4.8** shows hydrogeological section within this profile. The pumice layer in this profile ranges between 15 and 40 m and overlies tuffs/weathered pyroclastics. At depths greater than 200m, the formation changes to basalts.

Profile 3

This profile covers the northern parts of Lake Naivasha. Most boreholes were drilled up to 160 m below ground level (see **Figure 4.6**) while water levels are shown in **Figure 4.9**. The major formation is lake sediments with unconsolidated materials. Pumice formation have a depth ranging from 10 to 30 m and embedded between pyroclastics. Some boreholes penetrated the trachytes from depths of 80 m to 170 m. The boreholes which penetrated trachytes are situated further north from the lake. It should be noted that the vertical scales are exaggerated in each case.

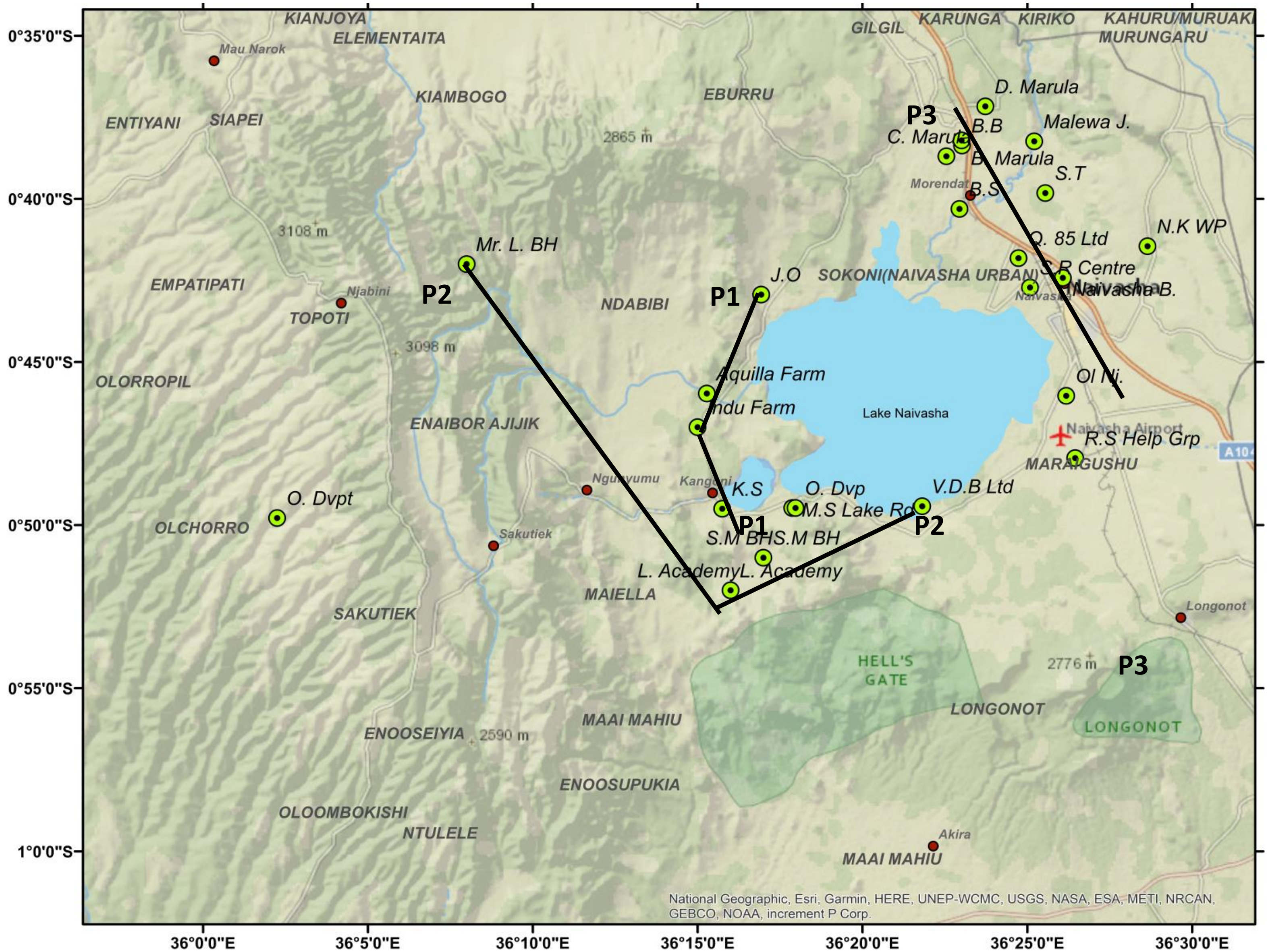


Figure 4.3: Position of Geological Logs and Three Profiles (Modified from Google Earth)

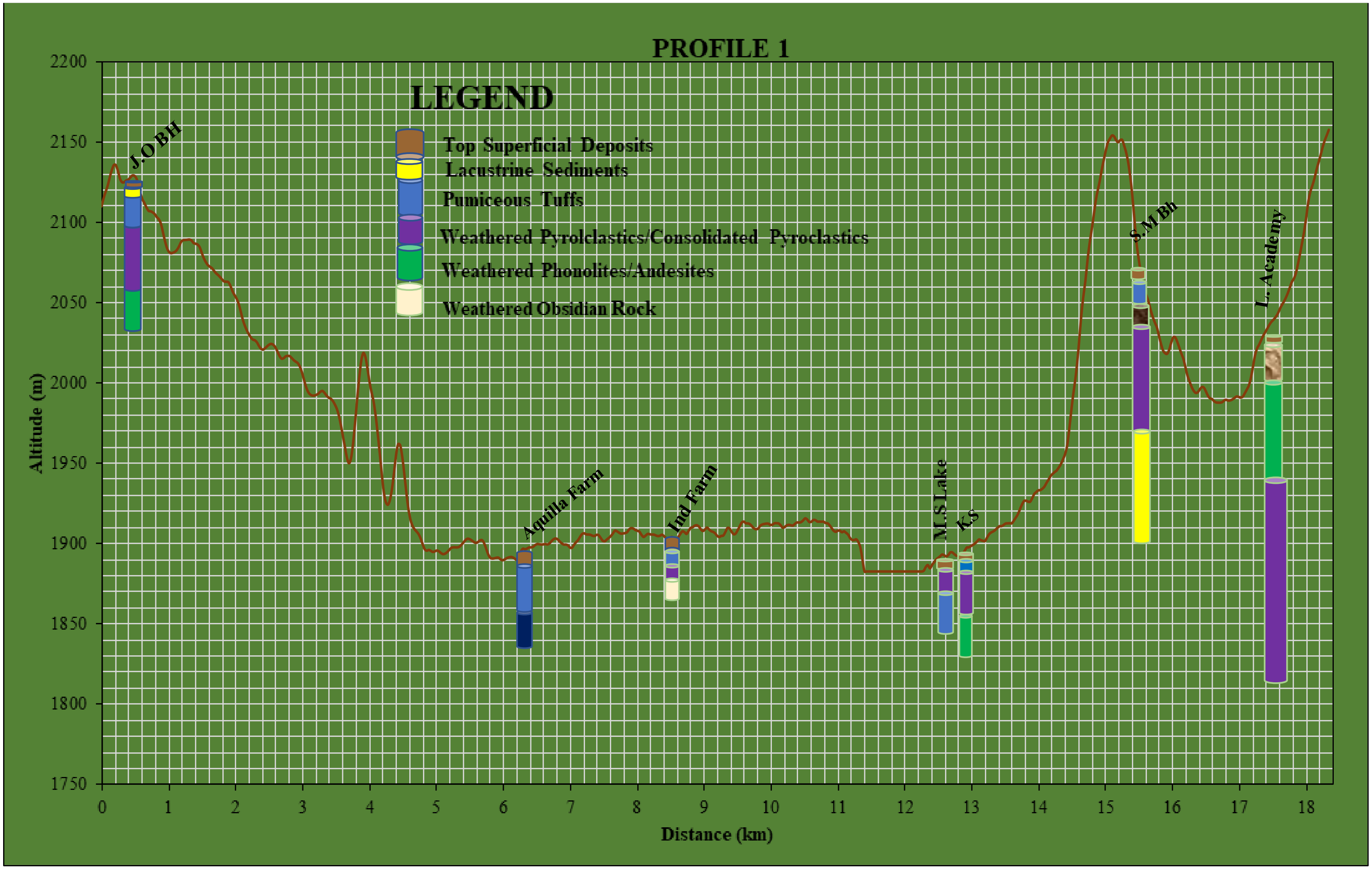


Figure 4.4: Geological Logs Along Profile 1

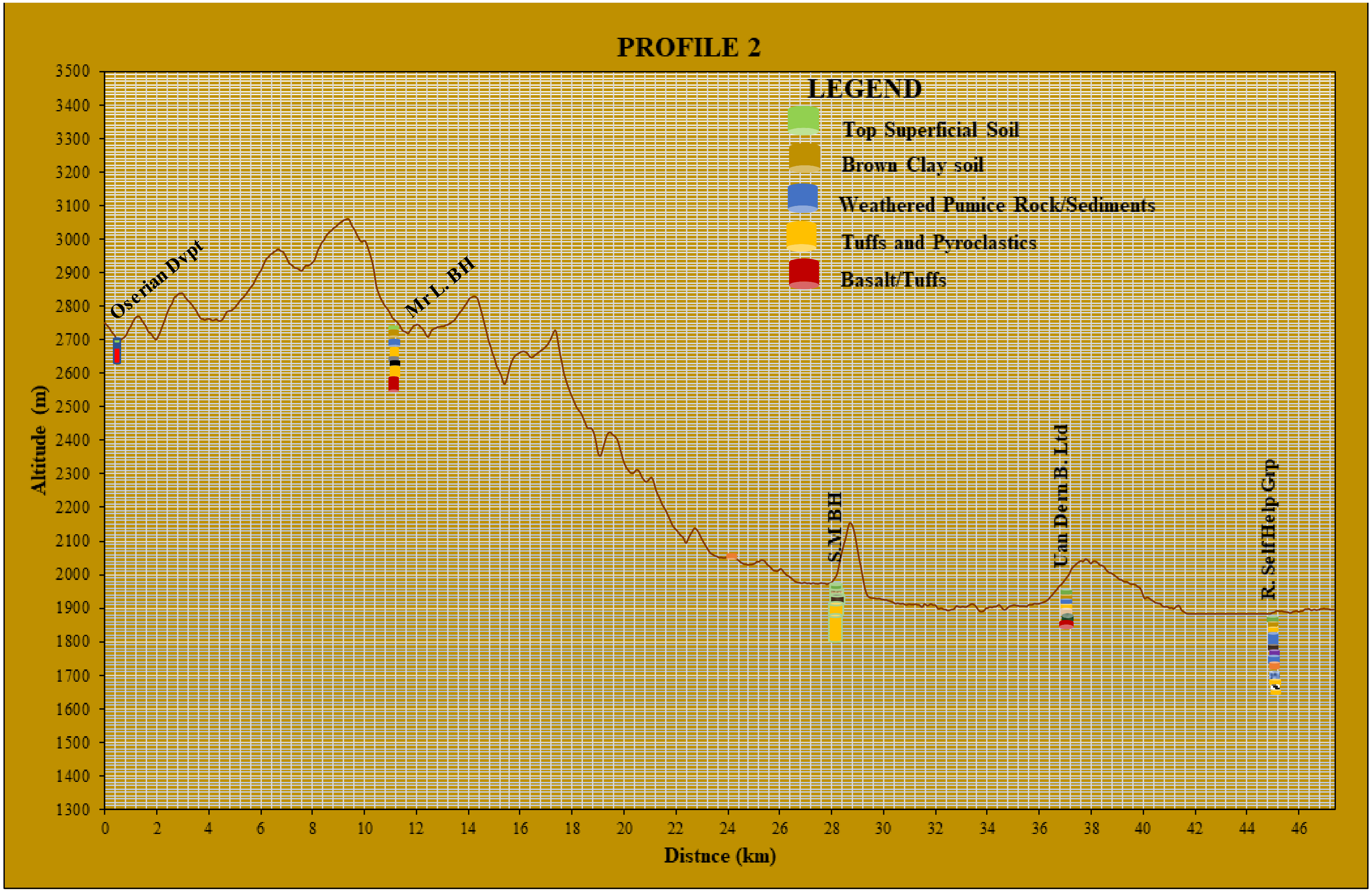


Figure 4.5: Geological Logs Along Profile 2

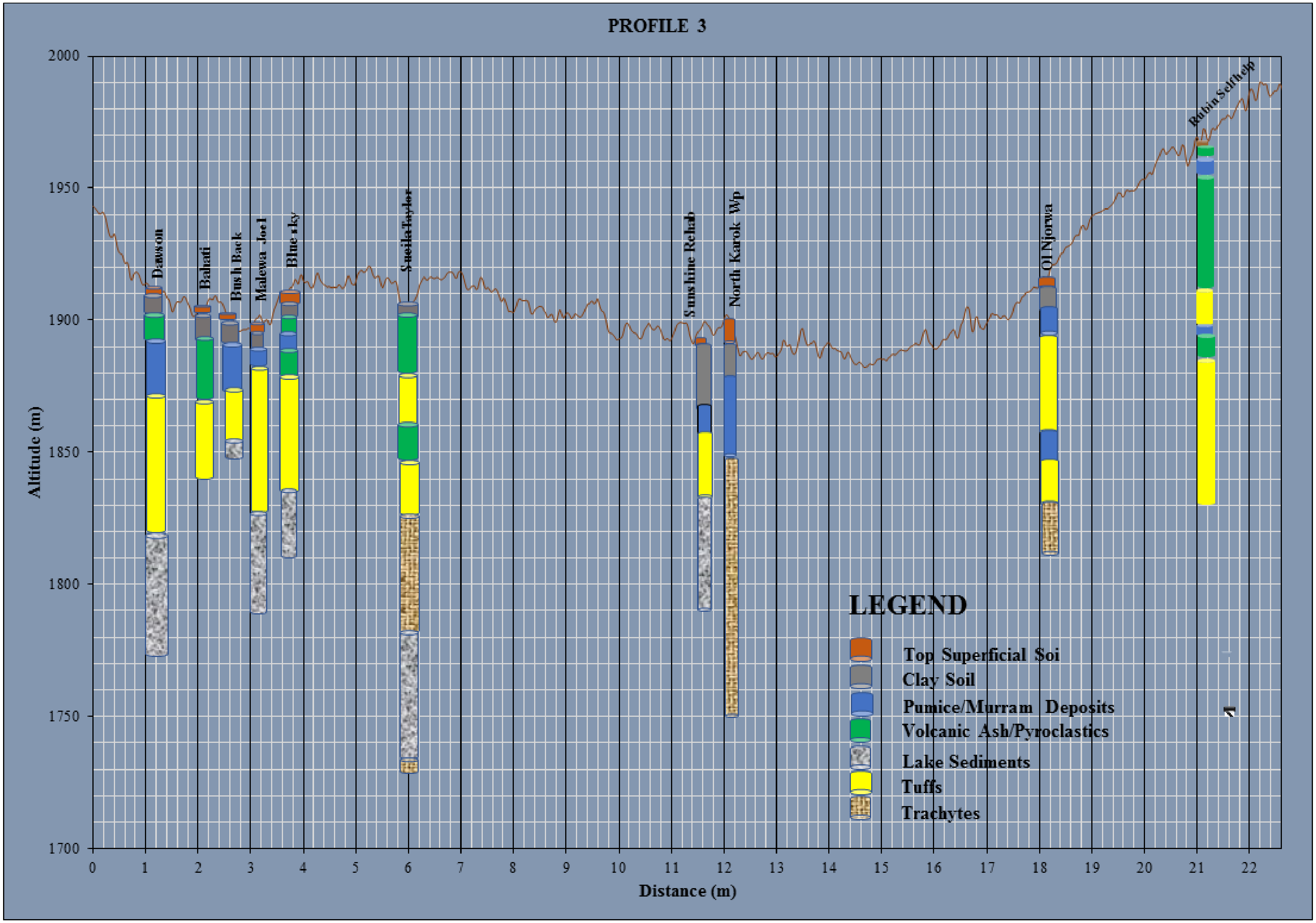


Figure 4.6: Geological Logs Along Profile 3

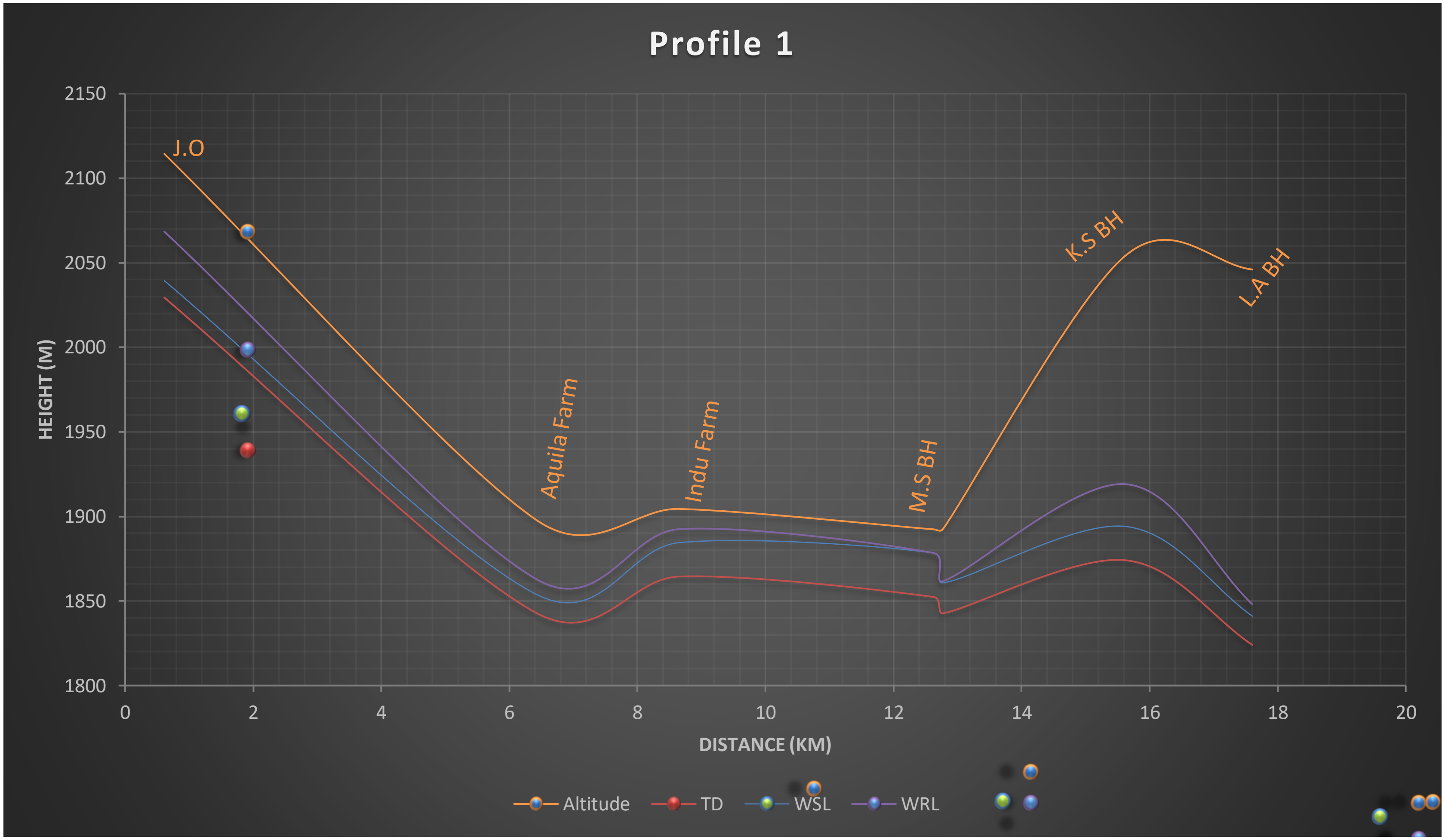


Figure 4.7: Hydrogeological Section along Profile 1

Figure 4.8: Hydrogeological Section along Profile 2

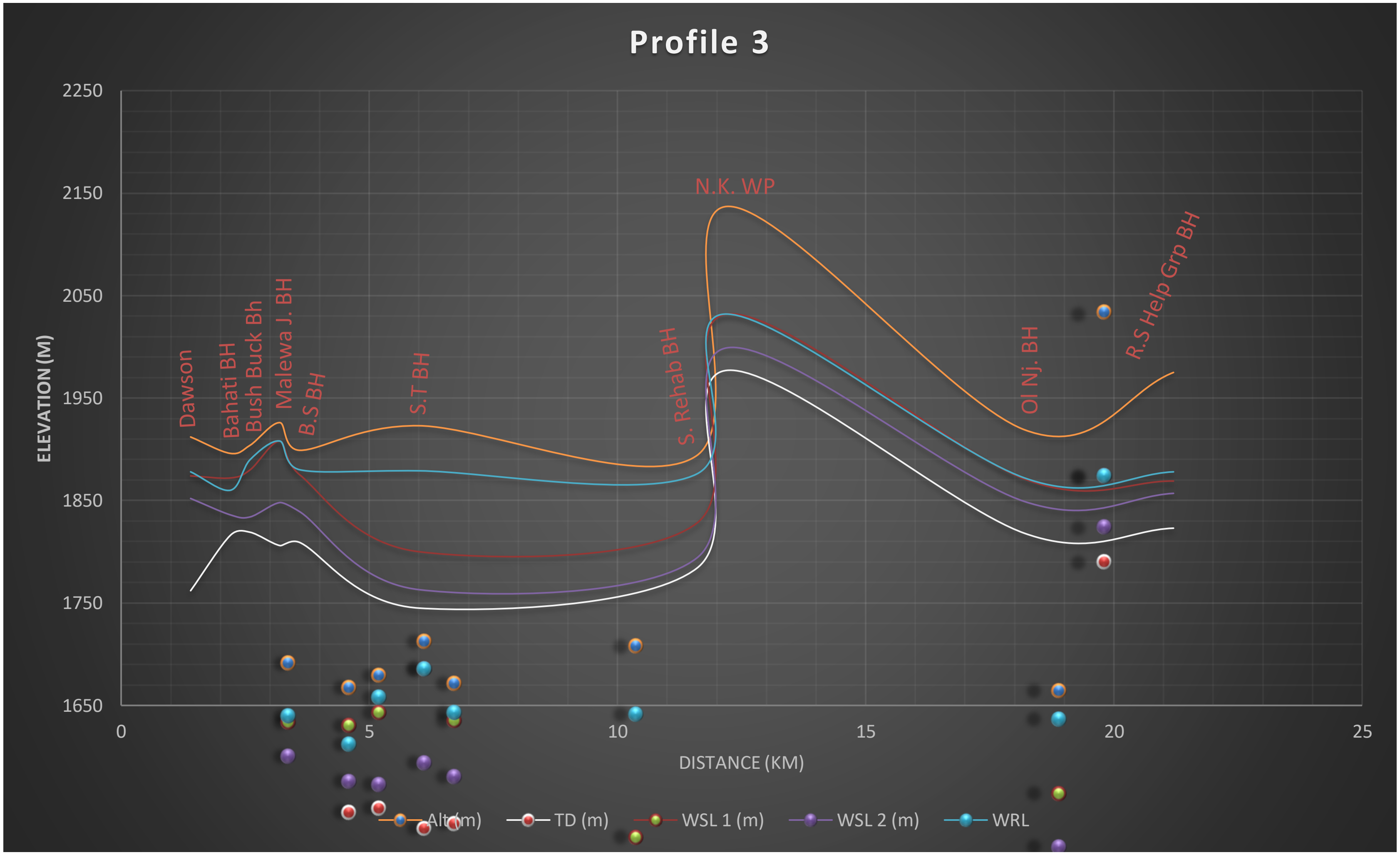


Figure 4.9: Hydrogeological Section along Profile 3

4.5 Surface and Groundwater Interactions

4.5.1 Introduction

The geochemical data comprised water quality taken from boreholes, wells, rivers and lakes. The main sources of data for groundwater used are from boreholes and shallow wells. Surface water samples include the three lakes and River Marmanet. The three lakes are: Sonachi, Oloiden and Naivasha. Some of the boreholes are in the proximity of the two lakes of interest and this helped in the evaluation of interactions between the two sources. The maps are presented first for major elements to see the general distribution in the area.

Finally, the results are presented according to the role of some element in determining both lateral and vertical flow of surface and groundwater. This is done to show paths and identification of groundwater flow directions. Some correlations are made and presented on certain conspicuous elements from the distribution in the final sub-section. Overall descriptive analyses of elements are shown in **Table 4.4** for both surface and groundwater data, while **Table 4.6** presents the surface water quality data for Lake Sonachi, Oloiden, Naivasha and River Marmanet.

4.5.2 General Distribution of Major Elements

Most of the elements sampled are positively skewed with values greaters than 0.5. The highly skewed elements are major anions: SO_4, Cl, NO_3 and NO_2 with values 2.11, 1.28, 3.83 and 1.77 respectively. This suggests that most of the elements are greater than median values especially for the major anions which are highly positively skewed. Alkali metals are moderately skewed while alkaline earth metals portray symmetrical distribution. The skewness of the data and kurtosis indicates the extreme set of data within the samples collected instead of the averages alone. Sodium is the dominant cation with maximum value of 270 mg/L and minimum value of 33.70 mg/L with a range value of 236.30 mg/L. Among the alkaline earth metals, Ca dominates followed by Mg in most parts of the area.

Among the anions, Cl and SO_4 are dominating; SO_4 has the largest range of 89.80 mg/L with the minimum and maximum values of 89.80 and 0.0 mg/L respectively. The minimum value of sulphate may be due to a sample error, the values may have not been well recorded at three locations; Wiley River House, P. K.P well and at Aquila Lake side. However, the lowest value measured is 5.44 mg/L from Oloiden well. It is noted that all the elements are within the WHO standard of drinking water except fluoride. The pattern of distribution is similar for Lake Oloiden and Sonachi except Lake Naivasha.

Table 4.4: Descriptive Analysis of Water Quality Data

a) Groundwater Water Quality

Statistics	*K (mg/L)*	*Na (mg/L)*	*Mg2 (mg/L)*	*Ca2 (mg/L)*	*F (mg/L)*	*SO4 (mg/L)*	*Cl (mg/L)*	*NO3 (mg/L)*	*NO2 (mg/L)*	*NH4 (mg/L)*
Mean	18.00	120.59	8.98	20.67	6.60	19.34	21.00	0.37	0.01	0.01
Median	16.70	101.00	9.77	22.30	6.50	12.20	16.00	0.17	0.00	0.01
Standard Error	1.71	14.33	1.57	2.93	0.74	5.66	2.77	0.15	0.00	0.00
Standard Dev.	7.82	65.67	7.20	13.44	3.40	25.94	12.68	0.68	0.01	0.00
Sample Variance	61.18	4313.06	51.78	180.61	11.57	672.90	160.72	0.47	0.00	0.00
Kurtosis	0.73	-0.53	-1.36	-1.15	-0.49	3.76	0.37	16.03	2.20	-2.22
Skewness	0.90	0.59	0.09	-0.05	0.59	2.11	1.28	3.83	1.77	-1.08
Range	29.96	236.30	21.13	42.52	11.50	89.80	40.49	3.16	0.03	0.00
Minimum	7.84	33.70	0.07	0.78	1.90	0.00	9.01	0.02	0.00	0.01
Maximum	37.80	270.00	21.20	43.30	13.40	89.80	49.50	3.18	0.04	0.01
Sum	378.08	2532.30	188.62	434.13	138.69	406.18	440.90	7.73	0.19	0.11
Count	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.01
Confidence Level (95.0%)	3.56	29.89	3.28	6.12	1.55	11.81	5.77	0.31	0.00	0.00

b) Lake Naivasha

Statistics	*PH*	*Temp (°c)*	*Ecµs/cm*	*Cl (mg/L)*	*SO4 (mg/L)*	*NO3 (mg/L)*	*F (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*K (mg/L)*	*Na (mg/L)*	*Mg (mg/L)*
Minimum	7.40	19.10	0.22	5.07	0.53	0.15	0.27	14.90	0.05	10.50	16.50	3.43
Maximum	8.30	22.60	208.00	6.94	1.09	0.71	5.43	63.80	0.38	75.70	66.90	12.00
Median	8.17	20.30	203.00	6.93	1.01	0.50	1.22	15.47	0.18	11.51	18.39	4.80
Standard Deviation	0.38	1.43	91.84	0.93	0.26	0.23	2.31	24.27	0.15	32.28	24.63	4.03
Skewness	-2.07	1.31	-2.23	-2.00	-1.79	-0.91	1.77	2.00	0.46	2.00	1.97	1.49
Sum	40.34	101.40	822.22	25.85	3.65	1.86	8.13	109.64	0.78	109.21	120.17	25.02
Count	5.00	5.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

c) Lake Sonachi and Lake Oloiden

Statistics	*PH*	*Temp (°c)*	*Ecµs/cm*	*Cl (mg/L)*	*SO4 (mg/L)*	*NO3 (mg/L)*	*F (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*K (mg/L)*	*Na (mg/L)*	*Mg (mg/L)*
Minimum	9.72	21.80	3.56	135.67	1.47	0.15	32.59	3.90	0.03	178.00	756.00	0.43
Maximum	10.02	28.20	14.08	751.57	79.17	5.00	74.98	7.29	0.14	493.90	4274.00	4.00
Median	9.86	21.90	6.55	199.80	38.85	2.51	56.86	6.49	0.04	211.00	1540.00	3.25
Standard Deviation	0.12	2.77	4.01	254.08	42.58	1.98	18.24	1.61	0.05	147.79	1542.62	1.69
Skewness	-0.40	1.69	1.70	2.15	0.01	0.09	-0.41	-0.96	1.83	1.93	1.64	-1.13
Sum	49.44	117.70	36.27	1503.14	158.35	10.18	221.29	24.17	0.25	1093.90	8110.00	10.92
Count	5.00	5.00	5.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

d) River Water

Statistics	*PH*	*Temp (°c)*	*Ecµs/cm*	*Cl (mg/L)*	*SO4 (mg/L)*	*NO3 (mg/L)*	*F (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*K (mg/L)*	*Na (mg/L)*	*Mg (mg/L)*
Minimum	7.80	17.90	419.00	12.70	0.00	0.34	2.06	18.40	0.49	22.50	51.00	4.68
Maximum	8.92	18.10	733.00	33.22	24.70	32.08	6.18	53.20	3.21	43.30	108.00	27.50
Median	8.16	18.00	576.00	26.64	1.66	4.12	3.85	43.30	1.85	31.80	72.30	21.20
Standard Deviation	0.57	0.10	222.03	10.48	13.81	17.34	2.07	17.93	1.92	10.42	28.80	11.79
Skewness	0.99	0.00	-	-0.99	1.70	1.64	0.39	-1.16	-	0.32	0.73	-1.19
Sum	24.88	54.00	1152.00	72.56	26.36	36.54	12.09	114.90	3.70	97.60	231.30	53.38
Count	3.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	2.00	3.00	3.00	3.00

Calcium

Generally, the areas around Lake Naivasha have high concentration of calcium except in the northern parts, which have intermediate concentration ranging from 17 to 25 mg/L. A few patches within the higher altitude areas with values above 25mg/L are conspicuous. Ndabibi area have concentration below 17 mg/L. Calcium shows a strong correlation with magnesium and potassium with values of positive correlation co-efficient of 0.90 and 0.76 respectively.

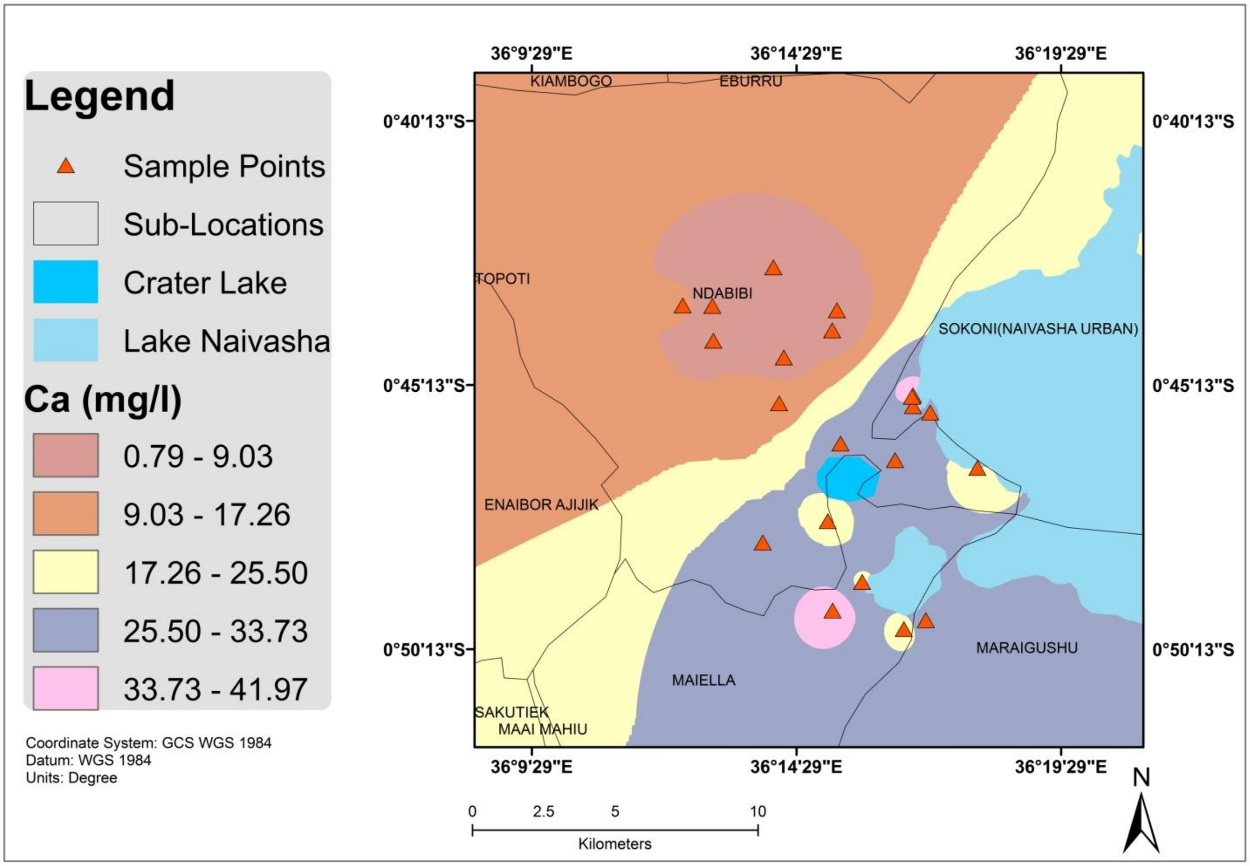


Figure 4.10: Calcium Distribution Map

Magnesium

Magnesium concentration is high around the southern parts of the lake in Maiella and Maraigushu areas. The concentration ranges between 12 to 20 mg/L. Ndabibi areas records lower values of magnesium concentration of values below 4 mg/L. North of the lake where there is recharge of the lake via river Malewa, the values are intermediate.

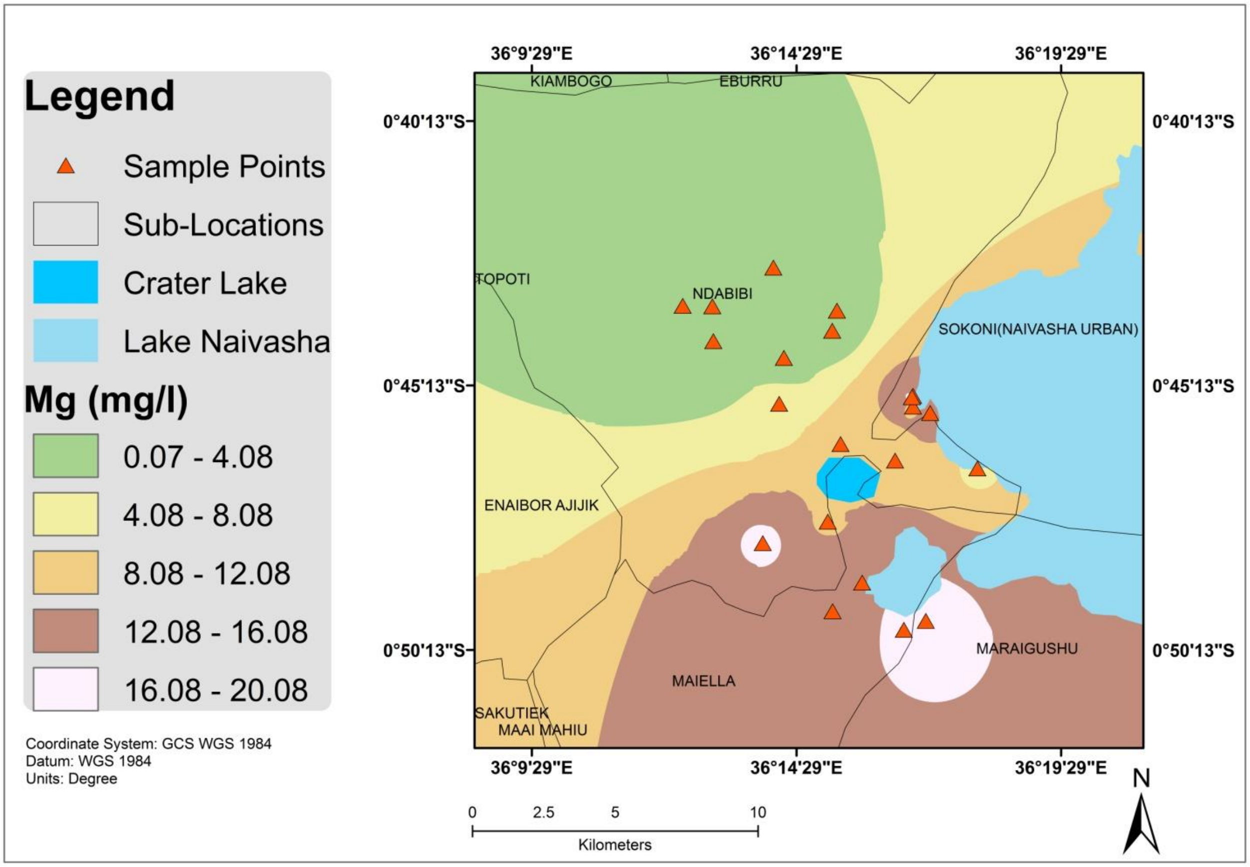


Figure 4.11: Magnesium Distribution Map

Sodium

Sodium distribution in the area follows no specific pattern. There are high concentration values of sodium compared to potassium and this indicates a good trend of the two elements in the area. Southern parts are having fairly higher sodium levels in the groundwater with values above 129 mg/l but few areas especially near the Crater Lake with slightly higher values of about 269 mg/l (**Figure 4.12**).

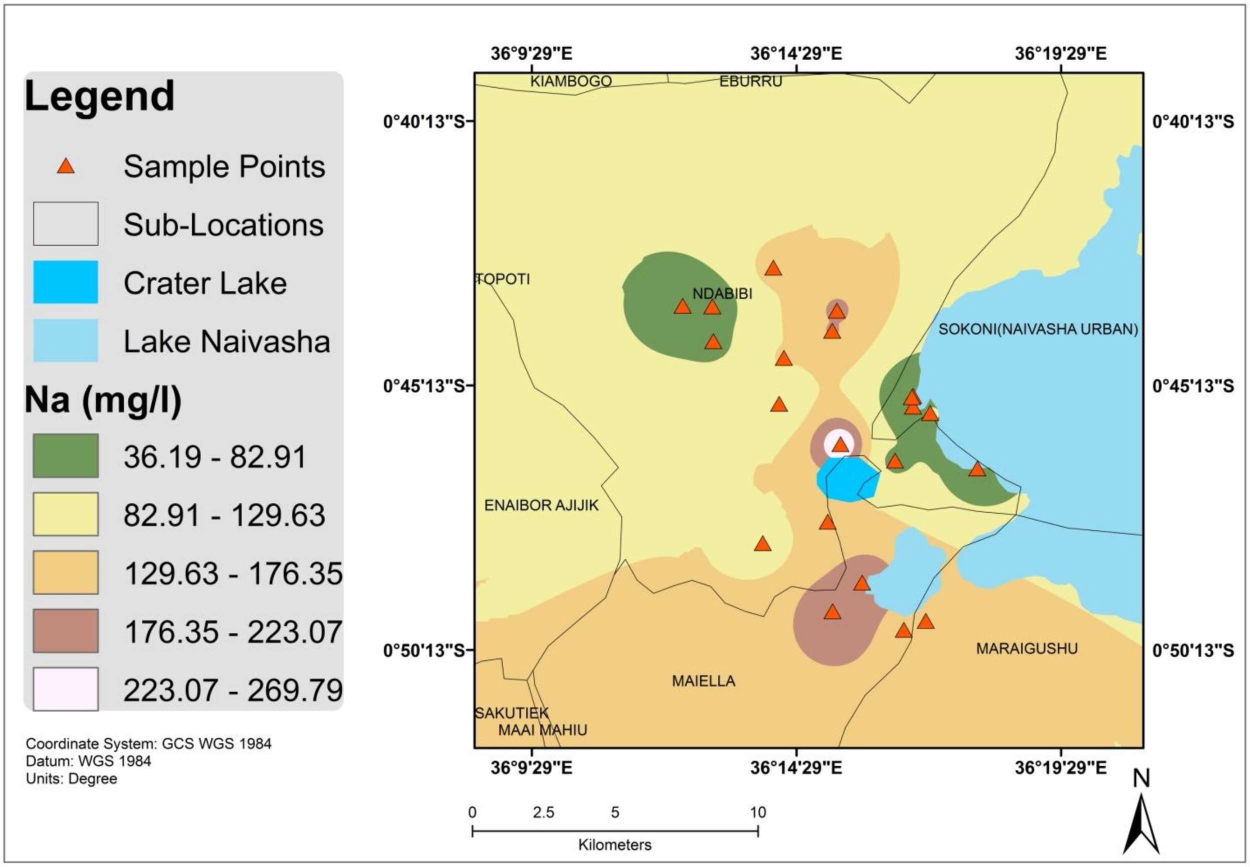


Figure 4.12: Sodium Distribution Map

Potassium

The general distribution pattern of potassium in water (**Figure 4.13**) follows that of sodium with the southern parts having higher values compared to the northern parts of the lake. Two distinct areas can be spotted with higher concentration marked with red colors as in the case of sodium concentration in **Figure 4.12** above but with lower concentration in the whole area compared with sodium. They have a low positive correlation (0.29) while higher positive correlation with calcium and magnesium (0.76 and 0.70 respectively).

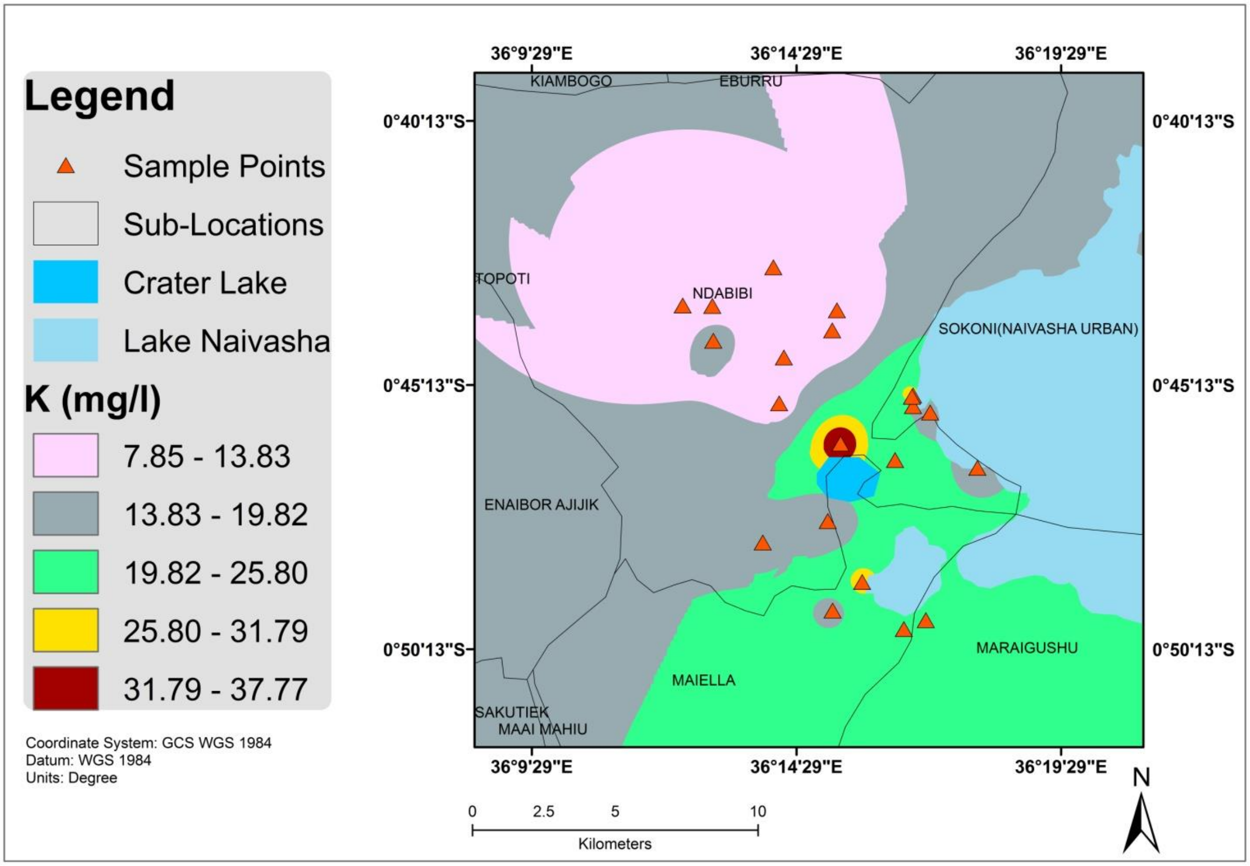


Figure 4.13: Potassium Distribution Map

Sulphate

The northern parts of the lake have low values of sulphate ion concentration (< 17 mg/l) while the southern parts ranges between 17 to 35 mg/L (**Figure 4.14**). The highest concentrations are found in Maiella area with values up to 89 mg/L. The sample points, which were recorded as zero could have resulted due to incorrect entries at Wiley House River Cave and a borehole at Aquila lake side. However, the lowest value measured is 5.44 mg/L from Oloiden well. The pattern is fairly following that of the calcium concentration. Sulphate and chloride distribution correlates and are the major anions in distinguishing the fresh and salty waters. A high positive correlation between sulphate and chloride is noted with a correlation co-efficient of 0.82 and sodium (0.71).

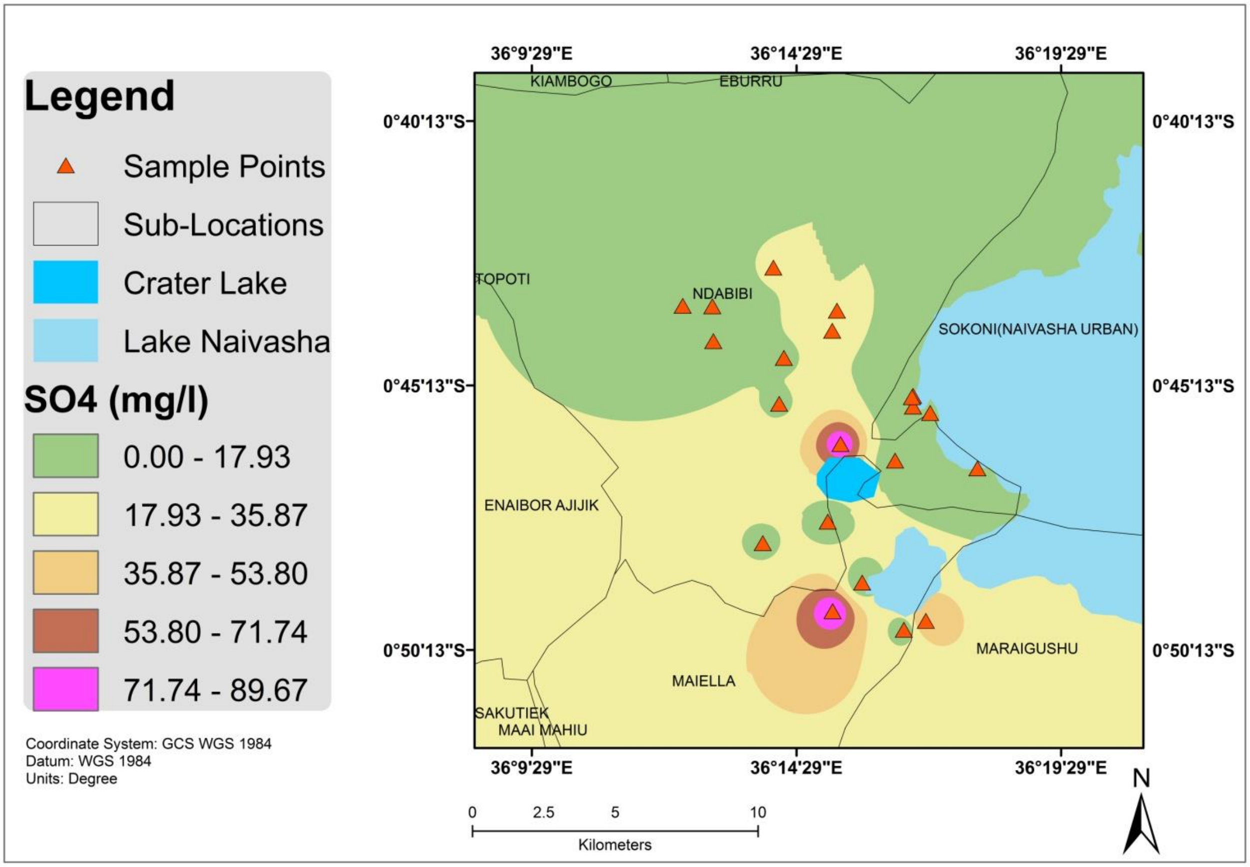


Figure 4.14: Sulphate Distribution Map

Chloride

The chloride concentration follows the same pattern as that of the sodium. In **Figure 4.15**, it clearly indicates that chloride ion in the water is high in the southern parts of the area compared to the northern and western parts of the lake. The values range between 25 and 49 mg/L with specific areas around Maiella (South of Lake Oloiden), whose values are outliers. The spatial distribution is similar to that of sodium because the ions are adsorbed at the same time. It has a high positive correlation co-efficient with sodium (0.80), boron (0.75), sulphate (0.82) and bromide (0.97) ions (**Table 4.5**).

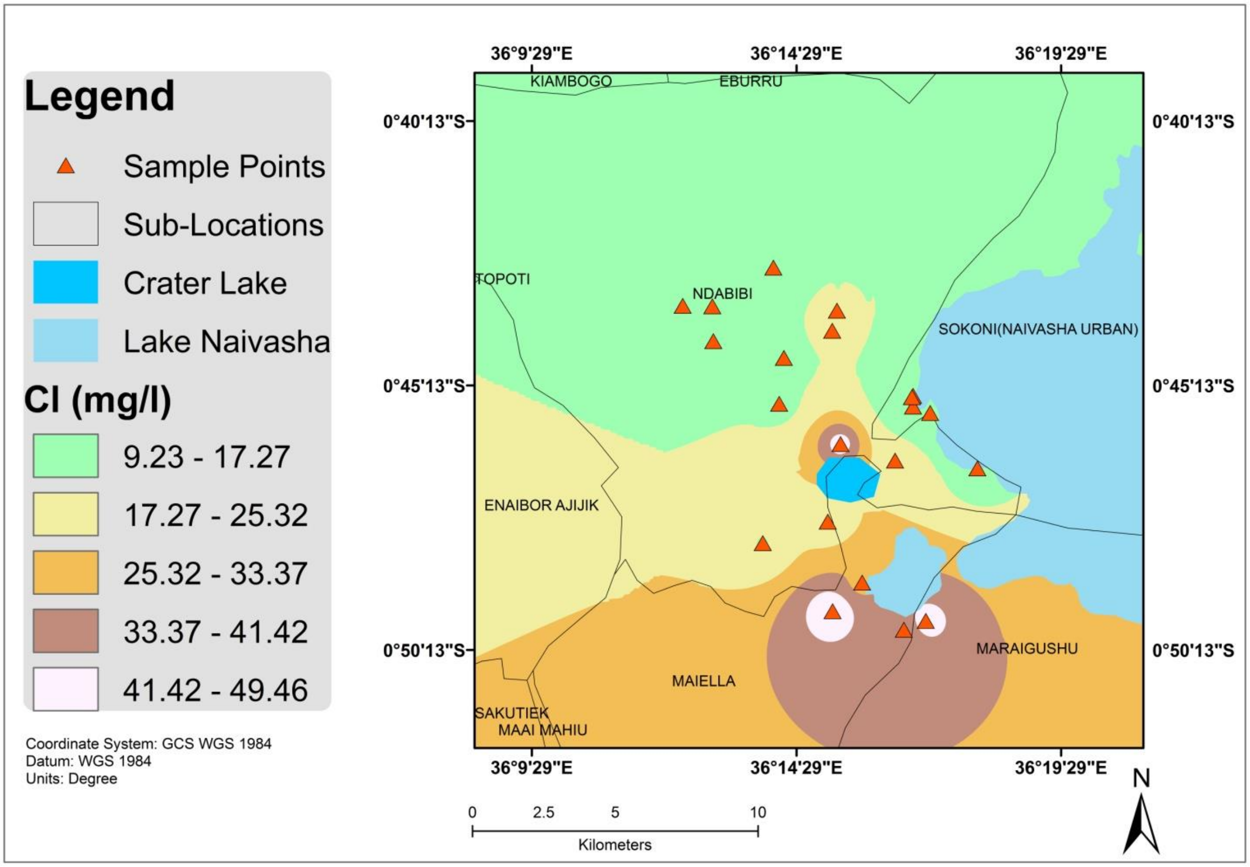


Figure 4.15: Chloride distribution Map

Fluoride

The southern parts of the study area contain high concentration of fluoride concentration above 8 mg/l compared to the western and northern areas whose values lies between 4 and 6.5 mg/l (**Figure 4.16**). The median value is 6.5 mg/L with minimum and maximum values of 1.9-13.4 mg/L respectively. Generally, the fluoride concentration in the groundwater is above the WHO limit (1.5 mg/L) of drinking water. The source of fluoride in the groundwater is as a result of weathering of volcanic rocks that composed of fluoride like muscovite and cordierite. The alkaline conditions and elevated temperatures around the saline lakes favors the fluoride desorption resulting to higher concentrations compared to the fresh groundwater surrounding Lake Naivasha. The source rocks from the borehole logs includes pumice and obsidian formations with varying depths surrounding Lake Naivasha aquifers.

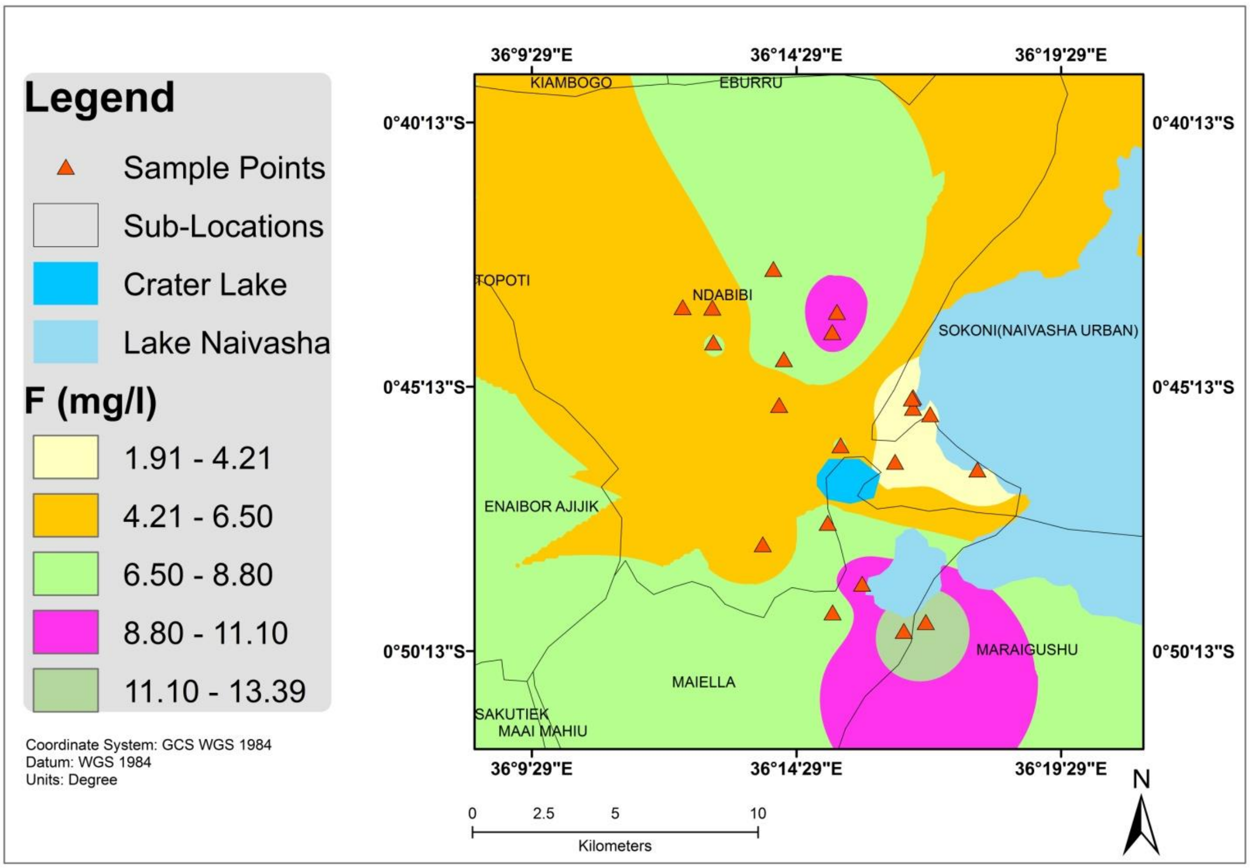


Figure 4.16: Fluoride Distribution Map

4.5.3 Correlation Matrix

The correlation matrix (**Table 4.5**) shows a correlation for both groundwater and lakes waters. The lakes water quality is analyzed independently because they are totally different in terms of their characteristics. In the groundwater, Na^+ indicate high positive correlation with F (0.71), SO_4 (0.71), Cl (0.80) while Mg^{2+} and Ca^{2+} has higher positive value of 0.90. K^+ also shows a high positive correlation coefficient with values 0.70 and 0.76 for Mg and Ca respectively. Sulphate and chloride have a value of 0.82. pH has negative correlation with B, Mg and Ca (-0.60, -0.52 and -0.48), B and Cl has a strong positive value of 0.75.

In Lake Naivasha, pH favors the concentration of K and Na (0.90 and 0.95 respectively). Cl is strongly related with Na (0.99) and negatively correlated with Ca and Mg (-0.84 and -0.86 respectively.) Alkali metals are negatively correlated with alkaline metals in Lake Naivasha water. EC is correlated with Cl and, K and Na (0.97, 0.98 and 1.0 respectively).

For Lake Sonachi and Oloiden, nitrate is negatively correlated with K, Na, Ca and Mg (-0.93, -0.91, -0.91 and -0.92 respectively). Alkali and alkaline earth metals in the lake are strongly correlated in the two lakes compared with Lake Naivasha. Temperature is negatively correlated with major anions with values above -0.83 and while this is contrary with pH relations with these major anions. The nitrates and nitrites have ranges of -0.17 and +0.37 with most elements except nitrate and sulphate (+0.57).

Table 4.5: Correlation Matrix of Water Quality Data

a) Groundwater

	PH	Temp_C	B_µg_L	Se_µg_L_	Br_µg_l_	Ba_µg_L_	V_µg_L_	As_µg_L_	Cr_µg_L_	K_mg_l	Na_mg_l_	Mg2_mg_l	Ca2_mg_l	Pb_µg_L_	Ni_µg_L_	Mn_mg_L_	Li_µg_L_	Fe_mg_L_	Cu_µg_L_	Al_mg_L_	F_mg_L_	SO4_mg_	Cl_mg_L_	NO3_N_mg	NO2_N__mg
PH	1.00																								
Temp_C	0.26	1.00																							
B_µg_L	-0.60	-0.37	1.00																						
Se__µg_L_	0.11	0.42	-0.03	1.00																					
Br__µg_l_	-0.42	-0.39	0.85	0.28	1.00																				
Ba__µg_L_	0.22	-0.19	-0.14	-0.30	-0.23	1.00																			
V__µg_L_	0.06	0.17	0.01	0.34	0.29	-0.10	1.00																		
As__µg_L_	0.20	0.09	0.32	0.28	0.43	-0.05	0.04	1.00																	
Cr__µg_L_	-0.36	0.20	0.02	0.20	0.10	-0.12	0.12	0.00	1.00																
K__mg_l_	-0.12	-0.31	0.47	-0.06	0.57	0.41	0.50	0.21	0.05	1.00															
Na__mg_l_	0.00	0.01	0.55	0.53	0.76	-0.40	0.47	0.57	0.03	0.29	1.00														
Mg2__mg_l	-0.52	-0.51	0.67	-0.28	0.59	0.41	0.07	0.16	0.31	0.70	0.14	1.00													
Ca2__mg_l	-0.48	-0.37	0.53	-0.07	0.53	0.50	0.21	0.16	0.26	0.76	0.06	0.90	1.00												
Pb__µg_L_	0.03	0.28	-0.32	0.20	-0.16	-0.19	0.25	-0.23	0.45	-0.06	-0.15	-0.13	-0.10	1.00											
Ni__µg_L_	0.28	-0.09	0.10	-0.23	0.04	0.39	-0.14	0.63	-0.09	0.32	-0.01	0.22	0.22	-0.14	1.00										
Mn__mg_L_	-0.16	-0.41	0.20	-0.53	-0.02	0.57	-0.30	-0.06	-0.22	0.39	-0.44	0.37	0.43	-0.33	0.49	1.00									
Li__µg_L_	-0.05	-0.01	0.37	0.31	0.41	-0.55	-0.36	0.45	0.07	-0.27	0.53	-0.13	-0.30	-0.10	0.05	-0.29	1.00								
Fe__mg_L_	-0.12	-0.17	0.07	-0.35	-0.15	0.29	-0.26	-0.18	-0.19	0.14	-0.47	0.04	0.18	-0.14	0.28	0.80	-0.23	1.00							
Cu__µg_L_	-0.33	0.05	0.03	0.11	-0.04	-0.16	-0.13	-0.16	-0.03	0.00	-0.22	-0.09	0.01	-0.01	-0.15	0.22	-0.03	0.16	1.00						
Al__mg_L_	0.63	0.17	-0.01	0.15	0.01	-0.15	-0.07	0.54	-0.22	-0.10	0.44	-0.28	-0.41	-0.16	0.36	-0.27	0.51	-0.24	-0.23	1.00					
F__mg_L_	0.03	-0.26	0.47	0.19	0.58	-0.40	-0.08	0.36	-0.07	-0.02	0.71	0.05	-0.22	-0.19	0.01	-0.33	0.70	-0.44	-0.27	0.43	1.00				
SO42__mg_	-0.14	-0.07	0.30	0.78	0.70	-0.32	0.54	0.32	0.16	0.30	0.71	0.11	0.26	0.07	-0.22	-0.38	0.26	-0.32	0.03	-0.05	0.35	1.00			
Cl__mg_L_	-0.34	-0.29	0.75	0.47	0.97	-0.33	0.33	0.42	0.10	0.48	0.80	0.44	0.41	-0.07	-0.04	-0.16	0.45	-0.21	-0.03	0.03	0.60	0.82	1.00		
NO3_N__mg	-0.15	0.19	0.12	0.77	0.28	-0.12	-0.17	0.26	0.19	-0.11	0.23	-0.02	0.16	-0.04	-0.17	-0.23	0.37	-0.17	0.32	-0.04	0.09	0.57	0.41	1.00	
NO2_N__mg	-0.08	-0.25	0.10	0.40	0.37	-0.11	0.07	0.09	0.05	0.05	0.28	0.06	0.16	-0.21	-0.20	-0.15	0.35	-0.15	-0.01	-0.09	0.15	0.59	0.44	0.52	1.00

b) Lake Naivasha

	pH	*Temp (?c)*	*Ecµs/cm*	*Cl (mg/L)*	*SO4 (mg/L*	*NO3 (mg/L*	*F (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*K (mg/L)*	*Na (mg/L)*	*Mg (mg/L)*
pH	1.00											
Temp (?c)	0.78	1.00										
Ecµs/cm	0.72	0.89	1.00									
Cl (mg/L)	0.70	0.96	0.97	1.00								
SO4 (mg/L)	0.36	0.43	0.75	0.64	1.00							
NO3 (mg/L)	-0.48	-0.82	0.30	-0.23	0.89	1.00						
F (mg/L)	0.41	-0.23	0.95	0.65	0.90	0.56	1.00					
Ca (mg/L)	-0.50	-0.89	-0.70	-0.84	-0.10	0.49	0.96	1.00				
Fe (mg/L)	-0.66	-0.15	-0.46	-0.26	-0.97	-0.49	-0.97	-0.31	1.00			
K (mg/L)	0.90	0.99	0.98	1.00	0.63	0.35	0.91	-0.83	-0.27	1.00		
Na (mg/L)	0.95	0.97	1.00	0.99	0.72	0.47	0.96	-0.75	-0.40	0.99	1.00	
Mg (mg/L)	-0.55	-0.91	-0.73	-0.86	-0.16	0.50	0.97	1.00	-0.26	-0.86	-0.78	1.00

c) Lake Sonachi and Oloiden

	PH	*Temp (?c)*	*Ecµs/cm*	*Cl (mg/L)*	*SO4 (mg/L)*	*NO3 (mg/L)*	*F (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*K (mg/L)*	*Na (mg/L)*	*Mg (mg/L)*
PH	1.00											
Temp (?c)	-0.82	1.00										
Ecµs/cm	0.98	-0.92	1.00									
Cl (mg/L)	0.99	-0.92	1.00	1.00								
SO4 (mg/L	1.00	-0.83	0.98	1.00	1.00							
NO3 (mg/	0.84	-1.00	0.92	0.91	0.81	1.00						
F (mg/L)	0.44	-0.62	0.52	0.65	0.48	0.88	1.00					
Ca (mg/L)	0.24	-0.46	0.32	0.99	0.98	-0.93	-0.37	1.00				
Fe (mg/L)	0.65	-0.59	0.64	0.93	0.86	1.00	1.00	-0.45	1.00			
K (mg/L)	0.23	-0.45	0.32	-1.00	-0.99	-0.91	-0.37	1.00	-0.46	1.00		
Na (mg/L)	0.19	-0.42	0.28	-1.00	-1.00	-0.91	-0.40	1.00	-0.49	1.00	1.00	
Mg (mg/L	-0.05	-0.20	0.04	0.93	0.90	-0.92	-0.61	0.91	-0.67	0.96	0.97	1.00

4.5.4 Tracing Groundwater Flow using Hydrochemical Parameters

Groundwater flow can be traced using the cation exchange between the major cations in water, which are sodium and calcium or magnesium and by noting the concentration gradient of lithium ions in water. Calcium has greater influence in the study area among the alkaline earth metal elements and therefore used together with sodium to investigate the lateral groundwater flow. The distribution maps are shown in **Figure 4.18**. High gradient of lithium ion concentration in water also shows the direction of flow, and the map for Li^+ is presented in tracing the flow direction. The areas around the lake where we have shallow aquifers, there is low concentration of lithium ions in water (compare **Figure 4.19** with **Figure 5.1**). The areas around Lake Sonachi and Oloiden have relatively higher values of Lithium ion.

In **Figure 4.17**, a line plot is given to demonstrate cation exchange between Na^+ and Ca^{2+} as source of elevated values of Na ions in the groundwater. Crater Lake and around Oloiden Lake have high spikes of sodium ions with comparatively low values of calcium ion in the same areas. The low values of both Na^+ and Ca^+ ions between Aquila Lake Side and W. BH may be attributed to the two rivers (River Marmanet and Mereroni) which recharges the aquifers within the vicinity of these boreholes. The sample points are arranged from north to south to clearly indicate the cation exchange along the path. The groundwater pH is shown in **Figure 4.20** indicating that Ndabibi area have elevated values compared to the surrounding Lake Naivasha and the saline lakes.

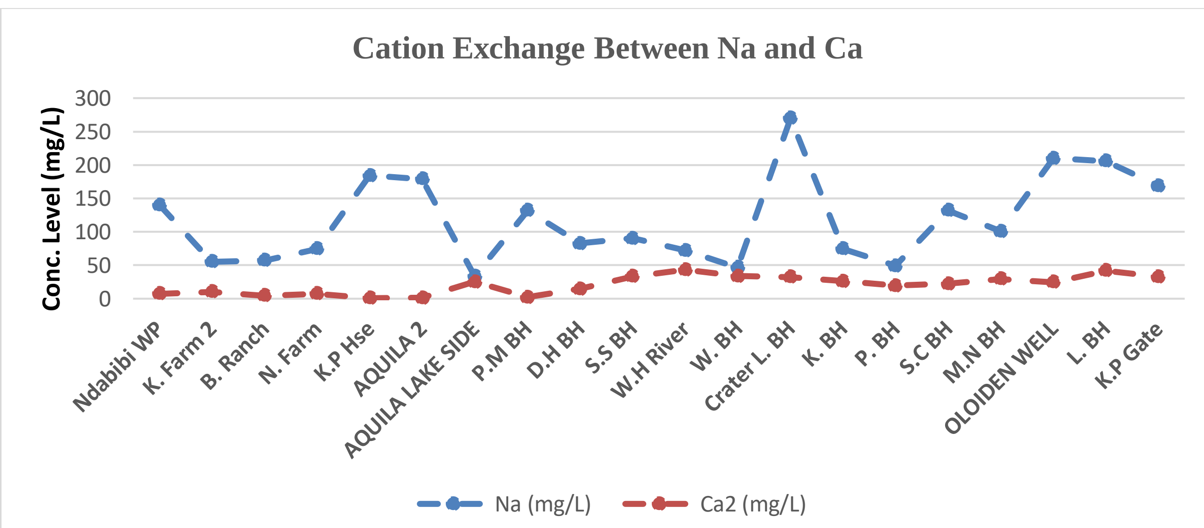


Figure 4.17: Line Plots for Sodium and Calcium Ions

Sodium, Calcium and Lithium Concentrations

The background in the graduated maps in **Figure 4.18** and **Figure 4.19** is the study area sub-locations. Sodium and Calcium show an increase in the concentration in the groundwater from northern to southern parts of the area. They have a low positive correlation co-efficient of 0.06 and both determine the alkaline nature of water. Lithium on the other hand shows two main parts with high concentration.

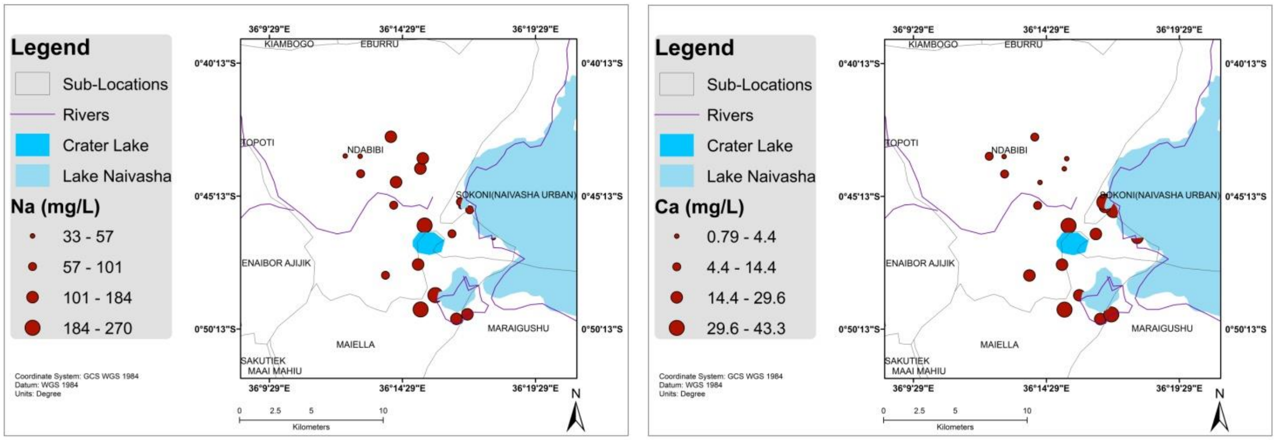


Figure 4.18: Sodium and Calcium Concentrations

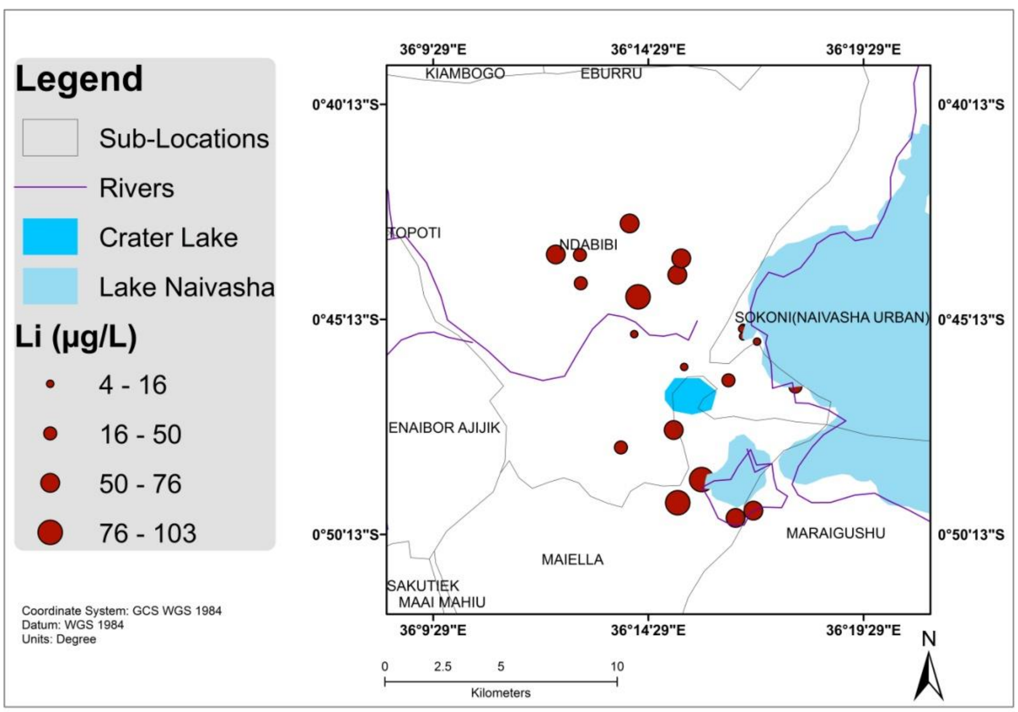


Figure 4.19: Lithium Distribution Map

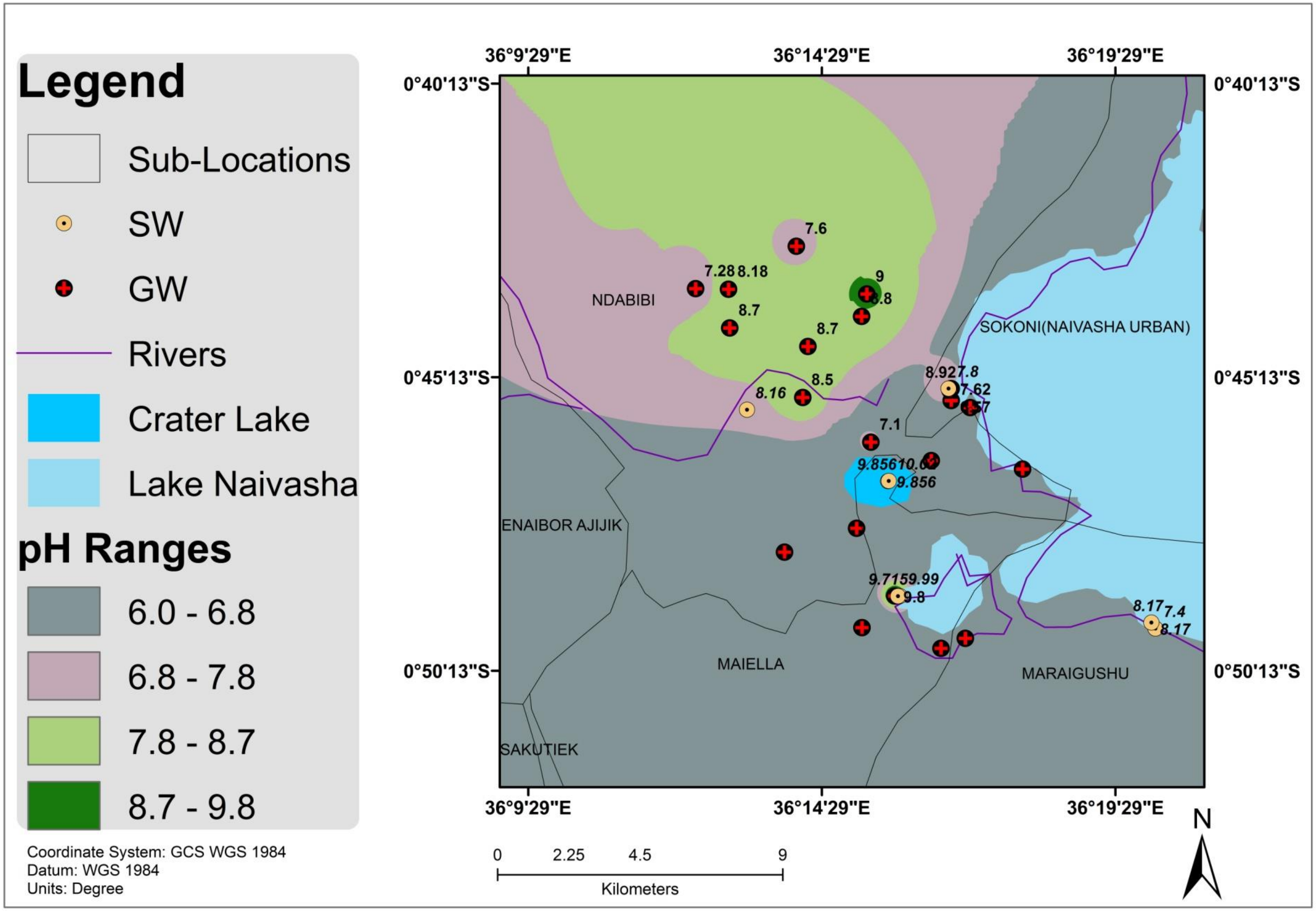


Figure 4.20: pH Map for Surface and Groundwater

4.5.5 Indicators of Interaction between Surface and Groundwater

The correlation between surface and groundwater concentration of both chloride and nitrate indicate the interactions between these waters. The Cl^- and NO_3^- are used to show up-downward flow direction due to their high solubility (Li et al., 2017; Meijia et al., 2018; Varsanyi, 1989). They both have a positive correlation coefficient of 0.41 in the groundwater. Boron which is a conservative element has also been used to show the interactions by plotting a line graph together with chloride from northern to southern parts of the study area. The result shows a progressive increase of the Cl^- and B^+ southwards, indicating that there shallow and deeper aquifers are connected because the boreholes penetrated several aquifers.

The concentration increases south of the study (**Figure 4.21**). **Figure 4.22** shows the spatial distribution of these two elements in groundwater while this has been compared with the nearby surface water quality data in

Table *4.6*. Nitrate level concentration above 20 mg/L in groundwater is considered contaminant. While in groundwater, the maximum value measured and recorded is 3.18 mg/L, which are within the limits of the natural sources. The nitrate is not adsorbed by the clays and this allows it to move as a contaminant in the direction of groundwater flow (Morgan, 1998). The Marmanet River recharges its water directly in the area located between P.M and D.H boreholes within Ndabibi Plain.

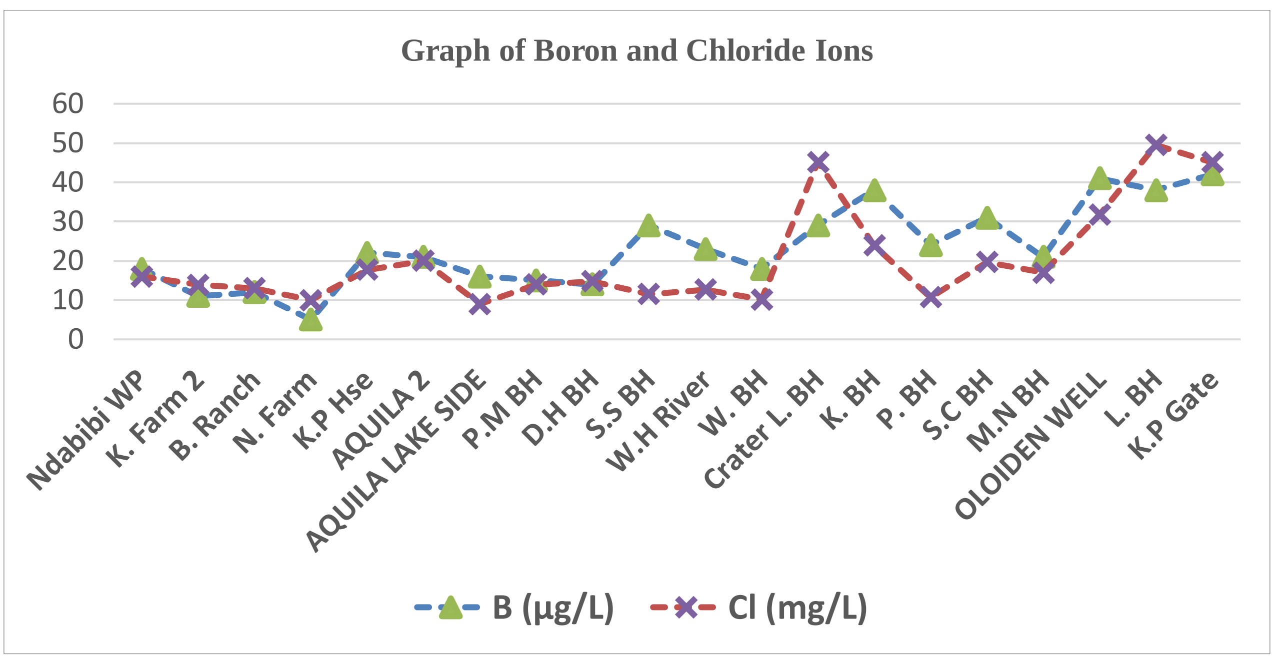


Figure 4.21: Line Plots for Boron and Chloride Ions

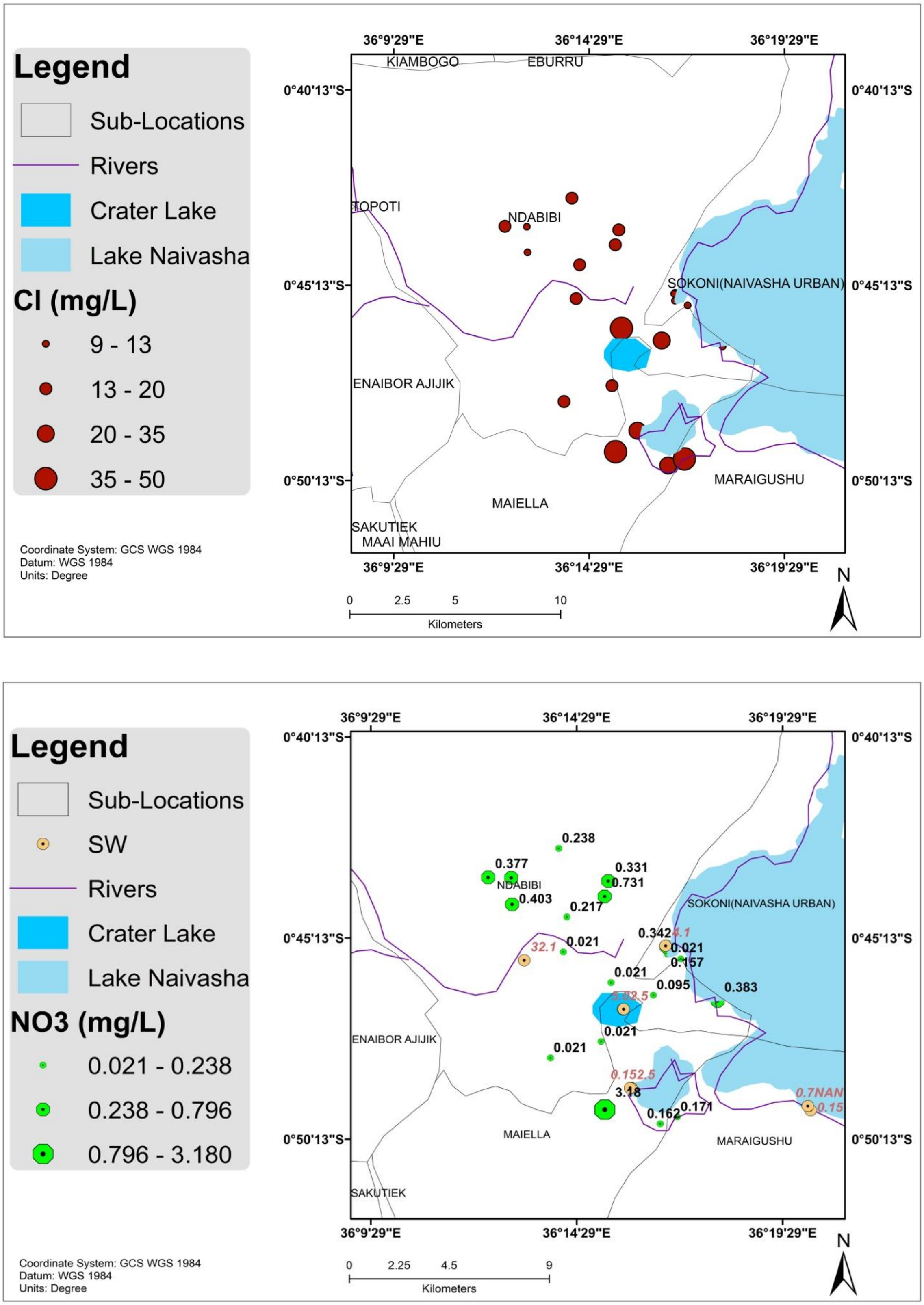


Figure 4.22: Chloride and Nitrate Distribution Map

Box plots

The box plots (**Figure 4.23-Figure 4.26**) are used to demonstrate the relationships among the water sources that is Lake Sonachi and Oloiden, Lake Naivasha, groundwater and River water distinctively. The elements plotted are the dominant cations and anions: Na and Ca for cations while Cl and SO_4 for anions. Sodium has the highest median value in Lake Sonachi and Oloiden (1540) while lowest in Lake Naivasha (16 mg/L), groundwater value ranges from 33 to 270 with a median value of 101 and the rivers with a median value of 72.

On the other hand, Cl concentration in the groundwater ranges from 9-50 with a median value of 16. This is contrary in the lake water, which have values between 5 and 7 with a median of 6.9 for Lake Naivasha and median value of 199.8 for Lake Oloiden and Crater Lake, while the river water has the median value of 26.6.

The median values for calcium are as follows: groundwater (22.3), Crater Lake and Lake Oloiden (6.49), river water (43.3) and on Lake Naivasha (16.04). The median values for SO_4 are; groundwater (13.65), Crater Lake and Oloiden (38.85), Lake Naivasha (0.972) and river water (0.415). This shows similarity between groundwater and lake Sonachi and Oloiden and on the other hand, river water is similar to that of Lake Naivasha based on sulphate concentrations.

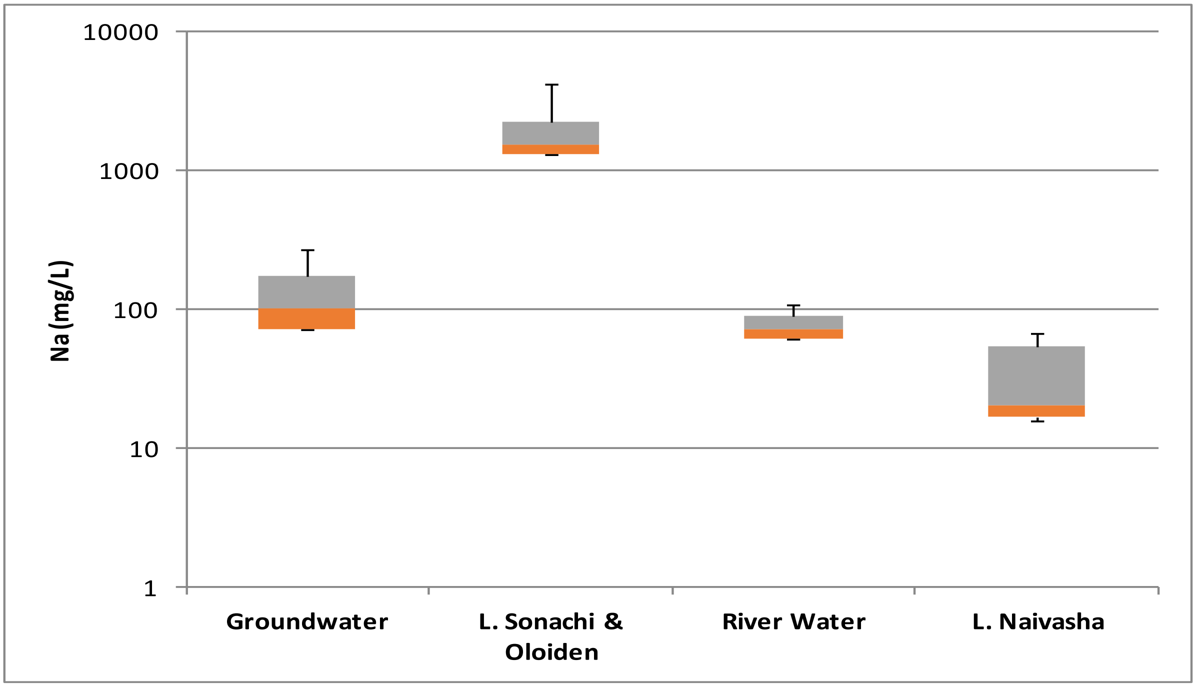


Figure 4.23: Box-plots of Sodium Concentration for Groundwater and Surface Water

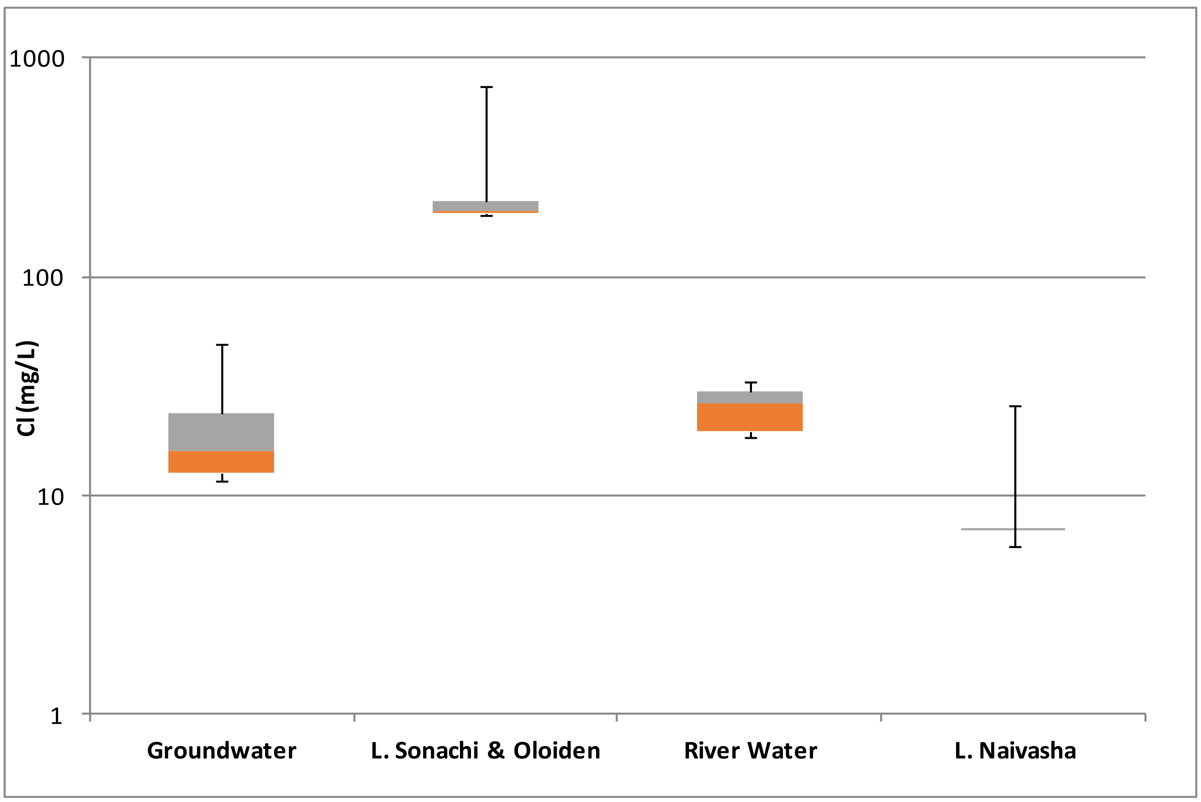


Figure 4.24: Box-plots of Chloride Concentration for Groundwater and Surface Water

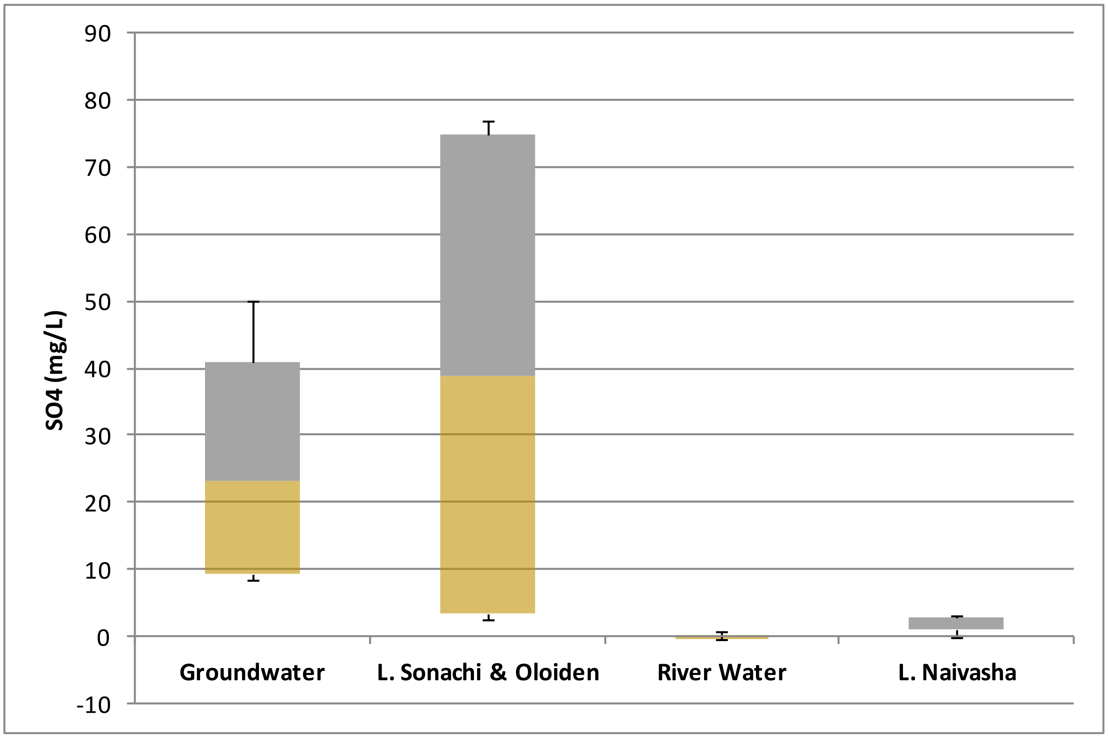


Figure 4.25: Box-plots of Sulphate Concentration for Groundwater and Surface Water

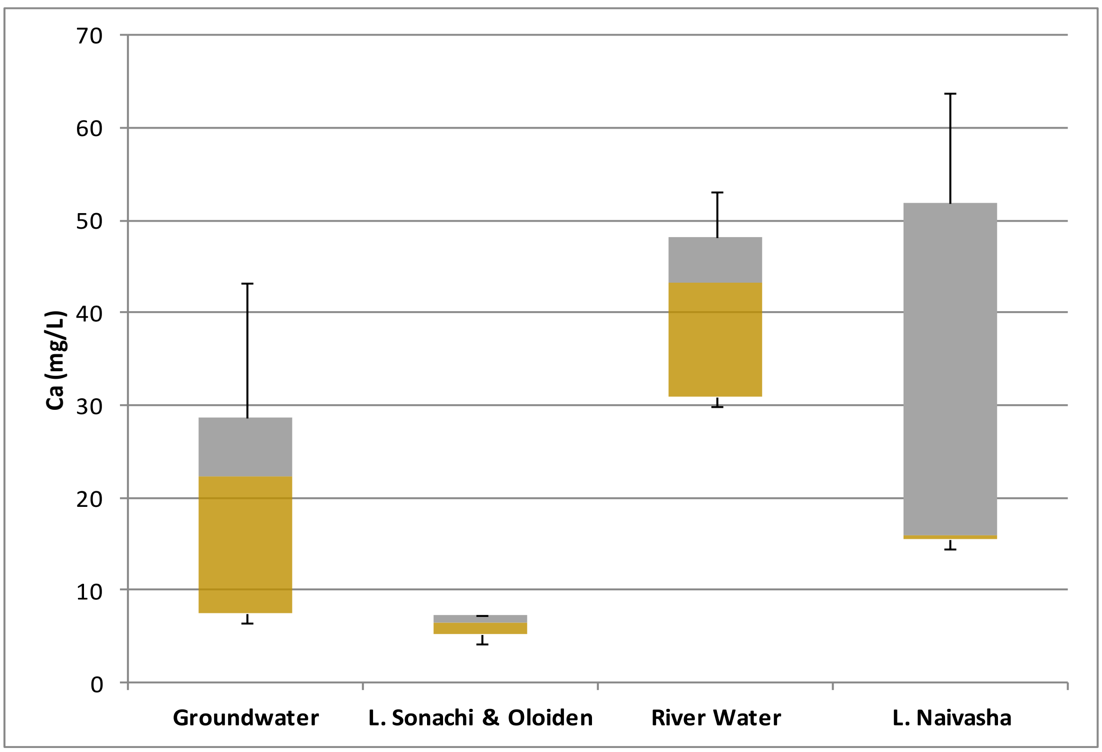


Figure 4.26: Box-plots of Calcium Concentration for Groundwater and Surface Water

Table 4.6: Surface Water Quality Data

NAME	PH	Temp (°c)	Ecµs /cm	Cl (mg/L)	SO4 (mg/L)	NO3 (mg/L)	F (mg/L)	Ca (mg/L)	Fe (mg/L)	K (mg/L)	Na (mg/L)	Mg (mg/L)
L. Naivasha	8.3	20.3	203	6.9	1.1	0.5	-	14.9	0.255	10.5	16.5	3.43
L. Naivasha	8.3	20.3	203	6.9	1.1	0.5	1.2					
L. Naivasha	8.2	19.1	208	6.9	1.0	0.7	5.4	14.9	0.377	10.6	16.7	3.49
L.Naivasha	7.4	22.6	0.2	5.07	0.53	0.15	0.27	16	0.05	12	20	6.1
L. Oloiden	10	24.0	5.5	221	1.47	0.15	50.14		-	-	-	-
L. Oloiden	9.7	21.9	3.6	136	4.1	2.5	32.6	5.7	0.143	178	756	2.5
L. Sonachi	9.9	21.8	6.6	200	73.6	5.0	75.0	7.28	0.03	208	1530	4
L. Sonachi	9.9	21.8	6.6	195	72.2	2.5	63.6	7.29	0.03	214	1550	3.99
Crater Lake	10.0	28.2	14.1		-	-	-	3.9	0.05	494	4274	0.43
River Marmanet	8.2	18.1	419	33.2	24.7	32.1	2.1	18.4	3.21	22.5	51	4.68
WIL ELI House River	7.8	18.0	733	26.6	1.7	4.1	6.2	53.2	0.49	43.3	108	27.5

4.6 Geophysical Measurements

A total of 11 sites (**Figure 4.27**) were investigated and electrical potential measurements taken following various profiles, targeting northern, central around Lake Sonachi and the southern parts of the study area. The locations where resistivity profiles were carried were chosen after carefully analyzing the boreholes logs, geological structures and areas with known geochemical anomalies from Section 4.5. From the borehole data, some sites were performed on targeted aquifers and across the faults controlling the surface flow.

The results are presented as profile curves and profile maps (pseudo-sections) autogenerated from the curves, and finally the excel plots are given in Appendix 3. The sites investigated were grouped in three zones; Zone A targeted the profiles around the crater lake, Zone B constituted the profiles in the northern parts of the study area while Zone C contains profiles in the southern parts of the study area and mostly southern parts of Lake Naivasha. The grouping of the sites helped in analyzing the electrical resistivity data in comparison with the borehole logs for sur-surface geology.

The results are shown from **Figure 4.28** to **Figure 4.38**, in each, the profile curve and profile map are presented accompanying each other. The profile curves indicate where we have the anomalies while profile maps reveal the sub-surface image. Most profiles were done E-W direction across the general orientations of the faults in the area.

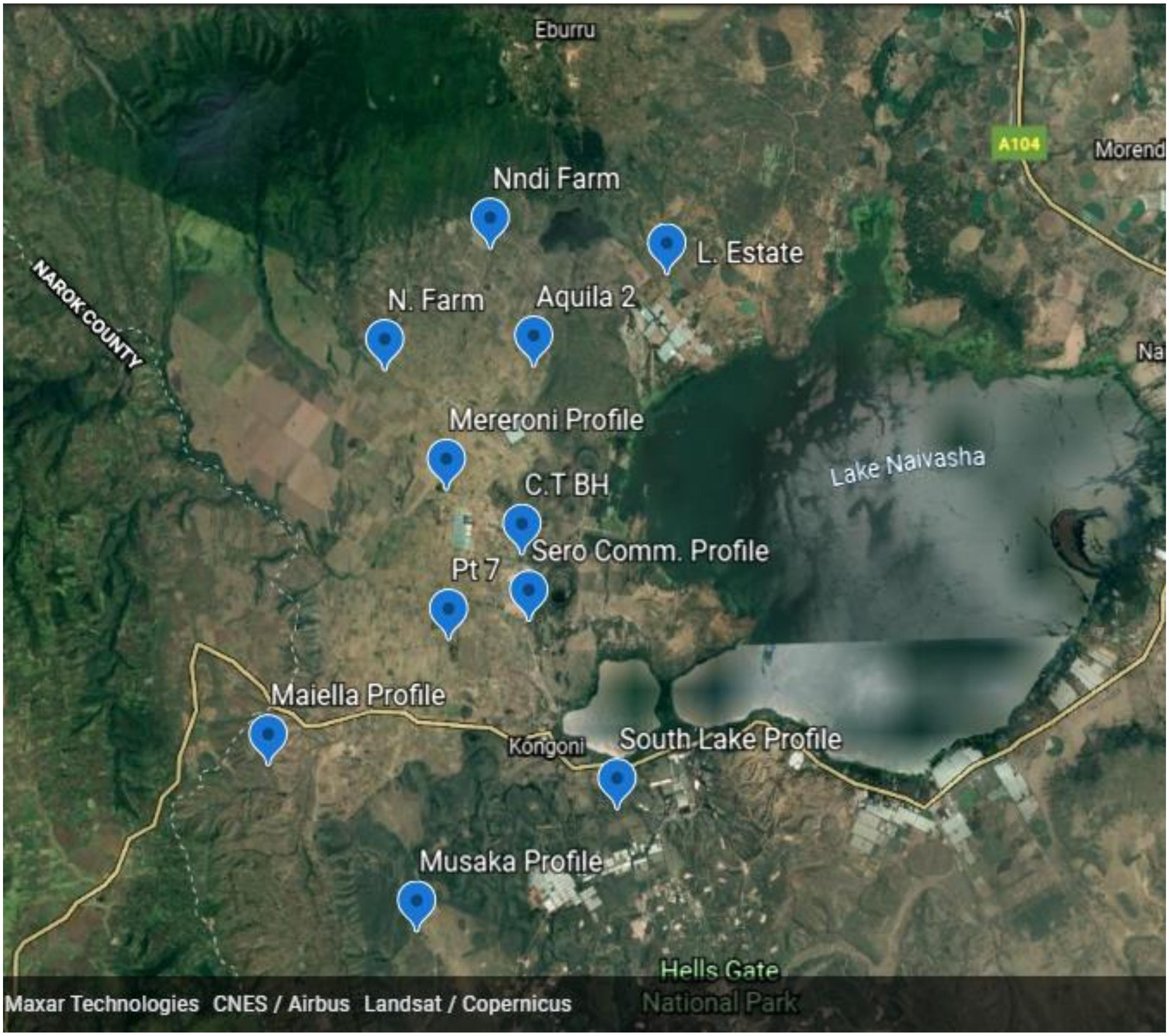


Figure 4.27: Location of the Resistivity Profiles (Modified from Google Earth)

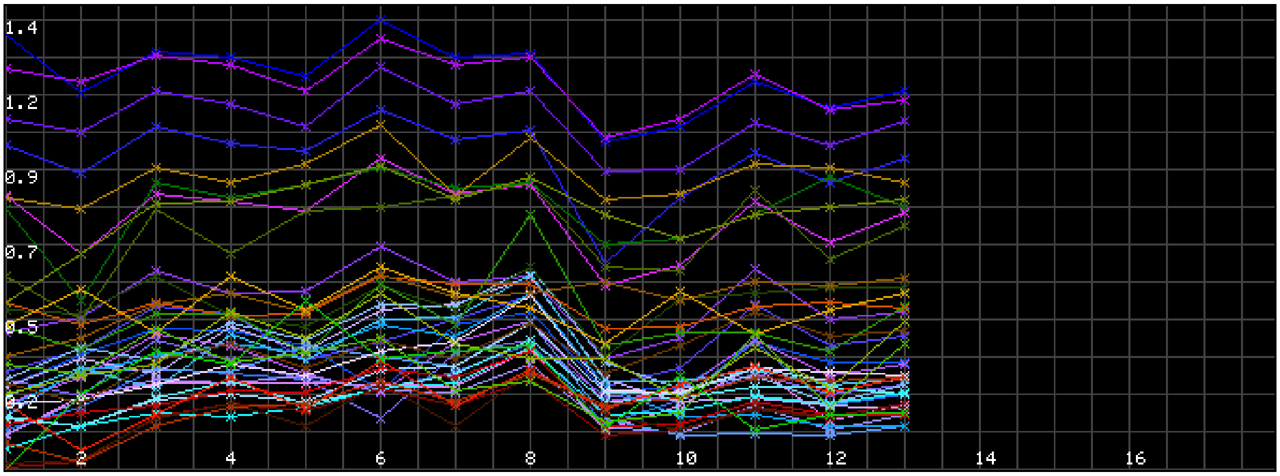
Zone A

This zone constituted the profile investigated on the central part of the study area, around the Crater Lake (Lake Sonachi), western part of Lake Naivasha. A total of six profiles were done from the existing boreholes and across the loosing stream (River Mereroni).

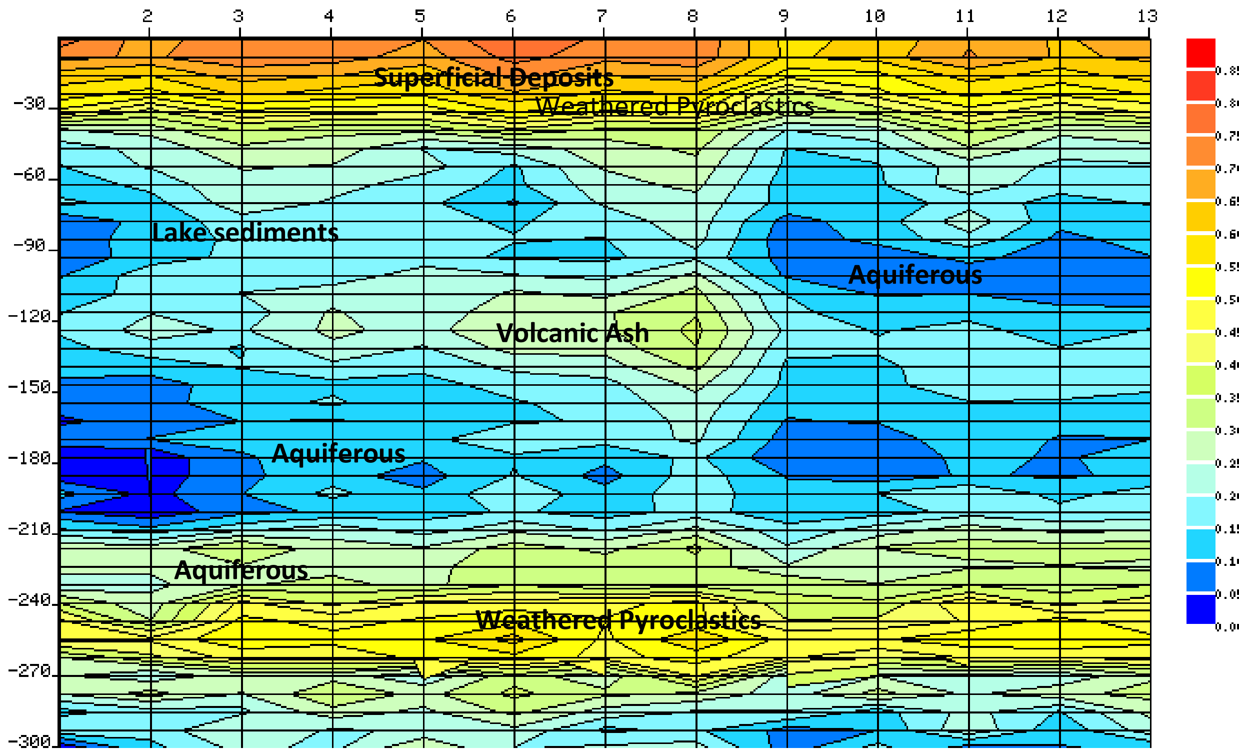
C.T Borehole Profile

The measurements were executed at C.T borehole situated approximately 1.6km north west of the Crater Lake. The profile (**Figure 4.28**) reveals that the subsurface is composed of four main layers. The upper layers comprise superficial deposits (0.75-0.85 mV) underlain by pumice tuffs (0.60-0.75 mV) to a depth of 55m bgl. This is followed by low resistivity (<0.25 mV) of unconsolidated layer with pockets of clay embedded within it, interpreted as lacustrine sediments/weathered pyroclastics. The layer extends to 210 m bgl where there is a contact zone with the weathered pyroclastics/unconsolidated materials. The rocks are fractured at point 8 to a depth of 180m. Shallow aquifers are found between 30 and 60 m while deep aquifers are found at depths ranging from 180 to 240 m bgl. The aquifers terminate on the faults along the profile.

Note that in each profile map: y-axis (m below ground level) and x-axis (m horizontal surface) while the legend represents differences in the electrical potentials (mV) reflecting the changes in the sub-surface lithology.



a)



b)

Figure 4.28: Profile Curve and Profile Map along C.T Borehole

Sero Community Profile

The site is situated south of C.T borehole profile and about 2.4 km south west of the Crater Lake. The profile map in **Figure 4.29** (b) indicates that at depths between 90 and 270 m bgl, the materials have moderately higher resistivity values compared to the upper values (0.26-0.31 mV). These layers constitute of consolidated materials intercalated with materials of low resistivity (0.06-0.09 mV) interpreted as pyroclastics. The materials are interpreted as tuff formations and the superficial deposits ae underlain by weathered pyroclastics and other unconsolidated materials. The pyroclastic materials have a thickness of 90m from the surface, with various degrees of weathering. The groundwater occurs in pools within the weathered unconsolidated materials between 100 and 270 m bgl, while the shallow aquifer is extensive across the profile. Aquiferous zones have relatively low resistivity due to the saline nature of the crater lake and the surrounding area. The points 8 to 12 indicates that the rocks are fractured.

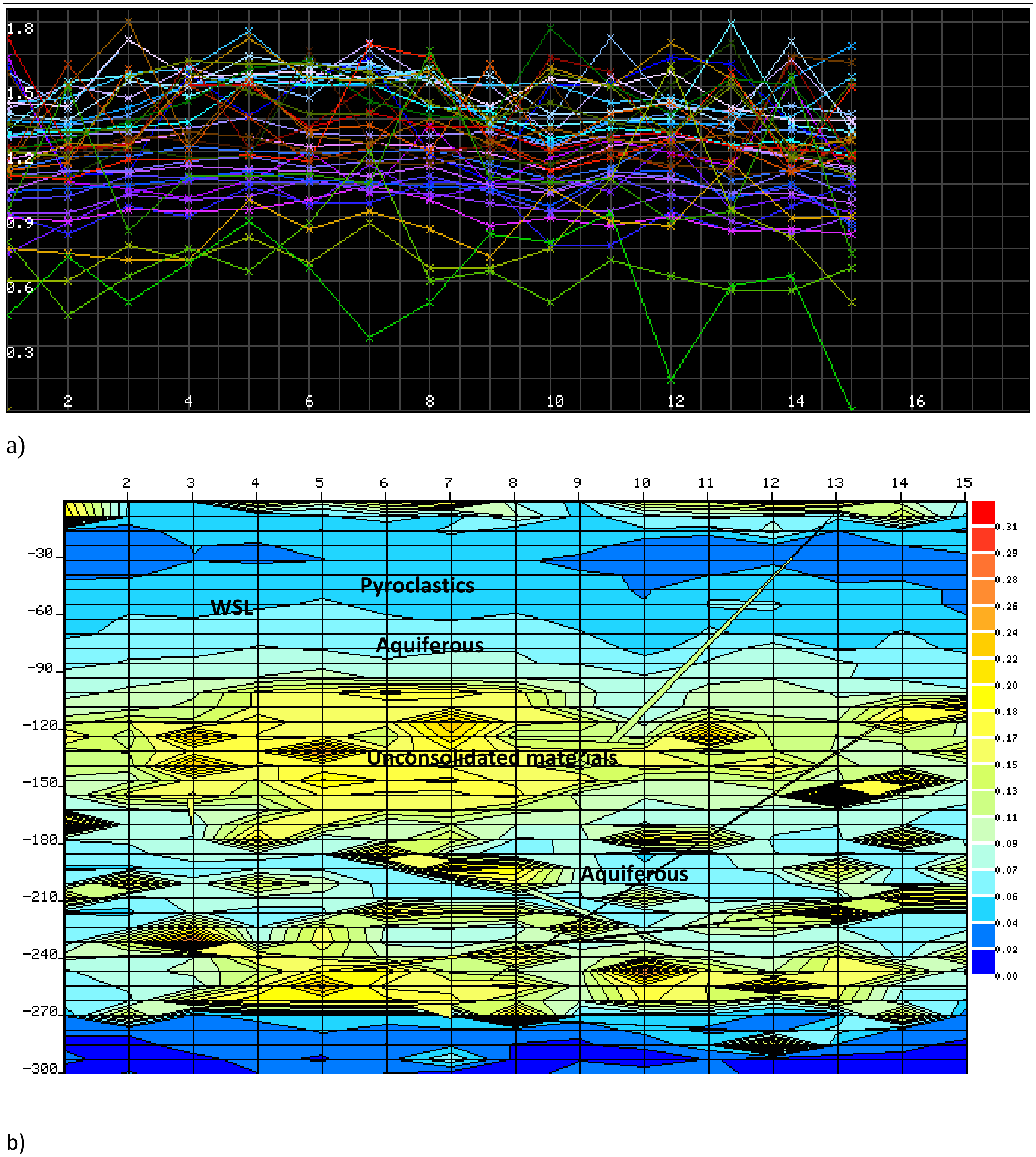
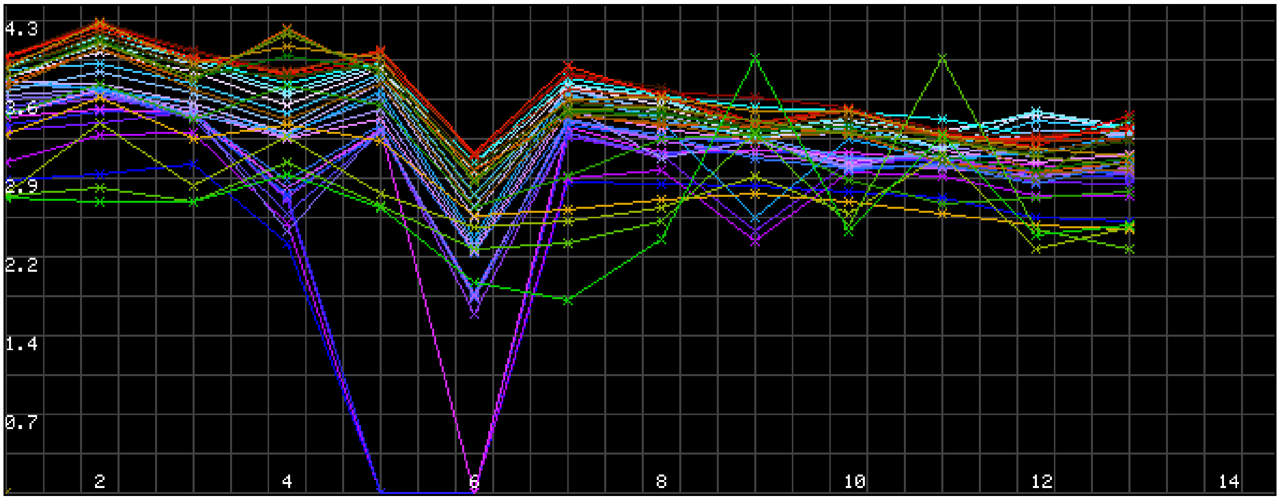


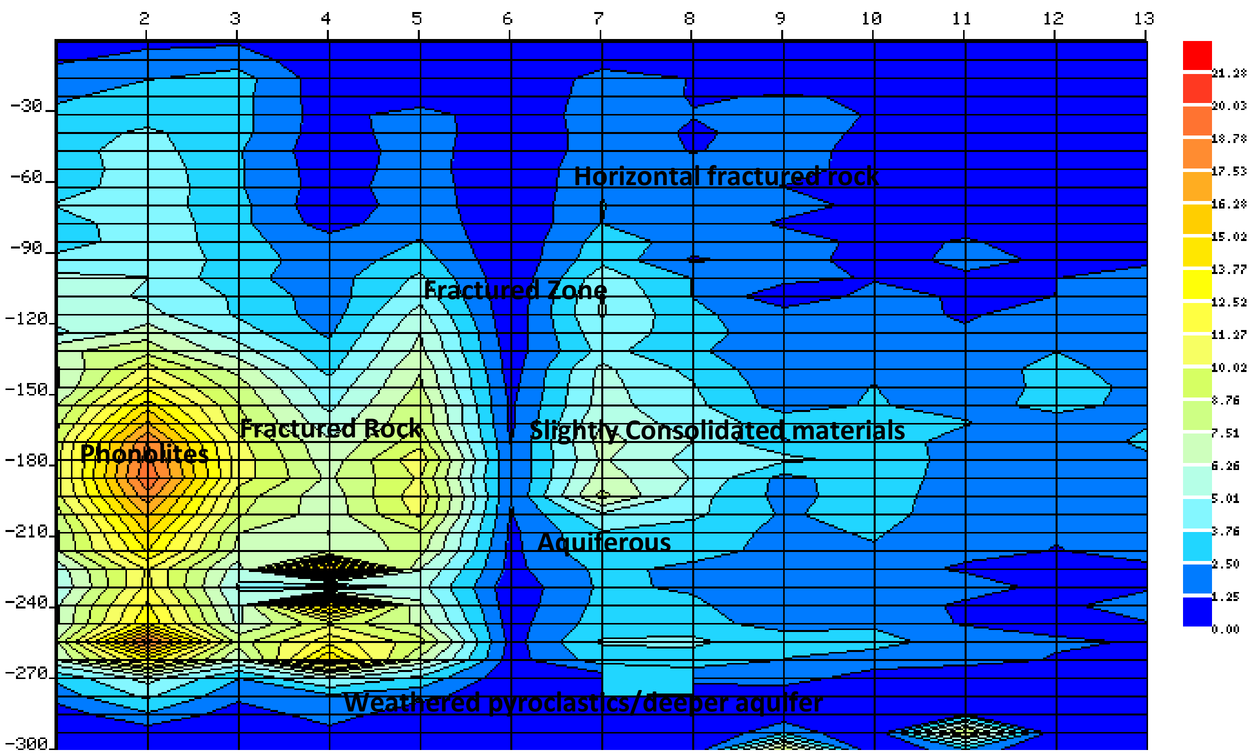
Figure 4.29: Intercalations of Impermeable Materials (Unconsolidated Formations) along Sero Community Indicating the Pockets of Saturated Zones

Mereroni River Profile

The profile was carried out across Mereroni River where the stream recharges the aquifers, western part of Lake Naivasha. River Mereroni is a tapering stream whose relation with lake water is similar from the surface water quality measurements in the previous studies. Four main layers are distinct (**Figure 4.30**, b): the top superficial deposits which are underlain by weathered pyroclastics with electric fields ranging from 0-2.5 mV, the layer extends to greater depths on the locations between point 9 and point 13. There exists a fault between location five and seven of about 4m wide (**Figure 4.30**, a) at the surface and thinnest at 180 m bgl. The fault is filled with weathered materials. Pyroclastic materials are underlain by the trachytes and phonolites with high resistivity values ranging from 17 to 21.28 mV from 120 to 270 m on the western side along the profile. The fault acts as a conduit to groundwater flow thereby diverting the surface flow to deeper flows recharging the deeper groundwater aquifers.



a)

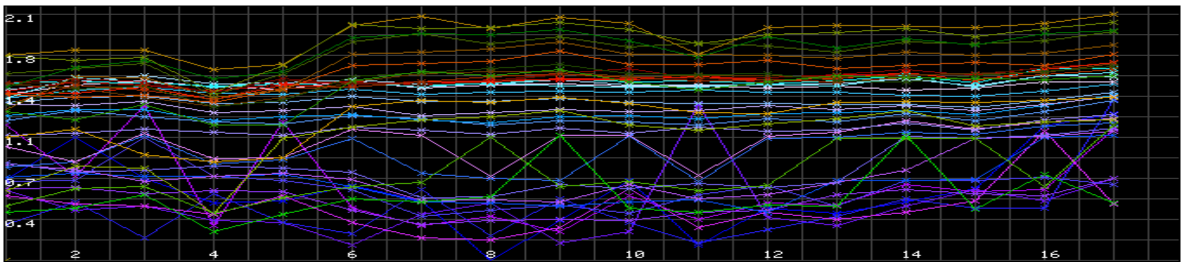


b)

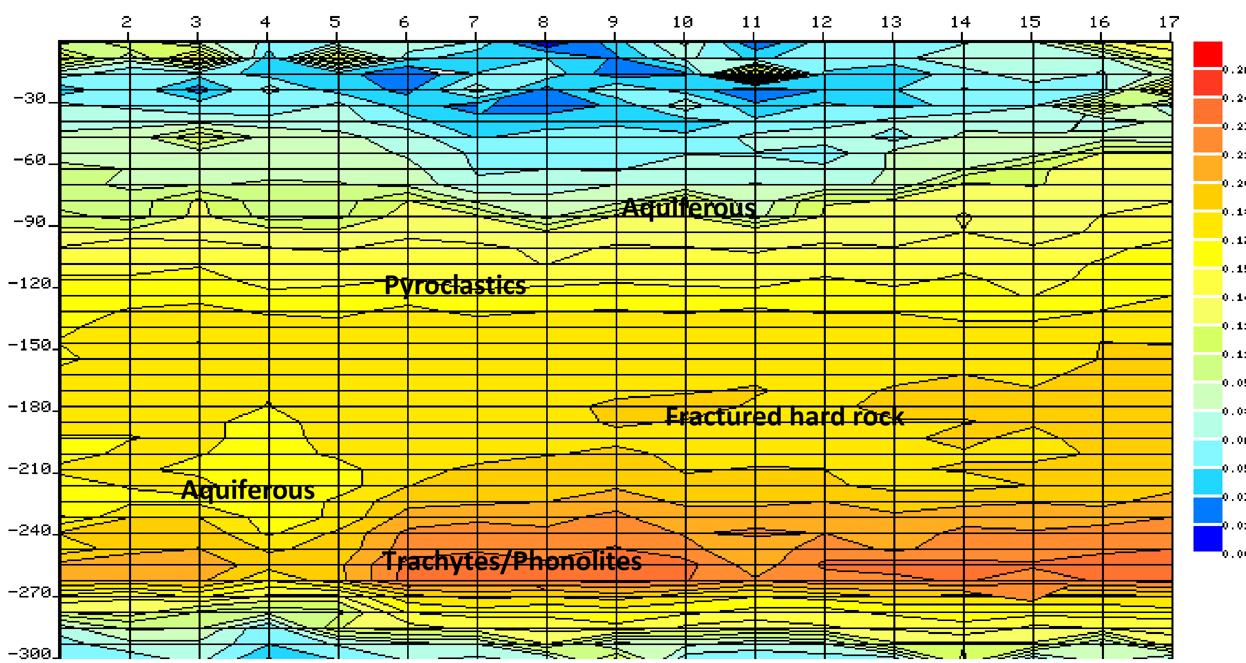
Figure 4.30: Profile Curve and Profile Map Across River Mereroni Showing the Depth of a Faultline

N. Farm Profile

The profile is situated west of L. Estate and the formations appears the same except the degree of weathering which has increased in this area compared with the profile above. Deeper aquifers occur between 180m and 240m within fractured trachytes and phonolites, while shallow aquifers are found between 30-60 m bgl within the lake sediments. The pyroclastics overlies andesitic/phonolitic formation which are underlain by weathered tuff formations. The andesites/phonolites have relatively higher resistivity values ranging from 0.24-0.24 Ω-m, with a thickness of about 60m from 210 to a depth of 270m bgl and with various degree of weathering/fracturing. The thin layers noted within pyroclastics are probably tuffs, occurring at depths between 90 and about 140 m bgl.



a)

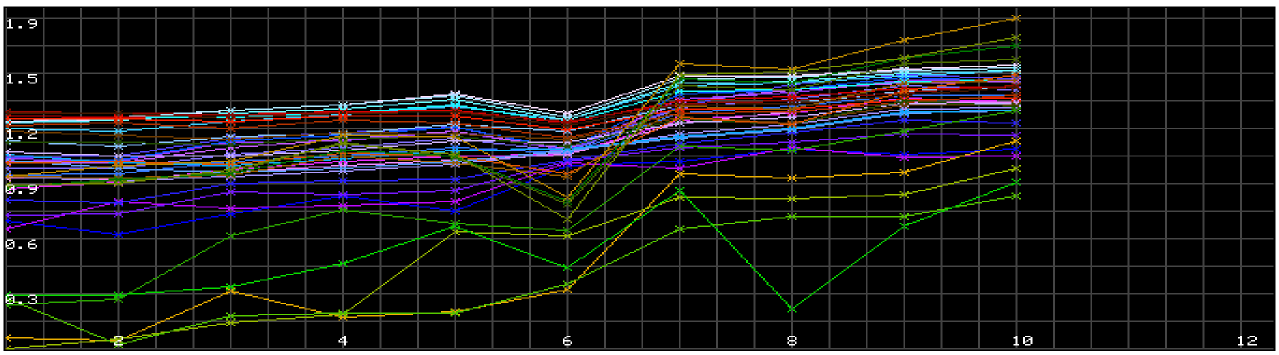


b)

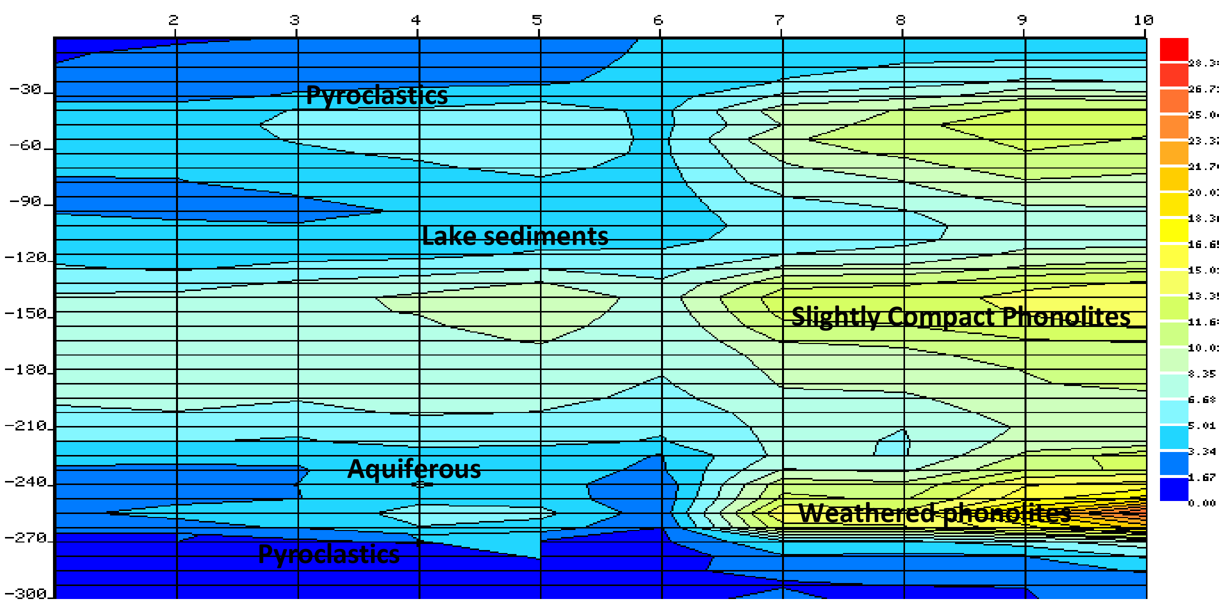
Figure 4.31: Profile Curve and Profile Map along N. Farm

Aquila Farm Profile

The site investigated is situated at Aquila on the north western side of Lake Naivasha. Shallow aquifers are located at depths between 35 and 65 m bgl within lacustrine sediments and tuff formations and terminates within the compact phonolite formations (**Figure 4.32**, b). Tuff formations in this area, are pumice from borehole logs and they range from 30 to 125 m bgl underlain by fine materials of pyroclastics or lake sediments. On the eastern side of the profile, the layers comprise weathered phonolites/trachytes to a depth of about 280 m where they are underlain again by the volcanic ash materials. Lake sediments varies in depths along the profile from one point to another with an average thickness of about 70 m on the upper layers. The phonolites terminate at the faultline where the aquifers also terminate.



a)



b)

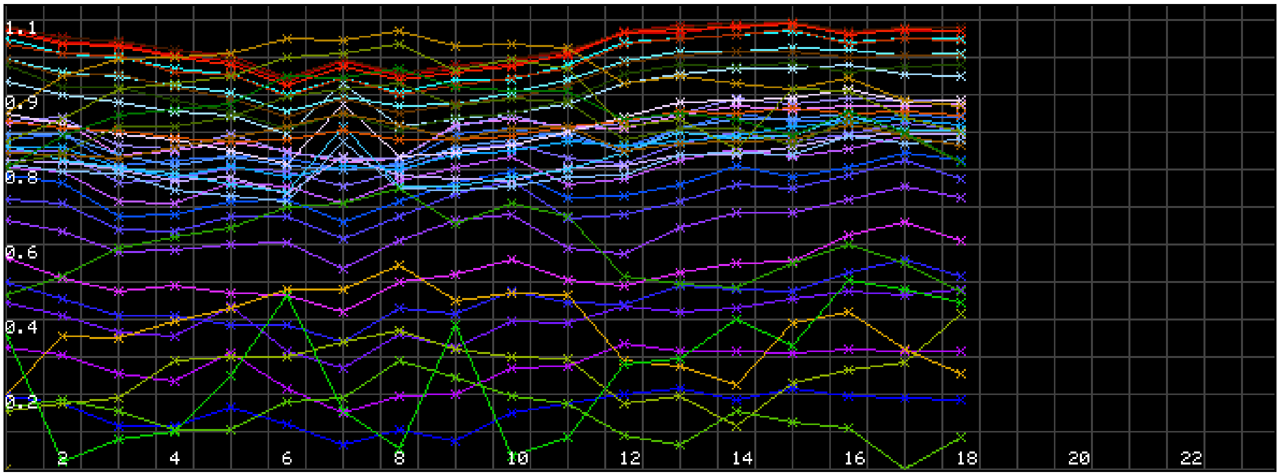
Figure 4.32: Sharp Terminations of Phonolites and Aquifers along Aquila Area Profile

Zone B

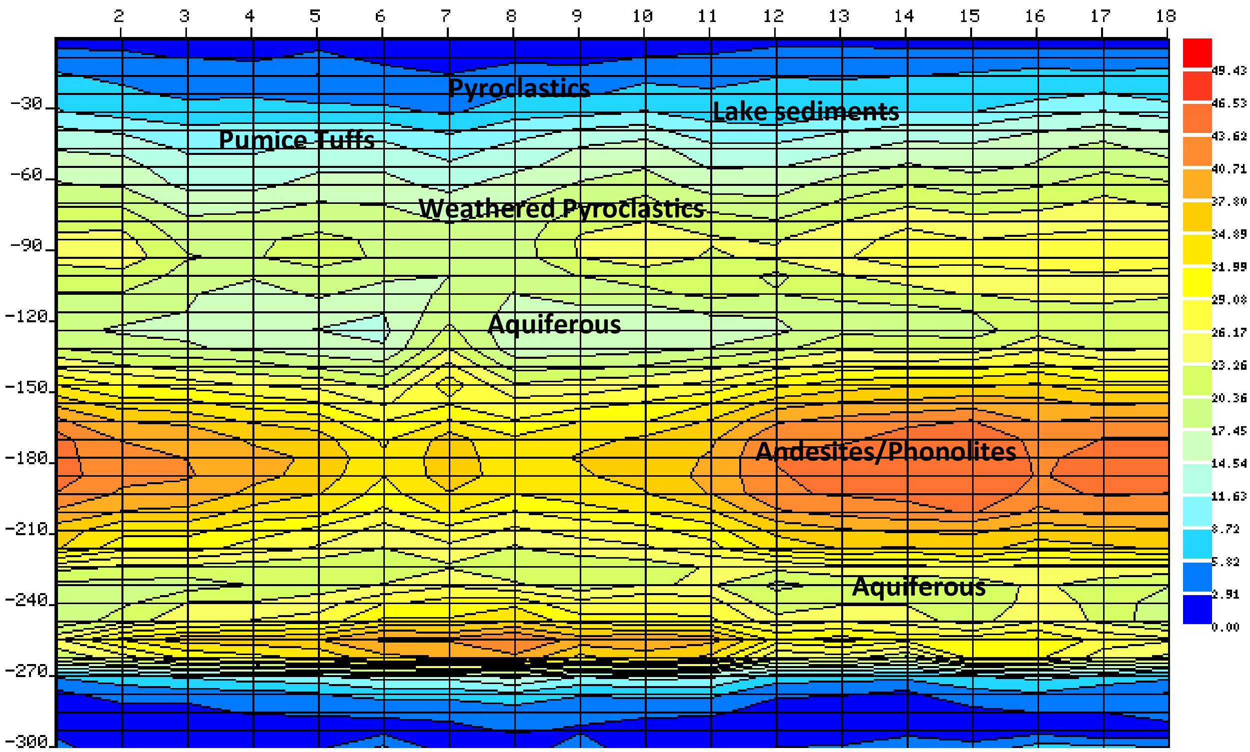
The profiles around this zone are located northern parts of the study area and north west of Lake Naivasha. A total of four profiles were done targeting fractured zones from the surface and reveal the occurrence of the groundwater.

L. Estate Profile

The area is located north west of Lake Naivasha and south of Kingono Game Ranch. **Figure 4.33** (b) reveals the hydrostratigraphy of the sub-surface. The pyroclastic materials comprise the top most deposits to a depth of 60 m bgl. They are underlain by tuffaceous pumice approximately to a depth of 150m bgl with the electrical potential values ranging from 23-31 mV, some locations are penetrated as lacustrine deposits overlying weathered phonolites/andesites to a depth of 180 m bgl (37-50 mV). The lower formations to a depth of 300 m bgl is composed of pyroclastics. Shallow aquifers in this profile are found between 35-55 m bgl while the deeper aquifers are found between 210 and 240m bgl. The shallow aquifers are mostly found within lake sediments and deeper aquifers are localized within fractured rocks/weathered phonolites.



a)

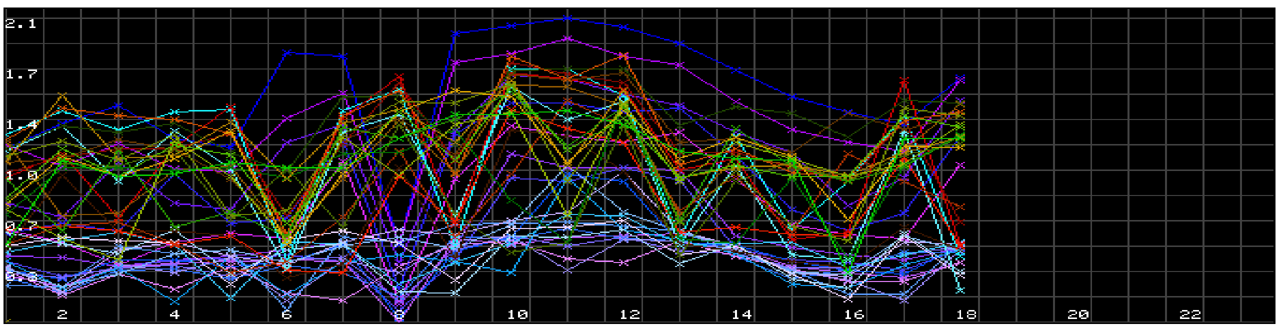


b)

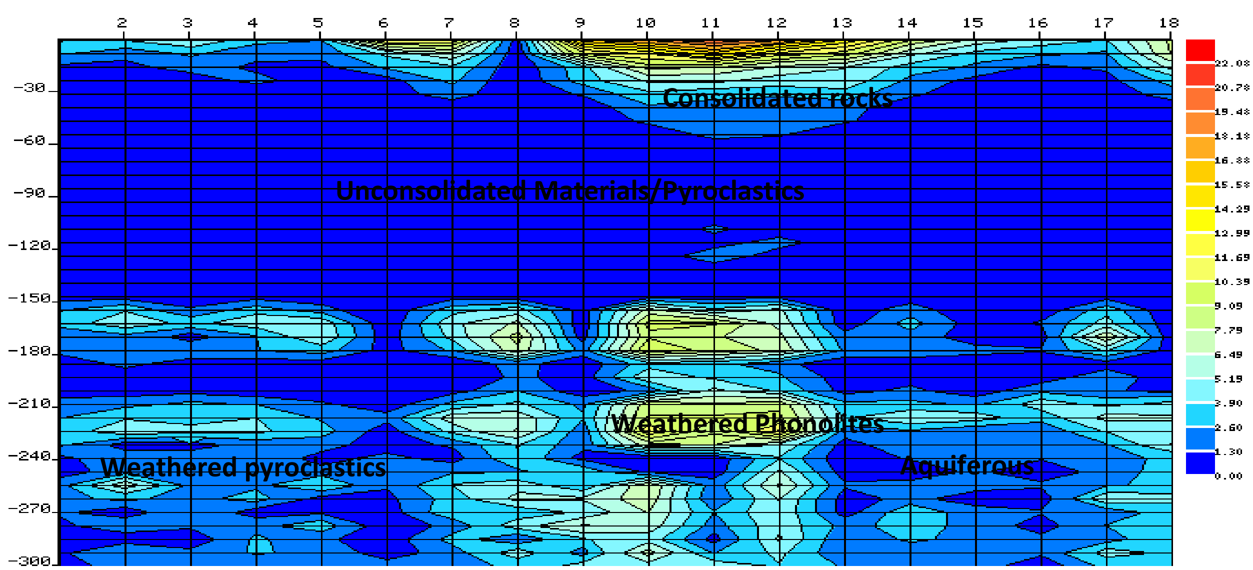
Figure 4.33: Profile Curve and Profile Map along L. Estate

Nndi's Farm Profile

The profile is situated on the western side of L. Estate, south of Eburru area. The area consists of a number of fractured surfaces exposed at the surface (**Figure 4.34**, a and b). Brown clay soil is the top most layer in the area with values ranging from 2.6 to 3.9 mV. The compact formations are interpreted as consolidated materials exposed at the surface from points 5-15 along the profiles, which overlies tuff formation as a thin sheet. From the borehole logs, the tuff formations are mainly pumice in nature. Pyroclastics underlies tuff formations at from 30m bgl to about 250 m bgl. The layer is penetrated from the boreholes logs as weathered pyroclastics. The highly fractured rocks at depths between 150 and 240 at locations 8 and 9 along the profile, interpreted as phonolites and deeper aquifers found within these rocks. The western parts, the weathered pyroclastics/lake sediments containing clastic materials exist at depths greater than 300m bgl.



a)

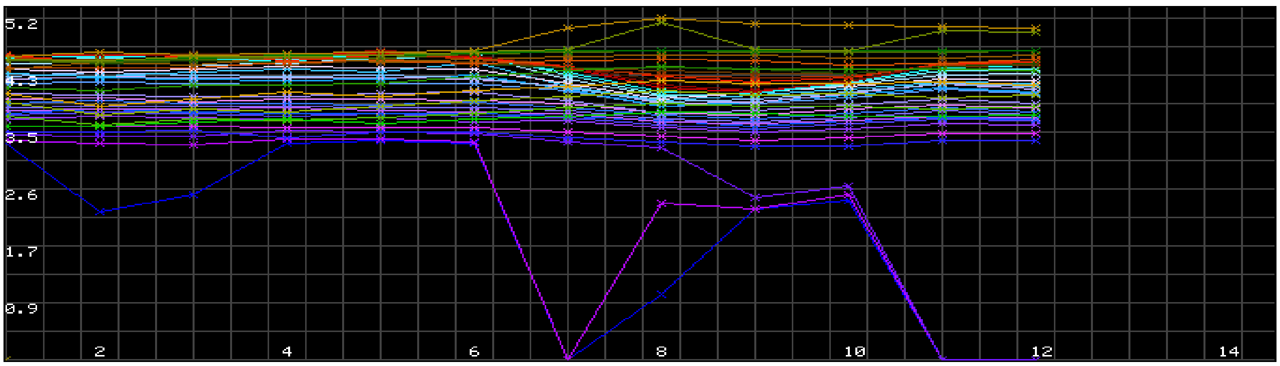


b)

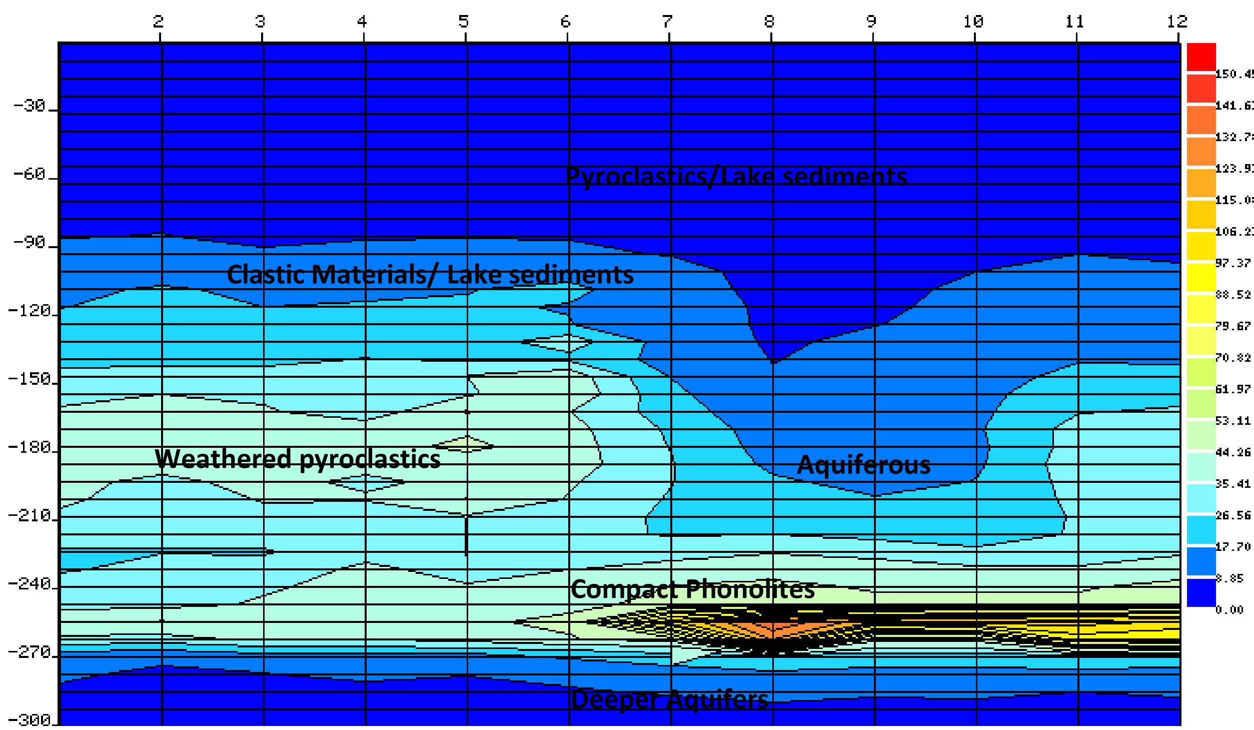
Figure 4.34: Profile Curve and Profile Map along Nndi's Farm

Mirera Profile

The area is found north of Lake Naivasha and the profile followed 12 points of 2m interval. The area is composed of lake sediments to a depth of 150m intercalated with pyroclastics. The compact phonolites occur at depths between 240 and 280m bgl. The intermediate aquifers are found within the lake sediments (120-180m) while deeper aquifers are found at about 300m bgl within weathered pyroclastics and phonolites. However, shallow aquifers are found within the saturated lake sediments at depths less than 60m bgl in this area (**Figure 4.35**, b).



a)



b)

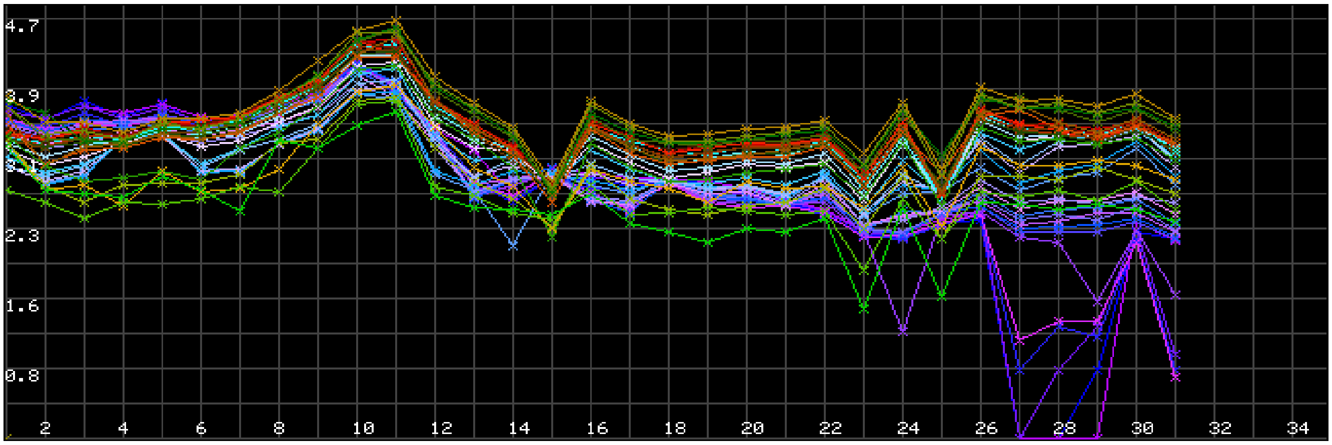
Figure 4.35: Profile Curve and Profile Map along Mirera Area

Zone C

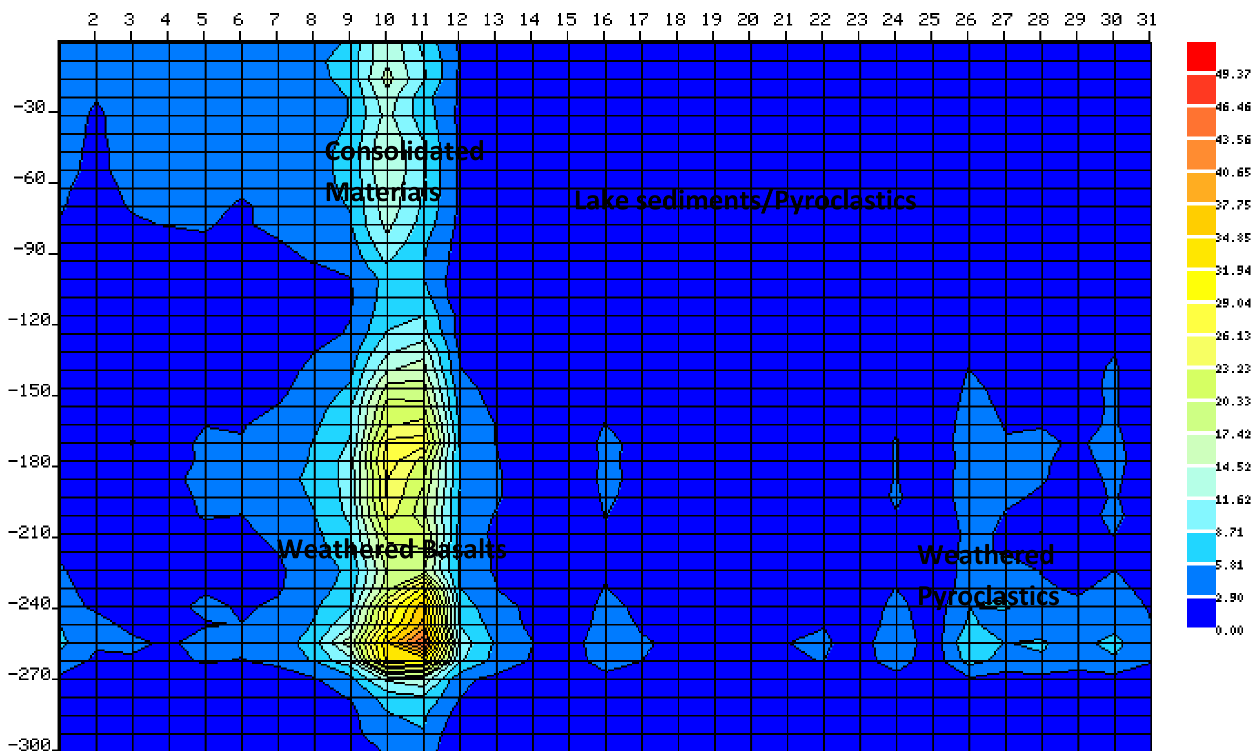
The zone targeted the profiles on the southern parts of the study area and the profiles are mostly located on the south of Lake Oloiden and Lake Naivasha. All the profiles are oriented in E-W direction across the N-S orientations of the major faults. A total of three profiles were performed to understand the sub-surface geology and the occurrence of groundwater.

South Lake Profile

The area is situated about 1.5km south of Oloiden Lake. The subsurface is composed of lake sediments with <5.91 mV and groundwater are confined within the tuffs whose values range between 5.91 and 8.71 mV at depths between 200m bgl to 280 m bgl (**Figure 4.36**, b). However, the aquifer zones are not clearly distinctive along the profile and that may be attributed to the shortcoming of the equipment in a nearly uniform formation. The formation between 9th and 11th points comprise of hard formations and from the borehole logs, volcanic units are made up of basalts as the main formation in this area. At the surface, the formation is weathered and the compactness increases downward. The profile curve indicates that the rocks are fractured at point 15, 23 and 25.



a)

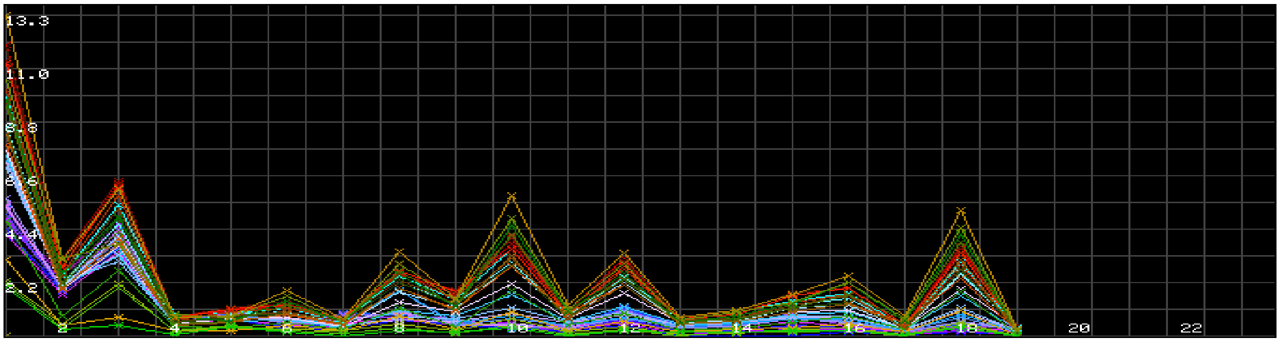


b)

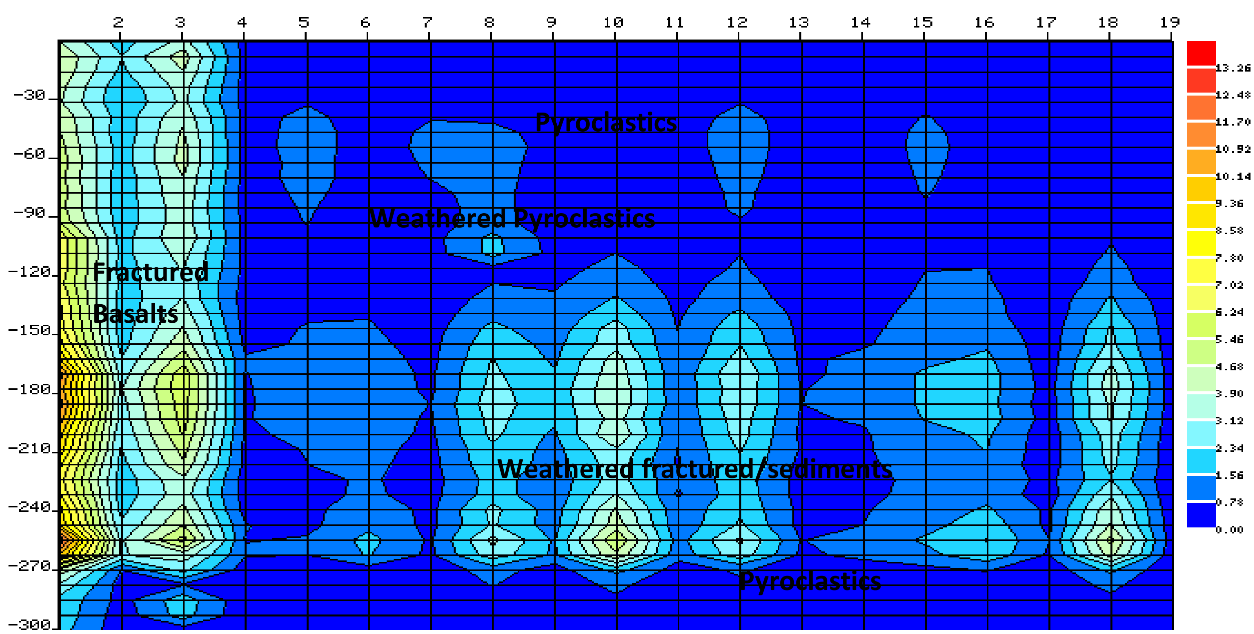
Figure 4.36: South Lake Profile Curve and Profile Map

Maiella Estate Profile

The profile is situated on the at Maiella Estate, Maiella location, southern part of the study area. The deeper aquifers in this profile are found at depths ranging from 180m to 270m bgl. From the profiles in (**Figure 4.37**). The shallow aquifers occur within the lenses of weathered unconsolidated materials at depths between 40 and 60 m bgl. The hard formation on the western parts of the profile at location 1-3 is composed of fractured basaltic rocks to a depth of 270 m bgl. Thin formations of resistivity values ranging between 2.34 and 5.46 mV are considered to be tuffs. From the profile curves, the area is densely fractured and extends to depths ranging from 120 to 270 in which the deep groundwater occurs.



a)

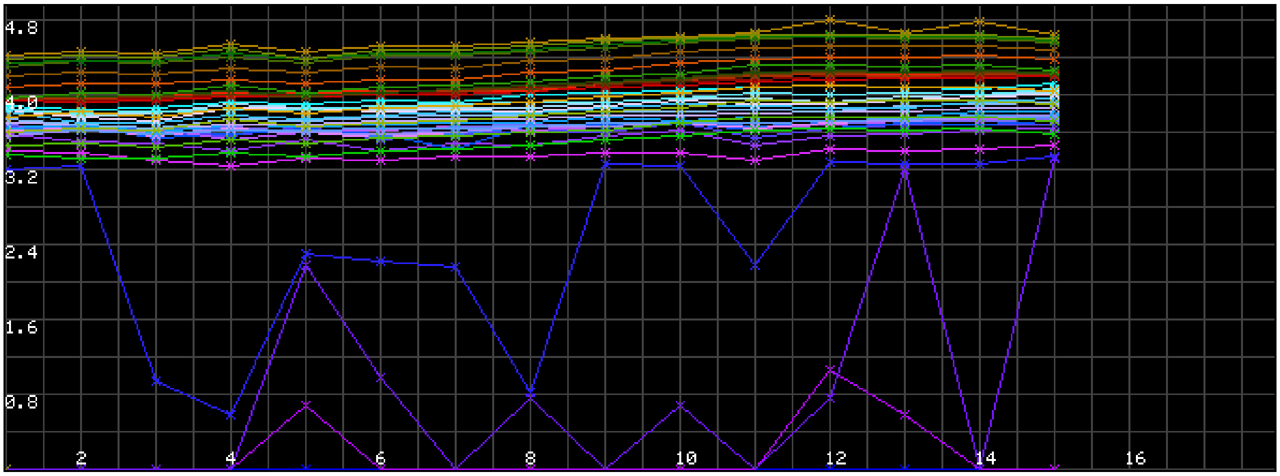


b)

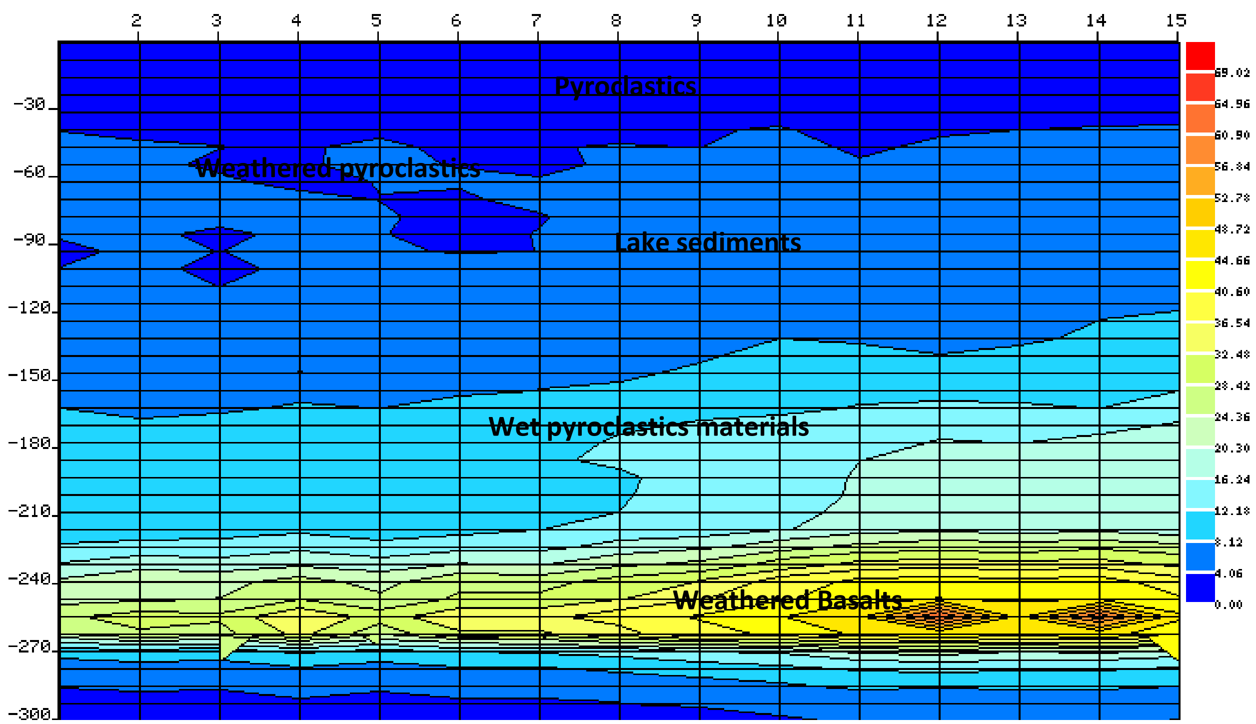
Figure 4.37: Profile Curve and Profile Map along Maiella Estate Farm

Musaka Estate Profile

The area is found in the southern parts of Lake Naivasha. The top soil is underlain by pyroclastics of about 60m thick overlying clastic sediments. These are underlain by weathered pyroclastics and some instances consolidated materials (**Figure 4.38**, b). The basalts with higher values of resistivity from 40-70 mV lies at greater depths between 240-270m bgl and deeper aquifers occur at the contact and weathered surface of the weathered lava.



a)



b)

Figure 4.38: Profile Curve and Profile Map along Musaka Farm

5 DISCUSSION

5.1 Aquifer Transmissivity

The aquifers in the area can be divided into three according based on the borehole depths and penetrated aquifers. These include shallow aquifers with depths ranging from 20-42 m below ground level, moderate aquifers ranging from 62-130 m below ground level and deep aquifers between 167-297 m below ground level. **Figure 5.1** shows the classified aquifers based on the current borehole data.

Ndabibi Area bounded on the west by Mau Forest and Lake Naivasha to the east have an average transmissivity of 544 m^2/day. This is an intermediate transmissivity range in the volcanic terrain. The sub-surface is made up of clay sediments. Transmissivity values increases toward the lake up to 1042 m^2/day, attributed to the presence of weathered rocks or gravel that have high hydraulic conductivity. Boreholes drilling logs in Ndabibi location shows that the sub-surface consists of sandy deposits and clay materials as weathering products of Pyroclastics. Most aquifers are struck at depths between 40 and 60 m below ground level. Possibly, the values and distribution of transmissivity represent borehole properties taping groundwater from shallow aquifers in this area.

The southern parts of the Crescent Lake and areas around Kiambogo location have low transmissivity ranging from 3 to 138 m2/day. It consists of places such as Sakutiek, Maiella and Maraigushu. However, the estimated transmissivity may not be accurate since there are few representative boreholes used in this area. The boreholes with transmissivity values of 20.83, 132.63, 6.53 m2/day have depths of 229, 32 and 78 m below ground level respectively. The large variation is due to depths and aquifers penetrated. For borehole drilled at a depth of 229 m below ground level, an aquifer was struck at 201 m with no encounter of a shallow aquifer, probably due to incomplete recording/reporting during borehole drilling process.

The high transmissivity zone is found north of Lake Naivasha, around Eburru with an average transmissivity of 2000 m2/day. There is high rate of groundwater abstraction in this area due to intense irrigation to support horticulture farming. In addition to faults, the area is located at high altitude and water catchment zones within the basin. Presence of faults in the northern parts controls the flow as discussed in the next section.

Generally, there is high rate of groundwater flow from the recharged zones to areas where the groundwater flow discharges. The high elevation areas such as north of the lake have high pressure that influences the groundwater flow. In Ndabibi area, the area is plain and with very small gradient, but this changes as it approaches the lake. This may indicate a steep gradient toward the lake described by Sikes (1936) in his notes on the hydrogeology of surrounding Lake Naivasha.

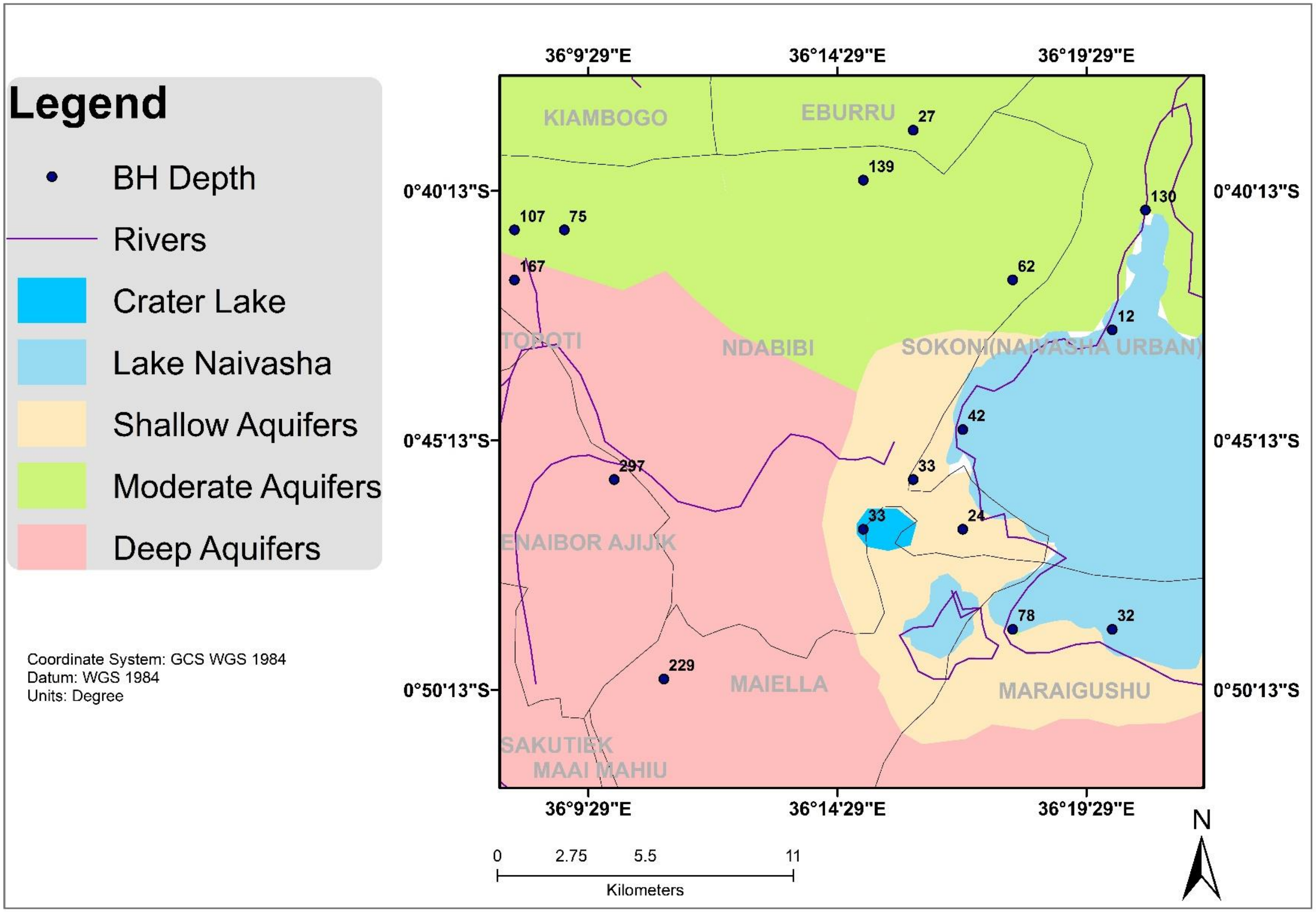


Figure 5.1: Aquifers Classification Map

5.2 Groundwater Flow

The general groundwater flow is toward south west in the western part from Mau escarpment and toward Lake Naivasha as depicted from the piezometric levels in **Figure 4.2**. Within the lowland areas in Ndabibi plain, the groundwater head changes direction with respect to the altitude and orientation of the fault line. The flow follows the fault lines in the southwestern parts and flow toward south.

Faults, which are permeable to groundwater flow, include faults C, F, E and D as labeled in **Figure 4.2**. In these, groundwater flow maintains the direction that is toward west. The groundwater flow is controlled by fault A1 that slightly changes direction to the north toward the fault's orientation and empties its water into the Crater Lake. On the other hand, fault A2 directs the groundwater flow toward Lake Oloiden contrary to A1 while fault B directs the flow toward the southern parts from Eburru hills. This is the same with fault G, oriented in southwest direction and all the groundwater flows in the same direction. The general head of the groundwater flow in the northern parts are in the direction of the general orientations of the faults. There exists a water divide between Lake Sonachi and Lake Naivasha. The hydraulic heads show that some groundwater flows into the Saline Lake while some flows into Lake Naivasha.

Groundwater flow terminates at the faults from the resistivity measurements and geological units discontinuous at the fault lines within Ndabibi area. Shallow structures control surface and groundwater flow. Mwaura (2016) found out that the recharge of groundwater in Eburru Area depends on the pattern of the shallow structures. The shallow aquifers and deeper aquifers (>500m bgl) are connected by the deeper faults (Wanjohi, 2014; Mwaura, 2016). From the groundwater flow direction and resistivity results, it is deduced that the depths to groundwater are influenced by the geological structures and subsurface geology.

Shallow aquifers are found around Lake Naivasha that are underlain mostly by pyroclastics and lake sediments while moderate aquifers are found to the north of the lake, but some patches can be seen in parts of the western area. Northern parts are composed of lake sediments, pumice tuffs, andesites, trachytes and phonolites intercalated by pyroclastics. Aquifers surrounding the lake are highly conductive due to the presence of pumice which is highly permeable (Becht et al., 2005b). This means that the seepage from irrigation waters and introduction of pollutants is envisaged.

The areas bordering Mau forest like Kiambogo and Sakutiek have deeper aquifers, which may be attributed to elevation of the surface and geology. From the geological logs and geo-electric profiles, aquiferous formations are mainly lake sediments, pyroclastics and weathered tuffs.

Tracing Groundwater Flow using Hydrochemical Parameters

The systematic changes in the concentration of Na^{+} ions and Ca^{2+} ions illustrate the general aspect of cation exchange between the two elements. In assuming that the flow path determines the rate of ion exchange, the concentration of these two cations will vary along the path (Varsanyi, 1989). This variation is a factor of time of residence and flow gradient. The study area has varying concentration of both sodium and a calcium ion at the two ends that is, southern and northern parts.

Water in the area is increasing getting highly concentrated in the southern parts compared to the northern parts of the study area. This possibly explains why Lake Oloiden and Sonachi has the elevated values of sodium ions. Most of the groundwater discharges their waters into the two lakes. The mono and divalent ions plotted in the scatter diagram in **Figure 4.17** indicates that there is a progressive exchange of ions favoring the formation of water with more sodium ion in it. This follows the general groundwater flow pattern in the area.

Lithium concentration gradient is also used to identify the flow direction. The areas around the lake where we have shallow aquifers there is low concentration of lithium ions in water. The areas around Lake Sonachi (Crater Lake) and Oloiden (Crescent Lake) have higher values of Lithium ion. The higher values show the areas where groundwater flows toward, the direction of higher concentration gradient. It can be deduced that there exist two flow directions; one is toward Lake Oloiden and the other around Lake Sonachi in Ndabibi plain. From the piezometric heads in **Error! Reference source not found.**, the flow from the western flanks of Mau Forest and north of the study can be seen to be converging around these two points. The southern being influenced majorly by the faults marked A-A (see **Figure 4.2**).

Sodium ion shows low concentration around the lake and increases slowly as one moves to the west where there is high concentration bounded on the western flanks of Mau Forest constituting low concentration again. This has high correlation with the transmissivity map with similar distribution. Sodium has strong correlation with sulphate, chloride and fluorine (correlation co-efficients of 0.71, 0.80 and 0.71 respectively) distribution in the area. For the groundwater flow, there is general convergence of flow of groundwater into the Plain before low flow gradient into Lake Naivasha. There is groundwater flow convergence around the two smaller lakes: Lake Sonachi and Lake Oloiden.

The areas of low concentration of sulphate ion in water correspond to the areas of high transmissivity of groundwater. This is true on the northern parts of the lake except on the western area. It is attributed to high abstraction rates of groundwater from boreholes and shallow wells support farming activities in these areas.

5.3 Geophysical Interpretation Summary

Zone A

The areas around Lake Sonachi and areas north of Oloiden Lake. From the geophysical data, deeper aquifers occur at depths between 180 and 240m bgl within the weathered pyroclastic materials and lake sediments in some instances. Most of the localized aquifers occur in pockets of weathered tuffs/pyroclastics materials. These pockets of secondary minerals also exist around Eburru area, characterized by low resistivity to depths greater than 300m (Mwaura, 2016). The shallow aquifers exist at depths varying between 30 and 60m within lake sediments. Pumiceous tuffs have an average thickness of 55m north of the crater lake. The formation is underlain by pyroclastics or lake sediments, which in turn overlies the phonolites/trachytes at greater depths (150-270 m bgl). The pumice content in the aquifers makes it high permeable and this allows the flow to deeper aquifers if the shallow aquifers are semi-confined (Becht et al., 2005; Mwaura, 2016). The last layer detected were pyroclastics, continuing to depths greater 300m. The fault identified along Mereroni Profile (**Figure 4.30**) controls the flow of water from the tapering River Mereroni to underground aquifers. Fault zones are filled with weathered formations and which acts as conduits to groundwater flow to deeper structures as also found in the resistivity measurements by previous studies (Mwaura, 2016; Mwangi and Bromley, 1986).

Zone B

Black clay soil is the uppermost layer underlain by a thin sheet of tuff of about 10m in some places. This overlies lacustrine sediment/unconsolidated materials with an average thickness of 120m. The lacustrine deposits rests on weathered on phonolites and trachytes at depths between 130 and 240 m bgl followed by weathered pyroclastics/sediments. The shallow aquifers are found at depths between 35 and 60 m bgl within lake sediments or pyroclastics while deeper aquifers range from 150 to 250 m bgl within weathered pyroclastics/fractured phonolites. The shallow structures correlate with what Mwaura (2016) found within Eburru area, these shallow structures direct flow to deeper flow to greater depths (> 1000m bgl). He further suggested that deep faults in Eburru connects both shallow and deeper aquifers. This is possible where the faults are filled by permeable materials. Recharging the deeper aquifers depends on the patterns of the shallow structures within Eburru (Clarke et al., 1990; Pastor, 2001).

Zone C

This zone covered the southern parts of the study area and south of Lake Naivasha. The uppermost layer is clay soil and followed by a thick layer of pyroclastics of an average of about 130m thick underlain by basalts of about 100m thick. The tuff formations are found at around 120 to 180 m bgl in some places according to the borehole logs analyzed for S.M (see **Figure 4.5**). The deeper aquifers are found between 200 and 280m within weathered pyroclastics/basalts and tuffs. However, deeper flows are expected below 500m depth. According to Wanjohi (2014), most faults are concealed by volcanics. Nyakundi et al. (2017) in the study within the rift found out that deeper faults at the rift scarps directs the surface flow to deeper flow.

5.4 Surface and Groundwater Interactions

Indicators of Interaction between Surface and Groundwater

The best hydrochemical ion used to show the interactions between surface and groundwater is by comparing the concentration of Cl^- and NO_3^-, which shows up-downward flow direction depending on the levels of surface water concentration and the surrounding groundwater levels. The two ions are used to show the vertical movements due to their high solubility rates (Meijia et al., 1998).

Lake Sonachi and Oloiden have higher concentration of chloride ions. Lake Sonachi has an average value of 200 mg/L while Lake Oloiden has an average of 178 mg/L with a maximum value of 221 mg/L. River Marmanet that terminates its water into Ndabibi Plain have maximum value measured as 33 mg/L. The boreholes around the two lakes have higher values compared to other boreholes in the surrounding study. Their values range between 35 and 50 mg/L of chloride from the borehole sampled near these lakes compared to other areas, which are less than 23mg/L. Boron concentration also show a similar pattern in the groundwater with southern parts having higher elevated values (48 µg/l).

The nitrate levels within these two lakes are slightly high values between 2.5 to 5 N mg/L compared to other areas that have less than 1.0 N mg/L. These two elements clearly suggest that there is mixing between the surface and groundwater between the lakes and the surrounding groundwater. The lakes may be acting as the outcrops of the groundwater aquifers while River Marmanet recharges the shallow aquifers within Ndabibi Plain that finally discharges into Lake Sonachi?

Geochemical Processes

Hydrochemical facies result from precipitation and evaporation rates, lithology, and solution kinetics and groundwater flow pattern (Olago et al., 2009; Tiwari and Singh, 2014). The ratios of Na/Cl and Ca/SO_4 for rivers, lakes and groundwater are used to determine the possible source of major elements on water. Na, F and SO_4, which are highly correlated in the groundwater, possibly derived from the soda-rich volcanic and Pyroclastics while Na, F, Cl and NO_3 correlation in groundwater may be due to the infiltration of surface soils (Olago et al., 2009; Hounslow, 1995). The increase of sulphate and chloride toward the rift is also attributed by the natural evolution of the chemicals from the highlands. It is a trend witnessed in the water around Afar in Ethiopia (Ayenew, 2005).

The weathering of silicate rocks is the main controlling factor of ionic concentration in the groundwater (e.g. Hounslow, 1995; Morgan, 1998; Olago et al., 2009; Tiwari and Singh 2014; Li et al., 2018). When the source of Na in the water is not halite, the molar ratio of Na/Cl will be greater than one. The ratio of Na: Cl in the area for groundwater ranges from 3 .13 to 10.40, with the sum average of 5.74. This is an indication of other sources of Na^+ other than halite (Hounslow, 1995; Morgan, 1998). In this case, the source could be from the albite (plagioclase). According to Li et al (2018), excess of Na ions in water, is due to the cation exchange from clay particles as water flow with Ca or Mg ions.

While the ratio of Ca: SO_4 ranges from 0.04 to 4.52 with sum average of 1.07, this is an indication that Ca is derived from mainly two sources: oxidation of pyrite or removal of Ca due to ion exchange or derived from silicates/dolomite/calcite. In this case, the source of Ca is mainly from silicates as the source rock. From the sodium and calcium exchange analyzed to determine the groundwater flow, cation exchange can be the source, an idea supported from the study carried out by both Morgan and Olago within the rift.

The well near Lake Oloiden with Na/Cl of 6.62 resembles that of Lake Oloiden with an average ratio of 6.50. Lake Sonachi water on the other hand has an average value of Na: Cl of 6.7 with the lowest value of 5.6 and maximum value of 7.9, which resembles the boreholes (Na: Cl, 5.97) around it. River Marmanet, which could be possibly recharging the nearby lake, has an average value of 2.79 resembling that of Lake Naivasha in terms of the source with an average value of 2.91. This suggests that the groundwater feeds the two lakes but does not receive water from Lake Naivasha. Therefore, Lake Naivasha may not be acting as the groundwater outcrop from the surrounding aquifers as suggested before in the previous studies.

Boreholes found in the deeper aquifers have higher Na/Cl ratio and these include Burji Ranch (4.4), N. Farm (7.4), S.M BH (9.4), Aquila BH (8.9) and K.P House (10.3). On the other hand, shallow aquifers have the values ranging from 3.1 to 4.8 except the boreholes around Lake Oloiden and Crater Lake. The shallow aquifers close to the lake have water resembling in terms of evolution considering Na/Cl. An example is K. BH (3.1), P. K.P BH (4.6) and Kiangazi Power Gate BH (3.7). This indicates that the groundwater close to Lake Naivasha are fresh compared to the ones around the Crater Lake and Oloiden are more alkaline.

Using the rationing reasoning, considering the ratios of Ca: SO_4, according to Hounslow (1995), when the ratio Ca>SO_4 then the source of Ca in the groundwater is possibly from silicates, dolomite or calcite rather than gypsum. In this case, the average value is 1.07 suggesting that the source of Ca is silicates. The geochemistry of the groundwater of the groundwater reflects the volcanic mineralogy within the area where the composition of rhyolitic is responsible for the presence of Na+ and Ca+. These are derived from the pantellerites and commendites, which formed trachytes/andesites and pumice that weather to produce to smectites clays dissolving in the groundwater producing Na-Cl or Ca-Cl type of water within the study area. In the southern parts where we have basalts penetrated by the drilled boreholes, weathering of the plagioclase feldspars could be the source of these mineral in the groundwater.

Fluoride is derived mostly from the rocks with fluoride minerals such as muscovite, fluorite, biotite as the main natural sources. In the rift, the source is mainly from the weathering by dissolution from fluoride rich minerals (Olaka et al., 2016; Appelo and Postma, 1996). Negative correlation with Mg/Ca may be due to solubility to the natural groundwater flow (Handa, 1975; Hem 1991). Olaka et al. (2016), analyzed the rocks in the area around Eburru and Oloiden, found out that the source rocks for F^-, include muscovite, cordierite and kaolinite derived from weathered sediments, pyroclastic and obsidian. From the borehole logs and resistivity measurements, the main source rocks of fluoride could be pumice layers and obsidian formations within the study area. Additionally, the fluoride ca be added into the groundwater during the time when Ca+ are removed from solution. The groundwater values are low compared to the two lakes with a median value of 6 mg/L. Lake Sonachi have higher values (average of 69 mg/L) and Lake Oloiden (41 mg/L) contrary to low values in Lake Naivasha (average of 2.0 mg/L and Marmanet River (4.0 mg/L).

Geological logs around Lake Sonachi shows that the subsurface is composed of pumice overlying weathered pyroclastics which are underlain by the obsidian rocks. This is the same formation on the southern parts of Oloiden Lake for the two boreholes that is Kenya Society and Moi South Lake Rd (see **Figure 4.4**).

Physical Parameters

The pH for groundwater ranges from 6.57 to 9.0 with an average value of 8.2, suggesting a neutral to alkaline in nature of the groundwater. The neutral groundwater occurs on the boreholes drilled around Lake Naivasha (see **Figure 4.20**). For the two lakes, the maximum value is 10 while the minimum is 9.7 with an average of 9.9. For Lake Naivasha, the 7.4 to 8.3 with an average value of 8.1. This suggests that the water is alkaline. For river Marmanet and Wiley House River, the pH changes with season, the measured values have an average value of 8.3.

This clearly shows that the two lakes have higher pH compared to the surrounding groundwater and river water. The dissolved substance and the rate of evaporation influence the pH. Lake Sonachi and Oloiden are more alkaline compared to Lake Naivasha water. The pH could change for the surface waters, depending on the dry and wet seasons due to changes in the rate of dissolution. The alkaline nature accelerates the mobilization of F^- from the minerals composed of fluoride mineral. The Na: Ca (> 7) and the alkaline nature favor the dissolution of fluoride bearing rocks (Tiwari and Singh, 2014). The loss of Ca/Mg in the groundwater may be attributed to the pH of the waters, specific geology and cation exchange (Morgan, 1998; Olago et al., 2009).

Groundwater tends to have stable temperatures compared to surface waters. Higher temperature values were measured on the northern parts of the area (areas of deeper aquifers) and decreases gently toward the lakes. Around Lake Naivasha the maximum value in the borehole is 21 °C. The temperatures range from 19.3 to 27.7 °C for groundwater with an average of 22.7 °C while the river water temperatures have an average value of 18.0 °C. Lake Sonachi and Lake Oloiden have 23.5°C and minimum and maximum values are 21.8 and 28.2 °C respectively. For Lake Naivasha, the average value of temperature recorded was 20.3 °C, correlating with the groundwater temperatures around the lake for the shallow aquifers. It is worth noting that the temperatures for Lake Naivasha water vary depending on the point where the water sampled was taken. The northern parts of the lake are recharged by the two major rivers: River Malewa and River Gilgil.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The study found out that the localized aquifers are influenced by shallow explored structures and the sub-surface geology. Groundwater flow are influenced by the existence of network of faults around Eburru area and buried faults within Ndabibi Plain. Electrical potential measurements carried out within Ndabibi Plain, identified three faults only to a maximum depth of 300m, these faults and fractures divert surface flows to shallow and deeper aquifers. Aquifers explored terminate at the fault lines and where there are intercalations of impermeable unconsolidated materials within the regional geology. The two factors explain the presence of pockets of isolated saline aquifers within fresh water aquifers. Deeper penetrated aquifers are situated south of Lake Naivasha and high-altitude areas bordering Mau Forest with depths between 200-280 m below ground level. These aquifers penetrate fractured volcanic rocks and weathered Old Land Surfaces.

The general groundwater flow is toward south west, from Mau Escarpment toward Lake Naivasha. The groundwater flow map developed is an updated map from Clarke et al, (1990) and will be useful in tracing pollutants within the western parts of Lake Naivasha. Faults labelled C, D, E, F and G are permeable to groundwater flow and therefore allows the continuous flow of groundwater. Faults A1, A2 and B oriented in north south direction, influences the groundwater flow to northern parts and southern parts respectively. The hydraulic heads show that some groundwater flows into the Saline Lake while some flows into Lake Naivasha. The two waters are hydraulically separated by a dyke and do not resemble in chemistry. The shallow faults connect shallow aquifers with deeper aquifers and this may aid the transport of pollutants further south from the northern parts where major agricultural activities take place. The faults are expected to control the groundwater flow at greater depths (> 500m) around Eburru and southern parts in Maiella Area, where groundwater occurs at great depths.

The lowland areas have low transmissivity values compared to the highland areas. The northern parts of Lake Naivasha have the highest transmissivity values (average of 2000 m2/day) attributed to the steep slopes and agricultural activities and network of faults. The western parts near Lake Naivasha have moderate values (138-1042 m2/day) while southern and areas bordering Mau Forest have lower transmissivity values (<138 m2/day). The aquifers around Lake Naivasha are highly conductive due to the presence of pumice that is highly permeable, the flow of surface water into shallow aquifers due to irrigational activities is envisaged. There should be proper management strategies to protect the vulnerable groundwater aquifers in areas where we have direct recharge from the surface waters and at the same time protecting available fresh water aquifers surrounding Lake Naivasha and ones occurring within the pockets of impermeable materials from pollution. River Mereroni is an example of a possible chain in which pollutants may reach shallow aquifers around and deeper aquifers in the south.

Geochemical parameters including Li, B, Na, Ca, Cl and NO_3 has been used to show the interactions and groundwater flow directions within the study area and possibly first within the Central Kenya Rift (CKR). Using lithium ion, two flow direction are realized; one is toward Lake Oloiden and the other around Lake Sonachi in Ndabibi plain. These two directions are influenced greatly by faults A1 and A2. The boreholes around the two saline lakes (Lake Sonachi and Oloiden) are hydraulically connected with the surrounding groundwater. Shallow aquifers around Lake Naivasha are connected with it. Lake Naivasha surrounding aquifers recharges or discharges the lake water depending on the lake water level. Both the waters are similar and water quality deteriorates as one approaches the two smaller lakes. From the sodium and calcium exchange analyzed to determine the groundwater flow, cation exchange is the main source, an idea supported from the study carried out by both Morgan and Olago within the rift.

6.2 Recommendations

The study focused on characterizing groundwater resources and the influence of faults on the groundwater flow in the western parts of Lake Naivasha.

The following are recommended to be done in the subsequent studies and to improve the management of groundwater resources in the study area: -

1. Constructing more monitoring boreholes close to Lake Naivasha to help in understanding the exchanges between Lake Naivasha and the surrounding aquifers due to the dynamic changes of the lake level.
2. Monitoring groundwater water chemistry especially nitrogen components released into sub-surface in the northern parts of Lake Naivasha where intensive agricultural activities takes place to avoid the groundwater pollution. This will ensure a trend in the analysis.
3. The deeper aquifers ranging between 180 and 240 m bgl can be assessed for groundwater abstraction to avoid the depletion of shallow aquifers within Ndabibi Plain.
4. Assessing the effects of seismic waves on faults in the scenarios when they occur since the area is within the active rift and how that will influence the groundwater resources within the study area.

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APPENDICES

Appendix 1: Borehole Data Used

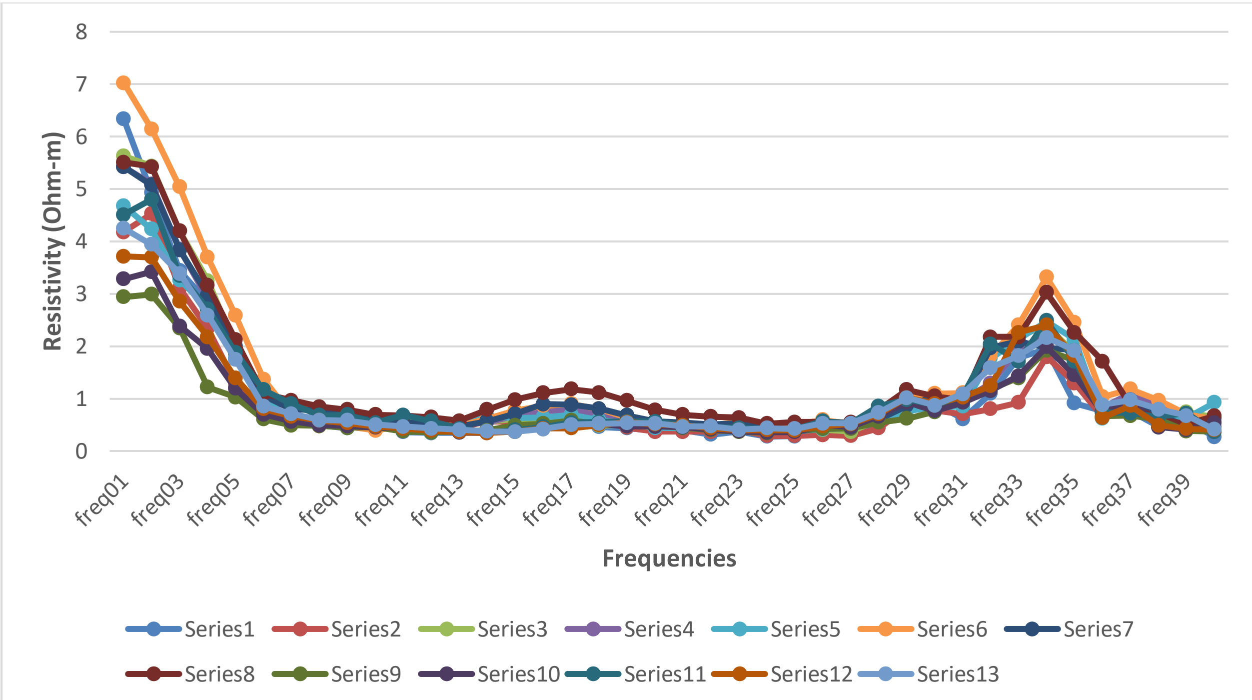
Owner	Location	x	y	ID	Alt (m)	TD (m)	M WSL (m)	WSL 1 (m	WSL 2 (m	WRL	Yield (m3/hr)	s (m)	Sp. Capacity	Transmissivity (m3/day)
MAIELLA ESTAT	NAIVASHA.LR1380	36.1833	-0.8333	C-2709	2133	229	216	201	0	196	4.98	7	17.07428571	20.83062857
NDABIBI ESTAT	NAIVASHA.LR.7281	36.15	-0.6833	C-3164	2484	75	55	0	0	19	5.4	2.7	48	58.56
KONGONI FARI	NAIVASHA.LR.7276	36.2667	-0.65	C-2701	1890	27	48	15	0	7	31	4.6	161.7391304	197.32
YUANMI	NAIVASHA.LR.6854/9	36.2833	-0.7833	C-2659	1890	24	9	0	0	8	27	3	216	263.52
CAPT.TAILBY G.	NAIVASHA.LR.6525	36.25	-0.7833	C-2657	1890	33	30	0	0	23	13.68	1.8	182.4	222.53
YUANMI	NAIVASHA.LR.6524/8	36.2667	-0.7667	C-2661	1890	33	20	0	0	21	31.86	2.4	318.6	388.69
NDABIBI FARM	NAIVASHA.LR.6233	36.1333	-0.6833	C-3024	2438	107	95	0	0	93	3	7	10.28571429	12.55
LOLDIA LTD	NAIVASHA.LR.419	36.3333	-0.7167	C-2539	1905	12	0	0	0	5	9.06	3	72.48	88.43
W.C.COOPER	NAIVASHA.LR.404/4	36.3333	-0.8167	C-2015	1890	32	18	0	0	12	9.06	2	108.72	132.64
OSSERIAN	NAIVASHA.LR.1340/R	36.3	-0.8167	C-2069	1890	78	76	54	48	46	4.02	18	5.36	6.54
LOLDIA ESTATE	NAIVASHA LR.418	36.3	-0.7	C-2706	1920	62	39	0	0	39	27.18	0.3	2174.4	2652.77
COMMISIONER	NAIVASHA	36.25	-0.6667	C-4600	1920	139	101	0	0	45	9	80	2.7	3.29
NDABIBI ESTAT	NAIVASHA	36.1333	-0.7	C-3932	2255	167	161	131	0	125	8.1	9.1	21.36263736	26.06
KARONGO FAR	NAIVASHA	36.2833	-0.75	C-2304	1935	42	8	0	0	5	49.5	2.1	565.7142857	690.17
MIRERA MIGAA	MIGAA	36.3444	-0.6767	C-9345	1950	130	100	70	115	71	7.2	0.1	1728	2108.16
		36.1667	-0.7667	C-4897	2103	297	267	0	0	213	39	6	156	190.32

Appendix 2: Borehole Data

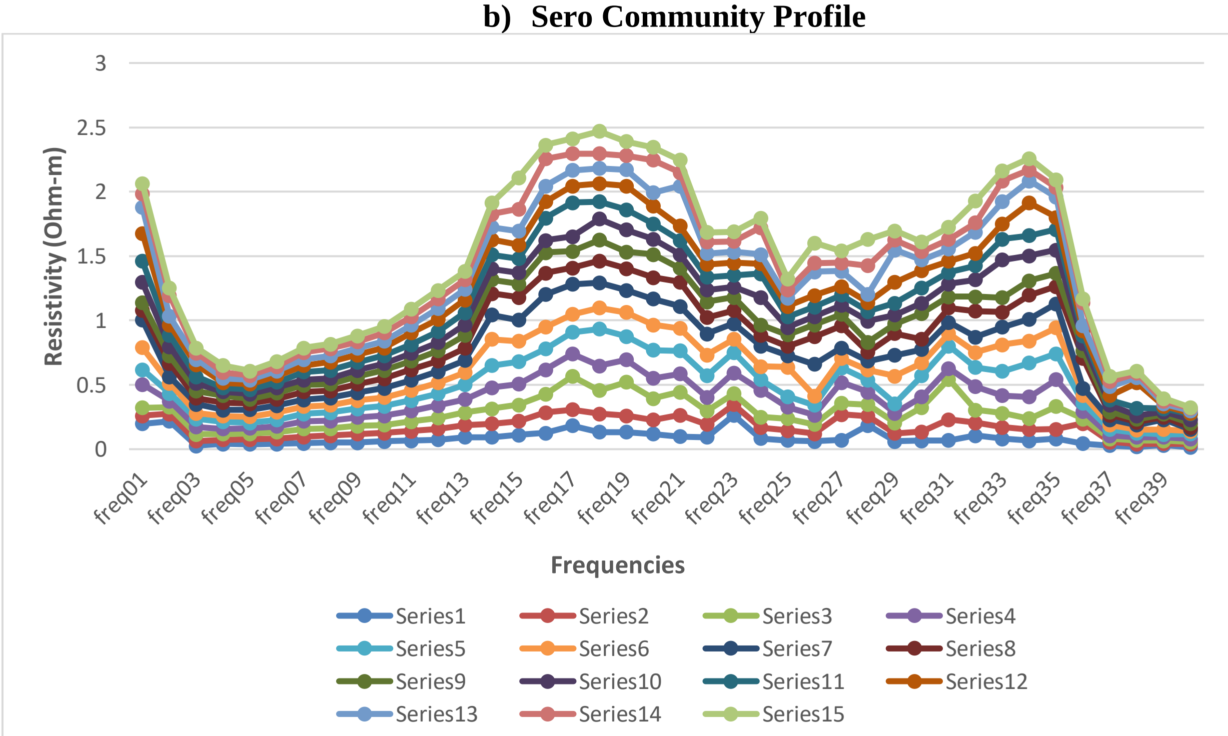
OWNER	x	y	ID	LOCALITY	MAPNO	LONGI	LAT	GRIDY	TDEPTH	CONT	GRAVEL	DCASING	LCASING	M_WSL	O_WSL1	O_WSL2	WRL	TESTDATE	HRS	YIELD	DRAWDOV	RECOVERY
KONGONI	36.2625	-0.825	11033	SOUTH LA	133/4	361545	4930	0	52	808	Y	203	42	0	21	0	20	34707	12	28.02	0	0.1
CRANCH E	36.2333	-0.7833	1405	RONDIAN	133/3	36	-1	9913326	147	120	N	152	18.3	134	0	0	77	18485	15	4.56	0	0
EGERTON	36.2667	-0.8333	4503	NJORO	119/2	355552	-2207	0	112	0		152	0	90	0	0	50	0	4	2.52	0	0
LEREMATE	36.2667	-0.8333	4501	NDABIBI E	133/4	36	-1	9907796	61	0		254	0	42	0	0	15	0	6	0	0	0
KAMAU H	36.2833	-0.75	8996	NDABIBI	133/2	361631	-1	0	61	0		31	0	48	0	0	9	0	1	40.62	11	0
G.D.P.COL	36.2167	-0.7333	2241	NDABIBI	133/1	36	-1	9918857	148	120	N	152	77	121	0	0	107	19922	11	9.06	0	0
M.ROCCO	36.2833	-0.7167	631	NAVAHSA	133/4	36	-1	9920698	46	120	N	152	23.1	33	27	0	27	17488	5	8.1	0	0
MR ANDRI	36.2833	-0.85	2886	NAKURU	133/4	36	-1	9905949	939	120	N	0	0	0	0	0	0	0	0	0	0	0
COUNTES	36.2667	-0.8167	137	NAIVASHA	133/4	36	-1	9909632	0	120	N	0	23	0	0	0	0	15752	24	1.86	0	0
TARA	36.2333	-0.7167	2521	NAIVASHA	133/1	36	-1	9920695	104	24	N	152	56	100	0	0	75	20553	0	11.34	0	0
MAIELLA E	36.1833	-0.8333	2709	NAIVASHA	133/3	36	-1	9907789	229	24	N	203	229	216	201	0	196	20995	32	4.98	7	0
KAMERE E	36.3167	-0.8167	3616	NAIVASHA	133/4	36	-1	9909636	57	120	N	203	19	24	0	0	22	24736	0	0	0	0
NDABIBI E	36.15	-0.6833	3164	NAIVASHA	133/1	36	-1	9924385	75	120	N	152	6.4	55	0	0	19	22712	4	5.4	2.7	0
KONGONI	36.2667	-0.65	2701	NAIVASHA	133/2	36	-1	9928078	27	24	N	152	18	48	15	0	7	21757	9	31	4.6	1
KONGONI	36.2667	-0.8	3767	NAIVASHA	133/4	36	-1	9911480	72	120	N	0	0	37	27	2	27	26079	0	10.92	0	0
YUANMI	36.2833	-0.7833	2659	NAIVASHA	133/4	36	-1	9913329	24	24	N	254	24	9	0	0	8	20885	16	27	3	1
CAPT.TAIL	36.25	-0.7833	2657	NAIVASHA	133/3	36	-1	9913327	33	24	N	152	32	30	0	0	23	20927	12	13.68	1.8	1
YUANMI	36.2667	-0.7667	2661	NAIVASHA	133/4	36	-1	9915165	33	24	N	254	33	20	0	0	21	20916	12	31.86	2.4	1
NDABIBI F	36.1333	-0.6833	3024	NAIVASHA	133/1	36	-1	9924384	107	47	N	152	3.6	95	0	0	93	22040	18	3	7	0
NDABIBI F	36.1333	-0.7	3032	NAIVASHA	133/1	36	-1	9922536	229	47	N	0	0	42	0	0	40	22022	24	0.9	0	0
B.L.TURNE	36.3333	-0.8167	2071	NAIVASHA	133/4	36	-1	9909637	18	120	N	152	12	16	0	0	12	19637	10	4.02	0	0
GREEN PA	36.3333	-0.6833	3674	NAIVASHA	133/2	36	-1	9924397	31	120		203	12	6	0	0	6	25678	0	22.56	0	0
LOLDIA LT	36.3333	-0.7167	2536	NAIVASHA	133/2	36	-1	9920702	10	24	N	152	3	5	0	0	5	20631	4	11.4	0	0
LOLDIA LT	36.3333	-0.7	2535	NAIVASHA	133/2	36	-1	9922549	13	24	N	152	6	7	0	0	7	20628	1	13.62	0	0
LOLDIA LT	36.3333	-0.7167	2539	NAIVASHA	133/2	36	-1	9920702	12	24	N	203	1.5	0	0	0	5	20637	2	9.06	3	0
LOLDIA LT	36.35	-0.7167	2537	NAIVASHA	133/2	36	-1	9920703	16	24	N	254	16	8	0	0	3	20633	1	13.62	0	0
LOLDIA LT	36.3167	-0.7167	2538	NAIVASHA	133/2	36	-1	9920701	14	24	N	152	6	12	0	0	10	20635	1	13.62	0	0
TARA	36.25	-0.7333	2522	NAIVASHA	133/1	36	-1	9918859	52	24	N	203	52	51	0	0	46	20573	7	12.6	0	3
TARA	36.3	-0.7167	2523	NAIVASHA	133/2	36	-1	9920700	57	24	N	152	35	53	32	0	30	20603	0	9.06	0	0
LOLDIA ES	36.35	-0.7167	2703	NAIVASHA	133/2	36	-1	9920703	31	24	N	203	15	3	0	0	3	20944	3	28.26	0	0
W.C.COOI	36.3333	-0.8167	2015	NAIVASHA	133/4	36	-1	9909637	32	120	N	152	12	18	0	0	12	19479	8	9.06	2	0
OSSERIAN	36.3	-0.8167	2069	NAIVASHA	133/4	36	-1	9909635	78	120	N	152	76	76	54	48	46	19626	0	4.02	18	0
KORONGC	36.2833	-0.75	1464	NAIVASHA	133/2	36	-1	9917014	31	120	N	152	11	11	0	0	8	18332	5	12.72	0	0
LOLDIA ES	36.3	-0.7	2706	NAIVASHA	133/2	36	-1	9922547	62	24	N	203	0	39	0	0	39	21044	6	27.18	0.3	0
LT.COL.RO	36.2833	-0.7167	2813	NAIVASHA	133/2	36	-1	9920698	63	120	N	32	14	63	46	0	41	21380	8	13.5	0	0
DEVILLIER	36.3333	-0.8167	578	NAIVASHA	133/3	36	-1	9909637	33	120	N	152	31	20	0	0	20	17430	6	8.04	0	0
NDABIBI E	36.2167	-0.7667	1404	NAIVASHA	133/3	36	-1	9915161	105	120	N	203	96.7	85	0	0	59	18691	24	13.62	0	0
TAILBY G.\	36.2667	-0.8	563	NAIVASHA	133/4	36	-1	9911480	31	120	N	152	12	21	0	0	7	17371	3	6.24	0	0
NDABIBI E	36.2167	-0.75	466	NAIVASHA	133/2	36	-1	9917009	79	120		152	77.1	53	0	0	50	17071	24	8.16	0	0
OSSERIAN	36.2833	-0.85	630	NAIVASHA	133/4	36	-1	9905949	114	120	N	152	114.3	119	104	0	99.4	17469	12	3.6	0	0
MAJOR W	36.3167	-0.8	579	NAIVASHA	133/4	36	-1	9911484	43	120	N	152	49	27	0	0	22	17423	7	6.84	0	0
OSSERIAN	36.3	-0.8167	581	NAIVASHA	133/4	36	-1	9909635	31	120	N	101	14	27	0	0	23	17360	4	7.2	0	0
LEREMATE	36.2667	-0.8333	4500	NAIVASHA	133/4	36	-1	9914350	61	0		254	0	42	0	0	15	0	24	19.5	0	0
GREEN PA	36.2667	-0.8333	4504	NAIVASHA	133/2	36	-1	9925900	130	0		33	0	35	0	0	11	0	0	8.22	0	0
COMMISIC	36.25	-0.6667	4600	NAIVASHA	133/2	36	-1	9926229	139	0		203	0	101	0	0	45	0	90	9	80	8
TARA FAR	36.3	-0.7167	3064	NAIVASHA	133/2	36	-1	9920700	18	120	N	0	0	15	0	0	15	22137	0	0	0	0
NDABIBI E	36.1333	-0.7	3932	NAIVASHA	133/1	36	-1	9922536	167	120	N	152	61	161	131	0	125	26789	5	8.1	9.1	0
CHELINDA	36.2833	-0.7167	2705	NAIVASHA	133/2	36	-1	9920698	31	24	N	203	30	19	0	0	17	21025	7	10.26	0	0
BALFOUR	36.2667	-0.8667	2885	NAIVASHA	133/4	36	-1	9904100	377	120	N	0	0	0	0	0	0	0	0	0	0	0
MAIELLA E	36.1833	-0.8167	2042	NAIVASHA	133/3	36	-1	9909626	192	120	N	0	0	0	0	0	0	19565	0	0	23	0
KARONGC	36.2833	-0.75	2304	NAIVASHA	133/2	36	-1	9917014	42	120	N	254	40	8	0	0	5	20066	14	49.5	2.1	0
NDABIBI	36.2167	-0.8167	2300	NAIVASHA	133/3	36	-1	9909628	113	120	N	152	113	113	0	0	101	20046	6	9.54	0	4
MIRERA M	36.3444	-0.6767	9345	MIGAA	133/2	362040	4036	0	130	91	Y	152	123	100	70	115	71	33491	24	7.2	0.1	0.1
MARDON	36.2667	-0.65	704	EBURU	133/2	36	-1	9928078	152	120	N	152	42	0	0	0	0	0	0	0.36	0	0
MARDON	36.2667	-0.65	707	EBURU	133/2	36	-1	9928078	103	120	N	152	24	0	0	0	0	0	0	0	0	0
	36.3333	-0.8333	1751		133/4	36	-1	9907801	92	0		0	0	23	0	0	0	0	0	0	0	0
	36.35	-0.8333	594		133/4	36	-1	9907802	34	0		152	0	18	0	0	16	0	12	7.98	0	0
	36.1667	-0.7667	4897		133/3	36	-1	9915158	297	0		152	0	267	0	0	213	0	24	1.68	39	6

Appendix 3: Geophysical Measurement Curves

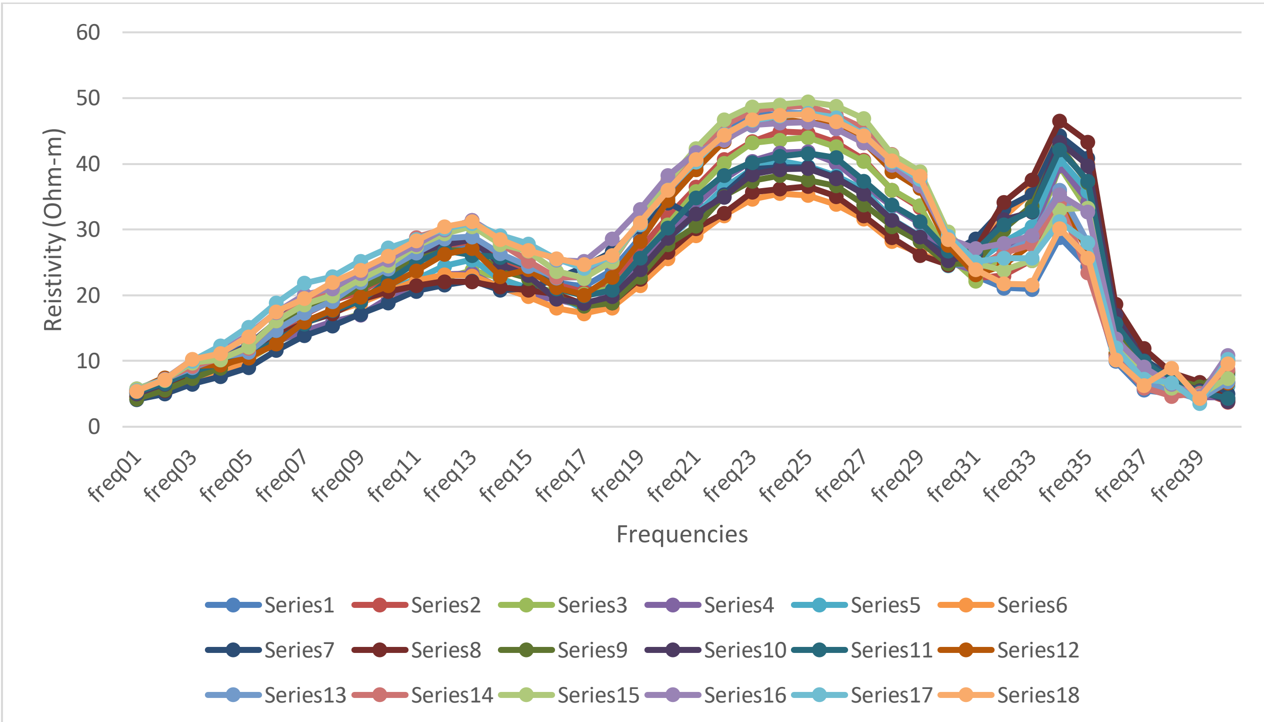
a) C.T Profile



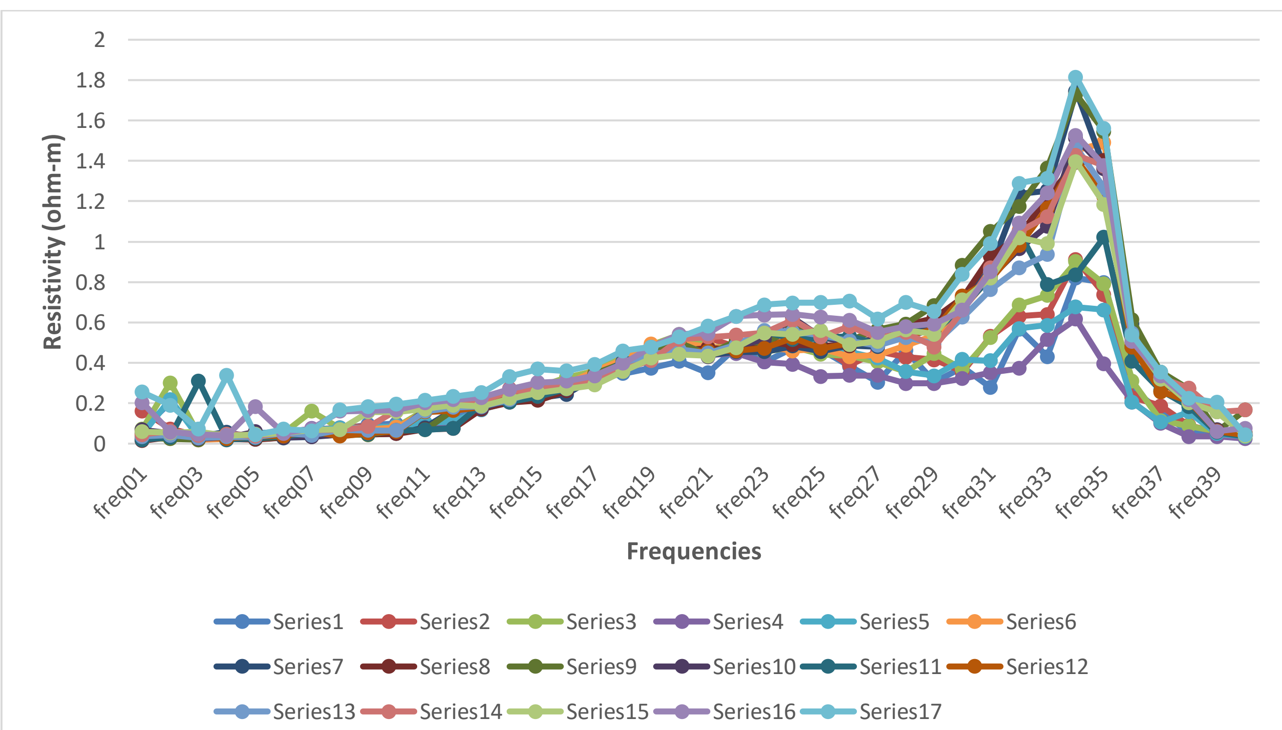
b) Sero Community Profile



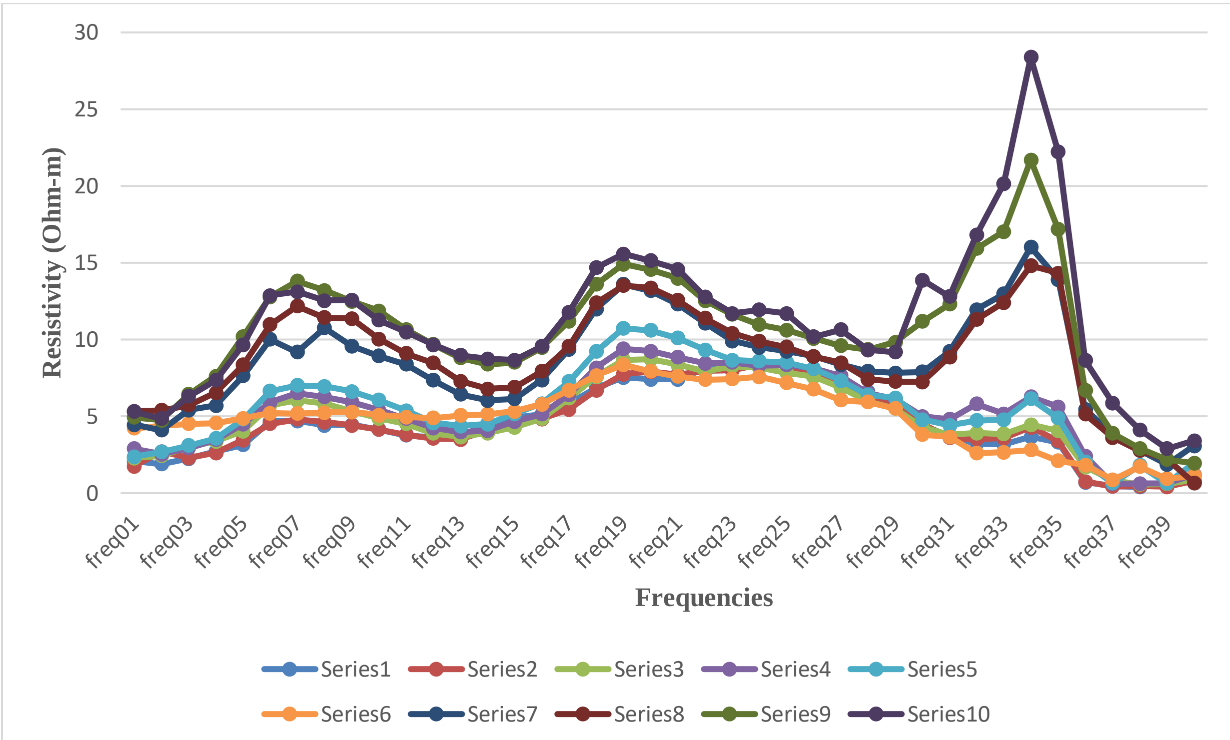
c) L. Estate Profile



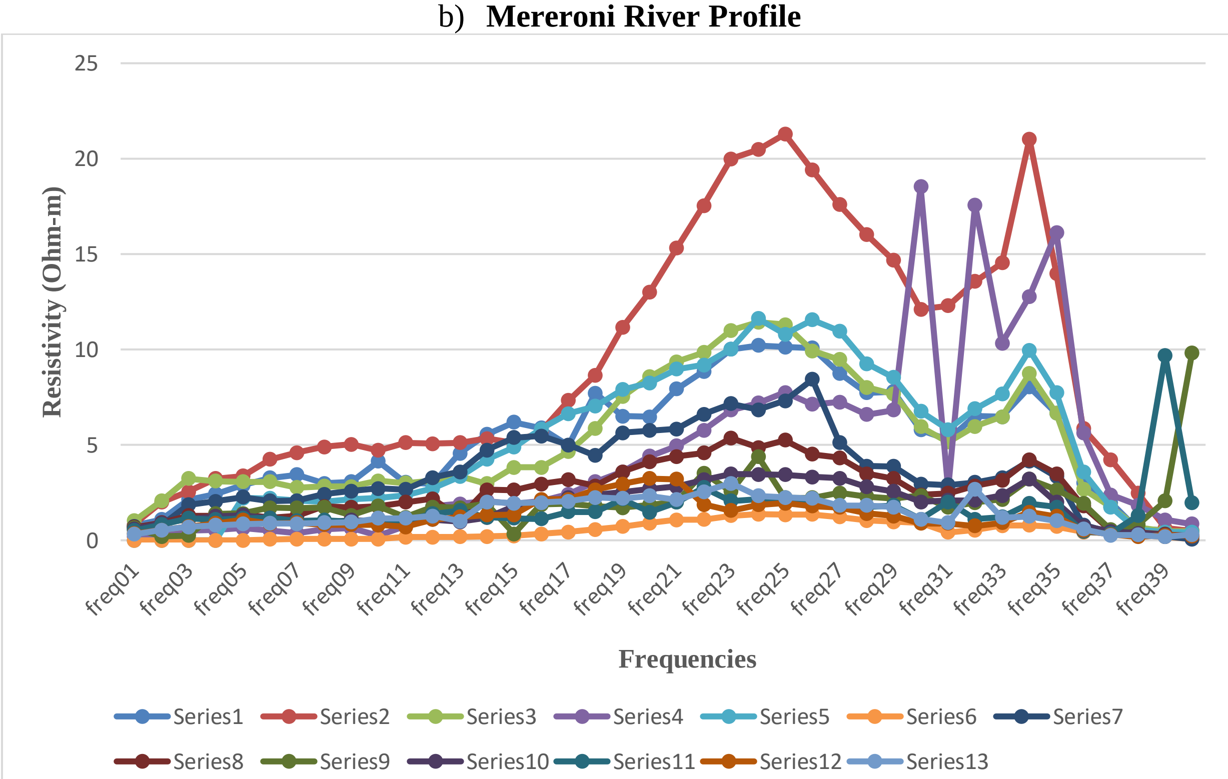
d) N. Farm Profile



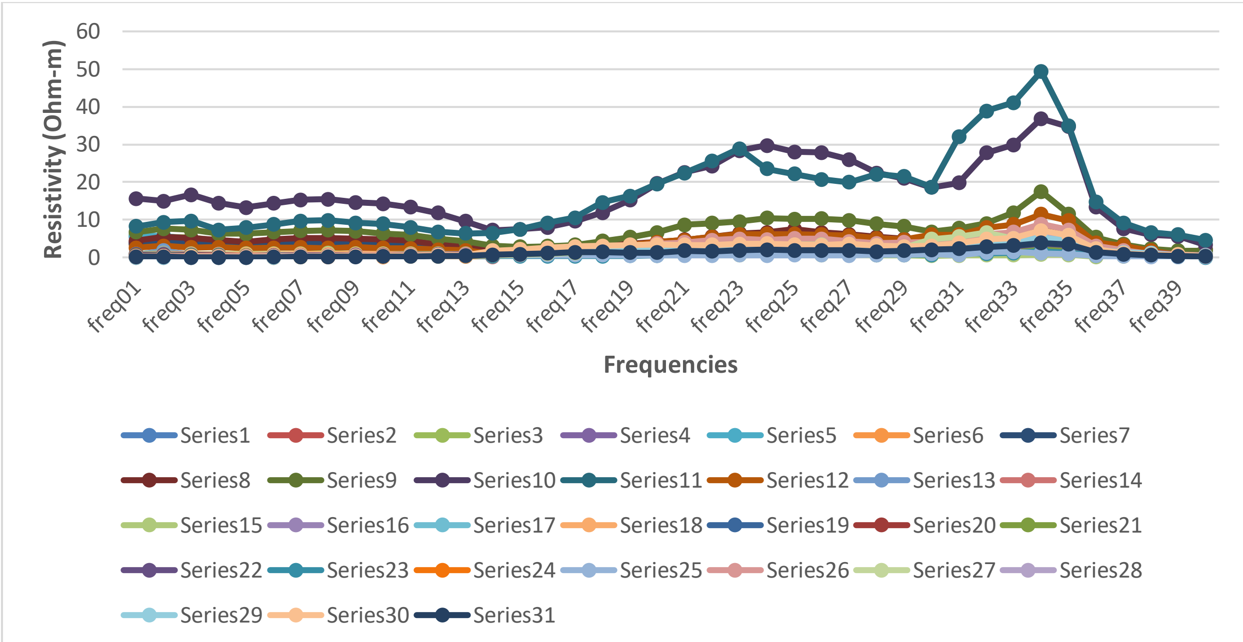
a) Aquila Farm Profile



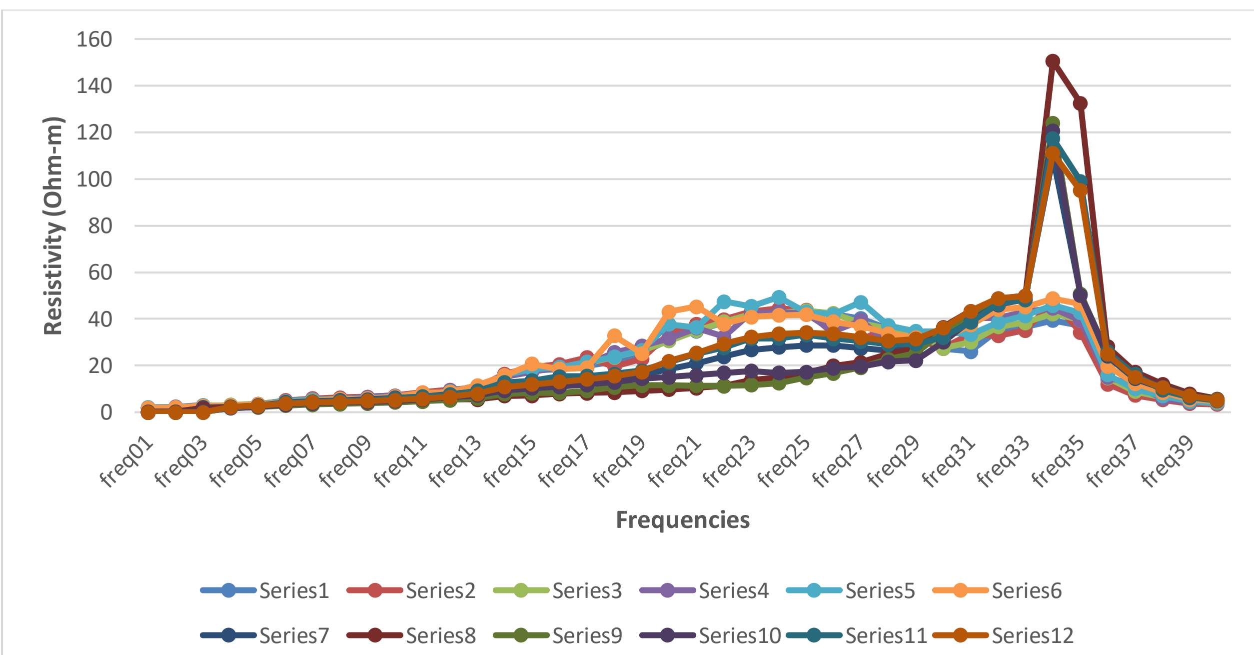
b) **Mereroni River Profile**



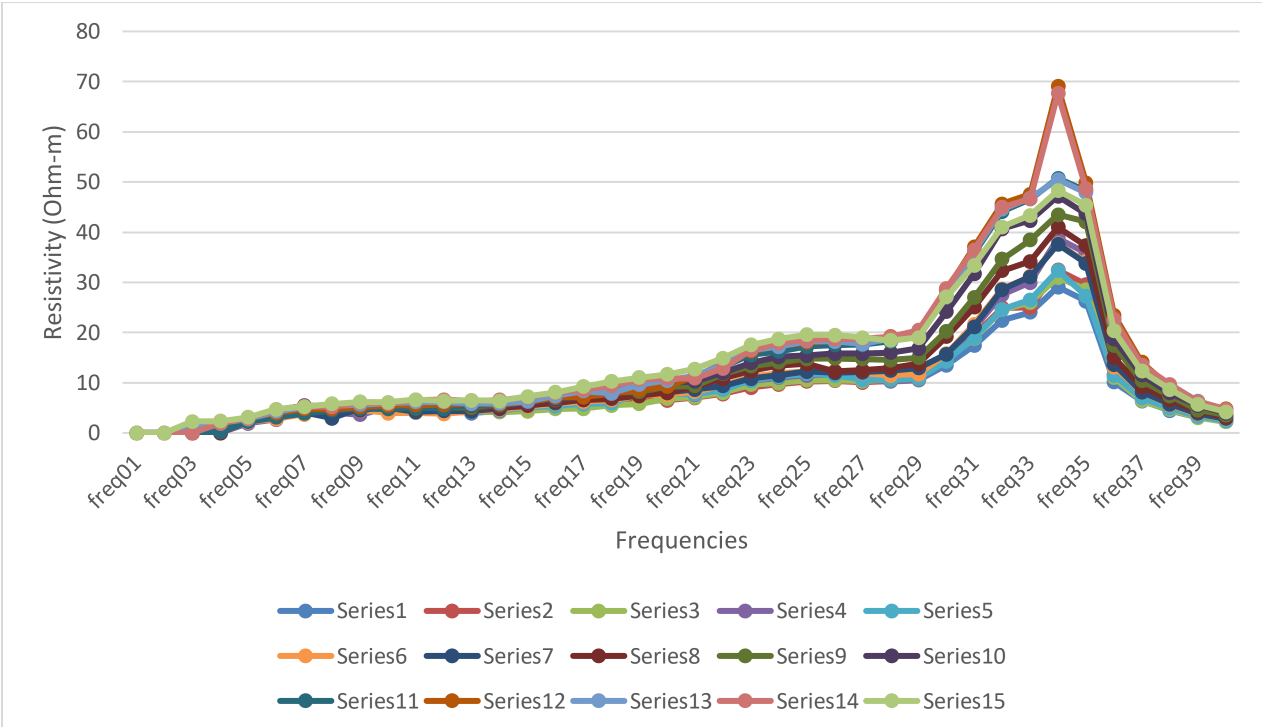
c) South Lake Profile



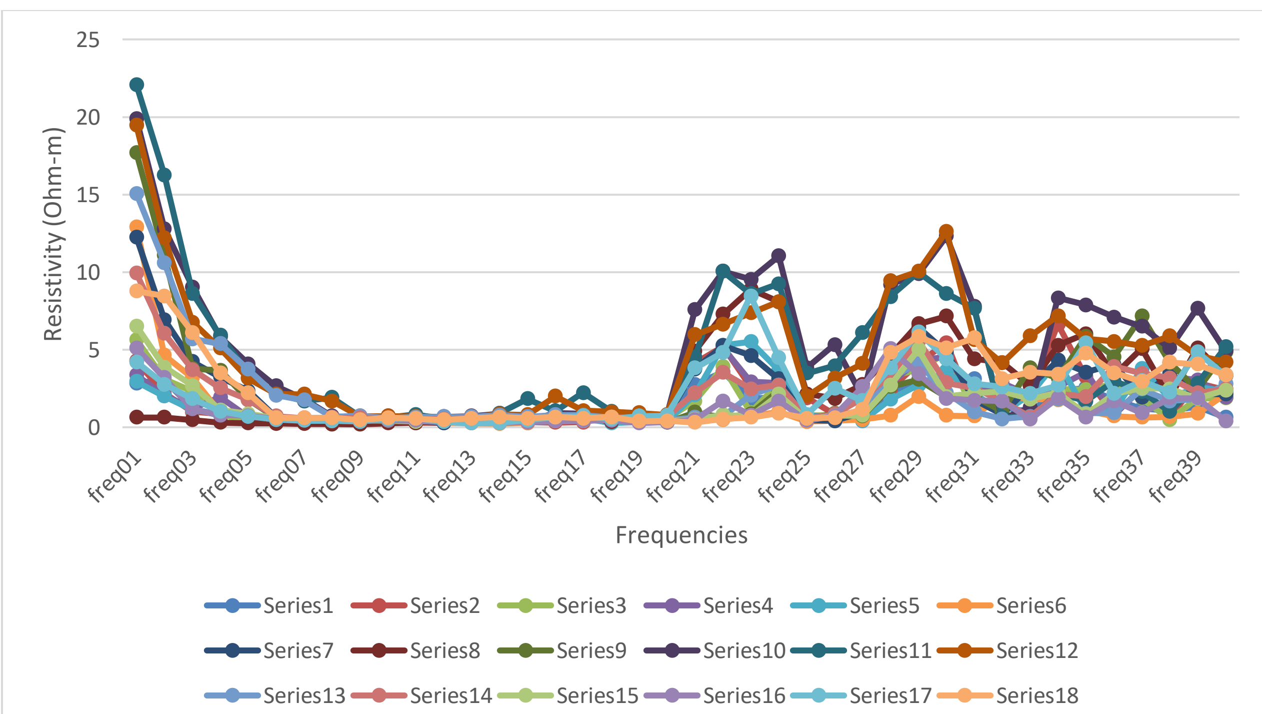
d) Mirera Estate



e) Musaka Area



f) Nndi Farm Profile



g) Maiella Estate Profile