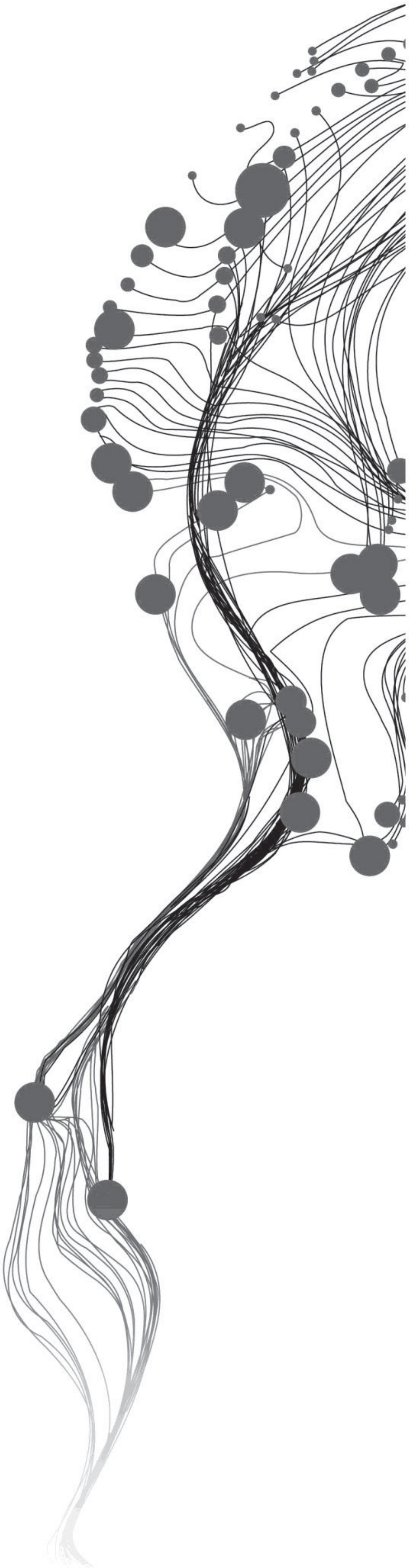
LAKE AQUIFER INTERACTION NORTH EAST OF LAKE NAIVASHA, KENYA

AMHA GESSESSE BEZABIH
March, 2011

SUPERVISORS:
Drs. Robert Becht
Dr. Maciek Lubczynski



LAKE AQUIFER INTERACTION NORTH EAST OF LAKE NAIVASHA, KENYA

AMHA GESSESSE BEZABIH

Enschede, The Netherlands, March, 2011

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources

SUPERVISORS:
Drs. Robert Becht
Dr. Maciek Lubczynski

THESIS ASSESSMENT BOARD:
Professor Dr., W., Verhoef (Chairman)
Dr., F. H., Kloosterman (External Examiner, Deltares, Subsurface and Groundwater Systems - Utrecht)

ABSTRACT

The study of water resources in the Naivasha basin is important for domestic, agricultural and geothermal issues, and it depends on good understanding of the relationship between the lake and the groundwater system. The purpose of this study was to investigate the interaction between the lake and the aquifers to its northeast.

To understand the interaction processes different methodological approaches have been followed. These approaches include geophysical studies, isotopic data analysis, and reassessment of geological and hydrogeological set up of the basin. And finally using the PMPATH modelling the flow paths and arrival times of the lake water to the wellfield area has been predicted.

Stable isotopes of Hydrogen (^{2}H) and Oxygen (^{18}O) have been used to investigate the extent of mixing of waters and the flow direction of the groundwater system in the study area. Isotopic analysis of the water samples collected from boreholes around the lake area and the wellfield showed the following results. The shallow boreholes (17 to 37m deep) have similar isotopic composition to the lake water. Based on mixing ratio calculations percentages of the lake water in these wells was estimated up to 77 %. The main source of recharge for these wells is the lake water.

The isotopic plots of the deep wells lie very close to the Global Meteoric water Line (GMWL) and they are depleted in the heavy isotopes. With the exception of one, all the deep wells are located around the well field (Panda and Delamere farms). These wells are predominantly recharged by precipitation from the eastern rift flank. Only smaller percentages of the lake water are traced here, indicating that the lake is not a major contributor of recharge to the wells. According to the current results there is no significant difference in the percentages of the lake water between 2004 and now; which are 16% and 14% respectively. The boreholes at Marula and Three Point Farms have similar isotopic compositions to that of River Malewa. Isotopic signature of the lake water is generally getting weaker further from the lake towards the well field, which is located northeast of the lake.

Based on the 2D Resistivity Imaging surveys, formation resistivity ranges of the main aquifer materials is found out to be between 12 – 335 Ohm.m. No prominent geological structures are observed on the sedimentary environment of the basin but towards the eastern margin of the study area.

The hydrogeological investigations have demonstrated that the main aquifer units in the Naivasha basin can be divided as sedimentary units and volcanic rocks. The lacustrine deposits are thicker northeast of the lake, where their thickness could reach up to 120m. The water levels are shallower near the lake but gets deeper towards the wellfield. Pumping test results of previous works showed that the transmissivity values of the lake bed sediments in Panda flowers ranges between 460 to 1150 m2/day. However the aquifer units are highly heterogeneous throughout the basin.

And finally using the Advective Transport model, PMPATH the flow paths and travel times of the lake water to the wellfield was predicted.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the Netherlands Government through the Netherlands Fellowship Programme for granting me the opportunity to study at ITC. I would also like to acknowledge my government and my office Tigray Water Resources Mines and Energy Bureau for granting me long leave of absence to pursue my study, and for all the help they have offered me so far.

I am deeply indebted to my first supervisor Drs. Robert Becht for his guidance and support during the fieldwork, and his insightful suggestions and comments throughout the study. I would also like to thank my second supervisor Dr. Maciek Lubczynski for his fruitful comments during the course of the study. I am also grateful to Drs. Boudewijn de Smeth for all the support he gave me during my laboratory work. Generally I would like to Thank Mr. Arno Van Lieshout and all WREM staff members for all their support throughout the whole programme.

I would also like to acknowledge all the support I have got from different offices and staff members in Naivasha during the fieldwork. The fieldwork wouldn't have been a success with out their help. I gratefully appreciate the support of Panda Flower Farm, Shell Kenya and Naivasha WRMA Office and all the management and staff members. The Panda drilling crew members were wonderful throughout the fieldwork, thank you.

I would also like to acknowledge the assistance of Mr. Dominic Wambua and Joseph from the WRMA office. Their assistance have been very crucial through out my stay there.

I would like to extend my appreciation to all my classmates and friends in WREM course for the wonderful time we had together. And special thanks go to fellow Ethiopian students. I'm also greatly indebted to my good friends back home for their wonderful support.

I am very grateful to my mother and all my family, thank you very much for all your moral support and patience during my absence.

Above all I would like to thank the Almighty God.

TABLE OF CONTENTS

1. Introduction 1
   1.1. Research problem 1
   1.2. Importance of the study 2
   1.3. Objectives 2
   1.4. Research questions 2
   1.5. Literature review 3
   1.6. Methodology 4
   1.7. Materials used 5
   1.8. Outline of the thesis 6
2. Description of the study area 9
   2.1. Location of the study area 9
   2.2. Physiography 10
   2.3. Climate and soil types 11
   2.4. Drainage network 12
   2.5. Regional geology and structure 13
   2.6. Regional Hydrogeology 16
3. Geophysics 19
   3.1. Basic principles and surveying procedures 19
   3.2. Interpretation of the 2D Imaging 20
   3.3. Discussion of the 2D Imaging reults 24
   3.4. Geophysical investigations around the wellfield 25
4. Stable isotopes 29
   4.1. Basic principles and sampling protocols 29
   4.2. Estimation of Lake water content 30
   4.3. Interpretation and discussion of results 32
5. Hydrogeology 37
   5.1. General hydrogeology of the northern plain 37
   5.2. Characterization of the aquifers NE of the lake 37
   5.3. Groundwater abstraction 42
   5.4. Correlation of Lake level and groundwater levels 44
6. Modeling 45
   6.1. Model development 45
   6.2. The Advective Transport Model, PMPATH 49
7. Conclusion and recommendation 53
   7.1. Conclusion 53
   7.2. Recommendations 54

LIST OF FIGURES

Figure 1-1: Flow Chart of the whole process 7
Figure 2-1: Location map of the study area 9
Figure 2-2: Physiographic Map of the Naivasha Basin (After Clarke et. al., 1990). 11
Figure 2-3: Distribution of meteorological stations in the study area 12
Figure 2-4: Geological map of the study area 15
Figure 2-5: Piezometric map of Lake Naivasha and its vicinities (After Clarke et at., 1990) 18
Figure 3-1 : Resistivity of rocks and minerals (Taken from Electrical Surveying Lecture Note, WS0607) .. 21
Figure 3-2: Location map of the 2D resistivity surveys 21
Figure 3-3 : Time Domain EM Sounding Positions and Resistivity Imaging profiles locations (Tsiboha, 2002) 25
Figure 3-4: Lithological logs for four boreholes: BH.4, BH.8, BH.7 (Manera Farm) and BH.B (Pivot B), Three Point Farm. 26
Figure 3-5 : Geological Interpretation of 2D Resistivity Imaging Lines 2 and 3(Tsiboha, 2002). 27
Figure 3-6 : Geological interpretation of the model sections of Line9 for resistivity imaging and TEM (Tsiboha, 2002) 27
Figure 4-1 : Plot of δ2H versus δ18O for waters in the Naivasha area 31
Figure 4-2: Proportion of lake water versus distance 33
Figure 4-3 : Location map of isotope samples and geophysical survey lines 34
Figure 4-4 : Plot of δ2H versus δ18O for rain, surface and subsurface waters in the Naivasha area (after Ojiambo, 2001). Where; MWL - Meteoric water Line, Geo - Geothermal wells, GW – Groundwater 35
Figure 5-1 : Geological logs of the four test wells 38
Figure 5-2 : West - East cross section from Mau to Kinangop Plateau showing the major hydrogeologic units 40
Figure 5-3 : Simplified geological map of the study area 40
Figure 5-4: Distribution of transmissivity values around the lake (After Owor, 2000) 42
Figure 5-5 : Cross-section of the water levels from the lake to well field 43
Figure 5-6 : Groundwater abstraction of Naivasha basin from 1970 to 2010 43
Figure 5-7 : Temporal variability of lake level and groundwater levels of wells (After Behar, 1999) 44
Figure 6-1: Schematic representation of the cross section of the conceptual model from the lake to the eastern escarp the Naivasha basin 46
Figure 6-2 : Grid design and model boundary conditions of regional model (Adopted from Kibona, 2000) 47
Figure 6-3 : Scatter plot of observed and simulated heads 48
Figure 6-4: PMPATH particle tracking after 20 years 51
Figure 6-5 : PMPATH particle tracking after 30 years 52
Figure 6-6 : PMPATH particle tracking after 40 years 52

LIST OF TABLES

Table 2-1: Rock classification in Naivasha area according to their age (After Thompson et. al. 1957) 13
Table 2-2: Description of the geological units in legend A 16
Table 3-1 : The 2D_ Resistivity Imaging Survey lines 20
Table 3-2 : Estimated resistivity ranges of the rocks in the study area 22
Table 4-1 : Stable isotopic data of the study area 30
Table 4-2: Relative percentages of lake water and direct recharge 32
Table 5-1 : Percentages of grain size analysis 39
Table 5-2 : Average aquifer characteristics and lithologies, after Clark 1990(figures in brackets are arithmetic mean) 42
Table 6-1 : Observed and simulated heads of the observation wells 49

1. Introduction

Groundwater and surface water are not isolated components of the hydrologic system but instead interact in a variety of physiographic and climatic landscapes. Thus, the development or contamination of one frequently affects the other. Groundwater flow to and /or from lakes and rivers has always been estimated using simple flow nets (Hunt et al. 2003). However, groundwater interaction with lakes and rivers can vary spatially (Krabbenhoft, 1986) and/or temporally (Sacks et al. 1999). To understand these interactions, a sound hydrogeological framework is needed. Moreover, the groundwater flow pattern in the vicinity of such hydrologic interaction domains is controlled not only by the configuration of the groundwater and surface water level but also by the distribution of hydraulic conductivity in the rocks, the topographic and geologic effects as well(Sophocleous, 2002).

To understand GW–SW interactions, it is necessary to understand the effects of the hydrogeologic environment on groundwater flow systems that is, the effects of topography, geology, and climate.

The main focus of this study is to investigation of the hydraulic interaction of Lake Naivasha with the surrounding aquifers. Lake Naivasha is a shallow and freshwater lake in the Kenyan Rift Valley. It is part of a series of lakes occupying the valley floors of the East African Rift system. The lake is situated in a semi-arid zone and has no surface outlet and the natural change in its water levels over the last 100 years is more than 12 meters. Within just a few months the water level can change several meters causing a shift of the shoreline several kilometres. These dynamics add an extra dimension to the riparian ecosystem as well as to the water resource management issues (Becht and Higgins, 2003).

Around the lake the booming horticultural economy is almost fully dependent on the available groundwater sources. However knowledge of the linkages between the lake and the aquifer system is limited. Therefore understanding their interaction in detail will be very helpful so that the effect of changes on either of the water sources on conditions of the other will be estimated by the resource managers.

1.1. Research problem

Lake Naivasha is a fresh water lake on the floor of the Kenyan rift valley. Its water is highly utilized for irrigation, water supply, geothermal power generation, tourism and recreational activities. This excessive use of the resource is causing a decline on the lake water level, hence posing danger to its sustainability.

Due to the increasing demand of water for irrigation and domestic water supplies several wells have been drilled. The groundwater level is fluctuating with the increased abstraction. As a result large cone of depression and lowering of the groundwater level has been observed to the north of the lake (Yihdego, 2005).

The lake and its surrounding aquifers are believed to form one tightly linked system and the groundwater levels in the vicinity of the lake closely follow the water level variations of the lake. However knowledge of the hydraulic interaction of the lake with the groundwater system is limited. Since the introduction of the commercial flower farms in the late 1980s the abstraction of groundwater has been highly increasing. Especially the farms northeast of the lake are totally groundwater dependent. Hence understanding the effect of this abstraction on the lake level is becoming crucial.

Groundwater is critical for understanding most lake systems because it influences a lake's water budget, nutrient budget, and acid buffering capacity. Stresses on the groundwater system and changes in groundwater fluxes affect surface water levels, which in turn affect groundwater levels in a dynamic feedback process.

1.2. Importance of the study

In regions with economically important lakes like Lake Naivasha, it is helpful to have an available technique to describe the hydraulic interaction between a lake and the surrounding aquifers so that the effect of changes in either water body on conditions in the other can be estimated by resource managers.
Groundwater is critical for understanding most lake systems because it influences a lake's water budget, nutrient budget, and acid buffering capacity. Stresses on the groundwater system and changes in groundwater fluxes affect surface water levels, which in turn affect groundwater levels in a dynamic feedback process.

1.3. Objectives

1.3.1. General objective

The main objective of this study is to investigate the hydraulic interaction between the lake and the aquifers northeast of the lake.

1.3.2. Specific objectives

- To study whether the lake is hydraulically connected to the aquifers to its northeast
- To investigate the geological setup of the aquifers between the lake and the well field through test well drilling and geophysical investigation
- To trace the possible sources of the groundwater around the lake and their degree of mixing through the analysis of stable isotopes of hydrogen and oxygen(^{18}O and ^{2}H)
- To estimate the flow paths and arrival times of the lake water to the well field using the advective transport model, PMPATH

1.4. Research questions

- What is the detailed hydrogeological setup of the northern plain?
- Is there hydraulic interaction between the lake and the surrounding aquifers?
- How can we integrate drilling, geophysical and stable isotope data in the understanding of the lake aquifer interaction?
- Can we trace the lake water in the aquifers northeast of the lake (well field) and what are the possible sources of recharge for the wells there?
- What could be the possible factors affecting the interaction between the lake and the aquifer?

1.5. Literature review

One of the features of the Kenyan and main Ethiopian Rift is the chain of lakes occupying the valley floors. The existence of these lakes is partly due to Late Quaternary central volcanic structures, which often separate the lakes from each other. The relationship between these lakes and regional groundwater vary considerably, and the lakes range from fresh to highly alkaline in their chemistry. The relationships of the highly alkaline lakes with the regional groundwater are less significant in terms of groundwater resource management. However in the case of the fresher lakes with no surface outlets, the relationships with the groundwater are not so apparent but much more important to the assessment of resources (Darling et al. 1996). Lake Naivasha is one of these fresher lakes in the Kenyan rift valley.

Lake Naivasha is the highest of Kenyan rift valley lakes, and has no surface outlet. Unlike other rift lakes it has not become saline despite high potential evaporation rates, which indicates that there must be some subsurface drainage. However, the fate of this outflow has been the subject of speculation for many years, especially during the general decline in the lake water level during the 1980's.

The water balance of the lake has been studied for more than half a century. Owing to its situation on the culmination of the floor of the up domed Kenyan Rift Valley, the potential exists for leakage to occur in both northerly and southerly directions. Darling et al. (1990) used stable isotope analysis techniques to show that the lake water appeared to be detectable at least 30km to the south at the Suswa volcano. The use of a simple mixing model between the Rift-flank groundwater and the highly evaporated lake water has enabled subsurface water flow to be contoured by its lake water content.

The lake is fed mainly by the perennial Malewa and Gilgil rivers, which collect runoff from the Aberdare Mountains and their foothills to the northeast of the lake, and which discharge into a papyrus swamp forming part of the lake.

Three studies based on river gauging and evaporation – rate measurement have given comparable results for subsurface outflow of 43 MCM/yr (Sikes, 1935), 34 MCM/yr (McCann, 1972) and 46 – 56 MCM/yr (Ase et al., 1986). These results are likely to be underestimates, as all inflows could not be gauged; however they suggest that substantial outflow is occurring.

The first attempt to address the direction of flow in the Naivasha area was made by "Thompson et al. (1958)". They constructed basic piezometric map with inferred flow direction. "McCann (1992)" attempted to look at the integral water balance of Lakes Naivasha, Elementaita, Nakuru, Solai, Baringo and Bogoria (Cross referenced from Becht et al., Groundwater links between Kenyan Rift valley Lakes). He estimated a subsurface outflow to the Nakuru and Elementeita catchment to be about 37 million cubic meters per year using Darcy's law.

Gaudet and Melack (1981), extensively studied the chemical and water balance of Lake Naivasha. They concluded that there is a subsurface water outflow from the Lake Naivasha but this plays a minor role to explain the freshness of the lake. The water balance for 1973-1975 shows equal groundwater in and outflow.

Clark et al. (1990) mentioned that the regional groundwater flow is generally from the flanks of the Rift Valley towards the Rift floor, and subsequently southward into and then out of Lake Naivasha.

Ojiambo (1992) deduced from piezometric surfaces that the subsurface outflow from Lake Naivasha originates from the southern shores of the lake, and then flows southerly and southwesterly toward Olkaria. He also indicated that the main lake outflow fluxes ranges from 18 and 50 million cubic meters per year.

A number of studies have been made by ITC students and several models were developed to understand the long term water balance of the lake and the groundwater system of the basin.

In addition to the groundwater models, characterization of the aquifers around the lake using different geophysical techniques has been done. Among the numerous researches carried out in the basin, the works which are more related to the current study are mentioned below.

Behar (1999) used a cross sectional model to improve the knowledge of interaction of the lake and the surrounding aquifers and the change in groundwater storage since 1958 up to 1999. In his study he indicated that the long term yearly groundwater storage change around the lake was estimated to be 0.15 MCM which is 0.1% of the lake storage change.
Kibona (2000), studied the temporal and spatial variation of groundwater level north of Lake Naivasha. She has indicated that the transmissivity of the upper layer/lacustrine sediments which is composed of clay, silt, diatomite and sand was not more than 10 m^2/day and in the second layer (reworked volcanics or weathered contacts between the different lithological units), ranged from 10 to 1500 m^2/day. Additionally she has shown the simulated recharge was 25 and 50 mm/year for the thin (thickness < 10 m) and thick sediments respectively.
Owor (2000), studied the long term interaction of groundwater with Lake Naivasha over 66 years (1932-1997) for both steady and transient states. He noted that the regional groundwater flow patterns indicate major outflow areas to the south and southeast of the lake and to the lesser extent to the north and northeast.
Another regional three dimensional steady state groundwater model of the aquifers around the lake was developed by Yihdego (2005).
Moreover the extent of the zone of influence of the lake varies with the direction. The northern and western parts of the lake show the highest fluctuations in lake-groundwater flow interactions; and the response of the groundwater levels to selected periods of lake level rise, fall and stability shows mimicry.
Elisabeth Nalugya (2003) has worked in the estimation of groundwater recharge around the lake aquifer based on field measurements using the SWAP numerical model; she has also used stable isotopes to estimate how much recharge is contributed by both the lake and rain towards the aquifer. Another work which is concerned with the assessment of artificial recharge from the greenhouses northeast of the lake was done by Abdulwahab (2006).
Apart from the groundwater models and recharge estimations a few works have been done on the characterization of the aquifers around the lake through the application of variable geophysical methods. Among these researches the most notable work was done by Tsiboha (2002). He has applied two-dimensional (2D) Resistivity Imaging and Transient Electromagnetic (TEM) methods. He combined the formation resistivity physical property, groundwater quality and lithological data to model the aquifers northeast of Lake Naivasha.
Integration of different techniques such as local geology and hydrogeology, geophysical data and isotope analysis of the different water bodies will add a lot to the current understanding of the lake aquifer linkages.

1.6. Methodology

The methodology followed during this study was based on the research objectives as stated in section 1.3. Besides, the major sources of information and materials used are stated. The layout of the Thesis and diagrammatic representation of the whole process is also presented in this chapter. Generally the methodology involves the following main stages;

1.6.1. Pre fieldwork

At this stage of the study the following activities were performed

- Literature review of previous works and collection of available data from different archives
- Identification of the areas where there is scarcity of data
- Compilation of the isotopic, geophysical , geological and hydrogeological data of previous works so that it will be integrated with the new work

- Proposing the sites for test borehole drilling
- Acquisition of the necessary materials for fieldwork

1.6.2. Fieldwork

During the three week fieldwork period, from September 14 to October 7, 2010 the following main activities were performed.

- Drilling of test boreholes in areas where there is scarcity of data. For this purpose four test wells were drilled
- Collection of water samples for stable isotope analysis; 11 water samples were collected from the new test wells, the lake and the functional wells around the well field
- Two dimensional resistivity imaging was conducted at 16 points in between the lake and the well field
- Levelling of 36 wells around the lake in order to define the exchange of flow of water between the lake and the groundwater in the surrounding aquifers.
- Collection of newly drilled borehole data

1.6.3. Post Fieldwork

- Analysis and interpretation of the isotopic data
- Analysis and interpretation of the geophysical data
- Reassessment of the hydrogeological set up of the area
- Advective transport modelling with PMPATH
- Conclusion and recommendation

1.7. Materials used

Topographic maps
Naivasha, Sheet 133/2, 1975, 1:50,000
Longonot, Sheet 133/4, 1975, 1:50,000

Satellite Images
Aster image 2009

Equipments
SAS 4000/1000, geophysical instrument
Hand held garmin GPS, deep meters
Geological hammer, magnifier lens
Microscope, sampling bags
Differential Leica GPS for levelling
50 mL, double capped polyethylene bottles for collecting water samples

Additional sources of information
Research papers of the study area by ITC students and other researchers
Geological logs of the boreholes in the area from the Naivasha water office
Geological map of the area from WREM database
Stable isotope data compiled by various researchers

1.8. Outline of the thesis

Chapter One: This is an introductory chapter. In this chapter research problem, importance and objectives of the study and literature review are elaborated.

Chapter Two: This chapter provides general information about the study area. In this chapter the location, physiography, climate, geology and hydrogeology of the basin are discussed in brief.

Chapter Three: This chapter deals with the geophysical investigation of the study area which is 2D_Resistivity Imaging. The subsurface geology and hydrogeology of the area and the effect of geological structures, such as faults and fractures on the groundwater flow system of the basin has been discussed. It also tries to integrate the current investigation with previous works.

Chapter Four: This chapter deals with stable isotope data analysis and interpretation in order to understand the relationship between the lake and the surrounding aquifers. The possible sources of recharge for the wells northeast of Lake Naivasha, and estimation of the contribution of the lake water to the surrounding aquifers are also discussed. Stable isotopes of hydrogen and oxygen have been used. Several data sets from the past are analyzed and integrated with the newly collected data.

Chapter Five: Deals with the hydrogeological description of the study area. The hydrogeology is discussed by integrating the geological, geophysical and isotopic data of the past and present. This chapter also discusses lithologic logs of the test wells, and laboratory analysis of particle size distribution to estimate hydraulic properties of the aquifers. Moreover the abstraction history of the groundwater is also mentioned.

Chapter Six: This chapter investigates the flow paths and travel times of the lake water to the wellfield to its northeast using the Advective Transport Model, PMPATH.

Chapter Seven: This chapter incorporates the conclusions and recommendations based on outcome of all the findings envisaged in all the analysis

Schematic representation of the whole process is shown as follows

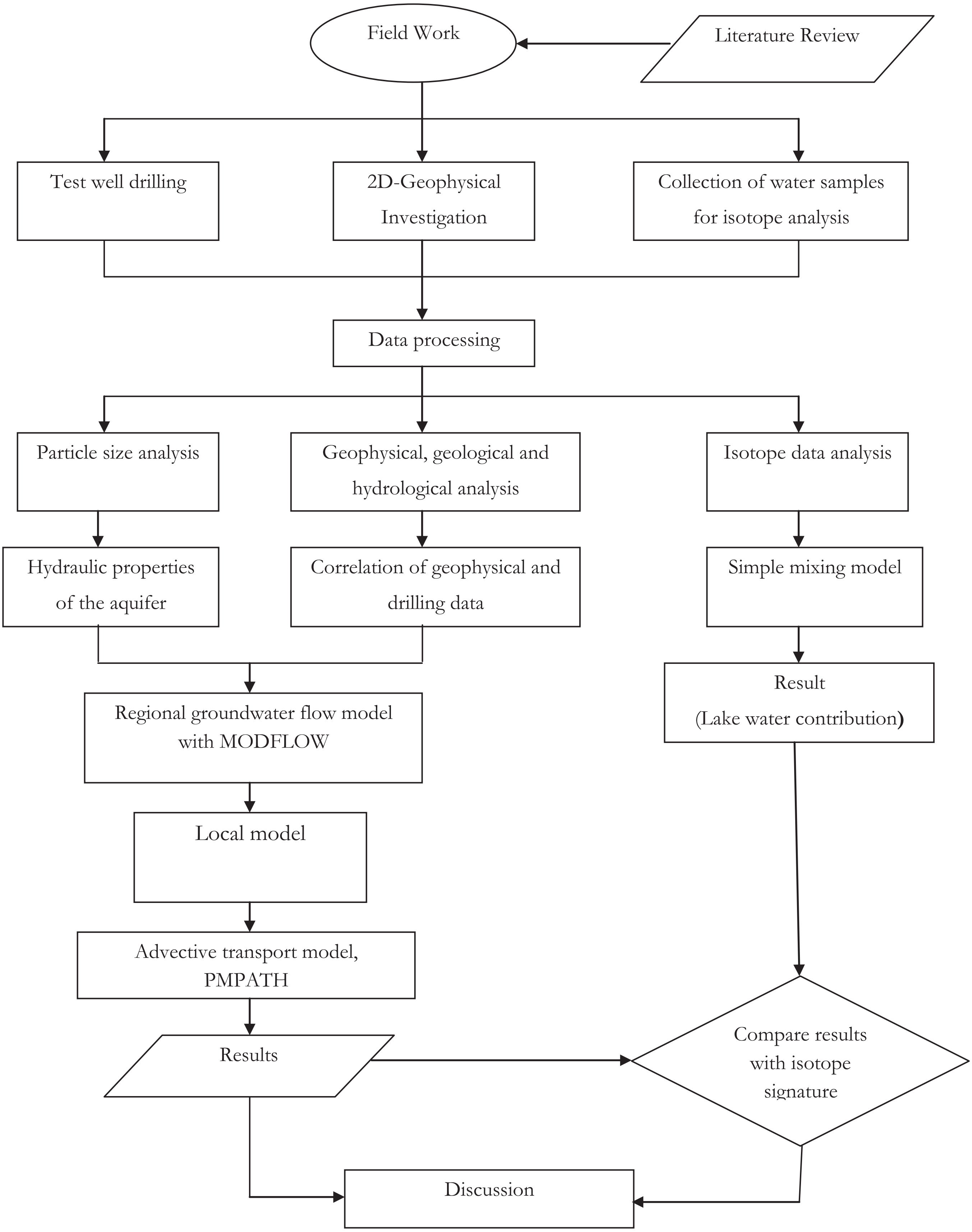


Figure 1-1: Flow Chart of the whole process

2. Description of the study area

2.1. Location of the study area

Naivasha town is located in the Rift Valley Province of Kenya, at about 80 kilometres northwest of the capital Nairobi, on the shore of Lake Naivasha along the Nairobi – Nakuru highway and Uganda Railway. The Naivasha basin lies with in UTM zone 37 and geographic coordinates 0°0' to 1°0' South and 36°0' to 36°45' East, in the central Kenya Rift valley. The basin covers an area of approximately 3400km² (Figure 2-1). The area of interest for this research is northeast of Lake Naivasha where the well field is located.
Lake Naivasha is part of a series of lakes in the East African Rift valley spanning from Ethiopia to Tanzania. Being located at 1890 m above sea level, Lake Naivasha is the highest lake in the Central Kenya Rift (0°55'S 36°20'E). The Mau Escarpment (3080 m.a.s.l.) and the volcano Mt. Eburru (2840 m) bound the closed-basin lake to the west. To the north and east (Kinangop Plateau), the basin is bordered by fault scarps, whereas the volcano Mt. Longonot (2776 m) and the Olkaria Volcanic Complex (2440 m) define a southern barrier.

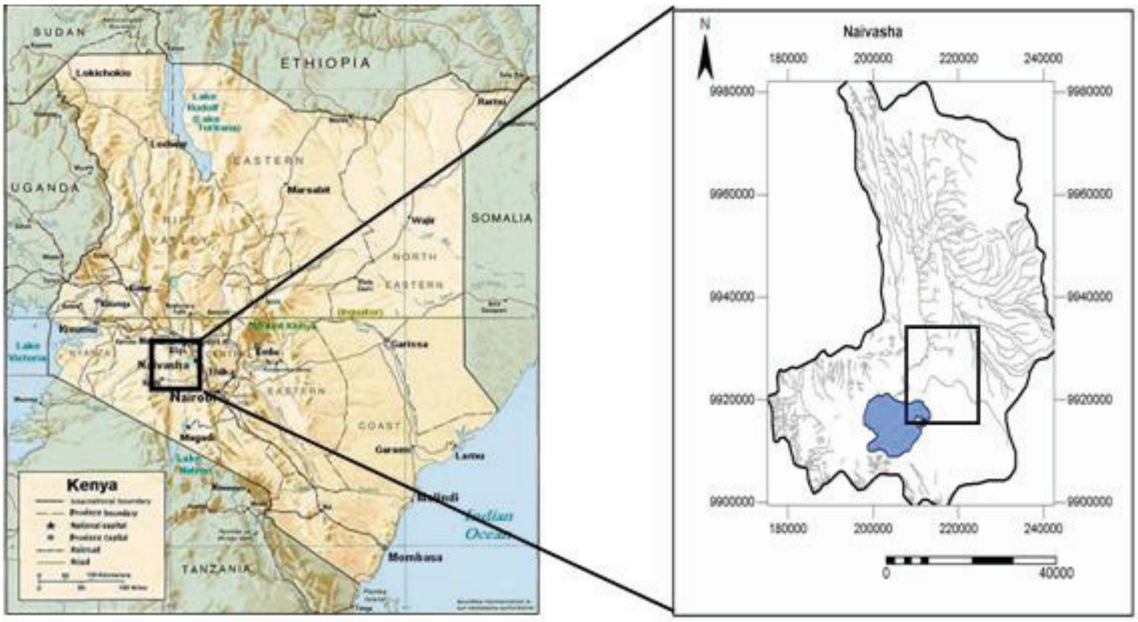


Figure 2-1: Location map of the study area

2.2. Physiography

The Naivasha area can be divided in to three main physiographic units namely the Kinangop plateau, the Mau escarpments and the Rift floor (Thompson et. al., 1963).

The Kinangop plateau appears in the north-eastern part of the area only, where it lies between the southern mountains of the Aberdare range and the Rift floor. It is a broad flat plain ranging in height from about 2379 m to a little over 2440 m in altitude above sea-level. It is deeply incised by the Makungi, Kitiri and Engare Magutyu tributaries of the Turasha river, which forms part of the Malewa river, the largest river flowing into Lake Naivasha. Along the northern edge of the area gorges between 61 and 122 m deep have been formed. The tributaries of the Malewa river within the area mapped flow in a general northerly direction, but are diverted to the south-west by their confluence with waters draining from Kipipiri to the north-east and beyond the limits of the present area, the combined streams soon joining the Malewa which flows in a southerly direction. This reversal of direction is believed to be due to capture of the Kinangop rivers by the Malewa River.

West and south-west of the Kinangop plateau, the rocks that form the plateau have been down-faulted in a series of steps. The majority of the faults are short, and can be seen to die in one direction or another. Several of the fault-line scarps suggest slightly curved faults, with the downthrown blocks on the convex side.

The Mau escarpment forms the western wall of the Rift Valley in the Naivasha area. It is composed largely of soft volcanic ashes and tuffs with only rare outcrops of agglomerate and lavas. Parts of the escarpment rise to over 3050 m in the region west of the Eburru volcanic pile, which is linked to the escarpment by a ridge standing about 2591m above sea-level caused by the pilling up of pyroclastics from Eburru against it. The ridge, like the escarpment, is deeply incised by water-courses.

Unlike the Kinangop plateau, the Mau escarpment is not flat - topped rather it is rugged and deeply incised; the divides separating the drainages to Lakes Nakuru, Natron and Naivasha are sharp. Drainage from the escarpment probably does not reach Lake Naivasha by means of surface water-courses. The Marmonet River is a tapering stream, which loses itself on the Ndabibi plain.

The Rift floor in the Naivasha area forms part of the Gregory Rift Valley, and is diverse in its structures and topography. The Rift floor incorporates Lake Naivasha, the Ndabibi plains which lie west of the lake and the Ilkek plains to the north. The Rift valley plains are found in between the two highlands. High points are formed by Longonot and Eburru, both of which rise to over 2745 m. On the western and south-western shores of Lake Naivasha numerous volcanic craters, some faulted, are built up of acid lavas and basaltic ashes. North of Lake Naivasha as well as on the slopes of Longonot, eruptions of lava have taken place in very recent times some probably in the last hundred years.

The lake dominates the central part of the basin. Being located at about 1890 m above sea level, Lake Naivasha is the highest lake in the Central Kenya Rift.

The Ndabibi plains extend up to 9km west of the lake and separate the Olkaria and Eburru volcanic complexes. The plains are about 1980m in elevation along their western edge and slope very gently towards the lake (Clark et. al.., 1990). On the other hand the Ilkek plains extend up to 23 km north of the lake and they range in width from a maximum of 13 km in the south, near Naivasha town to a minimum of 4 km in the extreme north near Gilgil town. They slope gently southward with a maximum elevation of 2000 m.

The Rift floor is largely covered with sediments that accumulated in lakes during the Gamblian stage of the Pleistocene period. They contain a large proportion of volcanic ejectamenta, and a few diatomaceous beds are known to occur. Despite their extensive distribution the Gamblian lake beds are not thick and rarely exceed 31m.

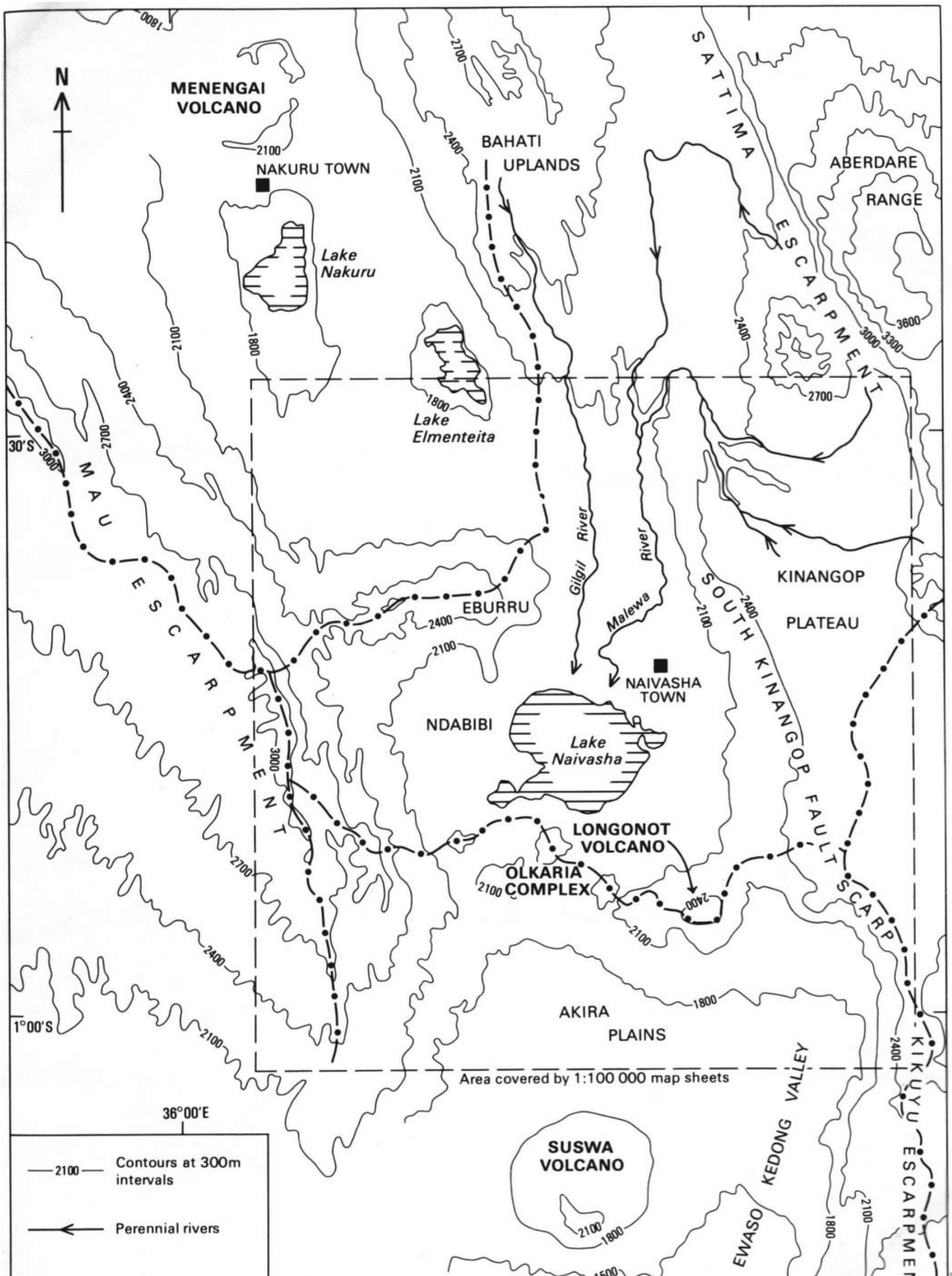


Figure 2-2: Physiographic Map of the Naivasha Basin (After Clarke et. al., 1990).

2.3. Climate and soil types

The climate of the basin lies within the semi-arid belt of Kenya with average annual precipitation of 700 mm. Some precipitation occurs during each month of the year, although there are two main rainy seasons per year, "the long rains" occurring in March, April and May and the "short rains" in October and November (Stuttard et. al 1995). The rainfall distribution in the area is a function of the topography. The highest rainfall is received along the Mau and Aberdare escarpments, with an average ranging from 1250 – 1500 mm annually. Where as, in the rift floor including Lake Naivasha, the rainfall averages 608 mm/yr but low relative humidity and an average daily maximum temperature of 25 $^{\circ}C$ combine to cause annual potential evaporation of 1500 – 1900 mm/yr (Ase et. al., 1986), far in excess of rainfall. There are several

rainfall stations around the lake including those owned by the private farms. From these stations the Naivasha Division Office (Naivasha D.O.) is located in the vicinity of the study area and it has several years of data. The location of some selected rainfall stations is shown below in (Figure 2-3).
The distribution of soils in Naivasha area is complex having been influenced by intensive variation in relief, climate, and volcanic activities and underlying rocks (Siderous, 1980). The soils are derived basically from weathered volcanic and basement rock system and occupy the floor of the rift valley in Naivasha as light grey or brown to pinkish non-calcareous soils. Soils of the study area can be grouped in to soils developed on the lacustrine plain, soils developed on volcanic plain and, soils developed in the highland area, considering the geo-pedologic landscape units. The soils of the volcanic plain are formed mainly from weathered volcanic and pyroclastics. The soils of the lacustrine plain are the result of reworked volcanic and pyroclastic deposits.

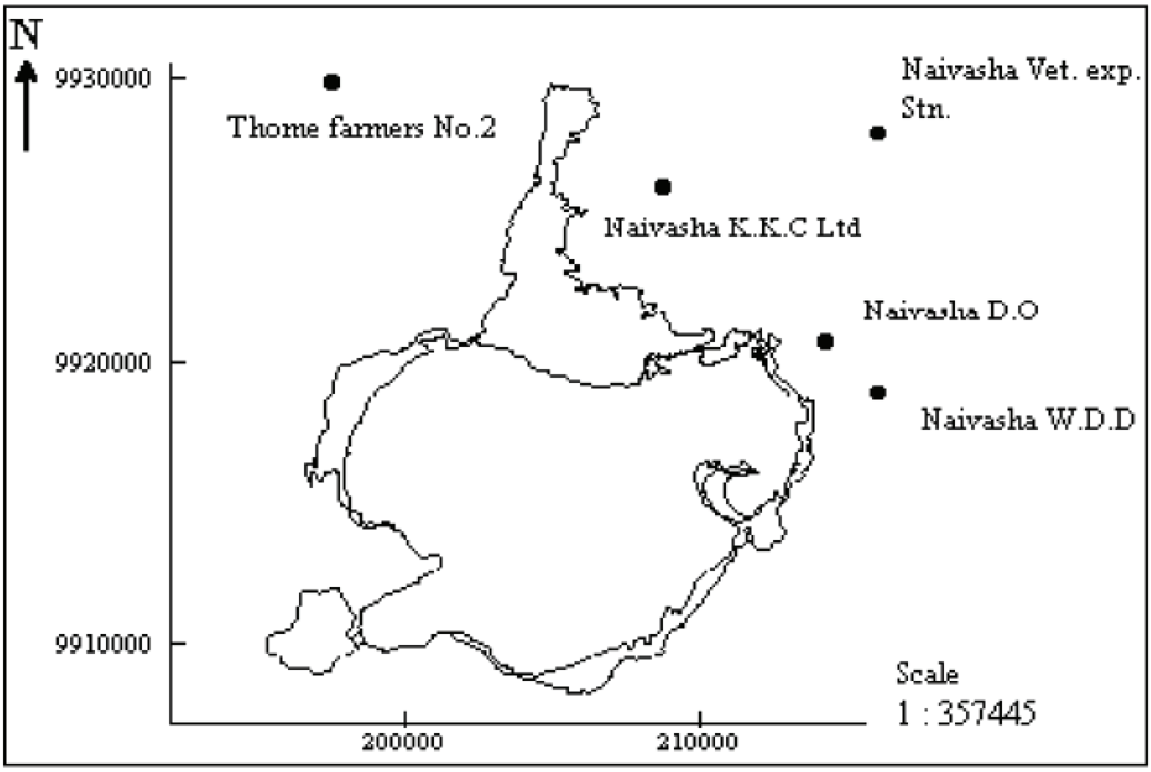


Figure 2-3: Distribution of meteorological stations in the study area

2.4. Drainage network

The geomorphology of the rift valley plays an important role on the surface drainage. Most of the surface drainages occur within the rift valley. Among the number of rivers and streams around the basin only two have substantial flows into the lake.
The main rivers that drain the basin are the perennial Malewa and Gilgil Rivers, which together account for 90 percent of the river flows to the lake (Abiya, 1996). These two rivers collect runoff from the Nyandarua (Aberdare) Mountains and their foothills to the north of the lake, and which discharge into a papyrus swamp forming part of the lake.
In addition to the two main rivers there are also a few seasonal streams; including the Karati River which drains from the northeast. However the flows from these streams often do not reach the lake as surface water.
Malewa River rises on the western slopes of the Nyandarua range at an altitude of 3000 to 4000 m. The small streams flow westwards and develop into four main tributaries; the Mugyutu, the Turasha, Kitiri, and Makungi. Turasha is the most important tributary and joins River Malewa at approximately 8 km east of Giligil. All four flow from north-south before turning west and joining the Malewa. Giligil river's

headwaters are situated in the Bahati forest where it drains along narrow basin. The river rises at 2740 m in an area where rainfall is high at 1300 mm per annum. There are few tributaries. Karati River flows from the north and rises on the Kinangop plateau at an altitude of 2620 m where there is a mean annual rainfall of 800 mm. Streams in the western part of the basin disappear before reaching the lake.

2.5. Regional geology and structure

2.5.1. Geological settings

Thompson et. al. (1957) tentatively classified the rocks in the Naivasha area according to their age as follows;

Table 2-1: Rock classification in Naivasha area according to their age (After Thompson et. al. 1957)

Age	Rock type
Holocene	volcanics, lake and fluviatile sediments
Upper Pleistocene	volcanics and lake sediments
Upper Middle Pleistocene	volcanics and lacustrine sediments.
Lower Middle Pleistocene	volcanics and lake sediments
Pleistocene	volcanics

The volcanic rocks in the area consist of tephrites, basalts, trachytes, phonolites, ashes, tuffs, agglomerates and the acid lavas rhyolite, comendite and obsidian. The lake beds are mainly composed of reworked volcanic material or sub-aqueously deposited pyroclastics. The structures of the area comprise faulting on the flanks and in the floor of the Rift Valley, and slight folding in the Njorowa gorge. Slight unconformities are present in the lake beds, and can most clearly be seen along the Malewa river drainage. Even though the lake beds are extensively distributed in the study area, they are not thick and rarely exceed 30m. The simplified geological map of the study area is presented in (Figure 2-4) below.

The Kenyan Rift Valley is mostly underlain by volcanics with phonolitic, trachytic and rhyolitic composition and their sedimentary derivatives. The Kenyan Rift Valley volcanics were erupted nearly continuously from Early Miocene to Holocene times. The geology of the area is generally made of volcanic rocks and lacustrine deposits. In the basin are complex geological structures, which have been subjected to several tectonic processes leading to varying structural features.

Clark et al. (1995) described that west and southwest of the Kinangop plateau, the soft volcanic rocks that form the plateau have been down-faulted in a series of steps. These include ignimbrite succession, mostly welded tuffs, paleosols and weathered zones at the top of most beds. The maximum exposed thicknesses are about 150 m. The Mau escarpment is largely composed of the ignimbrite succession dominated by tuffs with only rare outcrops of agglomerates and lavas. The rifting has produced blocks down-faulted to the east along the escarpment. The maximum exposed thickness is about 100 m. The rift valley floor is largely covered with sediments that accumulated in the lakes during the Gamblian stage of the Pleistocene period. They contain a large proportion of their volcanic material, and a few diatomaceous beds are known to occur. The floor abounds with the greatest variety of topographic features caused by earth movements: craters, remnants of pre-existing craters, fault scarps, fissures, and steam jets. The rocks found on the Rift floor vary from under saturated tephrites to highly acid rocks such as rhyolites and sodic rhyolites.

The lake beds are mainly composed of pumiceous granules (pebble gravel, diatomites, coarse sand, silt and clay). The maximum thickness of exposed beds is about 15 m.

Along the Malewa River valley are alluvial deposits that include silt, fine sand, some ferruginous coarse sand and boulder gravel

2.5.2. Structures

The rift basin is asymmetric and bounded by step border faults showing 2- 3 km displacements. Along the rift there is North-South variation in volcanism, structural style and crustal and upper mantle seismic velocities. The variety and differences in the volume of magma products varies from flood basalts - Miocene, phonolites - Pleistocene and trachytes - Quaternary. Baker, (1972) and Williams, MacDonald and Chapman (1984) indicate that these magma evolutions are a key issue in understanding the rifting processes. Their observations suggest that the locus of extension and volcanic eruptions relocated to the axis of the rift valley in the Pleistocene with cinder cones becoming active 1.6 Millions of years ago. Within the Kinangop and Gilgil Plateau the fault systems show an echelon pattern.

Structurally, with the exception of Lake Naivasha, all the Rift Valley lakes are elongate in the direction of the Rift Valley fault structures. Lake Naivasha forms a near circular trough (Figure 2-2) with two half buried craters forming the Small Lake (Lake Oloidien) and the Crescent Island, and another satellite basin forming the Crater Lake. Crescent Island crater is a small-submerged crater basin within the main lake and occurring along the eastern shore of Lake Naivasha. Lake Naivasha is hydrologically open, with river and groundwater inflow from the north and from western rift border escarpments.

According to Thompson et. al. (1963) the rocks forming the Kinangop Plateau have been down-faulted in a series of steps. Where rivers have incised themselves on the western edge of the plateau deep valleys have been formed. The Malewa River from the northern edge of the area flows in a graben at the foot of the Kinangop plateau.

In the Mau escarpment the rifting has produced blocks down-faulted to the east along the escarpment. The faults and fault-line scarps are often difficult to trace owing to vast accumulations of ejectamenta banked up against the escarpment. Recent earth movements along the old fault-lines have rejuvenated some of the fault scarps.

The Rift floor in the Naivasha area forms part of the Gregory Rift Valley, and is diverse in its structures and topography. Numerous volcanic cones and craters, scarps and lakes, are found on its otherwise monotonous terrain. High points are formed by Longonot and Eburru, both of which rise to over 9,000 ft. (2,745 m.). On the western and south-western shores of Lake Naivasha numerous volcanic craters, some faulted, are built up of acid lavas and basaltic ashes. North of Lake Naivasha as well as on the slopes of Longonot, eruptions of lava have taken place in very recent times; some probably in the last hundred years.

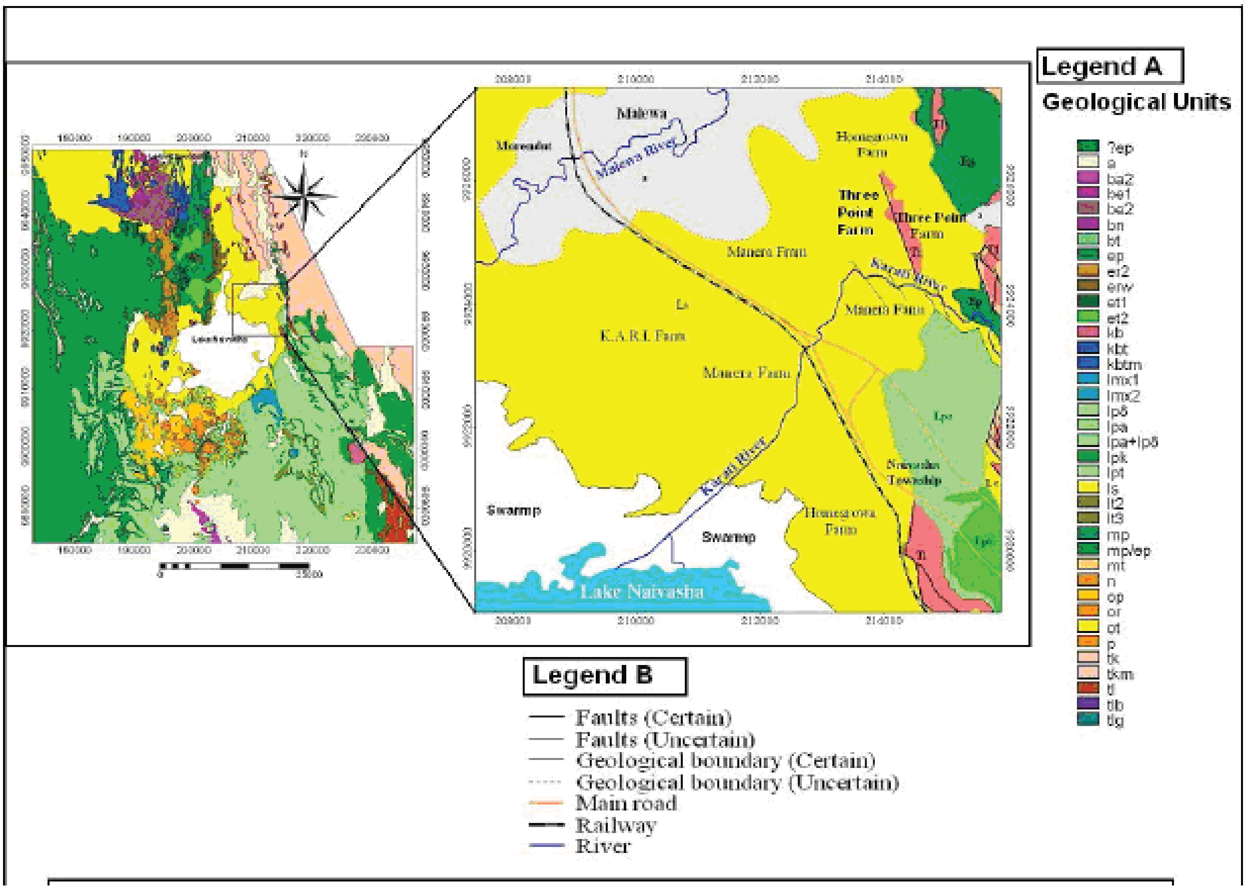


Figure 2-4: Geological map of the study area

Table 2-2: Description of the geological units in legend A

Unit	Description
?ep	Eburru pumice, pantellerite, trachytic pumice, ash fall deposits
a	Alluvial deposit
ba2	Alkaria basalt, basalt and hawaiite lava flows, pyroclastic cones
be1	Older elementeita basalt, hawaiite lava flows, pyroclastic cones
be2	Younger elmenteita basalt, basalt, hawaiite and mugearite / benmoreite lava flows and pyroclastic cones
bn	Ndabibi basalt, hawaiite lava flows, pyroclastic cones
bt	Surtseyan / strombolian ash cones
ep	Eburru pumice, pantellerite, trachytic pumice, ash fall deposits
er2	Eastern eburru pantellerite and trachyte pumice, ash deposit
erw	Waterloo ridge pantellerite, welded and unwelded pyroclastics
et1	Older eburru trachyte, lava flows and pyroclastic
et2	Younger eburru trachyte, lava flows and pyroclastic cones
kb	Kijabe hill basalt
kbt	Surtseyan tuff cones
kbtm	Surtseyan tuff cones with laterally equivalent fall tuffs
lmx1	Lower longonot mixed basalt / trachyte lava flows and pyroclastic cones
lmx2	Upper longonot mixed basalt / trachyte lava flows and pyroclastic cones
lp8	Longonot ash
lpa	Longonot alkaria pumice
lpa+ip8	Longonot ash and alkaria pumice
lpk	Kedong valley tuff, trachyte ingimbrites and associated fall deposit
lpt	Longonot volcanic, pre-caldera welded pyroclastics and lava flows
ls	Lacustrine sediments
lt2	Lower longonot trachyte, lava flows and pyroclastic cones
lt3	Upper longonot trachyte, lava flows and pyroclastic cones
Mp	Maiella pumice, trachyte, pantellerite pumice and ash fall deposits
Mp/ep	Maiella pumice/trachyte pumice
Mt	Magaret trachyte, unwelded and welded pyroclastics
N	Ndabibi comedite lava flows, domes and pyroclastics
Op	Olkaria comendite, pyroclastics (include pre-lpk lacustrine sediments, reworked pyroclastics in ol Njorowa gorge
Or	Olkaria comendite, lava flows and domes (includeNjorowa pantellerite lava and welded pyroclastics
Ot	Olkaria trachyte, lava flows
P	Ndabibi pantellerite lava flows
Tk	Kinangop tuff (eastern rift margin)
Tkm	Mau tuff (western rift valley)
Tl	Limuru trachyte
Tlb	Karati and ol mogogo basalt
Tlg	Gilgil trachyte

2.6. Regional Hydrogeology

The hydrogeology of central to southern portion of the rift valley is mainly controlled by the rift flanks faults, the grid faulting and the tectono-volcanic axis along the rift floor. Fluids are recharged laterally from the high rift flanks and axially along the rift floor southwards as indicated by the piezometric map of the study area in (Figure 2-5). Analysis of groundwater elevation of the boreholes in the area done by Clarke et al. (1990) shows that the water table is shallowest around Lake Naivasha but getting deeper towards the south. Those wells drilled between Longonot and Suswa didn't encounter water at drilled depth. The grid faulting act as channels for groundwater or they provide permeable barriers to lateral flow. A microseismic study has shown that the grid faulting unlike the escarpment faulting is quite active suggesting they are open (Allen et al., 1989). Thus the faulting causes the groundwater to flow from the escarpments to the center and then follow longer flow paths reaching greater depths, and aligning their flow within the rift along its axis. Due to the southward sloping of the rift floor, the axial flow from Lake Naivasha could also be an important source of recharge in the area south of the lake. The N-S normal faults could be very instrumental in channelling the fluids to the area. In Olkaria and Eburru where drilling has been carried out, the geothermal reservoirs are hosted by the faulted Plio-Pleistocene Plateau Trachytes, which are common within the floor of the southern Kenya Rift valley. It is therefore probable that the reservoirs of Suswa and Longonot are hosted in the same formation. The hydrogeology of Naivasha basin is complex and it is greatly influenced by the geology, topography and climatic factors that pertain in the area (Clarke, 1990).

Groundwater occurrence is greatly determined by the geological conditions as well as the available water for storage. Fresh volcanic rocks tend to be compact with no primary porosity although secondary porosity may be well developed. These rocks underlying the rift valley therefore have low permeability though there are at times considerable variations where layers with poor hydraulic conductivity may be overlain with layers of good hydraulic properties.

In the localized highland areas, there exist deep groundwater tables as well as steep groundwater gradient. This environment is often associated with high rainfall values, which are sources of groundwater recharge if all conditions are fulfilled.

The high hydraulic gradient accounts for the outflow of groundwater from the lake to the south as well as some infinitesimal outflow towards the north. Structural features such as faults often optimize storage, transmissivity and recharge with the significant of these occurring in places that are adjacent to or within a surface drainage system. Shallow groundwater table, low precipitation and low values of recharge characterize the valleys.

The main aquifer is found in sediments covering parts of the rift floor. These, aquifers usually have relatively high permeability and are often unconfined with high specific yield (Stuttard, 1995 as sited by Nabide, 2002). Clark et. al. (1990) estimated by inventory of boreholes and envisaged that the lake sediments have permeability of 12-148m/d. Besides, aquifers are found in fractured volcanic rocks and at times along weathered contacts between different lithological units and they are often confined or semi-confined with low storage coefficient. Permeability is generally low in aquifers but there exist some variations locally as a result of some formations.

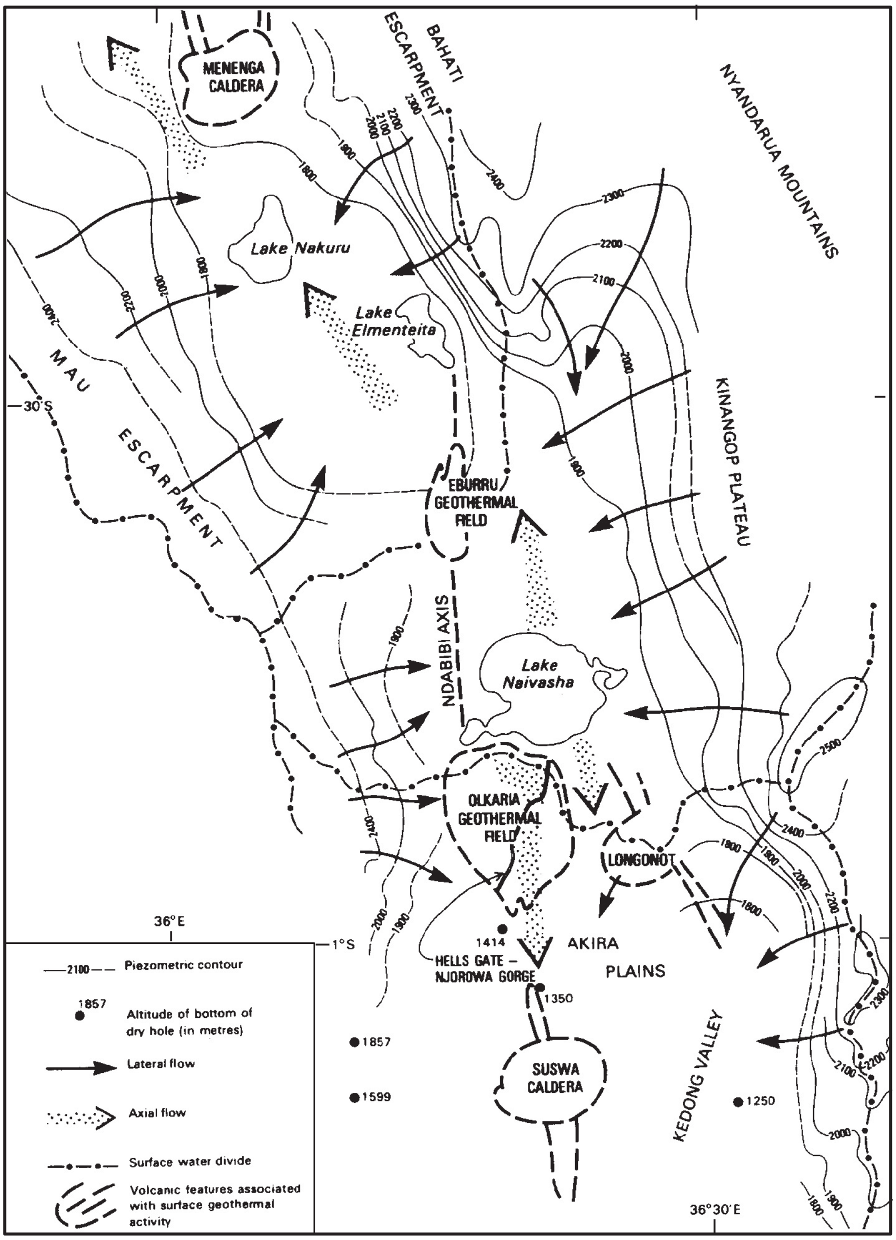


Figure 2-5: Piezometric map of Lake Naivasha and its vicinities (After Clarke et at., 1990)

3. GEOPHYSICS

3.1. Basic principles and surveying procedures

One of the main objectives of this study was to make use of the application of geophysics in the understanding of the subsurface geology and hydrogeology of the area and the effect of geological structures, such as faults and fractures on the groundwater flow. Some geophysical surveys have been conducted around Lake Naivasha that includes gravity, magnetic anomaly surveys and resistivity soundings. Some of these works have been done regionally for the purpose of geothermal prospecting.

A number of geophysical techniques have been used for groundwater studies. However electrical resistivity and electromagnetic (EM) geophysical methods are commonly recognized as being the most useful for groundwater exploration (Goldman et. al.., 1994).

In electrical resistivity method a variety of electrode configurations or arrays (Wenner, Schlumberger, and dipole-dipole) can be used depending on the application and the resolution desired. Typically, an electric current is applied to the ground through a pair of electrodes. A second pair of electrodes is then used to measure the resulting voltage. Because various subsurface materials have different resistivity values, measurements at the surface can be used to determine the vertical and lateral variation of underlying materials, Figure 6-1.

The method applied in this study was 2D Resistivity Imaging with Wenner array electrode configuration. This electrical resistivity imaging method uses a multi-electrode array system at the same time and records maximum number of independent measurements.

ABEM Terrameter 1000, was used during the field measurement. SAS 1000/4000 utility software was used to retrieve the measured data from the terrameter to the PC for processing. Additionally it is used to install new software and protocol files to the terrameter.

EarthImager2D software package was used for processing the 2D Resistivity Imaging Data. It inverts the "apparent resistivity" data obtained from electrical imaging surveys into a two dimensional (2D) "true resistivity" model of the subsurface in an automatic and robust manner. The raw data files are converted with the 2D-CONV.EXE software into the appropriate format, in this case (·DAT Format) readable by the inversion software EarthImager2D. The individual input files for all the resistivity imaging survey lines were generated and made ready for inversion into 2D "true resistivity" image in the program.

The depths of the layers and the resistivity values of the formations under consideration can be adjusted closer to the reality if there is borehole information in the area. This will reduce the effect of equivalence on the inversion results. In the area where the geophysical survey was carried out the only available borehole data are, TBH1 and TBH3. Hence an attempt was made to correlate the lithologic data with the inversion results as much as possible. But for some of the inversions the interpretation was done based on the geologic knowledge of the area and the data from previous deep boreholes and geophysical surveys in the basin. The difference between the measured and calculated apparent resistivity values are given by the Root Mean Squared Error (RMS).

Table 3-1 : The 2D_ Resistivity Imaging Survey lines

Profile	Electrode Spacing	Total Length	X	Y	Z	Orientation
NAIV2D_1	10m	580m	212675	9919528	1889	NW - SE
NAIV2D_2	2m	200m	212182	9919858	1896	NW - SE
NAIV2D_3	2m	80m	212094	9919680	1896	NW - SE
NAIV2D_4	10m	400m	212592	9920587	1892	NW - SE
NAIV2D_5	10m	400m	212151	9920964	1893	NW - SE
NAIV2D_6	10m	400m	212907	9921136	1893	NW - SE
NAIV2D_7	10m	400m	213247	9920735	1892	NW - SE
NAIV2D_8	10m	400m	212271	9920044	1889	NW - SE
NAIV2D_9	10m	400m	212211	9919986	1895	NW - SE
NAIV2D_10	10m	400m	211392	9920057	1891	NW - SE
NAIV2D_11	10m	400m	211804	9919900	1893	NW - SE
NAIV2D_12	10m	800m	212389	9921336	1892	NW - SE
NAIV2D_13	10m	800m	211628	9920289	1894	N - S
NAIV2D_14	10m	800m	212941	9920252	1898	N - S
NAIV2D_15	10m	800m	212409	9920341	1900	N - S
NAIV2D_16	10m	800m	211837	9920608	1895	NW - SE

The geophysical survey was conducted northeast of Lake Naivasha on one of the commercial farms known as Home-grown. This farm is part of the north-eastern plain and is bounded by another commercial farm, called Manera. It is located south of the main Nairobi - Nakuru high way, Figure 6-3.
The home grown farm is one of several commercial farms in the area and is located between the lake and the well field. Most of the geophysical investigations (2D Imaging, TEM and VES) so far were conducted above/north of the main road. The amount of subsurface information south of the main road is very limited; and there are only a few borehole data as compared to the upper catchment.

3.2. Interpretation of the 2D Imaging

Resistivity is a fundamental physical property of the earth which is extremely variable between rock types, but also with in a rock depending on different factors. Some of the main controlling factors are porosity and connectivity of pores, amount and salinity of water, temperature of pore water and resistivity of minerals present the rock or soil. To transform the resistivity values into a meaningful geological picture it requires basic knowledge of the typical resistivity values for the different types of subsurface materials and geology of the surveyed area.
Hence the geological data obtained from existing boreholes and the test wells are the basis for interpreting the 2D resistivity Imaging. According to the lithologic logs of the test wells and data gathered from archives the major subsurface formations of the study area are clay, silty clay, fine to coarse sand, pebbles and boulders, and volcanic rock (trachyte??). The common resistivity values of various rock types are shown in Figure 3-1, however during the field work an attempt was made to correlate the resistivity values with the lithologic logs of one of the test wells (TBH1). This is important due to the fact that it will reduce the effect of equivalence in addition to estimating the resistivity values of the different formations.
Roughly the following resistivity values are obtained for the different lithologies in the study area; however there may be some overlaps and discrepancies during the correlation; Hence during interpretation of the recent study, an attempt was made to integrate the results with previous studies and geological logs of the wells around.

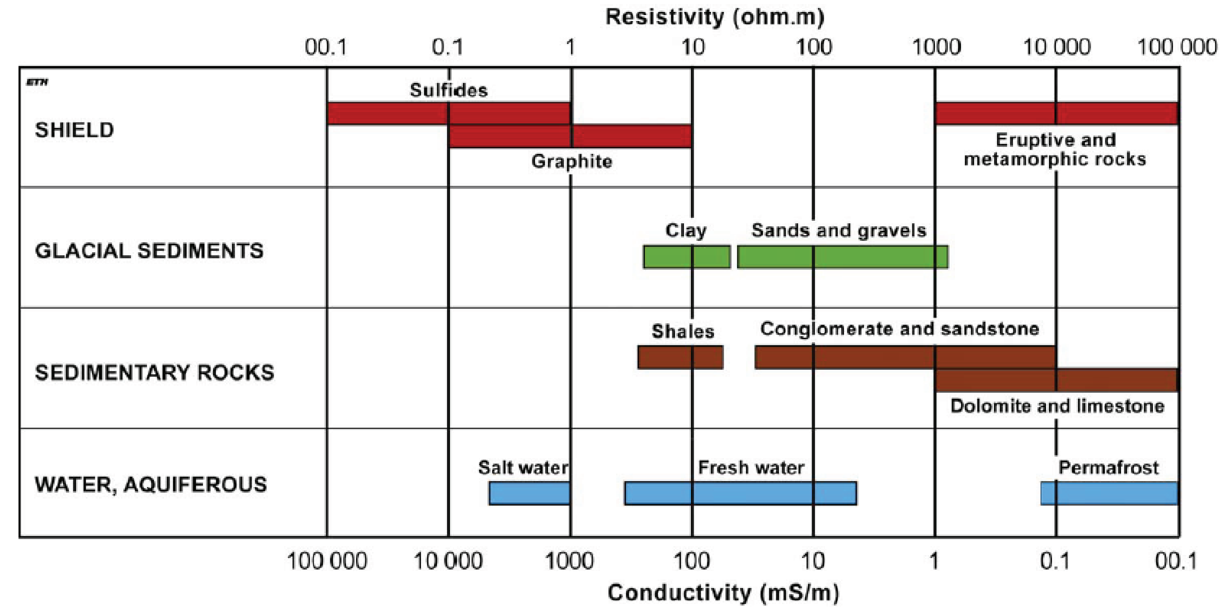


Figure 3-1 : Resistivity of rocks and minerals (Taken from Electrical Surveying Lecture Note, WS0607)

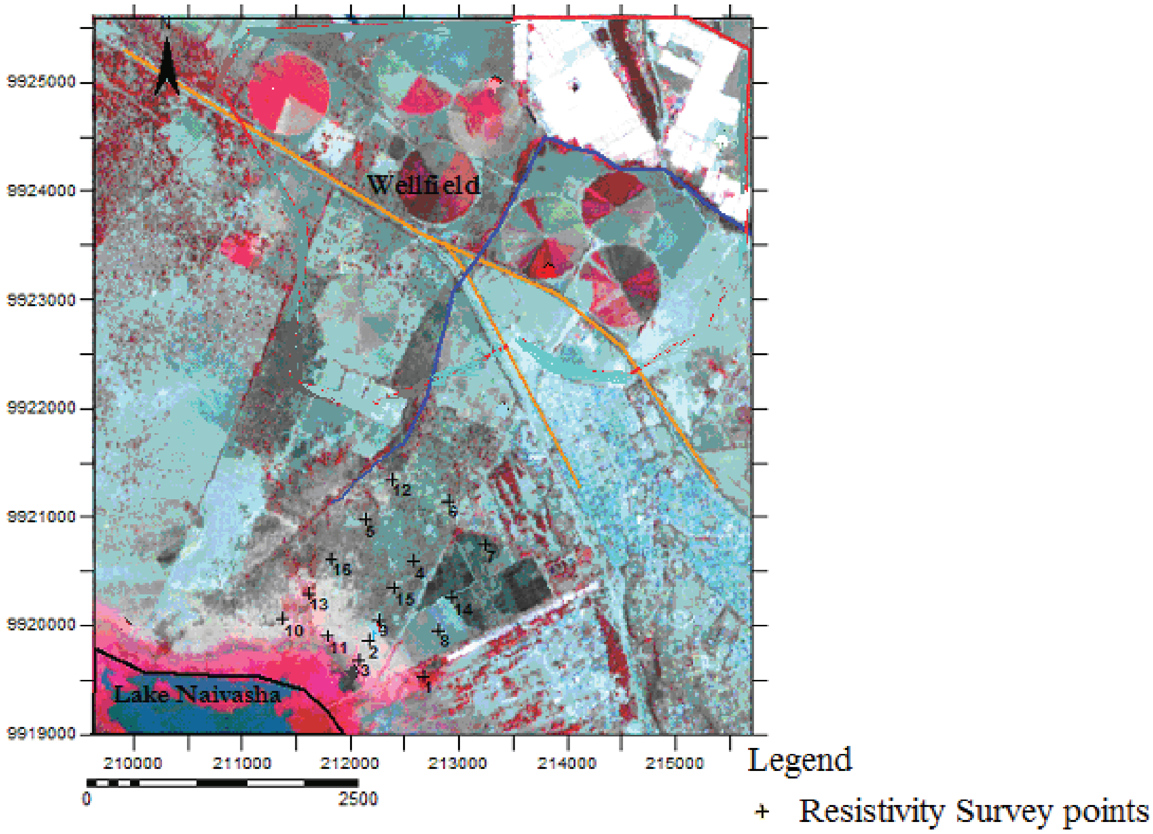


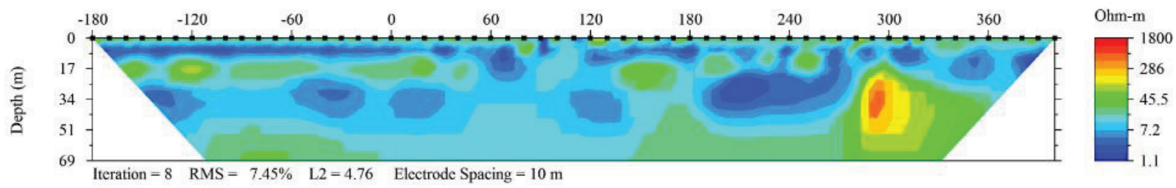
Figure 3-2: Location map of the 2D resistivity surveys

Table 3-2 : Estimated resistivity ranges of the rocks in the study area

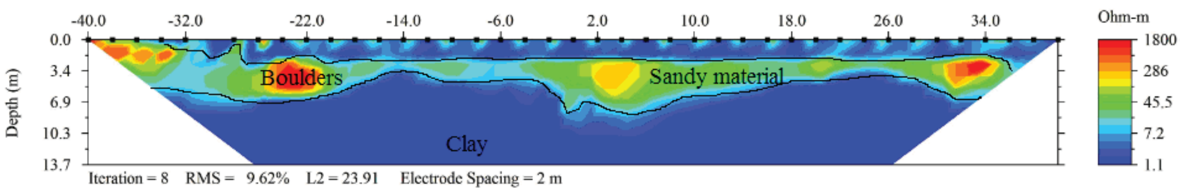
Material Type	Formation Resistivity Range (Ohm-m)
Boulder and fractured trachytes	335 -- 2000
pebbles, gravel and boulders	80 -- 300
medium to coarse sand	45 -- 80
fine to medium sand	20 -- 45
Silty and sandy clay	7 -- 20
clays	< 7

During the inversion of the 2D imaging some of the profiles showed similar results, hence only the ones which are supposed to be representative of the area are discussed below.

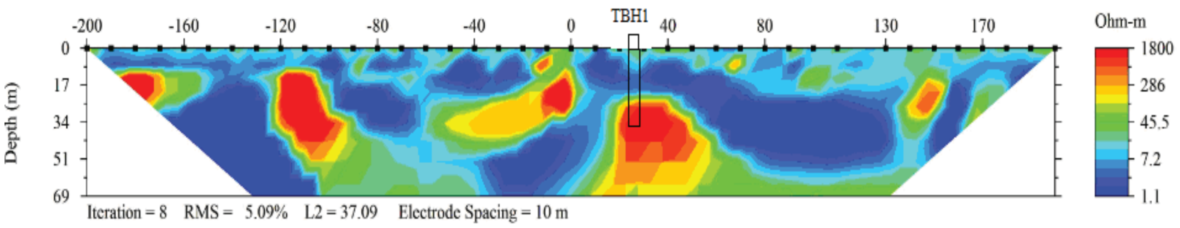
NAIV2D_1



NAIV2D_3



NAIV2D_9



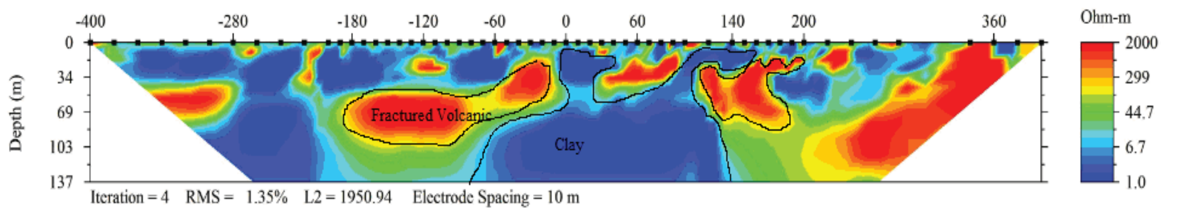
NAIV2D_1 is located closer to the lake and the orientation of the profile is nearly NW-SE with electrode spacing of 10m.

The geological interpretation of the 2D resistivity imaging incorporates information from the new test boreholes (Test BH1, and TBH3) which are the closest to the area where the geophysical survey was carried out.

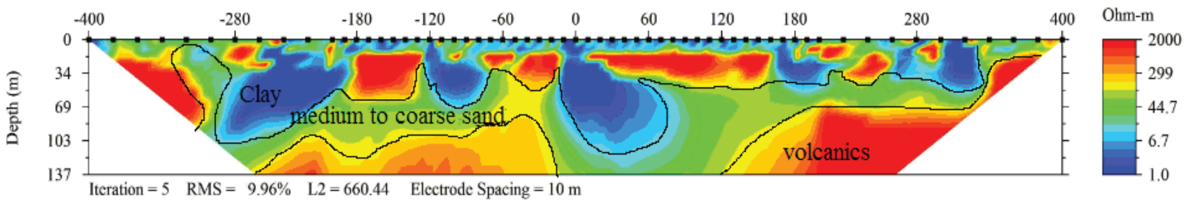
The top formation (0 - 10m) towards the lake side is clay dominated, where as away from the lake the formations are intercalation of silty clay to fine sandy clay materials. The clay is forming continuous thin layer (blue colour). The formation between 10 - 55m is an intercalation of clayey and silty materials but in between there is thin layer (green colour) of fine to medium sand (15 – 20m). Away from the lake at a depth of 30 – 40m there is an indication of a patch of gravel to boulder material. Below 55m the formation is uniform and it could probably be fine to medium sandy material.

NAIV2D_3 is located further northwest of NAIV2D_1 closer to the lake, and the orientation of the profile is nearly NW_SE. This resistivity imaging was done with electrode spacing of 2m (higher resolution than NAIV2D_1) to observe closely how thick the clay layers are near the lake. As can be seen from the inversion result, there is clear distinction between the coarser sediments and the clay layer. This result is supported by the lithologic logs of the test borehole, TBH3 which is the closest to the profiling. The formation between 0 - 3m is a mixture of silt and clay soils; however in between 3 - 7m the formation is dominated by medium to coarse sandy materials. The clay layers are mainly observed starting from around 7m and below. The core samples taken at a depth of 8 - 9m from TBH3 also show that the main formation at that depth is clay.

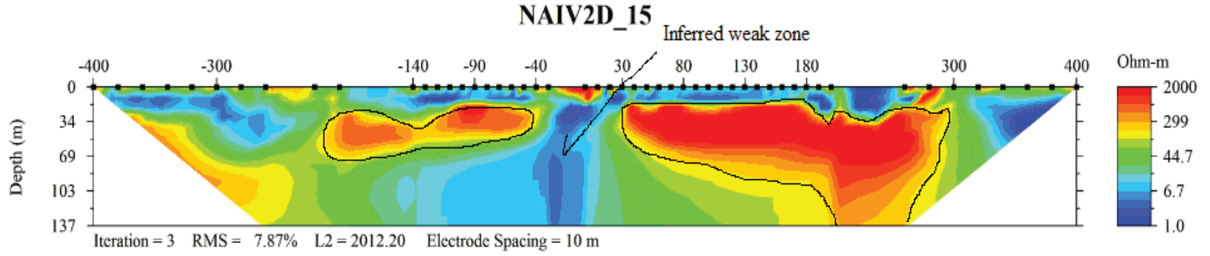
NAIV2D_13



NAIV2D_14



NAIV2D_15



NAIV2D_9 Resistivity Imaging was carried out very close to TBH1, and its orientation is nearly NW-SE. The unit electrode spacing is 10m and the electrode separation 400m. This site was mainly chosen to look how closely the inversion of the 2D-imaging resembles the actual drilling results, and to explore the geological formation beyond the drilled depth of the borehole which is 38m. The subsurface geology of this area can be subdivided in to three major materials as can be seen in the image. The very low resistivity values (blue colour) may belong to moist clayey materials where as the intermediate values (light green and yellow colour) are indicating medium to coarse sand. On the other hand the materials with higher resistivity values (red colour) can be mixtures of gravels and pebbles with fractured volcanics.

The lithologic logs of the test borehole (TBH1) are in good agreement with the 2D imaging results. The top most part shows intermediate resistivity (silty or sandy clay materials) followed by the low resistivity materials (probably clay) and again intermediate resistivity. At a depth of nearly 30m, where the borehole is located the materials show higher resistivity, which may be associated to fractured volcanics (trachyte).

The profile of NAIV2D_13 is oriented nearly north – south. The inversion result doesn't show well defined trend, but in general the following observations are made.
The top formation up to a depth of 34m towards the lake show lower resistivity values; however on the other side away from the lake the materials are intercalated with relatively coarser sediments. The materials with lower resistivity values are interpreted as moist clay and silt, but in between there are some intercalations of sandy and gravely deposits. Around the midpoint of the profile (-180 to -60m) underlying the silty clay formation, highly resistive material was detected; this material could be a volcanic sill (trachyte??).
In the nearby test borehole (TBH1) the trachyte was encountered around a depth of 35m, so it is reasonable to assume that this could be the same rock. However since the total depth of the test well is 38m it is difficult to know how deep this formation could go. The other interesting aspect of this profiling is that a formation with very low resistivity value was detected at about 70m and continues through out the depth of investigation. This material could be a mixture of clay and saline water. Similar results were reported in previous geophysical studies at about 80m around Three Point Farm (Tsiboha, 2002).

NAIV2D_14 is oriented nearly North-South direction. The upper most formation (0 -17m) almost throughout the survey line is dominated by relatively low resistivity material which is interpreted as intercalation of clay to fine sand materials. Underlying this formation highly resitive material is detected which is probably fractured volcanic rocks and boulders (34-50m), but it's not continuous through out the profile. Below this unit there is a thick and continuous layer of medium to coarse sand which is probably the main aquifer in the area. The basement rocks (volcanics) are found at an approximate depth of 104 m. The interesting aspect of this survey is that a weak zone is inferred about midway of the profile survey line; and is set to continue up to a depth of 100m.
NAIV2D_15 is also oriented in nearly North-South direction parallel to NAIV_13 but to the east. The formation at the middle of the profile shows lower resistivity which is probably an intercalation of silt and clay materials throughout the section (15 - 130m). Further from the centre on either side of this silty clay material, there is a big contrast in the resistivity values with the adjacent formations. These materials could be fractured volcanic rocks of trachyte origin. Hence the region in between the volcanic rocks could probably be a weak zone which is filled with low resistivity sediments (intercalation of silty clay materials with saline water).

3.3. Discussion of the 2D Imaging reults

The main findings of the 2D Resistivity Imaging surveys are summarized and discussed below

- In most of the survey lines the top layer formations(up to 15m) are made of silty clay to fine sand materials, but they are becoming progressively clay dominated towards the lake side
- Beneath these layers up to a depth of 34m relatively high resistive subsurface materials are found; but they are not continuous through out the profile lines. In between there are some materials with lower resistivity values. However based on evidences from lithologic logs of the test boreholes there (TBH1 and TBH3), these materials are interpreted as mixtures of gravels, sand, silt and clay sediments.
- In the profile lines with longer electrode separations (800m), higher resistivity materials are encountered at depths of 30 to 69m. These materials could be fractured volcanic rocks (trachyte) or boulders, but the later may not be true since some of these materials are extensive both laterally and depth wise. In TBH3 the hard rock was encountered at a depth of 34m, further supporting that the material could well be a volcanic rock.
- The subsurface materials below 69m are only detected in the longer profile lines (800m electrode separations). As we go deeper the resolution of the instrument may not be as reliable as the

shallower depths In profile NAIV2D_14 the materials between 69 to 103m are interpreted as medium to coarse sand and gravels. The hard rock is detected around 103m. But at about the mid points of profiles 14 and 15 very low resitivity materials were detected and set to continue up to a depth of 100m. These materials could be mixtures of clayey silt materials with saline water (resistivity values less than 10 Ohm.m).

- Based on the inversion results of this survey no significant structural features are detected. However in profile lines 13, 14 and partly 15 some weak zones are inferred which could be vertical openings filled with low resitivity materials.

3.4. Geophysical investigations around the wellfield

Prior to this study some geophysical surveys have been conducted around Lake Naivasha that includes gravity, magnetic anomaly surveys and resistivity soundings. Some of these works have been carried out regionally for the purpose of geothermal prospecting south of the lake. But the most important work was done by Tsiboha, 2002 to model the groundwater system northeast of the lake.

He has combined Two-Dimensional (2D) Resistivity Imaging and Transient Electromagnetic (TEM) methods to model the groundwater system of the aquifers northeast of Lake Naivasha on three farms; Three Point, Manera and Homegrown. In his study he has made13 Resistivity Imaging Survey profiles of different lengths (total length of 8,430m) and 137 TEM soundings. As can be seen in Figure 3-3, the main focus of that survey was north of the main road around the well field.

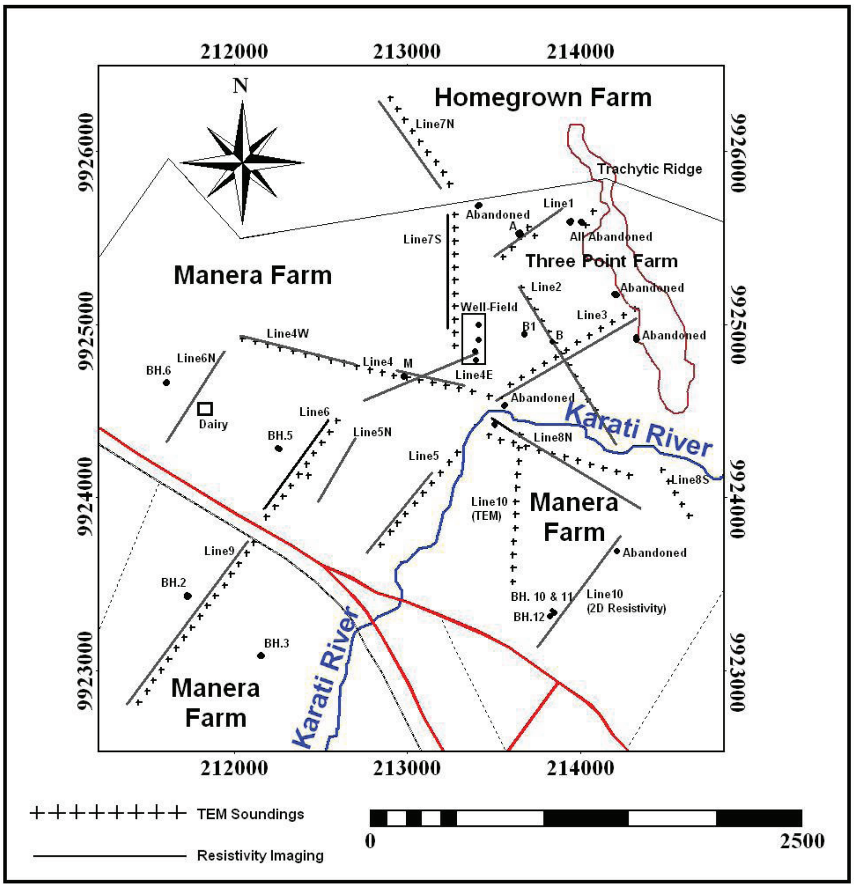


Figure 3-3 : Time Domain EM Sounding Positions and Resistivity Imaging profiles locations (Tsiboha, 2002)

The formation resistivity physical property, groundwater quality and lithology are used to model the aquifer. According to the analysis a representative aquifer model to meet the desires of the farmers had a formation resistivity range of 12 - 335 Ohm.m. The aquifer exists generally between depths of 20 to 80m in the Three Point Farm area.

However, in the Manera Farm, the aquifer splits up into two but remains hydraulically connected; a top (between 20 - 40m) and bottom (between 50 - 80m) aquifers towards the Lake. The main aquifer materials include fine sands, medium coarse sands, gravels, pebbles and fractured volcanics. Laterally, the main aquifer zone occurs within a radius of approximately 1km from the main Karati river (90^{o}) "bend" on the Three Point Farm (Figure 3-3). The ephemeral Karati River has also been identified as the main source of recharge into the aquifer. However, recharge to the immediate north would be high compared to the southern portions due the flow direction of the river. The very low resistivities at depths greater than 80m have been identified as a mixture of clayey materials and saline water.

Profile Line9 is the closest to the location of the current 2D Resistivity Imaging geophysical surveys. Using the two survey methods (2D Resistivity Imaging and TEM) it was carried out in front of the offices of Manera Farm (Delamere Office) along borehole numbers 2 and 8(Figure 3-6). The sections show a high resistive top layer of about 12m thick but not continuous. This could possibly be coarse sand, though it is labeled as sandstone in near by borehole No.8 litho-log (Figure 3-4). Beneath this layer is a complex mixture of coarse sand, silt and clay. However, towards the south where BH.8 is located, a continuous appreciable amount of clay exists at greater depths.

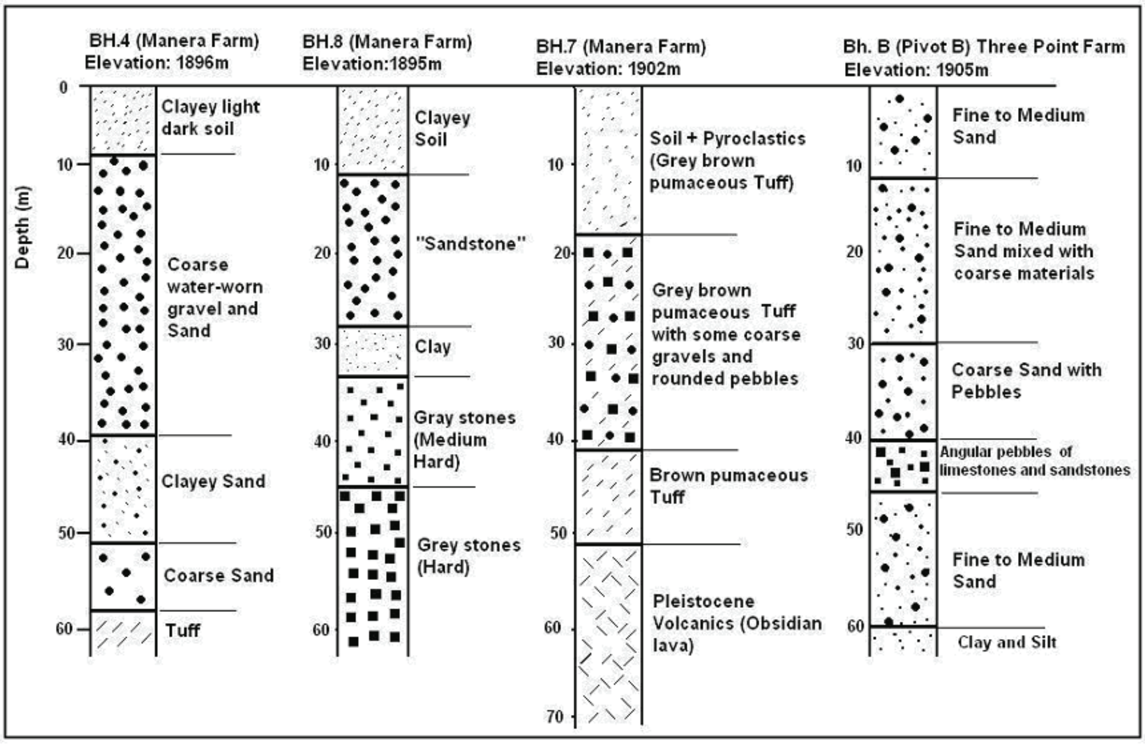


Figure 3-4: Lithological logs for four boreholes: BH.4, BH.8, BH.7 (Manera Farm) and BH.B (Pivot B), Three Point Farm.

3.4.1. Structural interpretation

No prominent geological structures are observed on the sedimentary environment of the study area. However vertical and sub vertical faults occur in areas closer to the rift wall that is the eastern margin of the study area. The presence of these minor faults has resulted in minor block shifting leading to horst and graben topography (Figure 3-5). The NW running portion of Karati River is fault controlled (Figure 3-3).

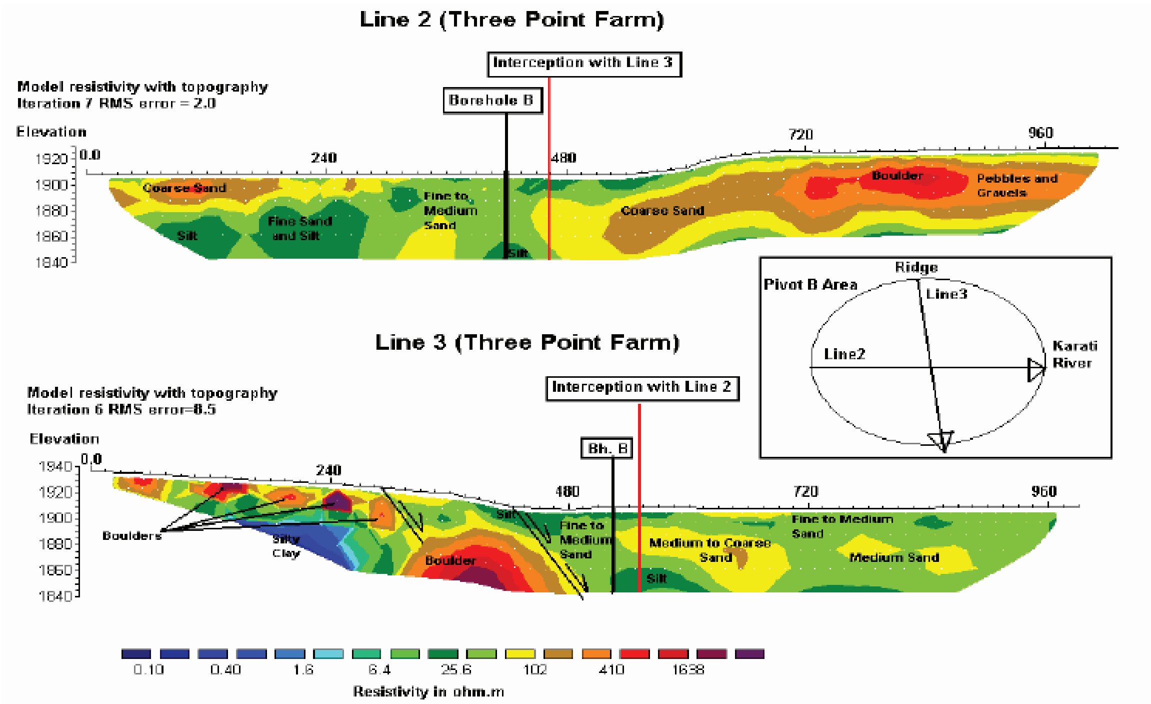


Figure 3-5 : Geological Interpretation of 2D Resistivity Imaging Lines 2 and 3(Tsiboha, 2002).

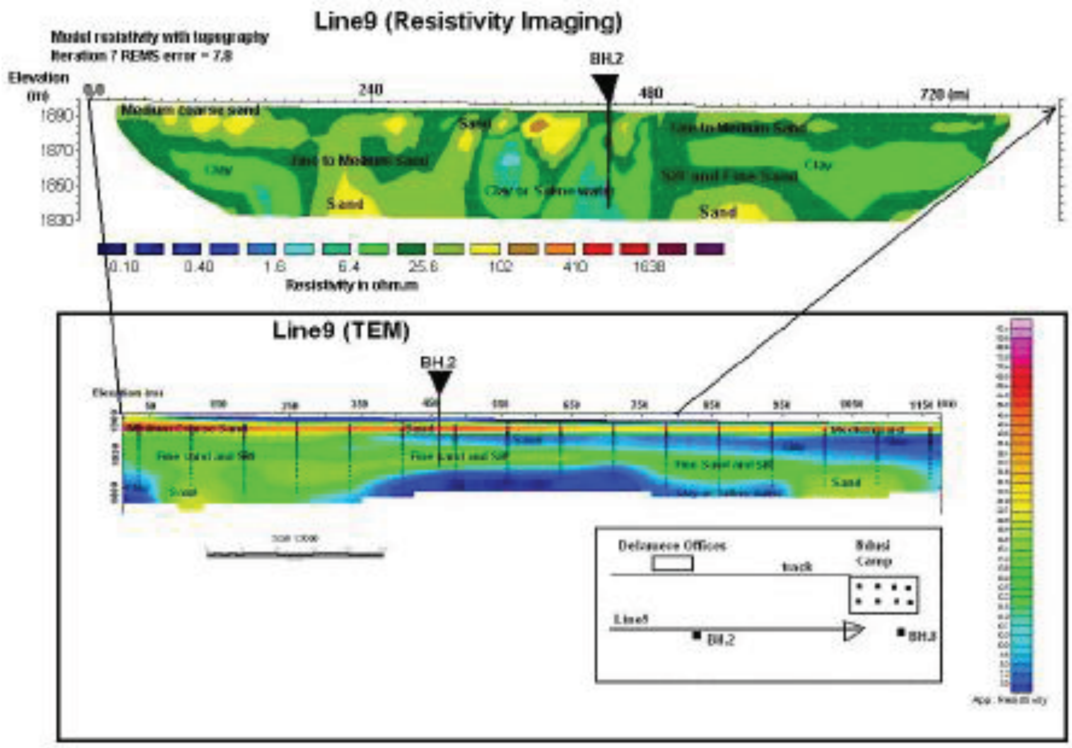


Figure 3-6 : Geological interpretation of the model sections of Line9 for resistivity imaging and TEM (Tsiboha, 2002)

4. STABLE ISOTOPES

4.1. Basic principles and sampling protocols

Stable isotope studies are based on the tendency of some pairs of isotopes to fractionate, or separate into light and heavy fractions. This fractionation occurs during some geologic process, such as evaporation or heating. The elements that are used in stable isotope studies are able to fractionate readily, are fairly common, have a relatively large difference in mass between the two isotopes, and have one isotope that is much more abundant than the other (Fetter, 2001).

The stable isotopic composition of a water sample is defined by the relative abundances of the heavy isotopes to the lighter ones ($^2H/^1H$ and $^{18}O/^{16}O$). Relative abundances are expressed in delta (δ) values that compare the isotopic composition of the water of interest to the isotopic composition of a standard, such as Standard Mean Ocean Water (SMOW).

$$\delta o/oo = \frac{R_{Sample} - R_{SMOW}}{R_{SMOW}} * 1000$$ ---------------------------- Equation 4-1

Where R is the ratio of the heavy isotope to the light one ($^2H/^1H$ or $^{18}O/^{16}O$) of the sample and the standard, and the results are expressed as parts per thousand (o/oo).

Graphs of δ^2H vs. $\delta^{18}O$ values for meteoric water samples tend to fall along a straight line defined by the following equation which is known as Global Meteoric Water Line (Craig, 1961);

$$\delta^2H = 8\delta^{18}O + 10$$ -- Equation 4-2

The Global Meteoric Water Line (GMWL) is an average of many local or regional meteoric water lines whose slopes and intercepts may differ from the GMWL due to varying climatic and geographic parameters. In general however, warmer, tropical rains have higher δ values, while colder, polar precipitation has lower δ values. Lake waters plotting on or close to the GMWL are isotopically the same as precipitation, whereas lake waters that plot off the GMWL on a Local Evaporation Line (LEL) have undergone kinetic fractionation. Molecular diffusion from the water to the vapour is a fractionating process due to the fact that the diffusivity of $^1H_2{}^{16}O$ in air is greater than $^2H^1H^{16}O$ or $H_2{}^{18}O$. With evaporation the isotopic composition of the residual water in the lake and the resulting water vapour become progressively more enriched, in both cases the kinetic fractionation of ^{18}O exceeds that of ^2H. In general, groundwater-fed open lake waters should have a $\delta^{18}O$ and δ^2H composition similar to mean weighted values for precipitation, and fall on a MWL. Evaporating lakes will have $\delta^{18}O$ and δ^2H values which lie on a LEL with a slope determined by local climate (Clark and Fritz,1997).

The isotopic composition of a water sample is often described by comparing the location of its δ^2H and $\delta^{18}O$ values with respect to the meteoric water line. Hence a water source's stable isotopic composition is a function of its origin and any subsequent isotopic fractionation. This is the basis for the interpretation of the stable isotopes of hydrogen and oxygen. Isotopic signatures imparted by surface evaporation makes it highly effective tracer of surface water flow to aquifers.

Water molecules containing the lighter ^{16}O molecules are slightly more prone to evaporate than water containing the heavier ^{18}O. Therefore, surface water exposed to evaporation will become relatively enriched by the ^{18}O isotope compared to average precipitation or groundwater. Lakes with water residence times of years will often show several parts per thousand, o/oo differences in the $\delta^{18}O$ values with groundwater values. Equation 4-1, describes the normally used calculation of fractionation where measured sample is compared with the Standard Mean Ocean Water value (Appelo and Postma, 2005).

During the fieldwork 11 water samples were collected from the newly drilled test wells, the lake and the production wells in the well field. The location and description of the samples is shown in Table 4-1.
The samples were collected according to International Atomic Energy Agency's (IAEA) guidelines for stable isotope sampling. When sampling for oxygen – 18 and deuterium, no sample filtration or preservation is required. The samples were collected using 50 mL, double capped polyethylene bottles directly from the sources. The bottles were tightly capped, and the samples were preserved in refrigerator before they were transported to the laboratory to prevent any fractionation, a process that would ultimately change the analysis results. Analysis of the samples was carried out at Health and Environment Department, Environmental Resources and Technologies, Austrian Institute of Technology (AIT) in Austria. Results of the laboratory analysis are interpreted and discussed in the next section.

Table 4-1 : Stable isotopic data of the study area

Codes	E	N	2H	18O
Malewa River	209179	9926386	-1.3	-1.94
TBH1	212252	9919976	+23.3	+3.44
TBH2	213408	9921984	-17.3	-3.65
TBH3	212041	9919574	+2.8	-0.14
TBH4	209933	9920016	+25.9	+3.78
pump house, BH	213334	9924976	-18.2	-4.00
Delamere (BH10)	213829	9923262	-19.0	-4.08
Creative	215440	9924462	-22.0	-4.40
Lake(pelican)	211827	9919424	+33.5	+5.46
Lake1	207523	9916287	+16.9	+1.97
Lake2	208012	9911358	+15.7	+1.81

4.2. Estimation of Lake water content

Interpretation of the Isotopic Signatures is based on the assumption that samples lie along the Direct Recharge_ Lake Water Mixing line. The assumption involves simple mixing model between Rift flank groundwater and highly evaporated lake water. Hence all the samples are assumed as mixture of the two end members, that is direct recharge water (rainwater) and lake water. Using this assumption it is possible to trace subsurface water flow by its lake water content.
Based on rainwater sampled from Rift Valley meteorological stations in the Naivasha area the average $\delta^{18}O$ and $\delta^{2}H$ values of rainwater is -4.8 o/oo and -25 o/oo respectively. Where as the mean δ values of ^{18}O and ^{2}H isotopes for Lake Naivasha is about + 6.6 o/oo and + 36 o/oo respectively (Allen et.al. 1989). Oppong Boateng (2001) has also found out closer mean $\delta^{18}O$ values for the lake and rain water. According to Boateng the mean $\delta^{18}O$ values of Lake Naivasha and the direct recharge from rainwater is +6.6 o/oo and -5.75 o/oo respectively. The mean $\delta^{18}O$ values from Boateng are used for calculating the lake water content.

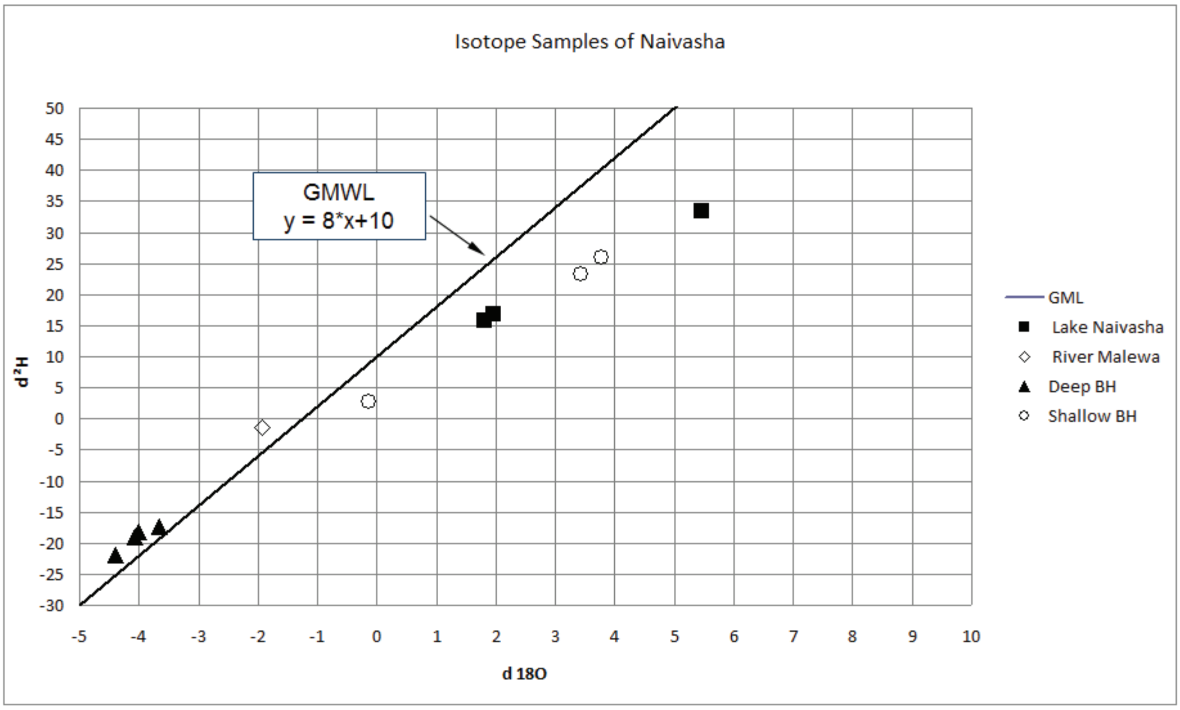


Figure 4-1 : Plot of δ2H versus δ18O for waters in the Naivasha area

In the figure above;
GML stands for Global Meteoric Water Line,
Shallow BH represents TBH1, TBH3, and TBH4
Deep BH represents TBH2, Pump house (BH), Delamere (TBH10), and Creative boreholes
Lake Naivasha represents the samples taken from the lake

Analysis of water level data generally shows flows are directed towards Lake Naivasha from the eastern and western rift flanks, figure 3-5. Therefore the groundwater is more likely to mix with evaporated water outflow from Lake Naivasha. Hence the boreholes in between the lake and the eastern Rift flank are assumed to lie along the Direct Recharge - Lake water mixing line.
Assuming the water from the sampled boreholes has a ratio X of lake water and the rest being direct recharge from rainfall (1-X), then:

$6.5\ \delta^{18}Ox + [-5.75\ \delta^{18}O\ (1-x)] = [Sample]^*\ \delta^{18}O$ --------------------- Equation 4-3

Where;
6.5 and -5.75 are mean $\delta^{18}O$ values of the lake and direct recharge water (rainfall) of the Naivasha basin respectively and [Sample] is the measured $\delta^{18}O$ value of the water sample under consideration.
Applying Equation 4-3, relative proportions of the lake water and direct recharge are calculated and the results are shown in Table 4 -2.

Table 4-2: Relative percentages of lake water and direct recharge

Sampled wells	Percentage of Lake water	Percentage of Direct Recharge
TBH1	75	25
TBH2	17	83
TBH3	44	56
TBH4	78	22
Pump house, BH	14	86
Creative	11	89
Delamere,BH10	13	87

4.3. Interpretation and discussion of results

All the sampled wells are found northeast of the lake, Figure 4-3. From the plots of Figure 4-1, two main observations can be made. The first observation is that the shallow boreholes along with the lake water are enriched in the heavy isotopes. The samples are plotted away from the GMWL, but along the evaporation line indicating that they are highly affected by evaporation. The second observation is the deep boreholes almost lie on or closer to the GMWL and they are depleted in the heavy isotopes.

The results of Table 4-2, showed that TBH1, TBH3 and TBH4 have higher proportion of lake water. These boreholes are located closer to the lake and their depth is shallower (17 to 37m) as compared to the other wells. The isotopic signature of the lake water is stronger in the nearby wells, as compared to the wells located further from it. However this may not be the case for all the wells. TBH3 is found closer to the lake but the proportion of lake water is lower than TBH1 which is located further away from the lake. One of the possible explanations for this phenomenon could be the contrast in hydraulic conductivity between the formations around the two wells. The 2D resistivity imaging results of NAIV2D_3 revealed a strong presence of very low resistivity material around TBH3 which is interpreted as clay layer. However, the isotopic signature of the lake water is generally weaker further from the lake towards the well field, which is located northeast of the lake.

The deep boreholes TBH2, pump house BH, creative BH and Delamere (BH10) are found a few kilometres away from the lake. The isotopic plots of these wells lie very close to the Global Meteoric water Line (GMWL) and they are depleted in the heavy isotopes. With the exception of TBH2, the three wells are found around the well field (Panda and Delamere farms); and they are also closer to the eastern escarpment than the shallow wells. As can be seen in Table 4-2 these wells are predominantly recharged by the direct recharge/precipitation from the eastern rift flank. Figure 4-2 below compares the proportion of lake water with distance.

The most important results of this isotopic analysis are, signature of the lake water is stronger in the nearby wells to the lake but gets weaker with distance. Secondly the wells around the well field are mainly recharged by direct precipitation from the eastern rift flank. The third observation is that the shallow wells have higher proportion of lake water than the deep wells. Eventhough the samples taken from the lake are plotting along the evaporation line, their degree of enrichment in the heavy isotopes varies. The sample with the highest isotopic enrichment (Lake Pelican) was collected from the very shallow swampy portion of the lake (Figure 4-3). The reason for the enrichment could be this portion of the lake doesn't get much of fresh river water flushing and it's relatively shallower depth may have exposed it to higher degree of evaporation. The lake sample which is relatively depleted (Lake 2) among the three is located around the suspected subsurface outflow zone of the lake. As a result the water is getting flushed more frequently and its residence time is relatively shorter. Hence its probability of exposing to evaporation is minimal as compared to the others.

These results are consistent with previous isotopic studies carried out around the area. Yihdego, 2005 has found that the main source of recharge for the wells around Three Point Farm (well field) is meteoric water. Two of the current samples were collected from the same area. This is done to observe the effect of abstraction around that area through the years and check whether the proportion of lake water has increased as a result. But according to the current results there is no significant difference in the percentages of the lake water between 2004 and now; which are 16% and 14% respectively. There may be two main reasons to explain this. The first reason can be with the current abstraction rate the cone of depression created in the wellfield doesn't reach the lake. And the second reason may be the wells around the wellfield are getting their recharge from the nearby rivers and direct precipitation from the rift flank. The second explanation is supported by previous studies made around the area. Even the current water sample taken from Malewa River has similar isotopic composition to GMWL and the deep wells in the Panda and Delamere farms.

Using the standard δ^2H vs. $\delta^{18}O$ isotope data, Ojiambo et al. (2001) have shown that Manera Farm wells and Nandarashi River water are depleted in the heavier isotopes as compared to the groundwater in the southern basin(Figure 4-4). The River and Manera Farm waters fall on or close to the meteoric water line indicating direct recharge from Rift flanks rain water. Rain water from the Rift floor is highly evaporated as compared to elevation rain water, which is similar to the Nandarashi stream water (Rozanski et al.1996). This implies that the rift floor rain water is enriched in the heavy isotopes of hydrogen and oxygen, probably due to the effect of evaporation. This may be another evidence that the precipitation recharging the deep wells around the wellfield has its source from the elevated/rift flank rainfall, not the local rainfall from the rift floor.

On the other hand when we look at the geological structures of the area, the place where Karati River is making a 90^o bend is believed to be the intersection of two faults (Tsiboha, 2002); and laterally the main aquifer zone occurs with in a radius of 1kilometer at the three point farm(Panda). Here the Karati River has been identified as the main source of recharge to the aquifer.

However, lake water and precipitation may not be the only sources of recharge for the wells in the northern plain. These wells may also get their recharge from the nearby streams Karati and Malewa.

The boreholes at Marula and Three Point Farms are highly depleted in δ^2H and $\delta^{18}O$, but have similar isotopic compositions to that of River Malewa (Boateng, 2001). The depleted isotopic composition suggests that the boreholes have their sources either from River Malewa or precipitation other than Lake Naivasha.

This is also confirmed from the isotopic composition of unsaturated zone of Marula ($\delta18O$ = -2.80 o/oo, $\delta2H$ = -23.6 o/oo) and Three Point ($\delta18O$ = -3.78 o/oo, $\delta2H$ = -26.7 o/oo) which are mixed of river Malewa and rain (Nalugya, 2003).

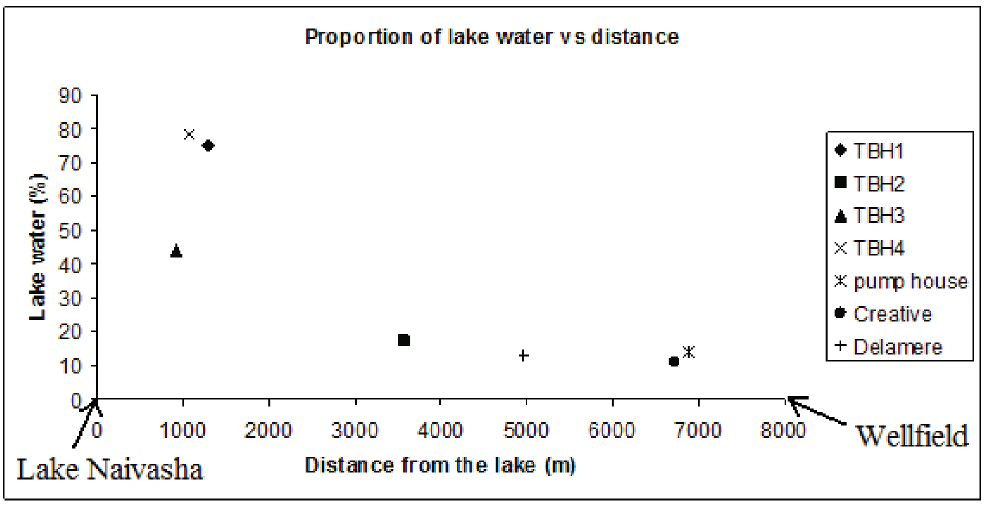


Figure 4-2: Proportion of lake water versus distance

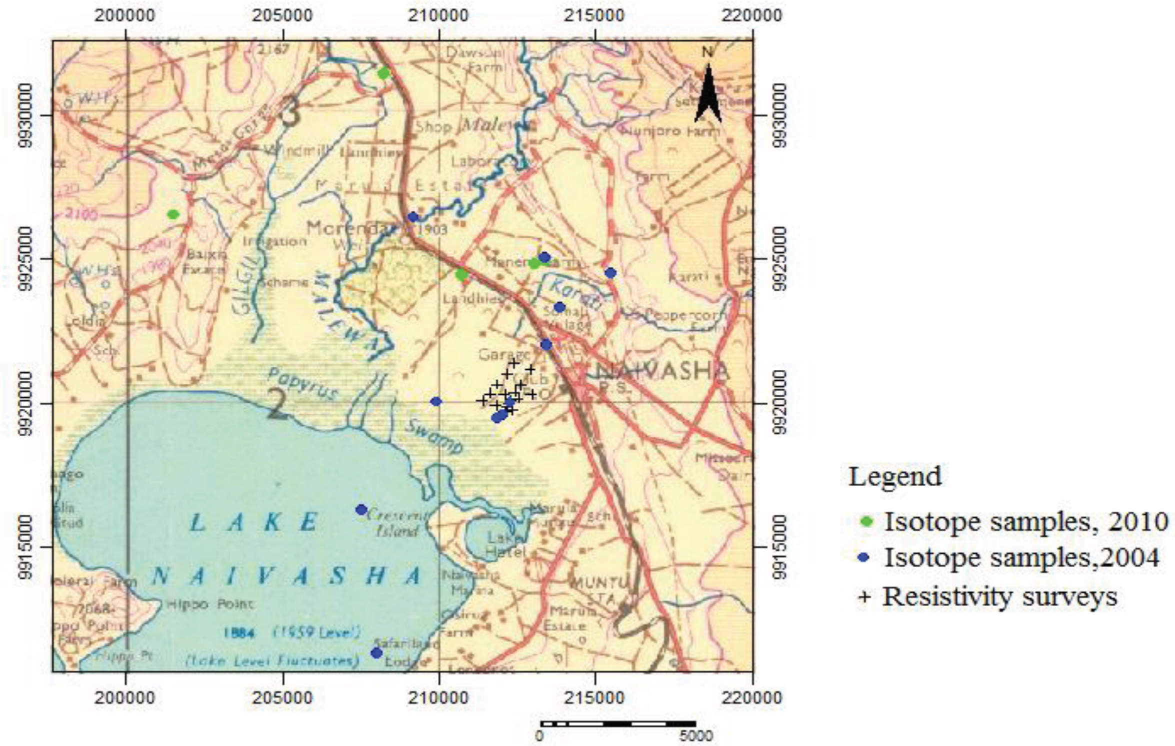


Figure 4-3 : Location map of isotope samples and geophysical survey lines

Lake Naivasha lies at around 2000 m.a.s.l. at the culmination of the Kenya Rift valley which extends from north to south. Because of this groundwater flow away from the lake is possible in both directions.

The high evaporation from the lake Naivasha has raised the amount of heavy isotopes in the lake water to concentrations considerably higher than those of river and groundwater from direct meteoric sources. The strong signal provided by this isotopic enrichment has enabled the progress of the subsurface outflow to be followed (Darling et al. 1990).

As can be expected the geothermal wells south of the lake are enriched in the heavy isotopes which is similar to the composition of Lake Naivasha (Figure, 6-9). The isotopic compositions are progressively enriched from Manera Farm wells to the geothermal wells, and Lake Naivasha where the highest value is observed in the Oloidien Bay. The reason why the Oloidien Bay is more enriched and more saline is that because it becomes highly evaporated for long periods during drought periods and during such times it receives no fresh water from the rivers (Verschuren 1999 as sited by Ojiambo 2002).

However Manera Farm wells and river water are depleted in the heavy isotopes as compared to the southern wells and plot on the meteoric water line, ruling out secondary processes such as evaporation prior to infiltration, or isotopic exchange with aquifer rocks and the lake. The groundwaters are probably recharged rapidly through fractures and faults with little influence of evaporation before recharge. Hence the most probable source of recharge here is that the rift flank rain water.

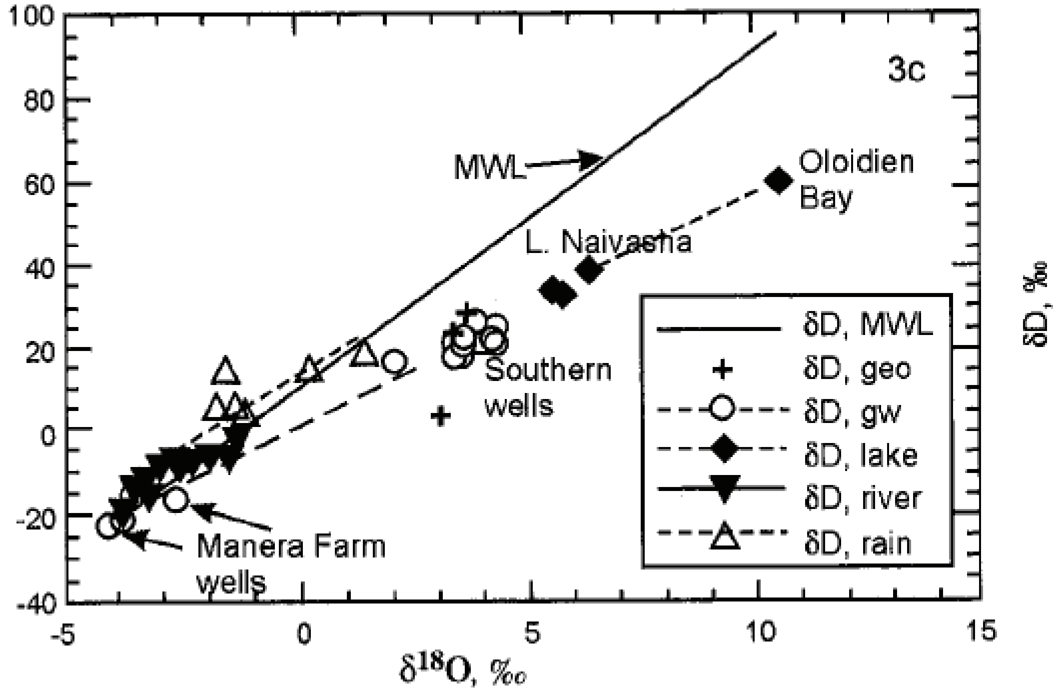


Figure 4-4 : Plot of δ2H versus δ18O for rain, surface and subsurface waters in the Naivasha area (after Ojiambo, 2001). Where; MWL - Meteoric water Line, Geo - Geothermal wells, GW – Groundwater

5. HYDROGEOLOGY

5.1. General hydrogeology of the northern plain

The hydrogeology of Naivasha basin is very complex and it is greatly influenced by several factors among which the geology, topography and climate are the most important ones (Clark, 1990).
Geological set up of the basin plays an important role in controlling the groundwater regime of the basin. Eventhough the geology of the basin is very complex, we can broadly classify it as sedimentary units and volcanic rocks (Figure 5-3). The sedimentary units are comprised of lacustrine and fluvial deposits of varying grain sizes. Some of the sedimentary deposits are also results of reworked volcanics. According to the data from test well drilling the lacustrine deposits are made of fine to coarse sediments. These materials include pebble, gravel, diatomites, coarse sand, silt and clay. The lacustrine deposits (Gamblian lake beds) are reported as rarely exceeding a thickness of 31m by Thompson et. al. (1963), and it thins out towards the scarps. However according to the data collected from test well drilling the thicknesses of these sedimentary deposits could reach up to 80 m (Figure TBH2). But that doesn't mean all the aquifers have uniform thickness through out the plain. This is especially true for the aquifers northeast of the lake. Since the main aquifer in the area is unconsolidated materials, the occurrence of groundwater is controlled by grain sizes, degree of compaction, and sorting of sediments. Based on lithologic logs of the test wells (Figure 5-1) the main aquifer units are composed of coarser sand, pebbles and gravels. Tsiboha (2002) in his geophysical modeling of the aquifers northeast of the lake showed that the main aquifer has a formation resistivity range of 12 – 335 Ohm.m, which are interpreted as medium to coarse sand, gravels and pebbles.
The other important geological units are the volcanic rocks. The Kenyan Rift Valley (KRV) is mostly underlain by volcanics with phonolitic, trachytic and rhyolitic composition and their sedimentary derivatives (Thompson et. al. 1963). The KRV volcanics were erupted nearly continuously from Early Miocene to Holocene times. These volcanic units widely vary in their distribution, thickness, lithology and degree of welding. Moreover the rocks have been subjected to several tectonic processes. As mentioned above, the lacustrine sediments northeast of Lake Naivasha are thicker. From the lithologic logs of the wells drilled so far only a few have struck the bed rock, indicating that most of the wells in the northern plain either have shallow depth or the sedimentary deposits are thicker. The lithologic log data of one of the wells around Three Point Farm, C11527 (see Appendix 2) showed that a bed rock (trachyte) was struck at a depth of 124m. The volcanic rocks in the area include lava flows, deposits of ash which may occur in loose unconsolidated piles or as welded tuff. The occurrence of groundwater under this formation is a function of different factors. These rocks lack primary porosity and the flow of water through them depends on secondary porosities, degree of welding, fracturing, weathering and faulting. In general these rocks are underlying the rift floor and most of the time they have low permeability unless they are affected by secondary processes such as fracturing and faulting. Faults and fractures could be the most likely controls of the flow of groundwater through the volcanic rocks in the rift valley.
The topography is also another factor influencing the hydrogeology of the Naivasha basin significantly. In the localized highland areas, there exist deep groundwater tables as well as steep groundwater gradient. This environment is often associated with high rainfall values, which are sources of groundwater recharge if all conditions are fulfilled.

5.2. Characterization of the aquifers NE of the lake

The north east part of Lake Navaisha area has been under continuous abstraction due to the large scale irrigation schemes in the commercial farms. This part of the basin is the place where maximum saturated

thickness of the lake bed aquifer is found and characterized by very high transmissivity. Characteristics of the aquifers are discussed based on the existing well records, geophysical survey interpretations and pumping test data where available.
The aquifers northeast of the lake can broadly be classified in to two major units as,

1. the lake bed aquifers and
2. aquifers in the fractured volcanic lavas or tuffs along the rift wall

The main aquifers in the study area include unconsolidated sediments, generally associated with the fluvial and lacustrine deposits. In addition to the lake bed sediments, reworked pyroclastic materials also make up the aquifer. The composition of these aquifer materials is highly variable, and their thickness could reach up to 80 m. According to the log data of boreholes in the area, the main aquifer materials include alternating layers of medium to coarse sand, gravels, weathered trachytic and pumiceous gravels and pebbles. However the lake bed aquifers are highly heterogeneous even with in a few kilometers radius. Borehole TBH1 was drilled very close to the lake and the bed rock was encountered around 34m; whereas in TBH2 there was no trace of the bedrock up to a depth of 84m (Figure, 5-1).

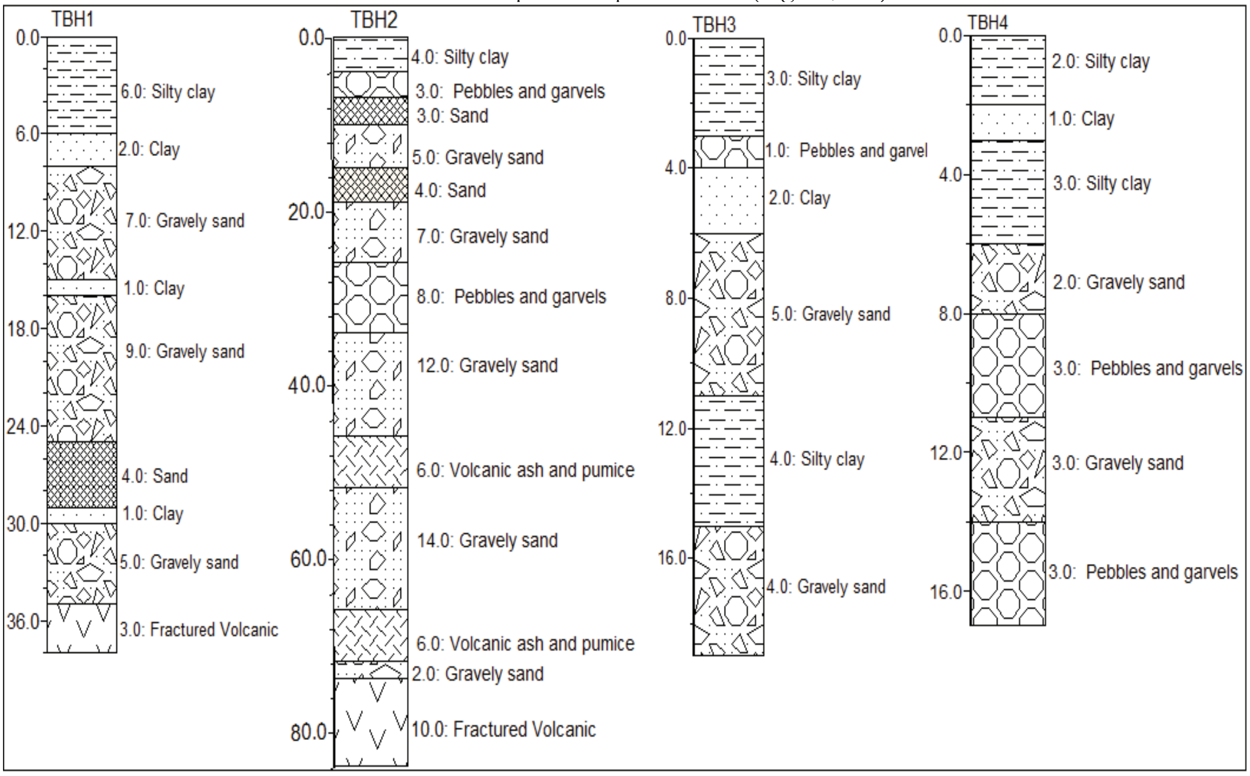


Figure 5-1 : Geological logs of the four test wells

Some important observations on the lithologic logs of the test wells are discussed below. TBH1 was drilled closer to the lake, and as can be expected the water table was shallow which is around 6m. The samples were collected every 1m; however core samples were also taken at 6m, 10m, 15 and 29m. At the different depths where the core samples were taken, thin layers of black sticky clays were observed. The main water bearing/aquifer unit is the relatively thick layers of sandy gravel materials. The drilling was stopped at 37m where a hard rock of volcanic origin, possibly trachyte was encountered. This material is also mapped during the 2D resistivity imaging survey. The depth of drilling for TBH2 was 84m, and the well is located about 2kms further NE towards the well field from TBH1. Depth of water table was around 19m, which is deeper than TBH1. This may be one indicator that the water table is getting deeper towards the wellfield. In the geologic log of this well no pure clay layer was found through out the whole section; and the main water bearing units were the gravely sand and pebble gravel formations. In some of the lithologic logs of the old wells (C11527) clay layers were reported in between 62 and 84m. However in

TBH2 with in the same depth range the materials are mainly pumiceous sand and gravel. Based on interpretation of the geophysical data NAIV2D_14, the formation between 69 to 103m was interpreted as medium to coarse sand and gravels. This could be one indicator that the aquifer materials are highly variable with in the basin. The lake bed aquifers are often unconfined but sometimes they could be confined/semi - confined under the clay layers as in the case of TBH1 and TBH4. Clark et al (1990) estimated by inventory of boreholes and envisaged that the lake sediments have permeability of 12-148 m/d.

In most of the wells around the well field the water levels are encountered at depths of 30 to 36m, but towards the lake side the water table is very shallow. In test wells TBH1, TBH3 and TBH4 which are drilled closer to the lake the water levels are encountered between 2 to 6m.

Boreholes in the Gamblian lake bed aquifers around Manera Farm are capable of producing yields in excess of 200 m^3/hr of water. However a drawdown as big as 6 m was also reported (Aquasearch Limited, 2001).

Particle size distribution analysis of soil samples taken from a shaft which is 45m deep in the middle of Three Point Farm (Panda) revealed that the grain size is generally increasing with depth (Table 5-1); and the main aquifers are sandy materials.

Table 5-1 : Percentages of grain size analysis

Soil depth, m	Gravel >2mm	Sand 50µm - 2mm	Silt 2µm - 50µm	Clay < 2µm
0	0.0	7.2	50.9	41.9
5	0.0	52.7	31.2	16.1
10	0.0	18.6	66.1	15.3
15	0.0	8.7	69.3	22.0
20	0.0	53.4	31.0	15.7
25	0.1	89.8	7.6	2.5
30	0.2	44.1	43.1	12.5
35	1.4	89.2	5.0	4.5
40	1.6	21.2	57.6	19.6
45	0.4	64.2	26.0	9.4

The general trend of particle size distribution shows that the proportion of sand particles is increasing with depth where as the clay particles are decreasing. On the other hand the proportion of silt doesn't show much difference with depth. The soil samples from a depth of 0 to 20m didn't show any kind of gravels, however this may not be necessarily true. Based on this observation we can generally say that the particle size distribution is fining upward. These fine grained materials could be representatives of lacustrine deposits. The geologic logs of most of the wells around the well field showed that the main aquifers are the sandy gravel materials.

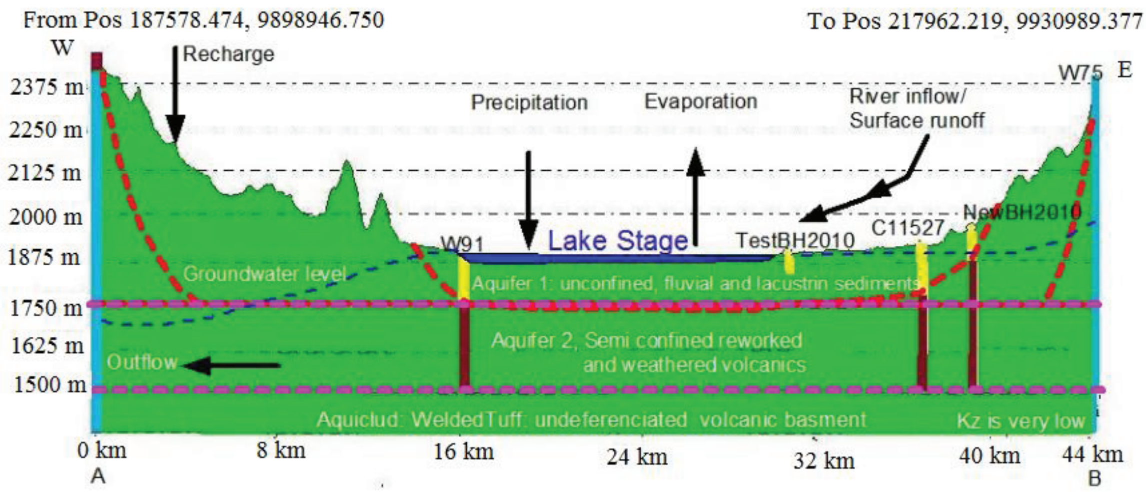


Figure 5-2 : West - East cross section from Mau to Kinangop Plateau showing the major hydrogeologic units

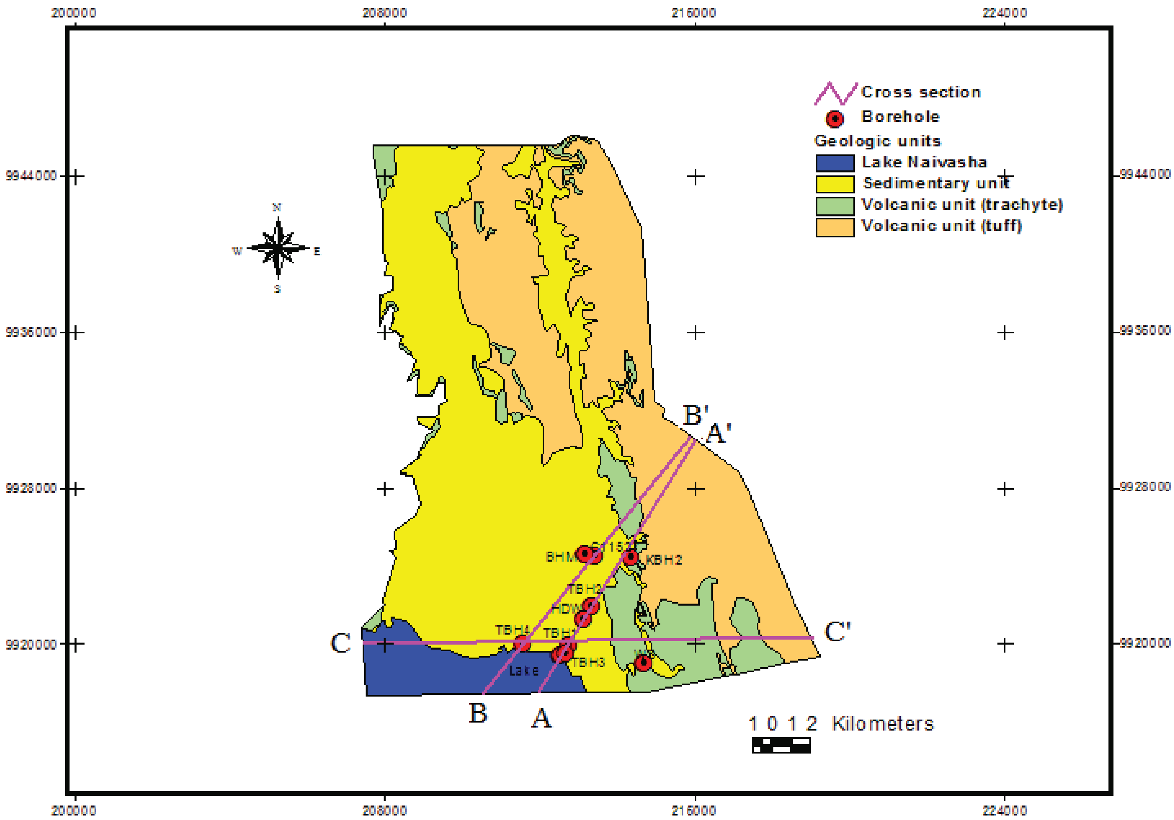


Figure 5-3 : Simplified geological map of the study area

The second aquifer is found in fractured volcanic rocks and at times along weathered contacts between different lithological units and they are often confined or semi-confined with low storage coefficient. Permeability is generally low in these aquifers but there exist some variations locally as a result of secondary processes. This formation is not exposed at the surface in the study area, but they are encountered at depth in certain boreholes. Towards the eastern margin of the study area they are found at shallow depth.

Borehole data are limited in the eastern escarpment, which is the eastern margin of the study area. However according to well data compiled by Clark et.al (1990) the estimated average hydraulic conductivity is 10 m/d and well capacity on average is 3 l/s/m.

Data from existing boreholes and wells reveal complex hydrogeological conditions and depth to water varies throughout the basin but it is generally ranging from 1.3m to about 240m.

According to historical piezometric heads of the 1980s the flow of groundwater is towards the rift floor from the eastern and western escarpments and consequently there is an axial north - south flow from the lake along the rift axis (Figure 3-5). The axial north – south flow of the lake can be explained by the relatively higher position of the lake in the rift floor. Moreover, based on stable isotope analysis of the geothermal wells and the lake water, most of the flow is directed towards the south (Clark et. al. 1990). Eventhough it is not as significant as the southerly flow, there is also northerly flow from the lake.

The current piezometric heads indicate a sink /cone of depression around Manera and Three Point Farms (Figure, 5-5), which are located in the northeastern part of the study area. This is believed to be the result of excessive abstraction of groundwater for irrigation around the commercial farms. The increase in the abstraction rate has got momentum starting from the 1980s. However the general groundwater flow is towards the lake. With the ongoing abstraction rate the groundwater flow doesn't show a reversal, i.e. from the lake to the wellfield. Based on stable isotope data analysis of water samples taken from three wells in the wellfield, no significant amount of lake water is found (refer Table 4-2). The insignificant amount of the lake water may be explained in two ways. Firstly the wells are getting their recharge not only from the lake but also from other sources. And secondly with the ongoing abstraction rate the cone of depression is yet to reach the lake. The first explanation is supported by the stable isotope data collected from the wells. The analysis results showed that the isotopic composition of the wells is similar to the direct recharge from the rift escarp and the nearby rivers. Moreover the two dimensional geophysical survey (Tsiboha, 2002) confirmed that the Karati River is fault controlled and it could be one possible source of recharge for surrounding wells. Here the role of the fault is to act as a channel of high permeability.

5.2.1. Pumping tests

Different researchers have calculated transmissivity of the aquifers around the lake and come up with different values. Kibona (MSc 2000) conducted pumping test in wells at Three Point Ostrich Farm in the lake sediments and come up with the following results. Using the Hantush method she estimated a transmissivity of 1150 m^2/d and storativity of 3.95×10^{-3}. While the Cooper-Jacob method yields a transmissivity of 462 m^2/d and storativity of 1.46×10^{-3}. Clark et.al. (1990) showed the average aquifer characteristics and lithologies of some selected areas around the lake from borehole data (Table, 5-2). Owor (MSc 2000) has summarized the pumping test results obtained from different sources (Figure, 5-4).

The distribution of transmissivity values shows high variation. This could be an indication of the heterogeneity of the geological formations in the area. The geological set up of the area may have great influence on the hydraulic conductivity. The area is highly affected by different types of geological structures such as volcanic cones and craters, faults and fractures.

In rocks with fractures, the size of the openings, degree of interconnectedness, and the amount of open space are important factors in determining the permeability. The volcanic rocks in the area may have high permeability if the openings are large and well connected. On the other hand these rocks may have low permeability if the openings are not interconnected. In this case the faults may play an important role by displacing the openings and even blocking the flow.

Table 5-2 : Average aquifer characteristics and lithologies, after Clark 1990(figures in brackets are arithmetic mean)

Area	Lithology	Geometric mean estimated Transmissivity m^2/day	Geometric mean estimated permeability m/day	Total number of boreholes
NE Naivasha	Sediment & volcanics	307 (1170)	12 (33)	35
SE Naivasha	Sediment & volcanics	502 (3082)	20 (114)	22
SW Naivasha	Sediment & volcanics	297 (940)	63 (196)	17
NW Naivasha	Sediment & volcanics	1601 (5308)	148 (818)	26

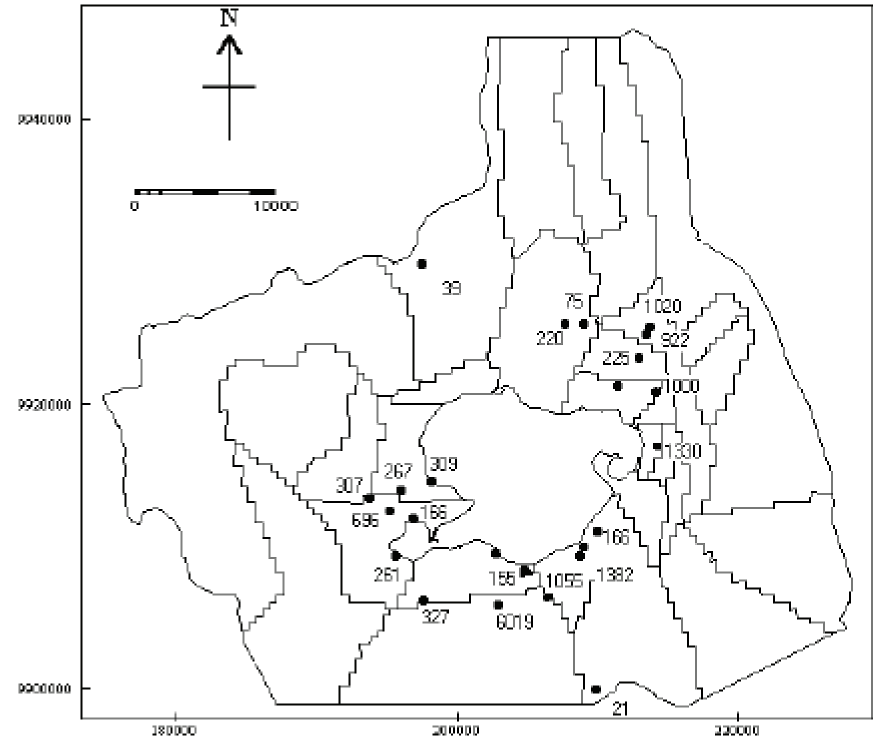


Figure 5-4: Distribution of transmissivity values around the lake (After Owor, 2000)

5.3. Groundwater abstraction

The study area has been subjected to intensive abstraction of groundwater for irrigational purposes since the 1980s. Especially northeast of the lake the groundwater is used as a primary source for irrigation by the commercial farms; and most of the wells are found as clusters.

Accurate estimation of the groundwater abstraction is difficult due to the fact that there is no well recorded data available through out the years. However the irrigated commercial farms are thought to be the biggest driving force behind water use as compared to domestic consumptions.

Here the groundwater abstractions are considered around the Manera and Three Point Farm (Panda) where most of the wells are clustered. The cone of depression is observed around these wells implying that the rate of abstraction is maximum. Richard Musota (MSc, 2008) has studied the irrigation water use and demand around the commercial farms starting from 1975. Estimation of the area under irrigation per crop and by irrigation type is done using remote sensing techniques. The general trend of historical development of irrigated area is also investigated.

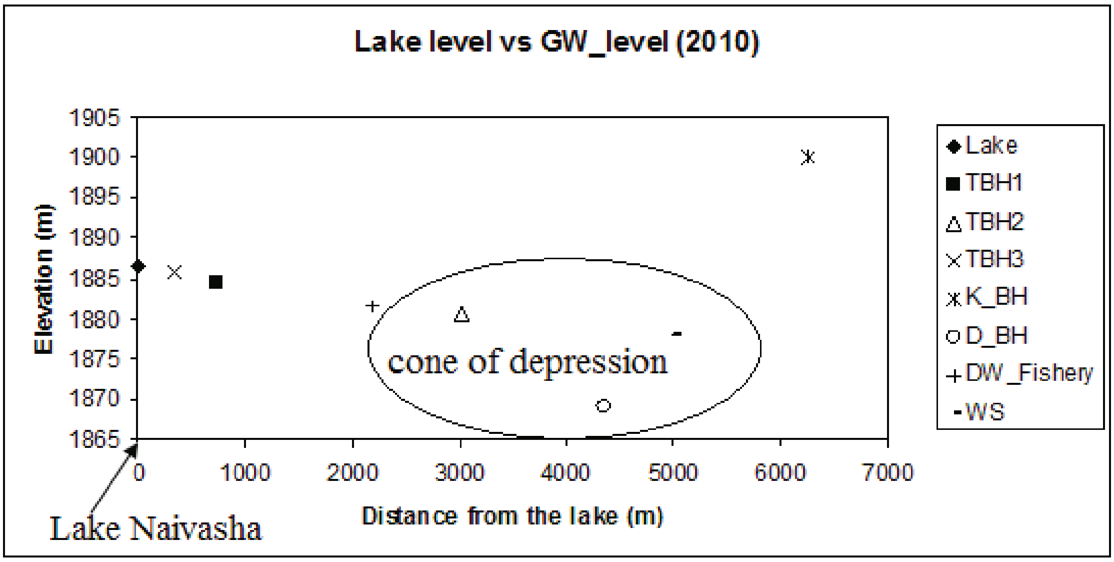


Figure 5-5 : Cross-section of the water levels from the lake to well field

The irrigated area for each year from the corresponding satellite images (Aster images) was digitized to delineate the areas under irrigation. And the water supply sources of the different crop types were identified. Then computation of the applied irrigation per hectare by crop type was done using the abstraction records collected from the users. Based on this computation the amount of abstraction was established. Accordingly the abstraction results are presented below (Figure 5-14).
The groundwater abstraction is calculated as the total sum of the consumptions by the green houses, pivot irrigations and the water consumed by the fodder vegetations which are all located northeast of the lake. According to the data the abstraction of groundwater shows a big increase between 2000 and 2008. The average monthly groundwater abstraction of the area between 1970 up to 2010 is estimated as 1.46*10^6 m3/month. On the other hand the average monthly groundwater abstraction of the area starting from the early 1980s is calculated to be 1.64*10^6 m^3/month which is equivalent to 54720 m^3/day.

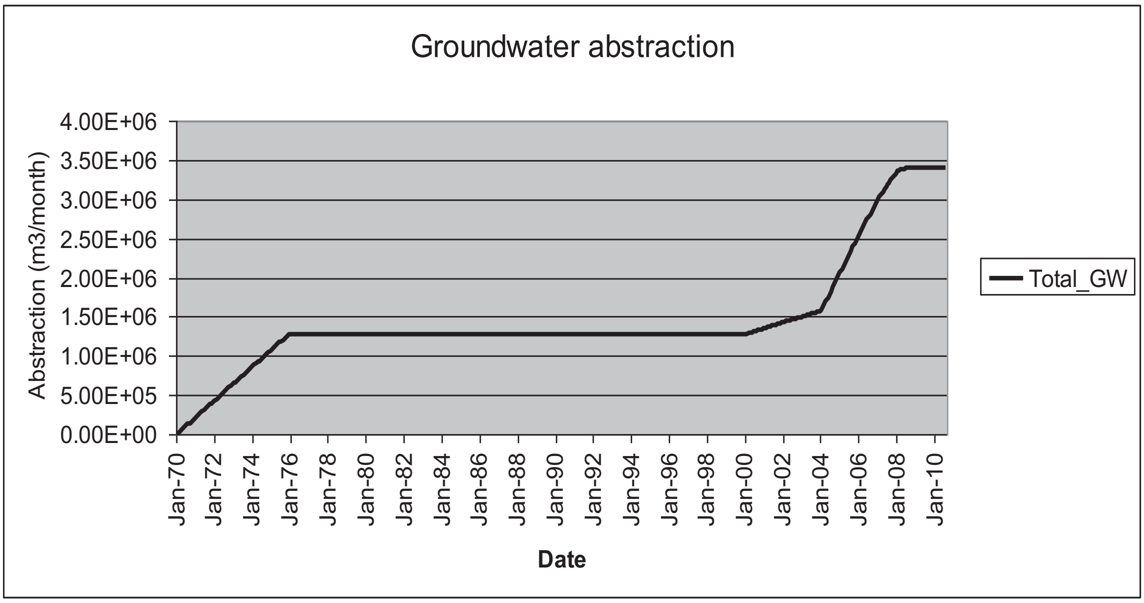


Figure 5-6 : Groundwater abstraction of Naivasha basin from 1970 to 2010

5.4. Correlation of Lake level and groundwater levels

Correlation of the lake level and groundwater levels may give us good insight how closely the two are connected. Monthly records of the lake levels are available since the 1930s. But it is difficult to find continuous water level data of the wells around the lake. However water level records of some wells are found between 1957 and 1970. Figure 5-7 shows temporal variability of the lake level with the water tables for wells north and northeast of the lake. From the figure it is clear that the water levels follow similar trend as the lake, or the water level mimics the lake level. This could be one indication that the lake is connected to the shallow aquifers to its north. Location of the wells is annexed at Appendix 8.

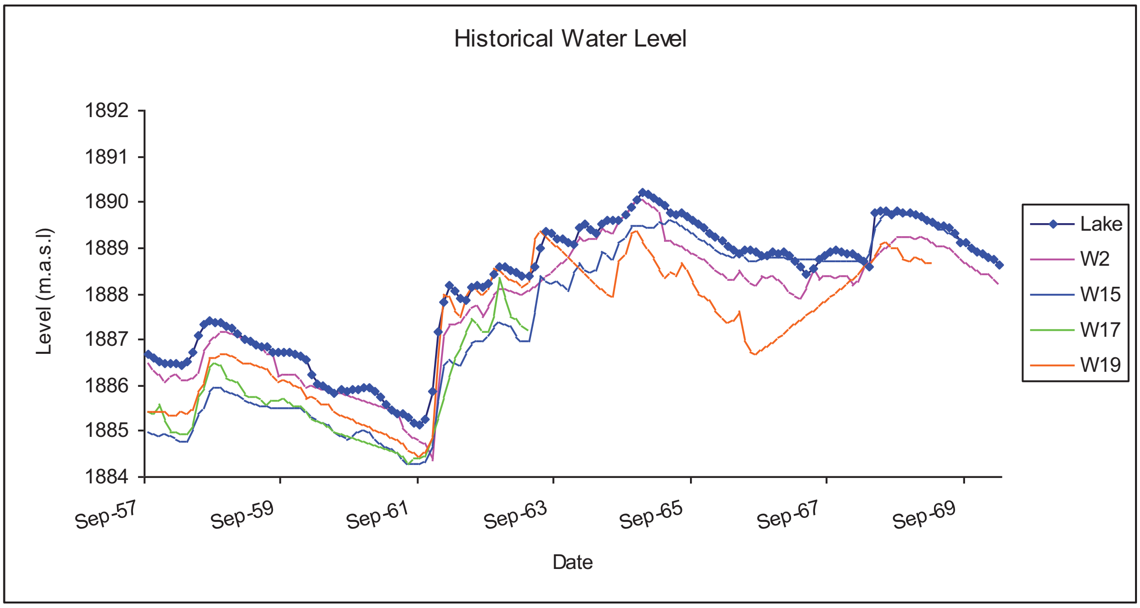


Figure 5-7 : Temporal variability of lake level and groundwater levels of wells (After Behar, 1999)

6. MODELING

The main objective of this section is to calculate or explain the flow paths and travel times of the lake water until it reaches the main well field northeast of Lake Naivasha. The Advective Transport Model, PMPATH is used for this purpose. The groundwater flow model and simulation results are retrieved from Processing Modflow for Windows (PMWIN). The core processes involved in the construction of the model and the main assumptions are discussed below.

6.1. Model development

6.1.1. Methodology

The simulation used by the Advective Transport Model, PMPATH was derived from a large scale model north of Naivasha developed by Kibona, 2000. Construction of the small scale model involves two main steps. In the first step the large scale model of Kibona was updated. In the second step the large scale model was converted in to local scale model using the functionality of PMWIN model converter, Telescoping Flow Model. This function allows creating local-scale models from regional models. PMWIN automatically transfers all model parameters and the calculated heads of the regional model to the local model. And the boundary of the local model is set to fixed – head boundary.

6.1.2. Hydrostratigraphy

The hydrostratigraphic units of the Naivasha basin can be divided as lacustrine sediments and reworked volcanic complexes underlying the sedimentary deposits. The lacustrine deposits are composed of pebbles, gravel, fine to coarse sand, silt, clay and diatomites. The thickness of these materials could reach up to 50m, but it is not uniform through out the basin. The sediments are generally thinning out towards the scarps to the east. The average depth to groundwater in the lake sediments ranges between 20 to 36m and the aquifers are usually unconfined. The second stratigraphic unit is made of reworked volcanic materials. These materials are highly weathered and fractured at the contacts with other lithologic units underlying them. These aquifers are more often semi-confined to confined. Based on drilling data of some deep boreholes around the well field (C_11527) the impermeable hard rocks are struck around 120m northeast of the lake.

Underlying the weathered and reworked volcanics there are undifferentiated basements, which are generally considered as aquicludes. The thickness of these volcanic complexes is not well known. Towards the geothermal area south of the lake, elevation of the deep aquifer is known from geothermal wells. Top of the geothermal aquifer is at approximately 1500 m.a.s.l., whereas further south in the Kedong valley no water has been found in boreholes at an elevation of 1400 m.a.s.l. This observation constraints the outflow mechanism of the lake, to the deep regional geothermal aquifer (Becht et. al., 2005).

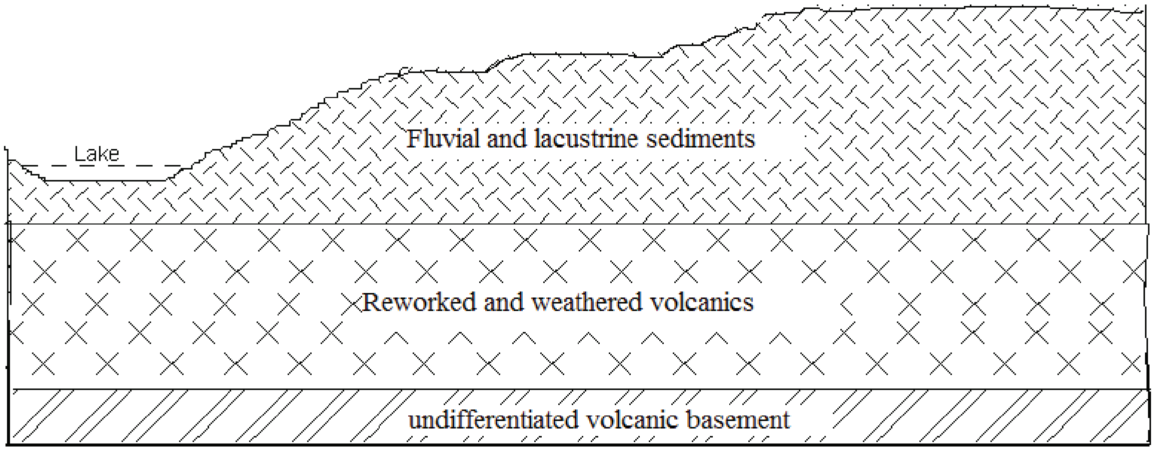


Figure 6-1: Schematic representation of the cross section of the conceptual model from the lake to the eastern escarp the Naivasha basin

6.1.3. Hydraulic properties of the aquifers

The hydraulic properties of the aquifers around the lake show wide range of variations. Clark et.al. (1995) indicated that the highest permeability values are found in the reworked volcanics forming the sediments. The specific capacities of the wells may exceed 3 l/s/m and the hydraulic conductivities are estimated around 10 m/day. In contrast these values could go as low as 0.21 l/s/m and 0.1 m/d towards the Kinangop Tuff. The study indicated that the permeability of the volcanic rocks underlying the Rift valley is generally low although there is local variation. Aquifers are normally found in fractured or reworked volcanics, or along the weathered contacts between different lithological units.On the other hand (Behar, 1999 and Kibona, 2000) showed that the hydraulic conductivity of the upper sediments is low. Based on inverse auger - hole data analysis method, they have calculated the hydraulic conductivities in the range of 0.1 – 0.4 m/d. The hydraulic properties of the stratigraphic units have been estimated from field tests and previous studies.

6.1.4. Model Boundaries

The regional model constructed by Kibona (2000) has two layers and both layers were assigned as confined. The model boundaries are set based on geological considerations (Figure 6-2). The lake which is covering the southern part of the model area is assigned as constant head boundary. In the east and southeastern part of the model area, the low permeability volcanic material forms a low flux boundary getting its recharge from the scarps. The water enters to the model area through the deep aquifer. Water flows out of the model area through the second aquifer in the western boundary. And finally the north eastern part of the model is assigned as no flow boundary because transmissivity of the volcanic materials several orders lower than the sediments.

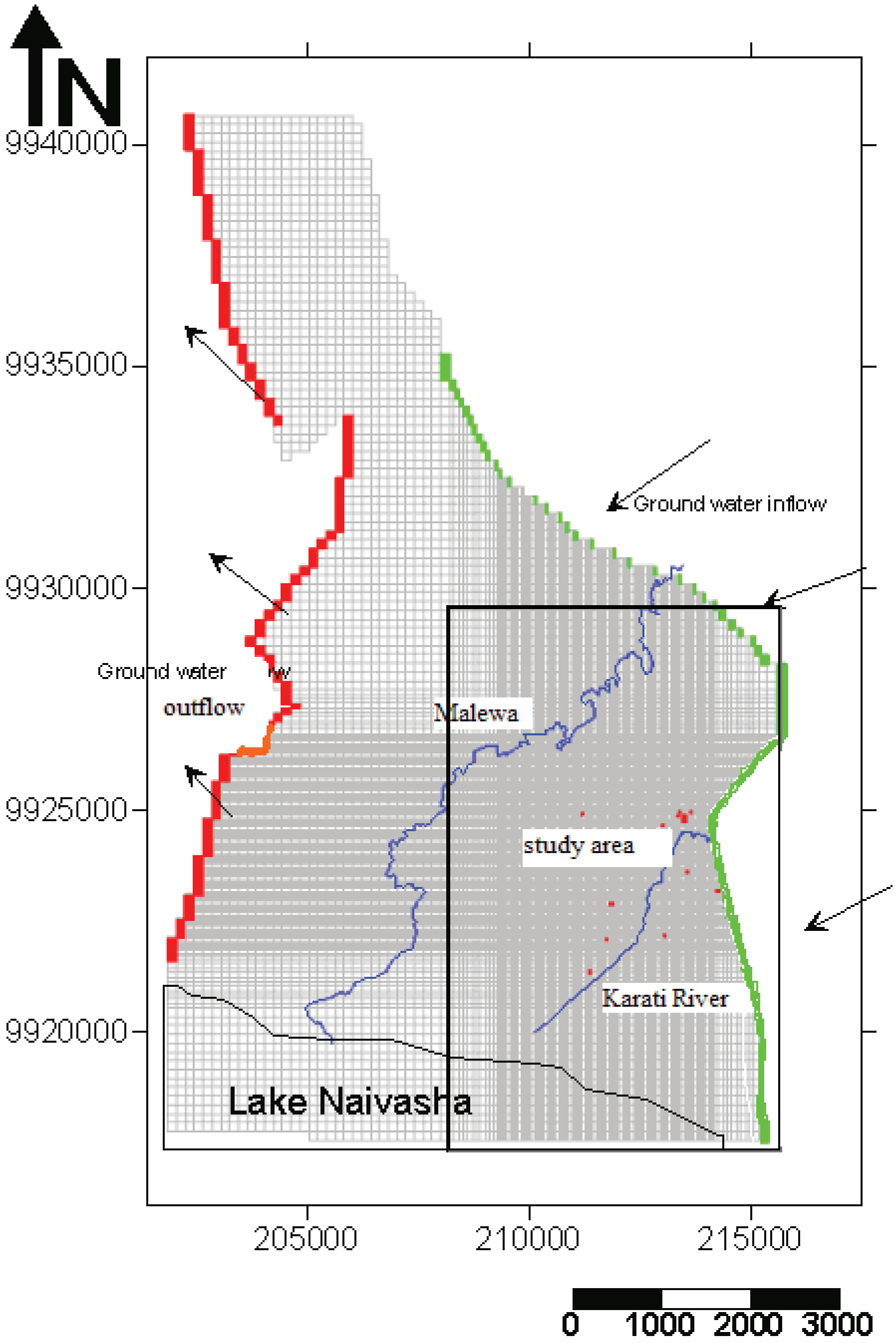


Figure 6-2 : Grid design and model boundary conditions of regional model (Adopted from Kibona, 2000)

6.1.5. Model Geometry

The total area of the regional model is 180 km^2. The model contains 157 columns and 211 rows; the grid size of the cells is 200 m by 200 m. But in places where there is strong groundwater extraction the grids were refined in to 50 m by 50 m. The local model which is extracted from the regional model has an area of 78 km^2; it contains 143 rows and 125 columns. For most parts of the study area the grid size is 50 m by 50 m.

6.1.6. Recharge

The recharge mechanisms to the model were assumed as direct recharge which was applied to the top most active cell; and the second recharge was assumed as groundwater inflow through the eastern model boundary (Figure, 6-2).

The main recharge mechanisms in the study area are direct recharge from rain, and indirect recharge from rivers Malewa and Gilgil. However the direct recharge is estimated about 1% of the annual rainfall. This could be due to the little and irregular distribution of rainfall, and high rates of evapotranspiration in the study area. In the study area the rate of evapotranspiration is higher than the annual rainfall. Hence the starting direct recharge to the model area was used as 4.8 mm/year (Nalugya, 2003).

6.1.7. Abstraction

The study area has been subjected to intensive abstraction of groundwater for irrigational purposes since the 1980s. Most of the farms northeast of the lake are using the groundwater as a primary source for irrigation and domestic uses. Most of the wells in the northeast are found as clusters. The average monthly abstraction of groundwater starting from 1980 up to now was calculated as 1.64*10^6 m^3/month which is equivalent to 54720 m^3/day(Section 5..xx).

6.1.8. Model calibration

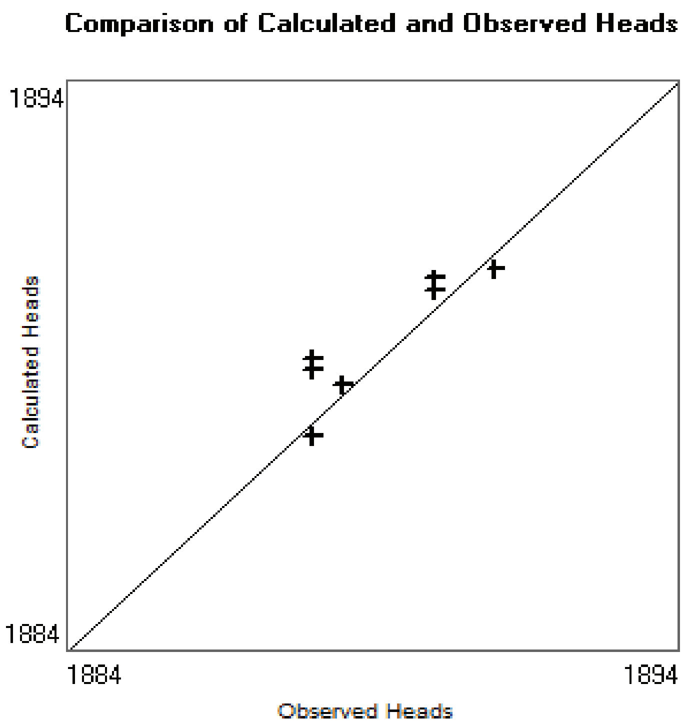


Figure 6-3 : Scatter plot of observed and simulated heads

The calibration results of the model were evaluated by computing the differences between the observed and simulated heads using the Mean Error (ME), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The calibration results are shown in table 6-1.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(hobs - hcal)_i$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(hobs - hcal)\right|$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (hobs - hcal)^2 \right]^{0.5}$$

Where: hobs is Observed head and
hcal is Simulated (calculated) head

Table 6-1 : Observed and simulated heads of the observation wells

Code	Easting	Northing	Observed	Calculated	Difference(m)	ME	MAE	RMSE
ITC027	207680	9925645	1888	1887.791	0.209	-1.17	1.31	2.58
ITC045	208741	9926237	1888.5	1888.669	-0.169			
ITC043	210769	9920726	1888	1888.935	-0.935			
ITC076	212463	9922555	1891	1890.715	0.285			
ITC074	213600	9921500	1890	1890.547	-0.547			
ITC156	214009	9917763	1882.4	1889.118	-6.718			
ITC084	214313	9920708	1890	1890.323	-0.323			

6.2. The Advective Transport Model, PMPATH

PMPATH is an advective transport model running independently from PMWIN. PMPATH can retrieve the groundwater models and simulation results from PMWIN and MODFLOW (Chang and Kinzelbach, 1998). A semi -analytical particle tracking scheme is used to calculate the groundwater paths and travel times. Through the interactive graphical modeling environment of PMPATH, it is possible to place particles where it is necessary and perform particle tracking automatically. Both forward and backward particle tracking are allowed for steady state and transient flow simulations. Moreover, PMPATH provides various on-screen graphical options including head contours, drawdown contours and velocity vectors for any selected model layer and time step.
In PMPATH it is assumed that fluid properties are homogeneous and concentration changes do not significantly affect the fluid density or viscosity and hence the fluid velocity. As a result it is assumed that the particles will travel at the same velocity as the groundwater flow. PMPATH provides the option of tracking particles forward in the direction of groundwater flow, or backward towards points of recharge. During backward tracking the particles terminate at points of recharge. The backward tracking option provides an efficient means of delineating the sources of recharge to localized points such as well fields. Applying the backward particle tracking we can find out the point of origin of water in specified zones. The particle tracking simulation proceeds until all particles have left the model via sinks or until the user-specified time limit is reached.Hence, the backward tracking option was applied in this model.

6.2.1. Assumptions of the solute transport (PMPATH) model

One of the main objectives of this study is to show the effect of continuous abstraction of groundwater from the well field on the lake-groundwater linkages and estimate the travel time of the lake water into the well field if possible. Generally the activities that have imposed a lot of stress on the lake and groundwater picked up after 1980. Prior to this period the effects of abstraction of groundwater in the basin on the flow pattern have little impact or they were negligible (Owor, 2000).
Here the advective transport model is used to estimate the possible groundwater flow paths and travel time of the lake water to the well field. As discussed above in the stable isotope data analysis, so far only

very small percentage of the lake water is traced in the well field. Moreover the general groundwater flow direction is towards the lake from the eastern scarp. Around the well field a cone of depression is observed due to excessive abstraction of groundwater for irrigation purposes; but so far there is no evidence indicating that this cone of depression has reached the lake. Probably the cone of depression persists with a small radius in the wellfield area. With the assumption that the main catalyst for the creation of this cone of depression is the increased abstraction after the 1980s, an attempt is made to predict the arrival time of the lake water to the wellfield using the PMPATH. Moreover the results obtained here are going to be compared with the stable isotope analysis results.

The regional model (Kibona, 2000) was calibrated by using historical data from 1930s to 1970s. Before 1970 there were only few drilled wells which were mainly used for domestic purposes. Hence the data prior to 1970 provides an estimate of the head distribution under relatively undisturbed condition.

Based on the above assumptions the Advective Transport model, PMPATH was used to predict the flow paths and travel times of the lake water to the wellfield. Particles were introduced around the wellfield where most of the abstraction is taking place. The average monthly groundwater abstraction rate of the farms around the wellfield was calculated between the years 1980 and 2010, and it is estimated about 1.64*10^6 m^3/month which is equivalent to 54720 m^3/day. The location and amount of abstraction assigned to the wells is annexed at, Appendix 5.

This abstraction rate (stress) was applied on the wellfield and the particles are back tracked for time intervals of 20, 30 and 40 years starting from 1980. These time intervals were chosen to look at the development of the cone of depression and the flow paths in response to the applied abstraction over the course of the years staring from 1980. The 30 years time interval is very crucial because it represents the current conditions it is also possible to compare the result with the current stable isotope data analysis results. The simulation results of the PMPATH for the three time intervals are shown in the figures below.

From the simulation results of the PMPATH over the given time intervals (20, 30 and 40 years) the following observations can be made (Figures, 1, 2, and 3). As discussed above, the particles were introduced at four different locations in the wellfield to identify the possible sources of recharge for the wells there. According to the flow paths of the particles three possible recharge areas can be identified. The first recharge is suspected from the direction of the lake which is indicated by the red colour flow paths. The second possible source is the Karati River where the flow paths are represented by the green colours. And finally there is some indication that the Malewa River could also be another source for some of the wells in the wellfield. The flow paths leading to river Malewa are represented by the blue colour.

Even with the longest time interval (40 years) the wells around the bending point of Karati River will not get receive the lake water.

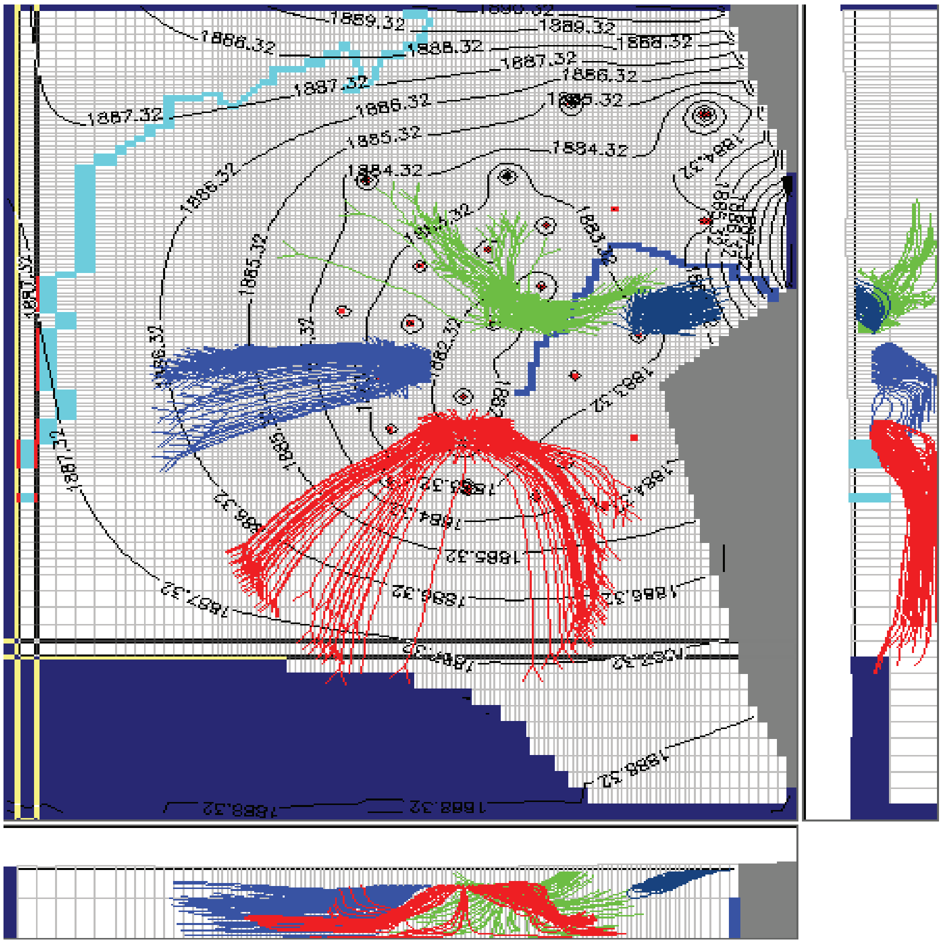


Figure 6-4: PMPATH particle tracking after 20 years

During the 20 year simulation period almost no particles were tracked from the lake. But after the 30 year time intervals some particles have been back tracked from the lake. This implies that some of the lake water has started entering the wellfield. However much of the lake water has started entering the wellfield during the 40 years time interval. This 40 year time interval is yet to reach, which is 2020.

If we compare the predictions made by the PMPATH with the results obtained from isotope data analysis, we can notice the following points. The sample taken from TBH2 has shown smaller proportion of lake water, and the particles placed there have tracked some lake water for the 30 year time interval. But for the wells located around the Karati River the prediction indicates that even for the longest time interval (40 years) the lake water is not reaching there. However isotopic analysis results of the wells there have shown that little proportion of the lake water has already been traced there. This is in contradiction to the prediction. This may be attributed to several factors. The first problem may arise from incorrect distribution of the abstraction wells and their discharge amount. The second possible reason could be incorrect designation of the model parameters during calibration, especially the hydraulic conductivities.

And the third reason could be the complexity of the hydrogeological setting of the basin.

But generally the PMPATH results have shown that so far no significant amount of the lake water is traced in the wellfield.

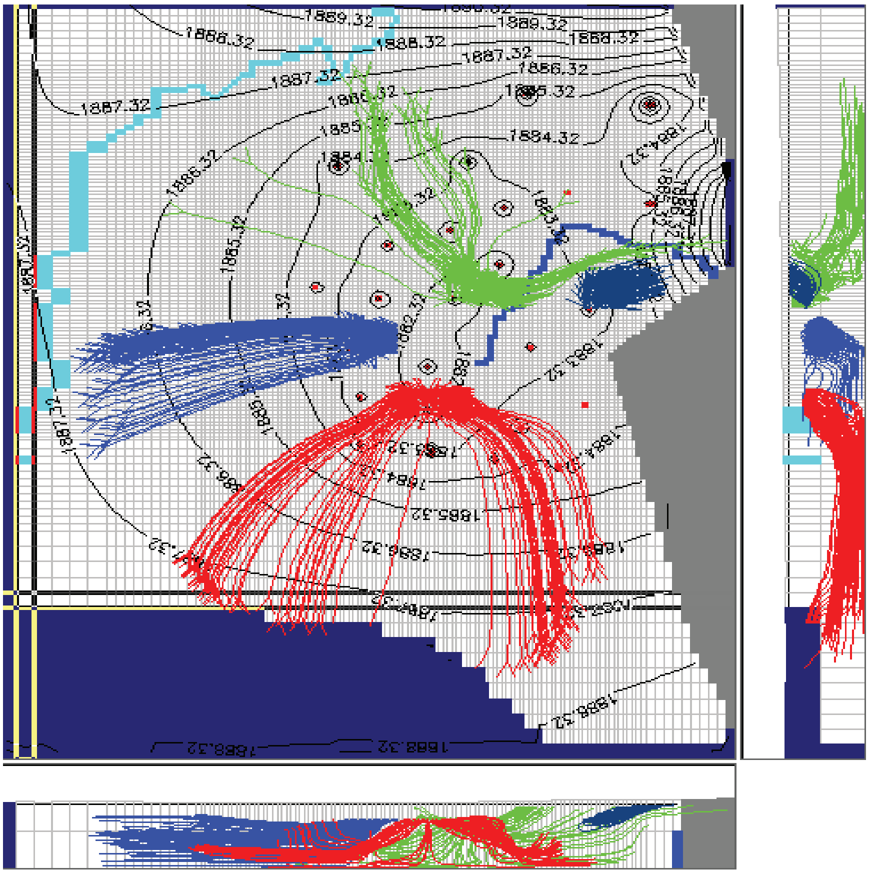


Figure 6-5 : PMPATH particle tracking after 30 years

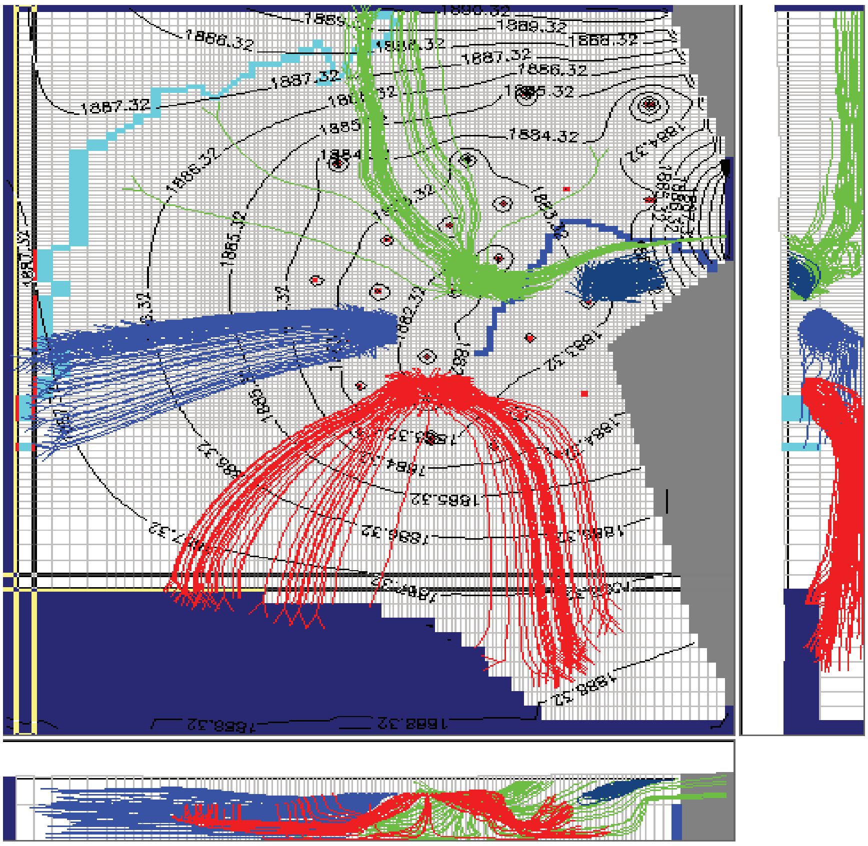


Figure 6-6 : PMPATH particle tracking after 40 years

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The groundwater flow pattern and hydraulic interaction of surface and groundwater systems of the Naivasha basin is very complex and is controlled not only by the configuration of the groundwater and surface water levels but also by the distribution of hydraulic conductivity in the rocks, the topography and geology as well.

To understand the interaction processes different methodological approaches have been followed. These approaches include geophysical studies, isotopic data analysis, and reassessment of geological and hydrogeological set up of the basin. And finally using the PMPATH modelling the flow paths and arrival times of the lake water to the wellfield area has been predicted.

The East African Rift System is one of those areas where a large amount of fluid rock interaction is taking place. In those situations it is difficult to use conventional hydrochemical techniques to discriminate between different water types as the original characteristics of one or more of the end members of any mixing may be obscured.

Hence stable isotopes of Hydrogen (^{2}H) and Oxygen (^{18}O) have been used to investigate the extent of mixing of waters and the flow direction of the groundwater system in the study area.

The ^{2}H vs. ^{18}O plots of the water samples taken from boreholes around the lake area and the wellfield showed the following results. The shallow boreholes (17 to 37m deep) and the lake water are enriched in the heavy isotopes and plotted away from the GMWL along the evaporation line. These boreholes are located closer to the lake. Based on mixing ratio calculations percentages of the lake water in these wells was estimated up to 77 %. The main source of recharge for these wells is the lake water.

The deep boreholes are located a few kilometres away from the lake. The isotopic plots of these wells lie very close to the Global Meteoric water Line (GMWL) and they are depleted in the heavy isotopes. With the exception of TBH2, the three wells are found around the well field (Panda and Delamere farms); and they are also closer to the eastern escarpment than the shallow wells. These wells are predominantly recharged by precipitation from the eastern rift flank. Only smaller percentages of the lake water are traced here, indicating that the lake is not a major contributor of recharge to the wells.

According to the current results there is no significant difference in the percentages of the lake water between 2004 and now; which are 16% and 14% respectively. There may be two main reasons to explain this. The first reason can be with the current abstraction rate the cone of depression created in the wellfield doesn't reach the lake. And the second reason may be the wells around the wellfield are getting their recharge from the nearby rivers and direct precipitation from the rift flank. The second explanation is supported by previous studies made around the area. The boreholes at Marula and Three Point Farms are highly depleted in $\delta^{2}H$ and $\delta^{18}O$, but have similar isotopic compositions to that of River Malewa.

Isotopic signature of the lake water is generally getting weaker further from the lake towards the well field, which is located northeast of the lake.

The geophysical survey was applied to understand the subsurface geology and hydrogeology of the area and the effect of geological structures, such as faults and fractures on the groundwater flow system. The surveying method was 2D Resistivity Imaging.

In most of the survey lines northeast of the lake the top most formations (up to 15m) are mainly silty clay to fine sand materials, but towards the lake side the clay layers are dominant. Underlying these fine sediments mixtures of clay, silt, sand and gravely materials are found. In some of the survey lines highly resistive materials are detected at a depth of 34m. These materials are interpreted as hard rocks (trachyte). The lithologic logs of a nearby test well also showed similar result.

In one of the profile lines with longer electrode separations (800m), highly resistive materials are encountered at 103m, which is also interpreted as hard rock. This may be an indication of how complex the geology is with in the basin.

The main aquifer materials in the basin include fine sands, medium to coarse sands, gravels, pebbles and fractured volcanics. Towards the wellfield the formation resistivity range of these aquifer materials is between 12 – 335 Ohm.m.

No prominent geological structures are observed on the sedimentary environment of the study area. However vertical and sub vertical faults occur in areas closer to the rift wall that is the eastern margin of the study area. And the NW running portion of Karati River is identified as fault controlled. Most of the highly productive wells are found with in 1km radius of the Karati River indicating that the faults have a positive impact in that they are acting as conduits for groundwater flows instead of being barriers.

The hydrogeological investigations have demonstrated that the main aquifer units in the Naivasha basin can be divided as sedimentary units and volcanic rocks. The sedimentary units are composed of lacustrine and fluvial deposits; where as the rift floor is mostly underlain by volcanics with phonolitic, trachytic and rhyolitic composition and their sedimentary derivatives. The lacustrine deposits are thicker northeast of the lake, where their thickness could reach up to 120m. The water levels are shallower near the lake but gets deeper towards the wellfield. Cones of depression have developed around the Manera and Panda Farms. Pumping test results of previous works showed that the transmissivity values of the lake bed sediments in Panda flowers ranges between 460 to 1150 m2/day. However the aquifer units are highly heterogeneous throughout the basin.

And finally the Advective Transport model, PMPATH was used to predict the flow paths and travel times of the lake water to the wellfield. Particles were introduced around the wellfield where most of the abstraction is taking place. Then the particles are back tracked for different time intervals (20, 30 and 40 years) starting from 1980. The model was calibrated for steady state based on initial conditions prior to 1980. The average monthly groundwater abstraction rate of the farms around the wellfield was calculated between the years 1980 and 2010. This abstraction rate (stress) was applied on the wellfield and the particles are tracked. According to the simulation much of the lake water started to enter the wellfiled during the 40 year time interval, which is nine years from now. When using the PMPATH the MOFLOW model.

7.2. Recommendations

Due to the complexity of the geological and hydrogeological settings of the Naivasha basin, it is difficult to accurately determine the linkages between the surface and groundwater sources. Accordingly the following points are recommended

- In future studies it is important to analyse more isotope data, especially in those areas where there is higher abstraction of groundwater for in depth analysis of the exchange of water between surface and groundwater sources.
- Eventhough the rivers around the wellfield are believed to be sources of recharge to the aquifers, they should be studied thoroughly to understand their role
- There is no well recorded data of the groundwater abstraction in the basin, so it is important to formulate a way of keeping the records
- It is recommended to install piezometers in areas south of the wellfield towards the lake; this is important because there are no continuous water level records for monitoring
- The hydraulic properties of the aquifers are very important in the understanding of the lake aquifer interaction, so detail studies of these properties is necessary

LIST OF REFERENCES

Abdulwhab, M. (2006). Assessment of artificial groundwater recharge using greenhouses runoff North-east Naivasha, Kenya. ITC, Enschede.

Anderson, M. p., & Woessner, W. W. (1992). Applied groundwater modelling Simulation of Flow and Advective Transport. 381.

Anderson, M. P., & X.Cheng. (1993). Long and short term transience in a groundwater/lake system in Wisconsin,U.S.A. Journal of Hydrology. *v. 145*, pp. 1-18.

Appelo, C. A. J., and Postma D. (1993). Geochemistry, groundwater and pollution.

Becht , R., Mwango, F., & Muno, F. A. Groundwater links between Kenyan Rift valley Lakes.

Becht , R., & Sarah, H. (2003). Sharing experience and early lessons in GEF and NON-GEF lake basin management projects,Lake Naivasha Brief.

Behar, H. A. (1999). Surface water groundwater interaction lake naivasha kenya. MSc Thesis, ITC, Enschede, ITC, Enschede.

Chiang W. and Kinzelbach W. (1996). Processing Modflow (for Windows). A simulation system for Modelling Groundwater Flow and Pollution.

Clarke M. C. G. (1990). Geological, volcanological and hydogeological controls of the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya. Min. of Energy, Kenya and British Geological Survey.

Craig, H. (1961). Isotopic variations in meteoric water. Science 133:1702-03.

Darling, W. G., Allen, D. J., & Armannsson, H. (1990). Indirect detection of subsurface outflow from a rift valley lake. Journal of Hydrology, 113(1-4), 297-306.

Darling, W. G., Gizaw, B., & .Arusei, M. K. (1996). Lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley: isotopic evidence. Journal of African Earth Sciences, 22, 423-431.

Fetter, C. W. (2001). Applied Hydrogeology. Prentice-Hall, Upper Saddle River, 474 pp.

Hernandez, R. R. (1999). Groundwater flow modelling of naivasha basin kenya. MSc Thesis, ITC, Enschede, ITC, Enschede.

Hunt RJ, Haitjema HM, Krohelski JT, & DT, F. (2003). Simulating ground water-lake interactions: Approaches and insights. Ground Water 41(2):227–237.

Kibona, S. R. (2000). Temporal and spatial variation of groundwater level north of lake Naivasha, Kenya. MSc Thesis, ITC, Enschede.

Krabbenhoft , D. P., & Anderson, M. P. (1986). Use of a numerical ground-water flow model for hypothesis testing, Ground-Water 24 (1986). no. 1: 49-55.

Krabbenhoft , D. P., Anderson, M. P., & Bowser, C. J. (1990). Estimating groundwater exchange with lakes, 2. Calibration of a three dimesnsional solute transport model to a stable isotope plume.Water Resources Research. v. 26, no. 10, pp. 2455-2462.

Ojiambo, B. S. (1992). Hydrogeologic, Hydrochemical and Stable Isotopic Study of Possible Interactions Between Lake Naivasha, Shallow Subsurface and Olkaria Geothermal.

Oppong-Boateng, R. (2001). Assessment of the use of groundwater for irrigation in the southern part of Lake Naivasha Kenya. ITC, Enschede

Owor, M. (2000). Long term interaction of groundwater with lake Naivasha, Kenya : a numerical simulation of the relationship between groundwater and lake allowing for fluctuating lake levels. ITC, Enschede.

Sacks, L. A., Herman , J. S., Konikow, L. F., & Vela, A. L. (1992). Seasonal dynamics of groundwater-lake interactions at Donana National Park,Spain. Journal of Hydrology 136, 123-154.

Sikes, H. L. (1936). Notes on the hydrology of Lake Naivasha,Journal of the East Africa and Uganda Natural History Society.

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal, 10(1), 52-67.

Thompson A.O. and R.G. Dodoson. (1963). Geology of the Naivasha Area. Geological Survey of Kenya, Report. No. 55.

Tsiboah, T. (2002). 2D Resistivity Imaging and Time domain EM (TEM) in aquifer mapping a case study north of lake naivasha. ITC, Enschede.

van Reeuwijk, L. P. (1993). Procedures for soil analysis. ISRIC Technical Paper. International Soil Reference and Information Centre (ISRIC), Wageningen, 125 pp.

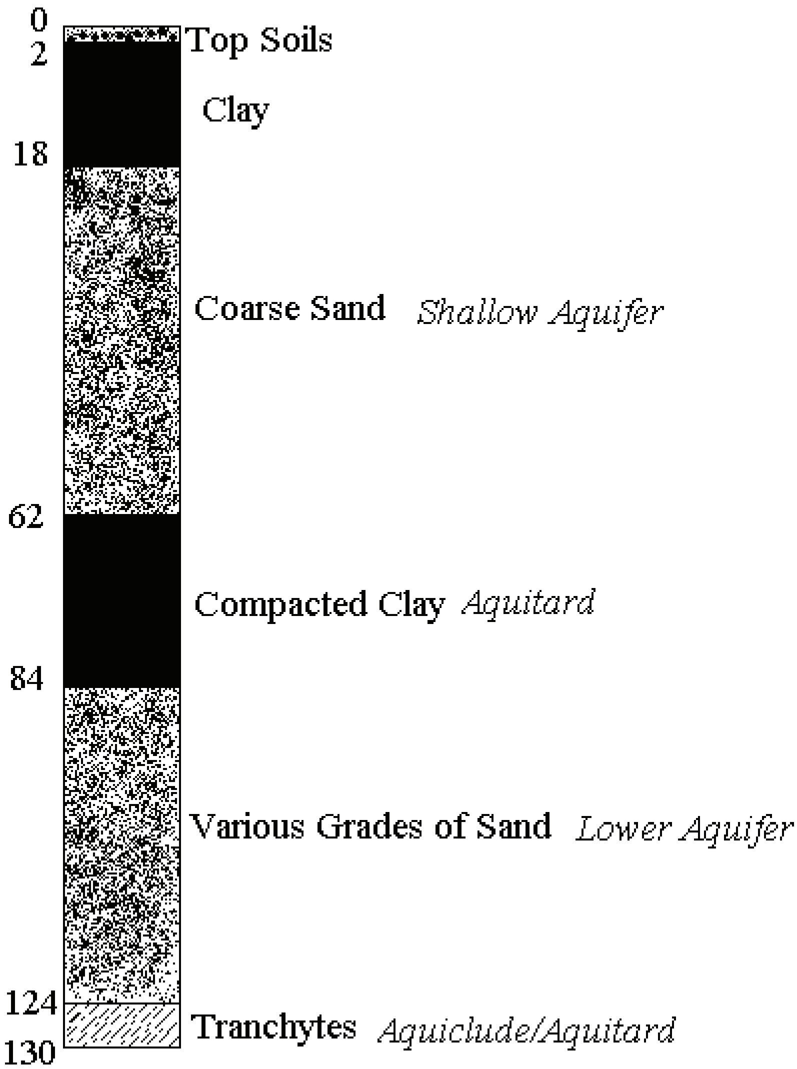
Viak Ltd. (1975). Naivasha Water Supply Project, Ministry of Agriculture, Republic of Kenya.

Yihdego, Y. (2005). A three dimensional ground water model of the aquifer around lake Naivasha area, Kenya. ITC, Enschede.

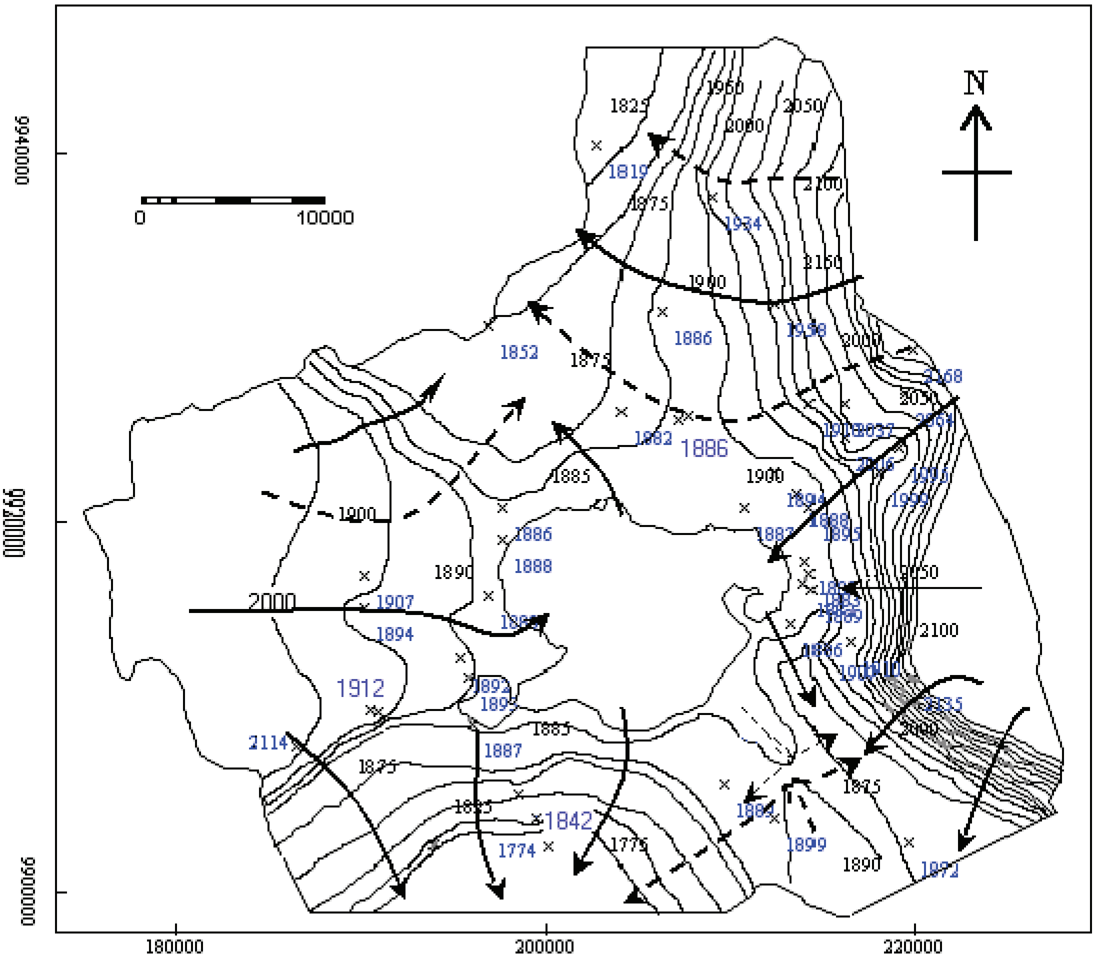
APPENDICIES

Material	Hydraulic conductivity cm/s
Clay	10^{-9}-10^{-6}
Silt, sandy silt, Clayay sands, till	10^{-6}-10^{-4}
Silty sands, fine sands	10^{-5}-10^{-3}
Well- sorted sands, glacial outwash	10^{-3}-10^{-1}
Well-sorted gravel	10^{-1}-1.00

Appendix 1. Range of Hydraulic conductivity test for unconsolidated sediments (Fetter, 2001)



Appendix 2. Lithologic log of well C11527



Appendix 3. Flow direction as dictated by historic heads of 1980(Owor, 2000)

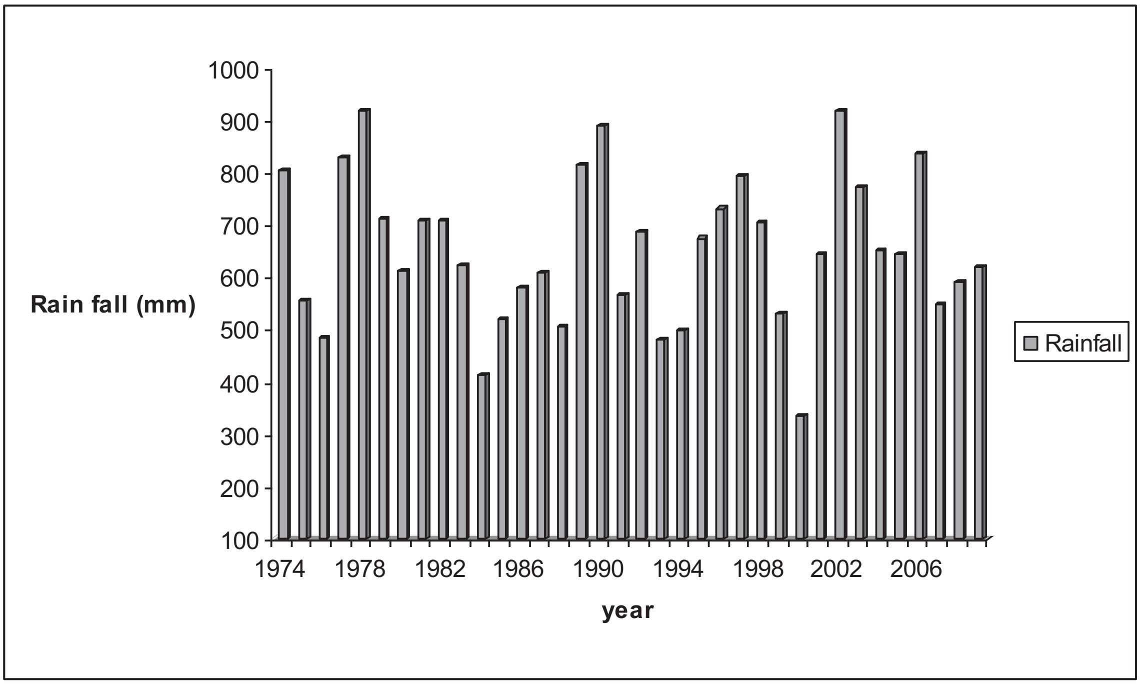
Easting	Northing	Abstraction (m3/d)
212918	9926274	4000
214300	9926132	4000
210829	9925318	3500
212281	9925389	3500
213379	9924982	1000
214300	9924822	2000
212670	9924769	2000
212068	9924486	1800
211378	9924256	1500
212600	9924026	2000
210563	9923725	1000
211271	9923566	1500
212121	9923583	2500
210988	9922911	2000
211820	9922663	3000
213627	9923424	2000
212972	9922929	1500
211076	9922274	2000
211803	9922114	3500
212848	9921884	1500
213556	9922185	600
211076	9921654	3000
211873	9921566	4000
212582	9921442	1500
213273	9921353	800
	Total	55700

Appendix 5, Location of abstraction wells used in PMPATH and their discharge

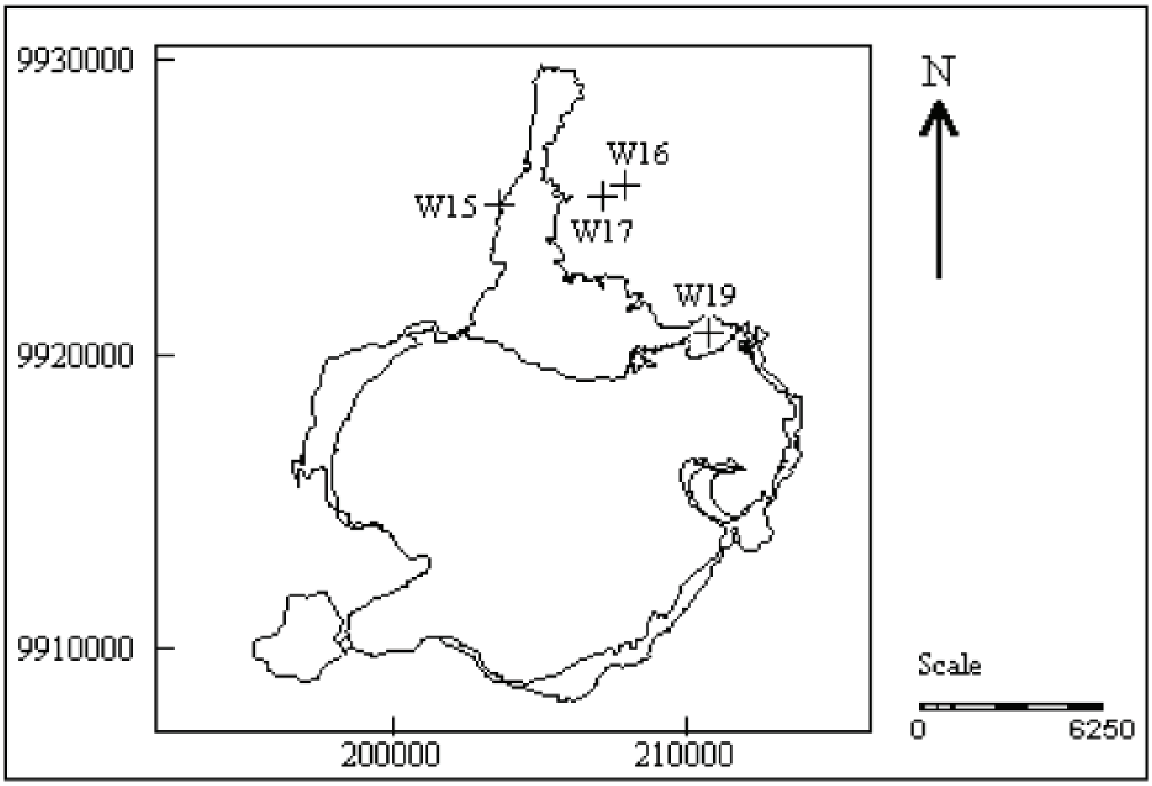
Depth, m	Lithologic description
1 – 5	dark red clay, but grey when dry
5	very fine (volcanic) sands
6	sands with rounded pumice
7	fine unconsolidated pumice sand + some what consolidated fine tuff layer
8	very fine layered pumice sand silt formations
9	coarse brown/ red stratified dark minerals and pumice sand
10	dust silt layer
11	similar to the 10m sample but slightly coarser

12	thin layer of ash plus some lighter materials (diatomite)
13	layered volcanic ash/clay/diatomite plus fine sands
14 - 15	grey colored ash
16 - 18	ash but with some layering
19 - 20	a mixture of coarse unconsolidated sand, pebbles of hard volcanic + clay
21	well layered ash dust plus diatomite
22	diatomite and ash
23	slightly consolidated dust with some clay
24	volcanic ash plus lighter materials
25	very fine red/brown sand, very well sorted, unconsolidated (cavity formation)
26	red/brown colored coarse sand
27	similar to the 26m sample but coarser
28 - 29	volcanic ash/dust with minor traces of structures
30 - 32	similar sample to 30-32m, but slightly coarser
33	very fine sand hard sands, which are consolidated
34	gradually coarsening mixture of dust/ash + very fine red/brown sand
35	ultra fine red/brown sands very vague sedimentary structure
36	the typical red brown coarse unconsolidated layer deposits, no pebbles
37 -40	identical brown colored unconsolidated deposits of silt and clay
40 - 45	brown to black colored coarse sand, with little gravels and silt clay materials

Appendix 6, Lithologic log of the shaft in Panda flower



Appendix 7, Annual Rainfall of Naivasha D.O. (1974 - 2010)



Appendix 8, Location map of wells