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DEPARTMENT OF GEOLOGY

AQUIFER STRATIGRAPHY AND HYDROGEOCHEMISTRY OF THE LAKE NAKURU BASIN, CENTRAL KENYA RIFT

By

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(I56/8526/2006)

Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Geochemistry.

MARCH, 2010

DECLARATION

I hereby declare that this dissertation is my original work and has not been presented for a degree in any other university or any other award.

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ABSTRACT

The geology of Nakuru area comprises mainly of volcanic soils and rocks (lava and pyroclastics) of Tertiary – Quaternary age, which has been affected by a series of faulting, and are overlain by recent sediments. This study considers groundwater to be the chief source of water for the expanding agricultural, industrial, domestic and wildlife demands, and thus there are possible negative effects on groundwater in the basin due to depletion of this resource and deterioration of its quality. Apart from anthropogenic factors, the geology of the area seems to contain a great potential to pose a risk to the regional groundwater variably depending on their/its elemental composition due to their persistent interaction with the water.

The general objective of this study was to relate aquifer stratigraphy and lithology to groundwater geochemistry and quality by assessing and determining the stratigraphy, lithology and spatial extent of aquifers present with respect to the possible influence on hydrogeochemistry. The approaches pursued here include the chemical analyses of major ions and heavy metals for constructing hydrogeochemical maps with focus on aquifer material and distribution. A total of 55 deep boreholes, 3 shallow boreholes, 3 springs and 19 river sites were sampled and water analyses performed for the major ionic composition, together with fluorite and selected heavy/trace metals. Saturation indices were calculated, ionic relationships were studied, hydrochemical facies were determined and water types were identified. Driller's logs from 33 boreholes were utilized to assess aquifer lithology and hydrogeostratigraphy. The data was analyzed and in effect interpreted by the help of appropriate computer programs such as SPSS, WinLog, AquaChem, Rockworks and PHREEQC.

Results indicated that aquifer distribution varies from single to three aquifer systems with three major aquifer lithologies. These include fissured trachyte, volcanosediments and pyroclastics revealing a dominant trend in lowlands (<2000m.a.s.l), midlands (2000 – 2200m.a.s.l) and highlands (>2200m.a.s.l) of the study area, respectively. Lithological logs analyses show aquifer thickness variation that ranges from 2 to 46 meters. The composition of dissolved ions in the groundwater is order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ (anions) and $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$ (cations), with considerable amounts of some heavy/trace metals (in the order of Zn>Fe>Mn>Pb>Cd>Cr).

The principal processes that control the groundwater quality variations are the influence of silicate rocks weathering and anthropogenic contribution which is also significant. Most of these ions surpass local and international recommended limits and areas with lofty values have been defined. The outcome of this study provides information needed for groundwater quality budgeting and management.

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DEDICATION

To my parents (Nahum & John), brothers (David & Philip) and sisters (Esther & Dinah)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

μS/cm	-Micro-Siemens per Centimeter
APHA	-American Public Health Association
AWWA	-American Water Works Association
BH	-Borehole
CDN	-Catholic Diocese of Nakuru
CB	-Charge Balance
CIFEG	-Centre International pour la Formation et les Echanges en Géosciences (International Centre for Training and Exchanges in the Geosciences)
DO	-Dissolved Oxygen
EC	-Electrical Conductivity
Eh	-Redox Potential
ENE	-East North East
ESP	-Exchangeable Sodium Percentage
EU	-European Union
GEMS	-Global Environmental Monitoring System
GPS	-Global Positioning System
IAP	-Ionic Activity Product
ILRI	-International Livestock Research Institute
ISE	-Ionic Selective Electrode
ITCZ	-Inter-Tropical Convergence Zone
KT	-The product of the Boltzmann constant, k, and the temperature, T.
KWS	-Kenya Wildlife Service
MASL	-Meters Above Sea Level
MAWARI	-Management of Water Resources in the East-African Rift system
MCN	-Municipality of Nakuru
Meg l^{-1}	-Milliequivalents per litre
Mg l^{-1}	-Milligrams per litre
N	-Number of variables
NAWASSCO	-Nakuru Water & Sanitation Services Company
NEMA	-National Environment Management Association
PCA	-Principal Component Analysis
PPM	-Parts Per Million
SAR	-Sodium Adsorption Ratio
TDS	-Total Dissolved Solids
TSS	-Total Suspended Solids
UNEP	-United Nations Environmental Programme
UNESCO	-United Nations Educational Scientific and Cultural Organization
US EPA	-United States Environmental Protection Agency
WHO	-World Health Organization
WNW	-West North West
WQA	-Water Quality Assessment
WRL	-Water Rest Level
WSL	-Water Strike Level

CHAPTER ONE

1.0 INTRODUCTION

1.1 General Introduction

About a million people currently live in Lake Nakuru basin, with almost a quarter living in the vast expanding Nakuru Municipality located about a kilometre from the lake (MCN *et al.* 2009). Nakuru town's population, the main urban centre in the region, has been growing by about 10 percent every year for the past three decades. Nakuru town, a major commercial, industrial and communication centre, links western Kenya, North Rift and South Rift with the rest of the country.

The increasing growth in various sectors is gradually putting pressure on the available resources. Consequently, demand for groundwater resources in the area has been recently increasing from a variety of users. For instance, increasing amounts of groundwater is pumped for both industrial and domestic use in relatively reliable and readily available amounts compared to other water supplies.This basin has forests that form part of Kenya's countrywide watershed; large farms that are among the most productive in Nakuru District; and Lake Nakuru National Park, habitat to diverse wildlife. Unpublished survey report of Kenya Wildlife report reveals that the park has 50 mammal species, over 400 bird species (among them perhaps a million flamingos, the park's best-known inhabitants), and 300 plant species, all relying on the fate of the available water resource. The park is an important source of revenue for the Kenyan Government and local communities, with additional monies flowing to the farming and commercial sectors of Nakuru Municipality.

Inconsistencies in supplies and indiscriminate use of the rivers and streams as pathways of sewerage and industrial waste by Nakuru town inhabitants and elsewhere within the basin has made the surface water less potable. This has led to the shift of water supply from surface water to groundwater. And as a consequence, several boreholes and a number of shallow boreholes have been developed in order to meet drinking, irrigation, and industrial water demands. While the demands on groundwater usage have increased, characterizing the water according to its quality needs to be done. The heterogeneity of aquifers lithology and general complexity of both structural and regional geology challenges the integrity of groundwater quality. Understanding the geochemistry of groundwater is important for maintaining the water quality and for its effective utilization and development.

In general, groundwater contains minerals carried in solution, the variety and concentration of which depends upon a number of factors like soluble products of rock weathering and disintegration in addition to external polluting activities and variations in space and time. As a result of chemical and biochemical interaction between groundwater and contaminants from urban, industrial and agricultural activities along with geological materials through which it flows, it contains a wide variety of dissolved inorganic chemical constituents in various concentrations.

In this study, geochemical assessment of groundwater quality and aquifer stratigraphy was done, and the contribution of geology to hydrochemistry was investigated through evaluation of geochemical interaction between groundwater and minerals within host-rocks.

1.2 Current status of knowledge in L. Nakuru Basin

1.2.1 Global Perspective

The character of groundwater in different aquifers over space and time proved to be an important technique in solving different geochemical problems (e.g., Hem 1959; Back *et al* 1993; Gibbs 1970; Srinivasamoorthy 2005). Computation of mineral saturation index and thermodynamic equilibrium studies were initiated by Garrels and Christ (1965) to decode the possible reactant and product minerals and indicate the equilibrium state of groundwater and the surrounding materials.

The physical character and properties of an aquifer are related to porosity, hydraulic conductivity and specific storage, and heterogeneity of such formations depends on spatial changes in physical properties (Fetter 1994), such as internal structure, material composition, orientation and geometry (Webb & Anderson 1996). Spatial heterogeneity associated with physical properties, but mostly hydraulic conductivity; dominate solute and/ or contaminant transport (Barber *et al.* 1992).

1.2.2 Regional Context - the Kenyan Rift System

Pioneering study of geology in the region can be traced back to Thompson (1885) whose observations and conclusions are contained in Gregory (1921) (McCall 1967). Subsequently, Gregory attempted to present stratigraphic classification of the volcanic and associated rocks of the rift valley as reported by Shackleton (1951) although his works apparently suffers major setbacks. Nilsson (1932) examined Quaternary lake deposits and shorelines in the Nakuru-Elmentaita, Naivasha and Baringo basins providing basic information as to Quaternary fluxes of the lakes as far as he measured it by means of recognizable shoreline features. Almost contemporaneously, Leaky (1932) investigated Pleistocene and Recent deposits and shoreline features in the Nakuru basin and adopted a classification based on climatic variations, equating certain deposits in the basin with the Pleistocene pluvial periods and minor post-Pleistocene wet periods using artifacts as a means of dating sedimentary formations.

Dühnforth et al (2006) used a hydrological model to compare the precipitation–evaporation balance during the early Holocene to today. Assuming that the Nakuru-Elmenteita basin was hydrologically closed, as it is today, they suggested that the most likely climate scenario includes a 45% increase in mean-annual precipitation, a 0.5°C decrease in air temperature, and an increase of 9% in cloud coverage from the modern values within the basin. It is proposed that a significant flow of water from the early Holocene Lake Naivasha in the south towards the Nakuru-Elmenteita basin occurs to compensate the extremely negative hydrological budget of this basin. Since no field evidence for a surface connection, as often proposed during the last 70 years, the hydrological deficit of the Nakuru-Elmenteita basin could have also been compensated by a subsurface water exchange which may probably be facilitated by buried fault lines (Dühnforth *et al.* 2006).

The highest concentrations of fluoride in groundwater occur in the peri-urban areas of Nairobi, in the Rift Valley around Nakuru, Naivasha and Mount Kenya, and near the northern frontier (Fawel *et al.* 2006). Local pockets of intermediate concentrations of 2–20mgl^{-1} have been reported throughout the country. According to Fendall and Grounds (1965) (in Fawell 2006) excess fluoride in surface water occurs in Lakes Turkana (12 mgl^{-1}), Bogoria (1,100 mgl^{-1}), Baringo (6 mgl^{-1}), Nakuru (2,400 mg l^{-1}), Magadi and elsewhere. In addition, Nair *et al.* (1984) reported concentrations of fluoride up to 1,640 mgl^{-1} and 2,800 mgl^{-1} in lakes Elmenteita and Nakuru respectively. In a study of over 1,000 groundwater samples taken nationally over 60 per cent exceeded 1 mgl^{-1}, 20 per cent exceeded 5 mgl^{-1} and 12 per cent exceeded 8 mgl^{-1}. The volcanic areas of the Nairobi, Rift Valley and Central Provinces had the highest concentrations, with maximum groundwater fluoride concentrations reaching 50mgl^{-1} (Nair *et al.* 1984). Nair and Manji (1982) realized that regional fluoride content of borehole water varies considerably across different boreholes (even when in close proximity) and also show temporal variations between the same boreholes, attributed to the structural and geological complexity.

A digitized map by Näslund & Snell (2005) using a GIS-software, and borehole data from the Catholic Diocese of Nakuru shows the location of the boreholes and the specific fluoride levels in each borehole along with other water characteristics of interest boreholes in Nakuru District (covering Lakes Naivasha, Nakuru and Elmenteita). Their interest was to facilitate development work connected to prevailing water situation. They saw the need of getting a good overview of the water sources/boreholes for both the government and the non-governmental organizations. Fluoride, the parameter of greatest interest for their study, had big variations between boreholes. The highest fluoride content was found to be 40.0mgl^{-1} while the lowest being 0.1mgl^{-1}. The compilation of about 358 boreholes shows that more than half of the measured boreholes had values that could lead to some kind of effect on humans' i.e. dental or skeletal fluorosis.

1.2.3 Local framework - Lake Nakuru Basin

A number of studies have been carried out within the area. Early documented works dates back to the eighteen century where most of the studies exposed an ardent interest on the River Njoro watershed, Lake Nakuru itself and Menengai crater. However, significant works have been conducted in the basin regarding geology and groundwater condition.

A detailed geological and hydrogeological survey was done by McCall (1957). He examined the geological evolution, formations and tectonics of Menengai Volcano and Nakuru area at large, and gave special descriptions on groundwater water conditions. His later report, McCall (1967), gave a descriptive account of the geology and geomorphology of the area covering almost the entire basin and elsewhere. He described extensively repeated rhythmic successions of lava types erupted at intervals from early Miocene times almost to the recent days, and demonstrated that the volcanic activity in the area was accompanied by major episodes of faulting which structured the Rift Valley as seen today. As a matter of interest, he presented results of petrographical analysis of different rock types sampled within region, a most important development on his earlier works. He did some revision of the distributions of geological formations and dating given in previous papers.

Geological structures in the basin have posed a lot of risk to development. In a more recent study, Ngecu and Nyambok (2000) taking Nakuru area as a case study of the Kenyan Rift Valley, surveyed the area on ground subsidence and its socio-economic implications. They discussed the implications of faults around Nakuru town and its environs and observed that subsidence especially during rainy season is widespread along the parallel fault zones as results of overlying unconsolidated volcanoclastic sediments becoming oversaturated with water eventually collapsing into subsurface water channels which loosely follow the fault zones, leading to formation of "sinkholes". Apart from being hazardous, ground subsidence degrades the environment when sewage water and garbage enter into the groundwater systems through the sinkholes. They suggested mitigation measures including control, channelizing of drainage, proper engineering practices and appropriate land use.

A study on the lake, rivers and sewage channel sediments in the catchment revealed the presence of heavy metal loading and pesticides residues. Raini (2005) reviews various results of field and laboratory measurements of pH, conductivity, Dissolved Oxygen (DO), temperature, alkalinity, salinity, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Secchi depth and nutrient level carried out at 13 sampling sites in Lake Nakuru, influent streams and urban effluent since 1993, and gave the results on the extent of pesticides and heavy metal effect.

The drainage basin is characterized by recurrence of seasonal dry spells with the losses in the lake exceeding the amount to cause a fall in water volume (Kulecho & Muhandiki 2005), hence the water level has been declining intermittently. As a result, the lake water salts content rose steadily as indicated by its conductivity, linked to the climatic cycle, responding from low to high conductivity states. Kulecho & Muhandiki (2005) investigated the trends of water quality and input loads to Lake Nakuru by monitoring the lake and its feeder streams in 2001 to 2004, at eleven stations in the lake and five stations on inflowing streams. They gave a descriptive account on lake levels fluxes, light conditions (transparency), dissolved oxygen, pH, conductivity and salinity, nutrients, as well as export load through influent streams.

Shivoga *et al.* (2005) investigated the impact of upland land use on downstream water quality in River Njoro watershed using data recorded from 10 sampling sites along the river. The data was used to examine the contribution of nutrients from sub-watersheds upstream draining each of the sampling sites. It was identified that the significant downstream water quality degradation is magnified by the additions from industrial, human settlements and agricultural land uses around the Egerton University. However, significant decrease in nutrient levels downstream indicating natural purification as the river flows through an area of large scale farming with intense well preserved riparian and in-stream vegetation. Gichaba *et al.* (2005), while using Lake Nakuru as a case study, surveyed the extent of sediment loading on inland lakes/wetlands. Total suspended sediments and discharge studies were carried on the river mouths (i.e. rivers Njoro, Makalia, Nderit and Baharini springbrook), and sewage drains that empty into the lake. They concluded that total suspended sediment loading into Lake Nakuru is a function of the concentration of total suspended solids and discharge at each mouth.

The incidence of the subsidence in the region has been a subject of concern to the residents, developers, engineers and earth scientists operational in the area for a long time (Nyambok & Dindi 1993). Subsidence in the region transpires in the form of rapid sinking or gradual downward settling of the earth surface with little or no horizontal motion (Abuuru 1990). The subsidence episodes which have left a trail of sinkholes result from the collapsed infilling sediments after subterranean denudation along the north-south running fault zones. Normally, water moves from the immediate small feeder channels in the porous pumice near the Menengai crater and enters into larger fissures down-slope. As a result, subsurface streams with turbulent flow are formed within the fissure. The turbulent flow causes progressive erosion within the fissures leaving large subsurface, long and horizontal continuous channels. These subsurface channels finally develop to catastrophic dimensions and lose their stability. Despite the fact that earth movements are at moment of a very small order, it is apparent that Nakuru is situated in a zone of crustal unsteadiness and there is a likelihood of the recurrence of catastrophic earthquakes.

1.3 Problem statement

Groundwater is the chief source of water for the expanding agricultural, industrial, domestic and wildlife demand in Lake Nakuru. However, its safety has not been fully assessed and documented appropriately as there are possible negative effects on groundwater in the basin induced by human as well as natural causes. These effects include depletion of the groundwater resource and deterioration of the water quality as a result of contaminated, agricultural, industrial and waste disposal activities, and from chemical processes in the aquifer due to the changed environmental conditions, and possibly from polluted lake-water seepage into the groundwater system. The geology of the area seems to contain a great potential to pose a risk to the regional groundwater quality as a result of its influence on elemental composition of both the major and trace elements due to their persistent interaction with the water. The value of these elemental compositions needs to be quantified and quality of water determined to check whether they exceed the required utilization limits or not. This will act as an awareness tool to the concerned parties utilizing this resource.

1.4 Research Objectives

1.4.1 General Objective

The general objective of this study is to relate aquifer stratigraphy and lithology to groundwater geochemistry in Lake Nakuru Basin, Central Kenya Rift.

1.4.2 Specific objectives

The general objective will be achieved by meeting the following three specific objectives;

1. To assess the stratigraphy and spatial extent of aquifers present in the Lake Nakuru Basin.
2. To determine aquifer lithology (and geochemistry) and its possible influence on hydrogeochemistry.
3. To carry out an assessment of groundwater quality

1.5 Justification and significance

Due to lack of enough hydrogeoscientific information on water quality, there was no adequately-defined legislation governing the development and use of groundwater in the area. This unregulated use of groundwater has the potential to have negative impacts on the sustainable development of the resource, and consequent negative impacts on long term social, economic, and agricultural activity in the watershed that relies on it. This key resource deserves detailed appraisal evidence based projection measures, and it is this crisis which the project at hand strived to address by way of carrying out groundwater vulnerability assessments that can be used in groundwater management and planning.

The scientific outcomes are linked to local, regional and provincial decision makers to enable them to come up with policies that will ensure that authorities answerable to the study area institute a sustainable groundwater management practice. This may involve developing water management strategies for local-scale applications and improving integrated understanding of factors affecting water quality as will be described by the project outcomes.

CHAPTER TWO

2.0 THE STUDY AREA

2.1 Location and description

The Lake Nakuru basin is located in the Central Kenya Rift extending within the bounds of 35°50' 35''E to 36°15'47.5''E and 0°42'56.5''S to 0°09'21.8''S. The catchment area of the Lake Nakuru basin is a closed drainage system of 1800 km^2 and the elevation ranges from 1760 to 3080 m. On the western side the basin is bounded by easterly dipping normal faults of the Mau Escarpment (3000 m.a.s.l). The northern boundary comprises the Menengai Crater (8060 – 2040 m.a.s.l) and Bahati Highlands to the northeast. To the south, the Mt. Eburru volcano (2820 m) separates the basin from the Lake Naivasha Basin (1890 m.a.s.l), whereas, a gently sloping grassland between the Lake Nakuru and Lake Elmenteita basins lies to the east. The lower section of this catchment basin is the insulated Lake Nakuru National Park (188 km^2), the buffer zone between human activities and the Lake Nakuru.

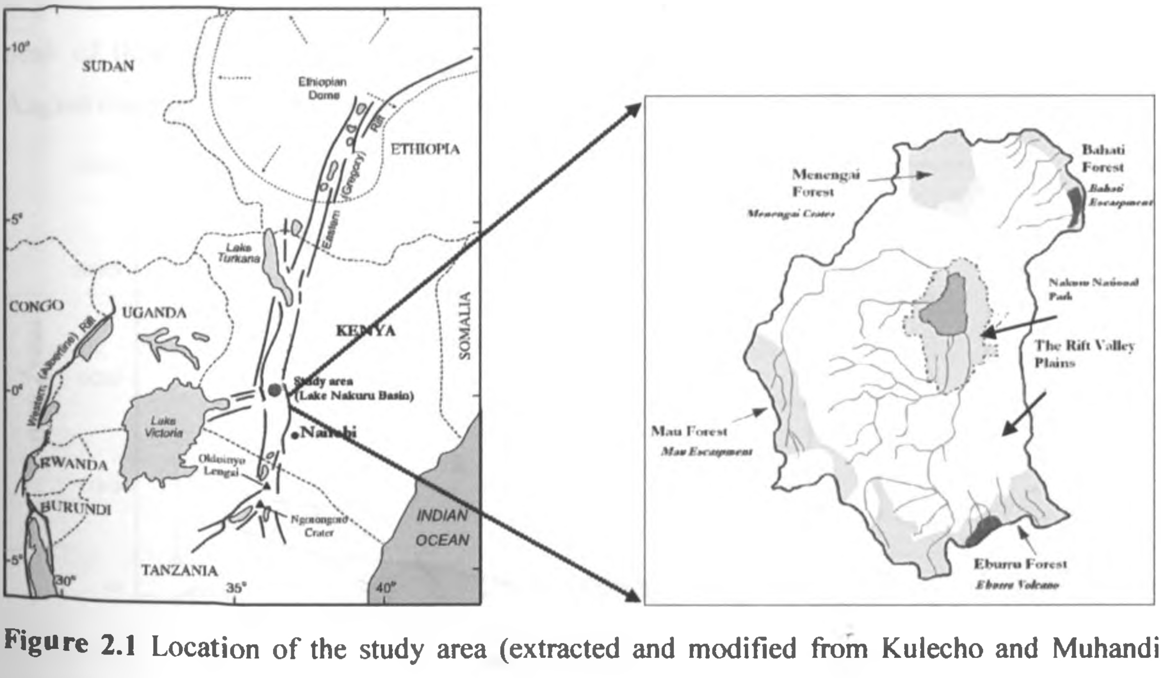


Figure 2.1 Location of the study area (extracted and modified from Kulecho and Muhandiki (2005)).

2.2 Climate Setting

Wetlands are valuable potential repositories of information on climate and hydrology of Africa (Thompson and Hamilton 1983). However, springs and wetlands in tectonically active areas, like the East African Rift, may be related to the interference of aquifers by faults and fractures (Deocampo 2002) and so in such settings the growth of wetlands does not necessarily indicate a change to moister climate. The regional climate is strongly influenced by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ) and the coinciding precipitation pattern (Nicholson 1996). Rainfall associated with the transition of the ITCZ follows the highest sun in March and September with a lag of three to four weeks (Nicholson 2000). Therefore, the basin receives most of its precipitation during the "long rains" in April to May and the "short rains" in November. A third lesser precipitation maximum occurs in September, when the Congo air masses transport moisture from the Congo basin to East Africa (Vincent *et al.* 1979). The amount of precipitation is strongly linked to topography, thus, the highest rates occur in the high altitude parts of the basin in the west and east, whereas the lower areas are relatively dry. The long term hydrologic budget of the basin is primarily controlled by the spatial and temporal distribution of rainfall, superimposed on tectonically- driven influences on the drainage network and basin geometry (Strecker *et al.* 1990).

A close relationship exists between stream-flow and precipitation in the catchment. The first peak of flow coincides with the first peak rainfall in May, while the second peak of flow in August overlaps the second peak rainfall.

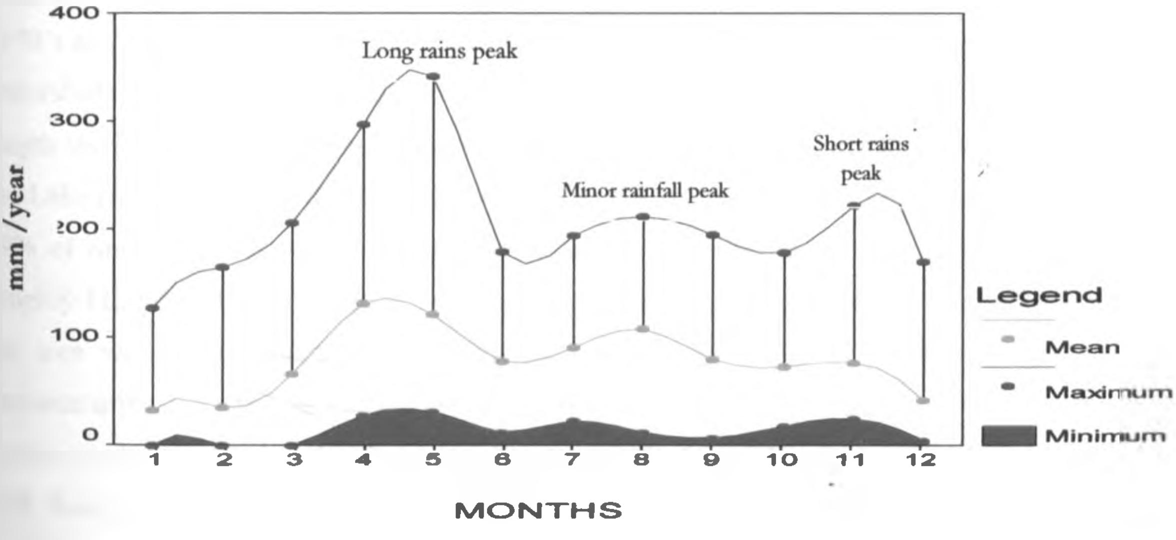


Figure 2.2 Mean monthly rainfall of Nakuru measured within the years 1964 – 2003. Note that the annual distribution has three peaks; May, August and November (data from Kenya Meteorological Department (2008)). NB: the weather stations are shown in Figure 2.8.

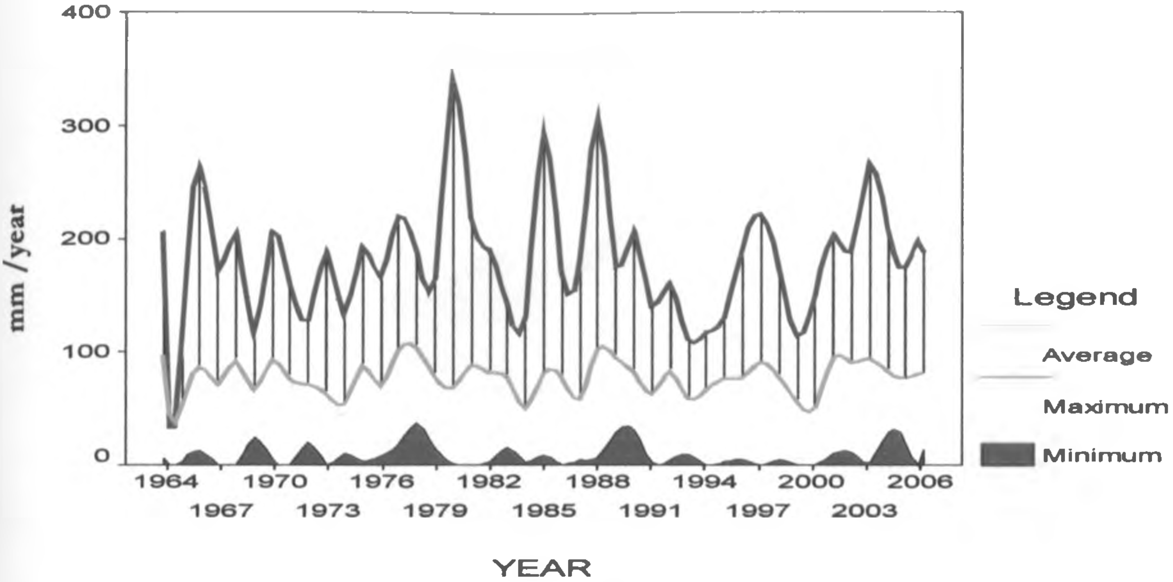


Figure 2.3 Mean annual rainfall of Nakuru area from the years 1964 – 2006 (data from Kenya Meteorological Department (2008)). NB: the weather stations are shown in Figure 2.8.

2.3 Vegetation and General Land Use

Land use in the watershed has been changing since the beginning of the last century following large scale settlement on the middle reaches of the watershed by colonial farmers and later in the 1970's and 1980's by Kenyan farmers. The basin consists of various river basins that form local watersheds with diverse vegetation cover and land-use. Njoro River, for instance, is 60 km in length surrounded by indigenous forests in the upper reaches and contributes about 302 Km^2 of the Lake Nakuru watershed (Shivoga *et al.* 2005). The river and its catchment contributes about 39% of runoff into lake from annual rainfall of 900 mm and potential evapotranspiration of roughly 1150 mm. Upper ridges of the Njoro watershed are thus critical water recharge zones in the area with human population in watershed averaging 75,000 in 1999 census. Regional resource utilization such as medicinal herbs, firewood, fodder, ground & surface water, timber, stones, sand, gravel, cultural uses, etc, are common in the basin. The semi-arid areas are common with fruits, and subsistence hunting for bush meat for the riparian and forest tribes and grazing grounds for the Maasai pastoralists.

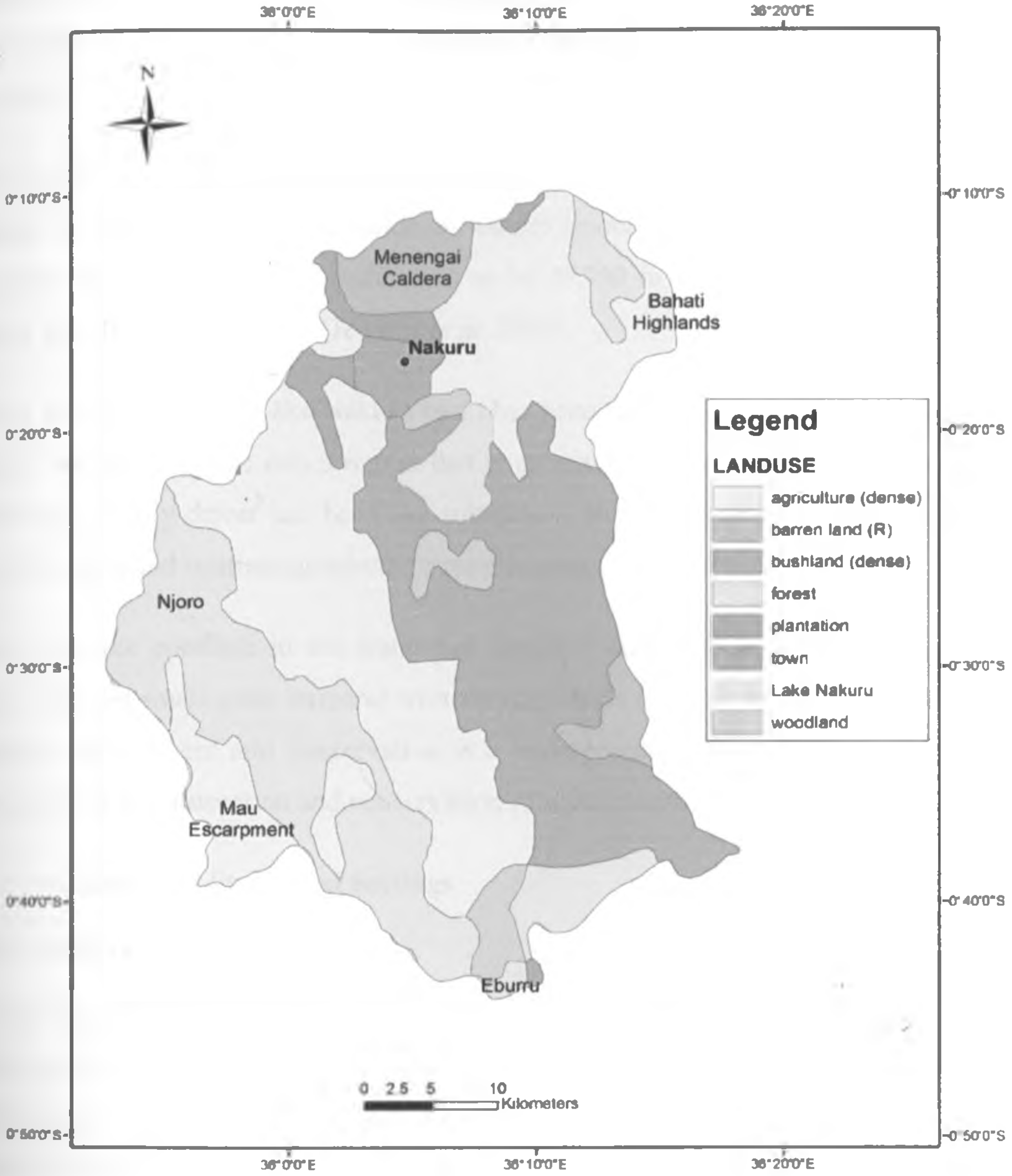


Figure 2.4 Land-use distributions in the basin. Statistics shows that; Agriculture (Dense) = 39.3%, Bush-land (Dense) = 24.8%, Forest = 21.5%, Barren land = 4.8%, Woodland = 3.1%, Plantation = 2.6%, Water Body = 2.1% and Town Centre = 1.7% (extracted from ILRI map (2008).

Forest degazettement and encroachment by agrarian communities has led to land degradation in as well as impairment of water quality across entire upland areas. A recent study reveals that forest cover reduced by approximately 50% between the years 1970 and 1987. Apparently, it covers roughly less than 15% in the Lake Nakuru basin. Farmland increased by ~30% whereas small scale farmers constitute 70% of land use. Urban settlements increased by 20% (Shivoga *et al.* 2005).

A case study on Njoro watershed shows that approximately 50% of population lives below poverty line hence increased demands on natural resources such as water. Livestock is part of the poor-farmer's households (estimated to be 25,700 in the watershed), and mostly comes among the Maasai pastoralists (Jenkins *et.al.* 2005).

During the last 30 years, Lake Nakuru basin has been transformed from a sparsely populated and densely forested expanse into a region that is greatly settled, extensively cultivated, and rapidly urbanizing. A key driver has been the substantial increase in the human population, resulting from both past and continuing extensive resettlement.

Water resource conflicts in the watershed between different communities (livestock keepers, large-scale and small-scale farmers) with varying levels of water use and perception about water resource management and conservation is a widespread problem. Community participation is paramount to the restoration and conservation of water resources in the watershed.

2.4 Geology and Structural Settings

2.4.1 General Geology

The geology of the basin consists of volcanic rocks (lava flows and pyroclasties) of the Tertiary – Quaternary age, which have been affected by a series of faulting. The soil also is of volcanic origin and, due to its high porosity, permeability and loose structure, is highly susceptible to erosion, land subsidence and fractures commonly during or after heavy rain (Ngecu & Nyambok 2000). The geology in the region can be described in relation to the main geomorphologic units observed; the Mau and Bahati Escarpments to the west and east respectively, the Menengai Crater to the North, Eburru volcanic cone to the south, and the centrally-located Rift Valley plains. Geology varies significantly from one geomorphologic setting to another, a phenomenon linked to the regional tectonic setting of the study area.

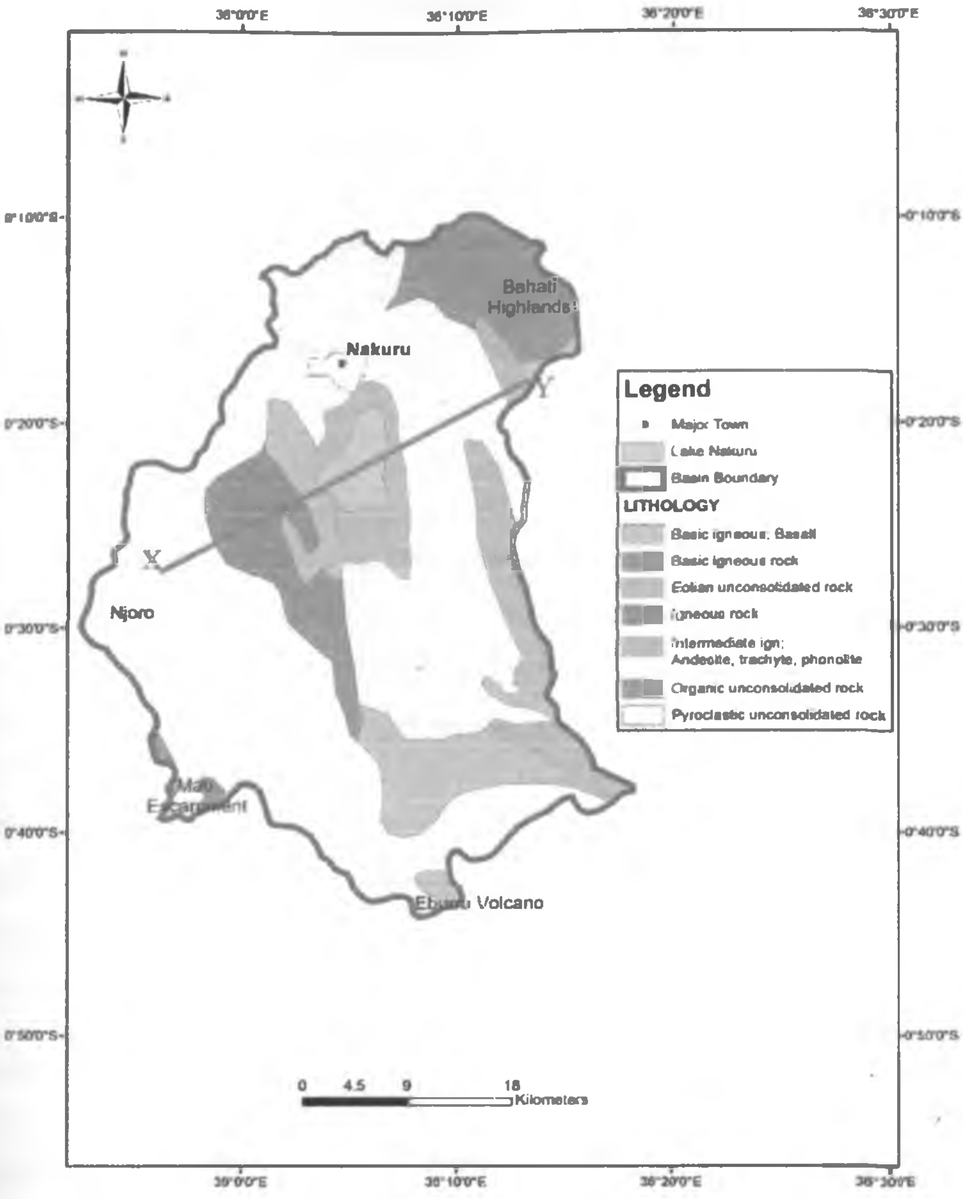


Figure 2.5 Geological map for Nakuru basin (extracted from ILRI maps (2008)). The thick blue line is a cross section line through points X-Y.

2.4.2 Bahati and Mau Escarpments

As documented by McCall (1957), volcanic rocks exposed in the Mau and Bahati Escarpments are thought to be the oldest volcanic rocks locally exposed. The majority of the volcanic rocks in Mau consist of a series of greenish-grey welded tuffs, together with yellow pumice tuffs, sedimentary intercalations, and reworked tuffs and clay. Similar welded trachytic tuffs and yellow pumice tuff are exposed in the Bahati Escarpment. The phonolites underlying the Mau and Bahati tuff formation have been named “Solai Phonolites”, consisting of series of flows characterized by abundant nepheline phenocrysts.

In the Njoro area the older faulted lavas and tuffs are covered by compact black ash from Menengai, approximately 10 to 15 m. thick, concentrated along river valleys as observed alongside Njoro River. The river is cut down through overlying unconsolidated pumice and ash and runs over the hard upper surface of the black ash. This ash has been disrupted by minor faults on the older north-south lines and probably about 8, 000 to 10, 000 years old (McCall 1957).

2.4.3 Menengai Crater

Menengai is known to be the largest caldera in Kenya, roughly trapezoidal in shape, and covers more than 90 Km^2 and having an ENE – WNW long axis of 15 to 18 Km. As illustrated by McCall (1957) the Menengai volcanics differ from the older volcanic rocks in that they can be related to a single central volcano, Menengai, which lies immediately north of Lake Nakuru. The floor of the crater is covered by trachyte lavas which were formed through several phases of eruption. The lavas are characteristically black in colour and are generally vitreous. In the thin section, the layers contain criss-crossing feathery prisms of aegirine-diopside, which are altered to amphiboles in some samples. Feldspars are abundant in these lavas and most of them have been identified as anorthoclase (McCall 1967).

A series of Menengai phonolitic trachytes outcrop in faulted blocks, emerging from thick Pleistocene deposits of the Lake Nakuru Basin. The earliest flows are composed of porphyritic trachyte with spherulitic microtexture. These lavas are black in color, but red coloration is seen in the vicinity of old land surfaces separating the flows. The lava is overlain by more glassy lava poured out and the topmost flow exposed in the wall consists of grey trachytic glass, passing up into green devitrified and scoriacious glass. Subsequently, overlaying this layer is the uppermost flow believed to be a welded tuff or trachyte ingnimbrite (McCall 1957).

2.4.4 Eburru Volcanic Cone

Eburru is a twin-peaked volcano whose geology can be divided into two groups; older porphyritic trachyte lavas showing a striking similarity to the earliest porphyritic trachyte lavas of Menengai and newer classy trachyte and trachy-obsidian flows. Eburru volcano is later than the grid faulting, though the older porphyritic trachyte lavas are affected by substantial posthumous fault displacements, whereas the latest glassy trachyte group is only affected by slight fissuring (McCall 1957).

2.4.5 Rift Valley Plains

This geomorphologic sheeting surrounds Lake Nakuru and consists of both lacustrine and volcanic plains. Lacustrine plain were formed due to fluctuation of the lake level and is composed of "Gamblian lake" sediments (Thompson & Dodson 1993) and some reworked pyroclastic material. Trachytes, phonolites, basaltic and tuffs form the volcanic plains. Nakuru Phonolitic Trachyte are envisaged as having been erupted from fissures during a subsequent renewal of tension and were restricted in extent to the floor of the earlier valley which they covered in flat sheets of lava. Subsequently large-scale faulting disrupted these flat sheets into fault blocks, at the same time forming the secondary steep set of faults scarps at the foot of the Bahati Escarpment and at the foot of the Mau on the west of Lake Nakuru. Unconformity exists between the Nakuru trachyte and the welded tuff and tuff formation of the Bahati Escarpment. Temperley (1957) (unpublished report) in McCall (1967) interpreted the slivers of later lava up to a some hundred meters thick seen throughout the length of Bahati Escarpment at the foot of the older rocks as due to refaulting – along the original boundary fracture of the rift graben, after erosion had cut back the fault scarp some hundred or so yards from the line of the fault and later trachyte had flowed over it and up against the eroded scarp.

On the west of Lake Nakuru an old surface separates the basalt from the overlying phonolitic trachyte. The Mbaruk basalt which underlies the phonolite was also erupted during the late Pleistocene. It is porphyritic feldspar-olivine basalt which is only a few meters thick. The rock is well exposed on the Lion Hill and on the western side of Lake Nakuru where it forms restricted flows which are concentrated along the fault zones. In thin section, the basalt shows broken and partially resorbed labradorite phenocrysts which are often 0.5 cm long. These phenocrysts are set in moderately fine ground mass of similar feldspars which occur in the form of short laths, olivine crystals and a few crystals of neutral colored pyroxenes. Iron oxide occurs as small granules which often surround the olivine and pyroxene crystals. The area which lies on the north-western side of Lake Nakuru is covered by Upper Pleistocene coarse yellowish, well stratified fluviatile sediments (McCall 1967).

The sediments are composed of tuffs and diatomite and are conformable with the underlying lava, often punctuated by minor agglomerate formations. The area around Lake Nakuru and Rhoda Hills are composed of lower Pleistocene phonolitic observed in thin sections made from fresh phonolite ignimbrite layers which are underlain by Mbaruk basalts and trachytes. The ignimbrites in the area are dense dark green compact lavas which are composed of green spongy glass, dotted with black opaque iron specks, which are surrounded by small partially resorbed feldspar phenocrysts. The feldspar phenocrysts consist mainly of anorthoclase and they show parallel banding. In the thin section most of the nepheline in the Rhoda phonolites has altered to analcite. However, fresh nepheline crystals were observed in thin sections made from fresh phonolite samples. It is observed that analcite usually infills linear elongated glass cavities; the analcite is generally pink and has low refractive index (Pulfrey 1951). Other minerals which were observed in the thin section of the Rhoda phonolite are cataphorite and riebeckite, Acmite and iron oxide occur as minute crystals haloing some of the nepheline or analcite crystals.

2.5 Geological structures

2.5.1 Major faults

The study area is part of the Gregory Rift Valley, which is a component of the greater rift system extending from Syria to the Zambezi. It is a multifaceted fault trough with a general north-south orientation (see Fig. 2.6), the entire system being broken up into oblique structures and other shorter fault troughs normal to the main trend, as demonstrated by Kavirondo Rift Valley (McConnell 1948). The study area is located at the intersection of the Kavirondo Rift Valley, a fault trough extending westwards to the shores of Lake Victoria, with the Gregory Rift Valley. The nature of its structural complexity central in the junction is brought about by the definite deflection in its course and can be observed resulting in more complex fault structures than are normally in other straighter sections of its course. In addition, the intersection had been a portion of a focal point of intense volcanism, evidenced by volcanoes – Menengai and Eburru. The latter is a twin-peaked massif, situated slightly to the south, forming a barrier across the Rift Valley floor.

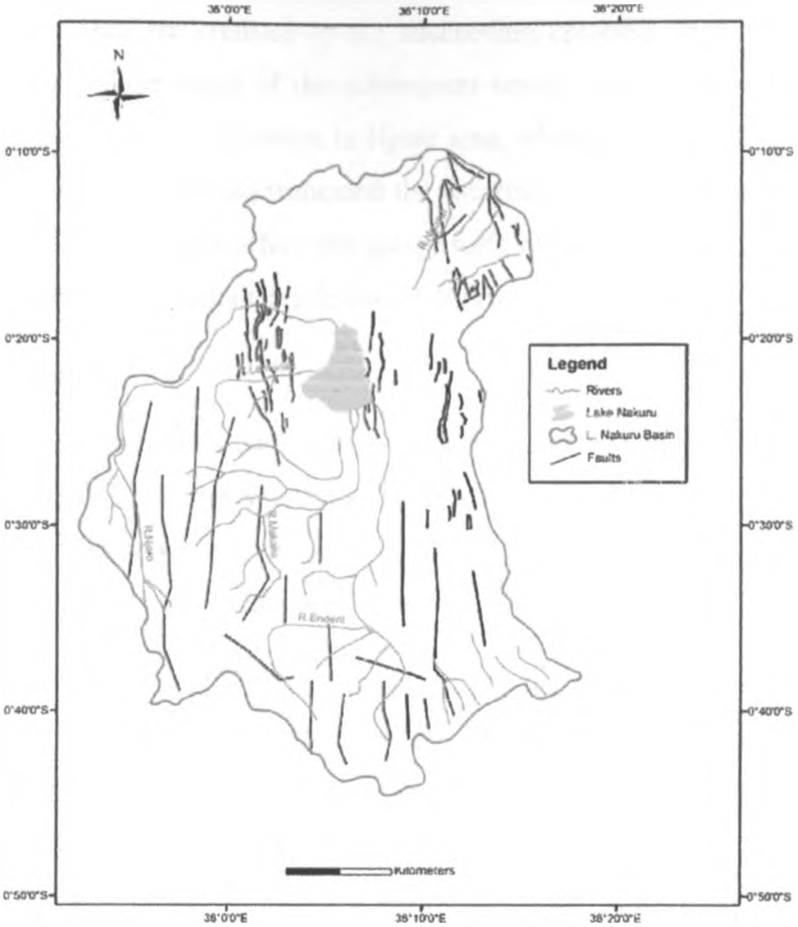


Figure 2.6 Structural map showing the major faults (extracted from Geological map (McCall 1967)

Tertiary history of the Rift Valley began with downwarping of narrow troughs on the site of the contemporary rift valley. This downwarping interrupted the drainage of that part of the African Shield, and a series of shallow lakes were formed. This formed the major faults and resulted in fault zones of massive displacement along the line of Mau Escarpment and Bahati-Subukia Escarpment. The actual faults are mostly obscured by later eruptives and are now characterized by fault line scarps. Later pyroclastics and sediments as obscured the faults in most areas especially the plains. The faults are open and devoid of resistant clay filling, and as a result acting as conduits where water is channeled to and from the aquifers. Aquifers from older formations seem to have undergone remarkable displacement resulting from faulting. Faults interconnect adjacent aquifers into distinct hydrostatic system hence forming irregular series of enclosed flat-lying aquifers (McCall 1957).

According to McCall (1957), the previous faults are not exposed, and the majority of the major faults seen in the area are credited to the succeeding episodes of faulting. There is a minor difference in trend of the faults of the subsequent series. The Mau Escarpment shows a west-north-west to east-south-east deviation in Njoro area, while the Bahati Escarpment trends north-west to south-east. Later faulting truncated the escarpment into a series of north-south troughs. For instant, posthumous faults affect the glassy tuffs of Menengai near the Crater Stream, also noted to have an effect on Makalian ash east of Njoro.

2.4.6 Minor faults

Fissures and very minor faults cut recent pyroclastics showing in a railway cutting at Mereroni (Lanet). McCall (1957) further illustrates the evidence of latest movement seen in the form of surface fractures most frequently found in the centre of fault troughs. A zone of recent fissuring crosses the Njoro River east of Glanjoro Farm.

Taking into consideration the Tertiary structures, the only kind of displacement exposed on the surface in the Rift Valley are steep normal faults. The actual fault planes are not very commonly exposed, but where they are there can be no uncertainty as to their nature. The fractures are open and generally packed with rubble. The entire pattern of the faulting suggests simple gravity collapse. It is suggested that the latest minor faults may perhaps be caused by subsidence of the crust successive to extrusion or great volume of lava and tuff.

Some parts of Nakuru Town and its surroundings frequently experience subsidence along the parallel fault zones during and after heavy rainfall. During the rainy season, when most of the subsidence occurs, the overlying unconsolidated volcanoclastic sediments become oversaturated with water. The water reduces the shear strength of the sediments and also introduces extra loading through saturation leading to subterranean erosion along faults. The unconsolidated sediments then collapse into the subsurface water channels which closely follow the fault zones, leading to formation of “sinkholes”. Several subsidence zones show a high level of instability in the layers of the overburden, which are composed of unconsolidated fine to medium volcanoclastic sediments, whose zones are usually governed by numerous north—south trending parallel faults (Ngecu & Nyambok 2000).

2.6 Geological and Structural Succession

The history of the evolution of the Rift Valley is remarkably complex in the central sector where Nakuru Basin is situated. The geological and structural succession has been tabulated in Table 2.1 below.

Table 2.1 Table showing geological and structural succession (extracted from McCall (1967))

EON	ERA	GEOLOGY AND STRUCTURES	THICKNESS
	RECENT	• **Superficial Deposits;** Soils, Alluvium, • **Upper Menengai Volcanics;** Trachyte (lava flow and scoria cones) • **Sediments;** Mainly deltaic, i.e., Makalian Sediments --------**Weak unconformity**---------- (?) Gamblian sediments of Nderit and Makalia	Unknown <100 feet
	UPPER	**Minor Faulting;** new fractures and renewals on older fracture lines at the West of Lake Nakuru	Thickness unknown for tuffs but it is <100 ft for sediments
		Tuffs and sediments(Lacustrine); • Lamurdiac Sediments of Nakuru Basin • Pumice showers from Menengai (Pumice mantle, possible much older)	
		Minor Faulting; new fractures and renewals on older fracture lines in Nakuru Basin	
	MIDDLE	• **Older basalts, tuffs and agglomerate of Elmenteita;** olivine basalt flows at Soysambu, phreatic tuff (Elmenteita cones), agglomeratic tuff of Honeymoon Hill cones	~200feet
		Third Major Faulting of the Rift Valley: Possible time of the formation of Menengai Caldera. Complex patterns, dropping Rift Valley floor a further few hundred feet	
		• **Lava flows and sediments;** Gilgil Trachyte, Mbaruk Basalt, Ronda Lacustrine Sediments, Ronda Phonolite and Trachyte	
	LOWER	• **Lava flows, Tuffs and Sediments;** Lake Nakuru Syndicate Phonolite, Late Pumice Tuff, Welded Tuff 'Ignimbrite' and sediments forming unconformable outliers on the Kinangop and Bahati Tuffs	
UPPER TERTIARY	PLIOCENE	**Second Major Faulting of the Rift Valley;** Forms a series of tilted blocks dropping the rift valley floor ~3000ft vertically in Nakuru Basin.	
		• **Tuffs, lava flows;** Mau Tuffs (pumice tuff 'Ignimbrite', sediments (lacustrine) with intercalated phonolites), Bahati Tuffs (pumice tuff 'Ignimbrite', sediments (lacustrine)) and Lower Menengai Volcanic Series.	Locally > 1000ft

		First Major Faulting of Rift Valley; Less complex compared to the third faulting episode. Dropping floor of the Rift Valley probably slightly less than 4000ft	
	MIOCENE	**First Minor Warping of the Rift Valley;** forming basins in which subvolcanic sediments were deposited.	
EARLY TERTIARY	**MESOZOIC PALAEOZOIC**	Interval of several hundred million years in which successive erosion cycles and epeirogenic movements affected the continental surface	
PRECAMBRIAN		**Basement System;** Precambrian Orogenic movements to some extent control Tertiary-Quaternary structures	

2.7 Hydrogeological setting

Hydrogeology is significantly controlled by the geology, tectonics, topography and climatic aspects. Topography in the vicinity creates two different hydro-geological environments, which affects significantly the hydrogeology; uplands and lowlands. The upland areas of Mau and Bahati are often associated with high rainfall values, which are the main sources of groundwater recharge for the lowland aquifers. Groundwater occurrence is greatly determined by the geological conditions and tectonics. Structural features such as faults often optimize storage, transmissivity and recharge significantly occuring in areas adjoining surface drainage system as seen in streams disappearing beneath land surface as typified by River Ngosur. Shallow groundwater table, low rainfall and moderately low values of recharge characterize the low lying areas.

The major aquifers are found basically on soft and porous volcanic ashes and tuffs, and volcano-sediments covering vast parts of the rift floor, alongside fractured volcanic rocks and at times along weathered contacts between different lithological units. These aquifers generally have relatively high permeability and are often vary from confined to unconfined with high specific yield. A typical example is the Bahati aquifers whose Kabatini boreholes supply most of the water requirement for Nakuru Municipality. The inconsistency of geological formations has complicated the hydrogeological studies of the basin particularly areas adjacent to Menengai Crater. Figures from existing boreholes and boreholes reveal complex hydrogeological conditions, with depth to water varying throughout the basin.

Geological formations in the study area are restricted to the Cainozoic volcanic rocks (i.e. Tertiary-Quaternary) as well as sedimentary deposits, essentially of lacustrine origin, extending in time of deposition from the Tertiary era to the present day. The volcanic formations consist of basalt, phonolite, phonolitic trachyte and trachyte flows, together with intercalated tuffs and reworked tuffs holding abundance of water rounded fragments. Welded tuffs are widespread throughout the area depicting a grey glassy matrix choked with pyroclastic fragments and are trachytic in composition; their impervious nature is analogous to that of trachyte lava flows. The main aquifer is the lacustrine volcanic/sedimentary series usually occurring as fractured or reworked volcanics, or along the weathered contacts between lithological units.

There is invariable grading from the reworked tuffs to lacustrine deposits with notable increment of rounding of particles in the coarser layers. Sediments extending to several hundred feet thickness are known to be the main aquifers. Perched water-tables are mostly encountered on the high ground above or upon steep scarp slopes (McCall 1967). This is typical to Njoro area where the perched water-table yields considerable supplies noted to occur alongside Njoro River believed to be as a consequence of seepage from the river bed. The availability of striking a perched water table depends in the presence of major faults within the region. In regions where the perched water-table is missing, boreholes may be requiring deeper drilling to strike the main water body.

A shallow water-table encountered along northeast corner of the study region is attributed to the disappearance of River Ngosur and other seasonal streams from Bahati highlands into the sub-surface environments, subsequently, forming unexpected hydrostatic ridges that eventually raise the water-table significantly within the aquifer.

2.8 Physiography and Drainage

A probable close link between surface and groundwater in the basin seems to exist particularly with the structural framework and permeability of the rock-types present, which leads to disappearance of surface water into subsurface environment.

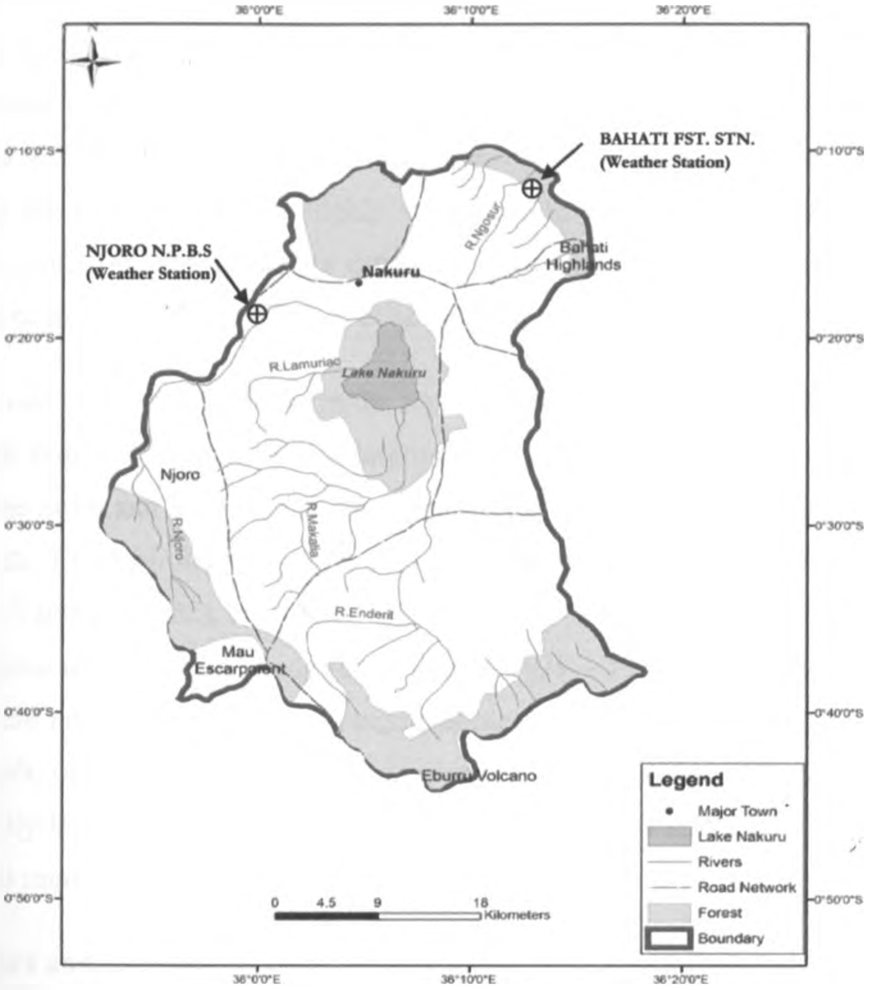


Figure 2.7 Spatial distribution of surface water resource and various land use in the area (extracted from ILRI map (2008)). NB: two weather monitoring stations are also presented.

2.8.1 Lake Nakuru

In the basin, Lake Nakuru forms an important surface hydrology feature in the basin lying within a graben which is flanked by the Mau Escarpment on the western side and the Menengai Crater on the northern side. The lake occupies the lowest part of the study area at an altitude of about an approximate area of 44 km^2 characterized by highly alkaline water with d 1440 meg/l (Talling & Talling 1965). The surrounding terrain forms a rises towards the Mau Escarpment on the western shoulder of the Gregory engai with Bahati uplands in the northern and north eastern corridors of the several shallow, alkaline-saline lakes lying in closed hydrologic African Rift Valley, which stretches from northern Tanzania through Kenya stone & Melack 1984). The primary contribution to its water budget are and springs known to the chief determinants of its salinity status. The om the adjacent Nakuru town sweeps across various human activities rendering it highly vulnerable to pollution. It is characterized by high es which with its catchment geochemistry make it an extreme ecosystem, aquatic life (Odada *et al.* 2005).

he highest lakes in the region, an issue that tends to affects the lake's water ble insignificant underground water input unlike lakes Bogoria and Magadi and south of the lake respectively, the two lakes are situated in a relatively hydrological inference is both altitude and axial fault line system dependent. hi (1982), the mean depth of the lake is 2.5 m, maximum depth of 4.5 m, and 92 ×10^6 m^3 (long-term mean of 1925 – 1979). Odada *et al.* (2005) records a depth of 1.01 m (range recorded during the 1997/1998 El Niño floods). Its combined with both high evaporation rates and seasonal rivers make the lake a impacted bionetwork, since it does not have any embankment capability to resist pacts driven by catchment processes.

2.4.2 Rivers and springs

by Odada *et al.* (2005), Baharini Springs, and other springs along the eastern perennial, contributing about 0.6m^3/s to the lake. The lake's catchment input is nal rivers that emanates from the upland areas (marked by bounding Menengai, and Bahati highlands) to the valley bottom. Five main seasonal rivers include rit, Naishi, Njoro and Larmudiac, draining the southern and western areas of the ated wastewater from Nakuru town, drain into the lake from the north (see Table these rivers (Njoro, Ngosur, and Naishi) become influent, disappearing along the recharge deep aquifers.

Table 2.2 Mean discharge rates (m^3/day) and input loads (tons/yr) to for the selected feeder stream of Lake Nakuru (2001-2002), (modified from Odada *et al.*, 2005).

Stream	Mean Flow	Minimum Flow	Maximum Flow	Suspended Solids	Total Phosphate	COD	Total Nitrogen	Other Inputs	Total Load
River Njoro	52116	0	268980	50	2.98	122	40.8	1164.22	1380
River Makalia	26065	0	174539	3	0.34	248	3.7	640.96	896
River Nderit	13703	0	53571	541	1.75	548	25	1107.25	2223
Baharin Springs	1831	301	3924	1852	10.52	168	56.6	7086.86	9173.98
Sewage Drain	2184	173	5140	200	20.88	712	176	26984.12	28093
Total Load	**95899**	**474**	**506154**	**2646**	**36.47**	**1798**	**302.1**	**36983.41**	**41765.98**

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1 Introduction

The method pursued in this study is based on the objectives of the study as acknowledged in section 1.2. The aspects of the basin considered indispensable to effect the set goals includes; geology, hydrogeology, hydrochemical analysis, and structures (i.e. faults, to be specific). The arrangement of the primary stages and the activities under them are presented by the flowchart in figure 3.1 below.

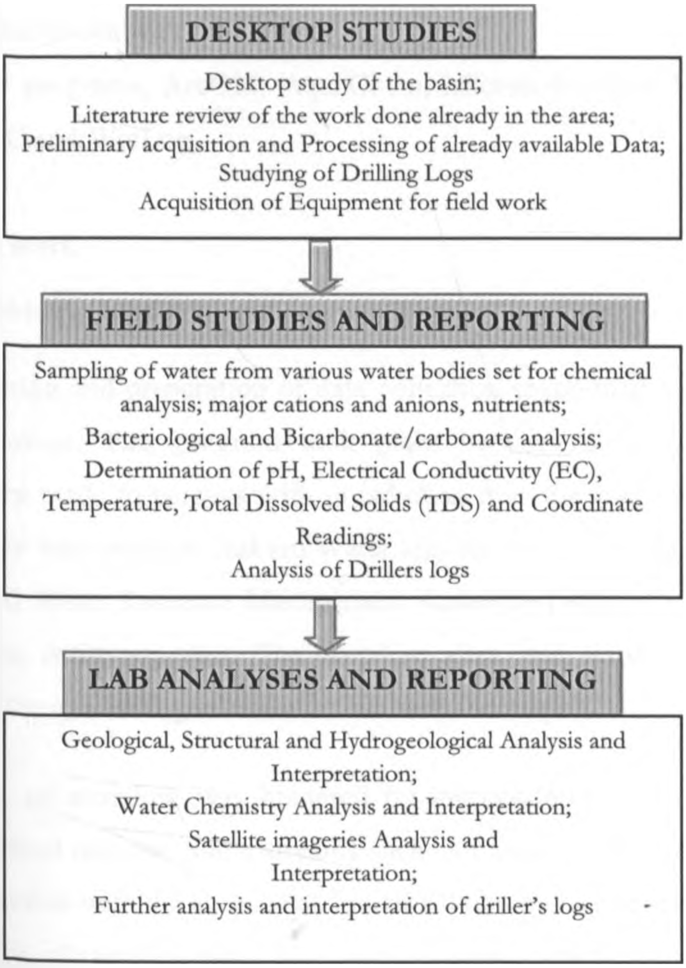


Figure 3.1 Descriptive flowchart showing primary stages pursued in this study

In addition, the major source of information and materials used are stated. Due to the diversity of the aspects involved in the study, procedures followed for the different individual aspects are explained in separate sections of this chapter. Other than the activities undertaken, the theoretic bases of the different aspects are presented in their respective sections.

The main materials to be used in accomplishing this task include;

- Driller's logs obtained from the Ministry of Water and Irrigation
- Geological Map of scale 1:10000
- Topographical Maps (Sheet No.'s 119/3 (Nakuru), 119/1 (Menengai), 133/1 (Ol Doinyo Oburu), 118/2 (Rongai) & 118/4 (Njoro)
- Surface and groundwater analytical data
- Computer programs; ArcGIS, AquaChem, Microsoft Office Excel, SPSS, Rockworks, PHREEQC and WinLog.

3.2 Pre-field work

3.2.1 Initial field-trip planning and preparations

Preliminary planning and preparation of data collection saved time and reduced the number of associated difficulties. This program took place between 6 – 18th of April, 2008. Prior consultations were made to persons with jurisdiction over the study area notifying them of the program. Requests were made to Nakuru Water and Sanitation Company (NAWASCO), Nakuru National Park and Water Resource Management Authority (WRMA), whose assistance became crucial during the entire program. The sampling sites were carefully established by making combined use of the available groundwater database and maps.

The initial order of sampling was hindered by inaccessibility of some areas due to social, physical and political reasons. Some streams such as Lamuriak and Enderit were dry during the period. These together with the absence of functional boreholes on some important areas resulted to uneven selection of sampling sites. Selection of boreholes to be sampled depended on aquifer, borehole type, water use, the study area, available data as a result of earlier sampling.

3.2.2 Geology and hydrogeology

The geological information was extracted from the studies of preceding workers who have mapped the area both from a regional point of view to a more detailed local study. Besides, information has been gathered from the drillers' logs for 33 boreholes and Geology Map of the study Area. Further information was gathered through observations made at some areas during fieldwork. Their locations were taken using GPS handset and they were plotted on the map of the study area. Geological map was digitized from the official Geological Map using ArcGIS version 9.1.

Drillers' logs were used mainly to assess aquifer lithology in the area of study. These together with the published geological map of the area and geological reports (McCall 1957, 1967) were used in evaluating the local geological characteristic and their possible impacts on hydrogeochemistry. The ions analyzed from the study include; Mg^{2+}, Na^{+}, K^{+}, Ca^{2+}, Fe^{3+}, Pb^{2+}, Mn^{2+}, Cr^{2+}, Zn^{+}, Cd^{2+}, NO_3^{-}, SO_4^{2-}, HCO_3^{-}, Cl^{-} and F^{-}. Other parameters include pH, Total Dissolved Solid and Conductivity.

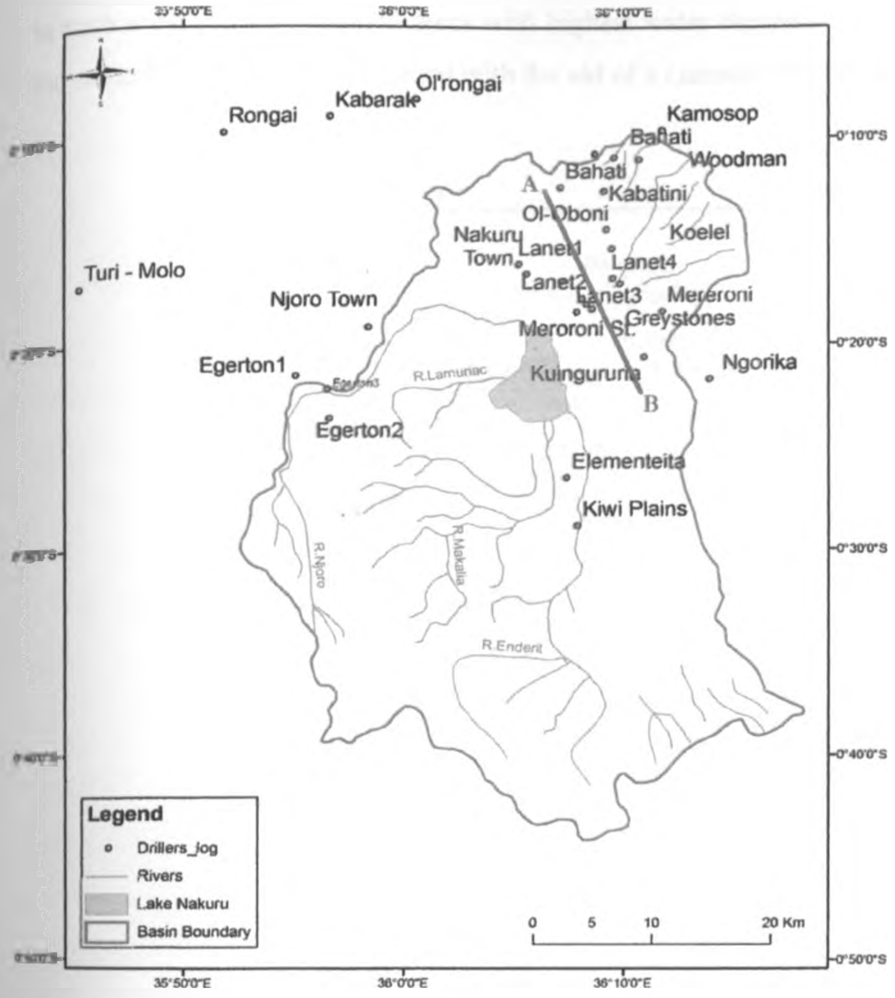


Figure 3.1 Driller's logs sites. The thick red line is a cross section line through points A-B.

3.3 Fieldwork

3.3.1 Fieldwork and Handling of Samples

The fieldwork program ran between 27th of April to 10th of May, 2008. Water sampling was carried out for various reasons with purposes surrounding groundwater quality assessment. The sample collection and chemical description procedures observed was conducted in line with the field sampling procedure for Texas Water Development Board (TWDB), (Boghici 2003). A total of 60 sets of samples were collected from various locations in the study area. Most of the sampling surrounded densely populated regions associated with availability of functional boreholes, thus, the southern part of the basin was scarcely represented. The sampling was concentrated in the northern, western, and eastern sides of the lake. Their locations were chosen in such a manner that targeted areas with highest water demand (see Fig. 3.2). The locations of the sampling sites were ascertained with the aid of a Garmin GPS handset.

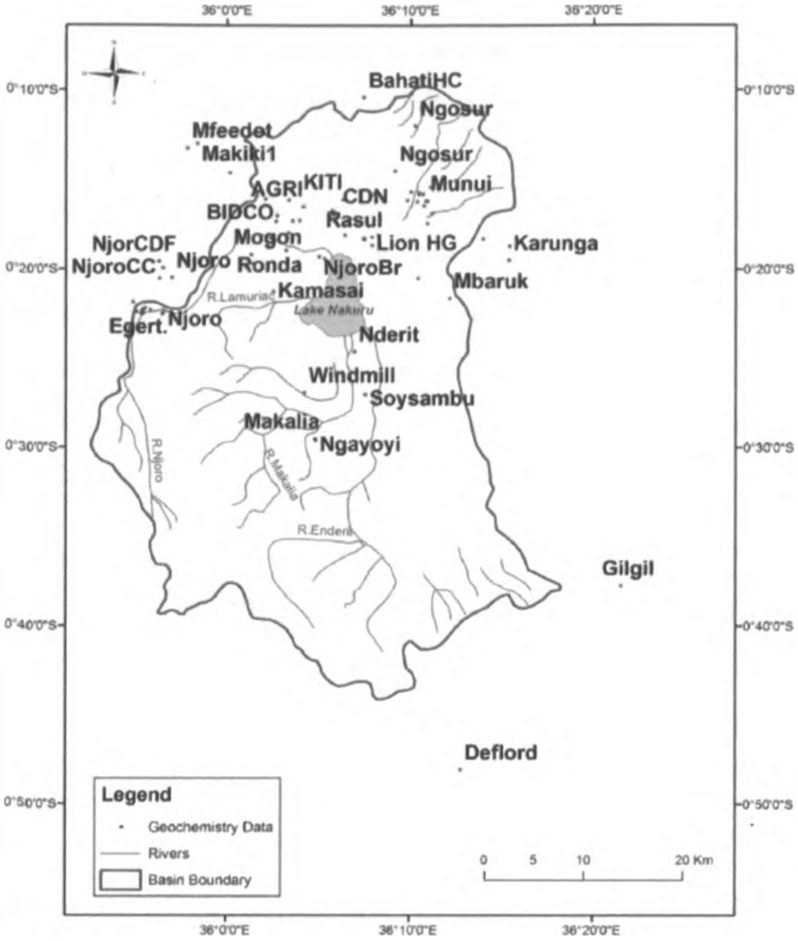


Figure 3.2 Groundwater sampling sites

Different water bodies required diverse sample collection procedure. Representative samples from river water were collected in various points, right in the middle of the channels, inclined at an angle to lessen turbidity. Lake water sample collection was done along the shorelines with specific interest being entry points of major rivers. Water from boreholes was first purged to empty any stagnant water in the borehole casing prior to sampling so as to provide a representative sample of in-situ groundwater with least disturbance of the flow system and the collected sample. The extent of purging was determined by the rate of stability of field parameters readings; pH, Eh, Specific Conductance and Temperature. The sample collection took place near the head of the borehole before the water goes through storage tanks or any kind of treatment. Shallow boreholes samples were fetched manually and the container used to draw the sample dipped to sufficient depth to minimize the abstraction of non-representative samples.

To ensure that the sample bottle conformed to the desired standards, prior arrangement enabled acquisition of appropriate sampling bottles and bags. To sample, each bottle was first carefully rinsed with distilled water. The bottles were then each totally filled with the respective water samples and carefully closed and was then dispatched to the laboratory for analysis. The bottles were completely filled so as to prevent any fractionation process from taking place in the sample bottle during transit, a process that would affect the analysis results. Bacteriological samples were analyzed in the Nakuru Water and Sanitation Laboratory, Ministry of Water and Irrigation. Other samples were sent to Ministry of Water and Irrigation National Laboratory in Nairobi, for major element and heavy metal analysis.

Field analyses done at the time of sampling include determination of pH, Eh, temperature, and specific conductance. Total alkalinity was also measured at the time of sampling to avoid the effect of dissociation of substance such as carbon dioxide during the holding time that may cause analytical errors. The pH measurements were taken using pH meter equipped in a combination of electrode and thermistor, and entailed the use of appropriate buffer solutions necessary for calibration.

The primary components of alkalinity in groundwater are carbonate ions, bicarbonate ions, and hydroxyl ions; of these three, carbonate and bicarbonate are the most common. Measurements were made in the field at the time of sampling since alkalinity is controlled by dissolution or degassing of carbon dioxide which can shift the source of alkalinity. Total Alkalinity as $CaCO_3$ - bicarbonate test procedure and Phenolphthalein Alkalinity as $CaCO_3$ - carbonate test procedure were used to measure alkalinity. These two methods for determining alkalinity are normally run in ground water sampling.

3.2.3 Recording field data

Field results were recorded in a field note book. These included; nature of various water bodies; surface or sub-surface; location name of the site; sample number; date of collection; pH, Eh, and conductivity readings; and alkalinity titration results. Helpful information such as borehole yield, depth, water use, GPS coordinates and potential contaminants near the borehole were also geo-referenced and coded.

3.4 Post-fieldwork

3.4.1 Laboratory methods

Chemistry tests methods were carried out at the Catholic Diocese of Nakuru (CDN) laboratory and followed the "Standard Methods for the examination of Water and Wastewater" published by American Public Health Association (APHA) and American Water Works Association (AWWA) (APHA & AWWA 2005). The following section enlists the test methods for each parameter.

Calcium, Nitrate, Fluoride, Sodium and Potassium were determined using ion selective method. Ion Selective Electrode (ISE) is an electrochemical sensor, based on thin films or selective membranes as recognition elements, and an electrochemical half-cell equivalent to other half-cells of the zeroth (inert metal in a redox electrolyte). The potential difference response has, as its principal component, the Gibbs energy change associated with perm-selective mass transfer (by ion-exchange, solvent extraction or some other mechanism) across a phase boundary. The ion-selective electrode is always used in conjunction with a reference electrode (i.e. 'outer' or 'external' reference electrode) to form a complete electrochemical cell. The measured potential differences (ion-selective electrode vs. outer reference electrode potentials) are linearly dependent on the logarithm of the activity of a given ion in solution (McNaught & Wilkinson 1997).

Chloride ions were determined by using Argentometric, which is a titrimetric method. In argentometric method, an indicator, potassium chromate, is added to the sample, which loosely binds up a few chloride ions. Silver nitrate solution is then titrated into the sample, producing the fine white precipitate, silver chloride. When all the free ions are complexed in this reaction, the silver nitrate takes the bound chloride ions from the indicator, producing the blood red precipitate, silver chromate, marking the end of the titration (Hauser 2001). Diagrammatically, the reaction looks as follows;

$$AgNO_3 \xrightarrow{K_2CrO_4 \text{ indicator}} \underset{\textit{White}}{AgCl} + \underset{\textit{Red}}{Ag_2CrO_4}$$

Sulfate ions were determined by turbidimetric method. Determination of sulfate by this method appears to be the simplest approach for analysis of water samples. It is usually rapid and sensitive and normally does not require special skill in handling a large number of analyses at one time. Sulfate ion reacts with barium chloride in acidic solution to form a suspension of barium sulfate crystals of uniform size. The resulting turbidity is proportional to the sulfate concentration of the sample. Results are expressed as ppm (mg/L) SO_4. Most turbidimetric methods, however, have a serious shortcoming in that they do not give reproducible results; the formation of reproducible $BaSO_4$ suspensions under uniform precipitating conditions is difficult.

3.4.2 Programs used in data screening and analysis

After analysis the data were screened to evaluate the distribution characteristics of each variable. To manage these, the chemical and some of physical data were subjected to some univariate and multivariate statistical treatments. Most of the statistical analyses were performed using a software package – Statistics Package for Social Sciences (SPSS). Statistical approach in this study was aimed at identifying the chemical relationships between water samples. Samples with alike chemical and physical characteristics often have related hydrologic records, recharge zones, infiltration pathways, and flow paths in terms of climate, mineralogy, and residence time(Guler et al. 2002).

The multivariate techniques used in this study were Principal Component Analysis (PCA). The objectives of PCA in this study were data reduction, data interpretation, and noise removal within the data set. PCA reduces the large data matrix into smaller matrices called principal component (PC) loadings and PC scores, which are obtained through the process of Eigen analysis. Because PCA is simply the generation of pairs of eigenvalues and eigenvectors, the data do not need to be normally distributed (Johnson and Wichern 2002). Eigenvalues describe the amount of variation within the original data sets, such as those with large numbers of samples and variables, can be attributed to the first one, two or three components (Johnson and Wichern 2002).

Groundwater is more often classified into chemical facies in such a way that the name of the cluster indicates the most concentrated cation and anions in the analysed samples. This exercise was done using piper, durov and stiff diagrams from AQUACHEM program. Most of these graphical methods are designed to simultaneously represent the total dissolved solids and the relative proportions of certain major ionic species (Hem 1989).

The Piper diagram (Piper 1944) is the most widely used graphical diagram and displays the relative concentrations of the major cations and anions on two separate trilinear plots, together with a central diamond plot where the points from the trilinear plots are projected. The diamond field can be defined to represent water-type categories (Back and Hanshaw 1965) that form the basis for one common classification scheme for natural water. Evolution pathways or mixing of different sources of water can also be illustrated by this diagram.

Disequilibrium indices log (IAP/KT) was calculated by PHREEQC program in AquaChem, an in-built graphical interface for calculating equilibrium concentrations (or activities) of chemical species in solution and saturation indices of solid phases in equilibrium with a solution. The disequilibrium indices of carbonate, fluorite and sulphate minerals aragonite, anhydrite, calcite, dolomite, fluorite and gypsum were presented from the data bank of PHREEQC.

Saturation indices or disequilibrium index is defined by the equation:

$$\textbf{Saturation Index} = \frac{\textbf{IAP}}{\textbf{K}_{eq}}$$

Where IAP is the ion activity product for mineral dissolution and K_{eq} is the equilibrium constant for mineral dissolution (Stumm and Morgan, 1981).

Disequilibrium indices log (IAP/KT) were calculated to determine, if water is in thermodynamic equilibrium log (IAP/KT = 0), oversaturated log (IAP/KT > 0) or undersaturated log (IAP/KT < 0) with respect to certain. Speciation modeling uses a chemical analysis of a water to calculate the distribution of aqueous species using an ion-association aqueous model. The most important results of speciation calculations are saturation indices for minerals, which indicate the saturation state of each mineral relative to the water (David *et al.* 1999).

3.4.3 Source rock inferences and analysis

In addition to the information obtained from the literature a source rock deduction was carried out using the water samples collected during fieldwork. This is done purposely to gain insight into the origin of dissolved solutes and hence substantiate geological descriptions given by geological reports.

Comparative analysis on the possible origins of major elements is assessed using AquaChem as an interface to PHREEQC, and source-rock deductions using simple graphical comparisons. In addition, source-rock deduction of reasoning using ratios adopted from Hounslow (1995) gives another simple approach to studying the hydrochemistry of the groundwater in the area. The purpose is to gain insight into possible origins of dissolved major elements and in this case corroborate the geology of the area as discussed in section 2.3.

Cation exchange is occurring within the clay products. Ca^{2+} is a product of albite weathering and the dissolution of Fluorite (CaF_2). Oversaturation (predominantly) and near saturation occurs when calcite is precipitated by the replacement of Na^+ (cation exchange) or as a function of temperature where high temperatures reduce (geothermal) the solubility of calcite.

Water data defined by pH of between 5 and 6 cannot be deduced with this scheme since clay minerals dissolve and release anomalously high silica. For our data with a pH ranging between 6.5 and 8.5, the technique was suitable. The concentrations of elements must be converted from mg/l to meq/l for comparing all parameters computed by AquaChem program. The accuracy of water samples can be checked by assessing the electro-neutrality of the analyses. The sum of cations and anions should be equal. The charged balance is expressed as:

$$\%\text{Charge Balance (CB) Error} = \frac{(\sum \text{cations} - \sum \text{anions})}{(\sum \text{cations} + \sum \text{anions})} \times 100$$

The following are steps in the deductions of source rock using simple comparisons and ratios by Hounslow (1995);

Table 3.1 A simple approach to studying the hydrochemistry of the groundwater in the area using simple comparison by Hounslow (1995).

Parameter	**Value (Meq/l)**	**Conclusion**
$Na^+ + K^+ - Cl^- / Na^+ + K^+ - Cl^- + Ca^{2+}$	< 0.2 and 0.8	Plagioclase weathering possible
	> 0.2 or 0.8	Plagioclase weathering unlikely
$Na^+ / Na^+ + Cl^-$	> 0.5	Sodium source other than halite- albite, ion exchange
	= 0	Halite solution
	< 0.5 TDS > 500	Reverse softening, seawater
	< 0.5 TDS < 500 > 50	Analysis error
	< 0.5 TDS < 50	Rainwater
	$HCO_3^- / SiO_2 > 10$	Carbonate weathering
$Mg^{2+} / Ca^{2+} + Mg^{2+}$	= 0.5	Dolomite weathering
	< 0.5	Limestone-dolomite weathering
	> 0.5	Dolomite dissolution, calcite precipitation, or seawater
	$HCO_3^- / SiO_2 < 5$	Silicate weathering
$Mg^{2+} / Ca^{2+} + Mg^{2+}$	> 0.5	Ferromagnesian minerals
	< 0.5	Granite weathering
$Ca^{2+} / Ca^{2+} + SO_4^{2-}$	$Ca^{2+} / Ca^{2+} + SO_4$	Gypsum dissolution
	2- = 0.5	Pyrite oxidation
	< 0.5 pH < 5.5	Calcium removal-ion exchange or calcite precipitation
	< 0.5 neutral	
	> 0.5	Calcium source other than gypsum-carbonates or silicates
TDS	> 500	Carbonate weathering or brine or seawater 2
	< 500	Silicate weathering

Cl- / sum anions	> 0.8 TDS > 500 > 0.8 TDS < 100 < 0.8	Seawater, or brine or evaporates Rainwater Rock weathering
HCO_3^- / sum anions	> 0.8 < 0.8 sulphate high < 0.8 sulphate low	Silicate or carbonate weathering Gypsum dissolution Seawater or brine
Langelier index 3	Positive 0 Negative	Oversaturated with respect to calcite (54 %) Saturated/ near saturated with respect to calcite (15 %) Undersaturated with respect to calcite (31 %)
Conclusion	Aquifer mineralogy Reactions	Rhyolitic composition suggested; high silica suggest volcanic origin Some ion exchange

3.4.4 Water Quality Assessment

Water quality assessment (WQA) can be defined as the overall process of evaluation of the physical, chemical and biological nature of water in relation to natural quality, human effects and intended uses, particularly uses which may affect human health and the health of the aquatic system itself (Bartram and Balance 1996). This includes the use of analysis to define the condition of the water, to provide the basis for detecting any water quality degradation and to provide the information enabling the establishment of management programs.

Suitability of water of irrigation is hereby evaluated by assessing sodium adsorption ratio (SAR), which estimates the extent to which sodium will be absorbed by the soil. High Na^+ ions in water affect the permeability of soil and causes infiltration problems. This is because Na^+ when present in the soil in exchangeable form replaces Ca^{2+} and Mg^{2+} adsorbed on the soil clays and causes dispersion of soil particles (i.e. if Ca^{2+} and Mg^{2+} are the predominant cations adsorbed on the soil exchange complex, the soil tends to be easily cultivated and has a permeable & granular structure).

SAR for irrigation waters is defined as:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2}$$

The concentrations of Na^{+}, Mg^{2+} and Ca^{2+} are expressed in milliequivalents per litre (meq l^{-1}). High values of SAR imply that the Na^{+} in the irrigation water may replace the Ca^{2+} and Mg^{2+} in the soil, potentially degrading the soil structure. Plants are detrimentally affected, both physically and chemically, by excess salt in some soils and by high levels of exchangeable sodium, in the others. Soils with an accumulation of exchangeable sodium are often characterized by poor tilth and low permeability making it unfavorable for plant growth. However the effect of SAR is moderated by the presence of magnesium and calcium ions. When SAR rises above 12 to 15 serious physical soul problems arise and plants have difficulty absorbing water (Munshower, 1994). The SAR values in table 4.5 were calculated using AquaChem program.

The sodium adsorption ratio (SAR) of soil solution extracts, irrigation waters and subsurface drainage waters has been an important tool for predicting the equilibrium exchangeable sodium percentage (ESP) in salt affected soils (Robbins and Carter 1983). The degree of sodium hazard in the soil has been then been related to the soil ESP (U.S Salinity Laboratory Staff 1954). ESP is usually defined as;

$$\mathrm{ESP} = 100 \times \frac{\text{Exchangeable Na}}{\text{Cation Exchange Capacity}}$$

The Giggenbach triangle representation used allows checking to what extent water-rock equilibrium has been attained. The linear log (K)-1000/T plots may be used for samples from boreholes, where the in situ temperature is known. The triangle is devised in three zones: immature waters (at the base) partially equilibrated waters in the middle and fully equilibrated waters along the upper curve. Depending on where the composition of a given sample lies within this triangle you may estimate the extent of rock-water equilibrium. For mature waters falling near the upper curve, you may as well estimate the temperature.

Ternary diagrams are used to represent the relative percentage of three components. These components can be anything; three minerals, three elements, three size classes, etc. In this study the three components are a set of major cations and anions. The requirement is that the three components have to sum to 100%.

CHAPTER FOUR

4.0 RESULTS

4.1 Introduction

The chemical composition of surface and groundwater is controlled by many factors that include composition of precipitation, mineralogy of the watershed and aquifers, climate, and topography. These factors combine to create diverse water types that change spatially and temporally. For groundwater, hydrogeological properties of aquifers vary naturally as a result of complex geological factors such as deposition and depositional environment, diagenesis and primary texture. These among other sets of geochemical reactions are responsible for the development of aquifer heterogeneity and hydraulic properties (Koltermann & Gorelick 1996).

This chapter focuses primarily on the results obtained from the acquired data. These include: aquifer stratigraphy; aquifer lithology, mineralogy and geochemistry; surface and groundwater assessment.

4.2 Aquifer stratigraphy

4.2.1 Geological setting

A cross section from point Foot of Mau escarpment (X) through Sabugo (Y) in Figure 4.1 reveals a number of subsurface geological rocks that are not readily seen in the surface.

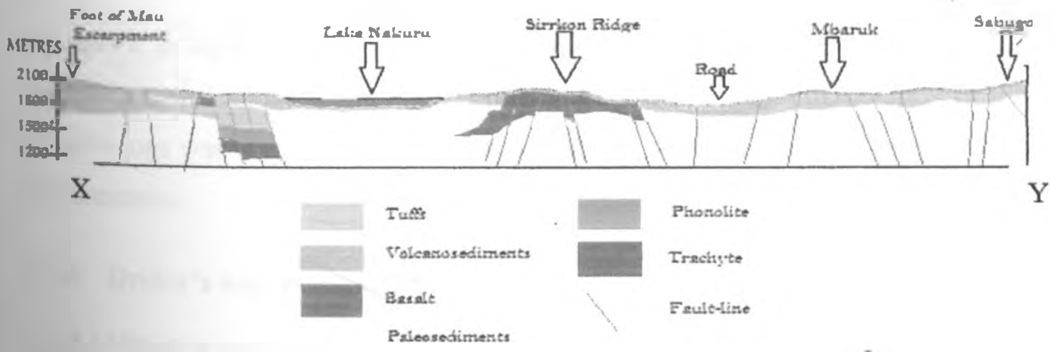


Figure 4.1 Geological cross section through points X and Y using geological map after McCall (1967) of the map in Figure 2.5.

The area at the foot of Mau Escarpment is underlain by volcanosediments and tuffs. This characteristic geology dominates the areas near Njoro and Molo. As you approach L. Nakuru, a basaltic material underlain by tuffs is sandwiched between two fault-lines. Phonolite and trachyte are also noted as you approach the lake, and similar to basalt, it is evident that their flow is structurally controlled.

The lake is underlain by recent sediments and these sediments overlays paleosediments that is seemingly quite extensive and deep. A trachytic deposit is seen in Sirrkon Ridge whereas Mbaruk and Sabugo hills are composed mainly of pyroclasts.

4.2.2 Borehole log stratigraphy

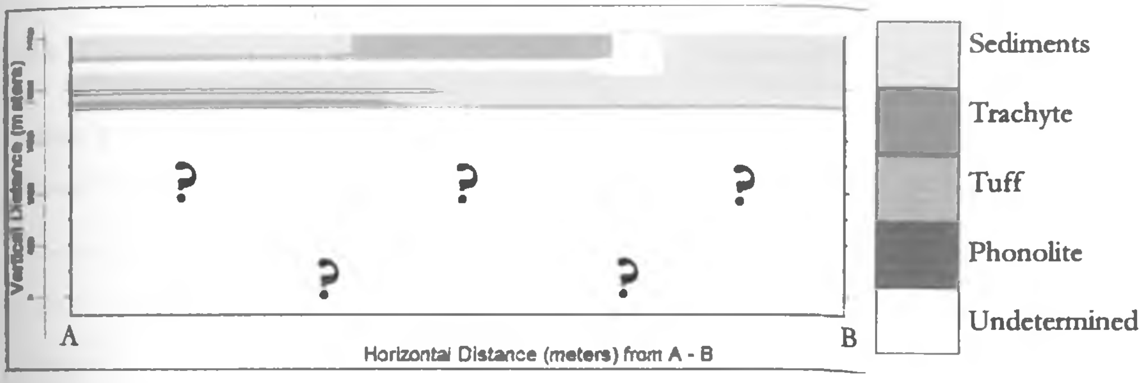


Figure 4.2 Geological cross section through points A and B using driller's logs of the map in Figure 3.1.

As shown in figure 4.2, the main lithological materials along axis A-B are sediments, tuffs, trachyte and volcanosediments of the map in Figure 3.1. This interpolation of lithologies using driller's logs was done considering the availability of enough data to give a suitable subsurface representation.

4.2.3 Driller's logs assessment

4.2.3.1 Whole basin assessment

A total of 33 lithological logs were analyzed and found to cover largely the northern part of Lake Nakuru. Areas south of the lake had few representative drillers' logs and had little emphasis. According to these logs, aquifers in the region are erratically distributed and are seen to vary spatially from a single to multiple layered aquifer systems. The borehole depth are noted to vary between 70 – 276 m with a mean depth of 150.7m spanning in altitude from as high as 2508 to as low as 1784 m above sea level. For the sake of this study, analyses of driller's logs have been divided into three subsections based on their altitudes: lowlands (<2000m), midlands (2000 – 2200m) and highlands (2200 – 2508m).

A frequency calculation of 33 water struck levels indicates a mean of 119.3 m with a standard deviation of 47.15. This differs with water rest levels (mean of 76.4 m and Std. Deviation of 38.49) and borehole depth (mean of 151.3 m and Std. Deviation of 56.84). In average, borehole water in the basin has the potential to rise and rest for about 42m above the stuck level (see Table 4.1 and Fig. 4.3). The table (4.1) shows the total number (N) of samples analyzed, minimum, maximum, mean, standard deviation, variance, skewness and kurtosis values of groundwater data.

Table 4.1 Descriptive statistics table displaying a summary of univariate statistics for depth, Water Rest Levels (WRL) and Water Struck Levels (WSL) variables in the basin.

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Depth (m)	33	206	70	276	151.25	56.839	3230.681	0.503	0.409	-0.425	0.798
WRL (m)	33	158	16	174	76.36	38.490	1481.443	0.376	0.409	0.168	0.798
WSL (m)	33	205	35	240	119.32	47.146	2222.716	0.848	0.409	0.955	0.798

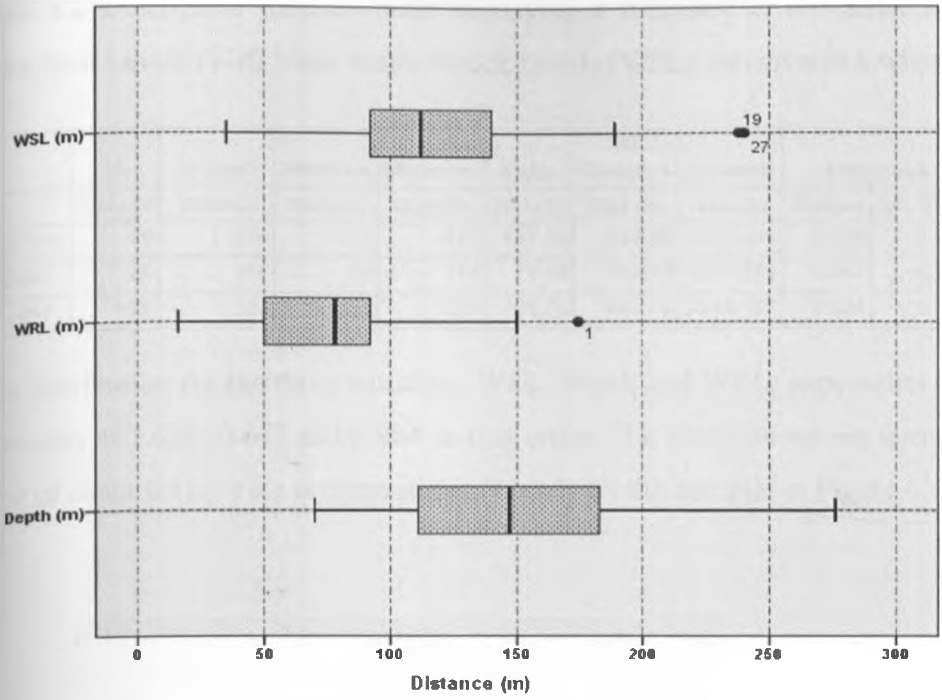


Figure 4.3 Relationships of the distribution of depth, water rest level and water struck level in boreholes across Lake Nakuru basin.

As indicated in the table, data distribution for the three variables (wsl, depth and wrl) approaches zero from positive skewness. The distributions are normal with low error-value of about 0.409. The box plot (Figure 4.3) gives a clear picture of the distribution showing how a sample lies about the mean or median and also identifies extreme values.

4.2.3.2 Lowlands (<2000m)

Lowlands covers a vast area within the project area, regions of altitude as low as 1784masl to 2000m asl. These include; area bordering Lake Nakuru, Nakuru town, Kabarak, most part of Lanet and regions tending towards Lake Elmenteita, Ngorika, Ol'rongai, Rongai and Kiwi plains.

A total of 20 driller's logs were analyzed for this region. The findings demonstrated that aquifers in the region are unevenly spread characterized by single to multiple layered aquifer systems. Frequency of water struck levels indicates a mean of 109.7m with a standard deviation of 48.4. This differs with water rest levels (mean of 74.2m and standard deviation of 41) and borehole depth (mean of 138m and standard deviation of 58.5) as illustrated in Table 4.2.

Table 4.2 Descriptive statistics table displaying a summary of univariate statistics for depth, Water Rest Levels (WRL) and Water Struck Levels (WSL) variables in lowlands.

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Depth (m)	20	206	70	276	137.98	58.545	3427.490	1.026	0.512	0.428	0.992
WRL (m)	20	158	16	174	74.18	40.953	1677.154	0.647	0.512	0.426	0.992
WSL (m)	20	203	35	238	109.73	48.376	2340.197	0.984	0.512	1.245	0.992

Data distribution for the three variables, WSL, Depth and WRL, approaches zero from positive skewness, of 1.026, 0.647 and 0.984 in that order. The distributions are normal with low error-value of about 0.512. This is demonstrated clearly by the box plot in Figure 4.4.

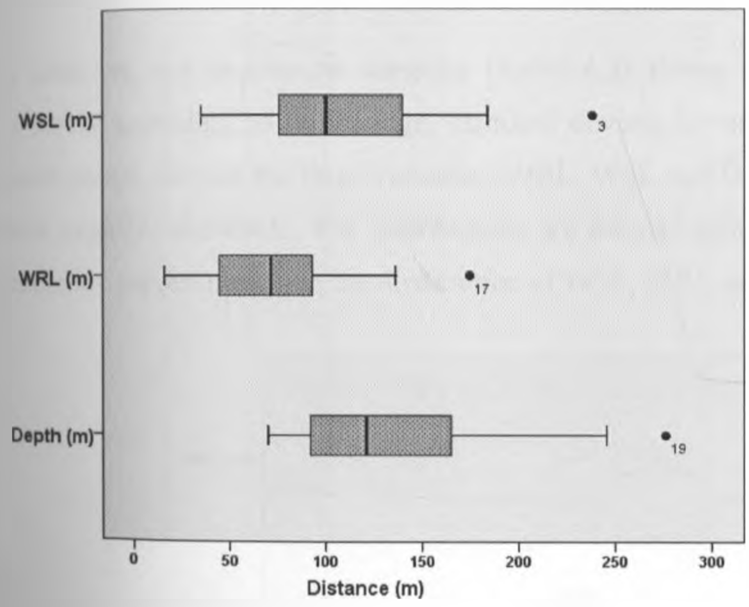


Figure 4.4 shows the relationships of the distribution of depth, water rest level and water struck level for boreholes present in the lowlands.

4.2.3.3 Midlands (2000 - 2200m)

The data for this sector were obtained from logs of boreholes dug around bahati estates, Kabatini area and lower part of Njoro. The boreholes spanned the area between altitudes 2000 and 2200masl. A total of five boreholes were analyzed and results indicated mean water rest levels and water struck levels of 71 and 104 m respectively, whereas the average depth of the boreholes is 140m (see Figure 4.3).

Table 4.3 Descriptive statistics table displaying a summary of univariate statistics for depth, Water Rest Levels (WRL) and Water Struck Levels (WSL) variables in midlands.

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
WRL (m)	5	74	18	92	70.60	30.262	915.800	-1.939	0.913	3.884	2.000
WSL (m)	5	49	73	122	103.60	19.832	393.300	-1.098	0.913	0.287	2.000
Depth (m)	5	107	76	183	140.18	42.108	1773.062	-0.976	0.913	0.267	2.000

Four of the five analyzed driller's logs displayed a single aquifer system. These data included driller's logs for Wamagata BH, Colquhoun H.G BH, and Kerma BH and H. Fraser BH. However Barton's BH in Dr. Woodman Farm displayed a double aquifer system.

In addition, the descriptive statistics (Table 4.3) shows the measures of dispersion of the variables according to their range, standard deviation, variance, skewness and kurtosis. The result points out that the three variables; WRL, WSL and Depth approaches normal distribution from negative skewness. The distributions are normal with low error-value of about 0.913. A schematic representation in the distribution of WSL, WRL and Depth is given in Figure 4.5.

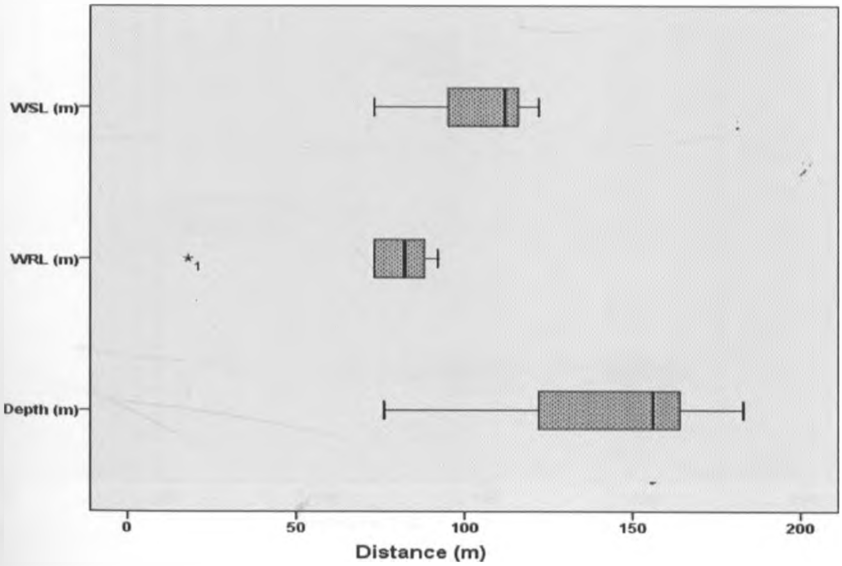


Figure 4.5 Shows the relationships of the distribution of depth, water rest level and water struck level inboreholes of midland sector of Lake Nakuru basin.

4.2.3.4 Highlands (> 2200m)

Area considered highlands were region of altitudes greater than 2200masl. About six well-logs represented this area and they included; three from upper part of Njoro (at around Egerton University), two around Molo and another at Kamosop (see Table 4.4).

Table 4.4 Descriptive statistics table displaying univariate summary statistics for depth, Water Rest Levels (WRL) and Water Struck Levels (WSL) as variables for highlands water samples

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
WRL (m)	6	89	21	110	70.73	31.423	987.418	-0.605	0.845	0.066	1.741
WSL (m)	6	79	110	189	137.50	27.610	762.300	1.562	0.845	3.036	1.741
Depth (m)	6	84	130	214	179.83	37.632	1416.167	-0.773	0.845	-1.861	1.741

As illustrated, in average, the water rest levels are shallower than water struck levels in corresponding boreholes. This indicates that the majority of boreholes up-wells to a level above the struck level and hence showing almost an artesian flow, a phenomenon that probably relates to the heterogeneous nature of aquifer materials and its caprock. A schematic representation of these variations is provided by the box plot in Figure 4.6.

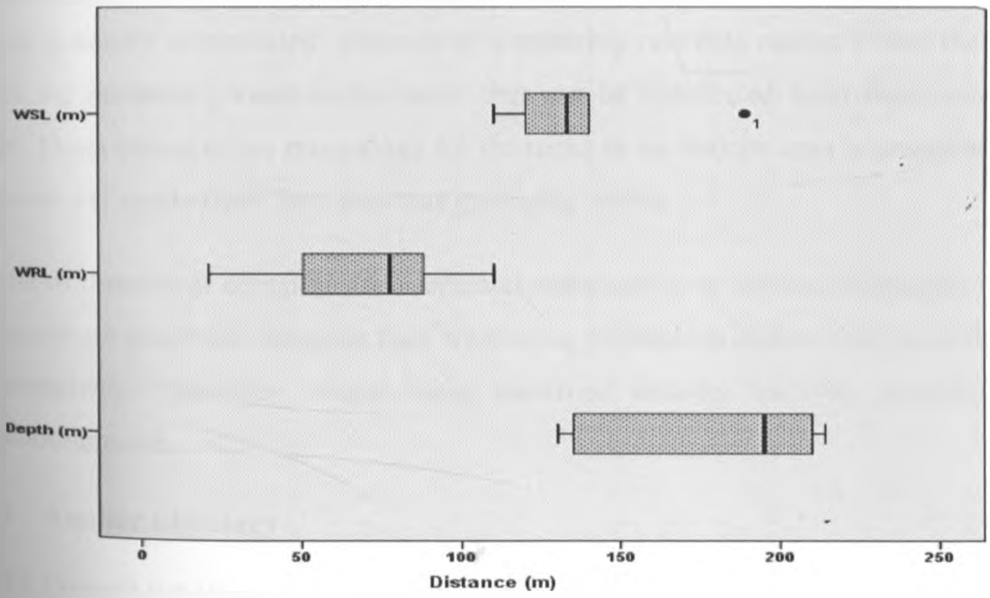


Figure 4.6 shows water struck levels and water strike levels of distribution with depth in highlands.

Aquifer distribution shows the number of aquifers struck is from a single to three aquifer system. The boreholes at Egerton Cooperative, Njoro canning factory and Molo Township Secondary School had two-aquifer system; a shallow and deep, whereas the ones at Turi (Molo) and Egerton University gave a three-aquifer system; shallow, intermediate and deep aquifers in that order. However, a single aquifer was noted in areas around Koiyo/Kamosop.

4.3 Aquifer Lithology, Mineralogy and Geochemistry

4.3.1 Introduction

The chemical character of an aquifer and its groundwater is a function of the mineralogy and lithology (Back & Baedecker 1989; Back *et al.* 1993). Interaction between groundwater and different geological units of variable mineralogy produces several reactions including: dissolution-precipitation, ion exchange, oxidation-reduction, sorption, etc., which can change water chemistry producing chemical boundaries. Recharge water chemistry and mineralogy plays a significant role in the overall chemical composition of the groundwater.

During rock weathering, elements such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, SO_4^{2-}, HCO_3^{-} and SiO_2 among others are added to the water dependent relative to the rock mineralogy (Hounslow 1995). The importance of chemical weathering of the rock in the basin as the source of major dissolved solutes is hereby accentuated. Absence of weathering rate data cannot hinder the possibility to depict the minerals present in the rocks that can be transferred from these compartments to others. Descriptions of the mineralogy for the rocks in the Nakuru area is presented in this study extracted and synthesized from previous geological works.

Details of theoretical chemical and elemental composition of various lithologies represented in the region are presented alongside their weathering products to deduce their possible contribution to groundwater chemistry. Major rocks identified include; trachyte, phonolite, basalt and volcanosediments.

4.3.2 Aquifer Lithology

4.3.2.1 Overall lithological assessment

Aquifer material was determined by examining rock matrix within water struck levels and water rest levels as shown in the driller's logs, and by lithostratigraphy done by previous workers. This helped in deducing the nature of materials in contact with groundwater and hence the possible chemical elements added to the water chemistry.

According to the driller's logs, three main types of aquifer matrix dominate; sediments, trachyte and tuffs. Sediments forms approximately 45% of the 33 aquifer materials analyzed as indicated in the driller's logs and consisted of largely volcanosediments, gravels and sands. Approximately 32% consist of fractured and weathered trachyte while about 19% comprised of pyroclastics (primarily tuffs). The remaining material remained undetermined.

Trachytes are fine-grained lava with an alkaline composition, typically with prominent large alkali feldspar crystals. Trachytes together with tuffs were deposited as a result of local volcanic eruptions in Menengai, at the edges of rift escarpments and other localized eruptions. Volcaniclastic sediments resulting from the reworking of deposited materials, both in sub-aerial and sub-aqueous environments, is a natural process in the life of any volcano. Unconsolidated fragmentary deposits are eroded from volcano, reworked and deposited. The composition of these volcanosediments relate to its host rock depending on the degree and vulnerability of specific constituents to weathering.

To assess lithological distributions the basin was subdivided into three subsections with respect to their elevation from the sea levels. These subdivision included; Lowlands lithology (<2000masl), Midlands lithology (2000 – 2200masl) and Highlands lithology (>2200masl).

4.3.2.2 Lowlands lithology (<2000masl)

Assessment of the driller's logs to evaluate lithological distribution in aquifers was done for areas having altitude below 2000masl. Fractured and weathered trachytes were found to dominate most of aquifer with a total of 8 boreholes analyzed. The location of these boreholes were distributed on the northern part of Lake Nakuru in the areas around Nakuru town, Ol'lorangai, Meroroni, Enderit, slopes of Menengai and Lanet. The extent of these boreholes with trachytic aquifers ranged between the depths of 72 to 276m below the surface.

Volcanosediments was the second dominant aquifer medium in this subsection and was noted to prevail in some parts of Lanet and Ngorika. Six boreholes were analyzed in total and the range in depth of these boreholes having volcanosediments as aquifer medium was identified to be between 77-170m below the surface. Other aquifers contains; tuffs (two boreholes), identified to cover some parts of Kabarak and the large Kiwi plains; sediments (three boreholes), in lower part of Bahati and Rongai; and Basalt (one well), located around Lanet. The depth of these boreholes hosting tufficeous, sediments and basaltic aquifers are in the range of 72-229m, 70-120m and 130m respectively.

4.3.2.3 Midlands lithology (2000 – 2200masl)

Unlike the lowlands lithologies, midlands aquifer lithology is mainly volcanosediments. These are represented by Wamagata borehole in Kabatini, Colquhoun H.G well in Ruaytamoh estate and H. Fraser well in Dr. Woodman farm. The range of these boreholes is between the depths of 76 to 174m below the surface.

The other lithologies include trachyte and tuffs, as seen by the logs of Barton's well in Bahati estate and Kerma One well in Njoro in that order. Their depth of Barton's borehole is 156m whereas that of Kerma One is 182m below the ground surface.

4.3.2.4 Highlands lithology (>2200masl)

Highland lithologies are represented by driller's logs mainly from Njoro, Molo and Kamosop areas. Tufficeous aquifers seem to dominate this subsection with a well-depth range of 130-210m. They include Molo Township Secondary School BH, Egerton University BH and Njoro Canning Factory BH.

Trachyte and volcanosediments are additional aquifer matrices identified in this region. Volcanosediments are found at Turi in Molo and Egerton Co-operative in Njoro with a well-depth range of between 190-200m. Trachytic aquifer was located in Koiyo/Kamosop with a well-depth of about 135m below ground surface.

4.3.3 Aquifer mineralogy and Geochemistry

As demonstrated by the findings in sub-section 4.3.2 above, the main aquifer materials are trachyte, sediments (including volcanosediments) and tuffs (and other pyroclasts). A simple tendency noted reveals that highlands aquifers is predominantly tufficeous, whereas midlands and lowlands are volcanosediments and trachytic in nature correspondingly. These aquifer formations have a lot of control over the chemical composition of groundwater.

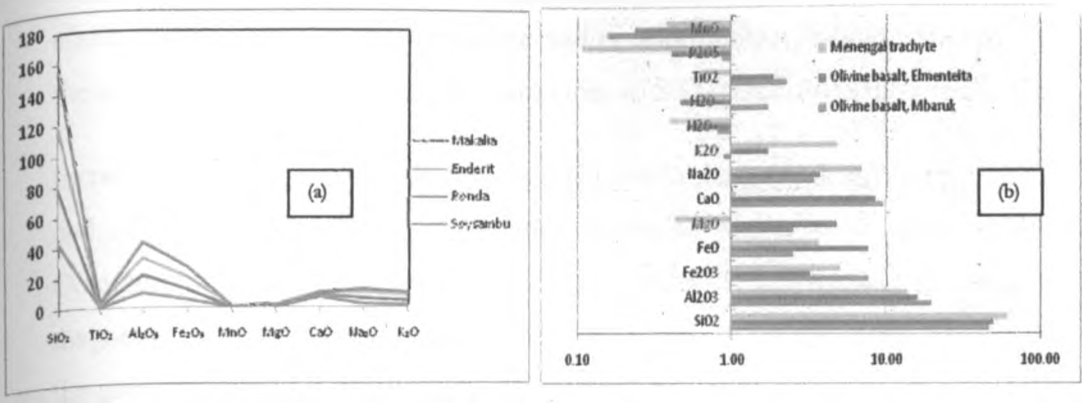


Figure 4.7 (a) Oxide composition in sediments from four sites; Makalia, Enderit, Ronda and Soysambu (*data extracted from Mboya (1993)*). (b) Oxide composition from dominant rock types found in the basin; Menengai trachyte, Elmenteita olivine basalt and Mbaruk olivine basalt (*data extracted from McCall (1967)*).

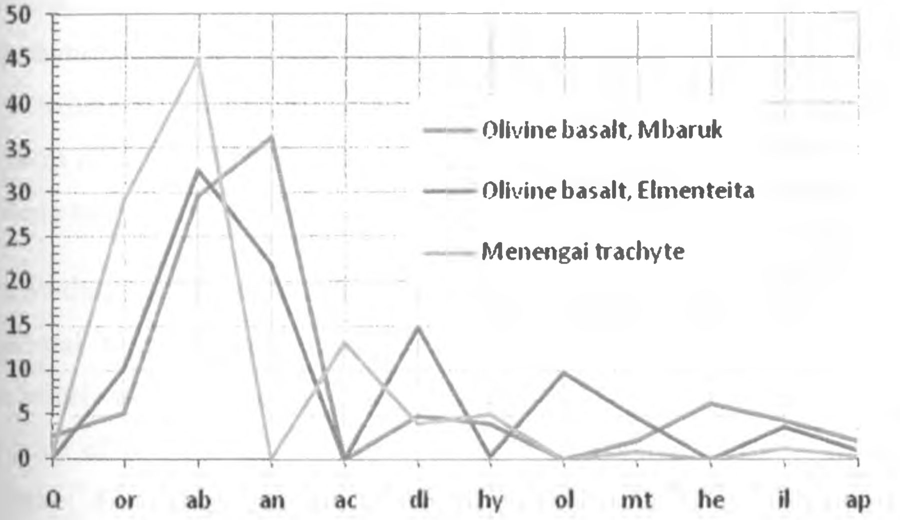


Figure 4.8 Mineralogical compositions of the main rock types as seen in the basin (*data extracted from McCall (1967)*).

4.3.3.1 Lowland mineralogy and geochemistry

As noted earlier, trachytes rocks are dominant in lowland areas of the study area, and are present together basalt and phonolite according to the geological map report but the latter two were represented in the driller's. Generally, trachytes are eruptive rocks containing principally alkali feldspars ($KAlSi_3O_8$, $NaAlSi_3O_8$), with subordinate amphibolites species (e.g. (Mg Fe)((Al Fe)O)$_2$SiO$_4$) but deficient of quartz (SiO_2) (Clarke, 1924). Trachytic rocks, being poor in quartz, tend to run lower in silica than the granites and rhyolites. The principal mineral of trachyte is alkali feldspar, usually sodic sanidine and/or anorthoclase, which typically forms over 80% of the mode. All trachyte by definition are close to SiO_2 saturation (Hess 1989).

Increasing silica content causes quartz trachytes to merge with rhyolites, whereas at the opposite end of the scale increasing SiO_2 undersaturation makes trachyte transitional to phonolites. Common phenocrysts in are plagioclase, calcic clinopyroxine, iron-rich olivine, ilmenite, magnetite, apatite and rare K-feldspar. Plagioclase, pyroxene, often olivine, and magnetite are the principal minerals of basalt (Clarke, 1924), but many variation of it are known. Some basalt are free from olivine, others contain such minerals as leucite (K_2Al_2 $(SiO_3)_4$), nepheline ((Na $K)_6((Na.K)AlSiO_3)_2Al_6(SiO_4)_7$), etc. Hornblende basalts are known but are rare. Quartz has been identified, but its presence is anomalous.
Figure 4.7a shows the dominance of silicate oxide (SiO_2) with fairly high Al_2O_3 and Fe_2O_3 values in general sediment chemistry than Na_2O, K_2O, MnO, CaO, MgO and TiO_2. Basaltic and trachytic rocks, the main rock types in the basin, show more less the same chemical signatures as the sediments. Unlike the basalts, trachytes suffers a relatively reduced CaO and MgO and higher values of K_2O and Na_2O, a probable reason why Na^+ and K^+ ions are the major cations in areas where trachytes predominates.

According to Figure 4.8, albite ($NaAlSi_3O_8$) (the source of Na^+ and SiO_2) is the predominant mineral in the selected rock types found in the area. Menengai trachyte is observed to contain relatively higher values to those of basalts. Albite correlates positively strong to orthoclase (the source of K^+) but negative towards anorthite (source of Ca^{2+}), ilmenite (source of F^{2+}) and apatite. Apatites are abundant in both basalts.

Diopside shows strong positive correlation with magnetite but strong negative correlation with hypersthenes. Diopside is more pronounced in Elmenteita basalts. Acmite are only seen to occur in Menengai trachyte, whereas olivine occurs specifically in Elmenteita basalt, in the other hand, hematite is exclusively noted in Mbaruk basalts. Quartz is lacking in Elmenteita basalts, identified as subordinate minerals in the trachyte peaking in the Mbaruk basalts.

4.3.3.2 Midland mineralogy and geochemistry

Driller's logs of this area indicate that the aquifers within this region are predominantly sediments mainly of volcanic origin. The mineral components identified in the conglomerate of the Enderit formation are quartz (SiO_2), K-feldspar ($KAlSi_3O_8$), plagioclase feldspar ($NaAlSi_3O_8$), perthite ($KAlSi_3O_8$ with exsolved lamellae of $NaAlSi_3O_8$) and chlorite, and carbonate cement ($CaCO_3$).

Most of the lake beds consist of clays and fine sand particles of mainly quartz (SiO_2) and feldspar ($NaAlSi_3O_8$) which grade into siltstone. The Soysambu formations comprises mainly of fine grained diatomaceous siltstones, volcanic claystones, tuffs and calcrenites. The quartz is predominantly polycrystalline while the feldspars are frequently highly altered microcline ($KAlSi_3O_8$).

Dominance of silicate oxide (SiO_2) in sediments indicates the existence of alkaline environment and the abundance of silicate minerals in the study area. The main Quartz (SiO_2) is stable over practically the whole range of geological conditions. It is present in silica-rich igneous rocks. Its hardness and extreme resistance to chemical weathering makes it the most abundant detrital mineral of most sandstone.

The volcanic rich sediments are best differentiated by their aluminium and titanium contents beside major element compositions of Fe, Mg, Al and K contents of the sediments groups. The increased proportion of aluminium and alkali metals in the sediments is indicative of terrestrial origin for the aluminosilicate phases of volcanic terrain of the area. Laminations are predominantly comprised of alternations of diatomite rich silts and volcaniclastic sands. The coarse sands have grains of clinopyroxene (augite) ($(Ca,Mg,Fe)SiO_3$), olivine ($(Mg,Fe)_2SiO_4$) and volcanic glass as the dominant phases. Secondary minerals include amphiboles (hornblende) ($Ca_2(Mg, Fe, Al)_5 (Al, Si)_8O_{22}(OH)_2$), orthopyroxene (hypersthene) ($(Mg,Fe)SiO_3$) and epidote ($Ca_2Al_2(Fe^{3+};Al)(SiO_4)(Si_2O_7)O(OH)$).

4.3.3.3 Highland mineralogy and geochemistry

Highlands's aquifers of this study area are mostly composed of pyroclastics (mainly tuffs) rock materials. The composition of pyroclastics is directly proportion to the ash chemistry, which in turn is directly related to the chemistry of the source magma. Volcanic glass commonly found as lithic in tuff is relatively high in silica compared to mineral crystals, but relatively low in non-silica elements (especially Mg and Fe). Both glass and most minerals almost always contain Si, Al, K, Na, Ca, Mg and/or Fe. Most of these elements are leached with time in varying proportion depending on the solubility and mobility rates. These factors depend as well on other factors such as porosity, grain size, availability of transporting and dissolving media among other factors.

Freshly fallen ash grains commonly have surface coatings of soluble components (salts) and/or moisture. These components can make ash mildly corrosive and potentially conductive. The soluble coatings are derived from the interactions in an eruption column between ash particles and volcanic-gas aerosols, which may be composed of sulphuric and hydrochloric acid droplets with absorbed halide salts. The amount of available aerosols varies greatly between eruptions of similar size and volume. These ash characteristics control the pH and hence influence ash particles (or tuff-water reactions. However we can't expect great variation to occur in chemistry between tuffs and its magmatic component, trachyte or basalt.

4.4 Surface and Groundwater Geochemistry

4.4.1 Physico-Chemical Characteristics of the Surface and Groundwater

A total of 33 water samples were analysed for heavy metals. These comprised of 22 boreholes, 8 river samples, 2 springs and 1 sample from L. Nakuru. The resultant chemical compositions of selected heavy metals (Fe, Mn, Cr, Cd, Pb and Zn) in these samples have been presented in Table 4.5 together with pH, Conductivity and Total Hardness. The table also contains sample location and site.

Table 4.5 Basic physical and heavy metals data of ground and surface water (in mgl^{-1}).

SAMPLEID	SITE	LOCATION	pH	Cond	T. Hardness	Fe	Mn	Cr	Cd	Pb	Zn
BH	Bahati HC	Bahati	7.75	316	40	0.18	0.001	0.08	0.167	0.22	2.84
BH	Nakuru Tun	Nakuru	9.03	2190	12	0.1	0.001	0.256	0.492	0.306	2.04
BH	Ngayoyi	Nakuru	8.52	593	86	0.17	0.001	0.266	0.58	0.224	2.11
BH	BIDCO	Nakuru	9.23	1643	40	0.14	0.001	0.271	0.556	0.204	2.91
BH	Windmill T	L. Nakuru Park	8.59	834	24	0.22	0.01	0.094	0.102	0.024	1.67
BH	Everyday	Nakuru	8.41	954	22	0.01	0.01	0.34	0.492	0.103	3.48
BH	Pyrethrum B	Nakuru	8.64	2500	24	0.08	0.001	0.339	0.495	0.137	3.08
BH	Nawasco	Nakuru	7.54	369	16	0.14	0.01	0.317	0.431	0.37	2.9
BH	Soysambu	L. Nakuru Park	8.57	2290	50	0.05	0.001	0.44	0.541	0.384	2.28
BH	L. Rhonda	Nakuru	8.75	3420	22	0.001	0.14	0.09	0.144	0.711	2.34
BH	L. Ronda	Nakuru	7.12	1528	36	0.52	0.01	0.204	0.372	0.192	3.92
BH	Ngorika		6.33	230	48	0.21	0.14	0.104	0.167	0.828	3.22
BH	Njoro B. HSch	Njoro	6.99	351	34	0.24	0.02	0.209	0.243	0.332	1.66
BH	Nakuru Sch B	Nakuru	8.21	649	14	0.07	0.001	0.188	0.209	0.34	2.81
BH	Karunga	Bahati	7.3	345	50	3.3	1.1	0.119	0.243	0.149	2.08
BH	Egert. Univ	Njoro	7.76	580	10	0.36	0.2	0.331	0.443	0.294	2.66
BH	Deflorid. Pl	Nakuru	8.1	554	10	0.1	0.03	0.3	0.281	0.034	0.341
BH1	Egert. Univ	Njoro	8.5	456	18	0.73	0.1	0.328	0.496	0.349	2.29
BH12	Egert. Univ	Njoro	8.25	421	22	0.82	0.2	0.284	0.555	0.299	2.18
BH15	Egert. Univ	Njoro	8.25	544	6	0.21	0.001	0.392		0.381	2.33
BH16	Egert. Univ	Njoro	8.26	495	26	0.02	0.001	0.271	0.449	0.302	2.69
BH2	Egert. Univ	Njoro	8.2	459	6	0.25	0.1	0.331	0.424	0.338	2.32
RW	Njoro Bridge	Njoro Village	8.13	254	42	1.75	0.04	0.329	0.372		4.11
RW	Egert. Univ	Njoro	8.24	225	32	0.69	0.2	0.294	0.373	0.184	2.67
RW	R. Gilgil	Marula	7.6	96.8	18	2.29	0.08	0.161	0.313	0.966	2.04
RW	R. Mbaruk	Nakuru	7.08	104.5	8	2.08	0.1	0.242	0.337	0.198	2.88
RW	R. Njoro	Sew.disge pt	7.64	1057	52	3.4	0.3	0.252	0.291	0.211	3.19
RW	R. Njoro	bridge aft KARI	7.29	369	48	1.9	0.6	0.229	0.313	2.98	3
RW	R. Njoro	Slaughter Hse	7.84	359	50	1.2	1.5	0.317	0.352	2.13	3.82
RW	R. Njoro	after sew.disp	7.84	307	42	1.11	0.4	0.342	0.379	1.45	3.44
Spring	Baharini spng	Nakuru	8.56	615	70	1.04	0.06	0.04	0.191	0.024	1.67
Spring	Ngorika spng	Bahati highland	7.39	334	46	0.23	0.001	0.122	0.148	0.09	1.66
Lake	Lake Nakuru	Nakuru	10.49	99700	20	4.58	0.02	0.53	0.814	0.281	4.66

Another set of analyses that targeted major elements alongside pH and Conductivity are provided in Table 4.6. The elements include Ca, K, Mg and Na (as cations) as well as HCO_3, Cl, SO_4, and NO_3 (as anions). Results for F are also presented together with sample location, site and GPS position and elevation.

Table 4.6 Basic physical and major element data of ground and surface water (in mgl^{-1}).

SAMPLID	LOCATION	SITE	Lat	Long	Z	pH	Cond	HCO3	Ca	Mg	Na	K	F	SO4	Cl	NO3
BH	Nakuru	Deflond	857734.91	9911307.08	1919	8.10	554.0	248.0	0.80	2.40	119.5	6.0	2.90	6.0	11.0	0.66
Bh	Nakuru	Ngayon	843005.57	9945386.99	1852	8.52	593.0	214.0	17.60	10.40	93.5	5.8	15.50	21.1	14.0	0.10
BH	Nakuru	Soysambu	848028.51	9950091.90	1875	8.57	2290.0	716.0	16.80	2.00	490.0	23.0	15.00	113.7	190.0	0.45
BH	Nakuru	Windmil	841864.87	9950316.32	2442	8.59	834.0	248.0	9.60	0.01	171.5	16.0	13.00	86.0	31.0	0.40
BH	Njoro	Egert12	827508.00	9958494.00	2250	7.87	410.0	30.0	2.98	2.63	121.0	23.0	4.27	13.0	20.0	0.06
BH	Njoro	Egert17	825448.00	9958558.00	2292	7.86	520.0	44.0	1.57	3.58	108.0	18.0	4.31	14.0	20.0	0.20
BH	Njoro	Egert11	825297.00	9958576.00	2298	7.26	440.0	-	1.29	3.56	115.0	20.0	3.72	15.0	18.0	0.07
BH	Njoro	Egert6a	825297.00	9958576.00	2308	7.46	540.0	50.0	4.17	1.41	130.0	19.0	3.28	8.0	10.0	0.20
BH	Njoro	Egert6b	825297.00	9958576.00	2308	7.46	570.0	50.0	2.65	3.12	128.0	23.0	2.95	12.0	12.0	0.07
BH	Njoro	Egert3	825490.00	9958912.00	2304	7.46	590.0	-	1.24	2.50	122.0	22.0	3.52	10.0	22.0	0.09
BH	Njoro	Egert1	826284.00	9958922.00	2267	6.88	440.0	30.0	3.48	3.31	112.0	19.0	1.99	10.0	21.0	0.09
BH	Njoro	Egert2	825742.00	9959088.00	2278	7.46	440.0	-	1.49	3.93	132.0	25.0	4.01	17.0	19.0	0.07
BH	Njoro	Egert15	824478.00	9959678.00	2274	7.49	450.0	42.0	5.50	3.86	129.0	17.0	3.88	15.0	19.0	0.10
BH	Nakuru	Kamasai	838718.60	9960796.92	1861	7.46	450.0	-	2.42	4.15	68.0	22.0	4.79	32.0	38.0	0.40
BH	Njoro	NjoroCC	827197.00	9962132.00	2160	8.60	340.0	28.0	1.52	3.31	92.0	15.0	1.46	12.0	18.0	0.09
BH	Nakuru	Grenstead	853394.39	9962139.85	1926	7.46	610.0	-	2.52	4.68	126.0	31.0	4.22	28.0	34.0	0.04
BH	Njoro	NjoroBSc	827563.90	9963245.14	2174	6.99	351.0	102.0	0.80	7.80	60.0	11.0	1.70	12.6	48.0	1.20
BH	Nakuru	Ingobr	836531.28	9963706.47	1940	7.46	460.0	34.0	7.45	6.03	89.0	24.0	3.57	19.0	22.0	0.10
BH	Njoro	NjorCDF	827152.00	9963910.00	2210	7.58	290.0	22.0	3.96	5.29	87.0	13.0	2.44	8.0	13.0	0.08
BH	Bahati	Karunga	862577.69	9964003.18	2052	7.30	345.0	98.0	9.60	6.30	55.0	6.0	2.05	0.3	36.0	6.00
BH	Nakuru	Mogon	836456.81	9964606.55	1941	7.46	430.0	-	6.77	7.23	98.0	18.0	3.72	25.0	34.0	0.09
BH	Nakuru	Ronda	840029.22	9965047.29	1811	8.75	3420.0	522.0	8.00	0.49	765.0	20.0	14.00	132.0	667.0	36.00
BH	Nakuru	Ronda2	840029.22	9965047.29	1811	7.12	1528.0	610.0	9.60	2.90	332.0	6.2	9.80	3.7	87.0	0.50
BH	Nakuru	Lion HG	848693.09	9965543.62	1886	7.46	560.0	34.0	17.46	5.77	98.0	12.0	2.41	15.0	26.0	0.80
BH	Nakuru	Bahrn11	847847.61	9966169.53	1828	7.08	480.0	240.0	10.50	7.87	98.0	15.0	1.82	8.0	26.0	0.20
BH	Nakuru	Bahrin9	847942.11	9966201.80	1831	7.17	490.0	228.0	11.89	9.84	89.0	20.0	1.89	12.0	28.0	0.20
BH	Bahati	Ngorik	859990.27	9966205.46	2251	6.33	230.0	92.0	16.80	1.47	30.0	7.0	1.50	1.1	7.0	3.60
BH	Nakuru	Bahrin7	847891.29	9966220.23	1830	7.37	470.0	228.0	14.64	5.11	86.0	17.0	1.99	7.0	32.0	0.30
BH	Nakuru	Rasul	848695.76	9966368.41	1882			-	17.25	7.57	52.0	11.0	3.29	12.0	18.0	0.04
BH	Nakuru	KPLC	849363.84	9966579.50	1881	7.46	560.0	38.0	23.97	5.47	132.0	23.0	2.48	26.0	32.0	0.09
BH	Nakuru	NakurTunn	840258.51	9966838.33	1812	9.03	2190.0	720.0	4.80	0.00	493.0	9.8	20.00	146.7	119.0	0.90
BH	Nakuru	Evrydy	839005.19	9968010.09	1875	8.41	954.0	232.0	0.00	5.30	208.0	2.4	16.00	116.6	57.0	0.10
BH	Nakuru	Londra	840666.07	9968098.47	1858	7.46	2880.0	240.0	2.52	3.11	258.0	46.0	26.67	78.0	112.0	0.50
BH	Nakuru	Bontna	841369.16	9968114.10	1846	8.53	2670.0	27.0	3.36	3.58	301.0	42.0	28.21	186.0	110.0	0.80
Bh	Nakuru	BIDCO	839126.14	9968588.01	1875	9.23	1643.0	614.0	4.80	6.80	348.0	20.0	2.60	61.4	96.0	0.15
BH	Nakuru	NrbRd4	844806.71	9968737.38	1885	7.46	570.0	344.0	3.76	2.75	126.0	26.0	5.45	23.0	12.0	0.40
BH	Nakuru	NRBRd5	844809.01	9968748.40	1885	7.46	580.0	38.0	4.43	2.43	146.0	31.0	4.78	32.0	38.0	0.08
BH	Nakuru	NrbRd6	844780.16	9968751.43	1885	7.46	580.0	330.0	3.76	2.16	132.0	22.0	5.94	28.0	17.0	0.60
BH	Nakuru	CDN	845286.12	9968778.16	1872	8.26	530.0	28.0	2.09	3.66	106.0	24.0	6.03	12.0	19.0	0.08
BH	Nakuru	NkrBSc	844676.16	9969075.88	2174	8.21	649.0	244.0	0.80	3.40	140.0	4.6	6.00	43.4	14.0	2.10
BH	Nakuru	AGRI	841723.94	9969538.10	1875	9.05	840.0	64.0	0.84	2.94	203.0	36.0	14.79	52.0	71.0	2.80
BH	Nakuru	Nyanjor	853976.81	9969647.97	1958	7.93	540.0	30.0	8.19	10.61	98.0	6.5	2.49	9.4	11.3	0.20
BH	Nakuru	Nyoike	853287.77	9970026.43	1950	6.64	300.0		8.19	6.67	62.0	12.0	1.36	15.0	19.0	2.20
BH	Nakuru	C.C.O	852276.52	9970146.97	1935	7.17	630.0	50.0	30.55	10.35	101.0	17.0	4.65	26.0	32.0	0.07
BH	Nakuru	Pyrthrm	840293.49	9970169.53	1875	8.64	2500.0	793.0	0.00	5.80	549.0	25.0	18.00	279.4	83.0	0.33
BH	Nakuru	KITI	845794.96	9970262.19	1908	7.46	900.0	480.0	2.75	3.76	112.0	33.0	10.52	28.0	53.0	0.20
BH	Nakuru	Olivein	837909.96	9970320.07	1936	7.46	1300.0	96.0	2.44	3.14	224.0	42.0	21.30	98.0	78.0	0.30
BH	Nakuru	Wamuyu	853441.20	9970806.61	1960	6.92	360.0	26.0	11.59	7.16	78.0	22.0	1.47	10.0	15.0	0.60
BH	Nakuru	Kabatni	848941.96	9970878.80	1901	7.46	370.0	192.0	8.71	5.17	26.0	12.0	2.02	13.0	13.0	0.08
BH	Nakuru	Tabuga	853441.30	9971004.67	1992	7.30	220.0	22.0	5.32	5.25	55.0	9.0	0.69	8.0	12.0	0.07
BH	Nakuru	Muhia's	852634.06	9971027.07	1956	7.46	260.0	20.0	6.27	6.06	52.0	7.0	0.95	16.0	19.0	0.02
BH	Nakuru	Makiki2	834299.10	9973013.86	2032	7.46	700.0	54.0	3.42	4.03	158.0	28.0	19.52	39.0	52.0	0.30
BH	Nakuru	Mfeedot	830008.00	9975572.00	2012	7.46	560.0	44.0	8.48	10.33	97.0	17.0	3.68	22.0	26.0	0.40
BH	Nakuru	Makiki1	831007.00	9976072.00	2012	7.46	670.0	46.0	9.91	8.77	102.0	26.0	6.62	20.0	27.0	0.07
BH	Bahati	BahtiHC	847851.42	9980794.44	2078	7.75	316.0	104.0	6.40	5.80	52.5	3.6	2.10	9.1	15.0	0.10
RW	Nakuru	Makalia	842972.29	9945555.90	1775	-		18.0	12.63	6.79	25.0	8.0	1.42	14.0	10.0	5.60
RW	Nakuru	Ndent	846924.41	9954526.27	1767				9.74	5.73	46.0	15.0	1.48	11.0	12.0	3.40
RW	Njoro	Njoro1	824839.00	9958696.00	2307	7.64	280.0		5.18	7.31	28.0	16.0	0.59	17.0	25.0	3.20
RW	Njoro	NjoroB	825488.00	9958840.00	2219	-	-	14.0	7.10	6.24	26.0	13.0	0.59	18.0	26.0	4.20
RW	Njoro	Njoro3	831312.00	9963989.00	2139	7.68	210.0	14.0	7.91	6.24	31.0	13.0	0.65	19.0	23.0	6.80
RW	Nakuru	NjoroLk	843882.30	9964138.13	1777	8.10	2030.0	152.0	22.00	12.09	114.0	26.0	13.56	31.0	42.0	0.80
RW	Nakuru	NjoroBr	843340.36	9964386.49	1767	7.02	1260.0	-	20.69	42.87	86.0	18.0	5.33	26.0	38.0	0.50
RW	Njoro	Njoro4	838451.91	9966319.51	1814	7.51	190.0	16.0	7.19	6.38	27.0	14.0	0.67	18.0	24.0	6.40
RW	Nakuru	Merem1	854286.95	9967785.19	1951	7.46	150.0	-	7.25	5.56	20.0	8.0	0.63	8.0	10.0	2.60
RW	Nakuru	Merem2	854822.67	9968817.26	1970	-	-	-	6.11	5.46	24.0	9.0	0.69	7.0	9.0	3.20
RW	Nakuru	Wany'ro	854622.94	9971528.29	2010	-		-	5.65	3.07	28.0	11.0	0.52	4.0	12.0	4.80
RW	Nakuru	Ngosur	851019.58	9973206.45	1953		-	-	5.05	5.11	23.0	4.0	0.59	7.0	3.0	4.30
RW	Marula	Gilgil	873914.85	9930410.68	1858	7.60	96.8	40.0	5.60	0.97	12.5	2.2	0.44	0.3	5.0	0.82
RW	SewDis	Njoro	827608.46	9958643.25	2287	7.64	1057.0	310.0	8.00	7.80	200.0	34.0	3.40	20.2	85.0	20.60
RW	Njoro	Egert.	824839.00	9958696.00	-	8.24	225.0	94.0	4.80	4.80	30.0	11.0	0.37	3.4	10.0	[illegible]
RW	BrdgEgt	Njoro	825488.00	9958840.00	2296	8.13	254.0	104.0	4.00	7.80	32.5	12.0	0.33	0.3	5.0	4.80
RW	Nakuru	Mbaruk	856573.47	9960042.25	1886	7.08	104.5	44.0	0.80	1.90	19.5	1.8	0.76	0.3	4.0	0.30
RW	SlghtrH	Njoro	828458.66	9962228.61	2170	7.84	359.0	132.0	9.60	6.30	52.5	15.0	0.63	3.1	25.0	2.20
RW	KARI	Njoro	841185.72	9963811.69	2296	7.29	369.0	130.0	11.20	4.87	55.0	16.0	0.62	1.1	22.0	5.40
S. Well	Nakuru	Njoroge	854290.13	9970075.95	1966	7.46	1150.0	94.0	15.42	7.70	56.0	11.0	10.92	8.0	12.0	0.06
S. Well	Nakuru	Munui	854175.11	9970130.03	1970	7.46	980.0	72.0	19.64	6.91	43.0	8.0	15.46	4.0	14.0	1.20
S. Well	Nakuru	Njogu	853877.35	9970822.40	1972	7.46	360.0	72.0	11.09	6.08	56.0	11.0	2.69	13.0	15.0	1.20
Spr	Bahati	Ngonka	862658.41	9965485.43	-	7.39	334.0	140.0	16.00	1.50	52.5	5.4	2.60	4.6	10.0	0.40
Spr	Nakuru	Baharin	845958.06	9966558.38	1959	8.57	610.0	-	2.64	4.32	25.0	8.0	7.85	0.2	11.0	4.80
Spr	Nakuru	Ngosur	853066.08	9977869.02	2100	-	-	-	4.43	4.21	21.0	5.0	0.56	9.0	5.0	[illegible]
Lake	Nakuru	Nakuru	842972.29	9945555.90	1787	10.49	99700.0	26762.0	0.80	4.90	22676.0	420.0	450.00	1828.3	14000.0	1.20

Major constituents of groundwaters (BH), Lake, Springs and Rivers are presented in Table 4.6 and heavy/trace metals in Table 4.5. Statistical analyses of the data show that the total cations T_{Z+} and total anions T_{Z-} are coupled by the relation T_{Z+} (meql^{-1}) = 0.93T_{Z-} (meql^{-1}) + 3.2 with correlation coefficient r = 0.941 in groundwater samples compared to T_{Z+} (meql^{-1}) = 1.1T_{Z-} (meql^{-1}) - 1.24 with correlation coefficient r = 0.831 in surface water samples. Thus, the observed total cations T_{Z+} and total anions T_Z^- balance attests to the good quality of the data.

In the basin, there is a general variation in pH in the region from 6.33 to 9.23 in boreholes, shallow boreholes and springs with equal mean value of 7.68, compared with river variations (7.02 – 8.24) having equal mean value of 7.63, and Lake Nakuru (10.48). Approximately 93.9% of 82 samples collected were alkaline. Groundwater in general was alkaline in nature apart from few samples with pH values slightly less than 7.0.

A higher value of EC was also noted during data collection in a number of boreholes relative to samples from rivers. The EC of groundwater shows variations of 220 µS cm^{-1} to 3420 µS cm^{-1} with average of 797.88 µS cm^{-1} in contrast with surface values of 506.56 µS cm^{-1} and 99700 µS cm^{-1} in mean-river values and lake respectively. Some specific boreholes adjacent to the Lake Nakuru and Menengai crater such as Soysambu, Londra boreholes, Olive Inn, Pyrethrum Board, Nakuru Tuners, BIDCO and Bontana Hotel indicates an increased concentration of major ions, which may be due to influence by the two features.

Groundwater is characterized by average TDS (a measure of water quality) concentrations of 227.27 mg l^{-1} with a range of values from as low as 52.8 mg l^{-1} to as high as 1642.5 mg l^{-1}. Average calculated TDS (277.27 mg l^{-1}) vary slightly with measured TDS (309.26 mg l^{-1}) i.e. 10.34% showing the influence of major ions in overall water chemistry in the basin (see Appendix VI).

4.4.1.1 Surface Water

The data presentation in Table 4.7 shows descriptive statistics of 11 variables and essentially is a summary that shows the central and dispersion properties of the selected variables. In the chemical components, HCO_3 content gives the highest range 296 mg l^{-1} that spans from as low as 14 mg l^{-1} to as high as 310 mg l^{-1}. Similar disparities are as well noted with the rest of the elements but with lower values, F showing the least range value of 13.23 mg l^{-1} spanning from as low as 0.33 mg l^{-1} to as high as 13.56 mg l^{-1}.

Table 4.7 Descriptive statistics of chemical data and physical characteristics of surface water

Variables	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
F	21	13.23	0.33	13.56	2.08	3.24	10.52	2.74	0.50	7.89	0.97
NO3	21	20.30	0.30	20.60	4.12	4.27	18.24	3.02	0.50	11.64	0.97
Mg	21	41.90	0.97	42.87	7.25	8.52	72.66	3.98	0.50	17.15	0.97
pH	15	1.55	7.02	8.57	7.68	0.43	0.19	0.46	0.58	-0.18	1.12
Ca	21	21.20	0.80	22.00	8.50	5.47	29.87	1.29	0.50	1.39	0.97
SO4	21	30.80	0.20	31.00	10.26	9.23	85.19	0.69	0.50	-0.47	0.97
K	21	32.20	1.80	34.00	12.45	7.48	55.97	1.25	0.50	2.56	0.97
Cl	21	81.00	4.00	85.00	19.67	18.45	340.33	2.44	0.50	7.48	0.97
Na	21	187.50	12.50	200.00	45.50	42.82	1833.20	2.77	0.50	8.51	0.97
HCO3	13	296.00	14.00	310.00	92.92	84.18	7086.41	1.41	0.62	2.66	1.19
Cond	15	1933.20	96.80	2030.00	501.95	541.93	293687.23	2.01	0.58	3.84	1.12

Representing the variation in the table above (Table 4.7), the box plot in Figure 4.9 displays concentrations of the elements in relation to NO_3, F, SO_4, Cl, K, Na, Mg, Ca and HCO_3 (in mg l^{-1}).

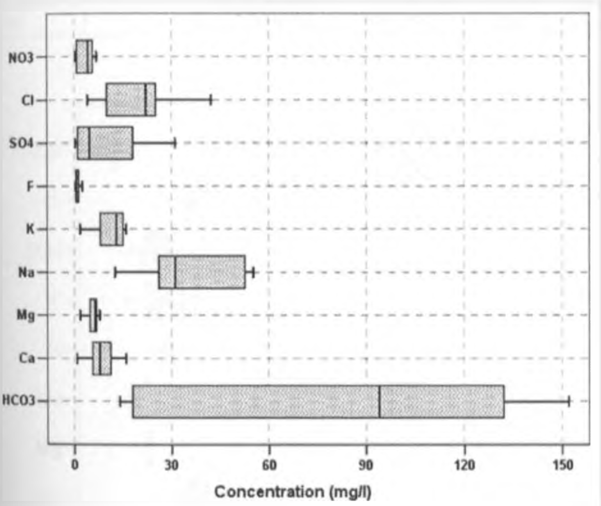


Figure 4.9 Box plots concentrations of selected ions in 21 surface water samples.

4.4.1.2 Shallow boreholes

Shallow boreholes in the study area are represented by Njoroge, Njogu and Munui boreholes. As shown in the descriptive statistics presented in Table 4.8, HCO_3 content has the highest discrepancy of 22 mg l^{-1} with a variance of 161.3, followed by Na and F with ranges of 13.0 and 12.8 and a variance of 56.3 and 41.9 respectively. The pH values are analogous in the three boreholes (i.e. 7.46), and hence having a variance value of zero. The box plot in Figure 4.10 gives a schematic presentation of distribution of the shallow boreholes.

Table 4.8 Descriptive statistics of chemical data and physical characteristics of shallow boreholes water

Variables	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
NO3	3	1.14	0.06	1.20	0.82	0.66	0.43	-1.73	1.22
Mg	3	1.62	6.08	7.70	6.90	0.81	0.66	-0.07	1.22
pH	3	0.00	7.46	7.46	7.46	0.00	0.00	_	-
SO4	3	9.00	4.00	13.00	8.33	4.51	20.33	0.33	1.22
F	3	12.77	2.69	15.46	9.69	6.47	41.90	-0.82	1.22
K	3	3.00	8.00	11.00	10.00	1.73	3.00	-1.73	1.22
Cl	3	3.00	12.00	15.00	13.67	1.53	2.33	-0.94	1.22
Ca	3	8.55	11.09	19.64	15.38	4.28	18.28	-0.04	1.22
Na	3	13.00	43.00	56.00	51.67	7.51	56.33	-1.73	1.22
HCO3	3	22.00	72.00	94.00	79.33	12.70	161.33	1.73	1.22
Cond	3	790.00	360.00	1150.00	830.00	415.81	172900.00	-1.41	1.22

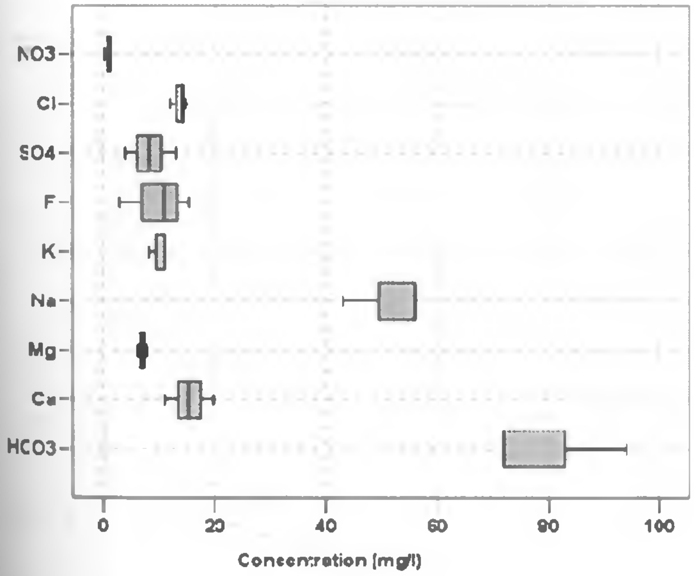


Figure 4.10 Box plots concentrations of selected ions in 3 shallow boreholes water samples

4.4.1.3 Deep boreholes

A total of 55 samples were analyzed for deep boreholes and as illustrated in Table 4.9, the variations are evident with HCO_3 ions displaying the highest variance followed by Na, Cl, SO_4, K, F, Ca, NO_3 and Mg ions in that order. All variables show positive skewness with a mean error of 0.32. Figure 4.11 shows a box plot that schematically displays the distribution of selected chemical elements concentration in these boreholes.

Table 4.9 Descriptive statistics of chemical data and physical characteristics of deep boreholes water samples

Variables	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
NO3	55	35.98	0.02	36.00	1.20	4.89	23.89	6.95	0.32	50.04	0.63
Mg	55	10.61	0.00	10.61	4.78	2.66	7.06	0.54	0.32	-0.17	0.63
F	55	27.52	0.69	28.21	6.79	6.88	47.30	1.59	0.32	1.67	0.63
Ca	55	30.55	0.00	30.55	6.87	6.35	40.35	1.60	0.32	2.93	0.63
pH	54	2.90	6.33	9.23	7.69	0.63	0.39	0.68	0.32	0.07	0.64
K	55	43.60	2.40	46.00	18.76	9.96	99.20	0.62	0.32	0.38	0.63
SO4	55	279.15	0.25	279.40	37.57	51.95	2698.67	2.78	0.32	8.87	0.63
Cl	55	660.00	7.00	667.00	48.97	91.81	8428.25	5.93	0.32	39.48	0.63
Na	55	739.00	26.00	765.00	155.56	139.21	19380.73	2.59	0.32	7.40	0.63
HCO3	47	773.00	20.00	793.00	186.94	214.57	46041.41	1.53	0.35	1.38	0.68
Cond	54	3200.00	220.00	3420.00	803.65	729.72	532493.10	2.18	0.32	3.99	0.64

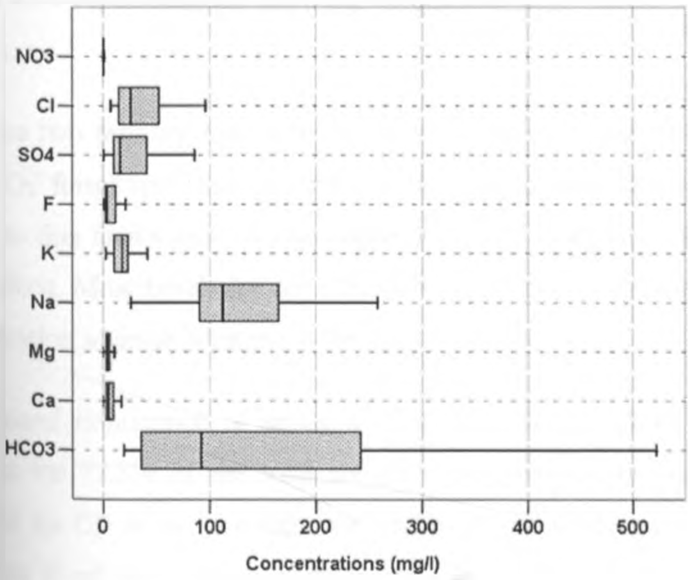


Figure 4.11 Box plots concentrations of selected ions in 55 deep boreholes water samples

4.4.2 Hydrochemical Facies

The ionic composition of groundwater (shallow and deep boreholes) and surface (springs, rivers and lake) water in this basin is shown in a Piper trilinear diagram (Figure 4.12). Distinctive chemistries of each of the above are evident.

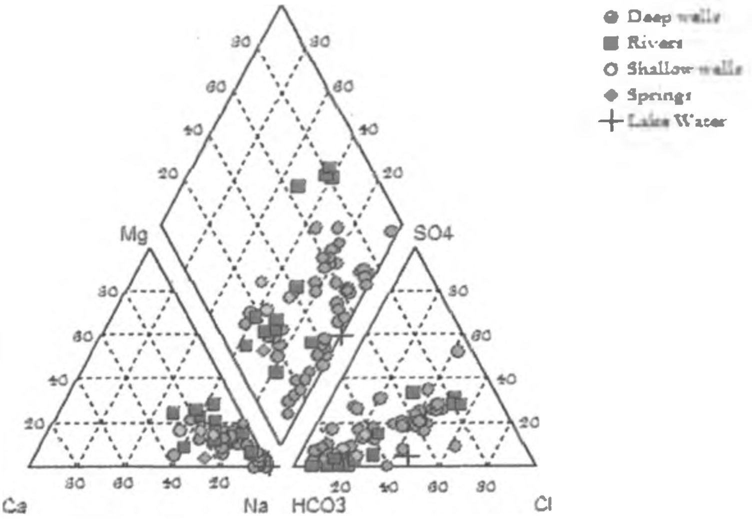


Figure 4.12 Piper diagram showing all the dominant facies in groundwater and surface water samples.

There are two primary hydrochemical facies; Na–HCO_3 & Na–Cl–SO_4 water-types (Fig. 4.12). Na-HCO_3^- forms approximately 60% of the groundwater samples. Most of the river samples also belong to this facies apart from samples collected from late stages of rivers Makalia and Njoro and Enderit. Most boreholes are rich in Na^+ and evolve gradually from HCO_3^- towards Cl-SO_4 concentration in areas adjacent to the lake.

The general dominance of anion was in the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$. HCO_3^- accounts for 77.3% of the total anions with average concentration of 178.32 mg l^{-1}; this is followed by Cl^- which accounts for 19.9% of the total anions, with average concentration of 45.82 mg l^{-1} of the total anion measured. SO_4^{2-} , F^- & NO_3^- accounts for 15%, 3% and 0.6% respectively. The general dominance of cations is in order of $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$. Na^+ accounts for 82.7% of the total cations with average concentration of 144.83 mg l^{-1} and K^+, Ca^{2+} and Mg^{2+} forming 10%, 4% and 2% in that order.

Figure 4.13 presents five stiff diagrams that show analytical results for selected river, spring, deep and shallow boreholes samples collectively with a sample from L. Nakuru. These representative samples include Soysambu borehole, River Njoro, Munui shallow well and Baharini springs. These diagrams are meant simply to display the diversity in chemical composition and their respective ratio within these various aquatic environments.

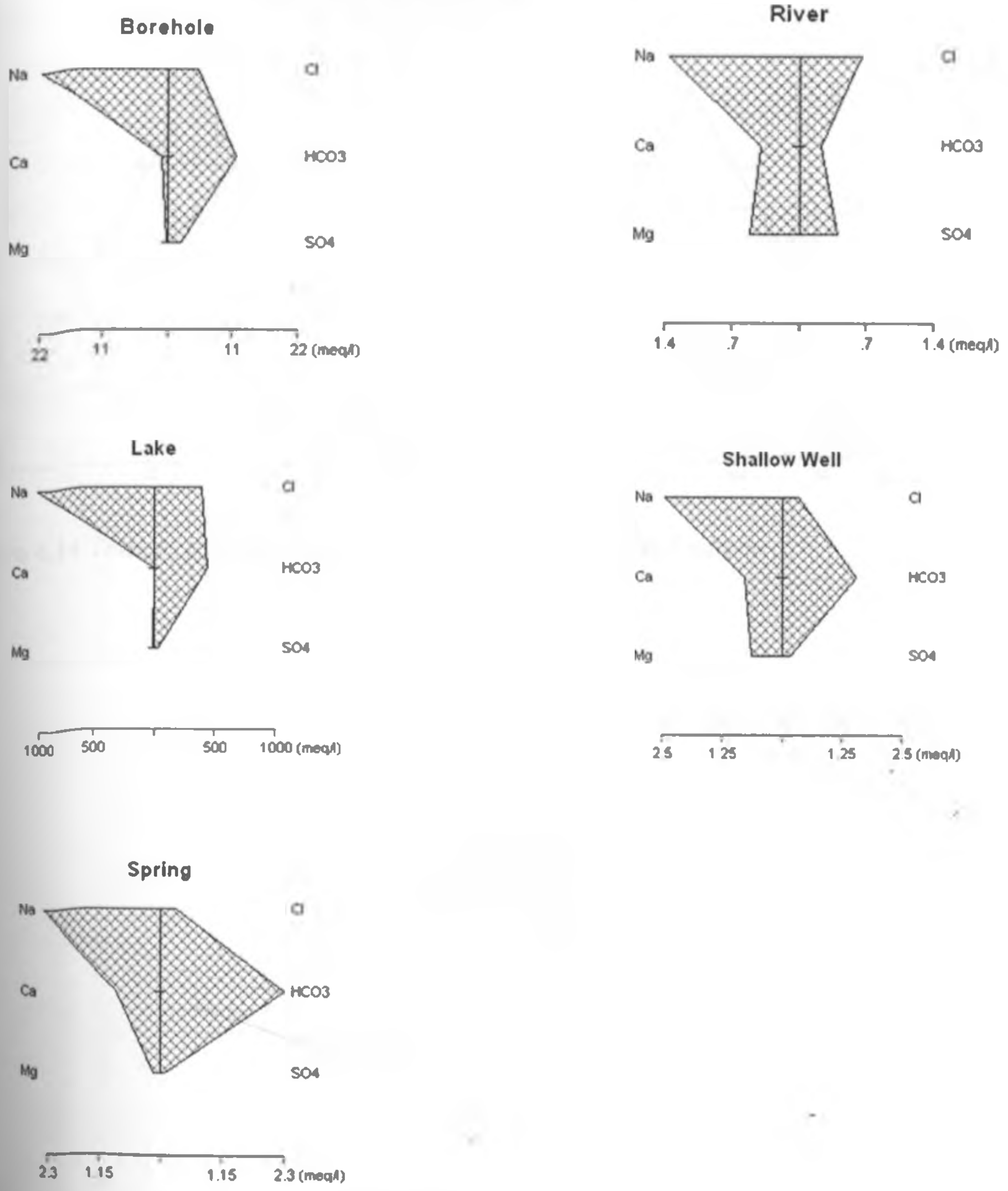


Figure 4.13 Stiff diagrams of representative samples from a Soysambu borehole, River Njoro, Lake Nakuru, Munui shallow well and Baharini Springs.

4.4.2.1 Groundwater

The two ternary diagrams in Figure 4.14 shows the relationship between the major cations and anions contained in groundwater correspondingly. From the diagrams, it is obvious that Na^+ is the most dominant cation (above 60% of cations) whereas in the other hand HCO_3^- is the dominant anion. Durov diagram in Figure 4.15 reveals the main geochemical facies for groundwater of the study area where Na-HCO_3 predominates.

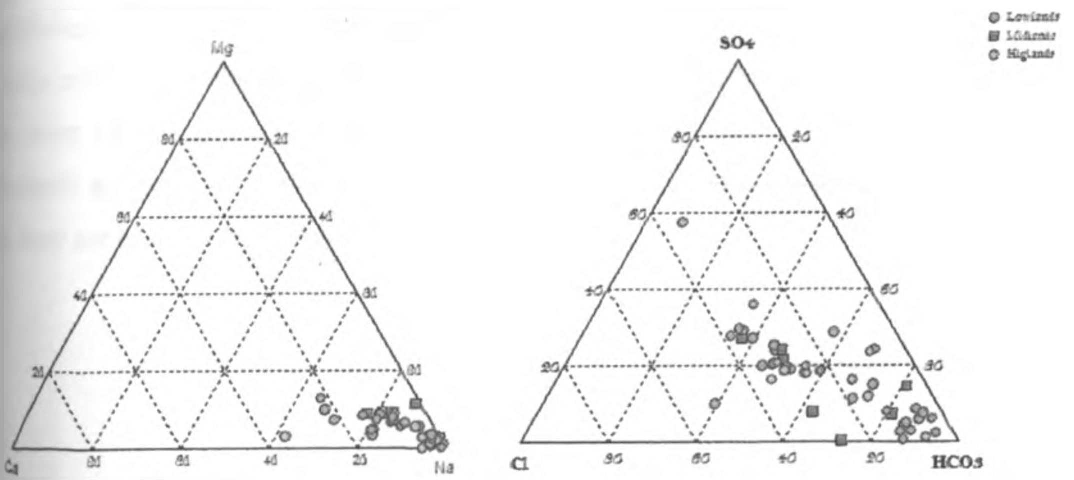


Figure 4.14 Ternary diagrams showing relations of cations and anions

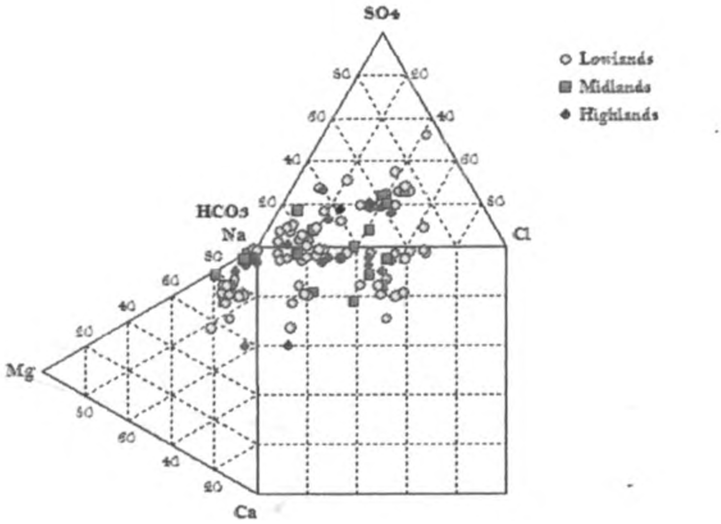


Figure 4.15 Durov plot showing the distribution of groundwater geochemical results across the main facies.

4.4.3 Rock-water interactions in groundwater

4.4.3.1 Using simple ratios

Chemical elements exchange between groundwater and minerals at temperatures of non-thermal groundwater bodies is usually slow. Therefore, cold groundwater rarely reaches chemical equilibrium with minerals of the aquifer. However, the chemical compositions of groundwater usually reflect the mineralogical composition of the rocks in the aquifer. Figure 4.16 indicates that most of the groundwater data fall under immature water apart from two data points; Windmill and Rhonda boreholes. These two boreholes approaches equilibrium and it is evident that they are as a result of thermal effect.

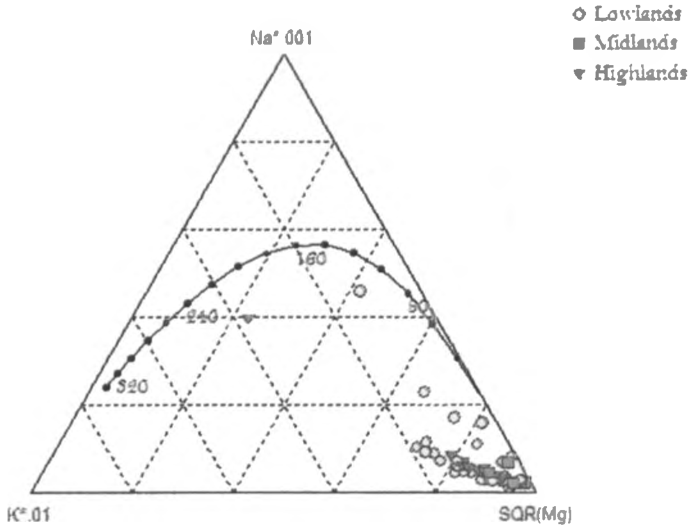


Figure 4.16 Giggenbach plot showing the extent of water-rock equilibrium attainment. NB: the line is the equilibrium line of Na, Mg and K and has the temperature of equilibration.

For cations Na^+ was higher indicating weathering of plagioclase bearing rocks. The lesser amounts of K^+ signify its lower geochemical mobility. During the course of continental weathering, Na^+ turns out to be more mobile than K^+ and dominates in the natural solutions (Milliot 1970). Ca^{2+} and Mg^{2+} indicate weathering from primary minerals sources.

The plot for Na^+ *versus* Cl^+ (Fig. 4.17a) shows that, all samples fall in Na^+ zone indicating Na^+ derived from weathering of silicate bearing minerals and not from halites. Since Cl^- bearing minerals are rare in silicate terrain, it might have been derived from anthropogenic sources that include fertilizer, industrial, human and animal waste. These sources can result in significant concentrations of chloride in groundwater because chloride ion is readily transported through the soil (Stallard and Edmond 1983). This is well evidenced from Cl^- levels of the study area which is a major industrial and agricultural town of the Province.

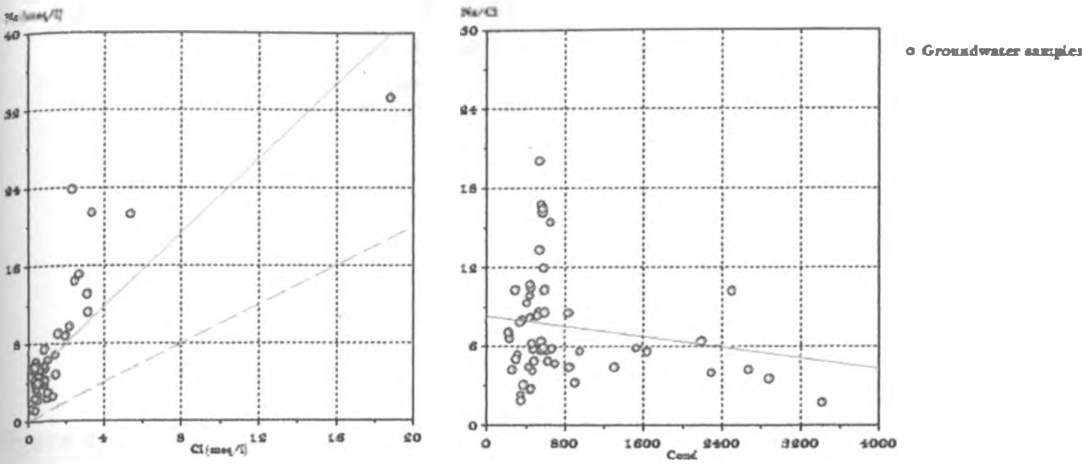


Figure 4.17 (a) relationship of Na^+ *versus* Cl^-, (in Meg/l) (b) relationship of Na^+/Cl^- *versus* conductivity, (in μS/cm). The continuous line shows trend lines whereas the broken line shows the equiline.

In the plot for Na^+/Cl^- *versus* Conductivity (Fig. 4.17b), the Na^+/Cl^- ratio shows a decreasing trend with increasing EC along with higher Na^+/Cl^- ratio, confirms the fact that Na^+ is being released from silicate weathering process. This is also supported by the higher values of HCO_3^- in groundwater that results from the reaction of feldspar minerals with carbonic acid (Jankowski & Acworth 1997), which might be one of the reasons for increase in conductivity.

The plot for Ca^{2+}+Mg^{2+} *versus* SO_4^{2-}+HCO_3^- is a major indicator to identify ion exchange process activated in the study area. If ion exchange is the process, the points shift to the right side of the plot due to excess SO_4^{2-}+HCO_3^-. If reverse ions exchange is the process, points shift left due to excess Ca^{2+}+Mg^{2+}. Most of the points in fig. 4.18 below are clustered left of the equiline 1:1 falling in SO_4^{2-} + HCO_3^- area suggesting some ion exchange process which may be due to the excess bicarbonate. However, the points clustered in the right side suggest reverse ion exchange.

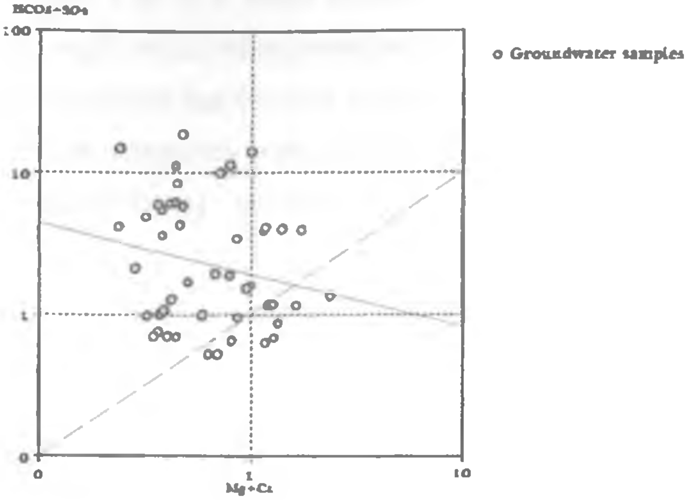


Figure 4.18 scatter diagram showing the relationship of Ca^{2+}+ Mg^{2+} *versus* HCO_3^- + SO_4^{2-}, (in mg/l) in. Note that the dash-line is the equiline 1:1. The continuous line shows trend lines whereas the broken line shows the equiline.

The plot in Figure 4.18a for Na^++K^+ *versus* HCO_3^- show points falling in either sides of the equiline without any clear trend. However, in average, the ratio of the two is in the same range suggesting a common source. The ratio of Na^+ *versus* Ca^{2+} + Mg^{2+} reveals a negative correlation that suggests the presence of ionic exchange process (see Figure 4.18b).

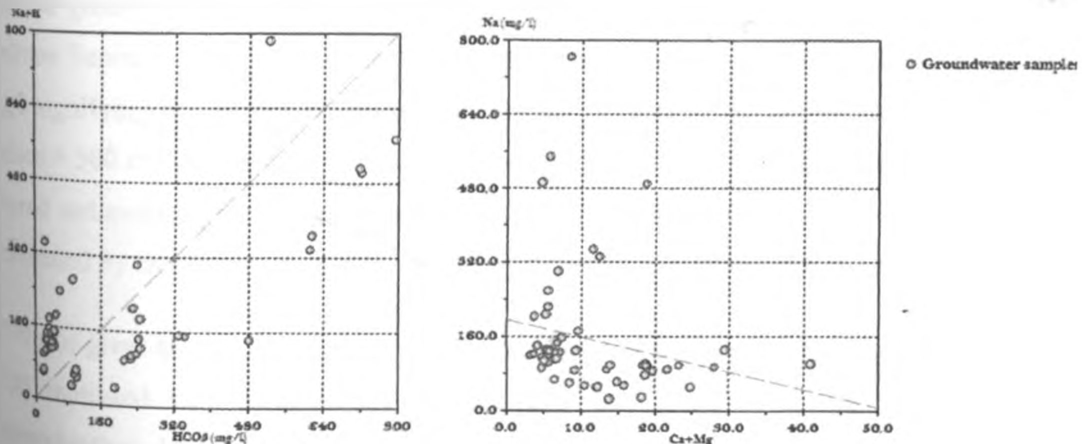


Figure 4.19 (a)relationship of Ca^{2+} and Mg^{2+} *versus* HCO_3^-, (in Meg/l) (b) relationship of Na^+ *versus* sum of Ca^{2+} and Mg^{2+} (in Meg/l).

EC is a good estimator of TDS (as it was not analyzed in the field) and can be estimated by multiplying EC by a factor of 0.55 - 0.76 (Hounslow 1995). EC has a high correlation with TDS (r^2 = 0.95) (see Fig. 4.20). TDS is a crude indicator of rock weathering, whether silicate weathering (TDS < 500 mg/l) or carbonate weathering (TDS > 500 mg/l). EC was used to estimate TDS and results indicated that 60.71 % of the calculated TDS values were below 500 mg/l; this means that silicate weathering is the dominant weathering process. Owing to the fact that silicate weathering releases HCO3 - the remaining 39.29 % indicating carbonate weathering, may be as a result of this.

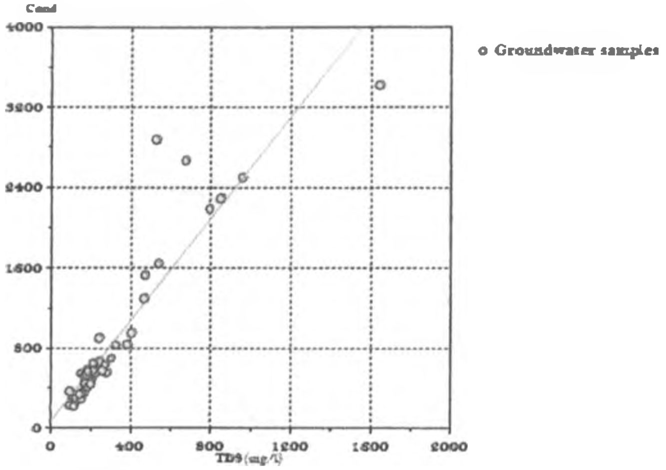


Figure 4.20 Bivariate diagrams of Electrical Conductivity (µS/cm) vs. Total Dissolved Solids (mg/l) showing relationship. The line shows the trend.

All the groundwater samples apart from boreholes in Londra, Soysambu, Pyrethrum Board, Nakuru Tunners, BIDCO and Bontana Hotel have calculated TDS (mg/l) values less than 500 mg/l signifying dominance of silicate weathering. However, the above indicated samples have values > 500 mg/l describing a readily weathering material such as carbonate materials or highly altered sediments. This is reasonable as the boreholes are located in a paleosediments terrain dominated by carbonaceous, highly altered pyroclastics and volcanosediments.

TDS also gives an indication of the mineralization level in water. For this data set the calculated TDS indicated that most of the groundwater has a low level of mineralization. Low mineralization, high silica content, coupled with groundwater flow predominantly through fissures indicates a short residence time for groundwater in the area (Hem 1989).

4.4.3.2 Principal Component Analysis

Table 4.10 shows the results of the principle components analysis of 9 variables in the 6 boreholes samples. This table reports the factor loadings in groundwater for each variable on th unrotated components. Each number represents the correlation between the items and th unrotated factor.

Table 4.10 Principal component analysis results showing loadings of nine chemical variables i groundwater

Component Component (PC) for Ground water				
	1	2	3	4
HCO3	**0.693**	0.125	0.259	-0.409
Ca	-0.228	0.554	**0.573**	0.320
Mg	-0.460	0.213	**0.644**	0.101
Na	**0.956**	0.171	0.061	-0.064
K	0.369	-0.543	-0.035	**0.671**
F	**0.753**	-0.421	0.201	0.207
SO4	**0.843**	-0.229	0.276	-0.066
Cl	**0.794**	0.508	-0.203	0.207
NO3	0.558	**0.662**	-0.384	0.205

In the results presented here, PCA has reduced the data set from 9 variables to four principa components (PC loadings), while still explaining ~75.6% of the total variance. These correlations help in formulating an interpretation of the components. The first principal component (PC1) contains 42.2% of the total variance the second principal component (PC2) represents 18.0% and the third principal component represents 10.6% of the total variance. The fourth principal component represents 4.0% of the total variance.

The chemical constituents with the highest positive PC1 loadings include Na, SO_4, Cl, F, & HCO_3. The chemical constituent with high positive PC2 loadings is NO_3^-, whereas PC3 and PC4 loadings include Ca^{2+} & Mg^{2+} and K^+ elements respectively. The first principal component is most likely controlled by the weathering of the silicates rocks in the basin. PC2 is probably due to anthropogenic contaminations and PC3 is most likely due to ferromagnesian weathering or water body influenced by cationic exchange. Although K^+ concentration is controlled by weathering of silicates, it is relatively immobile and hence its distribution is normally not even.

The results are in Table 4.11 shows the principal components analysis for surface water. The principal component analysis reveals here that the first three leading principal components explain 96.1% of the variance and relates to the origin of these elements. PC1 loadings constitute Na^+, Cl^-, HCO_3^-, K^+, SO_4^{2-} and F^- chemical elements. PC2 main loading is NO_3^-, Ca^{2+} and Mg^{2+}, whereas PC3 strongly associate positively with Ca^{2+} and negatively with NO_3^-.

Table 4.11 Principal component analysis results showing loadings of nine chemical variables in surface water.

	1	2	3
HCO3	0.998	0.059	0.020
Ca	-0.434	0.539	0.622
Mg	-0.112	0.917	0.075
Na	0.998	0.059	0.021
K	0.992	0.123	0.002
F	0.996	0.072	0.038
SO4	0.997	0.069	0.025
Cl	0.998	0.058	0.021
NO3	-0.194	0.522	-0.790

PC1 contains 68.8% of the total variance, while PC2 and PC3 constitute 16.0% and 11.3% of the variance respectively. PC1 can be associated with silicate weathering, PC2 with ferromagnesian/carbonates weathering and PC3 with anthropogenic sources.

4.4.3.3 Mineral Saturation Indices in Water

The samples in the region are undersaturated to equilibrium with aragonite, calcite, fluorite and dolomite. In general, carbonate results show that the solutions are undersaturated with respect to calcite, dolomite and aragonite minerals with some samples being in equilibrium or showing slight saturation to calcite and aragonite (13.73%), dolomite (7.84%) and fluorite (19%) of the total samples analysed. This indicates that there is less input of Ca and Mg ions from either carbonates or silicate weathering process to the hydrosphere. All the samples are undersaturated with respect to neutral salts like gypsum and anhydrite.

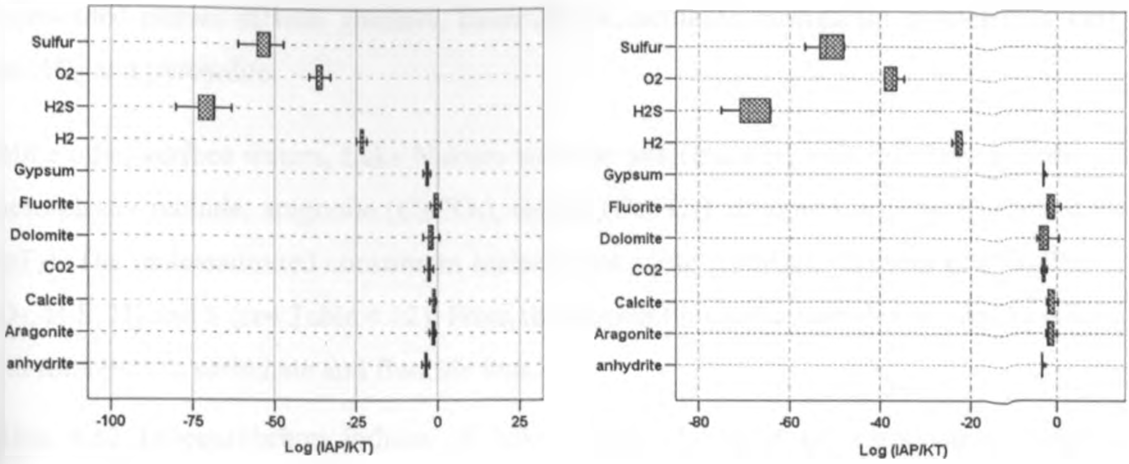


Figure 4.21 Equilibrium diagrams showing distribution of saturation indices of carbonates, sulphates and fluorite in groundwater (Figure 4.21a) and surface water (Figure 4.21b). Note that no silicate bearing minerals are included because SiO_2 was not included in the analytical data.

Both surface and groundwater solutions displays concentrations that ranges from saturation to over-saturation with ferric ions (see Fig. 4.22). The results show that the samples are saturated with FeOH and goethite, and over-saturated with respect to hematite. Conversely, the solutions generally are undersaturated with respect to hausmannite, manganite, pyrochroite and pyrosulite. In average, the solutions are in equilibrium concentrations with $Zn(OH)_2$, with samples falling on either sides of the equilibrium line.

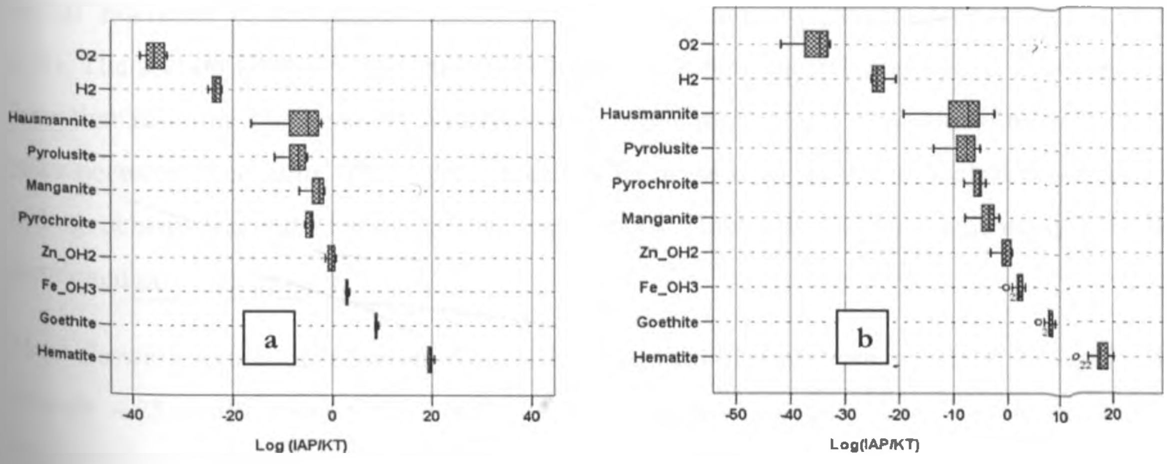


Figure 4.22 a&b Equilibrium diagram showing distribution of saturation indices of heavy metals, i.e., iron, manganese and zinc in groundwater and surface water respectively.

Represented phases include goethite, hausmannite, hematite, manganite, pyrochroite, $Fe(OH)_3$, $Zn(OH)_2$ and pyrosulite.

Unlike other surface waters, Lake Nakuru water is oversaturated with reference to most phases. These phases include; aragonite ($CaCO_3$), calcite ($CaCO_3$), dolomite (CaMg $(CO_3)_2$ and fluorite (CaF_2). The undersaturated constituent include; anhydrite ($CaSO_4$), Gypsum ($CaSO_4.2H_2O$), O_2, CO_2, H_2S, H_2 and S (see Table 4.12). From this account it can be seen that the waters is saturated with reference to carbonate and fluoride ions.

Table 4.12 Disequilibrium indices of Lake Nakuru basin of (a) carbonates, sulphates and fluorite, and (b) iron, manganese and zinc, respectively.

Phase	SI	log IAP	log KT	
Anhydrite	-4.31	-8.67	-4.36	CaSO4
Aragonite	0.42	-7.92	-8.34	CaCO3
Calcite	0.56	-7.92	-8.48	CaCO3
CO2(g)	-4.77	-22.92	-18.15	CO2
Dolomite	2.41	-14.68	-17.09	CaMg(CO3)2
Fluorite	0.84	-9.76	-10.6	CaF2
Gypsum	-4.12	-8.7	-4.58	CaSO4:2H2O
H2(g)	-28.98	-28.98	0	H2
H2S(g)	-97.91	-139.56	-41.64	H2S
O2(g)	-25.18	57.94	83.12	O2
Sulfur	-74.81	-110.58	-35.76	S

Phase	SI	log IAP	log KT	
Fe(OH)3(a)	2.11	20.02	17.91	Fe(OH)3
Goethite	8	20.02	12.02	FeOOH
H2(g)	-28.98	-28.98	0	H2
Hausmannite	10.75	71.78	61.03	Mn3O4
Hematite	18.01	40.04	22.03	Fe2O3
Manganite	3.42	28.76	25.34	MnOOH
O2(g)	-25.16	57.96	83.12	O2
Pyrochroite	-0.93	14.27	15.2	Mn(OH)2
Pyrolusite	1.87	43.25	41.38	MnO2
Zn(OH)2(e)	1.21	12.71	11.5	Zn(OH)2

4.4.4 Water Quality Assessment

This section identifies the status of water quality for groundwater, surface and lake waters with special reference to recognized international organization requirement (see Tables 4.13 and 4.14). The section identifies and quantifies trends in water quality and provides assessment in a form that resource management and regulatory agencies can use to evaluate alternatives and make necessary decisions. The objective of this exercise is to assess geological contribution to hydrogeochemistry, and its water quality implications. However, anthropogenic inputs have been mentioned on a lighter note.

Maps showing spatial distribution of specified chemical elements are presented in Figures 4.23 through 4.28. Both areas with water chemical composition above and below the required standards (i.e WHO & NEMA, see Table 4.13/14) are shown. These maps can be loosely used to suggest groundwater recharge zones. A high value proposes long residence time and hence ample water-rock interaction whereas low value is the possible recharge zone.

Table 4.13 Local and international drinking water quality recommendation and groundwater data. (*NB: Data source; NEMA (NEMA 2006), WHO (WHO 2008), EU (EU 1997), Canada (FPT Committee on Drinking Water 2008), USA (EPA USA 2006) and Russia (Moscow 2009)).*

	Ground water (shallow and deep)			Water Quality Standards					
	Min (ppm)	Max (ppm)	Range (ppm)	NEMA	WHO	EU	Canada	USA	Russia
pH	6.3	9.2	2.9	6.5 – 8.5	<8	6.5-8.5	6.5-8.5	6.5-8.5	6.0-9.0
Na	26.0	765.0	739.0		200	150			
F	0.7	28.2	27.5	1.5	1.5	1.5	1.5	2	<1.5
SO4	0.3	279.4	279.2		250	250	500	250	500
Cl	7.0	667.0	660.0		250	25	250	250	350
NO3	0.0	36.0	36.0	10.0	50	50			45
NO2	0.00	0.14	0.14	3.0					
Cr	0.08	0.44	0.36		0.05(P)	0.05	0.05	0.1	0.05
Cd	0.102	0.58	0.478	0.01	0.003	0.005	0.005	0.005	0.003
Pb	0.024	0.828	0.804	0.05	0.01	0.05	0.05	0.015	0.01
Fe	0	3.3	3.3		0.3	0.2	0.3	0.3	0.3
Mn	0.001	1.1	1.099		0.5(P)	0.05	0.05	0.05	0.5
Zn	0.34	3.92	3.58	1.5	3	0.1-5.0	5	5	5

Table 4.14 Local and international drinking water quality recommendation and surface water data. *(NB: Data source; NEMA (NEMA 2006), WHO (WHO 2008), EU (EU 1997), Canada (FPT Committee on Drinking Water 2008), USA (EPA USA 2006) and Russia (Moscow 2009)).*

	Surface Water (rivers and springs)			Lake water	Water Quality Standards					
	Min (ppm)	Max (ppm)	Range (ppm)	(ppm)	NEMA	WHO	EU	Canada	USA	Russia
pH	7.00	8.60	1.60	10.5	6.5 – 8.5	<8	6.5-8.5	6.5-8.5	6.5-8.5	6.0-9.0
Na	12.50	200.00	187.50	22676.0		200	150			
F	0.30	13.60	13.30	450.0	1.5	1.5	1.5	1.5	2	<1.5
SO4	0.20	31.00	30.80	1828.0		250	250	500	250	500
Cl	4.00	85.00	81.00	20.2		250	25	250	250	350
NO3	0.30	20.60	20.30	1.2	10.0	50	50			45
NO2	0.02	0.28	0.26	0.36	3.0					
Cr	0.16	0.34	0.18	0.53		0.05(P)	0.05	0.05	0.1	0.05
Cd	0.29	0.38	0.09	0.814	0.01	0.003	0.005	0.005	0.005	0.003
Pb	0.18	2.04	1.86	0.281	0.05	0.01	0.05	0.05	0.015	0.01
Fe	0.69	3.40	2.71	4.58		0.3	0.2	0.3	0.3	0.3
Mn	0.04	1.50	1.46	0.02		0.5(P)	0.05	0.05	0.05	0.5
Zn	2.04	4.11	2.07	4.66	1.5	3	0.1-5.0	5	5	5

4.4.5.1 Sodium (Na^+) and Sodium Adsorption Ratio (SAR)

Concentrations of sodium in natural waters vary depending on local geological conditions and wastewater discharges among other settings. The WHO guidelines limit for sodium in drinking water is 200mg/l (WHO 2008) and has been compared to both groundwater and surface concentrations, which shows significant discrepancies to some degree exceeding WHO specifications. High sodium rich areas have been shown in Fig. 4.23a.

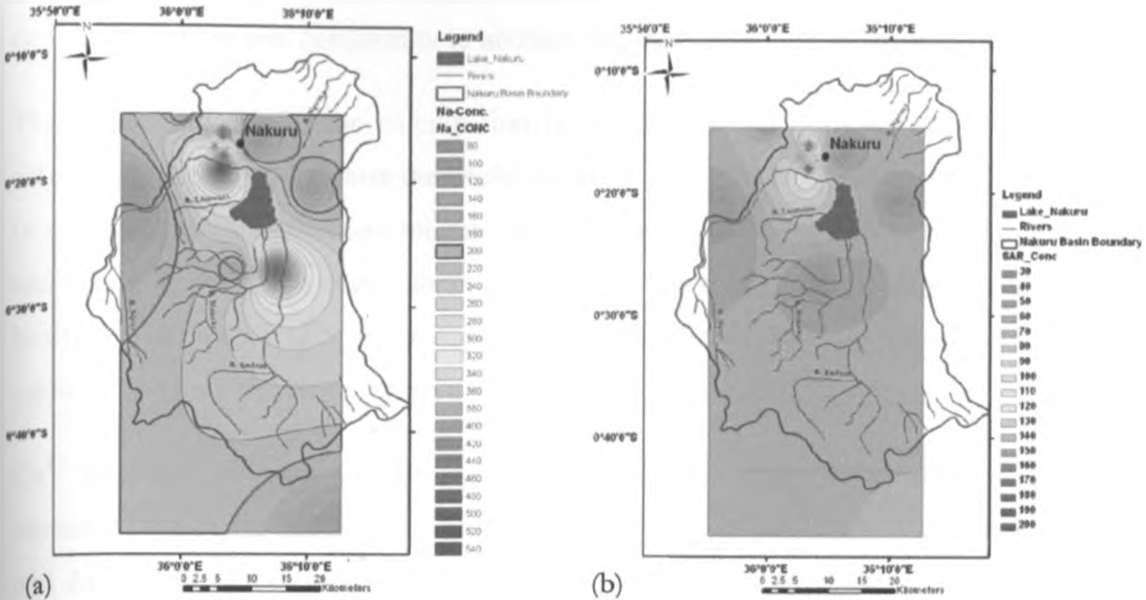


Figure 4.23 a&b diagrams showing a) Na^+ concentration and, b) sodium adsorption ratio (SAR) in mg/l. NB: the red contour is iso-concentration below which below which the waters are potable and above which they are impotable according to WHO and NEMA (see Table 4.13 & 4.14)

Sodium content is examined here not only as for drinking water quality assessment but also for agricultural purposes, particularly irrigation. Elevated sodium in certain soil types can degrade soil structure thereby restricting water movement and affecting plant growth (Fig. 4.23b). Sodium adsorption ratio varies from as low as 1.3mg/l in river water to as high as 71mg/l. Some of the boreholes waters that are unfit for irrigation purpose include; Ronda, Nakuru Tanners, Pyrethrum Board, Soysambu, Bontana, Londra, BIDCO, Agri, Olive Inn, Eveready, Nakuru Boys Secondary School, Windmill, Makiki, Nairobi Road and some Egerton university boreholes. When SAR rises above 12 to 15 serious physical soil problems arise and plants have difficulty absorbing water (Munshower 1994).

4.4.5.2 Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

Calcium and magnesium in natural waters are commonly present as Ca^{2+} and Mg^{2+} respectively and both contribute significantly to water hardness. Ca^{2+} is readily dissolved from rocks rich in calcium minerals, particularly as carbonates and sulphates. Generally, hardness caused by Ca^{2+} and Mg^{2+} is usually indicated by precipitation of soap scum and the need for excess use of soap to achieve cleaning. Public acceptability of the degree of hardness of water may vary considerably from one community to another, depending on local conditions (WHO 2008).

The taste threshold for the calcium ion is in the range of 100–300 mg/l, depending on the associated anion, and the taste threshold for Mg^{2+} ions is probably lower than that for Ca^{2+} ions. In some instances, consumers tolerate water hardness in excess of 500 mg/l. Depending on pH and alkalinity, hardness above about 200 mg/litre can result in scale deposition, particularly on heating. Soft waters with a hardness of less than about 100 mg/litre have a low buffering capacity and may be more corrosive to water pipes (WHO 2008).

Ca^{2+} and Mg^{2+} ions are less evenly distributed and are primary dominant in sediments laden terrains of the basin. The highest values obtained for groundwater are 30.6 and 10.6mg/l for Ca^{2+} and Mg^{2+} ions respectively. These concentrations are not expected to pose any health issue problem.

4.4.5.3 Nitrate (NO_3^-), Nitrite (NO_2) and Sulphate (SO_4^{2-})

Nitrate was detected in all samples, with concentrations ranging from 0.01 to 36mg/l whereas nitrite was not detected in most samples but considerable boreholes had values arising as high as 0.36mg/l. Nitrate concentrations in groundwater under natural conditions are usually less than 2-3mg/l (Mueller *et al.* 1995). When nitrate concentrations exceed 3mg/l, non-natural sources are suspected. Four boreholes had samples containing nitrate > 3mg/l (fig. 4.24a). Some nitrates samples had high nitrate vales that exceeds NEMA limits of <10mg/l. However, both nitrate and nitrite concentrations were within the limits as required by WHO, i.e., < 50mg/l and < 1mg/l respectively for drinking water. On the other hand, the possible sources of nitrate include nitrogen-based fertilizers, septic systems, animal feedlots and manure applied to land, among others.

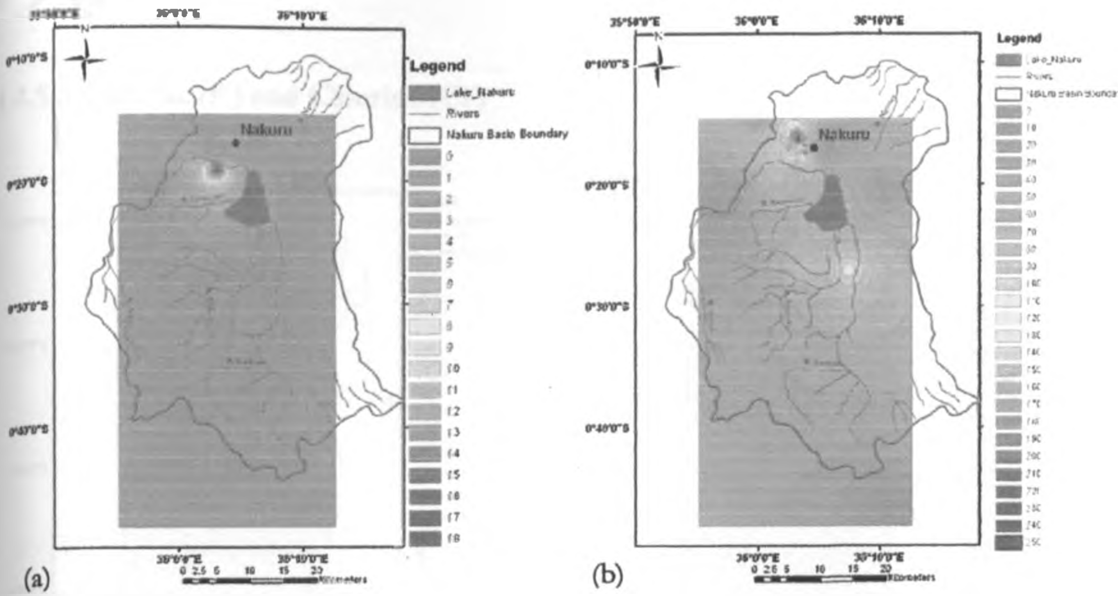


Figure 4.24 a&b Diagrams showing a) NO_3^- concentration and, b) SO_4^{2-} concentrations in mg/l.

In average, borehole data contains higher percentage of SO_4^{2-} ions (77.893mg/l) than surface water. Lake and rivers display close correlation in their contained sulphate ions percentage. Higher ratio values are seen in specific sites demonstrated by areas surrounding Nakuru area. This includes; Pyrethrum Board, Windmill trough BH, River Kitiri, Sewage discharge point 2, Nakuru School Boys BH, Lower Rhonda BH, Kenbrid Farm BH, Eveready BH and Baharini Springs. However, only a sample from pyrethrum board borehole exceeded the allowable water drinking limit of 250 mg/l (i.e. WHO, EU, USA). As indicated by Fig. 4.24b, spatial distribution of sulphate is biased to the area around Menengai crater and the lake. In fact the source of sulphates observed on boreholes adjoining the lake is probably conducted from the crater through subsurface structures.

4.4.5.4 Dissolved oxygen (DO)

Oxygen saturation ranges from 6.34 mgl^{-1} to as high as 8.24 mgl^{-1} in boreholes. The high values are found in boreholes around Njoro and Egerton located at the slopes of Mau Range that is highly deforested. The malpractice has paved way for organic pollution and hence the relative difference of DO concentration in the basin. Russian drinking water regulations give allowable guideline limit of 4 mgl^{-1}.

4.5.5 Fluoride (F^-) and Chloride (Cl^-)

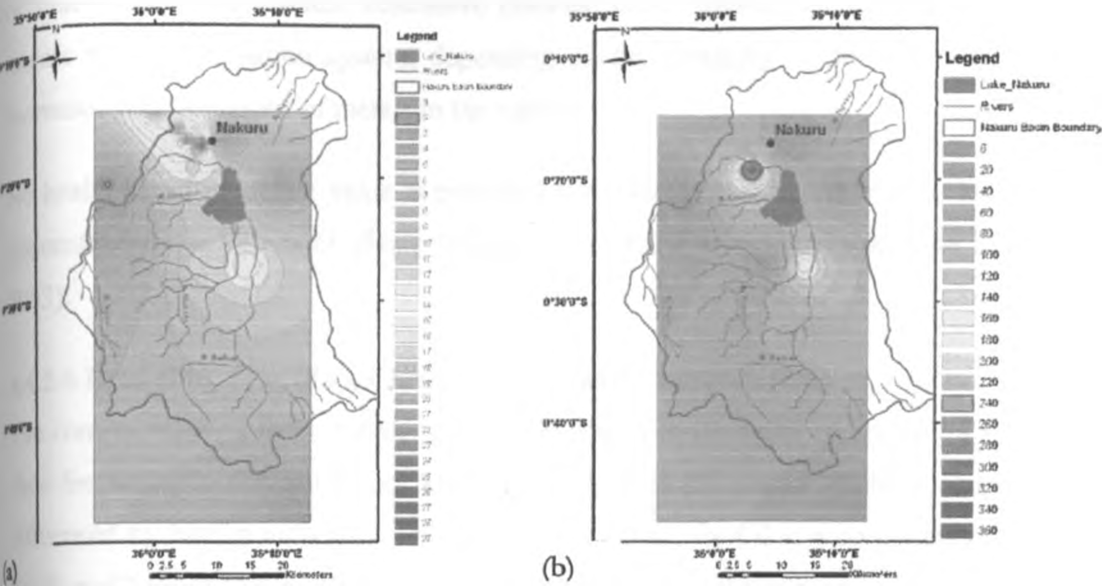


Figure 4.25 a&b Diagrams showing a) F^- concentration and, b) Cl^- concentrations in mg/l. NB: the red contour is iso-concentration below which below which the waters are potable and above which they are impotable according to WHO and NEMA (see Table 4.13 & 4.14)

Very high concentrations of fluoride, far exceeding the WHO guideline value of 1.5 mgl^{-1} are encountered in most boreholes which are basically volcanic aquifers. Analysis indicates that only 5 out of the 60 boreholes assessed contain fluoride of allowable concentrations. These boreholes include; Tabuga, Wamuyu, Nyoike, Muhia and Njoro Country Club boreholes. The rest contains concentrations exceeding 1.5 mgl^{-1} to values >20 mgl^{-1}, as note with Bontana, Londra, Olive Inn and Nakuru Tanners. The consequence of these elevated figures is readily seen by the extent of mottling of teeth in the people sourcing drinking water from these boreholes.

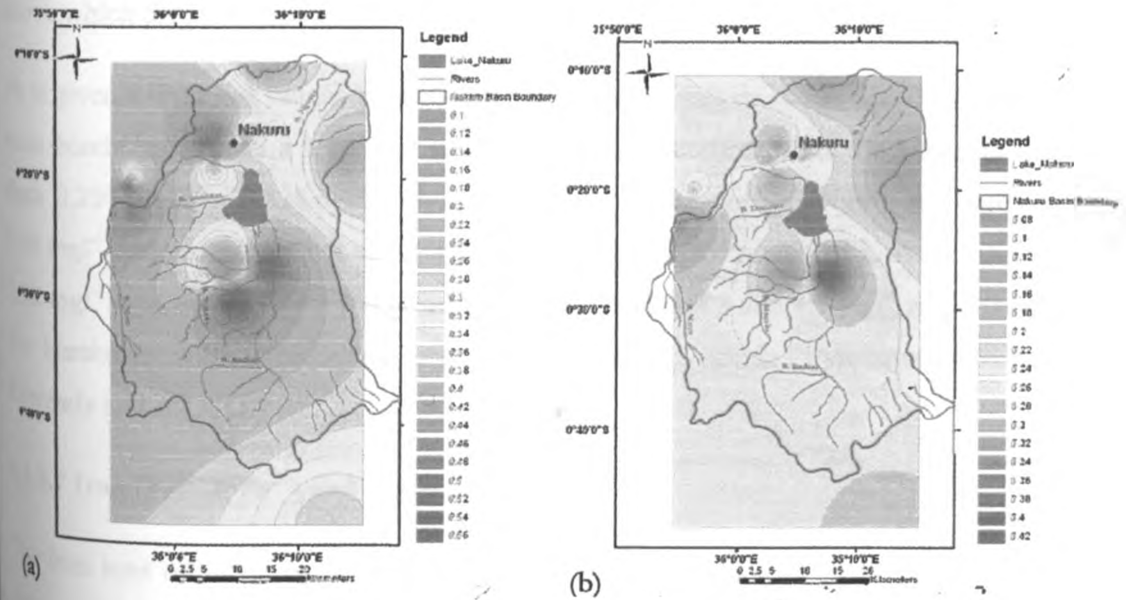
Spatial availability of fluoride ions is seen to dominate on volcanosediment areas and recent volcanic systems of Menengai Crater. The areas around Njoro and Bahati is seen to have relatively small content of fluoride ions probably because of its good underground drainage resulting to high groundwater discharge and hence the dilution factor.

Chloride in drinking-water originates from natural sources, sewage and industrial effluents, urban runoff containing de-icing salt and saline intrusion. The main source of human exposure to chloride is the addition of salt to food, and the intake from this source is usually greatly in excess of that from drinking-water. Excessive chloride concentrations increase rates of corrosion of metals in the distribution system, depending on the alkalinity of the water. This can lead to increased concentrations of metals in the supply.

No health-based guideline value is proposed for chloride in drinking-water. However, chloride concentrations in excess of about 250mgl^{-1} can give rise to detectable taste in water (WHO 2003).

4.4.5.6 Lead (Pb), Zinc (Zn), Chromium (Cr) and Cadmium (Cd)

The concentration of these metals in borehole waters in the basin varies over a wide range and rises frequently to concentrations which are dangerous for human health in some water bodies influenced by human activities. The specification given for Cd is a concentration of 0.003 and 0.005 mgl^{-1} for WHO and Russia, and EU, Canada and USA respectively, as compared to the observed concentration range of between 0.102 – 0.58 mgl^{-1} in the waters of the study area (see Table 4.5). NEMA specification limit is 0.01mgl^{-1}. Cr content in the boreholes spans between 0.08 to 0.44mgl^{-1}. These values still surpasses the recommended maximum allowable concentration by WHO of 0.05 mg/l in drinking water.



(a)

(b)

Figure 4.26(a&b) Diagrams showing a) Cadmium concentration and, b) Chromium concentrations in mg/l. NB: all the waters with reference to Cd and Cr are impotable according to WHO and NEMA (see Table 4.13 & 4.14)

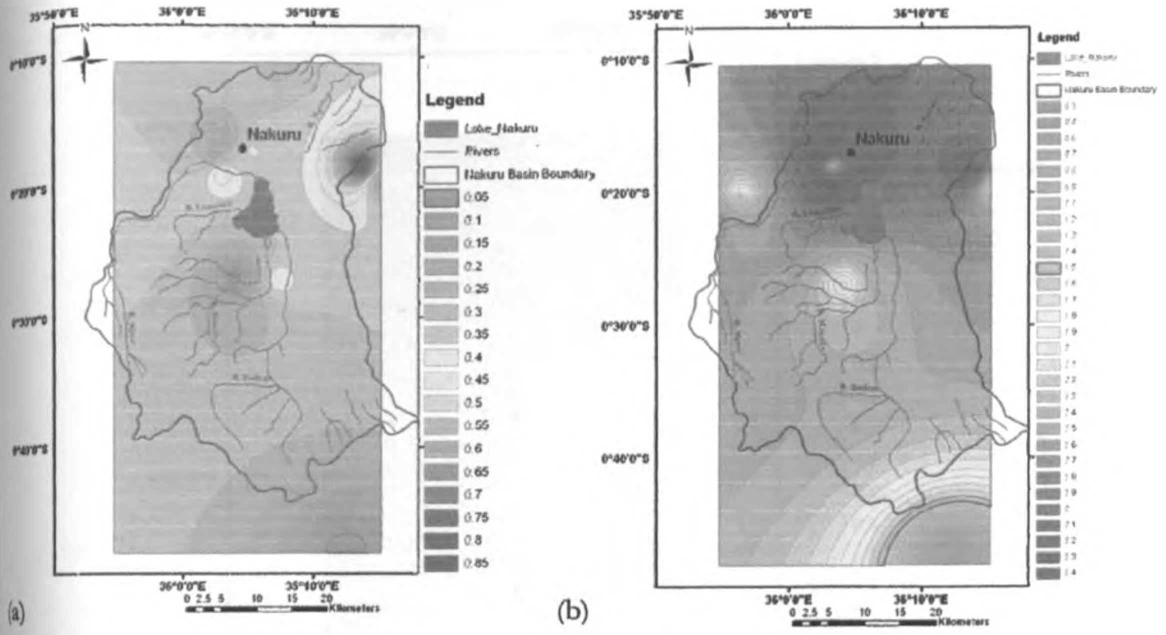


Figure 4.27 (a&b) Diagrams showing a) Lead concentration and, b) Zinc concentrations in mg/l. NB: the red contour is iso-concentration below which below which the waters are potable and above which they are impotable according to WHO and NEMA (see Table 4.13 & 4.14)

Pb is given a limit that ranges from 0.01 to 0.05 mgl^{-1}. Analysis shows that the concentrations of most boreholes as lead a level that goes beyond the specified limits. Pb varies in the samples from 0.208 mgl^{-1} to 0.828mgl^{-1} in boreholes and in rivers such as Njoro; it records as high as 2.98 mgl^{-1}, values that are not safe for human consumption. Zn content is in the range of 0.34 to 3.92 mgl^{-1} against the WHO and NEMA proposed limits of 3 and 1.5 mgl^{-1} respectively. Among the boreholes with exceedingly high values include; Ronda, Pyrethrum Board, Ngorika, Eveready and BIDCO.

4.4.5.7 Iron (Fe^{3+} & Fe^{2+}) and Manganese (Mn^{2+})

The iron ions originate by solution at sites of either reduction of hydroxides or oxidation of ferrous sulphide (Hem 1989). Dissolved iron ions are generally low especially with borehole samples. The mean dissolved iron in sampled rivers is higher than borehole figures, i.e., 1.8mgl^{-1} for rivers against 0.36mgl^{-1} for that of boreholes. This shows that weathering of iron depends majorly with mechanical action. The general dissolved iron ranges is 0-3.4 mgl^{-1} relative to lake values of 4.58 mgl^{-1}. Lower Ronda displayed the least with 0.001mgl^{-1} contained iron.

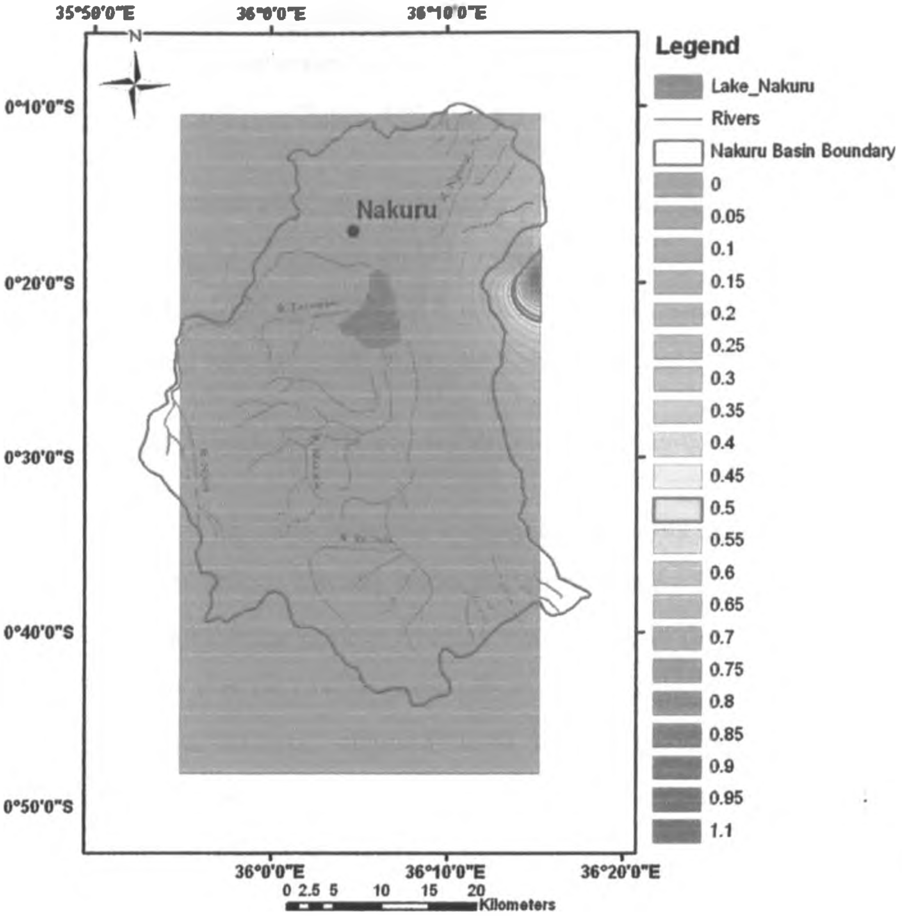


Figure 4.28 Diagrams showing manganese concentration in mg/l. NB: the red contour is iso-concentration below which below which the waters are potable and above which they are impotable according to WHO and NEMA (see Table 4.13 & 4.14)

Drinking water guideline of allowable dissolved iron concentrations for WHO is 0.3mgl^{-1} akin to those for Canada, Russia and U.S.A (FPT Committee on Drinking Water 2008, Moscow 2009, EPA USA 2006) (see Table 4.13 and 4.14). The boreholes at Ronda (0.52mgl^{-1}), Karunga (3.3mgl^{-1}) and some few boreholes at Egerton University (0.82, 0.73, 0.69 and 0.36mgl^{-1}) contain unacceptable iron concentration as stipulated by international guidelines on the limits of drinking water.

Mn^{2+} presents comparable lower amount of dissolved ions showing values ranging from $0.001mgl^{-1}$ to $1.5mgl^{-1}$ with an average of $0.16mgl^{-1}$ slightly higher than Lake Nakuru ($0.02mgl^{-1}$). Akin to iron, manganese ions are higher in rivers, peaking in River Njoro, at the slaughter house. Mechanical weathering seems to play a considerable part in the concentration of manganese ions in rivers. However, some boreholes also were observed to have high manganese content, as high as 1.1mg/l (see Table 4.13 and 4.14).

WHO recommends concentrations <0.5, making Karunga borehole waters (1.1mg/l) not potable. However, the limit of 0.05 recommended by Canada, EU and U.S.A (FPT Committee on Drinking Water 2008, Moscow 2009, EPA USA 2006) increases the number of samples with unallowable manganese ions concentration (see Table 4.13 and 4.14).

4.4.5.8 pH and Total Alkalinity ($HCO_3^- + CO_3^-$)

The pH is an important variable in water quality assessments as it influences many biological and chemical processes within a water body and all processes associated with water supply and treatment. The pH values differ greatly from as low as 6.33 at the borehole in Ngorika to as high as 9.23 in the borehole at BIDCO Company adjacent to Nakuru Tanners, 9.03. The collected lake sample shows a representative pH value of 10.49. In average, river pH (7.65) is lower relative to borehole value (8.10). Baharini springs registered an average value of 8.56 comparable to Ngorika springs showed a value of 7.39.

pH values recommended for drinking has a limit of between 6.5 to 8.5 (for NEMA, USA, EU and Canada) and 6.0 to 9.0 (for Russia). However, WHO recommends value of pH < 8. Some samples containing elevated values above the recommended include; Ronda, Nakuru Tanners, Pyrethrum Board, Soysambu, Bontana, BIDCO, AGRI, Eveready, Windmill, Njoro Country Club and Ngayoyi boreholes, along with Baharini springs. Ngorika springs in Bahati, however, gave pH value of 6.33, lower than recommended.

The presence of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) influences the hardness and alkalinity of water. The weathering of rocks contributes carbonate and bicarbonate salts. In areas of non-carbonate rocks, the CO_3^{2-} and HCO_3^- originate entirely from atmosphere and soil CO_2, whereas in areas of carbonate rocks, the rock itself contributes approximately 50% of the carbonate and bicarbonate present (WHO 2008). The relative proportion of carbonate, bicarbonates and carbonic acid in pure water is related to the pH. Carbonate was not common in the waters as it rarely exceeded pH of 9 to allow its dissolution.

4.4.5.2 Conductivity and Total Dissolved Solids

The variation in conductivity in the data gives a quick description of the dissolved solutes. A wide range of conductivity values beginning from 96.8µS in river Gilgil, soaring as high as 3,420µS at Lower Ronda BH. The lake registers unmatched 99,700µS. The mean river and borehole conductivity value is 787µS. The boreholes adjacent to the lake demonstrated by Soysambu, BIDCO, Nakuru Tanners, Lower Ronda and Pyrethrum Board, have lofty values. The high values associated to River Njoro; at the sewage discharge point is directly linked to the anthropogenic aspects and not geological.

The total dissolved solids limits prescribed by WHO and Russian drinking water proposed guidelines is 1000mg/l and only the boreholeat Ronda gives higher values. However, according to Canada and USA drinking water requirements, TDS content above 500mg/l is termed impotable. In this case, waters from Pyrethrum Board, Nakuru Tanners, BIDCO and Soysambu, in addition, can also be termed not potable.

CHAPTER FIVE

5.0 SYNTHESIS AND DISCUSSIONS

5.1 Introduction

The position of Lake Nakuru basin is within an area characterized by a complex tectonic activity associated with a rift triple junction centered at Menengai caldera that marks northern flank. This is at the zone where the Nyanza rift joins the main Kenya rift. A large area around the caldera is covered by mainly lava and pyroclastics that erupted from volcanic centers associated with Menengai volcano. As indicated by the results presented, the structural and geological settings of this basin seem to immensely influence the hydrogeology, groundwater geochemistry and aquifer stratigraphy and distribution. As observed,the main structures are elongated N-S along the rift, and one flanked on the northeast and west by Bahati hills and Mau escarpments respectively. Volcanic features (Menengai and Eburru) flank both the north and south of the basin.

Heterogeneity of aquifers in the basin is related to the spatial variability of subsurface geological materials and structures. These heterogeneities are linked to the physical properties of the material associated with flow pattern and solute transport. Such heterogeneities can as well result from chemical properties produced by distribution of geological material associated with chemical reactions and mobility of chemical elements.

5.2 Aquifer Stratigraphy

The 33 drillers logs used in aquifer stratigraphy analysis were used basically to decipher the general distribution and types of aquifer existing within the study area. The main objective was to understand how groundwater aquifers in the study area vary in space. However, some of the areas were not represented especially the southern part of Lake Nakuru due to absence of drillers logs in this region. Important aspects that were considered included borehole depth, water strike and water rest levels.

The three subsections discussed (lowlands, midlands and highland), reveals that aquifers in the region are erratically spread with no consistent propensity and are characterized by single to multiple layered (i.e. shallow, intermediate and deep aquifer) systems. These uneven aquifer systems, sometimes forming patches, are normally distinctive to volcanic settings similar to the one seen in the study area. The alternating layers of volcanic emplacement, lava and pyroclastics from diverse volcanic centers seem to be the major reason behind the complex distributions of local aquifers.

The cap-rock enveloping these aquifers also varies and thus the pressure contained within. This is seen by observing the variation between the water struck and rest levels. Some boreholes displayed scenarios where water rest levels assume a depth shallower than water strike levels. This is again characteristic of such volcanic system especially where the recharge areas is on a higher elevation and almost certainly controlled by geological structures. Such boreholes assume an almost artesian flow which may as well be as a result of overburdening by loose cap-rock materials. However, some of the structures act as channels in which pressure transpires to the surface and hence most borehole dug in such areas have their water rest and strike levels almost in the same levels or rather the former drops due to excess withdrawal of water.

5.3 Aquifer Lithology, Mineralogy and Geochemistry

Aquifer lithologies were determined by the help of driller's logs in correlation with lithological studies carried out by previous researchers. The reason was to assess the potential lithology (and geochemistry) poses in influencing hydrogeochemistry. As a result, four types of aquifers matrix have been identified to dominate; sediments (including volcanosediments), trachyte and tuffs. From a total of 33 drillers' logs analyzed, sediments forms approximately 45% of aquifer materials followed by fractured/weathered trachyte and pyroclastics (tuff) with 32% and 19% respectively. Some of the aquifer materials were not appropriately specified lithologically but owing to the description given by drillers who did the logging, they were identified accordingly.

The sources of the trachytes and pyroclastics are taken to arise from a number of volcanic centers within the basin (and elsewhere), Menengai and Eburru volcanoes being the main eruption points where most of volcanic pyroclastics and lava emplacement occurred. Most of the aquifers having trachytic matrix occur where the rock is highly weathered or relatively fractured. Such aquifers are known to be highly productive and this can be affirmed by Kabatini boreholes that yield most of the waters supplying Nakuru Municipality. Some of these fractures are believed to direct waters from as far as the edge of escarpments, channeling waters to aquifers or at some occurrences posing as local perched aquifers. Trachytic aquifers predominate in the lowland subsection according to the subdivisions created to assess lithological distributions within the basin.

Pyroclasts, mainly tuffs, were seen to compose most of the highland aquifer materials. As described by some of the earlier writers (e.g. McCall, 1967), they are taken to occur as a result of explosive eruption that lead to a huge pile of pyroclasts. Tuff, the most common pyroclasts in the area, has been utilized as building blocks and aggregates. However, the main pyroclastics hosted aquifers are characterized by highly weathered tuffs. In some areas, these rocks are well jointed and contain subsurface fractures that form the aquifer. From the drillers' logs analyses, productive aquifers are in general underlain by an impermeable rock material, for instance, weathered tuff overlying a fresh trachytic rock.

Volcanosediments are detritus constituents of lava or pyroclasts. They were noted to be contained in most of the boreholes found in the midland subsection. Most of these sediments resulted from deposition of weathered tuffs while others were paleosediments principally lacustrine in nature.

Other than a brief description given by McCall (1967) and Mboya (1993), aquifer mineralogy and geochemistry was deduced from aquifer lithology in relation to a general knowledge obtained from the available literature. The mineralogy of trachyte has been used and its chemistry and mineralogy translated to bear a resemblance to those in volcanosediments as well as pyroclastic formations. Beside trachytic formations, phonolite and basalt have been slightly mentioned. Although these latter rocks were hardly seen to occur in the aquifers, they form an important component of regional geology as described by preceding authors.

McCall (1967) and Mboya (1993) studies on oxide composition in sediments and oxide composition in the dominant rock types within the basin respectively gave a general tendency of relatively high silica oxide (SiO_2) content. This silicate laden terrain is a typical characteristic of a volcanic setting. The principal mineral components in these rocks and sediments are quartz (SiO_2), K-feldspar ($KAlSi_3O_8$), plagioclase ($NaAlSi_3O_8$) and amphiboloids (pyroxene and amphiboles).

5.4 Surface and Groundwater Geochemistry

As previously described, the chemical characteristic of an aquifer and its groundwater is a function of the mineralogy and lithology (Back & Baedecker 1989; Back *et al.* 1993). Interactions of groundwater and these lithological units within the basin have really influenced hydrogeochemistry. The significance of chemical weathering of the rock in Nakuru basin as the supply of major elements contained in water as been established in this study.

Discussions on water chemistry involve major constituents and heavy/trace elements of groundwater (deep and shallow boreholes), Lake, springs and Rivers. Statistical analyses of these data revealed that average variation of the total anions (T_{Z-}) and cations (T_{Z+}) in groundwater and surface water was negligeable attesting to the good quality of the data. However, T_{Z-} values for surface water was higher than T_{Z+} values in surface water as opposed to groundwater T_{Z-} *vs* T_{Z+} relationship which shows T_{Z+} exceeding T_{Z-}.

Two set of data was collected one of which contained major elements and the other having heavy/trace metals. As a rule of thumb, groundwaters are more mineralized than surface water apart from the lake water chemistry and Njoro River at the points entering Lake Nakuru. The latter is basically as a result of anthropogenic contribution to water chemistry.

5.4.1 Hydrochemical facies

Na-HCO_3 and Na-Cl-SO_4 water types are the two main hydrochemical facies. Approximately 60% of groundwater samples belong to Na-HCO_3 facies, and include the deep and shallow boreholes which demonstrates that Na^+ (>82% of all cations) and HCO_3^- (>77% of all anions) are the dominant cations and anions in the study area respectively. The boreholes flanking the lake belong to the second facies (Na-Cl-SO_4) and a clear evolving trend is seen where HCO_3 rich water transforms towards a more Cl-SO_4.

This characteristics are shown to translate to the later stages of most of the major rivers; Njoro, Makalia and Enderit. This may insinuate a scenario where groundwater and surface water interact, and thus the former contributing to the overall stream-flow as base-flow. These interactions and movement of water is capable of causing variations that has seen the composition of surface water chemistry tending towards those of groundwater. This hypothesis does not negate the input probably from surface water-rock interaction. Watershed weathering and erosion are of paramount importance in controlling river water chemistry. Chemical weathering of rocks and minerals determines the flux of dissolved materials carried by rivers. This makes the study of dissolved components of rivers important to characterize and quantify weathering. Water draining in each of the rock types is characterized by its own chemical signature (Meybeck 1983).

5.4.2 Rock-water interactions

About a dozen or so major hydrogeochemical processes seem to dominate the compositions of most surface and groundwaters. These probable processes include calcite dissolution and precipitation, pyrite oxidation and formation of hydrous ferric oxide, silicate mineral dissolution (feldspars, micas, chlorites, amphiboles, olivines, and pyroxenes) and clay mineral formation (kaolinitization, laterization, and illitization), dolomite dissolution, sulfate reduction and pyrite formation, silica precipitation, evaporation, and cation exchange. These processes are explained in several available textbooks (e.g., Appelo and Postma 1993; Langmuir 1997).

Source rock deduction is discussed using simple ratios and equilibrium indices. This source rock deduction process is after Hounslow (1995). Water data defined by pH of between 5 and 6 cannot be deduced with this scheme since clay minerals dissolve and release anomalously high silica. For our data with a pH ranging between 6.5 and 8.5, the technique was suitable.

The high concentration variation of major elements is mostly controlled by incongruent weathering of silicates and harmonious weathering of silicates. Weathering of carbonates is considered to be the major source of Ca^{2+} and Mg^{2+} in the aquifers, whereas HCO_3^- is produced predominantly by weathering of silicates and to some extent carbonates minerals.

$(Na^++K^+)/T_{Z+}$ ratio is an index to assess the contribution of cations via silicate weathering (Stallard & Edmund 1987). The ratio of Na^++K^+ *versus* T_{Z+} shows relative high ratio of an average of 0.93. This shows the enormous contribution and control of silicate weathering to chemistry of groundwater in the basin. For water bodies with prevailing carbonate weathering in their basins, a characteristic feature is the predominance of Ca^{2+} and Mg^{2+} cations and high $(Ca^{2+}+Mg^{2+})/(Na^++K^+)$ ratios. The $(Ca^{2+}+Mg^{2+})/ (Na^++K^+)$ molar abundance ratio in the silicate of the upper crust is 1.0 (Taylor & McLennan 1985). The milliequivalents ratio shows abundance of Na^+ and K^+ to Ca^{2+} and Mg^{2+} indicate silicate weathering, in average, controls the ionic content of the major elements.

As a result, $Na^+>Cl^-$ indicating albite solution as opposed to brine ($Na^+< Cl^-$) or rather bad analysis, the latter occurs where TDS is relatively low. The high Na^+ is confirmed by equally high HCO_3^- ions that results from the reaction of feldspar minerals with carbonic acid.

Ca^{2+} content are less than SO_4^{2-} suggesting either, removal of Ca^{2+} ions through calcite precipitation, ion exchange or pyrite oxidation.

Bicarbonate ions exceed silica content an indication that results from silicate weathering, and Ca^{2+} from anorthite and some ferromagnesian minerals. Some samples gave anomalously high HCO_3^- that exceeds SiO_2 by far. This show carbonates weathering contribution and thus Ca^{2+} comes from carbonaceous materials.

Principal component analysis (PCA) was used to decipher patterns within the hydrogeochemical data set. PCA is a data reduction technique used to simplify data sets while capturing the underlying patterns within the data. PCA involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. This helped in deducing the sources of elements in regards their groupings. From the analysis, silicate weathering displayed a huge loading relative to anthropogenic and ferromagnesian/calcite elemental sources.

5.4.3 Mineral saturation indices

These elements are noted to be undersaturated to equilibrium with aragonite, calcite, fluorite and dolomite an indication of limited weathering of rock materials to the extent that causes saturation of ions such as Mg^{2+}, F^- and Ca^{2+}. In the same manner, the concentration of heavy/trace elements in groundwater varies from undersaturated to equilibrium. Conversely, iron components are saturated to oversaturated, with hematite having a saturation index of up to 20. Samples from rivers closely resemble groundwater samples in saturation unlike lake water which is saturated with reference to most of the phases; aragonite, calcite, dolomite and fluorite, and all heavy/trace metals; goethite, $Fe(OH)_3$, hausmannite, hematite, manganite, pyrosulite and $Zn(OH)_2$.

5.4.4 Water quality assessment

5.4.4.1 Introduction

The importance of water, sanitation and hygiene for health and development has been echoed in the conclusions of a series of international policy forums. Such forums have included health-oriented conferences such as the International Conference on Primary Health Care, held in Alma-Ata, Kazakhstan (former Soviet Union), in 1978. They have also included water-oriented conferences such as the 1977 World Water Conference in Mar del Plata, Argentina, which launched the water supply and sanitation decade of 1981–1990, as well as the Millennium Development Goals adopted by the General Assembly of the United Nations (UN) in 2000 and the outcome of the Johannesburg World Summit for Sustainable Development in 2002. Most recently, the UN General Assembly declared the period from 2005 to 2015 as the International Decade for Action, "Water for Life" (WHO 2008).

In Kenya, right of entry to safe drinking-water is essential to health, a basic human right and an element of effective policy for health protection, and has been significant as a health and development issue at a national, regional and local level. Investments in water supply and sanitation has yielded a net economic benefit in most areas of the country, since the reductions in adverse health effects and health care costs prevailing over the costs of undertaking the interventions. Such involvement in improving access to safe water has favored the poor in particular, whether in rural or urban areas, and is an effective part of poverty alleviation strategies.

Results of major elements and heavy/trace metals have been presented in the previous chapter. Some of these elements have been shown to surpass the limits of the required concentrations hence unfit for human consumption. In this section a synthesis of water quality results are presented focusing chiefly on chemical composition with anomalous concentration that surpasses required standards and potentially poses adverse effect to health if human are exposed to it.

5.4.4.2 Sodium Concentrations

As shown from preceding discussions, the high Na^+ concentrations are connected to silicate weathering resulting from volcanic materials present in the aquifers. Albite is the main mineral that weathers to give Na^+ ions which dissolve in water. Other than drinking-water quality, high Na^+ ions in water affect the permeability of soil and causes infiltration problems. This is because sodium when present in the soil in exchangeable form replaces Ca^{2+} and Mg^{2+} adsorbed on the soil clays and causes dispersion of soil particles (i.e. if Ca^{2+} and Mg^{2+} are the predominant cations adsorbed on the soil exchange complex, the soil tends to be easily cultivated and has a permeable & granular structure). This dispersion results in breakdown of soil aggregates. The soil becomes hard and compact when dry and reduces infiltration rates of water and air into the soil affecting its structure.

5.4.4.3 Sulfate Concentrations

Sulfate is one of the major anions occurring in natural waters (Hauser 2001). It is of importance in public water supplies because of its cathartic effect upon humans when present in excessive amounts. Sulfate in water exists in equilibrium with hydrogen sulfide.

$$SO_4^{2+} \leftrightarrow H_2S$$

The direction of the equilibrium shifts depending on available oxygen in the water, and on pH (lower pH, more H_2S). Sulfate may occur in increased concentration due to industrial discharge contamination from tanneries, paper mills, and industries that use sulfates and sulfuric acid in their processes. Mine drainage wastes and acid rain can increase the sulfate concentration of the water. However, sulphates in natural waters arise from the leaching of sulphur compounds, either sulphate minerals such as gypsum or sulphide minerals such as pyrite, the appropriate cause of sulphate ions in the basin.

5.4.4.4 Dissolved oxygen concentrations

The oxygen content of natural waters varies with temperature, salinity, turbulence, the photosynthetic activity of algae and plants, and atmospheric pressure (WHO 2008). The solubility of oxygen decreases as temperature and salinity increase. Determination of DO concentrations is a fundamental part of a water quality assessment since oxygen is involved in, or influences, nearly all chemical and biological processes within water bodies. The measurement of DO can be used to indicate the degree of pollution by organic matter, the destruction of organic substances and the level of self-purification of the water, and also used in the measurement of biochemical oxygen demand (BOD).

5.4.4.5 Fluoride Concentrations

Fluoride originates from the weathering of fluoride-containing minerals and enters groundwater through direct contact. Volcanic settings of East African Rift System have been known to contain high values of F^-. However, liquid and gas emissions from certain industrial processes can also contribute fluoride ions (WHO 2008). Mobility of fluoride ions in water depends, to a large extent, on the Ca^{2-} ion content, since fluoride forms low solubility compounds with divalent cations. In most cases, the element F^- comes from the dissociation reaction of fluorite or CaF_2 (Appelo and Postma 1996):

$$CaF_2 \leftrightarrow Ca^{2+} + 2F^-$$

In essence, fluoride is an element which owes its occurrence in groundwater almost entirely to water-rock interaction, apart from an initial rainwater input concentration of approximately 0.1 mg l^{-1} (Edmunds and Shand 2008). Sources include the mineral fluorite (CaF_2) and phosphate minerals, such as fluorapatite; fluoride is also released from weathering of primary silicates such as biotite and hornblende (Edmunds and Smedley 2005).

5.4.4.6 Lead, Zinc, Chromium and Cadmium Concentrations

The assessment of metal pollution is an important aspect of most water quality programmes. The Global Environmental Monitoring System (GEMS) programme GEMS/WATER includes ten metals, among them are Pb, Zn, Cr and Cd. The US Environmental Protection Agency (US EPA), and most other countries, consider these metals as trace elements of the highest priority because of its toxicity and should be monitored where they are likely to occur. River water, other than that of the lake, is seen to have relatively high metallic concentrations.

Cadmium is an uncommon element and occurs as a trace constituent of sulphide minerals, particularly those containing Zn (e.g. sphalerite ZnS). It forms a divalent cation in solution under acidic oxidising conditions and may form a range of complex ions at higher pH. Natural concentrations in most groundwaters are limited, most likely by adsorption onto Mn or Fe oxide surfaces, although binding by organic substances may also be significant at high pH. Cadmium may also be adsorbed by calcite surfaces (Davis *et al.* 1987) or become incorporated into calcite via chemisorption. High concentrations, above 0.5 ppm, in soils are considered to be due to pollution including industrial, high-Cd phosphate fertiliser or sewage sludge applications (McBride 1994). Cadmium concentrations in study area are generally high in groundwaters with all values exceeding the recommended limits of NEMA (0.01ppm) and WHO (0.003ppm) (see Table 4.13). In humans, Cd interferes with the metabolism of Ca, vitamin D, collagen, and causes bone degenerations such as osteomalachia (or osteoporosis) (Bradl 2005).

Zn in the other hand is associated with sulphide minerals, typically those of Cu and Pb and is a trace constituent in most rocks. The most important sources of Zn in the environment are in ore deposits where it forms primary sulphide minerals such as sphalerite (ZnS) and is also released from secondary sulphate and carbonate minerals. It is relatively common in groundwaters but is strongly adsorbed on ferric hydroxides under alkaline conditions and may also bind with organic matter. For Zn, it is likely, as for other trace metals that groundwater concentrations largely represent the result of water-rock interaction. However, there are many sources of contamination including, for example, galvanized components of pumps, screens etc. The requirement limits for NEMA of acceptable Zn concentration is 1.5ppm. This renders all but one of the well samples impotable. However, those samples whose concentration exceeds WHO limits of 3ppm include Pyrethrum Board (3.08ppm), Ngorika (3.22ppm), Eveready (3.48ppm) and Ronda (3.92ppm).

Cr (III) is an essential element in animal and human nutrition. Cr (III) deficiency in humans causes impaired glucose tolerance, glycosuria, and elevations in serum insulin, cholesterol, and total triglycerides. As opposed to Cr (III), Cr (IV) is toxic. Both Cr(III) and Cr(VI) are potent human carcinogens. The major target organ for Cr(III) and Cr(VI) is the respiratory tract. Classical symptoms are perforations and ulcerations of the septum, bronchitis, decreased pulmonary function, and pneumonia. Cr is the second most skin allergen after Ni causing allergic contact dermatitis (Bradl 2005). From the data given in Table 3.13, all groundwater samples have Cr concentrations values high above the recommended WHO limits of 0.05ppm.

5.4.4.7 Nitrates and nitrites concentrations

Nitrate frequently occurs above natural baseline concentrations as a result of land use and other human impacts. Over the past century, there have been large changes to natural N cycles, mainly due to the application of fertilisers in agriculture (Edmunds and Shand 2008). Although point sources of pollution have not been clearly defined, diffuse pollution by fertilizer addition has led to significant increases in nutrient inputs with time. For instance, high concentration of nitrates noted with Ronda well discharge (36mg/l) revealed no specific point source. However, point sources are commonly observed with surface water in particular along river Njoro, for instance, at the sewerage discharge point where a concentration of 20.6mg/l was recorded.

In addition to the extensive but variable applications of fertilizer, denitrification reactions also make the determination of baseline nitrate values very difficult. Atmospheric inputs have also significantly increased in the past due to emissions from the burning of fossil fuels (Edmunds and Shand 2008); hence human impacts are present at the regional scale from recharge inputs and from the results, this has affected surface water rather than groundwater.

5.4.4.8 pH and total alkalinity

The average (median) pH varies from 6.3 to 9.2 in most aquifer types regardless of whether they are carbonate or siliclastic. This highlights the fact that only small amounts of carbonate minerals (calcite, dolomite) in an aquifer are sufficient to buffer the pH to circum-neutral values (Edmunds and Shand 2008). However, the overall acidity varies over several orders of magnitude (pH is the negative log of the hydrogen ion concentration, hence one unit increase is a tenfold decline in H^+ concentration) within many aquifers. Several aquifers contain alkaline waters that even exceed pH 9 especially areas with high $Na–HCO_3$ compositions. Many aquifers contain a small percentage of low pH groundwaters, occurring in shallow siliciclastic aquifers or within decalcified parts of the aquifer in which mobilization of trace metals such as aluminium may also be expected (Moss and Edmunds 1997; Shand *et al.* 2005).

5.4.4.9 Iron and manganese

Iron and manganese are common in aquifers both in primary minerals and as secondary oxides and oxy-hydroxides in most rock types. Primary sources of Fe and Mn include carbonates and silicates which release Fe^{2+} on weathering (Hem 1959). Both Fe and Mn are redox-sensitive elements in groundwater, being soluble in their reduced form but forming insoluble oxy-hydroxides under oxidising conditions. This is reflected in these elements having low baseline concentrations in unconfined parts of the aquifers where oxygen is present, but increasing significantly across redox boundaries.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

The general objective of this study was to try and relate aquifer stratigraphy and lithology to groundwater geochemistry. To be able to achieve this, the objective was broken down into three specific and separate areas trying to assess the stratigraphy and spatial extent of aquifers, to determine aquifer lithology (and geochemistry) and its possible influence on hydrogeochemistry, and to carry out an assessment of groundwater quality. Achieving these specific objectives has led to realization of the broad objective.

As indicated by the driller's logs, three main types of aquifer matrix dominate; sediments, trachyte and pyroclastics. Sediments form the highest proportion of aquifer materials analysed as indicated in the driller's logs and consisted of largely volcanosediments, gravels and sands. The other dominant materials are fractured and weathered trachyte, and pyroclastics (primarily tuffs). Distribution of aquifers is generally erratic in the area due to geological and geo-structural complexity. For the sake of this study the aquifers were loosely categorized basing on the aquifer matrix and the depth; i.e., either shallow or deep aquifers, or trachytic, volcanosediment and pyroclastics containing aquifers.

Aquifer settings within Lake Nakuru Basin are for the most part multilithological, comprising trachytes, basalts, phonolites, tuffs and volcano-sediments. Hence their significance in groundwater chemistry should not be underrated. Chemical weathering of such aquifers would supply major ions to solution from all these lithologies. Rocks and minerals weathering in a watershed are of paramount importance in controlling groundwater chemistry. The process of chemical weathering determines the flux of dissolved materials transported in aquifers and ultimately contained in boreholes. The main source of major elements and ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO^{2-}_3, and Cl^{-}) to the groundwater environment is due to weathering in the aquifer lithologies. The high concentration of major elements in the basin is mostly controlled by incongruent weathering of silicates and congruent weathering of carbonates. Weathering of carbonates is considered to be the major source of Ca^{2+} and Mg^{2+} in the water, whereas HCO^{-}_3 is produced by weathering of silicate and carbonate minerals.

Geomorphology tends to play a significant role in the general chemistry of the basin. The two geomorphological features; Menengai Crater and Lake Nakuru have greatly influenced the distribution of certain chemical elements in the basin. Since major portions of all the rivers as portrayed by R. Njoro pass through fairly populated areas, an increase of dissolved solid concentrations in the downstream direction may simply reflect human interference with the natural geochemical cycle (Subramanian 1979). As the river flow through areas affected by tectonics, the groundwater may therefore be more prone to contamination from surface drainage.

Broadly speaking, the desire for pure and wholesome water is deeply rooted in our culture evident from the reverence accorded to springs and underground water as a source of pure water. This has proved with time that though groundwater is relatively clean, it is also prone to pollution, and to define whether groundwater quality is natural or has been affected, to a greater or a less significant extent, by human activity or geological processes is one of the difficult challenges in hydrogeology, and this is one of the milestones that this study attempted to arrive at. From the examination of both groundwater and surface water chemical composition, anthropogenic sources of pollution have remarkably affected surface water as opposed to groundwater. Nevertheless, the overwhelming origin of major ions in groundwater is derived from the reactions between water and rock, as indicated by the results of the study.

These hydrogeochemical findings discussed have been weighed against the guidelines for drinking water as provided by NEMA and WHO, as well as other international recognized bodies. The primary purpose of observing such guidelines for drinking-water quality is the protection of public health. As it is apparent, water is crucial to uphold life, and a satisfactory supply, must be accessible to all. Improving access to safe drinking-water can result in tangible benefits to health. Every effort should be made to achieve a drinking-water quality as safe as possible. This aspect of water quality is indispensable to meet appropriateness of water usage purposes or the control of defined impacts on pollution, whether used for irrigation, drinking, and industrial uses, among others.

The stakeholders to the study area should embrace a holistic approach to drinking-water supply risk assessment and risk management in order to increase confidence in the safety of drinking-water. This approach should entail systematic assessment of risks throughout drinking-water supply – from the catchment and its source to the consumer – and identification of the ways in which these risks can be managed, including methods to ensure that control measures are working effectively. This will incorporate strategies to deal with day-to-day management of water quality, including upsets and failures.

Roles and responsibilities in drinking-water safety management of stakeholders need to be carefully observed. Preventive management is the ideal approach to drinking-water protection and should take account of the characteristics of the drinking-water supply from catchment and other sources to its utilization by consumers. As many aspects of drinking-water quality management are often outside the direct responsibility of the water supplier, it is essential that a joint multiagency approach be adopted to make sure that agencies with accountability for specific areas within the water cycle are involved in the management of water quality.

Currently in the study area, a number of agencies responsible for water quality exist and they target areas concerning water supply, sewerage system, industrial effluent, rivers and the lake. These agencies have clear objectives for water quality monitoring: NAWASSCO is responsible in checking and ascertaining the suitability of water supplied for consumption, ensuring adequate level of treatment for water supply, as well as treatment of sewerage system and monitor contamination loads flowing to Lake Nakuru; MCN is responsible in controlling and regulating industrial discharges from the factories as well as checking impacts on the operation of the sewage treatment works, groundwater quality and eventually, the lake; KWS is responsible in identifying the impact on pollutants from point and non-point sources in each river catchment and the impact to the lake as well as grasping the trend in surface water quality (State of Environment Report Nakuru, July 2009).

However, discussions with other indispensable bodies will generally be crucial for other elements of drinking-water quality management, emergency response plans and communication strategies to be fully effected. Other than the above mentioned, other stakeholders that could affect or be affected by decisions or activities of the drinking-water supplier should be encouraged to bring in their inputs and harmonize their planning and management activities where suitable. These could possibly include, for example, public health authorities, researchers, drinking water supply agencies, community management, industrial representatives, plumbers, water vendors and individual consumers. Fitting mechanisms and records should be established for each stakeholder commitment and involvement.

In order to protect public health, a dual-role approach, differentiating the roles and responsibilities of service providers from those of an authority in charge of independent oversight protective of public health, has proven to be effective elsewhere (WHO 2008). Organizational arrangements for the maintenance and improvement of drinking-water supply services should take into account the vital and complementary roles of the agency responsible for surveillance and of the water supplier. The two functions of surveillance and quality control are best performed by separate and independent entities because of the conflict of interest that arises when the two are combined. In this case, as NEMA provide a framework of targets, standards and legislation to enable and require suppliers to meet defined obligations, the agency supplying water for consumption by any means should be required to ensure and verify that the systems they administer are capable of delivering safe water and that they routinely achieve this, and in the other hand, a surveillance agency is responsible for independent (external) surveillance through periodic audit of all aspects of safety and/or verification testing.

An integrated active play of roles ought to be exercised by all to ensure that water is monitored and well-managed from the catchment groundwater feeding sources, water in aquifers, water withdrawal sites (boreholes), as well as delivery to the consumer. This should accommodate equally qualitative as well as quantitative aspects. The qualitative aspect should focus on the health-based targets as provided by NEMA, whereas quantitative facets such as the rate of water withdrawal from aquifer, type of aquifer systems, source and recharge rates of water to these aquifers along with structural controls of the groundwater system within the basin. Quality changes are not only due directly to human impacts but may also be brought about indirectly by pumping that in effect changes the aquifer system hydrodynamics, and this will in the long run degrade groundwater quality integrity. In relation to this, being the chief water consuming part of the basin, the population of Nakuru Municipality and its adjoining environ is on the increase, and as a result the need to maintain a flow supplying of clean water is a responsibility that stakeholders should not overlook.

In principle, it is generally difficult to estimate the rate at which aquifers in the study area are becoming contaminated as no criteria exist for such assessment. Both natural and anthropogenic source of pollution are apparent, and although human activities such as agricultural and industrial practices in the study area may have led to water compositions which exceed drinking water standards as provided by NEMA as well as WHO, water limits have as well been breached for some of the major elements and heavy/trace elements by natural processes, the results of geochemical conditions existing in the aquifer or due to the volcanic rocks that is contained within these aquifers. As a result, natural groundwater chemistry also has been found to have concentrations that exceeds water-quality standards requirement, NEMA and WHO limits have been utilized as the baseline (natural background quality) to check on the extent of water quality degradation. Such anomalously high concentrations (comprising of most heavy/trace metals and some of the major elements) in groundwater derived from aquifer lithology have not been clearly put into appropriate consideration and remain a huge challenge to the authority concerned, posing danger to the consumer.

As a general recommendation, a more detailed follow-up exercise needs to be conducted to affirm the herein stated chemical elements that exceeds water quality requirements limit. This will help improve and refine on the defined areas having impotable waters and hence enlighten the responsible stakeholders on the risk associated with such waters and offer a probable solution where necessary. This calls on the government, non-governmental organizations, the communities and persons directly or indirectly affected to support for the well being of the consumer.

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APPENDICES

Appendix I

Simple approach to studying the hydrochemistry of the groundwater in the study area using simple comparison by Hounslow (1995)

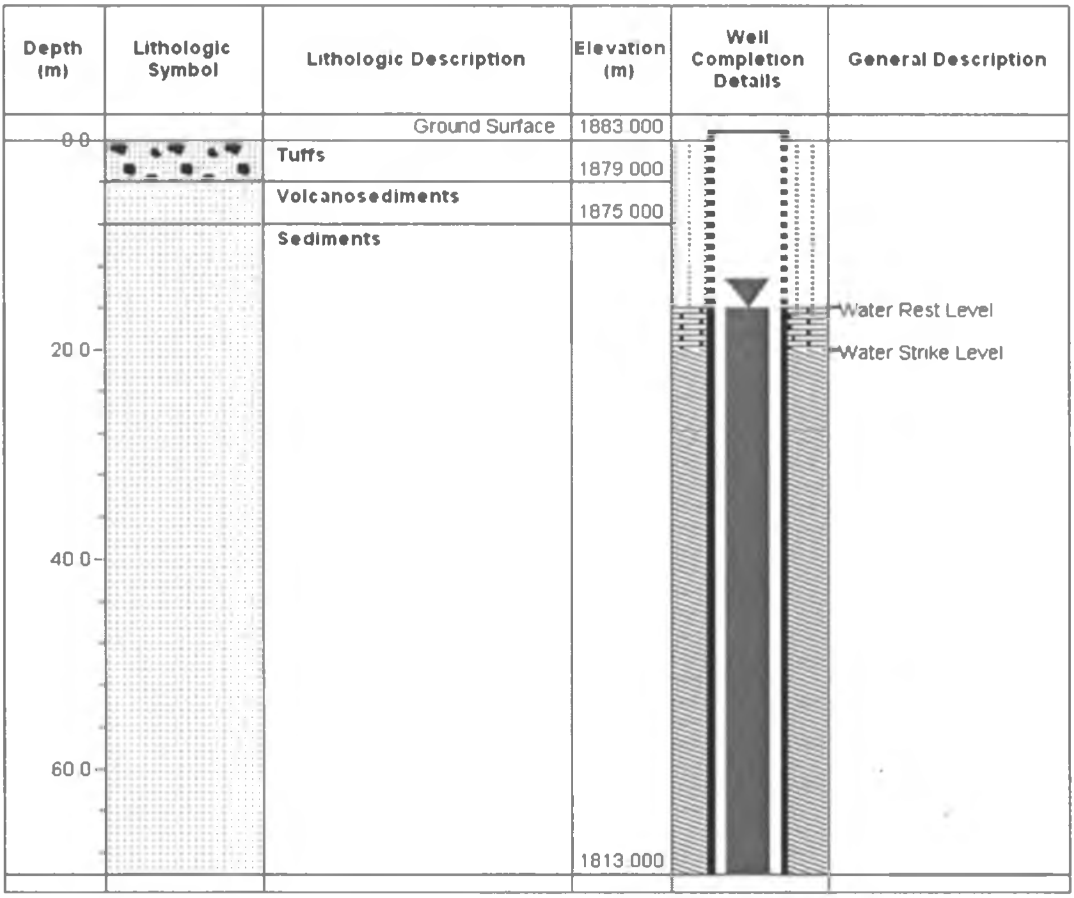
Parameter	Value (Meq/l)	Conclusion
$Na^+ + K^+ - Cl^- / Na^+ + K^+ - Cl^- + Ca^{2+}$	< 0.2 and 0.8	Plagioclase weathering possible
	> 0.2 or 0.8	Plagioclase weathering unlikely
$Na^+ / Na^+ + Cl^-$	> 0.5	***Sodium source other than halite- albite, ion exchange***
	$= 0$	Halite solution
	< 0.5 TDS > 500	Reverse softening, seawater
	< 0.5 TDS $< 500 > 50$	Analysis error
	< 0.5 TDS < 50	Rainwater
	$HCO_3^- / SiO_2 > 10$	Carbonate weathering
$Mg^{2+} / Ca^{2+} + Mg^{2+}$	$= 0.5$	Dolomite weathering
	< 0.5	Limestone-dolomite weathering
	> 0.5	Dolomite dissolution, calcite precipitation, or seawater
	$HCO_3^- / SiO_2 < 5$	Silicate weathering
$Mg^{2+} / Ca^{2+} + Mg^{2+}$	> 0.5	Ferromagnesian minerals
	< 0.5	***Granite weathering***
$Ca^{2+} / Ca^{2+} + SO_4^{2-}$	Ca2+ / Ca2+ + SO4	Gypsum dissolution
	2- = 0.5	Pyrite oxidation
	< 0.5 pH < 5.5	Calcium removal-ion exchange or calcite precipitation
	< 0.5 neutral	

	> 0.5	***Calcium source other than gypsum-carbonates or silicates***
TDS	***> 500*** ***< 500***	***Carbonate weathering or brine or seawater 2*** ***Silicate weathering***
Cl- / sum anions	> 0.8 TDS > 500 > 0.8 TDS < 100 ***< 0.8***	Seawater, or brine or evaporates Rainwater ***Rock weathering***
HCO_3^- / sum anions	***> 0.8*** < 0.8 sulphate high < 0.8 sulphate low	***Silicate or carbonate weathering*** Gypsum dissolution Seawater or brine
Langelier index 3	***Positive*** ***0*** ***Negative***	***Oversaturated with respect to calcite (54 %)*** ***Saturated/ near saturated with respect to calcite (15 %)*** ***Undersaturated with respect to calcite (31 %)***
Conclusion	***Aquifer mineralogy*** ***Reactions***	***Rhyolitic composition suggested; high silica suggest volcanic origin*** ***Some ion exchange***

Appendix II

Driller's logs from 33 boreholes created using WinLog Program

Borehole No.: C-11546	**X:** 818747.22
Borehole Name: S.Arasa P.A.Moraa	**Y:** 9981995.28
Location: Rongai	**Altitude:** 1883m
Owner:	**Map S No.:** 118 2
Area: Rongai	**Log Sheet No.:** 1 of 1

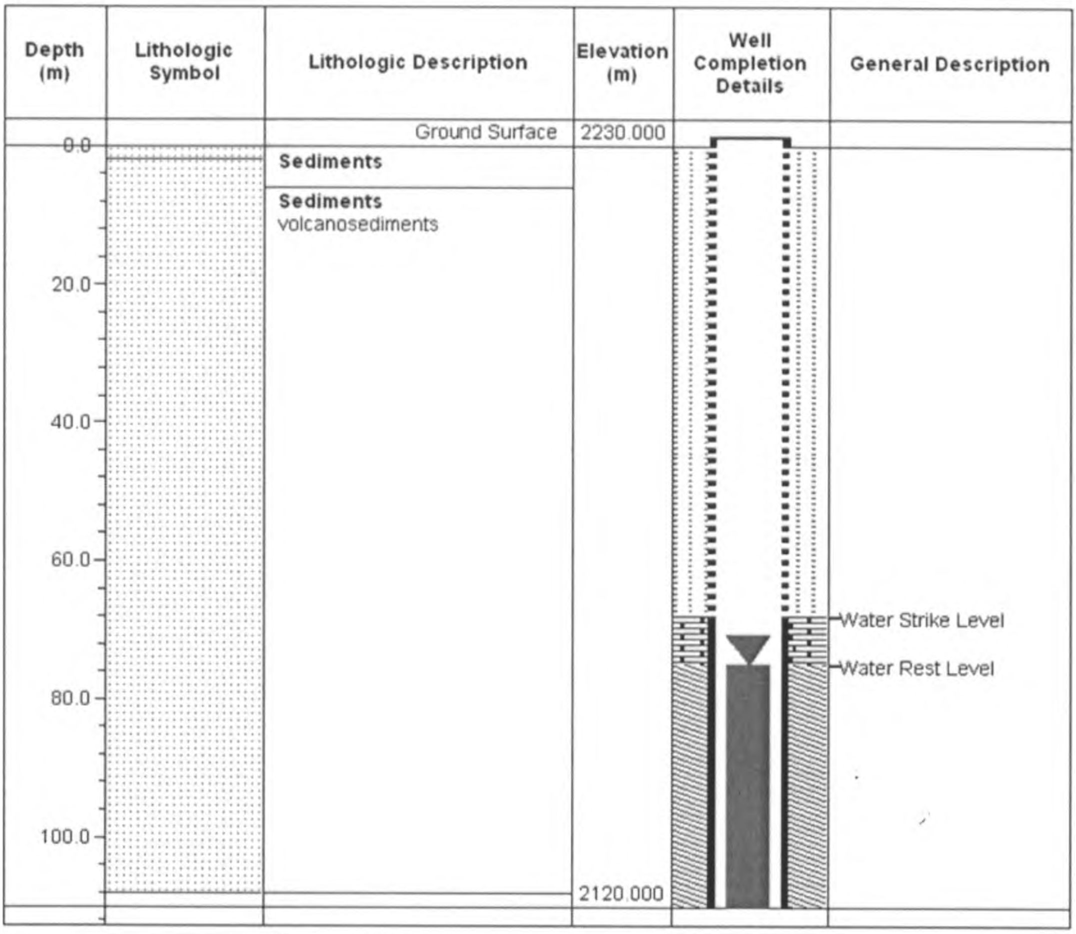


No. of Aquifers: 2	**Aquifer Material:** Clay & Fine sands.
Contractors:	**Borehole Completion Date:** 24-07-1997

Generated by:
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10270
Borehole Name: C-10270
Location: Ngorika
Owner:
Area: Nakuru

X: 859755.99
Y: 9959880.37
Altitude: 2230
Map S/No.: 119/3
Log Sheet No.: 1 of 1



No. of Aquifers: 1
Contractors:

Aquifer Material: Volcanosediments
Borehole Completion Date: 26-09-1993

Generated by:
Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10270

Borehole Name: C-10270

Location: Ngorika

Owner:

Area: Nakuru

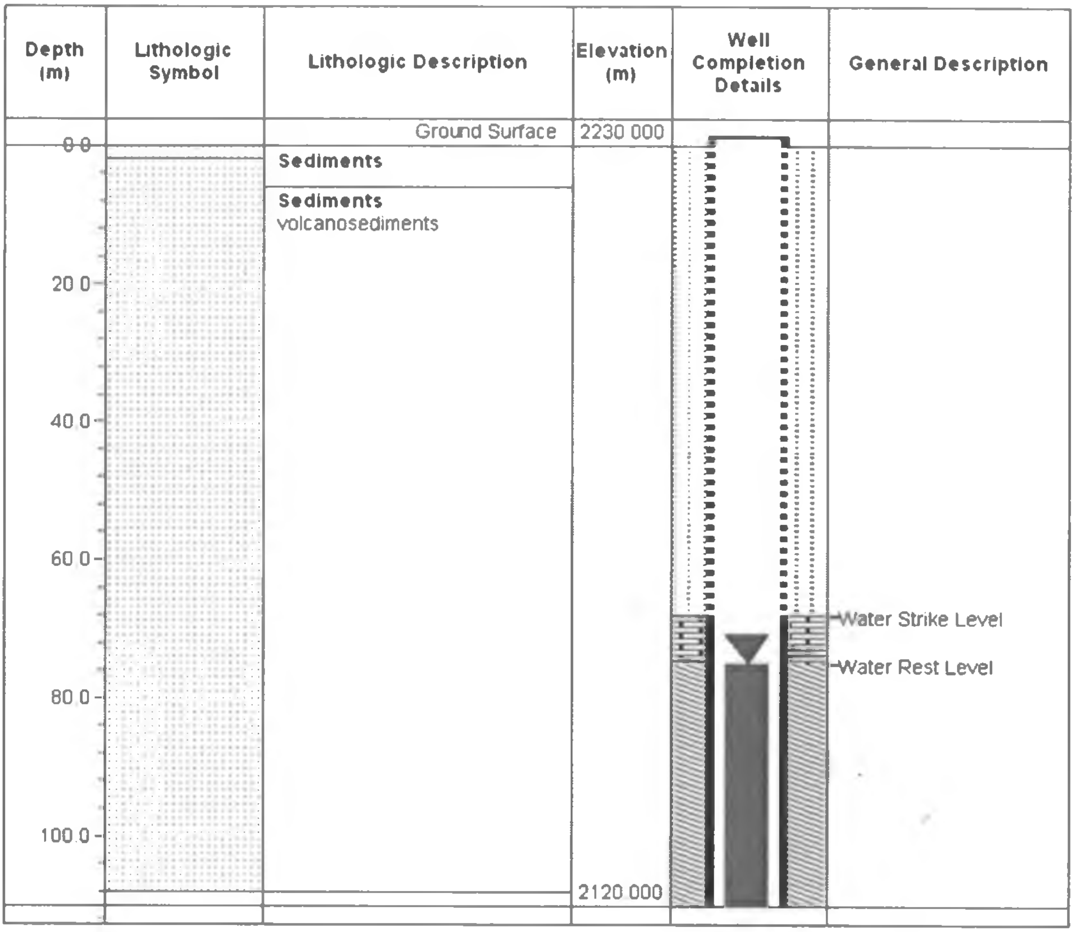
X: 859755.99

Y: 9959880.37

Altitude: 2230

Map S No.: 119 3

Log Sheet No.: 1 of 1



No. of Aquifers: 1

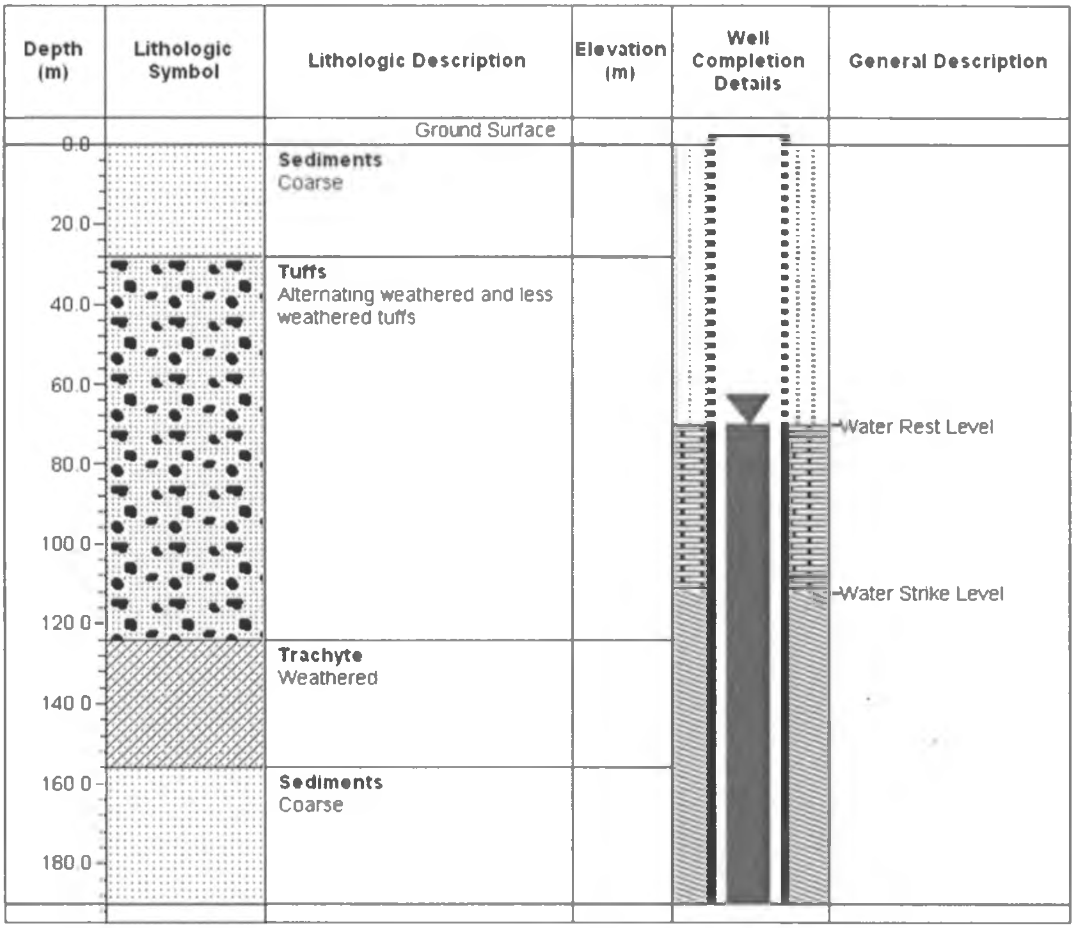
Contractors:

Aquifer Material: Volcanosediments

Borehole Completion Date: 26-09-1993

Generated by:
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10704	**X:** 827716.40
Borehole Name: Egerton co-op	**Y:** 9956417.58
Location: Njoro	**Altitude:**
Owner:	**Map S/No.:** 118/4
Area: Njoro	**Log Sheet No.:** 1 of 1

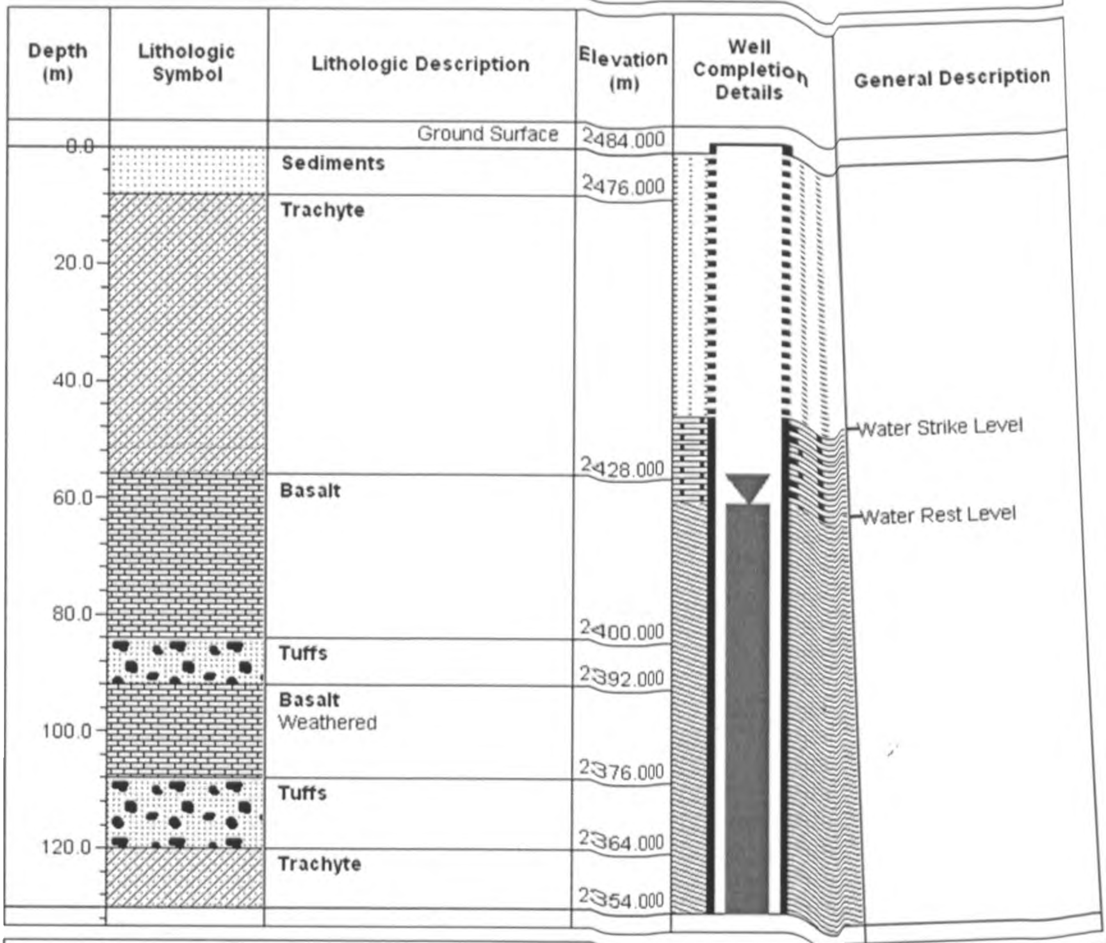


No. of Aquifers: 2	**Aquifer Material:** Weathered trachyte & Coarse vo cal
Contractors:	**Borehole Completion Date:** 31-08-1993

Generated by:
Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi.

Borehole No.: C-10719
Borehole Name: Molo Township sec.school
Location: Molo
Owner:
Area: Molo

X: 80382.00
Y: 997340.00
Altitude: 2484m
Map S No.: 118 1
Log Sheet No.: 1 of



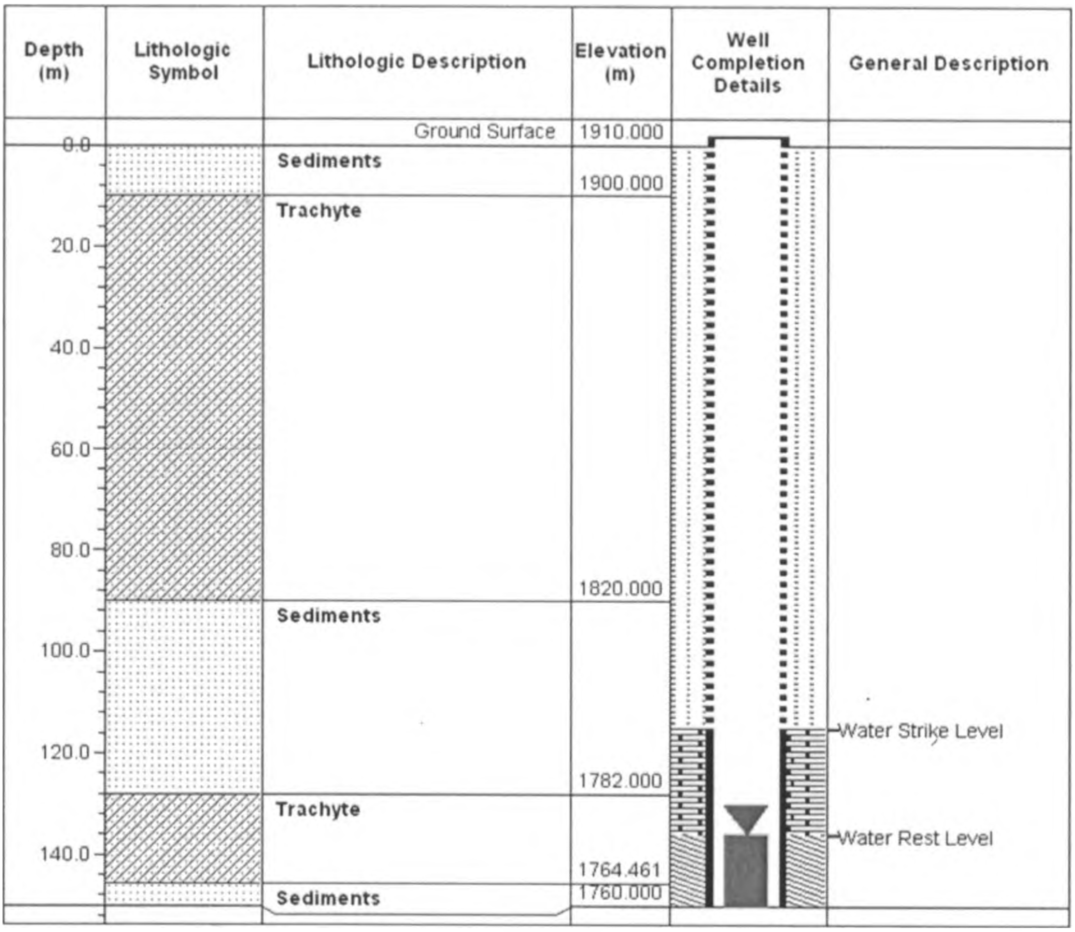
No. of Aquifers: 2
Contractors:

Aquifer Material: athered trachyte&Tuffs
Borehole Comple n Date: C-10719

Generated by:
Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10764
Borehole Name: M.H.M.N.T
Location: Lanet
Owner:
Area: Nakuru

X: 848582.16
Y: 9965587.81
Altitude: 1910m
Map S No.: 119 3
Log Sheet No.: 1 of 1



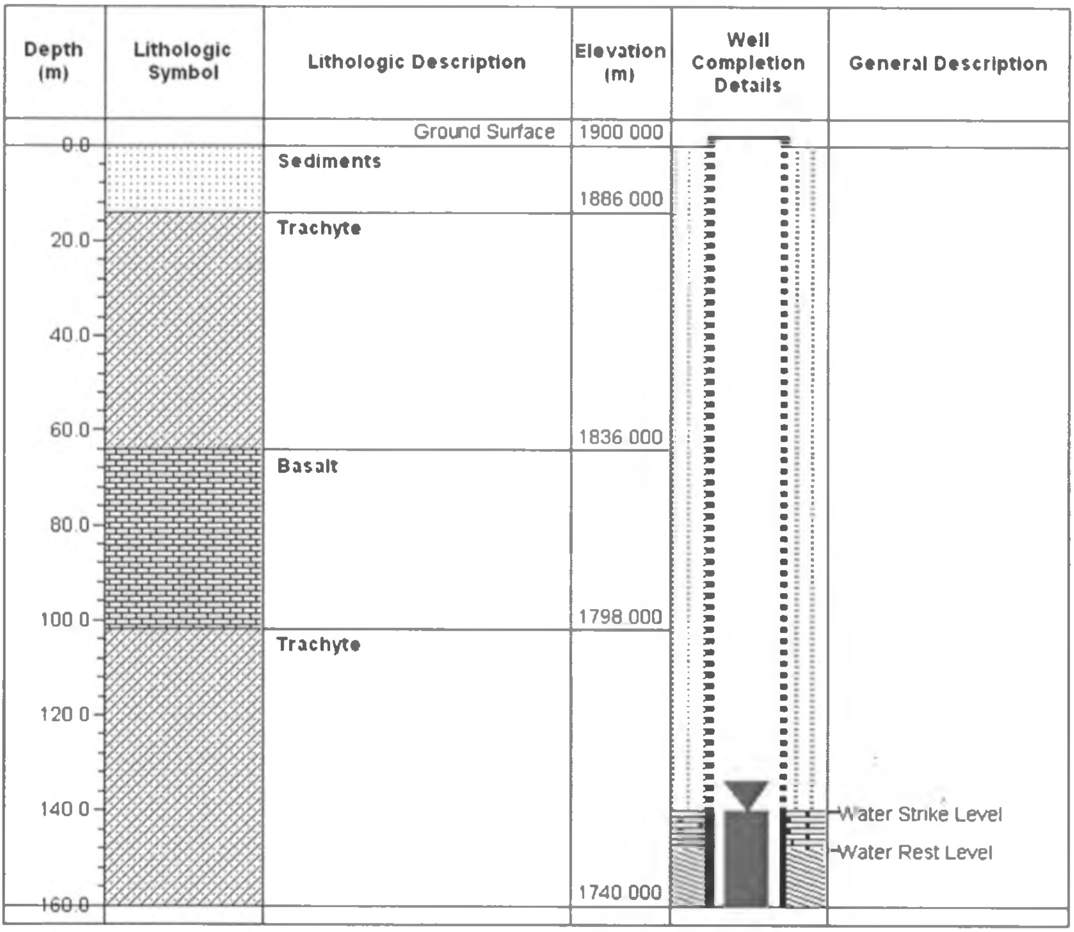
No. of Aquifers: 2
Contractors:

Aquifer Material: Fine volcano sediments
Borehole Completion Date: 20-03-1994

Generated by:
Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10812
Borehole Name: Chomu
Location: Lanet-Kiugururia
Owner:
Area: Lanet

X: 854246.05
Y: 9961880.93
Altitude: 1900m
Map S/No.: 119/3
Log Sheet No.: 1 of 1



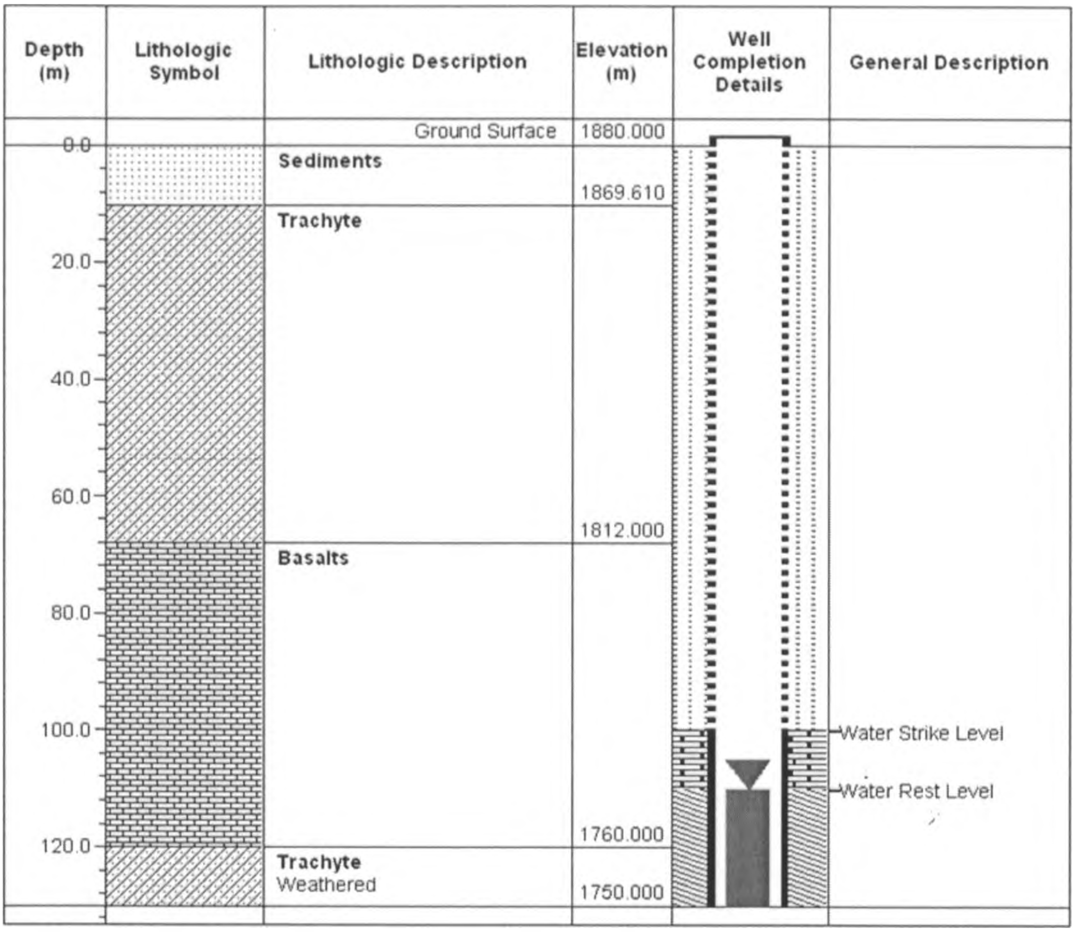
No. of Aquifers: 1
Contractors:

Aquifer Material: Trachyte
Borehole Completion Date: C-10812

Generated by:
Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10813
Borehole Name: Cdn plot Lanet
Location: Lanet
Owner:
Area: Nakuru

X: 849015.90
Y: 9967109.54
Altitude: 1880m
Map S No.: 119 3
Log Sheet No.: 1 of 1



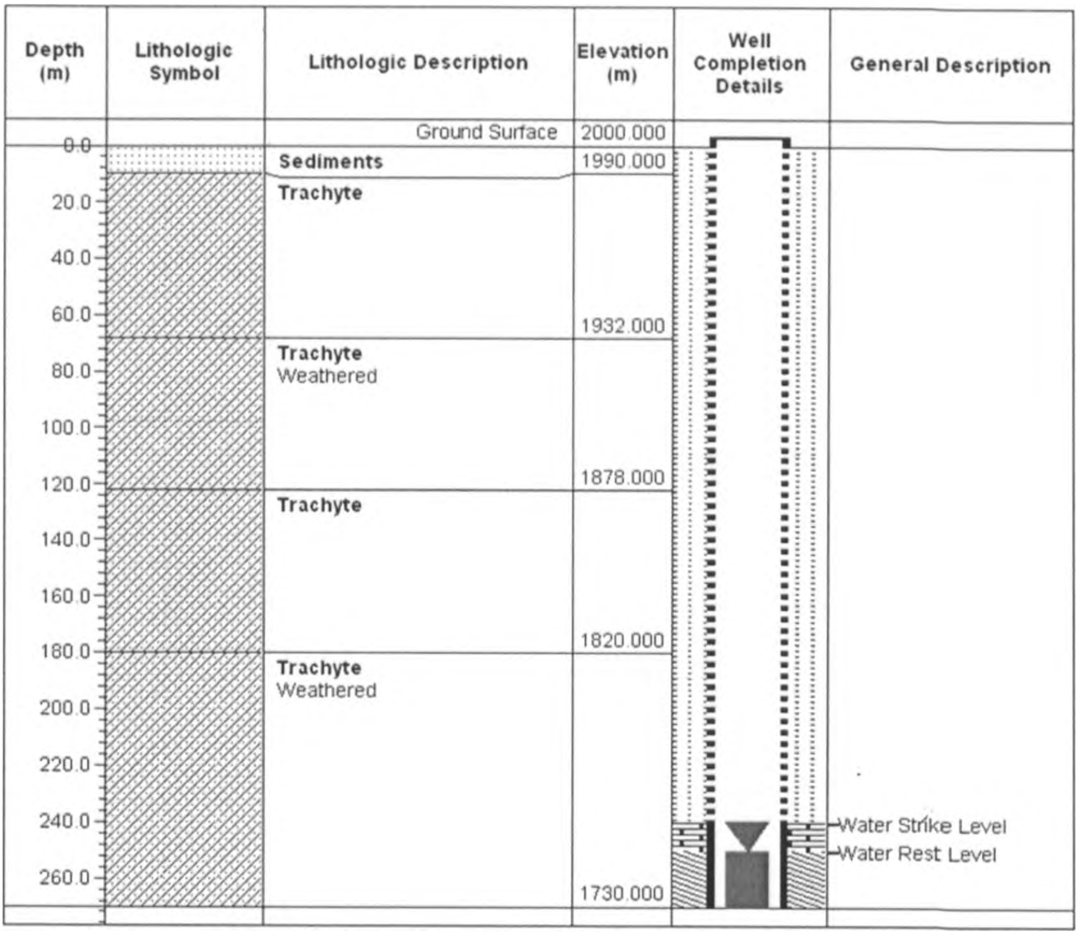
No. of Aquifers: 1
Contractors:

Aquifer Material: Weathered balastic rocks
Borehole Completion Date: 20-05-1995

Generated by:
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi

Borehole No.: C-10814
Borehole Name: Olrongai
Location: Rongai
Owner:
Area: Rongai

X: 742787.84
Y: 9979731.32
Altitude: 2000m
Map S No.: 118 2
Log Sheet No.: 1 of 1



No. of Aquifers: 1
Contractors:

Aquifer Material: Weathered brown fomations
Borehole Completion Date: C-10814

<u>*Generated by:*</u>
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi.

Borehole No.: C-11545

Borehole Name: St.Marys

Location: Kinangop

Owner:

Area: Kinangop

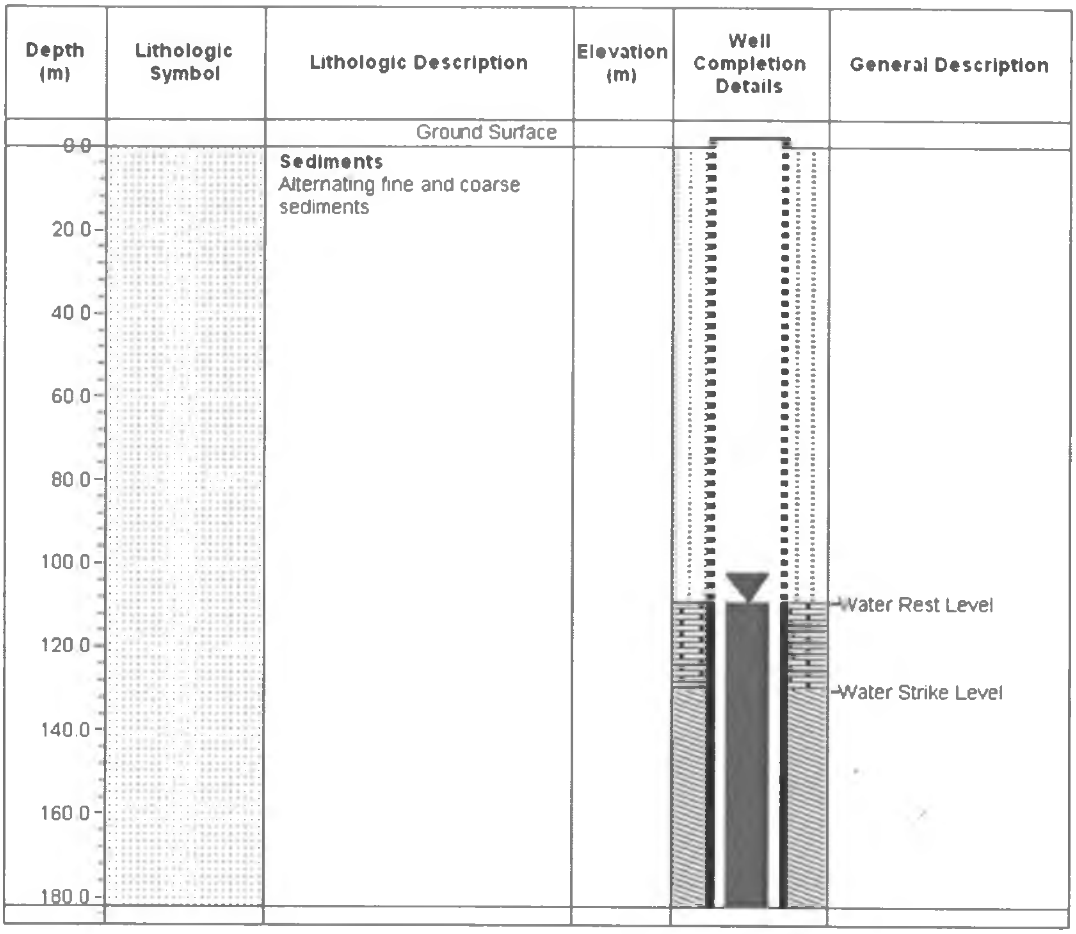
X: 72193.00

Y: 999352.00

Altitude:

Map S No.:

Log Sheet No.: 1 of 1



No. of Aquifers: 2

Contractors:

Aquifer Material: Coarse volcanoclastic seds&Volcan

Borehole Completion Date: 18-01-1997

Generated by:

Isaac Kanda, MSc student in Applied Geochemistry
University of Nairobi

Borehole No.: C-5997

Borehole Name: Kingori

Location: Olongai

Owner:

Area: Olongai

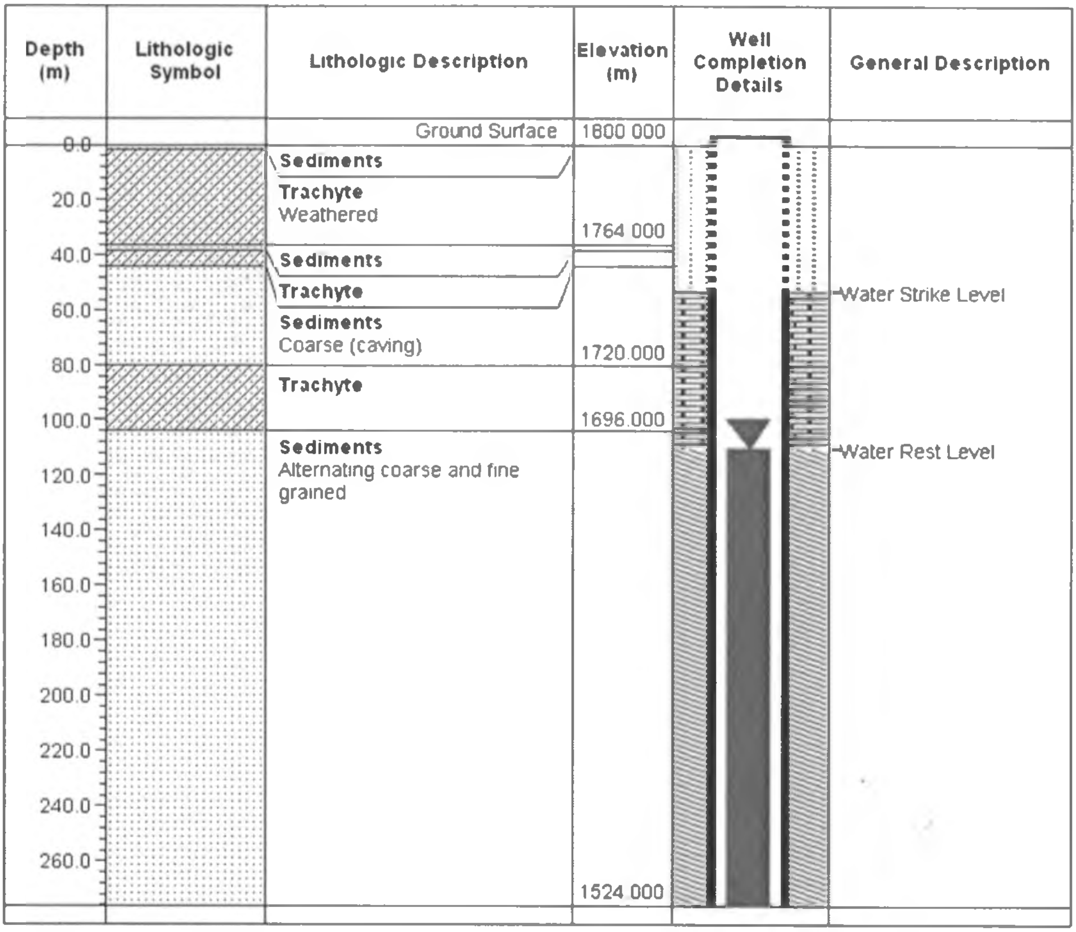
X: 837722.98

Y: 9983408.07

Altitude: 1800

Map S No.: 119/1

Log Sheet No.: 1 of 1



No. of Aquifers: 2

Contractors:

Aquifer Material: Volcanosediments. Trachyt

Borehole Completion Date: 26-07-1984

Generated by:
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi

Borehole No.: C-9672

Borehole Name: Karanja Ngugi

Location: Muguathi Koelel

Owner:

Area: Muguathi Koelel

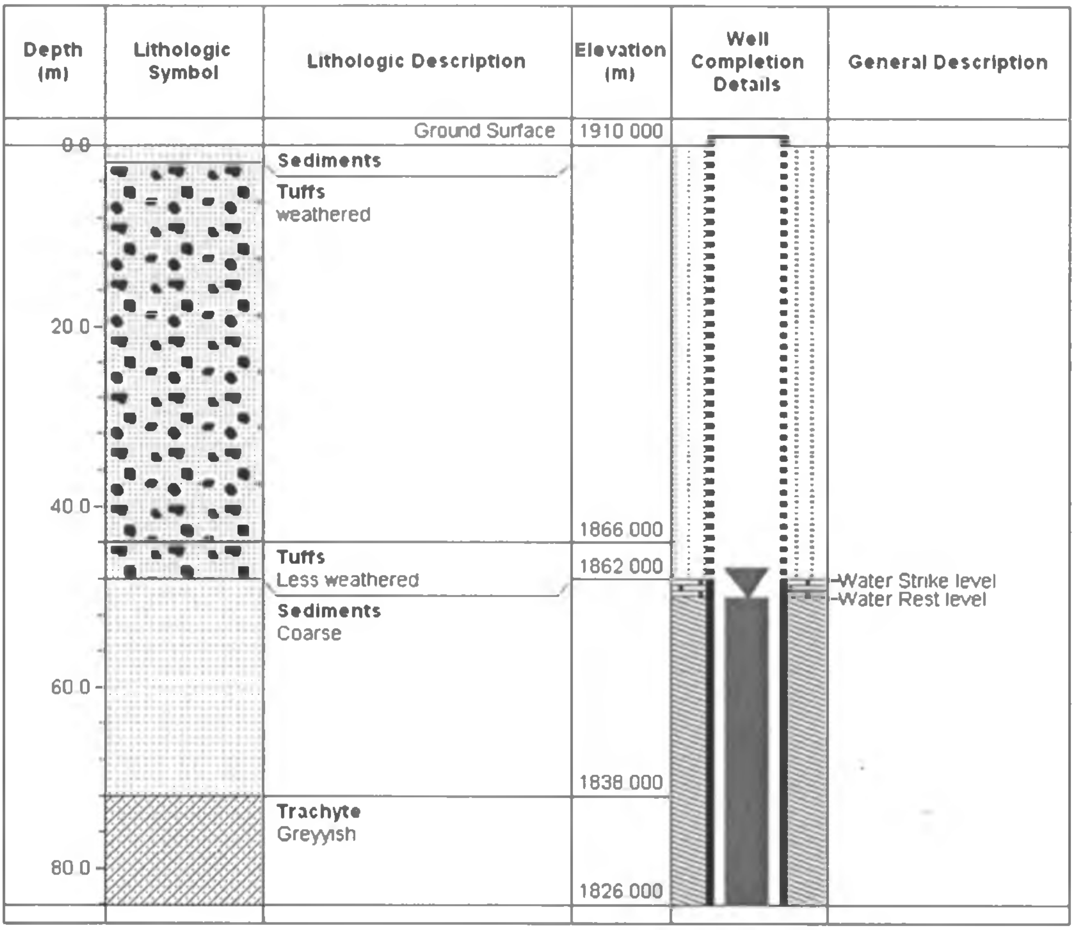
X: 851524.60

Y: 9971567.14

Altitude: 1910

Map S No.: 119/3

Log Sheet No.: 1 of 1



No. of Aquifers: 2

Contractors:

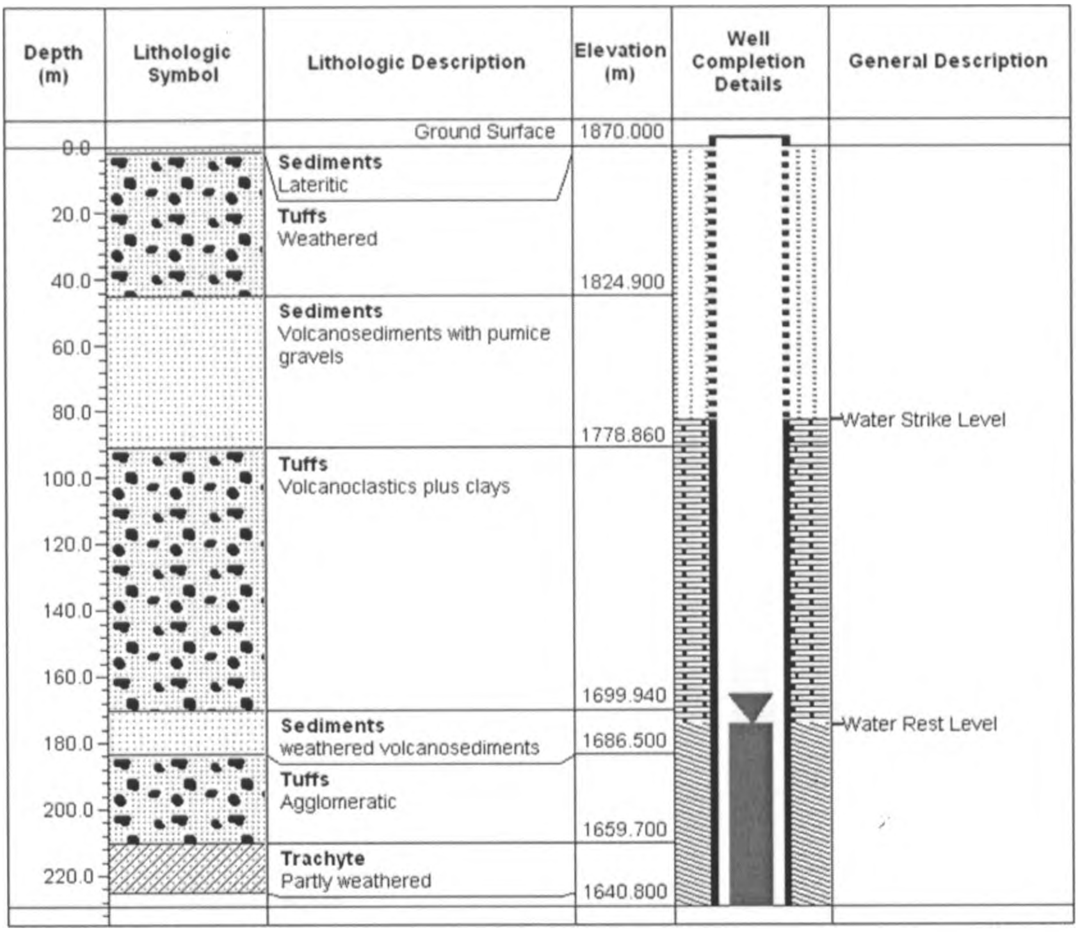
Aquifer Material: Weathered tuffs,Coarse volcanocla

Borehole Completion Date: 22-07-1991

Generated by:
Isaac Kanda, MSc. student in Applied Geochemistry
University of Nairobi

Borehole No.: C-9943
Borehole Name: Kabarak one
Location: Kabarak
Owner:
Area: Kabarak

X: 827722.98
Y: 9983408.07
Altitude: 1870m
Map S No.: 118 2
Log Sheet No.: 1 of 1



Depth (m)	Lithologic Symbol	Lithologic Description	Elevation (m)	Well Completion Details	General Description
		Ground Surface	1870.000		
		Sediments Lateritic **Tuffs** Weathered	1824.900		
		Sediments Volcanosediments with pumice gravels	1778.860		Water Strike Level
		Tuffs Volcanoclastics plus clays	1699.940		
		Sediments weathered volcanosediments	1686.500		Water Rest Level
		Tuffs Agglomeratic	1659.700		
		Trachyte Partly weathered	1640.800		

No. of Aquifers: 2
Contractors:

Aquifer Material: Tuff
Borehole Completion Date: 22-08-1991

Generated by:
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University of Nairobi

Appendix IIIA

Disequilibrium Indices calculated from major elements concentrations. Note that the red colorshows oversaturation with respect to the mineral or phase

	Anhydrite	Aragonite	Calcite	CO2(g)	Dolomite	Fluorite	Gypsum	H2(g)	H2S(g)	O2(g)	Sulfur
Kabatini BH	-3.44	-0.86	-0.72	-2.17	-1.32	-1.21	-3.22	-22.92	-68.96	-37.28	-51.92
Baharini BH7	-3.54	-0.68	-0.54	-2.01	-1.18	-1.04	-3.32	-22.74	-68.37	-37.64	-51.51
Baharini BH1	-3.63	-1.09	-0.95	-1.7	-1.68	-1.27	-3.41	-22.16	-65.41	-38.8	-49.13
Nairobi Rd	-3.56	-1.05	-0.91	-1.95	-1.72	-0.71	-3.34	-22.92	-68.66	-37.28	-51.62
Nairobi Rd	-3.64	-1.03	-0.89	-1.93	-1.57	-0.78	-3.42	-22.92	-68.75	-37.28	-51.71
Bontana Hotel	-2.92	-1.23	-1.09	-4.14	-1.83	0.49	-2.7	-25.06	-78.6	-33	-59.42
Lower Londra	-3.38	-1.42	-1.28	-2.1	-2.14	0.35	-3.16	-22.92	-68.27	-37.28	-51.23
KITI	-3.73	-1.05	-0.91	-1.79	-1.34	-0.38	-3.51	-22.92	-68.68	-37.28	-51.64
CDN	-4.09	-1.52	-1.38	-3.82	-2.17	-0.87	-3.87	-24.52	-77	-34.08	-58.36
Nairobi Rd	-3.38	-1.88	-1.74	-2.88	-3.4	-0.78	-3.16	-22.92	-68.59	-37.28	-51.55
Tabuga	-3.82	-2.14	-2	-2.95	-3.65	-2.32	-3.6	-22.6	-67.56	-37.92	-50.84
Mrs Njogu	-3.33	-1.17	-1.03	-2.6	-1.97	-0.85	-3.11	-22.92	-68.97	-37.28	-51.93
James Njoroge	-3.42	-0.92	-0.78	-2.49	-1.52	0.5	-3.2	-22.92	-69.2	-37.28	-52.16
Joseph Munui	-3.61	-0.92	-0.78	-2.6	-1.69	0.91	-3.39	-22.92	-69.5	-37.28	-52.46
Nyanjoro	-3.62	-1.22	-1.08	-3.46	-1.71	-1.06	-3.4	-23.86	-73.83	-35.4	-55.85
Muhia	-3.46	-1.96	-1.82	-3.15	-3.3	-1.98	-3.24	-22.92	-68.86	-37.28	-51.82
C.C.O	-2.68	-1.22	-1.08	-2.48	-2.29	0.01	-2.46	-22.34	-65.83	-38.44	-49.37
Egert Univ	-3.97	-1.76	-1.62	-2.76	-3.36	-1.1	-3.75	-22.92	-69.18	-37.28	-52.14
Egert Univ	-4.15	-1.84	-1.7	-3.22	-2.7	-1.29	-3.93	-23.72	-72.93	-35.68	-55.09
Egert Univ	-3.9	-1.72	-1.58	-3.39	-2.87	-1.02	-3.68	-23.74	-73.07	-35.64	-55.21
Egert Univ	-3.59	-1.69	-1.55	-2.87	-2.92	-0.85	-3.37	-22.98	-69.22	-37.16	-52.12
Egert Univ	-3.94	-2.63	-2.49	-2.4	-4.66	-1.61	-3.72	-21.76	-63.28	-39.6	-47.4
Njoro CDF	-3.97	-2	-1.86	-3.23	-3.25	-1.37	-3.75	-23.16	-70.37	-36.8	-53.09
Njoro C.Club	-4.21	-1.32	-1.18	-4.17	-1.68	-2.23	-3.99	-25.2	-80.39	-32.72	-61.07
Njoro Bridge	-3.34	-2.51	-2.37	-2.84	-4.45	-2.33	-3.12	-22	-64.21	-39.12	-48.09
Njoro pt. 3	-3.28	-1.79	-1.65	-3.53	-3.06	-2.21	-3.06	-23.36	-70.99	-36.4	-53.51
Njoro pt. 4	-3.34	-1.94	-1.8	-3.3	-3.31	-2.22	-3.12	-23.02	-69.31	-37.08	-52.17
Ingobor	-3.35	-1.68	-1.54	-2.93	-2.82	-0.79	-3.13	-22.92	-68.81	-37.28	-51.77
Njoro entry pt to lake	-2.78	0.01	0.15	-2.94	0.38	0.76	-2.56	-24.2	-75.06	-34.72	-56.74
Makalia falls	-3.21	-2.15	-2.01	-2.74	-3.94	-1.32	-2.99	-22	-64.33	-39.12	-48.21
Menengai Feedot	-3.26	-1.52	-1.38	-2.82	-2.33	-0.73	-3.04	-22.92	-68.77	-37.28	-51.73
Makiki 1	-3.24	-1.44	-1.3	-2.8	-2.31	-0.15	-3.02	-22.92	-68.81	-37.28	-51.77
Makiki 2	-3.44	-1.86	-1.72	-2.73	-3.04	0.3	-3.22	-22.92	-68.52	-37.28	-51.48
Olive Inn	-3.26	-1.81	-1.67	-2.49	-2.91	0.17	-3.04	-22.92	-68.15	-37.28	-51.11
Lion's Hill	-3.1	-1.31	-1.17	-2.93	-2.48	-0.77	-2.89	-22.92	-68.93	-37.28	-51.89
KPLC	-2.77	-1.15	-1.01	-2.89	-2.32	-0.63	-2.55	-22.92	-68.71	-37.28	-51.67
Bahati HC	-3.71	-0.96	-0.82	-2.73	-1.33	-1.3	-3.49	-23.5	-72.02	-36.12	-54.4
Nakuru Tunners	-3.09	0.61	0.75	-3.28		0.15	-2.87	-26.06	-83.75	-31	-63.57
Ngayoyi	-3.03	0.46	0.6	-3.22	1.32	0.78	-2.81	-25.04	-79.4	-33.04	-60.24
BIDCO	-3.44	0.72	0.86	-3.58	2.28	-1.61	-3.22	-26.46	-86.1	-30.2	-65.52
Windmill	-2.74	0.28	0.42	-3.23	-1.8	0.32	-2.52	-25.18	-79.49	-32.76	-60.19
Soysambu	-2.59	0.82	0.96	-2.78	1.35	0.52	-2.37	-25.14	-79.27	-32.84	-60.01
Lower Ronda	-2.92	0.48	0.62	-3.12	0.4	0.08	-2.7	-25.5	-81.05	-32.12	-61.43
Lower Ronda2	-4.15	-0.78	-0.64	-1.35	-1.46	0.05	-3.93	-22.24	-66.21	-38.64	-49.85
Ngorika	-4.19	-1.99	-1.85	-1.36	-4.41	-1.14	-3.97	-20.66	-58.73	-41.8	-43.95
Njoro Boys	-4.49	-2.64	-2.5	-1.98	-3.66	-2.4	-4.27	-21.98	-64.28	-39.16	-48.18
Nakuru Boys	-4.04	-1.12	-0.98	-2.83	-0.98	-1.38	-3.82	-24.42	-75.97	-34.28	-57.43
Karunga	-5.03	-1.25	-1.11	-2.3	-2.07	-1.15	-4.81	-22.6	-69.01	-37.92	-52.29
Ngorika	-3.62	-0.79	-0.65	-2.24	-1.99	-0.71	-3.4	-22.78	-68.72	-37.56	-51.82
Defloridation	-4.85	-1.18	-1.04	-2.71	-1.26	-1.97	-4.63	-24.2	-75.71	-34.72	-57.39

Appendix IIIB

Disequilibrium Indices calculated from heavy metal concentrations. NB: the coloured red shows oversaturation with respect to the mineral or phase.

	Fe(OH)3(a)	Goethite	H2(g)	Hausmannite	Hematite	Manganite	O2(g)	Pyrochroite	Pyrolusite	Zn(OH)2(e)
Njoro R1	3.09	8.98	24.26	6.47	19.98	3.11	34.60	5.10	7.02	0.40
Njoro R2	2.68	8.57	-24.5	-3.48	19.15	-2.08	-34.2	-4.18	-5.88	0.38
Ronda BH	2.11	8	-22.2	-16.36	18.01	-6.74	-38.6	-7.72	-11.66	-1.51
Njoro R3	3.35	9.24	-23.3	-7.76	20.49	-3.7	-36.6	-5.2	-8.1	-0.58
Njoro R4	2.91	8.8	-22.6	-9.67	19.61	-4.46	-38	-5.61	-9.21	-1.29
Njoro R5	2.93	8.82	-23.7	-4.08	19.64	-2.41	-35.8	-4.11	-6.61	-0.13
Njoro R6	2.89	8.78	-23.7	-5.79	19.58	-2.98	-35.8	-4.68	-7.18	-0.17
Njoro R7	2.67	8.56	-25	-2.3	19.12	-1.6	-33.1	-3.96	-5.14	0.62
Egert BH1	2.24	8.13	-24.4	-4.7	18.28	-2.5	-34.3	-4.56	-6.34	0.27
Egert BH2	2.81	8.7	-25.1	-2.48	19.41	-1.64	-32.9	-4.06	-5.12	0.54
Egt BH	1.69	7.58	-24.4		17.17		-34.3			0.36
Eg BH	1.14	7.03	-24.5		16.07		-34.1			0.42
Sprng	2.81	8.7	-25.1	-2.48	19.41	-1.64	-32.9	-4.06	-5.12	0.54
Nkr Boys BH	1.69	7.58	-24.4		17.17		-34.3			0.36
Egt BH	2.4	8.29	-23.5	-7.32	18.58	-3.52	-36.1	-5.14	-7.8	-0.43
Sprng	2.08	7.97	-22.8		17.95		-37.6			-1.34
Baht HC	2.09	7.98	-23.5		17.98		-36.1			-0.42
pipeline	1.93	7.82	-24.2	-8.33	17.65	-3.73	-34.6	-5.71	-7.65	0.04
Deflo	1.85	7.74	-24.2	-7.04	17.49	-3.31	-34.7	-5.27	-7.25	-0.72
Tunners	1.62	7.51	-26.1		17.04		-31			0.83
Ngayoyi	2.03	7.92	-25		17.85		-33			0.61
BIDCO	1.66	7.55	-26.5		17.11		-30.2			1.01
Windmill	2.13	8.02	-25.2	-4.57	18.04	-2.32	-32.8	-4.77	-5.77	0.56
Nkr			-24.1	-2.18		-1.71	-35	-3.6	-5.72	-0.09
Eveready	0.82	6.71	-24.8	-6.02	15.43	-2.87	-33.5	-5.14	-6.5	0.71
Pyrethrum	1.67	7.56	-25.3		17.14		-32.6			0.86
NAWASCO	1.94	7.83	-23.1	-12.99	17.66	-5.48	-37	-6.88	-9.98	-0.81
Soysambu	1.49	7.38	-25.1		16.77		-32.8			0.68
Ronda			-25.5	0.14		-0.7	-32.1	-3.31	-3.99	0.8
Ngorika	-0.37	5.52	-20.7	-19.23	13.05	-7.96	-41.8	-8.15	-13.67	-3.17
Egert BH	1.52	7.41	-22	-16.47	16.83	-6.82	-39.2	-7.67	-11.87	-2.14
Karunga	3.16	9.05	-22.6	-8.8	20.11	-4.16	-37.9	-5.32	-8.9	-1.43
Lake	2.11	8	-29	10.75	18.01	3.42	-25.2	-0.93	1.87	1.21

Appendix IV

Simple calculations used in the study for specific interpretation

SampleID	Site	Location	Sum Anions	Sum Cations	TDS (mg/l)	Cationic bal	Anions/cations	HCO3/Anions	Ca/(Ca+SO4)	(Na+K-Cl)/CNa+K-Cl+Ca)	(Ca+Mg)/SO4
SW	Lake Nakuru	Nakuru	895.35339	997.83405	39392.44531	5.413128031	0.89729689	29.89	0.00044	0.9999	0.0031
BH	L. Rhonda	Nakuru	32.01632	34.30305	1645.91492	3.448057483	0.933337415	16.30	0.05714	0.9365	0.0643
BH	Pyrethrum B	Nakuru	22.11497	25.09364	964.66193	6.30959056	0.881297811	35.86	0.00000	1.0000	0.0208
BH	Soysambu	L. Nakuru P	20.26681	22.9763	854.646	6.265714931	0.882074572	35.33	0.12874	0.9506	0.1653
BH	Nakuru Tun	Nakuru	19.29474	22.0003	797.40509	6.551779584	0.877021677	37.32	0.03168	0.9876	0.0327
Bh	BIDCO	Nakuru	14.19302	16.54157	543.87207	7.641390368	0.858021337	43.26	0.07247	0.9827	0.1888
BH	L. Ronda	Nakuru	13.06187	15.45618	476.14569	8.395770398	0.845090443	46.70	0.72180	0.9632	3.3784
BH	Everyday	Nakuru	8.68371	9.65202	409.83502	5.281000538	0.899677995	26.72	0.00000	1.0000	0.0455
RW	R. Njoro	Sew.diage pt	8.74889	10.84021	405.53378	10.67593713	0.807077538	35.43	0.28369	0.9490	0.7822
BH	Windmill T	L. Nakuru P	7.4292	8.40817	329.72	6.181392491	0.883569195	33.38	0.10042	0.9422	0.1117
Bh	Ngayoyi	Nakuru	5.16105	6.01986	220.18695	7.681038484	0.857337214	41.46	0.45478	0.8290	1.3270
BH	Nakuru Sch B	Nakuru	5.68156	6.61541	217.91803	7.594147176	0.85883717	42.95	0.01810	0.9939	0.0968
CS	Baharini spng	Nakuru	5.32757	6.22853	214.51382	7.7964019	0.855349497	42.05	0.07306	0.9650	0.4507
BH	Ainoptich	Nakuru?	4.61164	5.39754	192.14812	7.851792055	0.854396633	41.20	0.32117	0.8894	0.6828
BH	Egert. Univ	Njoro	4.87198	5.9301	159.85228	9.795520863	0.821567933	54.19	0.26667	0.9808	0.5106
BH	Njoro B. HSch	Njoro	3.41635	3.6329	158.38254	3.07195801	0.940391973	29.86	0.05970	0.9664	0.6825
BH	Karunga	Bahati	2.92993	3.76502	158.02525	12.47343147	0.778197725	33.45	0.97462	0.7225	63.6000
BH1	Egert. Univ	Njoro	3.86877	4.66979	157.173	9.381207136	0.828467661	41.36	0.03791	0.9897	0.2547
BH?	Deflorid. Pl	Nakuru	4.67722	5.60381	153.85828	9.012618386	0.834649997	53.02	0.11765	0.9931	0.5333
RW	R. Njoro	bridge aft KARI	2.98303	3.94277	153.37613	13.85746051	0.756582301	43.58	0.90762	0.8140	14.0965
BH15	Egert. Univ	Njoro	4.53686	5.53261	152.41402	9.888802489	0.820021653	53.34	0.19753	0.9871	0.3215
RW	R. Njoro	Slaughter Hse	3.03939	3.87904	151.69806	12.13642402	0.783541804	43.43	0.75353	0.8157	5.0637
BH16	Egert. Univ	Njoro	4.02203	5.07397	146.19124	11.56486368	0.792679105	54.70	0.16667	0.9926	1.7750
BH2	Egert. Univ	Njoro	4.05228	4.65635	145.02299	6.936452691	0.870269632	46.89	0.05839	0.9913	0.1744
BH12	Egert. Univ	Njoro	3.77755	4.39617	141.52786	7.568402147	0.859282057	45.53	0.05517	0.9896	0.4482
BH	Nawasco	Nakuru	3.20316	3.79751	130.45802	8.489901681	0.84348955	42.46	0.17518	0.9339	0.2562
RW	R. Njoro	after sew.disp	2.53154	3.28587	128.62265	12.966767	0.770432184	42.66	0.80899	0.8407	7.6471
CS1	Ngonka spng	Bahati H	2.82281	3.40258	120.05196	9.312990833	0.829608709	49.60	0.77670	0.7496	3.8043
BH	Bahati HC	Bahati	2.43186	3.26558	116.31475	14.63323879	0.744694664	42.77	0.41184	0.8653	1.3348
BH	Ngorika	Nakuru?	1.9249	2.55434	101.27473	14.05238389	0.753580181	47.79	0.93645	0.6410	16.0263
RW	Njoro Bridge	Njoro Vil.	2.02377	2.75176	98.3942	15.24417185	0.735445678	51.39	0.94118	0.9080	47.2000
RW	Egert. Univ	Njoro	1.98513	2.33435	87.9211	8.084769463	0.850399469	47.35	0.58323	0.8659	2.7988
RW	R. Gilgil	Marula	0.85258	1.10657	44.30116	12.96429574	0.770470915	46.92	0.95726	0.6340	26.2800
RW	R. Mbaruk	Nakuru	0.88936	1.25672	40.89787	17.11772161	0.707683494	49.47	0.76190	0.9558	10.8000

Appendix V

Some of borehole water properties calculated using AquaChem program.

Location	Site	X	Y	Z	pH	Cond (µS/cm)	TDS (mg/l)	Sum Cations	Sum Anions	Water Type	Total Hardness	Electro-Neutrality	Alkalinity (mmol)	SAR	ESR	MH
Bahati	BahtiHC	817851	9980791	2078	7.75	316	112.81	3.17	2.13	Na-HCO3	0.10	13.23	1.70	3.62	2.87	59.91
Bahati	Karunga	862578	9964003	2052	7.30	345	150.98	3.54	2.93	Na-HCO3-Cl	0.50	9.43	1.61	3.39	2.40	51.97
Bahati	Ngorik	859990	9966305	2251	6.33	230	96.56	2.44	1.92	Na-Ca-HCO3	0.48	11.90	1.51	1.88	1.36	12.61
Nakuru	AGRI	841724	9969538	1875	9.05	840	383.37	10.03	5.00	Na-Cl	0.14	33.46	1.05	23.44	31.11	85.23
Nakuru	Bahati7	847891	9966220	1830	7.37	470	194.20	5.33	4.90	Na-HCO3	0.58	4.17	3.74	4.93	3.25	36.53
Nakuru	Bahati9	847942	9966202	1831	7.17	490	207.41	5.79	4.88	Na-HCO3	0.70	8.46	3.74	4.62	2.76	57.71
Nakuru	Bahati11	847848	9966170	1828	7.08	480	197.54	5.82	4.94	Na-HCO3	0.59	8.20	3.93	5.57	3.64	55.27
Nakuru	BIDCO	839126	9968588	1875	9.23	1643	539.75	16.45	14.19	Na-HCO3	0.40	7.36	10.06	23.95	18.95	70.02
Nakuru	Bontna	841369	9968114	1846	8.53	2670	674.95	14.63	8.93	Na-SO4-Cl	0.23	24.20	0.44	27.24	28.33	63.72
Nakuru	C.C.O	852277	9970147	1935	7.17	630	271.61	7.20	2.51	Na-Ca	1.19	48.31	0.82	4.03	1.85	35.84
Nakuru	CDN	845256	9968778	1872	8.26	530	177.53	5.63	1.56	Na	0.20	56.50	0.46	10.24	11.37	74.27
Nakuru	Defload	857735	9911307	1919	8.10	334	152.63	3.39	4.67	Na-HCO3	0.12	8.91	4.07	15.09	21.90	83.18
Nakuru	Evrdy	839005	9968010	1875	8.41	954	405.40	9.54	8.68	Na-HCO3-SO4		4.72	3.80	19.38	20.75	100.00
Nakuru	Grenstd	853394	9962140	1926	7.46	610	230.46	6.78	1.77	Na Cl	0.26	58.70		10.85	10.73	75.38
Nakuru	Ingobr	836531	9963706	1940	7.46	460	185.32	5.35	1.76	Na	0.43	50.42	0.56	5.88	4.45	57.16
Nakuru	Kabatn	848942	9970879	1901	7.46	370	97.66	2.30	3.89	Na-HCO3	0.43	-25.77	3.15	1.72	1.32	49.46
Nakuru	Kamasai	838719	9960797	1861	7.46	450	171.76	5.98	2.00	Na-Cl-SO4	0.23	33.07		6.15	6.40	73.87
Nakuru	KITI	845795	9970262	1906	7.46	900	243.23	6.16	10.51	Na-HCO3	0.22	-26.06	7.87	10.31	10.91	69.27
Nakuru	KPLC	849364	9966580	1881	7.46	560	283.01	7.98	2.20	Na-Ca	0.82	56.76	0.62	6.33	3.49	27.34
Nakuru	Lion HG	848693	9965544	1886	7.46	560	211.44	5.92	1.76	Na-Ca	0.67	54.23	0.56	5.20	3.17	35.27
Nakuru	Londra	840666	9968098	1858	7.46	2880	526.80	12.78	10.14	Na-HCO3-Cl	0.19	11.53	3.93	25.69	29.41	67.05
Nakuru	Malaki1	831007	9976072	2012	7.46	670	246.36	6.32	2.28	Na	0.61	46.92	0.75	5.69	3.65	59.33
Nakuru	Malaki2	834299	9973014	2032	7.46	700	304.27	8.09	4.20	Na-Cl	0.25	31.65	0.89	13.[illegible]	13.68	66.02
Nakuru	Mfeedot	830008	9975572	2012	7.46	560	228.88	5.93	2.12	Na-Mg	0.64	47.32	0.72	5.29	3.31	66.76
Nakuru	Mogon	836457	9964607	1941	7.46	430	192.81	5.66	1.68	Na-Cl	0.47	54.23		6.24	4.57	63.78
Nakuru	Muhia's	852631	9971027	1956	7.16	260	127.30	3.25	1.25	Na-Mg-Cl	0.11	11.55	0.33	3.55	2.79	61.11
Nakuru	Ngarovi	843006	9945387	1852	8.52	593	216.84	5.95	5.16	Na-HCO3	0.87	7.09	3.51	4.37	2.35	49.35
Nakuru	NkrBSc	844676	9969076	2174	8.21	649	214.30	6.53	5.68	Na-HCO3	0.16	6.92	4.00	15.23	19.05	87.51
Nakuru	NkrTunn	840259	9966838	1812	9.03	2190	794.20	21.93	19.29	Na-HCO3		6.40	11.80	61.97	89.53	0.00
Nakuru	NrbRd4	844807	9968737	1885	7.46	570	199.36	6.56	6.76	Na-HCO3	0.21	-1.47	5.64	12.05	13.24	54.67
Nakuru	NRBRd5	844809	9968748	1885	7.46	580	258.72	7.56	2.62	Na-Cl	0.21	48.62	0.62	13.84	15.09	47.49
Nakuru	NrbRd6	844780	9968751	1885	7.46	580	211.46	6.67	6.80	Na-HCO3	0.18	-0.99	5.41	13.43	15.72	48.64
Nakuru	Nyanjor	853977	9969648	1958	7.93	540	176.69	5.71	1.14	Na-Mg	0.64	66.63	0.49	5.33	3.33	68.11
Nakuru	Nyoike	853288	9970026	1950	6.64	300	126.42	3.96	0.99	Na-Mg-Cl	0.48	59.98		3.90	2.82	57.31
Nakuru	OliveIn	837910	9970320	1936	7.46	1300	469.18	11.20	6.94	Na-Cl-SO4	0.19	23.44	1.57	22.35	25.63	67.97
Nakuru	Pyrthrm	840293	9970170	1875	8.64	2500	960.53	25.00	22.11	Na-HCO3-SO4		6.12	13.00	48.89	50.04	100.00
Nakuru	Rasul	848696	9966368	1882			121.15	4.03	0.93	Na-Ca-Mg-Cl	0.74	62.41		2.63	1.52	41.98
Nakuru	Ronda	840029	9965047	1811	8.75	3420	1642.49	34.23	32.02	Na-Cl-HCO3	0.22	3.34	8.56	70.98	75.71	9.17
Nakuru	Ronda2	840029	9965047	1811	7.12	1528	470.92	15.32	13.06	Na HCO3	0.36	7.95	10.00	24.11	20.12	33.25
Nakuru	Soysmbu	848029	9950092	1875	8.57	2290	850.95	22.90	20.27	Na-HCO3-Cl	0.50	6.11	11.74	30.10	21.25	16.41
Nakuru	Tabuga	853441	9971005	1992	7.30	220	117.33	3.32	0.90	Na-Mg	0.35	57.19	0.36	4.05	3.43	61.93
Nakuru	Wararu	853441	9970807	1960	6.92	360	171.82	5.12	1.15	Na	0.58	63.22	0.43	4.44	2.91	50.46
Nakuru	Windml	841865	9950316	2442	8.59	834	327.51	8.35	7.43	Na-HCO3-SO4	0.24	5.84	4.07	15.23	15.55	0.17
Njoro	Egert1	826284	9958922	2267	6.88	440	178.00	5.80	1.40	Na	0.22	61.13	0.49	10.32	10.92	61.06
Njoro	Egert11	825297	9958576	2298	7.26	440	176.64	5.87	1.02	Na	0.18	70.44		11.84	14.00	81.98
Njoro	Egert12	827508	9958494	2250	7.87	410	189.77	6.22	1.55	Na	0.18	60.02	0.49	12.32	14.42	59.27
Njoro	Egert15	824478	9959678	2274	7.49	450	201.73	6.64	1.74	Na	0.30	58.38	0.69	10.31	9.48	53.64
Njoro	Egert1	825448	9958558	2292	7.86	520	172.10	5.53	1.81	Na	0.19	50.68	0.72	10.88	12.63	78.99
Njoro	Egert2	825742	9959088	2278	7.46	440	202.50	6.78	1.10	Na	0.20	72.01		12.88	14.44	81.30
Njoro	Egert3	825490	9958912	2304	7.46	390	183.35	6.14	1.02	Na	0.13	71.57		14.51	19.83	76.87
Njoro	Egert6a	825297	9958576	2308	7.16	510	180.79	6.16	1.15	Na-HCO3	0.16	63.11	0.82	11.05	17.15	35.79
Njoro	Egert6b	825297	9958576	2308	7.46	570	187.96	6.54	1.57	Na-HCO3	0.19	61.40	0.82	12.63	14.32	66.00
Njoro	NjorBSc	827564	9963245	2174	6.99	351	155.68	3.57	3.42	Na-HCO3-Cl	0.34	2.24	1.67	4.47	3.83	94.14
Njoro	NjorCDF	827152	9963910	2210	7.58	290	154.77	4.75	1.02	Na	0.32	64.50	0.36	6.73	5.98	68.77
Njoro	NjoroCC	827197	9962132	2160	8.60	340	146.33	4.73	1.30	Na	0.17	57.00	0.46	9.59	11.49	78.21