THE OCCURRENCE OF HIGH FLUORIDE IN GROUNDWATER AND ITS HEALTH IMPLICATIONS IN NAKURU COUNTY IN THE KENYAN RIFT VALLEY

By

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ABSTRACT

Most semi-urban and rural communities in developing countries rely on groundwater for their daily domestic supply. Unfortunately, contamination from the local geology can render the often only source of water unhealthy for consumption. Such case is in Nakuru County in the Central Kenyan Rift Valley where high fluoride in groundwater causes dental and skeletal fluorosis. Public water supply by the government in the area has been faced with many challenges such as insufficient water for the increasing population, deterioration of infrastructure, and poor maintenance and only 36% of the households are reported to have access to piped water. As a result, most of the local population relies on private and community owned boreholes. Despite the known high fluoride in groundwater, its concentrations in the local aquifers is not yet known.

The aim of this study was to identify fluoride concentrations and distributions in the Nakuru aquifers and its correlation to the status of dental fluorosis affecting the local population. Water-quality data from 32 boreholes acquired from the Catholic Diocese of Nakuru-Water program (CDN), a water service organization in Nakuru, were used to determine fluoride's correlation and association with the physico-chemical parameters in groundwater and how they influence its concentrations and spatial distribution in the local aquifers. The prevalence and severity of dental fluorosis in the local population was investigated in 170 patients from two dental clinics in the area and correlated to fluoride distribution. All the data were statistically and spatially analyzed.

The results show a sodium-bicarbonate and slightly sodium-bicarbonate-chloride groundwater type in the area dominated by sodium, fluoride, chloride, sulphate, bicarbonate, TDS, pH, borehole depth, water hardness, and calcium, which where the principal parameters. More than 86% of the boreholes had fluoride levels higher than the WHO recommended value of 1.5 mg/l for safe drinking water. Fluoride levels ranged from 0.5 to 72 mg/l with a mean of 11.08 mg/l and had a strong positive correlation with most of the principal parameters except calcium, borehole depth, and water hardness, which had a weak negative correlation. The strong positive correlations between fluoride and the dominant parameters suggest that mineral dissolution and evaporative

enrichment might be the main processes of fluoride release and concentration in groundwater. Spatial analysis showed a cluster distribution of fluoride in groundwater where the hotspot is found in the central part of the rift floor. Spatial distribution of fluoride was not confined to the type of aquifers, but rather to the location of the aquifers. Aquifers in the rift floor had relatively higher fluoride concentrations than aquifers close to or in the Bahati escarpment in the north-east, and Mau escarpment in the south-west. Low concentrations in the elevated escarpments are due to dilution of groundwater from the high rainfall in these recharge zones, and little water-rock reaction time. Groundwater accumulates dissolved solutes as it flows from the escarpments, dumping the solutes into aquifers in the rift floor, resulting to high fluoride, which is further elevated by evaporative enrichment.

Results from dental fluorosis study showed 86% prevalence in 100 patients from St. Mary's Hospital-Gilgil, where, 54% of these patients had mild to moderate fluorosis and 32% had severe fluorosis. The prevalence in patients with developing dentition below 14 years was slightly higher (92 %) than those with developed dentition (85.56%), while the severity was higher in those with developed dentition (3.77) than the former group (2.18). Fluoride severity and prevalence did not show a considerable variation with sex of the patients. In 73 patients from Egerton University-Njoro clinic, the prevalence of fluorosis was 79.49%, which was higher in patients with developing dentition (100%) than those with developed dentition (79.38%). High fluorosis cases from these two studies were reported in patients from Njoro, Nakuru town area, Gilgil, and Bahati and low cases from Solai and Rongai.

The findings of this study highlight a potential of high fluoride concentrations in aquifers on the Rift Valley floor and relatively low in aquifers located towards the rifts escarpments. High fluoride in these aquifers correlated positively with dental fluorosis prevalence and severity in Nakuru area. Therefore, low-fluoride groundwater prospecting is encouraged in areas close to Bahati and Mau escarpments, which due to their recharge capability might have the potential to supply water to areas on the rift floor.

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DEDICATION

To my mother, Angeline Smaloi.

DISSERTATION OUTLINE

This dissertation covers studies on physico-chemical characteristics of high fluoride groundwater in Nakuru area in the Kenyan Rift Valley, to determine parameters associated with fluoride dissolution, concentrations, and distribution in the local aquifers. Fluorosis cases in the area were also investigated from two local dental clinics and correlated to the high fluoride in the aquifers. A brief outline of the chapters presented in this dissertation is provided below.

Chapter One: General introduction

This chapter consists of a general introduction to the research study, with a focus on the problem statement, the objectives of the study, as well as detailed steps of methodology undertaken in order to achieve the objectives.

Chapter Two: Literature review

A detailed review of the research topic is conducted in this chapter. Studies on the occurrences of fluoride and its health implications in different geological and hydrological environments in Africa are reviewed. Serious attention is given to the studies on the occurrence of high fluoride in the Kenyan Rift Valley, specifically the central Kenyan Rift where the study area is located. The purpose of the detailed review is to bring out the gap in research that this study aims to achieve.

Chapter Three: Case study: The occurrence of high fluoride in groundwater and its health implications in Nakuru County in the Kenyan Rift Valley.

This chapter consists of a detailed geological and health investigations of a case of fluoride and dental fluorosis in Nakuru area, Kenya. This chapter is divided into three main parts:

- Geological and hydrogeological background of the study area important for the identification of the rocks rich in fluoride-bearing minerals, and aquifers characteristics.
- Boreholes water data: Their analysis, interpretation, and discussion.
- Fluorosis investigation conducted in two dental hospitals in the study area: Their analysis, interpretation, and discussion.

Chapter Four: General Conclusions

This chapter addresses the following aspects:

- Some of the limitations that were considered during the discussion and interpretations of the results.
- Concluding remarks on the link between fluoride occurrences in the aquifers and fluorosis cases in the study.
- Some possible recommendations to be considered for further studies.

CHAPTER 1: GENERAL INTRODUCTION

This research explores the field of medical geology, which is aimed to establish the link between natural fluoride groundwater contamination and the occurrence of fluorosis on the local population consuming the contaminated water. As described by Buck et al. (2016), medical geology is a discipline with the potential to help medical and public health communities around the world solve a wide range of environmentally and naturally induced health issues. These studies are important because most of these problems are caused by long-term, low-level exposure to harmful materials such as fluoride in drinking water (Buck et al., 2016). This is evident and relevant in the current study, because the effects of high fluoride consumption which include dental and skeletal fluorosis, slowly manifest after long-term exposure.

The availability of clean and reliable water is essential for any country's domestic, industrial, and agricultural development. Access to reliable safe drinking water is considered a basic human right by the World Health Organization (WHO), because it is essential for good health (WHO, 2011; Berger, 2016). Due to rapid population increase, high demand constrains the supply potential of reliable piped water in most developing countries. Challenges to the provision of water include pollution and poor water management, and consequently, local communities resort to alternative reliable sources such as groundwater. Groundwater is often assumed to be cleaner and healthier than surface water, however, this is not always the case when concentrations of natural occurring elements exceed the safe thresholds (Fawel and Nieuwenhuijsen, 2003; Rango et al., 2009; Konikow and Glynn, 2013; Annapoorna and Janardhana, 2015). During water-rock interactions, different elements dissolve in water in different concentrations depending on their abundance in the rocks, chemical state, and physico-chemical properties of the groundwater (Fawel and Nieuwenhuijsen, 2003; Rango et al., 2009). One of the most common issues in groundwater natural contamination in the world is high fluoride content and its associated health effects.

Fluoride is a beneficial micronutrient required by the body for the proper development of bones and teeth, and its main pathway of exposure is through drinking water (Nordstrom et al., 1989; Chae et al., 2007; Fordyce, 2011). Fluoride deficiency effects are easily treated through fluoride supplementation in water and/or food, however, toxicity effects are irreversible and prevention is mostly advised (Alvarez et al., 2009; James, 2016). The WHO has set the optimal range of fluoride in drinking water to 0.7-1.5 mg/l, however, different countries have their own limits that fit their climatic conditions and water availability (Gizaw, 1996; Fawel et al., 2006).

It is known that, exposure to concentrations beyond the optimal range in drinking water set by the WHO can cause different biological effects (WHO, 1993; Fordyce, 2011). For example, concentrations below 0.7 mg/l can result in dental caries and above 1.5 mg/l (WHO, 1993) can cause dental and skeletal fluorosis, neurological effects, and reproductive complications according to a number of studies such as, Gizaw (1996), Ortiz-Pérez et al. (2003), and Edmunds and Smedley (2005). Of these effects, dental and skeletal fluorosis are the most common in most fluoride contaminated regions such as the East African Rift Valley (Ockerse, 1953; Kloos and Haimanot, 1999; Moturi et al., 2002; Edmunds and Smedley, 2005; Ayanew, 2008; Rango et al., 2009).

High fluoride concentrations in Africa have been reported in different geological environments such as: some parts of the East African Rift Valley, the Mozambique Mobile Belt, the Birimian Formation, and Saharan sedimentary basins (Nair et al., 1984; Gaciri and Davis, 1993; Smedley et al., 1995; McCaffrey, 1998; Salem and Pallas, 2002; Smedley et al., 2002; Nezli et al. 2009; Nkotagu, 2009; Rafique et al., 2009; Ghiglieri et al., 2010; Olaka et al., 2016). An example of a high fluoride area is the Kenyan Rift Valley running through Kenya in a north-south direction on the western side of the country, where Nakuru area is located (Nair et al., 1984; Gaciri and Davis, 1993; Reiman et al., 2003).

Groundwater is the main source of domestic, industrial, and agricultural water supply in Nakuru area and the entire Kenyan Rift Valley (ADF-African Development Fund, 2004; Mumma et al., 2010). This latter region is known as a high fluoride belt where elevated fluoride levels ranging from 0.2-2170 mg/l have been reported in both surface and groundwater (Nair et al., 1984; Gaciri and Davis, 1992; Olaka et al., 2016). Fluoride concentrations in the East African Rift Valley groundwater vary significantly in concentration due to the complex stratification of different geological formations (Ayanew, 2008). Processes leading to high fluoride concentration in groundwater such as mineral dissolution, evaporating enrichment, and groundwater chemistry also affect fluoride distribution in the aquifers (Ayanew, 2008; Olaka et al., 2016). Several studies have shown that high fluoride levels in groundwater in the Kenyan Rift Valley are associated with dental fluorosis cases (Williamson, 1953; Ockerse, 1953; Nair et al., 1984; Manji et al., 1986a; Gaciri and Davis, 1993).

Even though the Kenyan Rift Valley is a known high fluoride belt, fluoride concentrations and distribution in the different aquifers in Nakuru area, and the status of dental fluorosis in areas covered by these aquifers, is not well understood. The main objective of this study was to address this gap in knowledge in the area through: understanding the physico-chemical processes responsible for fluoride release and distribution in the aquifers, determining the spatial distribution of fluoride in the aquifers, and correlating fluoride concentration in the aquifers with fluorosis cases on the local population. This will help in prospecting of aquifers for clean groundwater with minimum fluoride levels for domestic use, and also with warning the local population of further health issues.

The study encompasses the area around Nakuru town from Bahati in the north, Gilgil in the South East, and Njoro in the west. The area was of interest due to its central position in Nakuru County, thus a good representative of the entire County. The geology of the area is also well understood and most of the local population rely heavily on groundwater for domestic use. A study on fluoride distribution in the aquifers was of interest due to lack of such information in literature.

1.2 OBJECTIVES OF THE PROJECT

The general objective of this investigation was to understand the sources and spatial distribution of high fluoride content in Nakuru area aquifers, its links to geological formation and possible health effects on the local population.

In order to achieve this objective, the following was undertaken in the study area:

1. Investigation on the geogenic sources of high fluoride levels in groundwater in the study area.
2. Investigation on the occurrence and distribution of fluoride in various aquifers in the study area
3. Investigation on the occurrence of dental fluorosis on the local population of the study area.

1.2 RESEARCH METHODOLOGY

This section describes the methods as well as a summary of instruments used to collect and analyze the data, which are needed to achieve the objectives of the study. Precautionary measures to maintain validity and reliability of the data are also discussed.

1.2.1 Literature Review

To ascertain the status quo of fluoride research in general and the study area in particular, a literature survey was first conducted from journal publications, books, theses and dissertations, websites, and geological reports. Key words used include fluoride in groundwater, fluoride in the East African Rift System (EARS), fluoride in Kenya, geology of Nakuru area, and fluorosis in the EARS. The results of this survey are presented in chapter 2 on literature review.

1.2.2 Field reconnaissance and data acquisition

This section presents information on how the field reconnaissance was undertaken, borehole and health data acquisition, and quality control measures used during data collections to ensure the data was of good quality.

1.2.2.1 Field reconnaissance

A reconnaissance trip to the study area was conducted in December 2014 to assess the general condition regarding accessibility, security, and conditions of the boreholes. Google Maps mobile application was used in accessing the study area. In addition, a visit to a borehole drilling service organization, Catholic Diocese of Nakuru (CDN)-Water Program was conducted to inquire about water analysis costs and information about locations and state of boreholes in the study area. The organization, located in Nakuru town, has offered borehole drilling, defluoridation, and water quality analyses services in the greater Kenyan Rift Valley region since 1985 and has the records of borehole and their water quality results from all their previous projects. Upon realization of the amount of unpublished raw data in their possession, a request to have borehole and water quality data for Nakuru was presented to the organization's officials and was granted under conditions that the data will be used for academic purposes only.

1.2.2.2 Borehole water data and quality assurance

From paper files in the company archives, drilling and water quality reports on boreholes falling under the area of interest were identified and organized. This was further narrowed down into reports with data including GPS coordinates of the boreholes and complete physico-chemical information of the water. After evaluation of all the material collected from the archives, data from 32 boreholes which contain the complete physico-chemical parameters required were selected for this study. The water quality data from these boreholes were recorded manually in an Excel spreadsheet for further processing.

The data were considered of good quality and reliable for this study based on the following reasons:

(i) An interview with drilling officers at CDN revealed that boreholes older than ten to twenty years in the area are either abandoned or closed due to poor maintenance and therefore cannot be accessed for analysis. Therefore, the data used contains information of boreholes up to 13 years old which may currently be unavailable, but whose fluoride health effects can be currently be manifested on the population.

(ii) The CDN laboratory is certified by ISO (International Organization for Standardization) with qualified staff, therefore, the data obtained are accurate and reliable.

Water collection and analyses were all done by CDN after drilling of the individual boreholes was completed between 1999 to 2013. The processes of water collection and analysis methods were illustrated in the water quality reports, and were confirmed by the laboratory technicians during the visit at CDN. The water test methods by the CDN follow the "Standard Methods for the Examination of Water and Wastewater" published by American Public Health Association and American Water Works Association (Federation and American Public Health Association, 2005).

Quality assurance is an important part in water sampling and analysis to ensure accuracy and reliability of the results. Quality control was followed by the CDN technicians during sampling, transport, and analysis of the water from the boreholes to the laboratory. Water samples were collected during test pumping, which was done after completion of the drilling, and stored in clean, labeled plastic bottles to avoid potential contamination and avoid accidental mix up of samples. The samples were then transported to the CDN laboratories within 48 hours for analysis. The following methods were used for chemical analyses:

1. Ion Selective Electrode- fluoride, sodium, nitrate, potassium, and calcium.
2. Electrometric Method- pH value.
3. ELE PaquaLab Conductivity meter test- conductivity.

4. Edta-Titrimetric Method- Hardness.
5. Turbidimetric method- Sulphates.

1.2.2.3 Health data acquisition

To obtain and use clinical data, ethical clearance was obtained from the University of Johannesburg ethical committee (Appendix 3) in November 2015 and the National Commission for Science, Technology, and Innovation (NACOSTI) in Kenya (Appendix 4) in December 2016. The plan was to acquire the health data from government and private health organizations. Government health organizations such as the Nakuru County Government's ministry of health, were initially selected as immediate places to start with because of the large amount of information in their possession. It was, however, resolved to directly visit dental clinics in the study area, which could have data for the specific area of interest.

A desktop study was then conducted on the availability and location of dental clinics in the study area. Several clinics were identified operating in Nakuru town, and other community centers such as Bahati, Gilgil and Njoro. It is worth noting that, in order to obtain appropriate health data, interviews with the patients were conducted by qualified and experienced dentists and dental technicians, and not directly with the patients. Discussions were conducted with resident dentist and/or dental technicians of the following clinics; Joel Teeth Clear clinic, Family Dental Clinic, Super Smile Dental Clinic, Rift Valley Dental Clinic, Deep White Dental Clinic, St. Mary's Hospital, Presbyterian Church of East Africa (P.C.E.A.) Dental Clinic, and Egerton University Njoro-Dental Clinic, in Nakuru town, Njoro, Gilgil, and Bahati areas. It was noticed that most dental clinics in the study area do not keep records of their patients' medical history especially pertaining to fluorosis. They, however, agreed to give their observations on fluorosis trends observed in their patients.

In addition, dentists and dental technician from St. Mary's Hospital south east of the study area and Egerton University-Njoro Dental Clinic, west of the study area agreed to participate in collection of dental fluorosis data from patients in their respective hospitals for the month of January 2017. Data collected include presence/absence of fluorosis, severity of fluorosis using the Thylstrup-Fejerskov (TF) index for St. Mary's Hospital, age, gender, and area of birth or area inhabited during the early ages of tooth development (0-14 years) as shown in Appendices 5 and 6.

The data was collected from patients who agreed to participate in the study. An informed consent containing an introduction to the research, confidentiality, and anonymity assurance of the data collected was prepared (Appendix 3) and presented to the patients before their participation. The presence or absence of fluorosis was recorded and the TF indexing method was used to rate its severity in St. Mary's Hospital. Due to the absence of a dentist in Egerton University-Njoro Dental Clinic at the time of data collection, the TF score indexing was not used, and only the presence or absence of fluorosis was recorded.

For quality control, qualified and licensed dentists and dental technologists collected the health data in their respective health institutions. They were informed in detailed about this projects' objectives to enable them to get valuable information relevant to the study. Data was collected in the dentist's examination room, with the help of surgical lights for illumination for proper and correct observation. Detailed information relating to this part of the study is presented and discussed in chapter 3 of this dissertation.

1.2.3 Data analysis

1.2.3.1 Borehole water data analysis

The borehole water data were statistically and spatially analyzed to discern the characteristics of each physico-chemical parameter, and how they correlate and associate with fluoride. The hydrochemical characteristics of the groundwater were used to provide descriptive statistics of quality parameters such as range, mean, median, and concentration levels, according to global permissible limits suggested by WHO (2006) and the Kenyan limits by NEMA (National Environmental Management Authority) (WSREB- Water Services Regulatory Board, 2002; Nema, 2016) for drinking water.

A GW_Chart program for plotting a piper diagram was used to determine the hydrochemical facies of the area using six chemical components as described by Piper (1944). Hydrochemical facies describes the chemical characteristic of groundwater by analyzing the composition of cations and anions. Cations and anions used were calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulfate (SO_4^{2-}), carbonates (CO_3^{-}), and bicarbonate (HCO_3^{-}). This is because, they account for electrical balance in most natural waters (Hem, 1989; Ging et al., 1996). These cations were plotted on the two ternary diagrams and on the central diamond diagram, each one summing to 100 %. The criteria used to determine the dominant anion is based on percentage of milliequivalents of the major cations and anions, where, for an ion or anion to be considered dominant it had to be greater than 50 % of the total ions or anions (Ging et al., 1996).

The data was subjected to several statistical analyses to determine the dominant physico-chemical parameters in groundwater and their relationships, which will explain their association with fluoride. Principal Component Analysis (PCA) was used to reduce the number of variables in the data, by determining the most influential physico-chemical parameters (principal components) that can describe the characteristics of groundwater in the study area (McKillup and Dyar, 2010). This is a technique that reduces variables in a dataset with many interrelated variables into fewer ones that best explain the variance observed in the data (McKillup and Dyar, 2010; Bhat et al., 2014; Mosaferi et al., 2014). Pearson's correlation and linear regression analyses were then used to determine the magnitude and nature of the relationships among the dominant parameters respectively. The statistical package used for data analysis was XLSTAT tool in Microsoft Excel.

Spatial analysis was then conducted to determine the nature and type of geographical distribution of fluoride and the dominant physico-chemical parameters. Spatial autocorrelation was first used to identify the nature and degree to which values of each physico-chemical parameter correlated to other nearby values (Dale and Fortin, 2002). This method determined whether the parameters have a dispersed, random, or clustered spatial distribution. Hotspot analysis was then conducted to determine the cluster of boreholes with the highest concentrations of fluoride and other dominant parameters. The Moran's index and variogram, as well as hotspot spatial analysis tools in GIS were used for this investigation. Kriging method in geostatistics analysis tools was then used to map fluoride and other parameters' spatial distribution in the boreholes, therefore, showing fluoride distribution in the local aquifers. These analyses were generated using Arc GIS software (version 10.5).

1.2.3.2 Health Data analysis

Observations and results from interviews and consultations with the various dentists in the study area were described. These include the observations on the number of patients with fluorosis, the most affected age bracket and dental diseases associated with fluorosis. The clinical data from St. Mary's Hospital-Gilgil and Egerton University-Njoro dental clinic were recorded in printed sheets and later transferred into Excel (Appendices 5 and 6) for analysis. The data was subjected to linear correlation analysis to determine the relationship between the severity of dental fluorosis and the patients’ age and sex.

Then, the spatial association between severity and prevalence of fluorosis and the patients’ area of residence was analyzed. Because the health data was collected in hospitals, it was not possible to get the GPS location of the specific patient’s home. Therefore, the general areas of residence of the patients were used for spatial correlation. The areas showing high or low prevalence and severity were correlated descriptively with the spatial fluoride distribution map.

CHAPTER 2: LITERATURE REVIEW: FLUORIDE OCCURRENCE AND HEALTH IMPLICATIONS

2.1 INTRODUCTION

This chapter reviews studies on fluoride's chemistry, its occurrence and distribution in geological and hydrogeological environments, and implications in human health associated with excessive or deficiency of fluoride ingestion. Research on high fluoride belts in Africa will be reviewed with special concern on the East African Rift Valley, especially the Kenyan part where the study area is located.

The impact of the natural environment such as rocks, soil, water, and dust on human health was realized as early as 5000 years ago, by Chinese scholars and later by Hippocrates in 400 B.C. who recorded how minerals in water affect human health (Baoshan et al., 2010; Selinus et al., 2010). With the improvement in technology and research, subsequent research identified medical properties of mineral water, and the impact of trace elements on human health (Finkelman et al., 1999). In Africa, the realization of the natural environment's effect on human health took shape in the 1960s when geochemical methods were incorporated in mineral exploration (Davies, et al., 2013). However, Davies et al. (2013) noted that, until 1999, there were still gaps in identifying distribution of harmful or beneficial minerals and elements in soil and water throughout the continent due to lack of sufficient geochemical data. Fluorine is one of the elements that has been identified to have adverse health effects on human beings.

Fluoride occurs in late crystalizing minerals and is found mostly in granitic and volcanic rocks where it is released in water mainly through minerals dissolution (Smedley et al., 2002). Physico-chemical parameters such as pH, calcium, and bicarbonate affect fluoride's distribution and concentration in groundwater (Gaciri and Davies, 1993). The use of fluoride toothpastes and mouthwashes and fluoridated water is widely advocated in cases of low fluoride in diet, while defluoridation of drinking water is practiced in areas with high fluoride (Smedley et al., 2002; Edmunds and Smedley, 2013). Low fluoride intake (< 1 mg/l) causes dental caries and long-term exposure to high dosages above 1.5 mg/l can result in dental and skeletal fluorosis (Dissanayake, 1991; Smedley et al., 2002).

2.2 FLUORINE

2.2.1 Chemistry and geological occurrence

Fluorine (F) is the 15th most abundant element on the earth's crust at 625 mg/kg, with atomic number 9 (Dean, 1999; Rudnick and Gao, 2003; Fordyce, 2011; Edmunds and Smedley, 2013; Garcia and Borgnino, 2015; Berger, 2016). Due to its high electronegativity, fluorine naturally does not exist as an independent element but in compounds with almost all elements (Gizaw, 1996; Edmunds and Smedley, 2013). It has higher tendency to be retained in minerals and rocks where, for example, its concentration averages 715 mg/kg in igneous rocks, than in aqueous environment where it averages 1.3 mg/l in sea water (Gizaw, 1996; Edmunds and Smedley, 2013). Fluoride (F^-) can occur as a main mineral component such as in fluorite (CaF_2), fluorapatite (Ca_{10} (PO_4) $6F_2$), and cryolite (Na_3AlF_6), or in trace amounts such as in apatite $Ca_5[PO_4]3(Cl,F,OH)$ (Edmunds and Smedley, 2013). Fluoride has a similar ionic radius and charge as hydroxyl (OH^-) ion and readily substitutes it during magmatic differentiation in hydrous minerals (Murray, 1986; Su et al., 2015; Berger, 2016). Examples of such hydrous minerals include biotite ($K_2(Mg,Fe)_4(Fe,Al)_2[Si_6Al_2O_{20}](OH)_2(F,Cl)_2$), hornblende $(Ca,Na)_{2-3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$), topaz ($Al_2$ (F,OH) SiO_4) and apatite $Ca_5[PO_4]3(Cl,F,OH)$ (Gizaw, 1996; Su et al., 2015). Fluoride can also be adsorbed onto surfaces of minerals such as clay and carbonates (Fordyce, 2011).

In rocks, Fluoride is enriched in late crystalizing magmas, and therefor highly concentrated in granitic and alkaline rocks (Berger, 2016). Felsic igneous rocks tend to have a higher fluoride content than mafic and ultra-mafic ones, where the average concentration ranges from 1000 mg/kg to 100 mg/kg in alkali and ultramafic rocks respectively (Dean, 1999; Edmunds and Smedley, 2013). In high fluoride rocks, fluoride tends to be higher in phonolites, rhyolites, and granites in igneous rocks, and dependent on its parent rock in metamorphic and sedimentary rocks (McCaffrey, 1998; Stecher, 1998; Fluorine, 2006). Typical concentrations in soil vary from 20 mg/kg to 400 mg/kg, however, values of up to 20,000 mg/kg have been reported in soils around hydrothermal mineralization areas (Edmunds and Smedley, 2013 and references therein). Micas tend to be the dominant fluoride rich minerals in intrusive igneous and metamorphic rocks while in volcanic rocks fluoride is rich in volcanic glass, fluorite, biotite, illite and montmorillonite (Carrillo-Rivera et al., 2002; Edmunds and Smedley, 2013).

2.2.2 Fluoride release and concentrations in groundwater

Fluoride is released in nature as a univalent anion (F^-) during physical and chemical weathering of the parent rocks. Its high dissolution in water is attributed to the high mobility of its small ion and maximum electronegativity (Su et al., 2015). Fluoride's concentration in natural groundwater depends on its abundance in the minerals present in the geological formation, groundwater's residence time, and physico-chemical characteristics (Handa, 1975; Smedley et al., 2002; Brunt et al., 2004; Reddy et al., 2010; Su et al., 2015).

The most common physico-chemical parameters affecting fluoride dissolution in groundwater include groundwater temperature, pH, and presence of calcium and bicarbonate (Handa, 1975; Edmunds and Smedley, 2013; Su et al., 2015 and references therein). Calcium and fluoride concentrations in groundwater have a known negative correlation (Smedley et al., 2002; Berger, 2016). Fluorite, which is considered the dominant source of fluorine in groundwater has been used to show calcium-fluoride solubility in water in equation 1-3 below (Edmunds and Smedley, 2013; Su et al., 2015 and references therein). These equations show that the absence or low concentration of calcium in solution allows increase in fluoride concentration, and fluorite solubility decreases with temperature (Edmunds and Smedley, 2013).

$$CaF_2 = Ca^{2+} + 2F^- \quad (1)$$

$$K_{fluorite} = (Ca^{2+}).(F^-)^2 = 10^{-10.57} \text{ at } 25°C \quad (2)$$

$$\text{Or, } \log K_{fluorite} = (Ca^{2+}) + 2\log(F^-) = -10.57 \quad (3)$$

Where $K_{fluorite}$ is the solubility product of fluorite.

Groundwater with high sodium concentrations allows dissolution of fluoride minerals due to exchange of calcium by sodium ions, which lowers calcium levels allowing an increase in fluoride (Handa, 1997; Edmunds and Smedley, 2013). Presence of some ions such as H^+, Fe^{3+}, Al^{3+}, B^{3+}, Si^{4+}, and Mg^{2+} in groundwater can form complexes with fluoride limiting its solubility (Su et al., 2015 and references therein).

Arid areas with little rainfall often have elevated groundwater fluoride levels due to slow water infiltration, which increases water-rock interaction thus high fluoride dissolution (Handa, 1975). Most humid areas have low fluoride groundwater due to the high rainfall and infiltration rates, which dilutes the groundwater (Smedley, 2002; Edmunds and Smedley, 2013). Late magmatic differentiation rocks have high fluoride concentrations and therefore, high fluoride groundwaters are associated with such geological formations (Edmunds and Smedley, 2013; Su et al., 2015).

2.2.3 Fluoride metabolism, dental and skeletal health effects

Fluoride is a very important dietary component whose health significance depends on the dosage taken, and its most common pathway into the body is through drinking water (Hammer, 1986; Smith, 1986; Baelum et al., 1987; McCaffrey, 1993; Kotecha et al., 2012; Berger, 2016). Other sources of fluoride include fluoridated drinking water, high fluoride food, and beverages (Manji et al., 1986b; Smith, 1986; Fawel et al., 2006; Berger, 2016). Although there are several effects of fluoride on the human body such as reduced immunity, effect on hormones, and reduced intelligence (Johansen, 2013). This review, however, focus on the effect on skeletal tissues specifically the dentition. This is due to the number of studies showing these effects are more manifested in Africa and mostly the Kenyan Rift Valley (Nair et al., 1984; McCaffrey, 1993; Johansen, 2013).

Ingested fluoride is incorporated in teeth by surface uptake or absorbed through the stomach walls and tends to accumulate more in calcified tissues such as bones and teeth (Ncube, 2002; Ozsvath, 2009; Pittalis, 2010; Skinner, 2013). In the teeth and bones, uptake of moderate fluoride (0.5-1.5 mg/l) changes the tooth hydroxyapatite, $Ca_5(PO_4)_3OH$, structure to fluorapatite, $Ca_5(PO_4)_3F$, which is more stable (Skinner, 2013; Berger, 2016). Bacterial carbohydrate metabolism in the mouth produces acids as by-products, which causes dental caries (Pittalis, 2010). However, the more stable fluorapatite is less susceptible to dental caries, thus, minimum fluoride consumption reduces dental caries (Pontius, 1993; Johansen, 2013; Skinner, 2013).

Excess fluoride consumption (above 1.5 mg/l) affects the developing enamel by rapidly replacing hydroxyl in apatite to form more fluorapatite, which results in structural damage, brittle teeth, superficial porosity, and the loss of continuity of the enamel layer, a condition known as dental fluorosis (Dean, 1942; Hammer, 1986; Fejerskov et al., 1990; Kloss and Haimanot, 1999; Mascarenhas, 2000; Dhar and Bhatnagar, 2009; Pittalis, 2010; Jiménez-Farfán et al., 2011; Johansen, 2013). Fluorosed enamel is described as unglazed opaque, chalky white with the presence of brown stains, which could lead to pitting of the enamel with excess fluoride intake (Thylstrup and Fejerskov, 1978; Fejerskov et al., 1990; Mascarenhas, 2000). Fluorosis is symmetrically distributed in teeth but its severity is higher in late developing teeth such as premolars (Dean, 1934; Larsen et al., 1985; Manji et al., 1986a; Baelum et al., 1987; Riordan et al., 1993; Mascarenhas, 2000). Mild fluorosis often causes cosmetic defects, but extreme effects results in fractured and even loss of the affected tooth (Jiménez-Farfán et al., 2011). Excess fluoride incorporated into hard tissues can be reduced in an extremely slow process of osteoclastic resorption over many years, but the structural defects caused are irreversible (Ozsvath, 2009).

Fluoride enhances bone mineralization and growth, however, doses above 3 mg/l causes over mineralization leading to skeletal and crippling fluorosis (WHO, 1984; Brouwer, et al., 1988; Pittalis, 2010; Kotecha et al., 2012; Johansen, 2013 and references therein). Skeletal fluorosis is characterized by weak and stiff joints, rheumatic pain, back stiffness, progressive kyphosis, brittle bones, added bone mass, and in extreme cases, impeded movements of limbs and joint contractions due to ossification of spinal ligaments and fusion of the vertebrate column (Nanyaro et al., 1984; Pittalis, 2010; jha et al., 2011; Johansen, 2013; Tekle-Haimanot and Haile, 2014). Up to 10% of people with crippling fluorosis develop a form of neurological complication caused by mechanical compression of the spinal cord and nerve roots by the increased bone mass and size (Tekle-Haimanot and Haile, 2014).

Different fluorosis degrees can occur in a population consuming the same level of fluoride due to factors such as individual response, age, duration of exposure, body weight, bone growth rate, degree of physical activity, and nutritional status (Jiménez-Farfán et al., 2011; James, 2016). Dental fluorosis is more common in children than adults because fluoride uptake is more efficient in children during tooth development, and in the general population the severity increases with time of exposure and fluoride concentration (Dean, 1942; Ockerse, 1953; Gaciri and Davies, 1992; Mascarenhas, 2000; Ozsvath, 2009). High altitude is also another significant risk factor identified for dental fluorosis prevalence and severity, due to the higher retention of fluoride by the human body under these conditions (Angmar-Mansson and Whitford, 1990; Yoder et al., 1998; Rweneyonyi et al., 1999).

An important risk factor in determining fluorosis occurrence and severity is assessing all sources of fluoride intake during tooth development (Mascarenhas, 2000). Fluorosis has been shown to occur at fluoride intake of about 0.03-0.1 mg/Kg of body weight (Larsen et al., 1985; Manji et al., 1986; Baelum et al., 1987; Mascarenhas, 2000). Apart from drinking water, other sources of high fluoride that can cause or increase fluorosis includes food and beverages. These sources include fluoridated drinking water, fluoride supplements, fluoride dentifrices, infant formula, and fluoride toothpaste (Mascrenhas, 2000; James, 2016 and references therein). In high fluoride areas, several foods and additives have been found to concentrate high fluoride such as; *Vigna unguiculata* (cow peas), *Brassica integrifolia* (kale), *Amaranthus hybridus* (amarantha), *Camellia sinensis* (tea), *Phoenix dactylifera* (dates), and rock salt ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), which can also elevate fluorosis degree and prevalence (Kahama et al., 1997; Tekle-Haimanot and Haile, 2014; Ali and Absulrahman, 2016). However, intake of some foods such as milk has been found to diminish fluoride uptake (Kahama et al., 1997 and references therein).

2.2.4 Measurement of dental fluorosis

A proper description of the prevalence and severity of fluorosis within a population or an individual needs a sensitive, precise, and valid classification system (Mascarenhas, 2000). Several methods have been used to diagnose and describe severity of dental fluorosis including Dean's Indices of 1934 and 1942, and Thylstrup and Fejerskov (TF) index of 1978 (Rozier, 1994; Funmilayo and Mojirande, 2014; Berger; 2016; James, 2016). Deans classification of 1934 divided fluorosis into seven classes including: 0- normal, 0.5- questionable, 1- very mild, 2- mild, 3- moderate, 3.5- moderate severe, 4-severe (Funmilayo and Mojirande, 2014; James, 2016 and references therein). This method has been criticized for lack of sensitivity and applicability around indices with small margins such as the 0-0.5-1 indices (Fejerskov, 1990; Funmilayo and Mojirande, 2014; James, 2016). A later modified classification in 1942, describes fluorosis severity observed on the most affected tooth in an individual using six categories as shown in Table 1 below (Funmilayo and Mojirande, 2014). This index has been widely used due to its ease of use and has been used as standard for comparison to developing indices (Rozier, 1994). Figure 1 below shows the change in surface structure and color observed as the severity of fluorosis increases in affected teeth.

Figure 1. Different grades of fluorosis severity showing the change in surface appearance from very mild to severe fluorosis. From dental fluorosis (2017).

To overcome the shortcomings of the Deans Index, the TF index was developed to assess fluorosis on both surfaces of every tooth, and classifies it on a 0-9 scale. It comprises of a ten-point scale classifying enamel changes in associated increasing fluoride exposure (Thylstrup and Fejerskov, 1978; Funmilayo and Mojirande, 2014). To examine, teeth are cleaned and indexed per the observed appearance described in table 2 below. This method is considered better than the Deans Index due to its sensitivity caused by the many scores, easy to understand, and reliability (Funmilayo and Mojirande, 2014). However, its many scores could be difficult for an inexperienced examiner to employ in order to produce accurate results (James, 2016).

Most professionals consider TF scores 1-2 to be mild forms of fluorosis, which can be aesthetically accepted and only scores above TF 3 have been reported to cause stigmatization and dental health deterioration (James, 2016). Treatment modalities for patients with TF score 1-4 require microabrasion and/or bleaching, score 5-7 require veneers, while levels above 8 require full coverage crowns (James, 2016 and references there in).

Table 1. Deans Index of classifying the severity of dental fluorosis from the normal (0) to severe (5). From Funmilayo and Mojirade (2014).

Deans Classification	Code	Criteria – description of enamel
Normal	0	The enamel represents the usual translucent semi-vitriform (glass-like) type of structure. The surface is smooth, glossy, and usually of pale creamy white colour
Questionable	1	The enamel discloses slight aberrations from the translucency of normal enamel, ranging from a few white flecks to occasional white spots. This classification is utilised in those instances where a definite diagnosis is not warranted and a classification of 'normal' not justified.
Very Mild	2	Small, opaque, paper white areas scattered irregularly over the tooth but not involving as much as approximately 25% of the tooth surface. Frequently included in this classification are teeth showing no more than about 1 – 2mm of white opacity at the tip of the summit of the cusps, of the bicuspids or second molars.
Mild	3	The white opaque areas in the enamel of the teeth are more extensive but do involve as much as 50% of the tooth.
Moderate	4	All enamel surfaces of the teeth are affected and surfaces subject to attrition show wear. Brown stain is frequently a disfiguring feature
Severe	5	All enamel surfaces are affected and hypoplasia is so marked that the general form of the tooth may be affected. The major diagnostic sign of this classification is discrete or confluent pitting. Brown stains are widespread and teeth often present a corroded-like appearance.

Table 2. The Thylstrup and Fejerskov (TF) index of classifying severity of dental fluorosis from normal (0) to the most severe (9). From Funmilayo and Mojirade (2014).

TF Classification	Criteria – description of enamel
0	Normal translucency of enamel remains after wiping and drying of the surface
1	Narrow opaque/white lines running across the tooth surface. Slight snow capping of cusps or incisal edges may also be seen.
2	Smooth surfaces. More pronounced lines of opacity that follow the perikymata. Occasionally confluence of adjacent lines. Occlusal surfaces: Scattered areas of opacity less than 2mm in diameter and pronounced opacity of cuspal ridges. Snow-capping is common.
3	Smooth surfaces: Merging and irregular cloudy areas of opacity. Accentuated drawing of perikymata often visible between opacities. Occlusal surfaces: Confluent areas of marked opacity. Worn areas appear almost normal but usually circumscribed by a rim of opaque enamel.
4	Smooth surfaces: The entire surface exhibits marked opacity or appears chalky white. Parts of surface exposed to attrition appear less affected. Occlusal surfaces: Entire surface exhibits marked opacity. Attrition is often pronounced shortly after eruption
5	Smooth surfaces and occlusal surfaces: Entire surface displays marked opacity Focal loss of outermost enamel (pits). less than2mm in diameter
6	Smooth surfaces: Pits are regularly arranged in horizontal bands less than2mm in vertical height Occlusal surfaces: confluent areas less than2mm in diameter exhibit loss of enamel Marked attrition

7	Smooth surfaces: Loss of outermost enamel in irregular areas involving less than half of the entire surface. Occlusal surfaces: changes in the morphology caused by merging pits and marked attrition
8	Smooth and occlusal surfaces: Loss of outermost enamel involving more than half of surface
9	Smooth and occlusal surfaces: Loss of main part of enamel with change in anatomic appearance of surface. Cervical rim of almost unaffected enamel is often noted.

2.2.5 Prevention of dental fluorosis

According to Ockerse (1953), Ripa (1991), Gaciri and Davies (1992), Ozsvath (2009) and James (2016 and references therein), developing dentition is more susceptible to fluorosis, and due to its irreversibility, the best prevention method for fluorosis is by controlling its intake in children. Nutritional factors play an important role in severity of fluorosis in a population (Rango et al., 2012). High calcium diet and supplements have been shown to reduce the rate of fluoride intake by the body, therefore reduce the severity of fluorosis (Gupta et al., 1994; Chen et al., 1997; Rango et al., 2012). Studies have shown low occurrence of dental fluorosis in milk-consuming children than non-milk-consuming ones (Gupta et al., 1994; Chen et al., 1997).

Defluoridation is another widely-used method to reduce or remove excess fluoride in drinking water especially in some parts of Asia, Ethiopia, Tanzania, and Kenya despite being less successful in most developing countries due to the complexity and high cost of setting up and maintenance (Gumbo and Mkongo, 1995; Kloss and Haimanot, 1999; CDN-Catholic Diocese of Nakuru, 2009; Brindha et al., 2011). Common methods of defluoridation used in Africa include granulated bone media, heat activated bone char, activated alumina adsorption, resin activated alumina absorption, and Nalgonda method (Kloss and Haimanot, 1999; CDN, 2009). In Northern Tanzania, the Nalgonda method has been reported to reduce fluoride from 22.1 mg/l to 3.5 mg/l (Johansen, 2013 and references there in).

Catholic Dioses of Nakuru (CDN) water programme is an organization operating from Nakuru town, offering groundwater services to Nakuru and the larger Kenyan Rift Valley. The organization offers borehole drilling and maintenance, water quality testing and defluoridation services. They use activated bone char defluoridation method due to its ease of operation and use of locally available material (CDN, 2009). The method involves burning bones to remove organic matter leaving calcium and phosphate which can absorb fluoride from water (CDN, 2009). The bone char is then packaged in filters of different sizes for households, communities, and institutions (CDN, 2009). Table 3 below shows different defluoridation methods used, their advantages, disadvantages, and relative cost of set up and maintenance.

Table 3. Different methods of defluoridation precipitation, adsorption/ion exchange, and hybrid used in Africa. Modified from CCEFW- Consultative Committee on Excess Fluoride in Water (2010).

Removal method	**Removal capacity per dose**	**Working pH**	**Interference**	**Advantages**	**Disadvantages**	**Relative cost**
Precipitation						
Alum (Aluminum sulphate)	150 mg/mg F	Non-specific	-	Established process	Sludge produced, treated water is acidic, residual Al present.	Medium-high
Alum + lime (Nalgonda process)	150 mg alum + 7 mg lime/mg F	Non-specific, optimum 6.5	-	Low tech, established process	Sludge produced, high chemical dose, residual Al present.	Medium-high
Adsorption/ion exchange						
Activated carbon	Variable	<3	Many	-	Large pH changes before and after treatment.	High

Plant carbon	300 mg F/ kg	7	-	Locally available	Required soaking in potassium hydroxide (KOH)	Low-medium
Bone char	100 g F/m^3	>7	Arsenic	Locally available, high capacity	Not universally accepted.	low
Ion exchange using resin	Variable	Non-specific	-	Locally available	Not known to be available in Kenya	Low-medium
Bone	900 g F/m^3	>7	Arsenic	Locally available	May give taste, degenerates, not universally accepted	low
Hybrid methods						
CDN hybrid	3.4-3.7 mg F/g	>7	Alkalinity	Locally available, high capacity	pH of treated water high, dissolved phosphorous high.	medium

2.2.6 Drinking water quality and guidelines for fluoride

For drinking water to be considered safe for human consumption, concentrations of common organic and inorganic components, and physical parameters levels should be within standards as set by the World Health Organization (Fawel, 2006). Permissible limits set for these parameters include: pH 6.6-8.5, total hardness 500 mg/l, TDS 1000 mg/l, alkalinity 600 mg/l, chlorides 200 mg/l, calcium 75 mg/l, magnesium 50 mg/l, and fluoride 1.5 mg/l (WHO, 2006; Kumar and Puri, 2012). The precise threshold for fluoride concentration in dental fluorosis risk areas has not been clearly established due to factors that affects the amount of fluoride ingested (Sohn et al., 2009; Rango et al., 2012 and references therein). These factors include: climate, individual susceptibility to fluoride exposure, varying fluoride concentration in diet sources, and amounts of sources of drinking water with fluoride (Selwitz et al., 1998; Chandrashekar and Anuradha, 2004; Acharya, 2005; EPA- Environmental Protection Agency, 2006; Rango et al., 2012 and references therein).

Several factors have been used to establish the fluoride threshold value, such as the temperature of a region, which affects the daily consumption of water (WHO, 1996; Hammer, 1986; Kloss and Haimanot, 1999 and references there in; Ncube, 2002; Johansen, 2013). The WHO permissible limit for fluoride in drinking water is 1.5 mg/l (WHO, 2006), and this regulatory guidance is widely used in many countries including Kenya. However, countries in arid and semi-arid climate regions have set different fluoride limits due to high water consumption rate caused by high temperature. High water consumption results in incidences of dental and skeletal fluorosis in arid areas with fluoride levels below 1.5 mg/l (Kloss and Haimanot, 1999; WHO, 1984). Countries with different standards and guidelines for fluoride in drinking water include South Africa with 1 mg/l (DWAF, 1996; Ncube, 2002), Senegal with 0.6 mg/l (Ulhaq, 2016 and references therein), and Tanzania with 8 mg/l (Kloss and Haimanot, 1999; Johansen, 2013 and references therein).

2.3 FLUORIDE IN AFRICA AND ITS HEALTH EFFECTS

In Africa, cases of high fluoride in groundwater have been reported in different geological formations including: crystalline basement formations such as the Birimian Formation in West Africa and the Mozambique Mobile Belt in East Africa, the volcanic East African Rift System (EARS), granitic provinces in Eastern and Southern Africa, and sedimentary basins in Northern and Southern Africa (Nanyaro et al., 1984; Gaciri and Davies, 1993; Dunkley et al., 1993; Antwi, 1995; Tekle-Haimanot et al., 1995; Kloss and Haimanot, 1999; Smedley, 2002; Naslund and Snell, 2005; Msonda et al., 2007; Nezli et al., 2009; Wandwi et al., 2010; Ramdani et al., 2012).

Most endemic fluorosis cases are reported in rural and sub urban areas where a large part of the population relies on groundwater for domestic use (Smedley et al., 1995). Surface waters like rivers and springs have reputedly low fluoride concentrations than groundwater in most parts of Africa, except in some cases in the Rift Valley where lakes have higher fluoride concentrations than groundwater (Gaciri and Davies, 1993; Ghosh, 2002). The highest fluoride belts in Africa are shown in Figure 2 below.

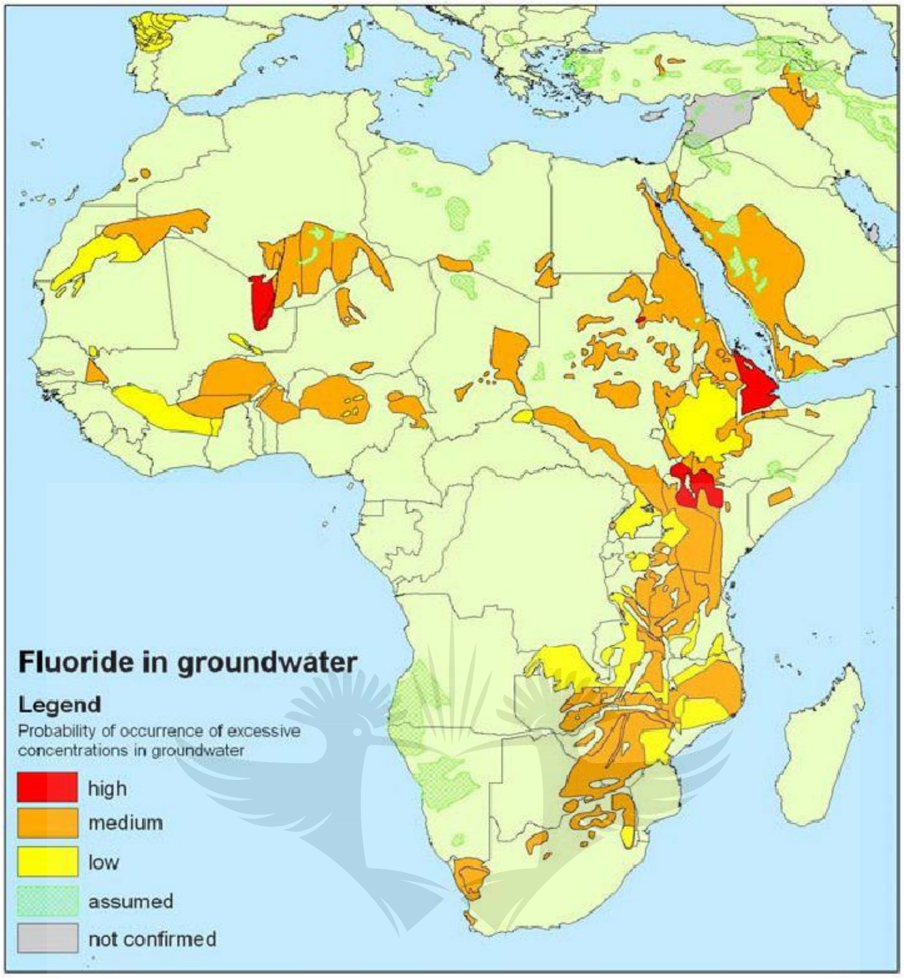


Figure 2. Map of fluoride distribution in Africa's groundwater showing high concentrations in the Rift Valley, the Mozambique Mobile Belt, and alkaline intrusions in East and South Africa, the Birimian Formation and Continental Intercalare in West and North Africa. From Thole (2013).

2.3.1 Fluoride in rocks

2.3.1.1 Metamorphic rocks

In metamorphic regions, high fluoride concentrations are found in some aquifers of the Birimian Greenstone belt in West African countries such as Ghana, Togo, Senegal, and Burkina Faso (Antwi, 1995), and the Mozambique Mobile Belt in Eastern and Southern Africa (Smedley et al., 2002). The West African metamorphic region is dominated by the upper Birimian (Precambrian) belt composed of meta-igneous, meta-volcanic, and meta-sedimentary rocks such as biotite gneisses, migmatites, and schists (Smedley, 2002). These rocks were intruded by post-Birimian granitic intrusions depositing high fluoride minerals such as biotite and apatite with up to 7 weight % fluoride (Antwi, 1995; Smedley et al., 1995; Smedley et al., 2002).

The Precambrian Mozambique Mobile Belt (MMB) in Eastern and Southern Africa is a metamorphic belt where, post-Mozambican age granitic intrusions deposited fluoride minerals in the old metamorphic formations (Smedley et al., 2002). The MMB high fluoride belts are reported in Kenya, Tanzania, and Malawi, where high fluoride contents are associated with granites, granitoids, gabbros, gneisses, schists, and migmatites (Bath, 1980; Smedley et al., 2002). Granites in Central Tanzania have been found to have high fluoride levels in apatite (up to 5-6 weight %), biotite, and muscovite (JICA, 1998; Smedley, 2002). In western and Central Malawi, weathering of basement granites rich in fluorite and apatite is the source of the elevated fluoride concentration in groundwater (Bath, 1980; UN, 1989 and references therein; Msonda et al., 2007).

2.3.1.2 Sedimentary rocks

Sedimentary basins in Africa with reported high fluoride groundwater include Continental Intercalaire in Northern Africa, sedimentary basins sitting on the Precambrian basement in West Senegal, and Cretaceous–Tertiary Karoo basin in Southern Africa (Salem and Pallas, 2002; Ncube, 2006; Edmund and Smedley, 2012).

The superimposed Cretaceous-Quaternary Continental Intercalaire (CI) and Complex Terminal (CT) are the two main aquifer systems in Northern African Saharan region that extends from Tunisia to Algeria (Salem and Pallas, 2002). The aquifers are mainly heterogeneous, and are composed of sandstones, clays, and evaporates (Nezli et al., 2009). High fluoride groundwater is associated with phosphatic sediments rich in fluorite and fluorapatite in Southern Algeria and Western Tunisia (Nezli et al., 2009; Edmund and Smedley, 2012 and references therein). Cretaceous-Tertiary basins sitting on the Precambrian basement in Western Senegal are reported to have fluoride levels of up to 13 mg/l (Travi, 1993). Sandstones and shales of the Karoo sedimentary rocks have been found to contain deposits of fluorspar and fluorapatite, and areas around these deposits show high fluoride concentration in groundwater (Ncube, 2006).

2.3.1.3 Igneous rocks

The East African Rift System (EARS) is one of the largest fluoride belt in Africa stretching from Ethiopia through Kenya, Uganda, Tanzania, Malawi, and Mozambique, with two main branches, the western and eastern. The eastern branch passes through Kenya and Eastern Tanzania, and the western branch through Uganda and Western Tanzania and they both meet in Malawi in the south. Tectonic activities on the rift deposit various volcanic material of Tertiary to Recent age rich in fluoride.

Young volcanic rocks such as basalts, basanites, tephrites, phonolites, trachites, obsidian, volcanic ash, and sediments have high level of fluorine-bearing minerals such as fluorite and fluorapatite (Gaciri and Davies, 1993; Tekle-Haimanot et al., 1995). Structures such as large fault systems in the rifts escarpments and floor allow deep percolation and long-term rock-water interaction, thus, promote fluoride dissolution (Tekle-Haimanot et al., 1995). High hydrothermal activities and geothermal hotspots also accelerate solubility of fluorine-bearing minerals into surface and ground-water (Dunkley et al., 1993).

Fluoride release from these volcanic rocks is attributed to dissolution, weathering, and ionic exchange of glass phases, volcanic rocks, and fluvio-lacustrine sediments (Rango et al., 2012). In Northern Tanzania, aquifers in fractured and auto-brecciated lava flows have been associated with low fluoride due to their high transmissivity, which reduced the residence time of groundwater (Bardecki, 1974; Mambali and Kilham, 1982; Gumbo and Mkongo, 1995; JICA-Japan International Cooperation Agency, 1998; Ghiglieri et al., 2010; Smedley et al., 2002; Johansen, 2013). These authors also reported high fluoride aquifers in basalts, phonolites, and volcano-sedimentary (lahars and lacustrine deposits), which have low transmissivity. In the Ugandan part of the rift, high fluoride is associated with the volcanic mountains Ruwenzori and Elgon on the western and eastern parts of the country (WRAP- Water Resources Assessment Project, 1999).

In the Bushveld Igneous Complex (BIC) and Pilanesberg Complex in South Africa, elevated fluoride levels averaging 15 ppm and 2-5.6 ppm were reported in granites and syenites respectively (Ockerse, 1947; Bond, 1947; McCaffrey, 1994; McCaffrey, 1998). The BIC is a large Paleozoic igneous body with several litho-units including the Lebowa and Nebo granites rich in high fluoride minerals such as fluorite, fluorspar, fluorapatite, micas and amphibolites (Fayazi, 1994). The Pilanesberg Complex is also an igneous body with rocks such as syenites and granophyres rich in fluorite and villiaumite (McCaffrey, 1998).

2.3.2 Fluoride in groundwater

In the Birimian Formation, fluoride levels between 0.9-4.37 mg/l were reported in boreholes in Bongo granites, granodiorites, and a few occurrences in meta-igneous rocks in Northern Ghana (Smedley, 2002). In Senegal, high fluoride in groundwater has been found in aquifers near phosphate ores of the Birimian Formation, at levels higher than the WHO recommended limits of 1.5mg/l (Pontie et al., 1995; Faye et al., 2007). In the MMB aquifers near granite intrusions have elevated fluoride levels of about 2 mg/l, 7.6 mg/l, and 7.02 mg/l in Central Tanzania, and Western and Central Malawi respectively (Bath, 1980; UN, 1989 and references therein; JICA, 1998; Smedley, 2002; Msonda et al., 2007; Sajidu et al., 2008; Nkotagu, 2009). In the Continental Intercalaire and Terminal Complex sedimentary aquifers in Northern Africa, high fluoride concentrations ranging from 0.3-2.3 mg/l were reported in groundwater of Ouargla, Touggourt, Biskra and El-Oued regions of Algeria and Western Tunisia (Nezli et al., 2009; Ramdani et al., 2012; Sekkoum et al., 2012; Baouia and Messaitfa, 2015).

In the Rift Valley, fluoride concentrations between 1 to 36 mg/l and above 5 mg/l have been reported in boreholes and hot springs respectively in Central Ethiopia (Tekle-Haimanot et al., 1987; Tekle-Haimanot et al., 1995; Kloss and Haimanot, 1999, Bjorvatn et al., 2003; Reimann et al., 2003). Fluoride levels of about 40 mg/l and 59-68 mg/l have been reported from boreholes and hydrothermal springs respectively in Arumeru District, Northern Tanzania (Ghiglieri et al., 2010; Thole, 2013). Crater lakes in Ruwenzori Mountain in Western Uganda have about 4.5mg/l fluoride concentration, which feeds nearby aquifers through underground recharge, and in result increase their fluoride concentration (WRAP, 1999; BGS, 2001).

2.3.3 Fluoride and health in Africa

Several health studies in areas with high fluoride concentration in groundwater in Africa show high prevalence of dental and skeletal fluorosis. In the Birimian Formation, a dental fluorosis prevalence of 25-50% and 40% in school children was reported in North-Eastern Ghana and Central Senegal respectively (Smedley et al., 2002; Faye et al., 2007). Dental fluorosis cases in those two countries were restricted to population drinking groundwater from high fluoride Birimian-types aquifers (Smedley et al., 1995). Children aged between 6-13 years showed high prevalence (63.1-95.8%) of dental fluorosis in areas covered by Continental Intercalaire aquifers in Southern Algeria (Almerich-Silla et al., 2008).

There is a high dependence on groundwater for domestic use by the local population in the high fluoride Main Ethiopian Rift, putting approximately eight million people at risk of fluorosis (Tekle-Haimanot et al., 1987; Ayenew, 1998; Gizaw, 1996; Gossa, 2006; Rango et al., 2009, Rango et al., 2012). Dental fluorosis prevalence of about 32-100% mostly in school children has been reported in the area (Tekle-Haimanot et al., 1987; Tekle-Haimanot et al., 1995; Kloss and Haimanot, 1999). These authors also observed mild to chronic skeletal fluorosis among adults above 40 years working in hot environments and consuming groundwater with fluoride levels above 4mg/l. Mungure (1987) reported a 77% dental and 34% skeletal fluorosis prevalence in local villagers in Arusha region, Northern Tanzania using water from a river with 22 mg/l concentration.

Consuming of certain foods or additives found in high fluoride areas in Africa has been shown to increase fluorosis prevalence (van Palenstein et al., 1995; Awadia et al., 2000; Johansen, 2013). Trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) is an evaporative mineral, which crystalize in most Rift Valley alkaline lakes and is used as a food tenderizer, flavor, or as a preservative by most communities in East Africa (Nielsen and Dahi, 1995). Samples of trona from Lake Magadi in Kenya and Lakes Natron, Balangida, Enyasi, and Manyara in Tanzania show fluoride concentrations ranging from 0.1 to 17.9 mg/g (Nielsen and Dahi, 1995; Van-Palenstein et al., 1995; Johansen, 2013). Cases of severe fluorosis have been reported in areas using these trona in Arusha Tanzania (Johansen, 2013) and Western Uganda (Rwenyonyi et al., 1997). Several types of food grown in high fluoride areas have been found to concentrate high fluoride, which increases fluorosis prevalence and severity in the local population (Opinya et al., 1991; Gikunju et al., 1992; Kahama et al., 1997; Almerich-Silla et al., 2008). Examples of such foods include brewed *Cammellia sinensis* (tea) with a mean fluoride of 0.86-2.1 mg/l and *Phoenix dactylifera* (dates) with fluoride ranging from 10.48 – 18.24 mg/l reported in Southern Algeria (Almerich-Silla et al., 2008).

2.4 FLUORIDE IN KENYA AND ITS HEALTH EFFECTS

The problem of high fluoride in natural waters in Kenya and its health effects has been known to be endemic for many years (Williamson, 1953; Bohdal et al., 1969; Ongw'enyi, 1973; Nair et al., 1984; Manji et al., 1986b; Moturi at al., 2002; Akinyi and Kyende, 2013). Early studies involving mapping the distribution of fluoride concentrations in Kenya showed levels of up to 43.5 mg/l in wells and boreholes from across the country, and 1640 mg/l and 2800 mg/l in lakes Elementaita and Nakuru found in the Rift Valley (Williamson, 1953). Later, detailed groundwater sampling in different regions of the country started to show patterns of high fluoride areas such as parts of Nairobi, Central, and Rift Valley Provinces associated with the volcanism of the Rift Valley (Williamson, 1953; Ongweni, 1973; Nair et al., 1984; Gaciri and Davies, 1993).

2.4.1 Fluoride in rocks

Local alkaline volcanic rocks such as basalts, basanites, tephrites, phonolites, trachites, and tuffs with fluorine-bearing minerals are the main sources of fluoride in groundwater in the Rift Valley (Williamson, 1953; Gaciri and Davies, 1993). High fluoride minerals reported in the region include fluorite, cordierite, muscovite, and villiaumite (McCall, 1962; Olaka et al., 2016). Olaka et al. (2016) reported fluoride concentrations averaging 6000 mg/l and 3400 mg/l in pumice and volcanic glass respectively from Naivasha, south of the study area. Magma at relatively shallow depths also injects high fluoride in groundwater, as shown by higher fluoride levels in fumaroles and hot springs than in cold springs near geothermal hotspots in Kenya (Williamson, 1953; Mutonga, 2012).

2.4.2 Fluoride in groundwater

High fluoride groundwater has been identified to have a characteristic geochemical signature by several researchers in the Kenyan Rift Valley region (Njenga, 1982; Maina and Gaciri, 1984; Gaciri and Davies, 1993; Coetsiers et al., 2010; Olaka et al., 2016). These researchers observed high total dissolved solids (TDS), alkalinity, sodium, potassium, bicarbonate, carbonate, and chloride, and low concentrations of iron, calcium, and magnesium. Olaka et al. (2016) showed mineral dissolution and evaporation as major contributors to fluoride release in groundwater, and fluoride enrichment increases from the escarpment to the rift floor. Evaporative enrichment is reported in most of the rift's lakes such as Lake Magadi in the southern part of the Kenyan Rift Valley, where the lakes water had higher fluoride levels (140 mg/l) than rivers feeding it (73 mg/l) (Gikunju et al., 1992).

In the Nakuru area, studies have shown high fluoride in household water and boreholes in Njoro, Molo, and Elementaita area (Gikunju et al., 1995; Kahama et al., 1997; Moturi et al., 2002; Naslund and Snell, 2005). However, despite high fluoride in groundwater, these studies did not show the geological factors associated with fluoride release, its concentrations in the local aquifers, or factors that contribute to high fluoride in groundwater. High fluoride in both rivers and lakes

(0.22-74.98 mg/l), and groundwater (0.09-43.60 mg/l) was reported in Naivasha area, south of the study area where 73% of boreholes analyzed had fluoride above the recommended WHO 1.5 mg/l health limit (Olaka et al., 2016). High fluoride is also reported in the Rift Valley lakes including Lake Naivasha (2-30 mg/l), Turkana (10-100 mg/l), and Bogoroa (1-2.8 mg/l) (Gikunju et al, 1995).

The Kenyan Rift Valley volcanic rocks extend to areas beyond the rift such as Nairobi and Central Kenya regions. Coetsiers et al. (2010) reported an increase in fluoride concentration in groundwater from the recharge zones along the groundwater flow path in Nairobi, where fluoride values ranged from 0.29 mg/l to 10.5 mg/l. Wambu et al. (2014) reported fluoride concentration ranging from 0.4 mg/l to 5.18 mg/l in surface and groundwater in Bondo-Rarieda area in the Kenyan Lake Victoria Basin (LVB), west of the Rift Valley. The high fluoride was associated with erosion of the volcanic highlands embanking the Lake Victoria Basin (Gaciri and Davies, 1993; Gikunju et al, 1995; Moturi, et al., 2010).

2.4.3 Fluoride and health

Epidemiological studies in the Kenyan Rift Valley show positive correlation between fluoride occurrence in groundwater and prevalence of dental fluorosis (Williamson, 1952; Ockerse, 1953; Nair et al., 1984; Manji et al., 1986b). Early studies reported fluorosis in areas in or close to the rift valley, where a prevalence of 47-67% was reported in Asian and African children (Ockerse, 1953). A countrywide study by Nair et al. (1984), reported a high percentage of fluorosis in children living in the Rift Valley (3-96%), Central (25-90%), and Nairobi Provinces (5-40%), which are covered by the Rift Valley geology. He observed a relatively low percentage of fluorosis in Western (2-32%) and Nyanza (0-40%) Provinces, which are not covered by the Rift Valley geology. Schwartz (1952) and Ng'ang'a (1993) reported a 24 % dental fluorosis prevalence in Maasai youth below 20 years in the Central Kenyan Rift. In Nakuru area, several studies have shown high prevalence of dental fluorosis such as: 48.30% prevalence in school children in Nakuru town area (Moturi, et al., 2002), 95.80% in children around Lake Elementaita (Kahama et al., 1997), and 48% in children from Njoro area (Moturi et al., 2002). A general oral health study by the Kenyan Ministry of Health (MoH) in 2015, also revealed high prevalence of dental fluorosis in Counties covered by the Rift Valley geology.

Several studies have shown the contribution of certain food that concentrate high fluoride or prepared using water with high fluoride, to fluorosis occurrence in Kenyan Rift Valley. Examples are: *Vigna unguiculata* (cow peas) with a mean 296.60 µg/g, brewed *Cammellia sinensis* (tea) with an average of 5.00 mg/l, *Amaranthus hybridus* (amarantha) averaging 59.30 µg/g, *Zea Mays* (maize) flour from Elementaita area, and *Oreochromis niloticus* (tilapia) fish with a mean of 15-641 mg/kg from Lake Magadi (Opinya et al., 1989; Gikunju et al., 1992; Kahama et al., 1997).

These studies have shown that the Rift Valley volcanism controls groundwater chemistry in most areas covered by these rocks. High fluoride in groundwater is associated with dissolution of fluoride rich minerals whose concentration varies in rocks, therefore releasing different concentrations of fluoride in groundwater. Several groundwater studies in the study area have shown different concentrations of fluoride. This fluoride variation in boreholes suggests that aquifers in the area have varying fluoride concentrations. In addition, physico-chemical factors such as presence of calcium, bicarbonate, pH, temperature, and water-rock interaction time have been known to affect fluoride dissolution and concentrations in groundwater (Njenga, 1982; Maina and Gaciri, 1984; Gaciri and Davies, 1993; Coetsiers et al., 2010; Olaka et al., 2016). Although high fluoride is reported in the study area, there is no information on its distribution in the aquifers and possible factors affecting the distribution. Additionally, the prevalence of fluorosis in the area has been studied in school children, and no information is available about its state in the general population.

There is need therefore, to understand fluoride concentrations in different aquifers in the study area and factors affecting its concentrations. This is because of the high dependence on groundwater for domestic purposes despite the knowledge of high fluoride in it (ADF- African Development Fund, 2004; Mumma, 2010; Akinyi and Kyende, 2013). Understanding fluoride distribution in the aquifers will assist in identification of aquifers to prospect for low fluoride groundwater, which can in turn reduce fluorosis cases. Despite several studies showing high prevalence of dental fluorosis in school children in the study area (Nair et al., 1984; Moturi, et al., 2010), there is no information on its severity and prevalence in the general population consuming water from different aquifers of the study area. This study will attempt to fill the gap in knowledge regarding fluoride distribution in aquifers in the study area, and how it affects the severity and prevalence of dental fluorosis on the local population.

2.5 CONCLUDING REMARKS

The following is a summary on the literature review chapter:

- Fluorine is a highly electronegative element that accumulates in late crystalizing minerals such as fluoride, fluorapatite, biotite, and hornblende, which are rich in granitic and volcanic rocks.
- Fluoride is released into groundwater mainly through mineral dissolution and its concentration is affected by physico-chemical parameters such as its concentration in the geological formation, groundwater residence time, groundwater pH, temperature, and presence of calcium and bicarbonate.
- Minimum fluoride intake (0.5-1.5 mg/l) by the body helps in bone and dental growth and reduces dental caries, but uptake beyond 1.5 mg/l results to several health complications such as dental and skeletal fluorosis.
- Most common methods used for measuring dental fluorosis include Dean's and TF indexing, which grade fluorosis severity according to the teeth appearance.
- In Africa, high fluoride in groundwater is associated with metamorphic rocks of the Birimian Formation in West Africa and the Mozambique Mobile Belt in East and Southern Africa. In volcanic areas, the high fluoride is associated with the East African Rift System countries including Ethiopia, Kenya, Uganda, and Tanzania, while in sedimentary rocks, the effect is mostly seen in the Continental Intercalaire aquifers in Algeria and Tunisia.
- In Kenya, high fluoride has been reported mostly in areas covered by the Rift Valley geology where mineral dissolution and evaporation has been linked to its release and concentration in groundwater. This high fluoride has been linked to the high cases of fluorosis.
- In the study area, high fluoride has been reported in both ground- and -surface water, which is associated with fluorosis cases mostly in minors. However, despite the known high fluoride groundwater little is known about its distribution in the local aquifers, and the dental fluorosis state on the general population. This study is therefore trying to bridge this gap by determining fluoride concentrations in local aquifers, and its effect on the local population consuming the water.

CHAPTER 3: CASE STUDY: THE OCCURRENCE OF HIGH FLUORIDE IN GROUNDWATER AND ITS HEALTH IMPLICATIONS IN NAKURU COUNTY IN THE KENYAN RIFT VALLEY

3.1 INTRODUCTION

'Nakuru area' as used in this study refers to the area around Nakuru town between Bahati and Rongai in the north, Njoro in the west to south-east, and Gilgil in the south-west. The area is located within latitudes 0°2''S and 0°35''S and longitudes 35°55''E and 36°25''E covering an approximate area of 2,241.85 km^2. The area is administratively under Nakuru Municipality, in Nakuru County, Kenya. It is in the central part of the Kenyan Rift Valley approximately 90 km North West of Nairobi as shown in figure 3 below.

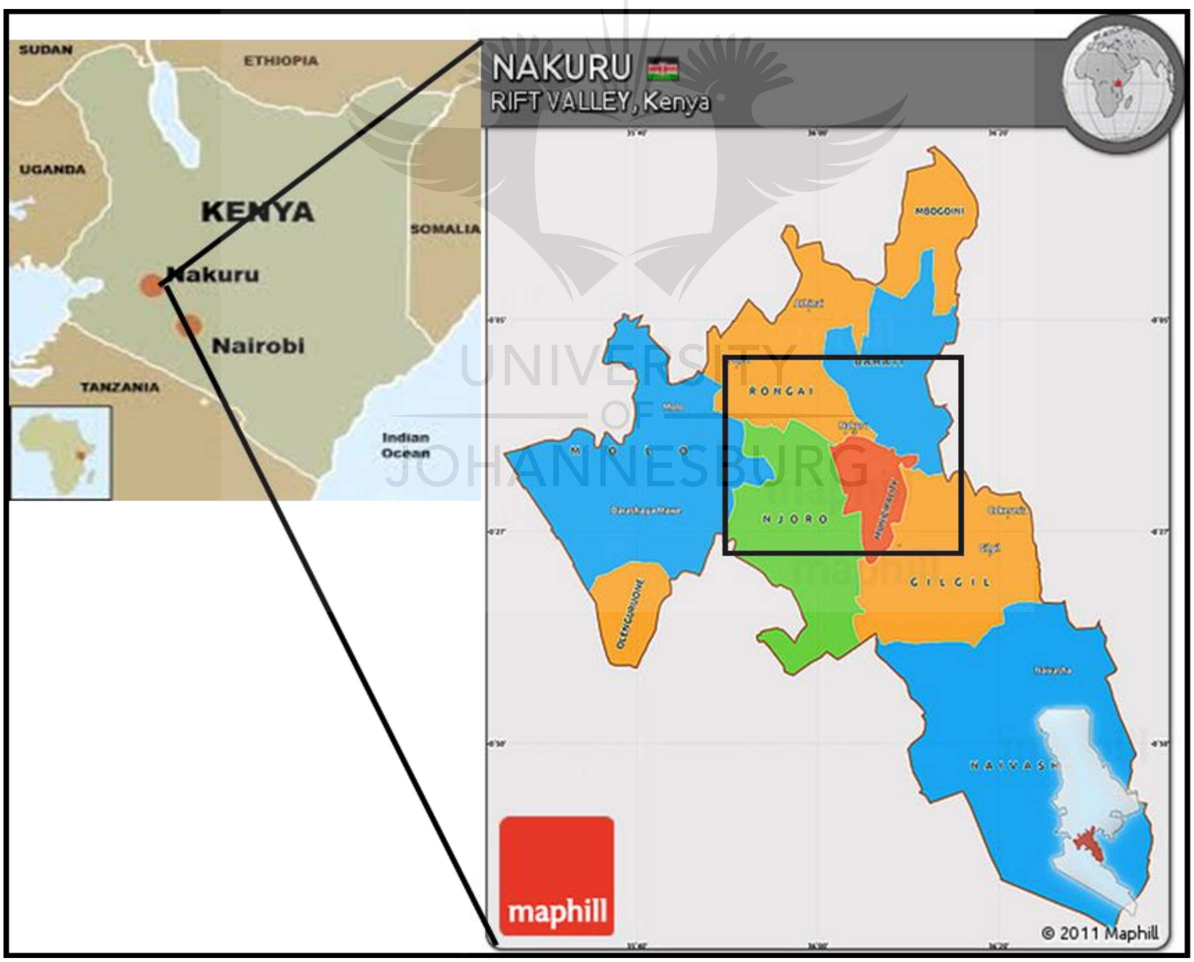


Figure 3. Location of Nakuru area in Kenya. Modified after Maphill (2011).

3.1.1 Physiography and climate

The physiography of the area includes the high rising Mau escarpment in the south-west, and Bahati escarpment in the east rising to about 300 and 400 meters respectively from the rift floor, and a gentle plateau in the rift floor (Bergner et al., 2009; Harper et al., 2013). The rift floor gently slops from the Menengai volcano in the north at 2273 m.a.s.l (Meters above sea level) towards L. Nakuru basin in the south at 1760 m.a.s.l, and slightly rises in the L. Elementaita trough further south at 1776 m.a.s.l (McCall, 1967). A DEM (digital elevation model) was constructed using ArcScene application in ArcGis software, to show the physiography of the study area and is shown in Figure 4 below.

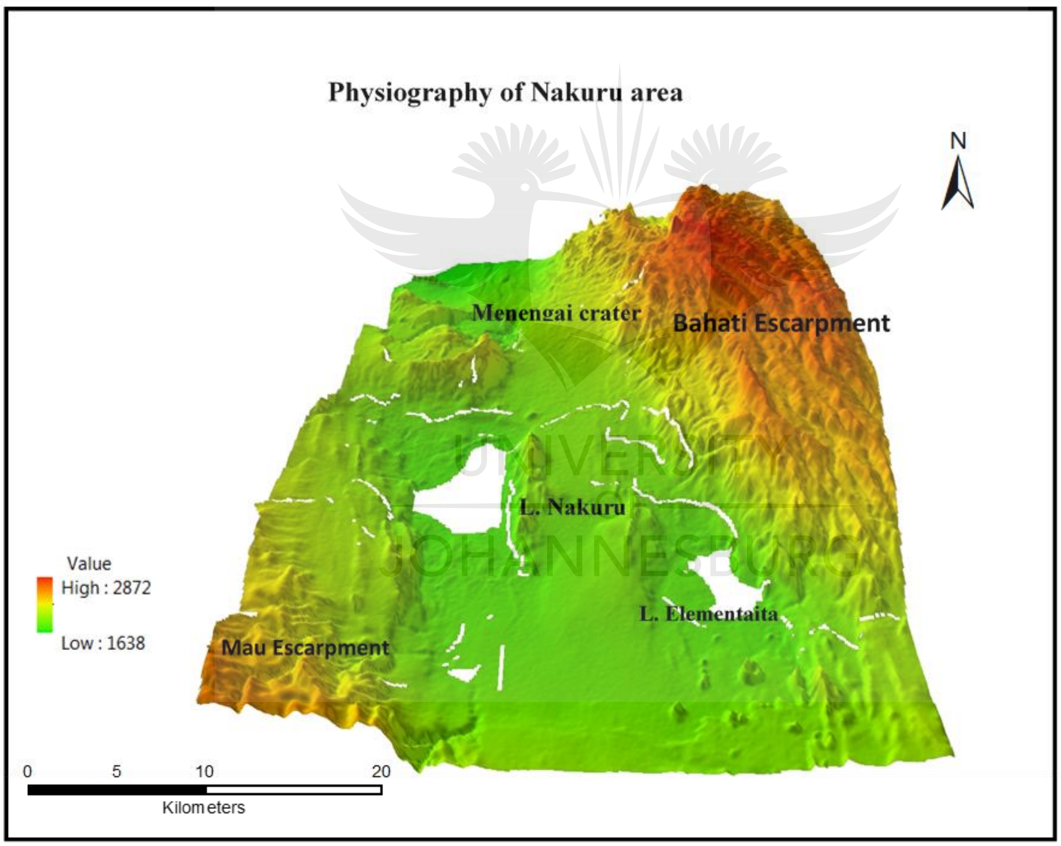


Figure 4. A DEM of the study area showing the high Bahati and Mau escarpments and the low rift floor in the middle. The green colours indicates low elevation while brown indicate high elevation in meters.

Rainfall patterns in the area differ from highlands to lowlands. The areas around Mau and Bahati escarpments in the west and east respectively are cool and wet, with a short dry season (Becht et al., 2006; Bergner et al., 2009). The lowland rift floor areas in the middle, are characterized by warm to hot, and arid conditions with short to long rainy seasons, where high evaporation is experienced close to the lake areas, as shown in Figure 5 below (Becht et al., 2006; Bergner et al., 2009). The Bahati and Mau escarpments are wetter averaging 1200 mm/year, while the low rift floor receives reduced precipitation of about 200-600 mm/year (Becht et al., 2006; Alamirew et al., 2007; Bergner et al., 2009).

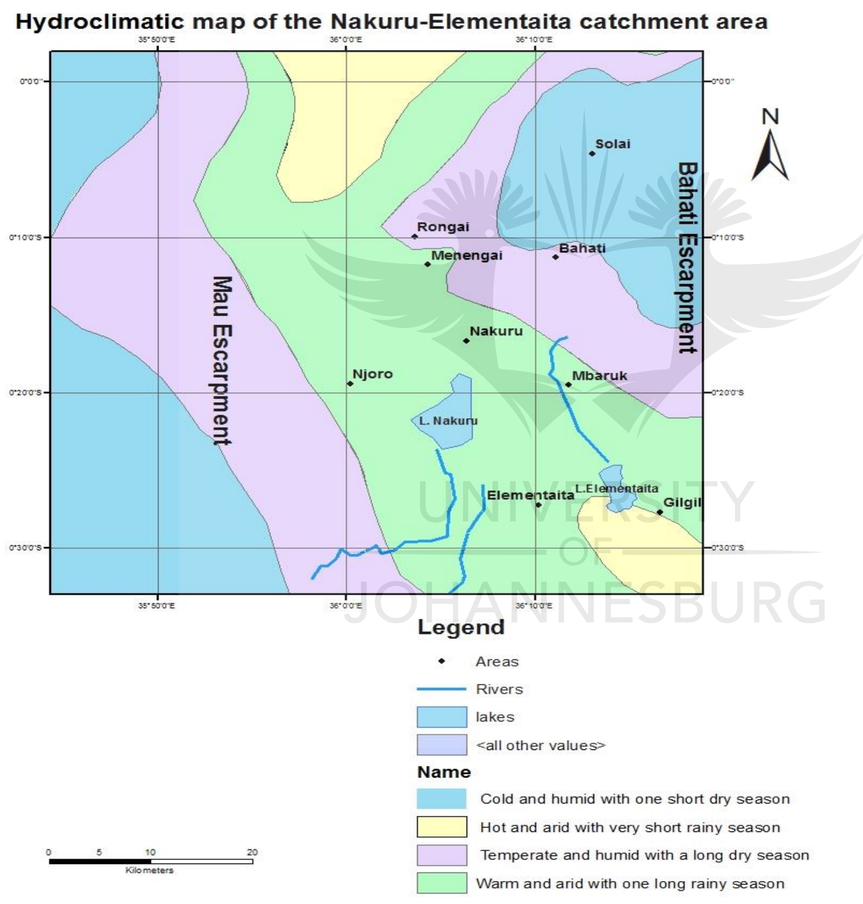


Figure 5. A hydro-climatic map of the Nakuru-Elementaita catchment area showing the hot, warm, and arid climate in the rift floor covering the Lake Nakuru-Elementaita Basin, and the temperate, cold, and humid climate in the rift escarpments. Modified from Bergner et al. (2009).

The average temperature of the entire area ranges from 12-29 °C, where February-March are the hottest months while July is the coldest as shown in Figure 6 below.

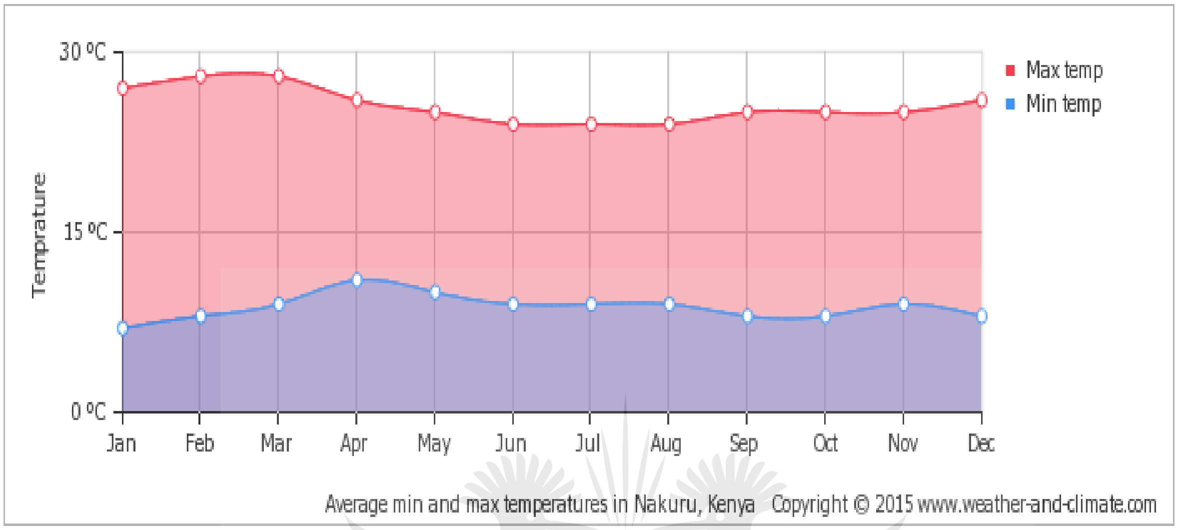


Figure 6. Average Min. and Max. Temperature of Nakuru County. From weather and climate (2015).

3.1.2 Population and water supply

The population of Nakuru County stands at about 1.9 million people, from The Kenya National Population Housing Census (KHPHS) projection of 2009, with a 3% annual growth rate (County Government of Nakuru, 2016; Infotrackea, 2017). The census also showed that, the population is made up of 50.2% males and 49.8% females, of which, 51% are youth aged below twenty years. The population increase in the area is caused by favorable climatic and weather conditions, recent increase in agriculture and industrial activities, which provide job opportunities and sufficient food (County Government of Nakuru, 2016).

Public water supply by the government in the area only covers about 36% of the households and is faced with challenges such as insufficiency for the increasing population, deterioration of infrastructure, pollution, and poor maintenance (ADF, 2004; Rutere, 2013). Natural water sources in the area include major and minor rivers Njoro, Makalia, Larmudiac, Nderit, Ngosor and streams from the Mau and Bahati forests, draining into Lake Nakuru, and Meroni, Kariandusi, Mbaruk, from Bahati highlands, draining into Lake Elementaita (McCall, 1967; Becht et al., 2006; Olago et al., 2009). This water shortfall, has resulted in the establishment of community schemes formed to facilitate water supply by drilling boreholes using funding from the government and donors. Private and mostly community owned boreholes, are the main source of domestic water especially in drier areas of Naivasha, Gilgil, Njoro and Rongai (County Government of Nakuru, 2016).

With a 3.05% population growth rate, Nakuru County which is the fourth most populous in Kenya is expected to pass the 2 million population mark in 2017 from 1.7 million reported in 2012 (KNBS- Kenya National Bureau of Statistics, 2015; ASDSP- Agricultural Sector Development Support Programme, 2016). The high demand for clean water for domestic, agriculture and industrial use has led to heavy dependence on groundwater to supply this increasing population (Olaka et al., 2016). Water extraction is through shallow hand dug wells and deep-drill tubes, which tap from shallow superficial water and several aquifers with varying fluoride levels exposing people to the risks and effects of fluoride (Nair et al., 1984; Nyaora et al, 2001; Akinyi and Kyende, 2013).

Long term use of high fluoride groundwater has led to high cases of varying degrees of fluorosis and related diseases observed in the County (Nair and Manji, 1982; Rombo and Muoki, 2012; Akinyi and Kyende, 2013). Most complications related to dental fluorosis include teeth sensitivity, bleeding gums, gingivitis, and dental caries (Ockerse, 1953; Chibole, 1988). The County health facilities in the area include seven hospitals, 21 health centers and 117 dispensaries (County Government of Nakuru, 2016). There are several private health facilities in the study area mostly located in urban centers such as Nakuru town. Health services are offered in most of the public hospitals, but due to their overcrowding and inadequate status most people opt to use private clinics (Muchukuri and Grenier, 2009).

3.2 THE GEOLOGY OF THE STUDY AREA

3.2.1 The tectonic and geological setting of the Kenyan Rift Valley

The Kenyan Rift Valley also known as the Gregory rift, named after Gregory's 1896 and 1921 works, cuts through Kenya in a roughly N-S direction from Lake Turkana in the north to Lake Magadi in the south as shown in Figure 7 below. The rift has an average of 40-80 km width, and the volume of volcanic rocks extends to areas beyond the rift valley (King et al., 1972; Wood and Guth, 2014). The rift is argued to be a tensional feature of an early continental break up, forming block faulting (Fairhead, 1976; Mbia, 2014). Extensional tectonism caused the uplift of the rift shoulder and volcanism, forming a typical horst and graben structure seen today as the shoulders and floor of the Rift Valley, with different volcanic suites deposited from the volcanism (Macdonald et al., 2001; Bergner et al., 2009 and references therein).

Volcanism, faulting, and extension started in Turkana in the north (35-30 ma) and propagated southwards to Northern Tanzania with time (MacDonald, 2003). The volcanic rocks show a range of composition from basic to acidic, but a range of mild alkaline-basalt-trachyte to strong alkaline and under saturated phonolites is more readily observed than the acid range (Bowen, 1938; King et al., 1972). The volume of these magmas in the Kenyan rift is estimated to be around 924,000 km^3, and believed to be both lithospheric and mantle derived (Macdonald, 1993; Macdonald et al., 1994). The rift overlies the Proterozoic Mozambique Mobile Belt in the north, the Archean Tanzanian craton in the south, and a margin of the Tanzania craton reworked and overthrust during the late Proterozoic collision with the mobile belt (Smith & Mosley 1993; Macdonald, 2003).

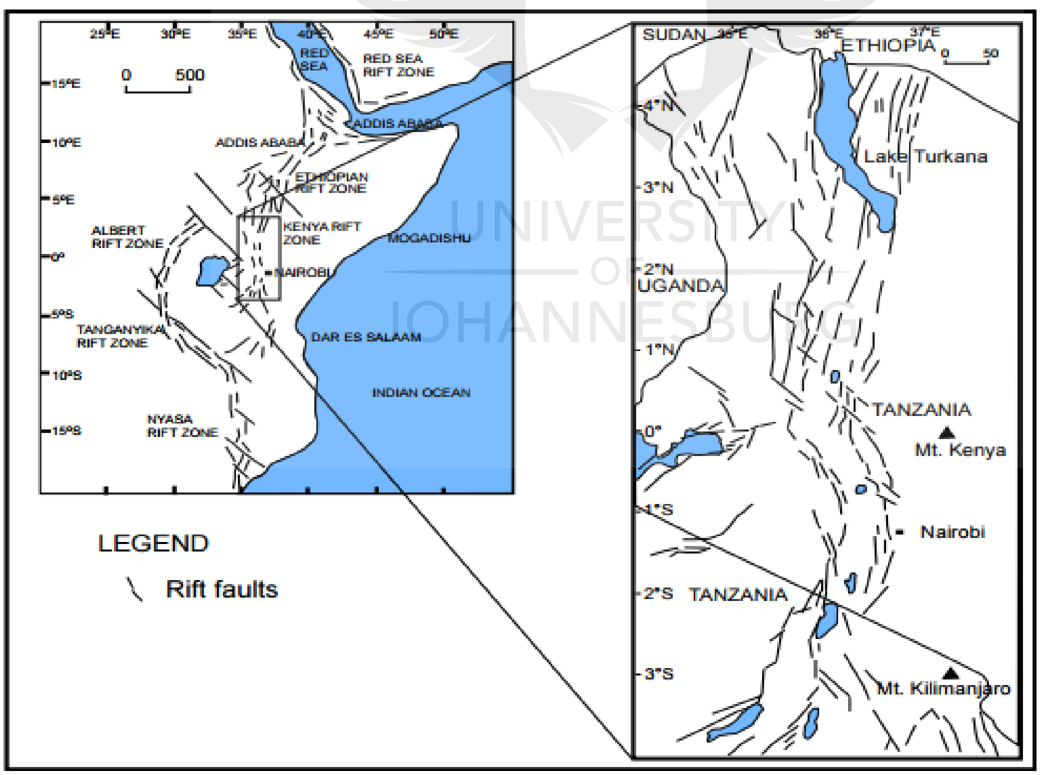


Figure 7. The location of the Kenyan Rift in the eastern arm of East African Rift Valley. From Mbia (2015).

3.2.2 Regional geology

Nakuru area lies in the central part of the Kenyan Rift Valley, composed of Late Quaternary volcanic rocks deposited during the development of the Rift Valley (McCall, 1967). Periodic eruptions deposited different lava suites and ash in the region, dominated by trachytes, basalts, rhyolites, volcaniclastics, ash flow tuffs, and their weathering products, erupted from volcanoes and fissures (McCall, 1967; MacDonald et al., 2011). The rift floor has about 400 meters' surficial throw from the escarpments (Olago et al., 2009). The major escarpments in the Central Kenyan Rift are the Mau on the west and Bahati on the east that also act as catchment channeling water into the rift graben (Olago et al., 2009).

The Mau-Kinangop tuff, ash, and ignimbrites deposits are the oldest rocks deposited during the Pliocene, which were followed by faulting that triggered the formation of an early graben structure (Baker et al., 1988). Increased faulting triggered the formation of the Mau escarpment and eruption of Limuru flood trachytes in the south in 2.0-1.8 ma (Baker et al., 1988). On the rift floor, lakes Baringo, Bogoria, Nakuru, Elementaita and Naivasha are located on lake basins filled with Quaternary deposits such as volcanic, lacustrine, and pyroclastic sediments, formed by erosion of the rift escarpment (Olago et al., 2009).

3.2.3 Local geology

The oldest rocks in the area were erupted from Menengai volcano in the north and several fissures depositing basalts, trachytes, phonolites, tuffs, and subaqueous tuffs (McCall, 1967). The northern part is composed of trachytes, pyroclastic tuff, pyroclasts, basalts, and trachy-basalts (McCall, 1967; Macdonald et al., 2011). On the west to north east side, there are a series of welded-vitreous to pumice Mau tuffs in the Njoro-Rongai area, and lower Menegai volcanics, which include vitreous tuff and phonolite-trachytes (Macdonald et al., 2011). Tuffs, pumice, and rhyolites cover most of Bahati area in the north-east, overlying phonolites. In the south, Sirrkon volcanics extend from Gilgil and include glassy trachytes, basalts, tuff, young lava flows overlain by agglomerates, and superficial deposits. Younger rocks of Pleistocene and Holocene in the area include basalts, trachytes, ashes found in Menengai in the north and Bahati escarpment in the east, basaltic flows, tuff, rhyolites, phonolites and pyroclastics in most parts of central Nakuru and Elementaita areas (McCall, 1967).

The rift flanks have over 2000m thick volcanic succession mainly ignimbrites, welded and un-welded tuffs, rhyolites, trachytes and basalts in the Mau escarpment in the west, and trachytic tuffs and ignimbrites in the Bahati escarpment in the north-east (McCall, 1967; Olaka et al., 2016). The thicker rift floor at about 3000-4000m, is composed of Plio-Pleistocene trachyte, rhyolites, phonolites, basalts, ignimbrites, and comendites (McCall, 1967). Overlying these rocks are Pleistocene pyroclastics, Holocene volcanics, lacustrine, and fluviatile sediments deposited in paleo lakes occupying the Nakuru-Elementaita basin in the rift floor (Bergner et al., 2009). These lake deposits are mainly volcanic ash, silts, clays, and diatomite, which can attain a maximum thickness of up 33m (Thomson and Dodson, 1963). Figure 8 below shows the geology of the study area originally mapped by McCall (1967), and digitized from Alamirew et al. (2007).

Erosion is evident in the area by the occurrence of stratified pumice with obsidian, trachytes, and syenite fragment beds in Menengai area, whose stratification and sorting was aided by wind deposition (McCall, 1967). In the lake basins, several deposits of diatomite and tuffs were periodically deposited in the Elementaita and Nakuru basins (McCall, 1967). Quaternary lacustrine sediments of varying thickness cover most parts of Nakuru-Elementaita basin such as stratified graded tuff, diatomite deposits, pyroclastic sediments, lacustrine sediments, gravels, coarse graded pumice tuff, and conglomeratic tuff (McCall, 1967).

Mineralogical analysis of rocks in the Kenyan rift reveals dominant minerals such as quartz, k-feldspars, olivines, pyroxenes, muscovite, cordierite, haematite, and alteration minerals such as illite and kaolinite as dominant in the volcanic rocks (McCall, 1967; Olaka et al., 2016). Peralkaline trachytes and tuffs in the Menengai area have varying compositions of volcanic glass, with fluoride values of up to 0.53 weight % (Macdonald et al., 2011). Other fluoride rich minerals reported are amphiboles and apatite in the Menengai tuff and trachytes, and cordierite, muscovite, illite, and kaolinite, in the southern part of the study area (Macdonald et al., 2011). Rocks rich in volcanic glass, cordierite, and muscovite have fluoride concentrations reportedly of about 3400 to 5000 ppm in Naivasha, south of the study area (Olaka et al., 2016).

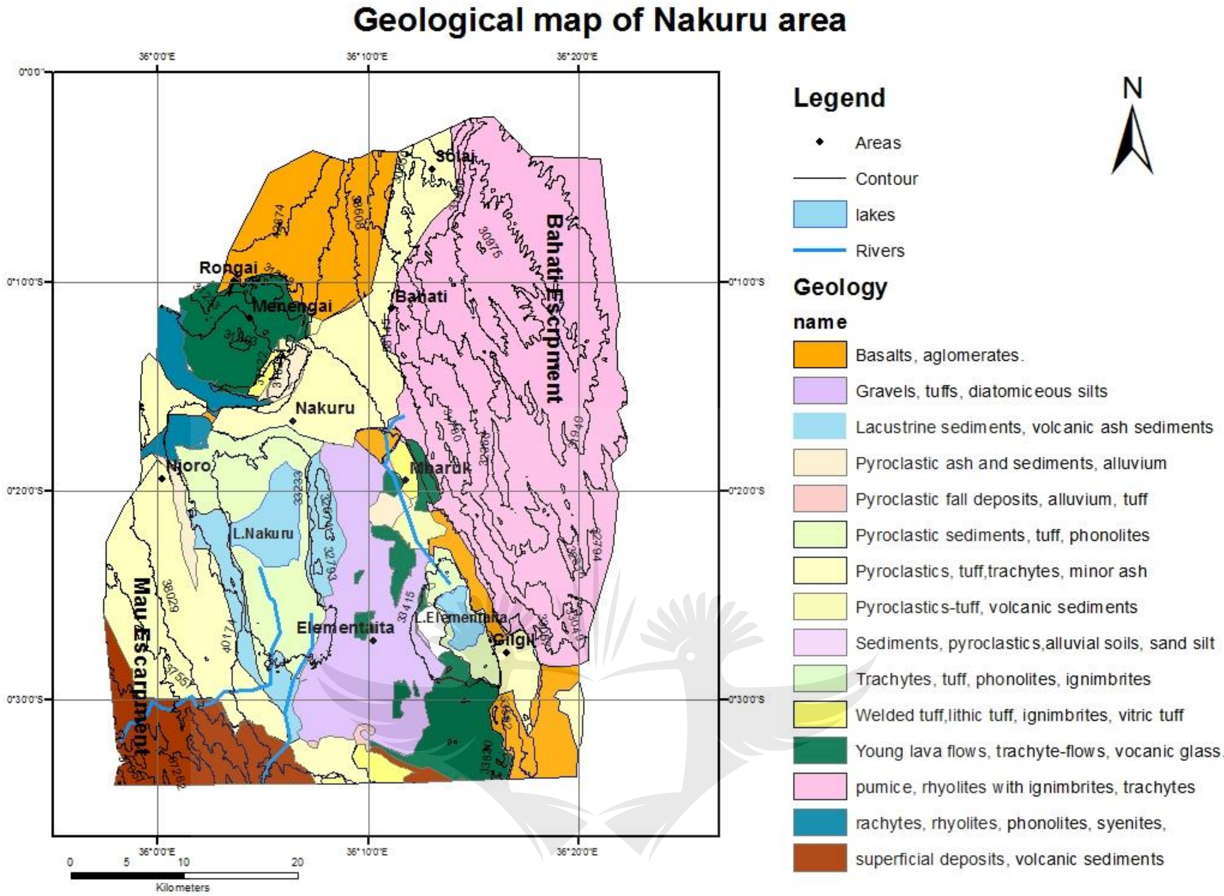


Figure 8. Geological map of Nakuru area. Modified from Alamirew et al. (2007).

3.3 SURFACE DRAINAGE AND HYDROGEOLOGY OF NAKURU AREA

3.3.1 Surface Drainage

The general drainage system of the Rift Valley is composed of closed basins, with inflow from the rift flank (McCall, 1967; Becht et al., 2006). Surface and groundwater flow is from the elevated rift escarpments into the rift floor (Olago et al., 2009). An example in the area, is the Bahati escarpment which feeds the aquifers around Bahati and Menengai area (Obiri, 2006; Olago et al., 2009). Surface run-off is poor in the rift floor due to porous rocks such as the pumice formations leading to high ground seepage (McCall, 1967; Allen et al., 1989; Alamirew et al., 2012).

The two lakes in the area, L. Nakuru and L. Elementaita are alkaline-saline, sitting on closed basins formed by tectonic and volcanic activities (Olago et al., 2009; Jirsa et al., 2013). The lakes sit on shallow pans floored by salt impregnated sedimentary materials (Allen et al., 1989; Becht et al., 2006). The sodium- and bicarbonate- rich Rift Valley lakes' water originates from the dissolution of the local alkaline rocks (Allen et al., 1989; Jirsa et al., 2013). Due to high evaporation rate and lack of surface outlets in the rift floor, these lakes have high salinity caused by evaporative concentration (Allen et al., 1989).

3.3.2 Hydrogeology

Groundwater flow in the study area has a radial flow from the escarpment into the rift floor, and a northerly flow from L. Elementaita and L. Nakuru at lower altitudes in the south towards the north, through diffuse inflow (Becht et al., 2006; Olaka et al., 2016). The groundwater accumulates solutes along the flow path and dumps them into the lakes causing an increase in salinity, therefore making the lakes sinks for dissolved solutes (Clarke et al., 1990; Becht et al., 2006).

Shallow faults on the escarpments cause fast flow of water into the rift floor leaving low productive zones in those areas, while grid faulting in the graben disrupts fast groundwater flow causing low and high productive zones for groundwater resources (McCall, 1967; Allen et al., 1989; Alamirew et al., 2007). Much of L. Nakuru water is from the rift flanks, unlike L. Elementaita, which receives much if its water from L. Naivasha further south out of the study area (Becht et al., 2006 and references therein). This groundwater flow within the rifts lakes and escarpments is linked to aquifers in the region and highly influences their geochemistry and productivity (Olago et al., 2009). Figure 9 below shows groundwater flow in the Central Kenyan Rift linking the lakes on the rift's floor.

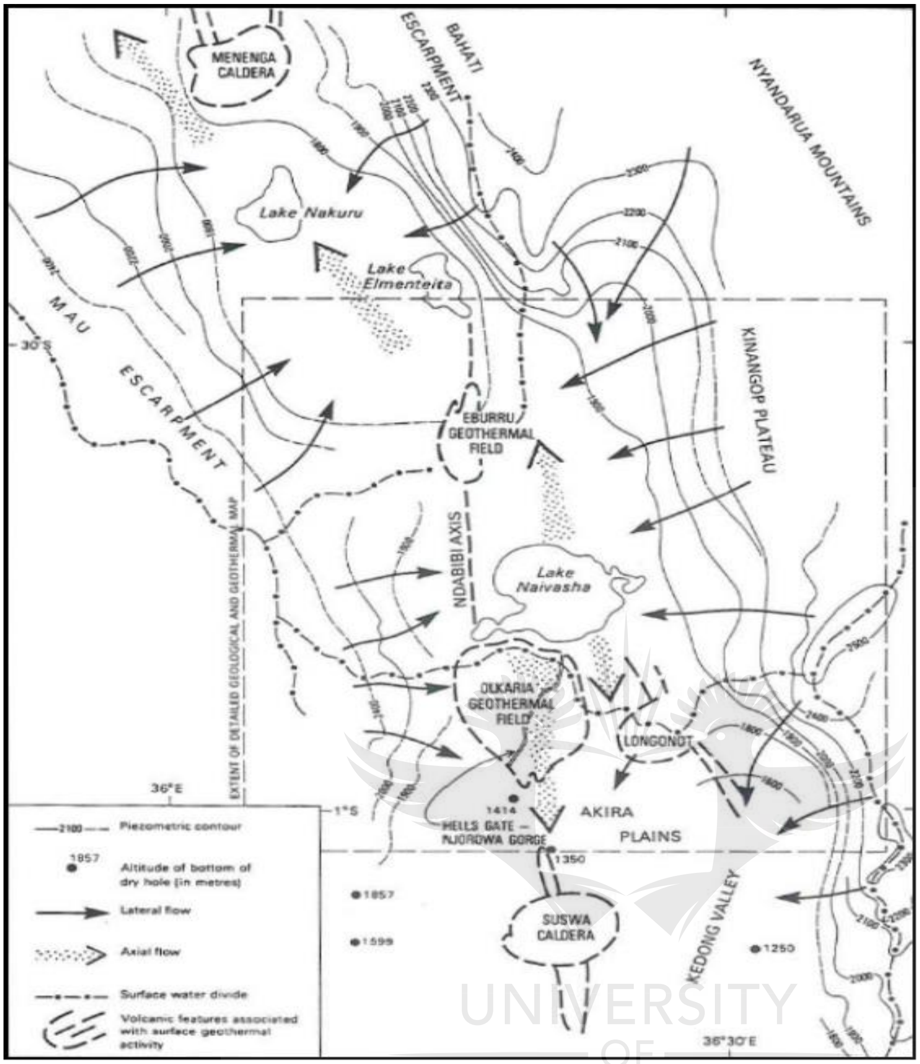


Figure 9. Groundwater flow between the rift valley lakes. From Clarke et al. (1990).

In the rift floor, porosity and faults promote groundwater storage where, high yield aquifers mostly occur in contact zones between rock types, weathered zones, fault zones, fractured volcanics, and in reworked volcanic sediment zones (Allen et al., 1989; Olago et al., 2009). High porosity and permeability of pumice and reworked alluvial and lacustrine sediments makes them the highest productive aquifers in the area (Alamirew et al., 2007). Low productivity is reported in aquifers with small grained sediments such as trachytes with ash, phonolites, volcanic ash, rhyolites, and syenite (Alamirew et al., 2007).

Generally, the Nakuru-Elementaita catchment is described as low productive compared to the Naivasha catchment located south of the study area, which has the highest production in the

Kenyan Rift Valley (Allen et al., 1989, Alamirew et al., 2007). Allen et al. (1989) observed low productivity in aquifers south of Elementaita due to low permeability of sand and silt deposits, and poor to good productivity in the Elementaita-Nakuru area which mostly has sediments, pyroclastic, and lava aquifers. They also reported low productivity in the escarpments due to poor permeability of the tuff.

3.3.3 Aquifer Types in the Nakuru area

Aquifers in the Nakuru area have been studied and characterized using: borehole specific capacities, groundwater flow maps, isochore maps, saturation indices calculation, ionic relationship, hydrochemical facies, and Vertical Electrical Sounding (VES) (Allen et al., 1989; Alamirew et al., 2007; Olago et al., 2009; Sosi, 2010; Kuria, 2013). The aquifers occur at different depths, are often superimposed, and semi-confined to confined, with yields of about 5-15.7 m^3/h (Olago et al., 2009 and references therein). Kuria (2013) characterized North Solai, Lomolo-Olobanita, and Rongai aquifers located north and north east of the study area using borehole specific capacities, groundwater flow maps, and isochure map. The aquifers had average borehole depth of between 105 and 225 meters, average borehole to groundwater depth of between 88 and 159 meters, and water rest levels between 52 and 166 meters. The average specific capacity of these aquifers indicated both medium to high (in the North Solai and Lomolo-Olobanita) and low (Rongai) groundwater potential. The Kabatini aquifer located in Bahati, north of the study area has been described as semi-confined, with high yield, and at a depth of 60 meters, with more than 100 meters in thickness (Sosi, 2010; Mwangi, 2012).

A study by Alamirew et al. (2007) will be used for characterizing and describing the aquifers in this study due to its detailed mapping and description of the aquifer systems covering the area of the current study. Using VES and borehole specific capacities, they categorized the major Nakuru aquifers per their productivity into four aquifer groups as described below and shown in Figure 10 below. The aquifer map by Alamirew et al. (2007) was digitized using GIS ArcMap tool and described below.

3.3.3.1 Aquifer group 1: extensive and low productive

These aquifers are in the highlands, mostly in areas above 2200 m.a.s.l. They have low productivity, due to low fissure connectivity and low intergranular pore space caused by the presence of volcanic ash. Groundwater flow is through fissures or weathered regions of volcanic rocks. This aquifer group covers the mid-northern, south-west, and small patches in the middle of the study area. The rock types include pyroclastics, minor ash, alluvial, gravel, sand, silt, and rocks such as pumice-tuff, tuff, trachytes, and phonolites.

3.3.3.2 Aquifer group 2: extensive and moderate productive

These aquifers are found in lowland areas mostly below 2200 m.a.s.l. They are extensive and groundwater flow is through fissures. They are mainly composed of faulted non-porphyritic basalts, obsidian and welded tuffs, lacustrine sediments, and graded pumice-tuff intercalations. This aquifer group covers the larger middle part of the study area from north to south, encompassing the lake Nakuru-Elementaita basin, and bordering the Bahati escarpment.

3.3.3.3 Aquifer group 3: extensive and highly productive aquifers

These extensive aquifers are mainly volcano-sedimentary and are mostly located in areas with elevations above 2200 m.a.s.l. Water flow is intergranular and productivity increases with pore space and interconnectivity. They are mostly composed of pyroclastic, lacustrine, and alluvium sediments at low altitude close to the lake Nakuru-Naivasha basin, and tuffs, rhyolites, and ignimbrites in the elevated Bahati areas. This aquifer system covers the major part of north-eastern Bahati area, the south-east area, and small patches east and west of L. Nakuru. The aquifers trend in a NW-SE direction.

3.3.3.4 Aquifer group 4: minor aquifers with local and limited productivity

This aquifer group is mostly local in extent, non-continuous, and often has limited capacity. It is localized around the western shores of L. Elementaita. It contains consolidated ash and those aquifers around the lakes have trona-impregnated silts gravels, tuff, and diatomaceous silts.

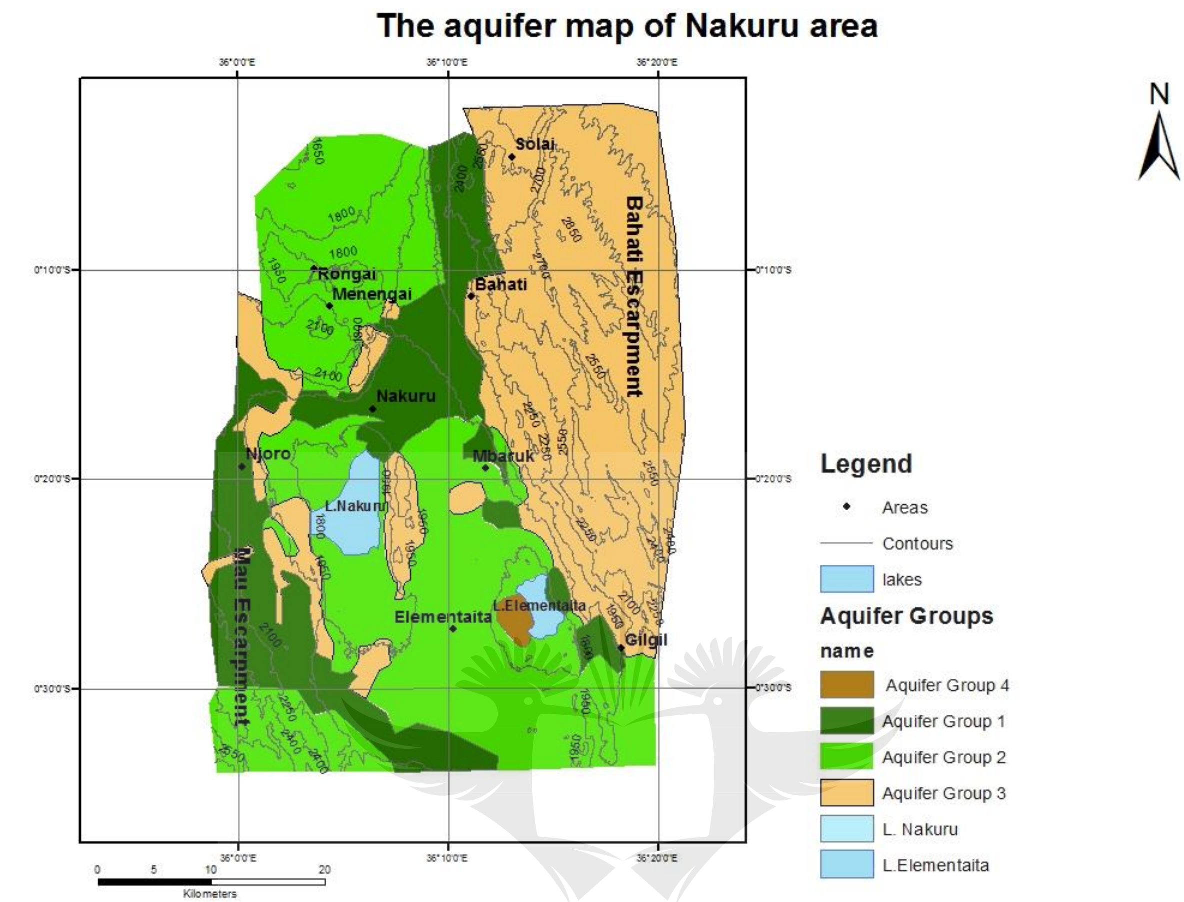


Figure 10. Aquifer map of the study area showing location of different aquifer groups and boreholes used for this study. Modified from Alamirew et al. (2007).

3.4 BOREHOLE WATER RESULTS AND DISCUSSION

The data from 32 boreholes used in this study are presented in Appendix 1, and the analysis presented in this section. The depths of the boreholes range between 65 and 250 meters with an average of 141 meters, and were drilled between 1999 and 2013. Physical properties recorded include: borehole identity, GPS location, depth, water pH, hardness, total dissolved solids, and rock type at water strike level. Ions and anions include: fluoride, calcium, magnesium, sodium, potassium, chlorine, sulphates, nitrates, carbonates, and bicarbonate. The geological map used was digitized from Alamirew (2012), which was modified from the original geological report covering the study area by McCall (1967) to a scale of 1: 100,000. Aquifer boundaries were digitized from Alamirew (2012) to a scale of 1: 100,000.

3.4.1 Hydrochemical characteristics

3.4.1.1 Groundwater quality

Groundwater quality was determined by analyzing the concentrations of dilute solids according to permissible limits set by WHO and NEMA (WHO, 2006; WSREB- Water Services Regulatory Board, 2002). The groundwater in the study area is slightly alkaline with pH values ranging from 5.8 to 9.1 and an average of 7.8, which falls within the permissible range of 6.5-9.5. Total dissolved solids (TDS) values ranged from 122 to 2210 mg/l with an average of 653.91 mg/l, and only 21.82 % (n=7) of the boreholes had values above the recommended value of 1000 mg/l for fresh drinking water by WHO (Todd, 1980; WHO, 1996; WHO, 2006), but were within NEMA's range of below 1500 mg/l. Total hardness ranged from 4.1 to 300 mg/l with an average of 50.4 mg/l, which is lower than the recommended value of 500 mg/l. Using Sawyer and McCarty's (1967) hardness classification scheme, 29 boreholes in the area (89.66%) had soft waters with total hardness < 75 mg/l, 2 had hard waters (Hardness 75-150 mg/l) and 1 had moderately hard water (hardness 150-300 mg/l). Magnesium ranged between 0.00 to 37.00 mg/l with an average of 4.24 mg/l, which is below the recommended limit of 50-100 mg/l. Calcium ranged between 1.30 to 35.00 mg/l with an average of 9.56 mg/l, which is below the recommended value of 75-250 mg/l. Carbonate concentrations ranged from 0.00 to 78.90 mg/l with a mean of 7.12. Nitrate concentrations were low ranging from 0 to 7.5 mg/l, with an average of 1.69 which is below the recommended value of 10 mg/l. These low nitrate values indicate low to no pollution of the groundwater by industrial input such as fertilizer from farms. The statistical summary of these parameters is shown in Table 4 below.

Fluoride concentrations ranged between 0.5 and 72 mg/l with an average of 11.08 mg/l, which is higher than the WHO and NEMA recommenced value of 1.5 mg/l (WHO, 2006; WSREB, 2002). 3.13% (n=1) of the studied boreholes showed fluoride levels below the recommended value of 0.5 mg/l for the proper growth and development of teeth and bones, 9.37% (n=3) of the boreholes had the recommended fluoride level of 0.5 – 1.5 mg/l, and 87.50% (n=28) had fluoride levels above 1.5 mg/l, which can cause dental, and skeletal fluorosis (WHO, 1984).

Geochemical characteristics observed include high sodium, sulphates, bicarbonates, potassium, carbonates, chloride, and fluoride and low concentrations of calcium, magnesium, and nitrates. These characteristics, agree with results from other studies in the Kenyan Rift Valley (Njenga, 1982; Maina and Gaciri, 1984; Gaciri and Davies, 1993; Coetsiers et al., 2010; Olaka et al., 2016). Dissolution of alkaline volcanic rocks and glass yields groundwater rich in sodium, bicarbonates, potassium, carbonates, chloride, and fluoride and high precipitation of the alkaline water depletes calcium and magnesium (Nanyaro et al., 1984; Gaciri and Davis, 1993; Rango et al., 2012). Sodium and calcium are primarily weathered from intermediate plagioclases, while fluorite, apatite, topaz, villaumite and sodic amphiboles release significant amounts of fluoride (Gaciri and Davis, 1993; Olaka et al., 2016).

Table 4. Statistical summary of geochemical properties of the groundwater in the study area showing physicochemical properties, numbers of boreholes as count, maximum and minimum values, mean and, standard deviation.

Variable	Count	Minimum	Maximum	Mean	Std. dev.
DEPTH(M)	32	65.00	250.00	141.41	43.93
PH	32	5.80	9.10	7.87	0.74
F^-	32	0.50	72.00	11.08	14.49
Ca^{2+}	32	1.30	35.00	9.56	8.34
Mg^{2+}	32	0.00	37.00	4.24	6.85
Na^+	32	13.0	995.00	222.37	270.82
K^+	32	1.000	82.40	12.78	13.62
HARDNESS	32	4.10	300.00	50.40	61.99
Cl^-	32	0.05	167.00	33.41	40.26
SO_4^{2-}	32	0.10	281.00	35.78	56.04
NO_3^{2-}	32	0.00	7.50	1.67	1.60
HCO_{3-}	32	100.00	1590.00	453.50	360.54
TDS	32	122.00	2210.00	653.91	597.18
CO_3^-	32	0.00	78.90	7.12	15.15

3.4.1.2 Hydrochemical Facies

The results from the piper diagram generated by the GW_Chart program, show a dominant Na-HCO_3 water type, with a slight Na-HCO_3-Cl type in the study area as shown in Figure 11 below. These results agree with most research in the Kenyan Rift Valley (Berner and Berner, 1987; Ging et al., 1996; Olago et al., 2009). Weathering of silicate minerals produces sodium as the dominant anion and dissolution of CO_2 in groundwater releases HCO_3 rich groundwater (Gaciri and Davis, 1992; Rango et al., 2012; Ghiglieri et al., 2012). The results indicate that most groundwater with low TDS values are mostly $NaHCO_3$ and meteoric, due to little dissolved alkali minerals soon after infiltration from recharge areas (Ging et al., 1996). The slight Na-HCO_3-Cl type water often forms in high evaporative environments such as around lakes in the Rift Valley rift floor, due to the presence of dissolving evaporated salts (Olago et al., 2009).

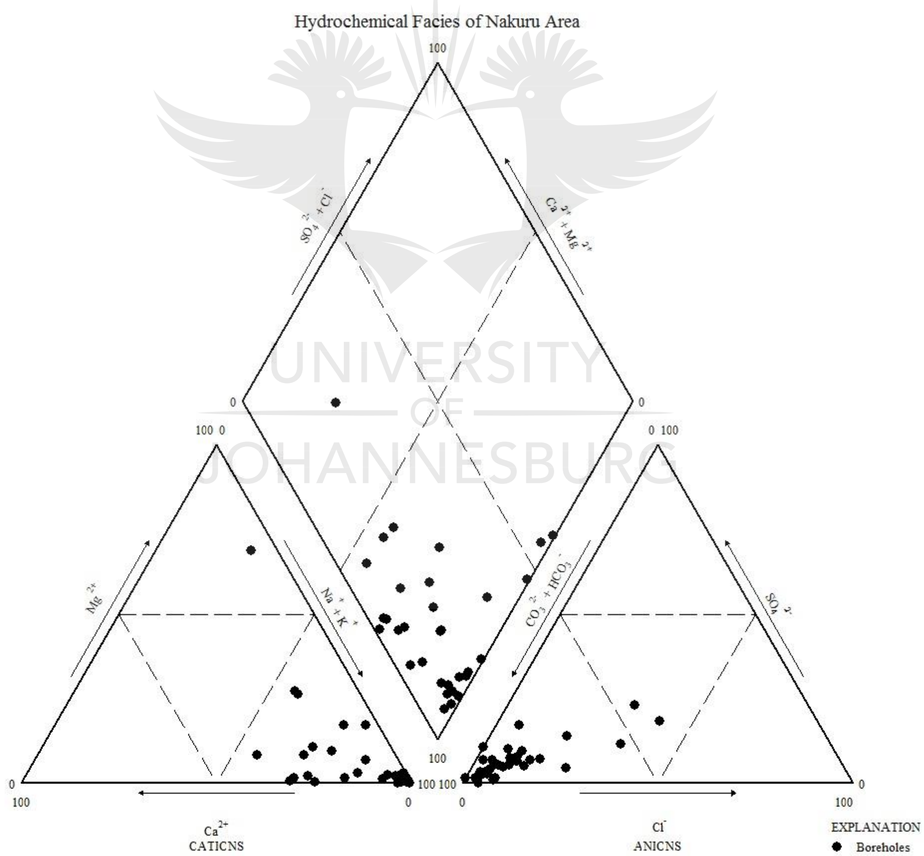


Figure 11. Piper diagram showing the dominant Na-HCO_3 and slight Na-HCO_3-Cl geochemical facies of the study area.

3.4.2 Statistical Analysis

The data was subjected to several statistical analyses including PCA (Principal Component Analysis), factor score, Pearson's correlation, and linear regression. PCA determined the dominant physico-chemical parameters in the groundwater, Pearson's correlation and linear regression were used to determine the nature and magnitude of the relationship between fluoride and the dominant physico-chemical parameters, while factor score determined the cluster of boreholes with similar characteristics, and was therefore, used to determine boreholes with the highest fluoride concentrations.

3.4.2.1 Principal Component Analysis (PCA)

PCA was used to group the dominant physicochemical parameters that show similar behavior and use them to explain the occurrence and association of all 14 parameters used in this analysis. XLSTART extension tool in Microsoft Excel was used for PCA. The data was run using the program and the results are discussed below.

Based on the eigenvalues screen plot shown in Figure 12 below, the 14 components (physicochemical parameters) were reduced to three main components (PC1 to PC3). This is because these components have eigenvalues greater than 1 and account for 64.75% of the total variables. The three components were therefore, considered significant and can be used to explain the association of all the parameters in groundwater (Bhat et al., 2014). Factor loadings matrix for these variables was generated and was used to show dominant parameters in the principal components as shown in Table 5 below.

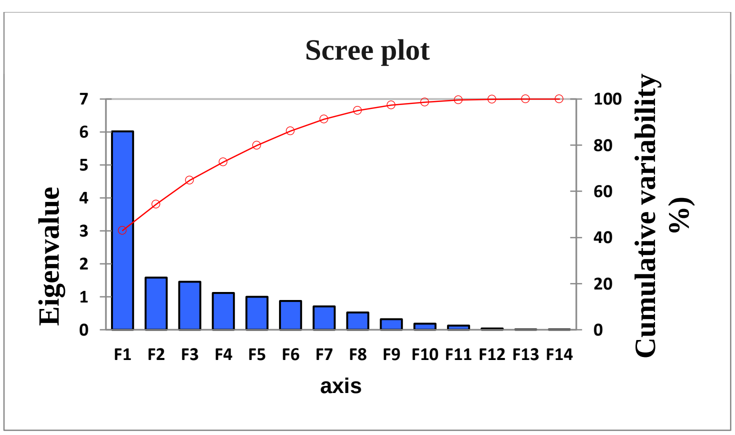


Figure 12. Score plot of eigenvalues versus components and % cumulative variability for Nakuru area.

According to the correlation matrix shown in Table 5 below, PC1 accounted for more than 43.00% of total variance and was loaded by TDS, fluoride, sodium, bicarbonate, sulphate, carbonate, pH, and calcium with factor loading values >0.52 shown in bold. This shows that these were the most dominant variables (physico-chemical parameters) in groundwater in the study area. The second component (PC2) explained about 11.34% of total variance and had strong loading of depth, potassium, and calcium with factor loading values >0.54, suggesting that they were the second dominant variables in groundwater. The third component (PC3) explained 10.41% of the variance and was loaded with magnesium and hardness with factor loading values >0.73.

The results of PCA show that the dominant variables (physico-chemical parameters) in groundwater in the study area were TDS, fluoride, sodium, bicarbonate, sulphate, carbonates, pH, and calcium. Calcium had a negative correlation meaning when PC1 increases, all the other parameters' concentrations increase, but calcium decreases. The second components, depth and calcium are positively correlated, however, correlate negatively with potassium, meaning as PC2 increases their concentrations increases while potassium decreases. PC3 had both magnesium and hardness, which correlated positively. PC1 and PC2 represent the major geochemical processes taking place in the study area and probably show the results of mineral-water interactions (Belkhiri et al., 2010). Therefore, fluoride is a dominant parameter in the study area and its concentration is likely to be influenced by mineral-water reactions. Fluoride being part of the most dominant components (PC1) will be correlated with the other principal components to determine their correlation and association in groundwater.

Table 5. Factor loadings of PCA application for groundwater physicochemical parameters in Nakuru area with 3 factor solution.

	PC1	PC2	PC3
DEPTH(M)	-0.237	**0.761**	-0.110
PH	**0.672**	0.021	0.098
F^-	**0.944**	0.130	0.100
Ca^{2+}	**-0.520**	**0.545**	0.027
Mg^{2+}	-0.235	-0.031	**0.793**
Na^+	**0.900**	-0.086	0.010
K^+	0.149	**-0.535**	0.174
HARDNESS	-0.417	0.303	**0.733**
Cl-	**0.713**	0.331	0.082
SO_4^{2-}	**0.822**	0.283	0.097
NO_3^{2-}	0.022	0.285	-0.426
HCO_3^-	**0.834**	0.121	0.131
TDS	**0.946**	0.029	0.050
CO_3^-	**0.75**	0.18	0.13
Eigenvalue	6.02	1.58	1.46
Variability (%)	43.00	11.34	10.41
Cumulative %	43.00	54.344	64.753

To determine the cluster of boreholes which have similar physico-chemical characteristics, factor score was determined. This analysis enabled to statistically determine boreholes containing the highest concentrations of the dominant parameters, through plotting of factor coordinates using factor loading values (Table 5 above), and the boreholes identity (observations) for principal components PC1 and PC2 as shown in the Bi plot in Figure 13 below. The plot explains the relationships between different boreholes, grouping those with similar characteristics. From the plot, boreholes in the first quadrant contain components in PC1 showing the highest concentrations of fluoride, TDS, sodium, bicarbonate, chloride, sulphate, carbonates, and pH and lowest calcium. Boreholes in the fourth quadrant contain components in PC2, which have the highest concentrations of calcium, the lowest of potassium, and are the deepest boreholes. Therefore, boreholes D308, D390, D562, D498, and D251 had the highest fluoride concentrations. From the borehole data in appendix 1, fluoride ranged between 11.10 to 72.00 mg/l, with an average of 30.22 mg/l in these 5 boreholes.

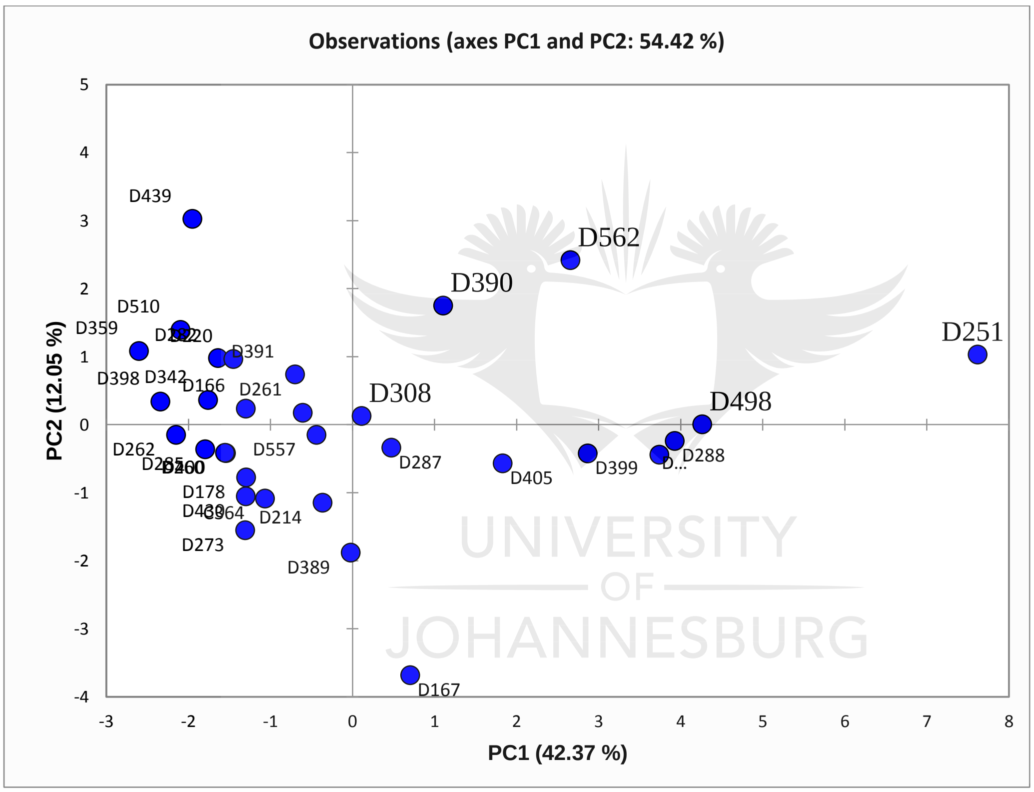


Figure 13. Bi plots for principal components PC1 and PC2 showing boreholes with similar physico-chemical parameters. The first quadrant shows the cluster of boreholes with the highest concentrations of fluoride, while boreholes in the fourth quadrant have the lowest. The numbers in the borehole points represent borehole identity.

3.4.2.2 Pearson's correlation analysis

To determine the magnitude of relationships among the dominant physico-chemical parameters (PC1 and PC2) identified in PCA above, the data was subjected to Pearson's correlation. The observed relationships are presented in the correlation matrix in Table 6 below, where values showing high correlation with r^2 greater than 0.5 are shown in bold. From the table, fluoride shows a strong positive correlation (in increasing order of strength of association) with pH, chloride, sodium, carbonate, bicarbonate, TDS, and sulphate. Fluoride relationship with the second components show a weak ($r^2 < 0.5$) negative correlation (in descending order of association) with depth and calcium, and a positive correlation with potassium. With the third components, fluoride shows a weak ($r^2 < 0.5$) negative correlation (in descending order of association) with magnesium and hardness.

Table 6. Correlation matric (Pearson) showing the coefficient (r^2) between the physico-chemical parameters in Nakuru area groundwater, where values of the dominant parameters are shown in bold.

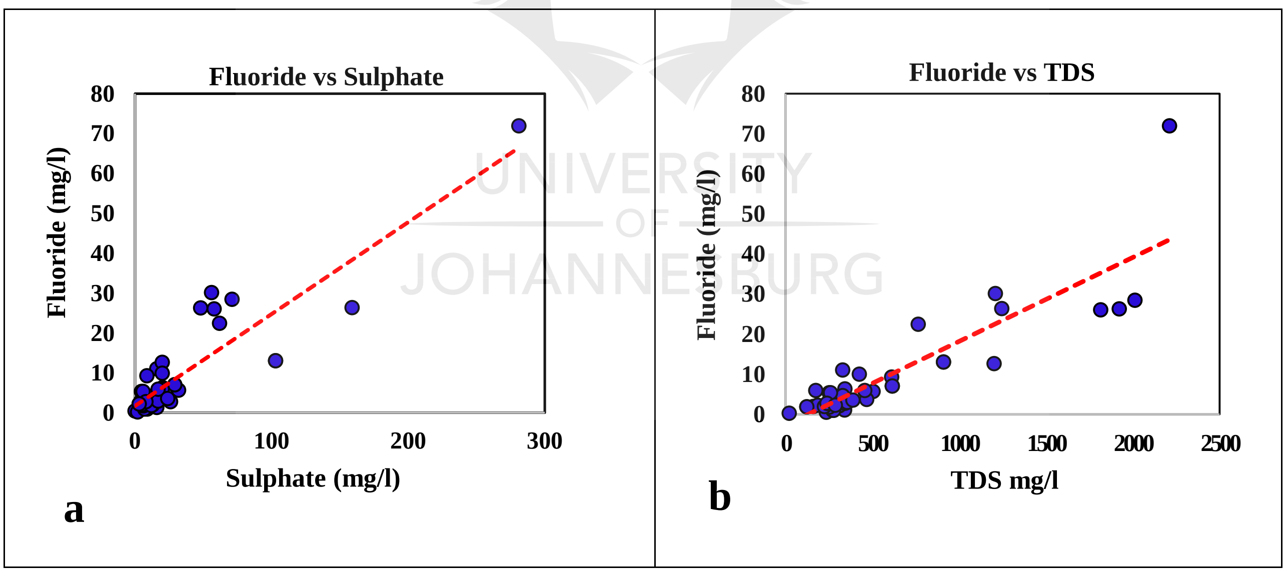
Table 6. Correlation matrix (Pearson(n)) showing the coefficient (r2) between the physicochemical parameters in Nakuru area groundwater, where values of the dominant parameters are shown in bold.

Variables	DEPTH(M)	PH	F^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	HARDNESS	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-	TDS	CO_3^-
DEPTH (M)	**1**	-0.167	-0.150	**0.418**	-0.028	-0.335	-0.216	0.125	0.095	0.027	0.094	-0.134	-0.209	-0.158
PH	-0.167	**1**	**0.591**	**-0.441**	-0.089	**0.562**	-0.099	-0.156	**0.394**	**0.438**	0.008	**0.581**	**0.531**	**0.496**
F^-	-0.150	**0.591**	**1**	**-0.413**	-0.126	**0.809**	0.116	-0.281	**0.629**	**0.906**	0.078	**0.834**	**0.872**	**0.831**
Ca^{2+}	**0.418**	**-0.441**	**-0.413**	**1**	-0.042	**-0.371**	-0.121	**0.482**	-0.258	-0.312	0.104	-0.301	-0.348	-0.257
Mg^{2+}	-0.028	-0.089	-0.126	-0.042	**1**	-0.230	0.029	**0.523**	-0.112	-0.132	-0.081	-0.116	-0.216	-0.140
Na^+	-0.335	**0.562**	**0.809**	**-0.371**	-0.230	**1**	0.228	-0.320	**0.602**	**0.593**	0.072	**0.730**	**0.945**	**0.513**
K^+	-0.216	-0.099	0.116	-0.121	0.029	0.228	**1**	-0.082	-0.044	0.024	-0.167	0.055	0.266	0.003
HARDNESS	0.125	-0.156	-0.281	**0.482**	**0.523**	-0.320	-0.082	**1**	-0.189	-0.243	-0.129	-0.201	-0.317	-0.143
Cl^-	0.095	**0.394**	**0.629**	-0.258	-0.112	**0.602**	-0.044	-0.189	**1**	**0.670**	-0.054	**0.434**	**0.732**	0.192
SO_4^{2-}	0.027	**0.438**	**0.906**	-0.312	-0.132	**0.593**	0.024	-0.243	**0.670**	**1**	-0.030	**0.681**	**0.726**	**0.769**
NO_3^-	0.094	0.008	0.078	0.104	-0.081	0.072	-0.167	-0.129	-0.054	-0.030	**1**	0.016	0.038	0.043
HCO_3^-	-0.134	**0.581**	**0.834**	-0.301	-0.116	**0.730**	0.055	-0.201	**0.434**	**0.681**	0.016	**1**	**0.789**	**0.751**
TDS	-0.209	**0.531**	**0.872**	-0.348	-0.216	**0.945**	0.266	-0.317	**0.732**	**0.726**	0.038	**0.789**	**1**	**0.536**
CO_3^-	-0.158	**0.496**	**0.831**	-0.257	-0.140	**0.513**	0.003	-0.143	0.192	**0.769**	0.043	**0.751**	**0.536**	**1**

3.4.2.3 Linear regression analysis

The nature of the relationship between fluoride and the dominant parameters was determined by plotting their concentrations using a linear regression model as shown in Figures 14 a-g and 15 a-d. From the graphs, fluoride shows a positive correlation with sulphate, TDS, bicarbonate, carbonate, sodium, chloride, and pH as shown in Figures 14 a-g. There was a negative correlation between fluoride and borehole depth, hardness, calcium, and magnesium as shown in Figures 15 a-d.

The relationships produced by these models are in good agreement with the correlation matrix in table 6 above. The parameters showing strong correlations ($r^2 > 0.5$) with fluoride in the matrix are shown by steeper trendlines, while parameters showing weaker correlations ($r^2 < 0.5$) with fluoride, are shown by gentler trendlines in the linear graphs. The nature of correlation shown in the Pearson's matrix is also shown in the correlation graphs, where, the positive and negative correlation observed in the matrix correlate to those observed in the graphs.



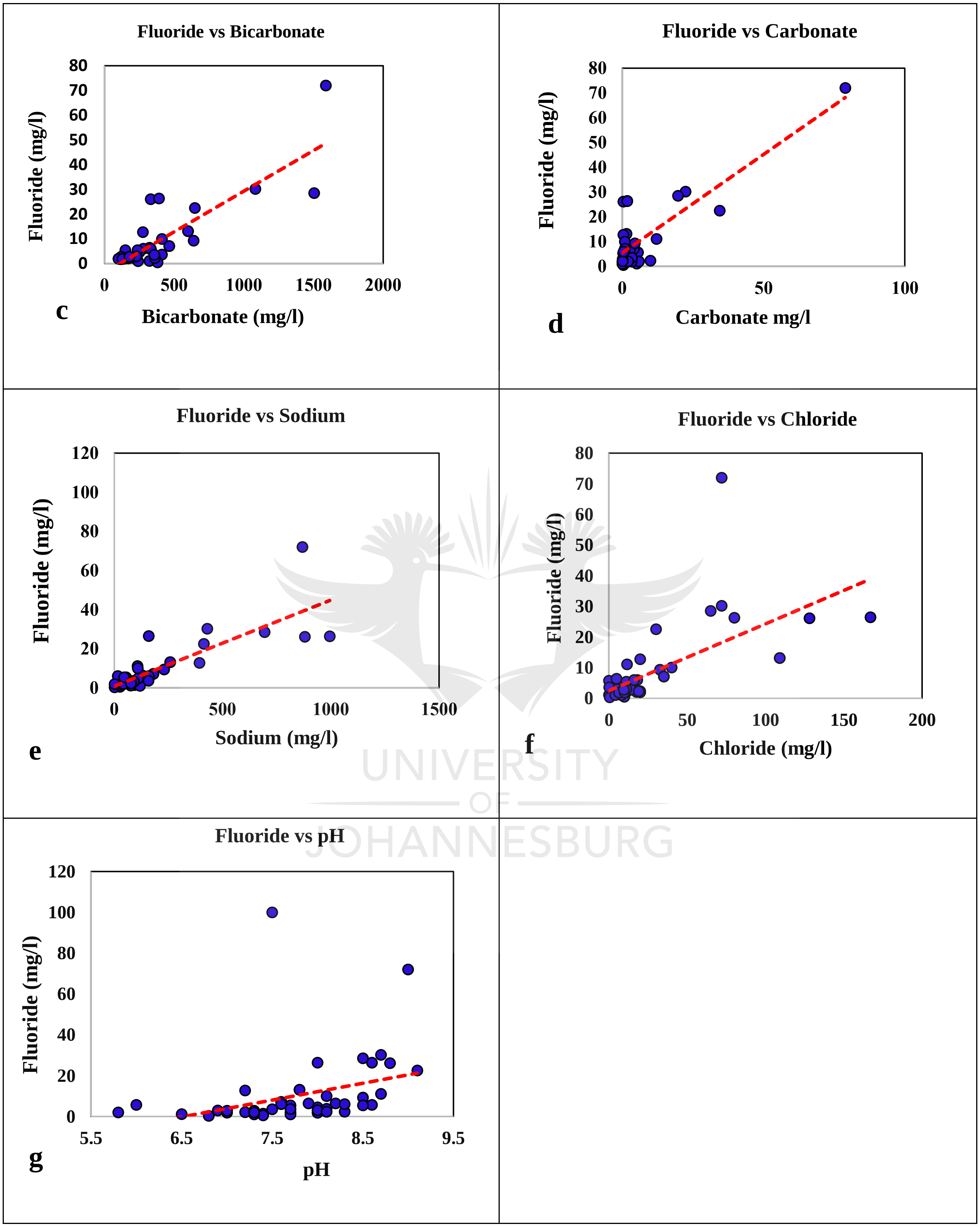


Figure 14 a-g. Linear regression graphs of fluoride vs sulphates, TDS, bicarbonate, carbonate, sodium, chloride, and pH respectively, showing positive correlations in descending order of association.

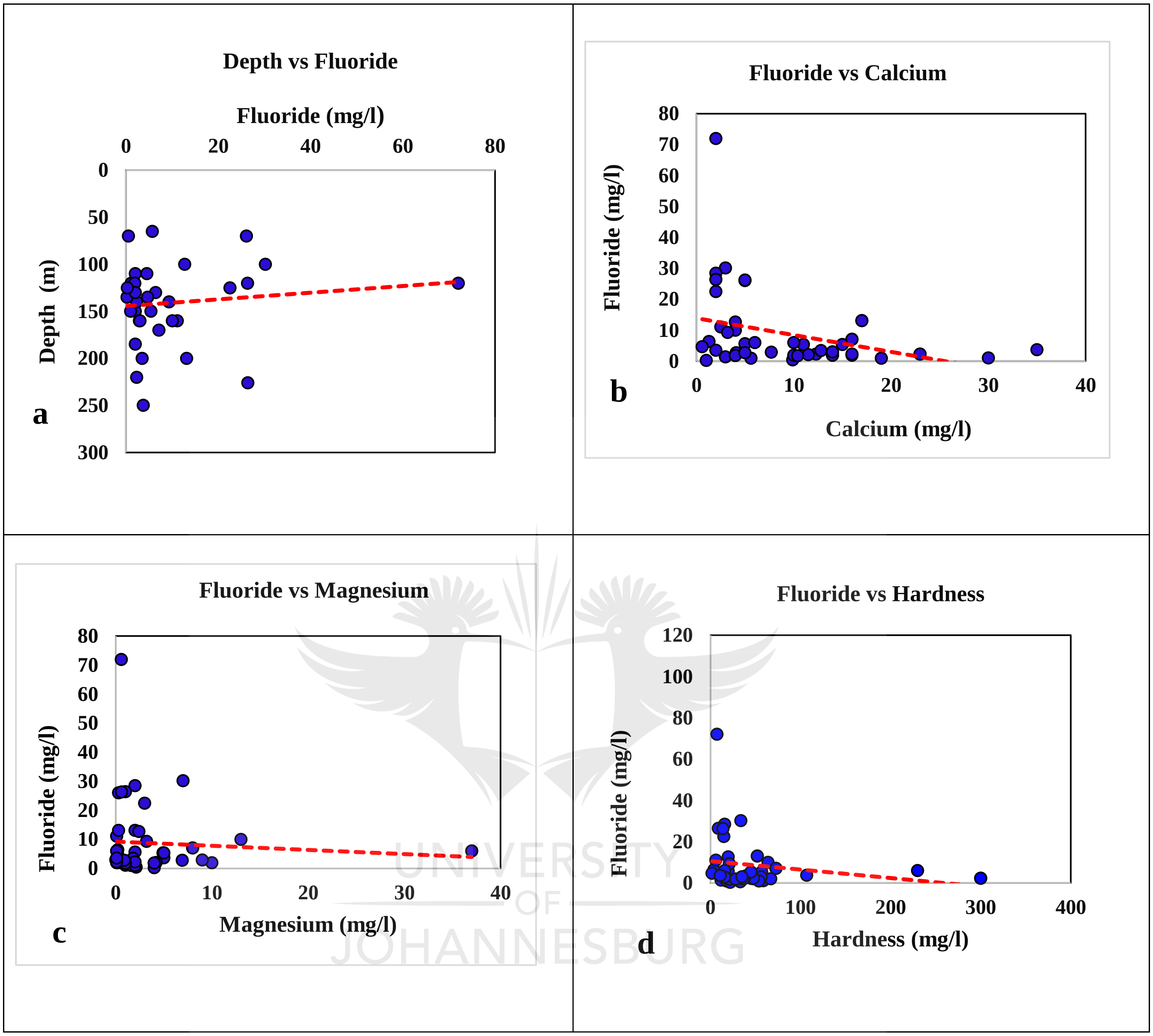


Figure 15 a-d. Linear regression graphs of fluoride vs depth, calcium, magnesium, and hardness respectively, showing negative correlations in descending order of association.

The observed positive correlation between fluoride and these parameters is attributed to dissolution of alkaline volcanic rocks and sediments in the Rift Valley, which produces the Na-HCO_3 water type as seen in the piper plot (Gaciri and Davis, 1992; Olago et al., 2009; Rango et al., 2012; Ghiglieri et al., 2012). High sodium concentrations allow dissolution of fluoride minerals due to exchange of calcium by sodium ions (Handa, 1997; Edmunds and Smedley, 2013), which explains the strong positive sodium-fluoride correlation. High carbonate is linked to volcanic, magmatic activities, while, chloride and sulphate concentrations in the Rift Valley lakes have been linked to evaporative enrichment, magmatic and hydrothermal activities (McCall, 1967; Olago et al., 2009; Olaka et al., 2016). In most of the Rift Valley groundwater pH values have a small range between 6 and 9 (Gaciri and Davis, 1992; Rango et al., 2012; Ghiglieri et al., 2012) thus, the weak positive correlation observed is caused by the small range in pH and wide range in fluoride values.

The poor correlation between fluoride and borehole depths is attributed to the complex stratification of different lithological units in the Rift Valley, which are not uniform throughout the aquifer thickness, and thus, release fluoride in different rates and quantities (Ayenew, 2007). The negative correlation fluoride had with magnesium and calcium, and therefore hardness (which is caused by ions of calcium and magnesium), is caused by the solubility product principle (Vogel, 1961), where an increase in fluoride level will automatically cause a decrease in calcium and or magnesium in water.

3.4.3 Spatial Analysis

Spatial analysis was used to determine the nature and type of distribution of fluoride and the dominant physicochemical parameters in groundwater using; Moran's indexing for spatial autocorrelation, Kriging method form generating spatial distribution maps, and hotspot analysis to show the cluster of boreholes with the highest fluoride concentrations in the study area. These analyses were conducted using Spatial Analysis tool in ArcGis.

3.4.3.1 Spatial autocorrelation

Moran's indexing and plots are commonly used to measure the degree and nature of spatial autocorrelation (Dale and Fortin, 2002). The autocorrelation can be positive when Moran's index value is between 0 and +1, negative when between 0 and -1, or null autocorrelation when the value is 0 (Dale and Fortin, 2002). A Moran's histogram plot was used to show the nature of autocorrelation.

Table 7 below shows the summary of the Moran's indexing analysis for fluoride autocorrelation. The Moran's Index of 0.20 and Z-score value of 3.89 indicates that, fluoride values have a positive autocorrelation with a high confidence level. Z-score is a components of confidence interval used in statistics, and the fluoride's Z-score of 3.89 is greater than the value of 2.58, which indicates a

99% confidence level (Dale and Fortin, 2002). The Moran's histogram plot in figure 16 below shows that, fluoride has a clustered distribution indicated by a Z-score value >2.58. The results, therefore, show that fluoride has a strong clustered distribution in the study area meaning it is possible to determine areas with high and low fluoride concentrations.

Table 7. Summary of the Global Moran's I summary for fluoride autocorrelation showing a Moran's index of 0.20.

Moran's Index:	0.20
Expected Index:	-0.03
Variance:	0.00
z-score:	3.89
p-value:	0.00

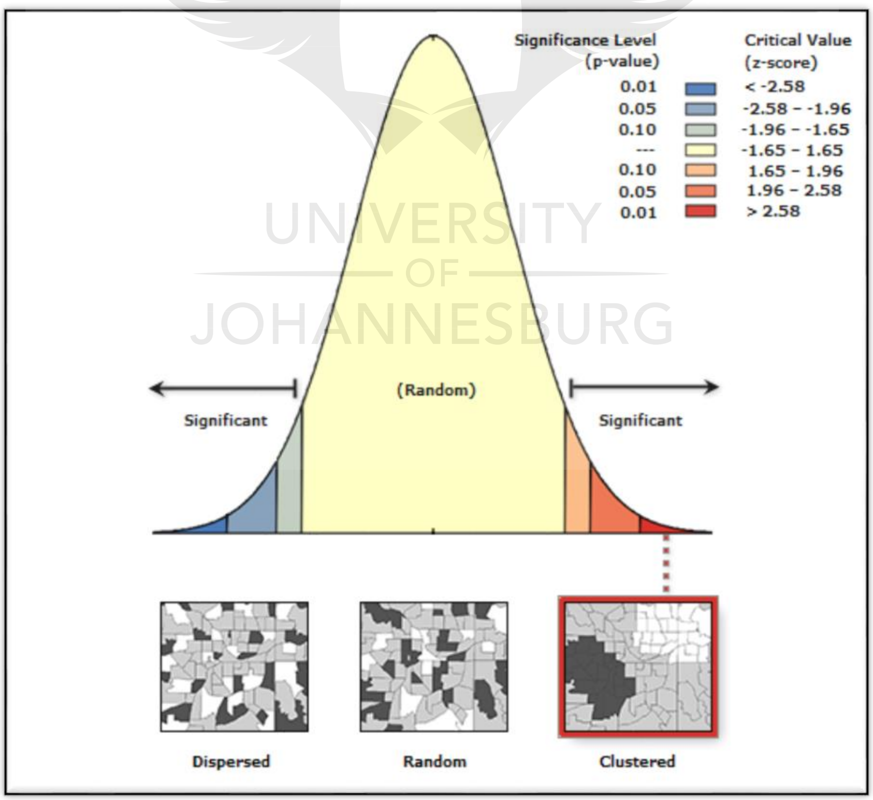


Figure 16. A Moran's histogram showing fluoride has a clustered distribution in groundwater in the study area as indicated by a Z-score value greater than 2.58.

Spatial autocorrelation was determined for the dominant parameters and the results in Table 8 below show that, most have a strong positive clustered distribution, except hardness and magnesium, which have a strong and weak random distribution respectively.

Table 8. Summary of Moran's index of physicochemical parameters in the study area showing a dominant clustered autocorrelation and a few random ones.

Physicochemical parameter	Moran's Index	Z-score/ Confidence level	Nature of autocorrelation
SO_4^{2-}	0.44	4.77 (> 99% confidence level)	Clustered
TDS	0.25	4.25 (> 99% confidence level)	Clustered
CO_3^-	0.14	2.6 (> 99% confidence level)	Clustered
HCO_3^-	0.12	2.45 (> 98% confidence level)	Clustered
Na^+	0.18	3.36 (> 99% confidence level)	Clustered
Cl^-	0.21	4.24 (> 99% confidence level)	Clustered
pH	0.1	2.04 (> 95% confidence level)	Clustered
Ca^{2+}	0.11	2.19 (> 95% confidence level)	Clustered
HARDNESS	0.03	1.44 (> 85% confidence level)	Random
Mg^{2+}	-0.05	-0.35 (< 50 % confidence level)	Random

3.4.3.2 Spatial distribution of fluoride and physico-chemical parameters

After determining the clustered distribution nature of most of the physico-chemical parameters, Kriging method was used to show the geographical distribution patterns of these parameters in the study area. The borehole data in the spreadsheet was loaded into ArcGIS, its projections defined, and interpolation was generated using logarithm transformation.

The spatial distribution map of fluoride in figure 17 below shows the highest concentrations in the north-west, some parts of the central, and the south-east parts of the study area forming a north-west to south-east high concentration trend. Locations covered with the high concentrations include Rongai and Menengai in the extreme north west, some parts of Njoro in the west, the western side of Nakuru town area, and Elementaita and Gilgil in the south west. The lowest fluoride concentrations are found in the north-east area around Bahati and north of Bahati, the eastern parts of Nakuru town area and the south west parts of the area. These distribution patterns agree with the results in the spatial autocorrelation where fluoride showed a strong clustered distribution.

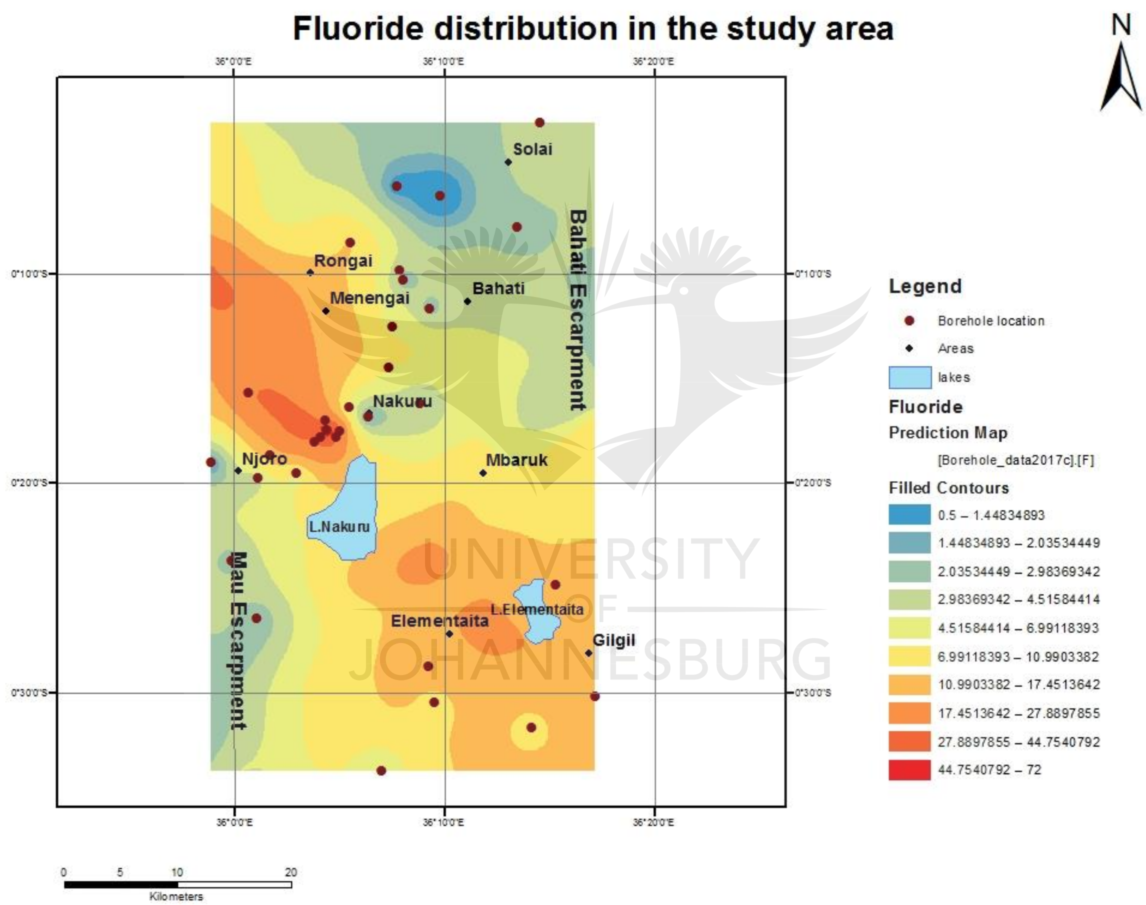


Figure 17. Spatial distribution map of fluoride in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations in the Bahati and Mau escarpments.

Spatial distribution of the other parameters was determined and is shown in the Figures 18 to 27 below. TDS, sulphate, sodium, chloride, carbonate, bicarbonate, and pH showed a similar distribution pattern as fluoride's, where, the highest concentrations of these parameters were in a general north-west to south-east areas, and the lowest in the north-east and south-west areas as shown in Figures 18 to 24. The results from the distribution maps agree with the results obtained from the nature and significance of correlation in the Pearson's correlation and lineal regression analyses. In the analyses, fluoride had a strong positive correlation with TDS, sulphate, sodium, chloride, carbonate, bicarbonate, and pH with $r^2 > 0.50$. The spatial analysis maps display similar positive correlations between these parameters. Clustered distribution is also echoed in the spatial maps, as initially determined in the spatial autocorrelation analysis.

Calcium, magnesium, and water hardness had their highest concentrations in the north-east and south-west areas and their lowest in the north-west and south-east areas. This was a negative distribution pattern compared to fluoride's, which agrees with the results obtained from the statistical analyses. From the Pearson's correlation and lineal regression analyses, there was a weak negative correlation between fluoride and calcium, magnesium, and water hardness with $r^2 < 0.41$. This weak negative correlation is also observed in the spatial distribution maps. Therefore, the highest fluoride groundwater areas have low calcium, magnesium, and hardness and vice versa. Most of these parameters also show varied clustering as shown in the spatial autocorrelation analysis. The spatial maps of calcium, magnesium, and hardness are shown in Figures 25 to 27.

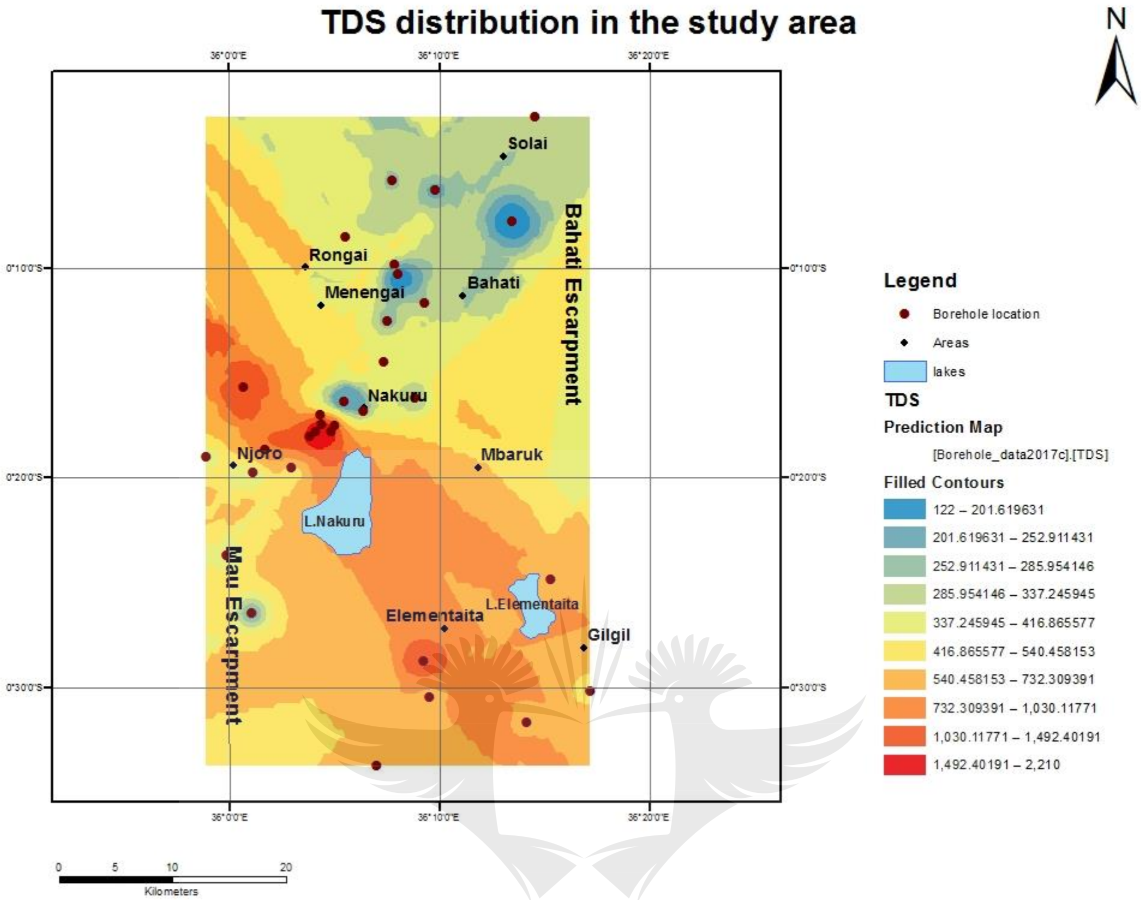


Figure 18. TDS distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations north of Bahati escarpment, and parts of Mau escarpment.

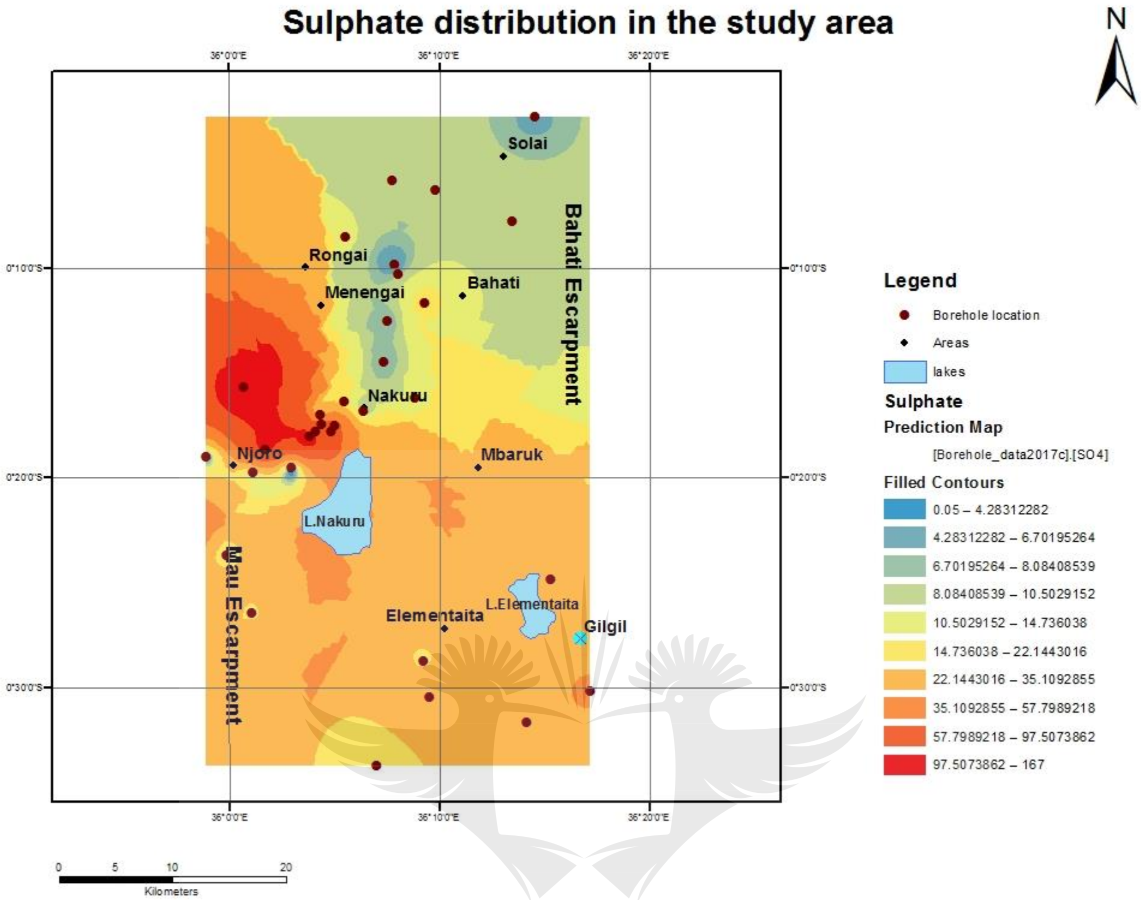


Figure 19. Sulphate distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations north of Bahati escarpment.

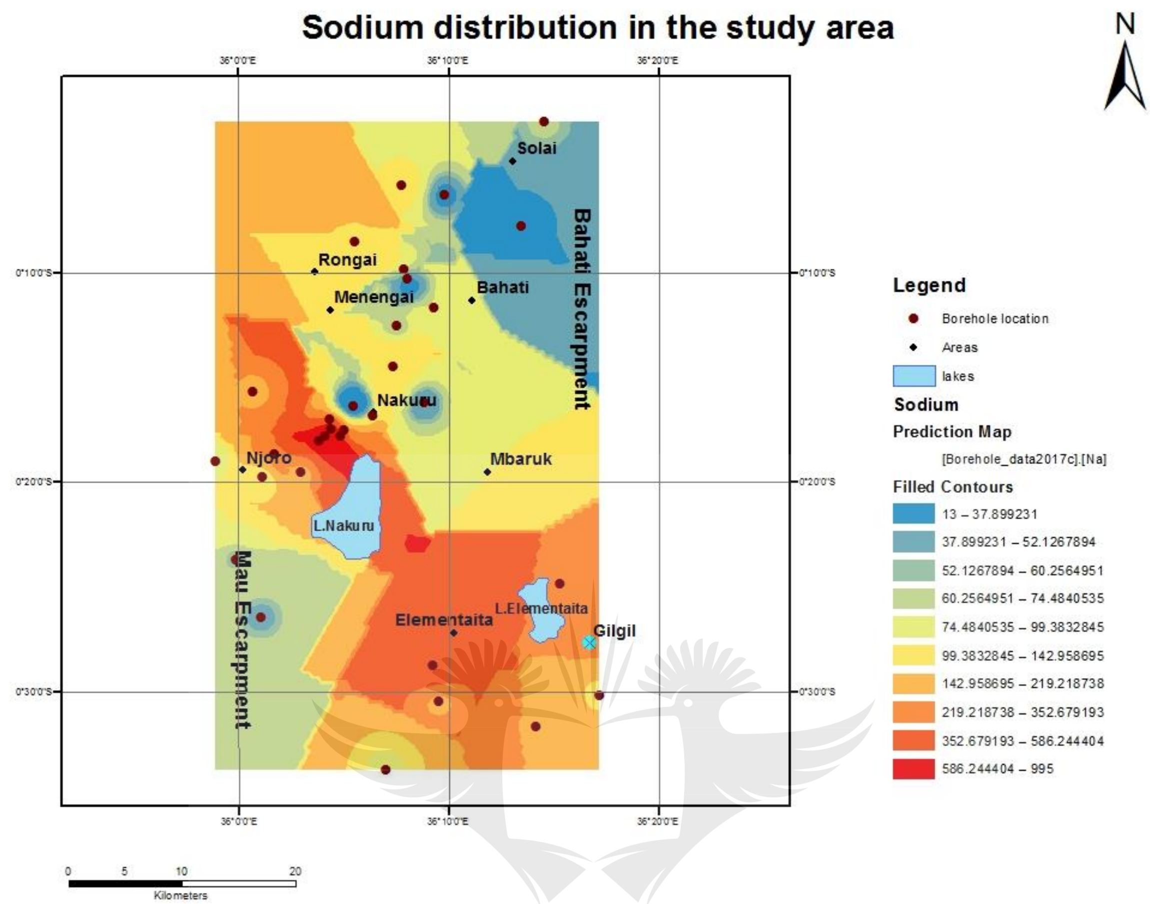


Figure 20. Sodium distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations north of Bahati, and south of Mau escarpments.

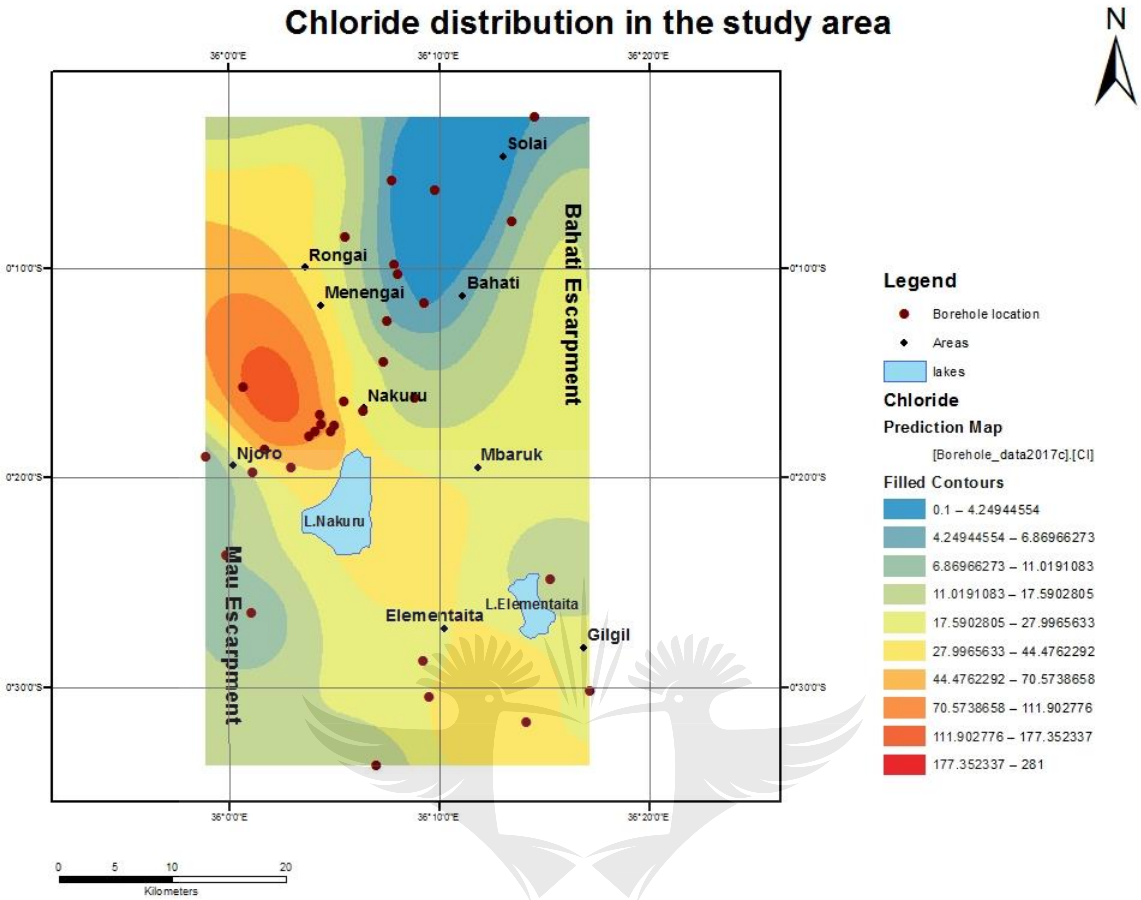


Figure 21. Chloride distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations north of Bahati escarpment, and in the Mau escarpment.

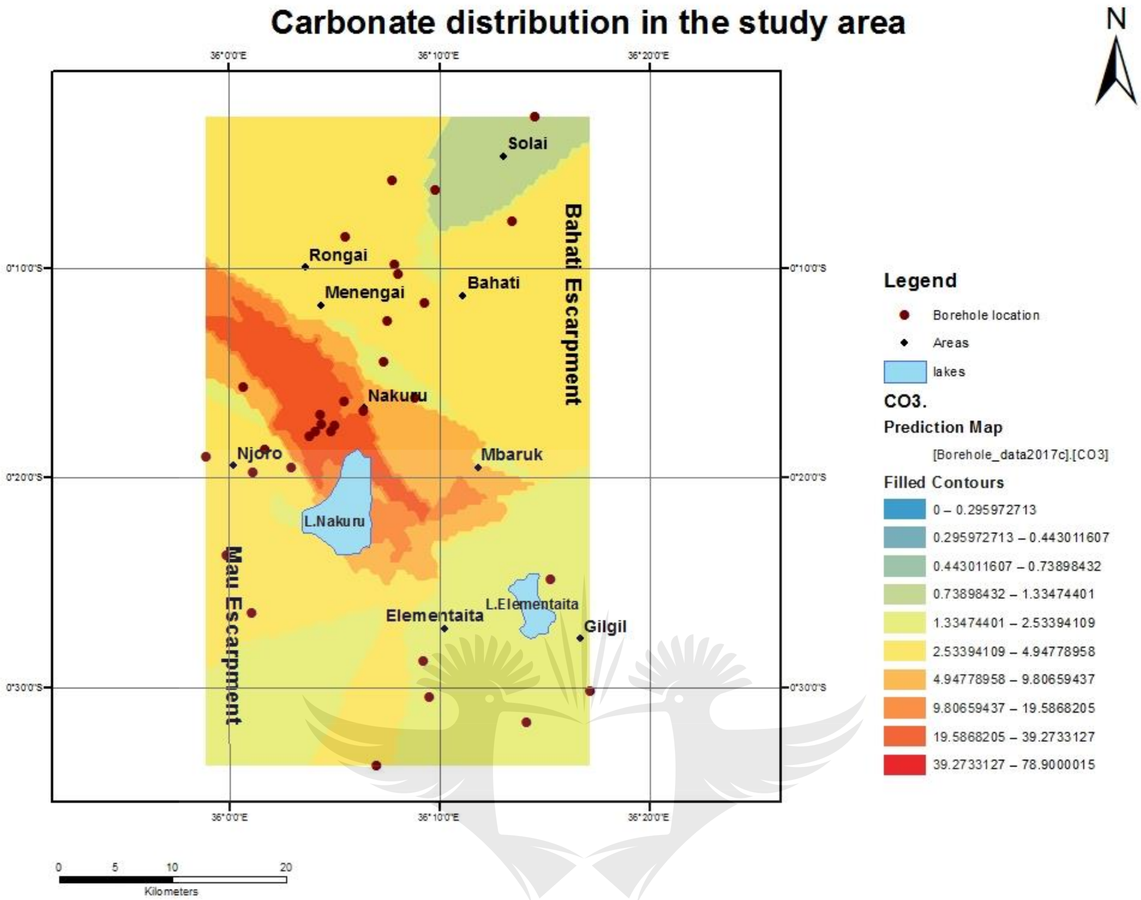


Figure 22. Carbonate distribution in the study area showing highest concentrations in the rift floor around Nakuru-Njoro area, and the lowest concentrations in north of Bahati escarpment.

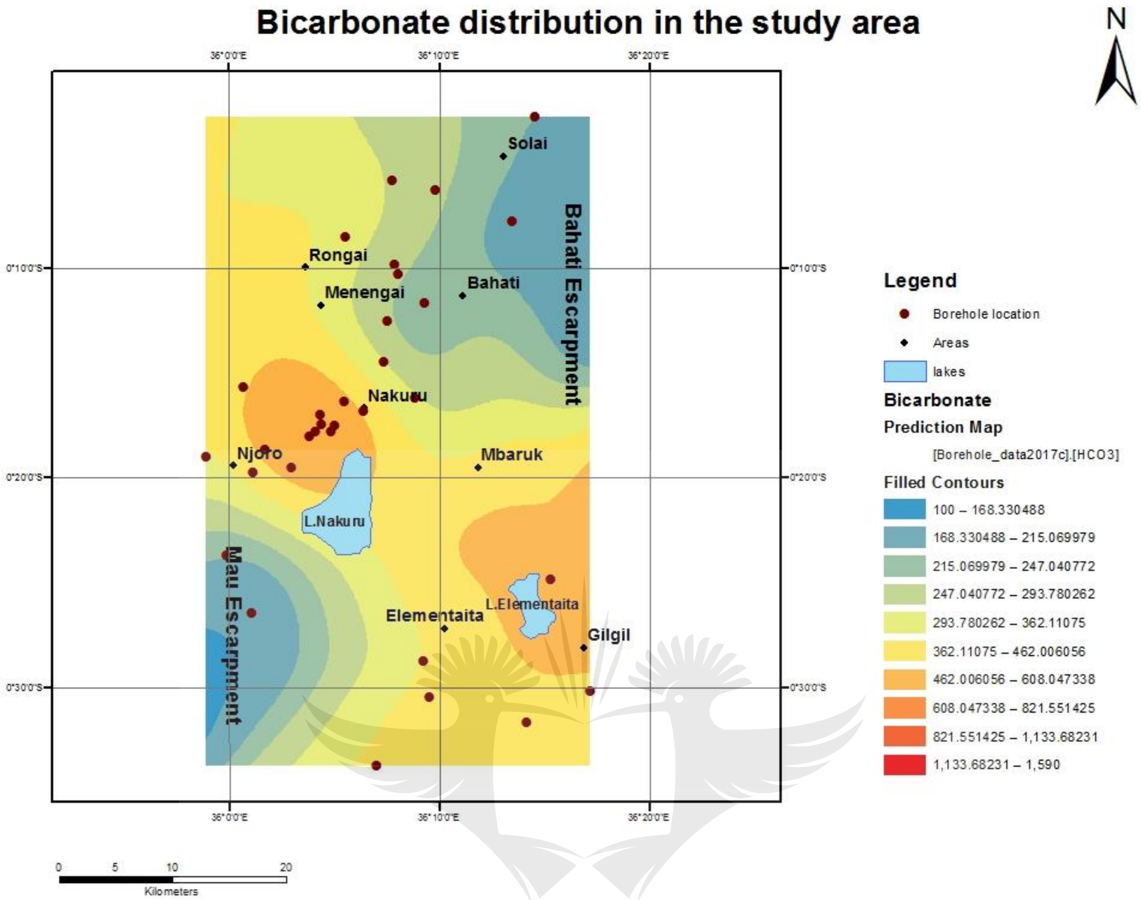


Figure 23. Bicarbonate distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations in the Bahati and Mau escarpments.

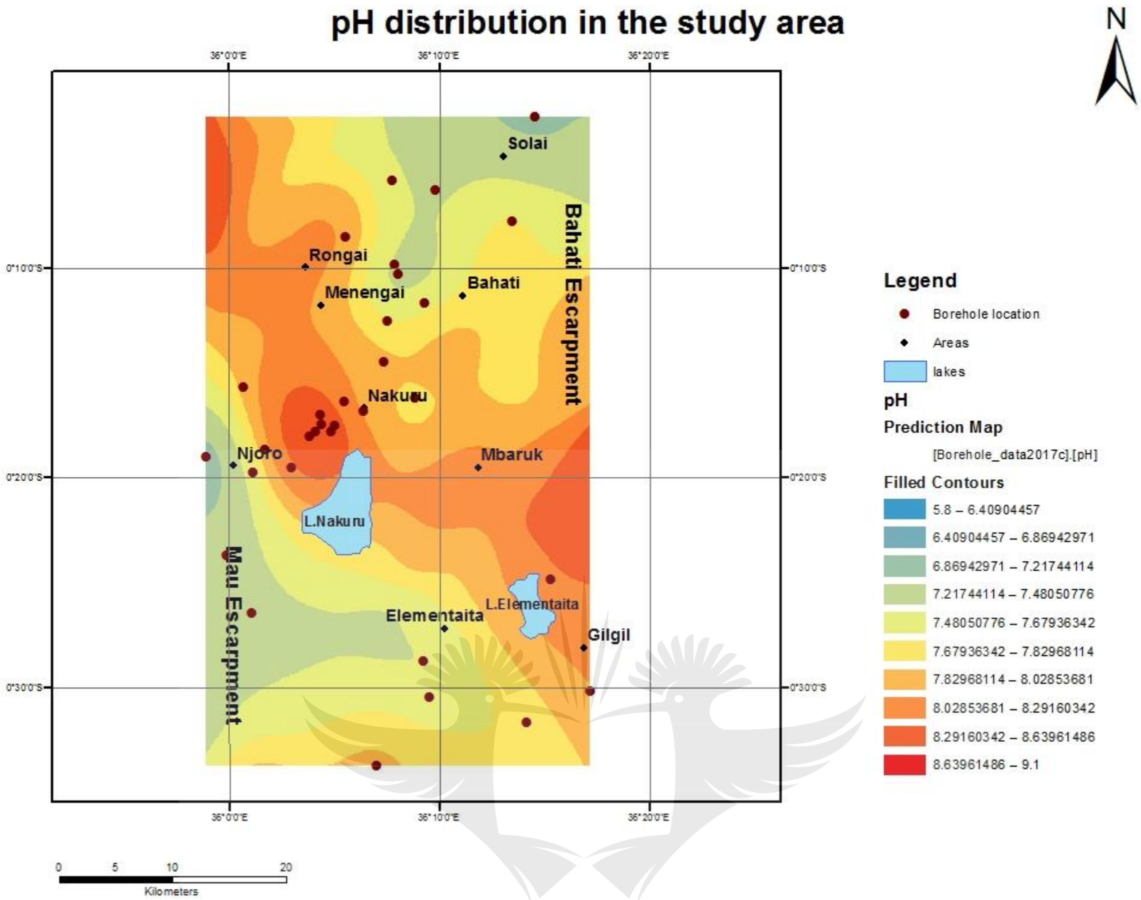


Figure 24. pH distribution in the study area showing the highest concentrations in the rift floor in a north-west south-east trend, and lowest concentrations north of Bahati escarpment, and in the Mau escarpment.

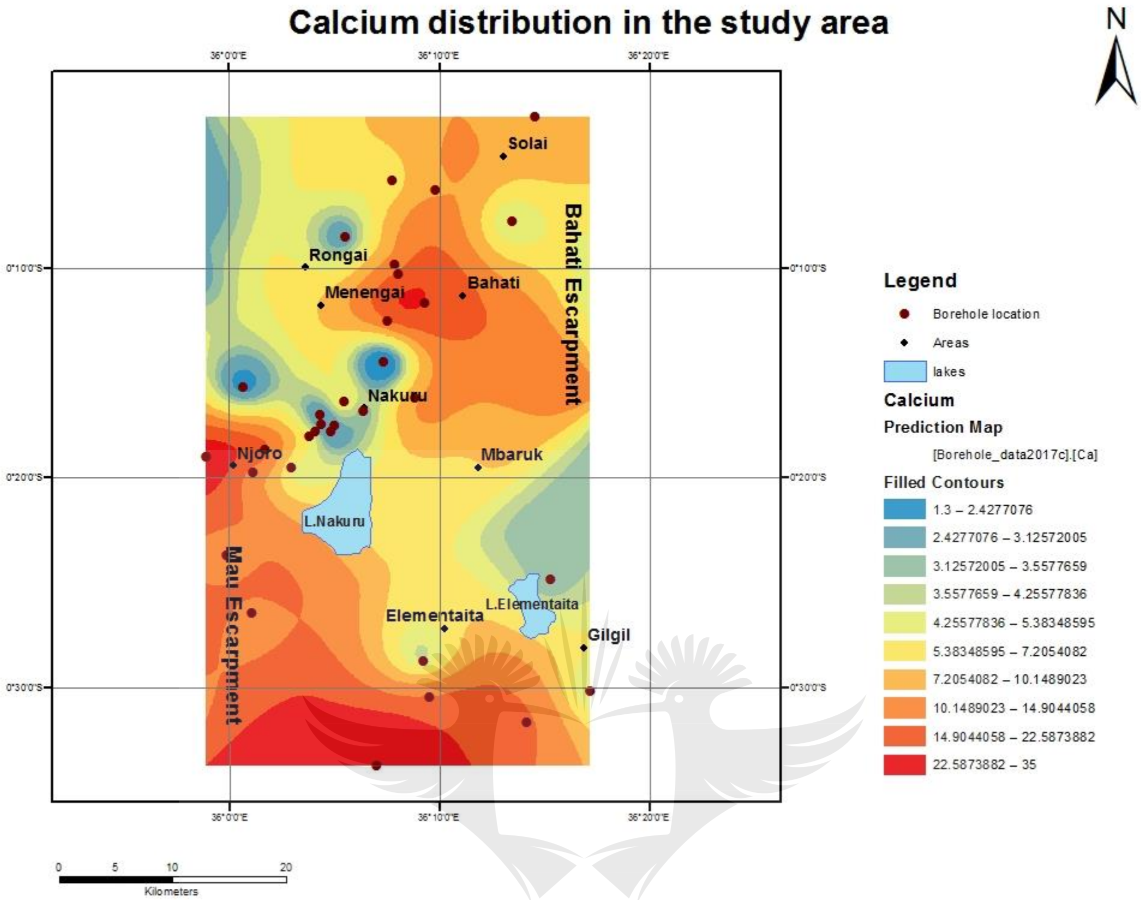


Figure 25. Calcium distribution in the study area showing the lowest concentrations in the rift floor in a north-west south-east trend, and highest in the north-east area around Bahati area and south-west around Mau escarpment.

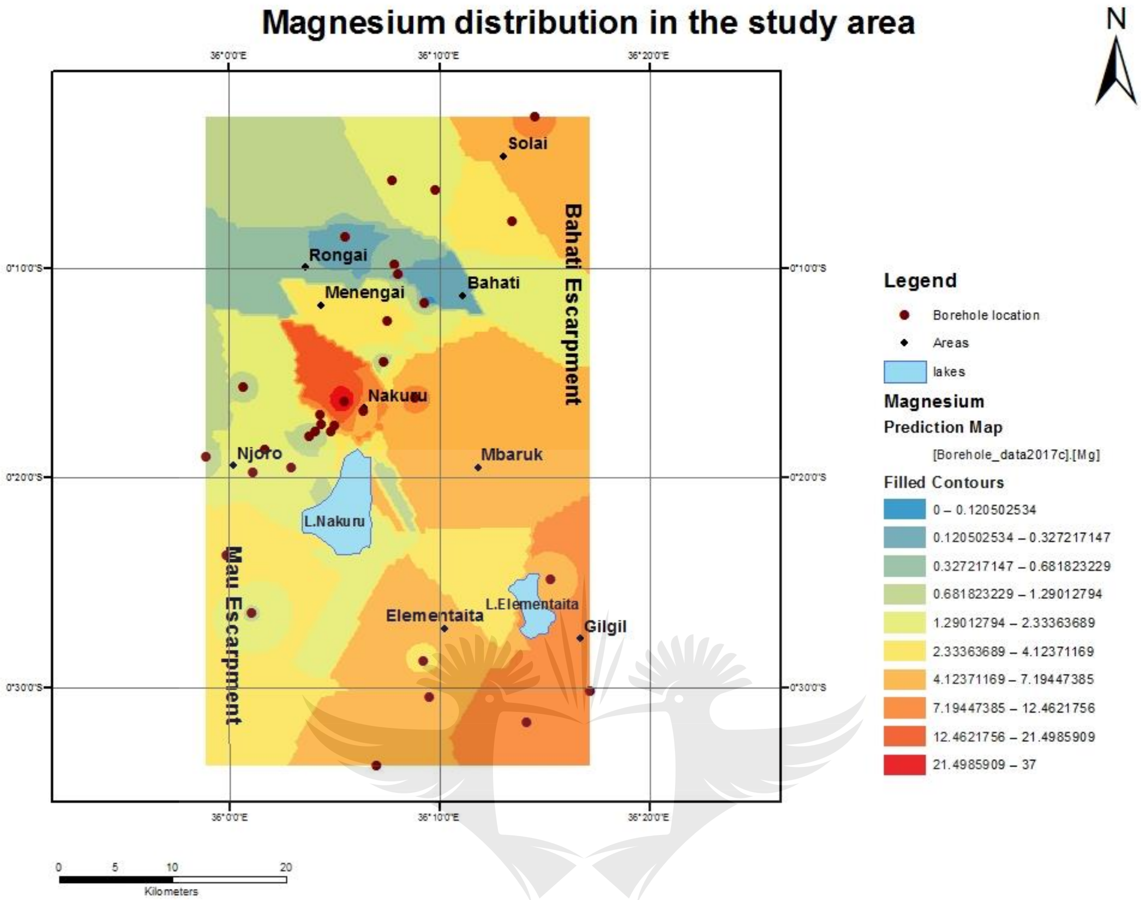


Figure 26. Magnesium distribution in the study area showing highest concentrations in the central area, and lowest in the north-west area.

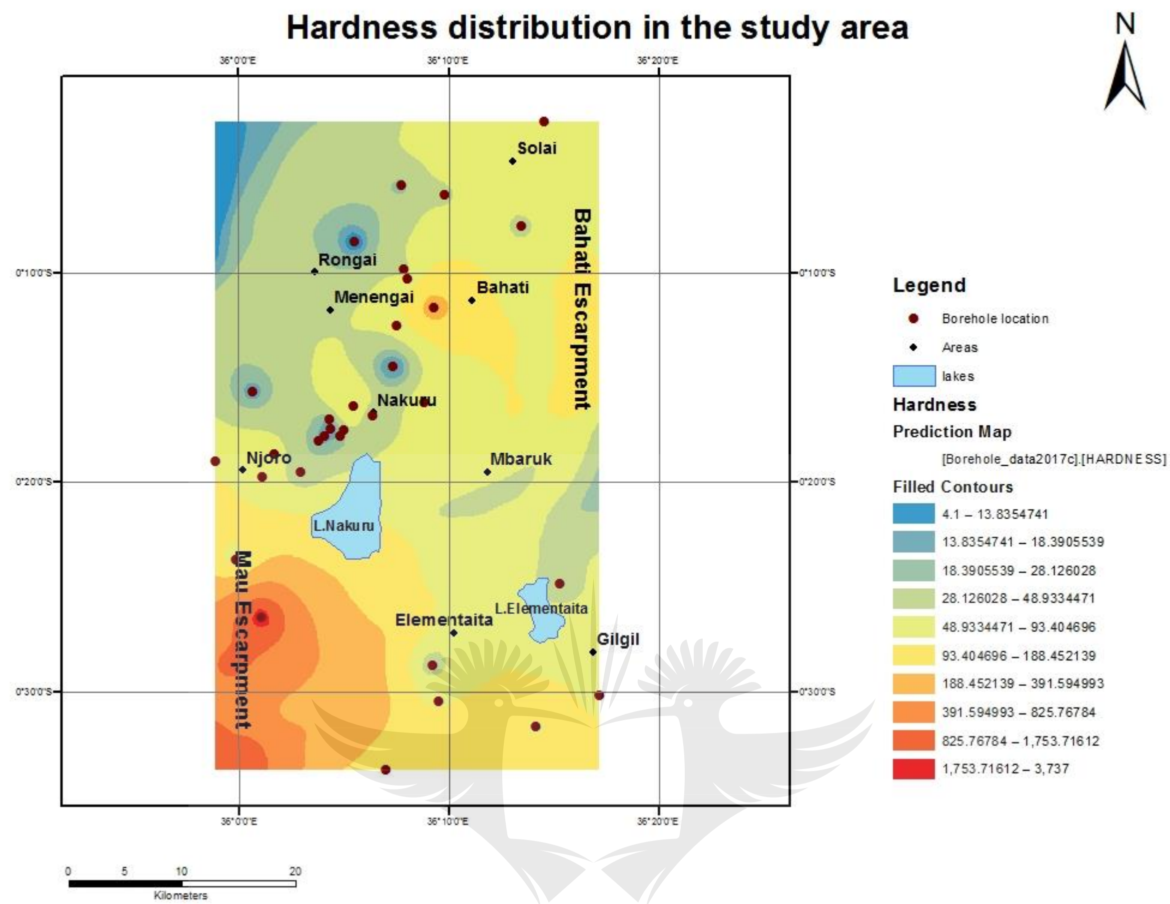


Figure 27. Hardness distribution in the study area showing the highest concentrations in the south-west area around Mau escarpment, and lowest in the rift floor covering the north-west and central areas.

3.4.3.3 Hotspot analysis

Upon identifying the spatial distribution pattern of fluoride and other physicochemical parameters, hotspot analysis in GIS spatial statistics tool was used to show the location of clusters of boreholes with the highest fluoride concentrations (hotspot). The results in Figure 28 below show the highest fluoride boreholes in the area between Nakuru town and Njoro in the floor of the Rift Valley. Hotspot analysis of the other physicochemical parameters were determined and the results show that parameters with positive correlations with fluoride have hotspots around the same area as fluoride while those correlating negatively have their coldspots correlate with fluoride hotspots. These results agree with factor score analysis in Table 5, which shows boreholes D308, D390, D562, D498, and D251, with the highest fluoride concentrations. These boreholes also appear in the fluoride hotspot in this analysis. The hotspot in the Nakuru town-Njoro area is likely to be the convergence point of groundwater from the escarpments, and along the rift floor, depositing the highest accumulation of dissolved solutes.

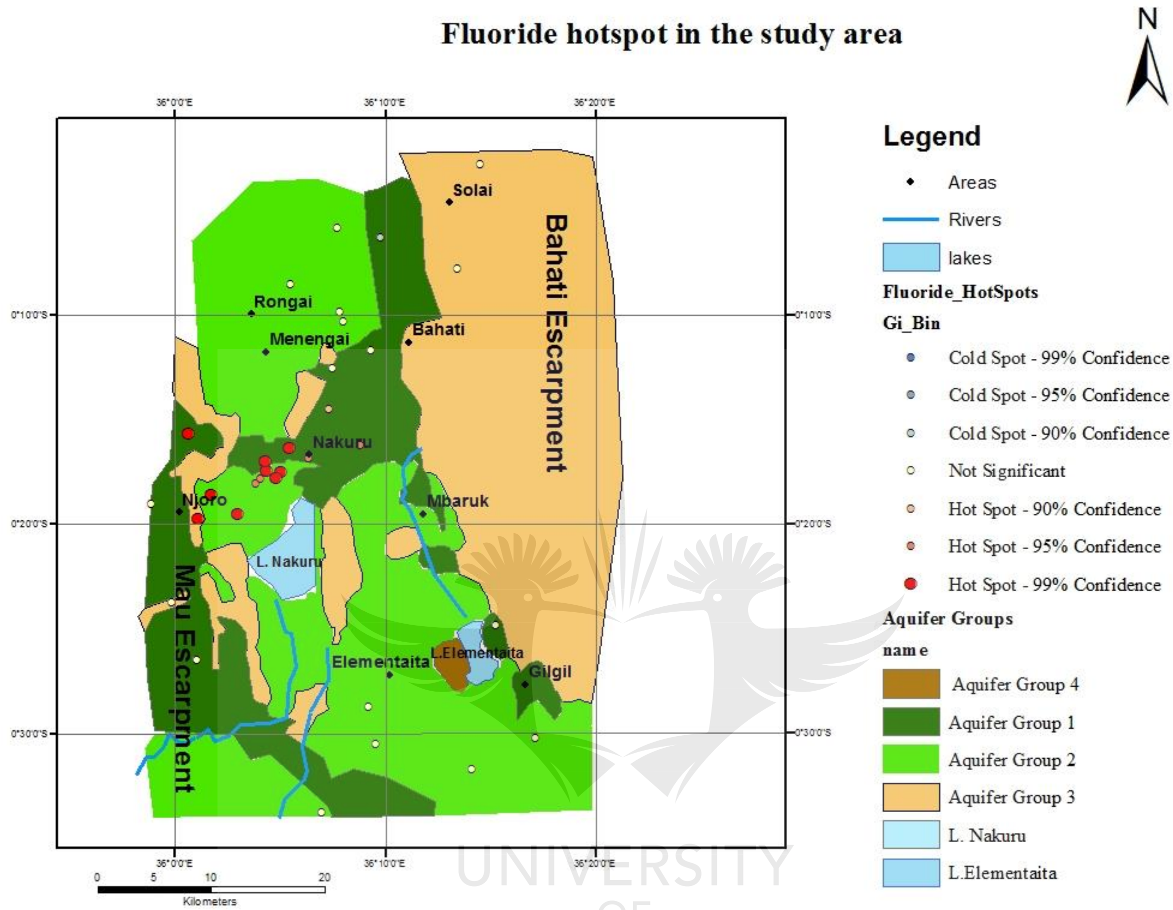


Figure 28. The aquifer Map of Nakuru area showing borehole clusters with different fluoride concentrations where, the fluoride hotspot in bright red circles is shown in between Nakuru-Njoro area.

3.4.3.4 Fluoride distribution in the aquifers

The spatial distribution map of fluoride was used to determine fluoride distribution in aquifers, and correlated the distribution with other physico-chemical parameters. The digitized aquifer map from Alamirew et al., (2007) in Figure 10 was used for the interpretation. The highest fluoride concentrations are distributed in a north-west south-east trend and the lowest concentrations are in the north-west and south-east areas as shown in the fluoride distribution map in Figure 17. All the high fluoride aquifers are found in the high fluoride north-west to south-east area covered by all the four aquifer groups. The low fluoride ones in the north-east in Bahati area covered by aquifer groups 1, 2, and 3 and south-east in the Mau escarpment area covered by group 1 and 2.

High fluoride concentrations, are therefore, found in all the aquifer groups and concentrations only varies with the location of the aquifers. The Rift Valley floor in the study area trends in a north-west south-east direction, which corresponds with high fluoride aquifers. Gilgil, Elementaita, Nakuru town area, and some parts of Njoro, Menengai, and Rongai are located on the Rift Valley floor and therefore covered by the high fluoride aquifers. Bahati escarpment, located in the north-east area, and part of Mau escarpment in the south-west corresponds to low fluoride aquifers. These aquifers cover some parts of Bahati area in the north-east, and areas close to Mau escarpment in the south-west.

The low fluoride concentrations in the north-east and south-west areas can be caused by high infiltration rates in the recharge zones. The Bahati escarpment and Menengai area are major recharge zones in the north and north-eastern parts of the study area (Olago et al., 2006; Obiri, 2006; Kemboi, 2007). Similarly, the high-altitude Mau escarpment area receives high rainfall (Kemboi, 2007) and acts as a recharge zone. In these areas, there is little groundwater residence time of the recently infiltrated groundwater, therefore there is less water-rock interaction time, which reduces the amount of fluoride dissolving in these areas. High rainfall received in these areas also causes dilution of groundwater, which further reduced fluoride concentrations.

Groundwater flows radially into the Rift Valley accumulating dissolved solutes along the flow path (Becht et al., 2006; Olaka et al., 2016). Therefore, concentrations of chloride, fluoride, bicarbonate, sodium, and sulphate increase along the flow path, which in turn increases TDS, and pH as observed from the spatial distribution maps. This explains the lowest concentrations of these parameters in the north-east and south-west areas and the highest concentrations in the rift floor. The concentrations of calcium and magnesium which influence water hardness decreased along the groundwater flow path, due to their complexing and exchange caused by fluoride and sodium respectively (Vogel, 1961; Nordstrom and Jenne, 1997). Therefore, as fluoride increases in groundwater, calcium and magnesium precipitates and reduce in concentrations hence, their negative correlation.

According to Becht et al. (2006), there is a radial flow of groundwater from the rift escarpments to the rift floor, and a north-westerly flow from L. Elementaita area. Therefore, according to this model the maximum accumulation area for dissolved fluoride in groundwater is towards the north-west area, which agrees with the results from this study. The fluoride hotspot map in Figure 28 and fluoride distribution map in Figure 17 shows the highest fluoride concentrations located in the area between Nakuru town and Njoro, and the north-western region respectively.

From the hydroclimatic map in Figure 5, areas around the rift floor experience warm, hot, and arid climate. This causes high evaporation resulting, to high concentration of dissolved solutes such as chloride and sulphates in the lakes and groundwater around them (Becht et al., 2006; Olaka et al., 2016). Evaporation is evident by the presence of trona impregnated silts in group 4 aquifer west of L. Elementaita (Alamirew et al., 2007). From the spatial distribution maps, high chloride and sulphate concentrations in the areas around lakes Nakuru and Elementaita also suggests evaporative enrichment. The strong positive correlation between fluoride, sulphate and chloride suggest that evaporative enrichment contributes to high fluoride concentrations in aquifers around lakes Nakuru and Elementaita. The intermittent interaction between the rift valley lakes and the adjacent aquifers (Ayenew, 1998; Becht et al., 2006; Ayanew, 2008; Olago et al., 2009; Olaka et al., 2016), cause the high fluoride in the rift lakes to diffuse into the surrounding aquifers. Areas around and close to the rift escarpments experience cool, temperate, and humid climate, which indicate very low evaporation rates in these areas. Therefore, in the Mau and Bahati escarpment, only mineral dissolution contributes to fluoride in groundwater, thus the relatively low fluoride than the rift floor.

The results of this study show presence of both high and low fluoride in all the aquifer groups in the study area and only the physical location of the aquifer system causes the variation in fluoride concentrations. An example of this occurrence is aquifer group 3 which shows high fluoride concentrations in the low elevation south eastern area near L. Elementaita where there is high evaporative enrichment, and longer water-rock interaction time. The same aquifer group shows low fluoride concentrations in the high elevation north-eastern area around Bahati catchment area where there is low evaporation, little water-rock interaction time, and high dissolution of groundwater.

3.6 HEALTH STUDY RESULTS AND DISCUSSION

3.6.1 Dental fluorosis in Nakuru area

This section covers the investigation on the effects of dental fluorosis on the local population in the study area. Consultations and interviews with resident dentists and dental technicians in the eight clinics visited confirmed the high prevalence of dental fluorosis in patients and the general population born and raised in Nakuru area as reported by several studies (Kahama et al., 1997; Moturi et al., 2002). A slightly higher fluorosis prevalence was reported in children below 10 years and residents from Njoro area.

Besides the dental fluorosis issue, a visit to P.C.E.A (Presbyterian Church of East Africa) Clinic in Njoro during the clinical field study, revealed numerous occurrences of bone fracture cases in children and adults. However, this observation was not followed up further because they were not within the scope of the present study. Prolonged use of high fluoride has been known decrease bone quality and strength leading to skeletal fluorosis (Alarcon-Herrera et al., 2001).

Dental records available in those clinics included diagnoses of several diseases such as bleeding gums, sensitive teeth, gingivitis, and dental caries, which are common in fluorosed teeth according to the dentists. Ockerse (1941) and Chibole (1988) reported similar diseases in children with high fluorosis. Since the clinics do not keep data for patients with fluorosis, the data was collected during the month of January 2017 from St. Mary's Hospital-Gilgil in the South-east part of the study area, and Egerton University-Njoro Dental Clinic, west of the study area. Results are presented in Appendices 5 and 6, and discussed below.

The patient's data such as in Table 10 below appears clustered due to methods used to record the 'areas of residence'. During data collection, all the patients were grouped into larger known areas such as 'Nakuru town area', signifying that the patient comes from within Nakuru town and its immediate environment. This was done because some patients gave names of areas or villages that are not officially documented, while others had their residence as an estimate distance to the major community areas such as ‘close to Nakuru town’. This factor is therefore important to consider in this section because the data appear clustered.

3.6.2 Fluorosis records from St. Mary’s Hospital-Gilgil

100 patients participated in the study (55 female and 45 male) and only 20 grew up outside the study area in the first 12 years. They were, however, included in the analysis because they grew up within the Kenyan Rift Valley. Of all the patients, 14 (14%) who include four males and ten females had no fluorosis (TF=0), making the prevalence of fluorosis 86.00%. The patients with no fluorosis were aged between 6 and 84 years where: five were from Nakuru town, four from Gilgil, one from Kabarak and one from Mbaruk, while two were from outside the study area. The TF score in patients with fluorosis ranged from 1 to 9 as shown in Table 9 below. When determining the severity, TF score between 1 and 3 is considered mild to moderate fluorosis, while scores above 5 are severe (James, 2016 and references therein; Rango et al., 2012). About 54% of the patients had mild to medium fluorosis while 32 % had severe fluorosis.

Table 9. Summary of TF score recorded from patients in St. Mary's Hospital-Gilgil.

Number of patients	TF score	
15	1	mild fluorosis
12	2	
15	3	
10	4	medium fluorosis
3	5	
9	6	severe fluorosis
6	7	
14	8	
2	9	
Total 86		

To establish the correlation between fluoride levels in the borehole data, severity of fluorosis, age, gender, and resident areas of the patients, a multivariate regression analysis was explored. From the spatial distribution of fluoride maps, the high fluoride areas were correlated with the average TF score of patients who reside in the area.

3.6.2.1 Fluorosis severity (TF score) vs spatial fluoride concentration in aquifers

Spatial variation of fluorosis severity and fluoride in groundwater was determined by comparing the spatial distribution of fluoride and the average TF score of patients according to their area of residence. Patients considered in this investigation came from different regions of the study area, and thus, provide a good representation of fluorosis prevalence and severity in the area. The average TF score for the patients in these areas was calculated and the results are presented in Table 10 below.

Table 10. The average TF score of patients from different locations in the study area recorded in St. Mary's Hospital-Gilgil.

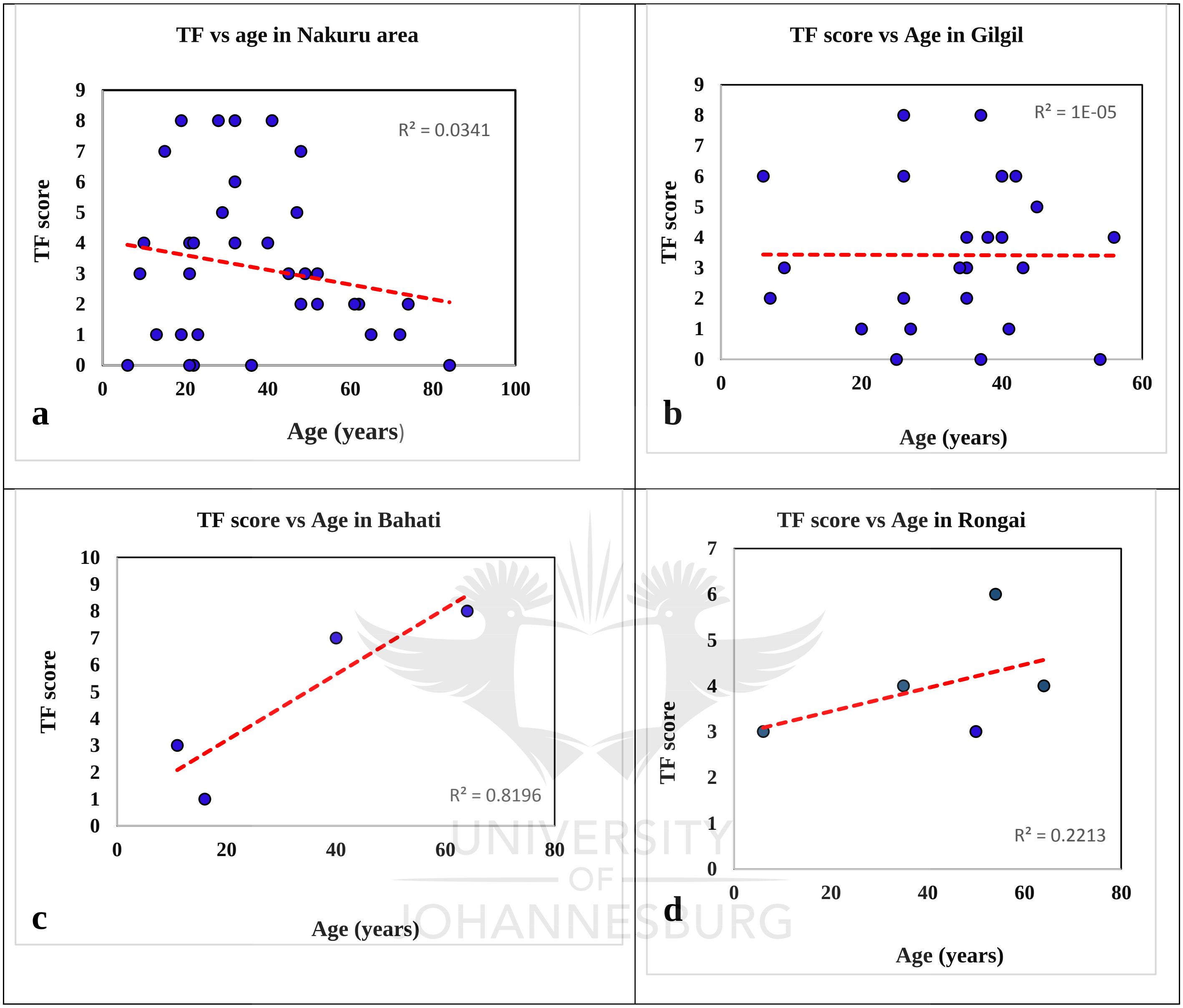
Area of residence	Number of patients	Average TF score
Around Nakuru town	33	3.4
Gilgil	27	3.7
Bahati	4	4.7
Rongai	5	3.3
Mbaruk	5	4.8
Solai	1	1
Njoro	2	4
Outside the study area	20	3.8
Sum	100	

In the table, most areas had patients with average TF higher than 3.3, the people have mild to medium fluorosis. The highest degrees of fluorosis were seen in patients from Mbaruk area located on the eastern side of L. Nakuru, followed by Bahati area in the north of the central part of the study area, then Njoro in the eastern part. The lowest degrees, were in patients from Solai, north of the study area, followed by Rongai in the north-west part, and patients around Nakuru town area. Patients from Mbaruk, Njoro, Nakuru town area, Gilgil, and Rongai areas showed high fluorosis, which corresponds to high fluoride in those areas as shown in the distribution map in Figure 17. High severity was observed in patients from Bahati, however, the fluoride spatial distribution map (Figure 17) shows low concentrations in the area. There was one patient from Solai in the northern part of the study area, therefore, not a good representative of the area to determine the average TF and derive conclusive correlation.

It should be noticed that the fluoride spatial maps show relative concentrations, therefore, Bahati area shows the lowest relative fluoride in the area despite having fluoride concentrations between 1.4 and 2.9 mg/l. The high severity recorded from patients from Bahati could be attributed to several factors such as: due to its rural locality, Bahati area does not have municipal water supply, therefore, there is high reliance on groundwater, unlike in areas like Gilgil and Nakuru town. This high reliance on groundwater, could be the cause of high average severity observed in the area despite having relatively lower fluoride concentrations in groundwater. The availability of municipal water supply in Nakuru town area, and Gilgil town also explains the relatively low average TF recorded in patients from these areas, despite having high fluoride in some parts of these areas.

3.6.2.2 Fluorosis severity (TF score) vs Age

To show how fluorosis severity varies with the age of the patients, a comparative analysis was conducted. Linear regression analysis graph of all the patients gave no correlation of TF score vs age, therefore, the analysis was done on each specific area where the patients live as shown in the graphs in Figures 29 a-e below. The results show a weak negative (R^2= 0.0341) correlation between TF score and age in patients from Nakuru town area, a positive correlation in patients from Bahati (strong, R^2=0.8196), Rongai (weak, R^2=0.2213), and Mbaruk (strong, R^2 = 0.7189), whereas, there was no correlation in patients from Gilgil (R^2 = 1E-05).


TF vs age in Nakuru area
TF score
R² = 0.0341
a
Age (years)
TF score vs Age in Gilgil
TF score
R² = 1E-05
b
Age (years)
TF score vs Age in Bahati
TF score
R² = 0.8196
c
Age (years)
TF score vs Age in Rongai
TF score
R² = 0.2213
d
Age (years)

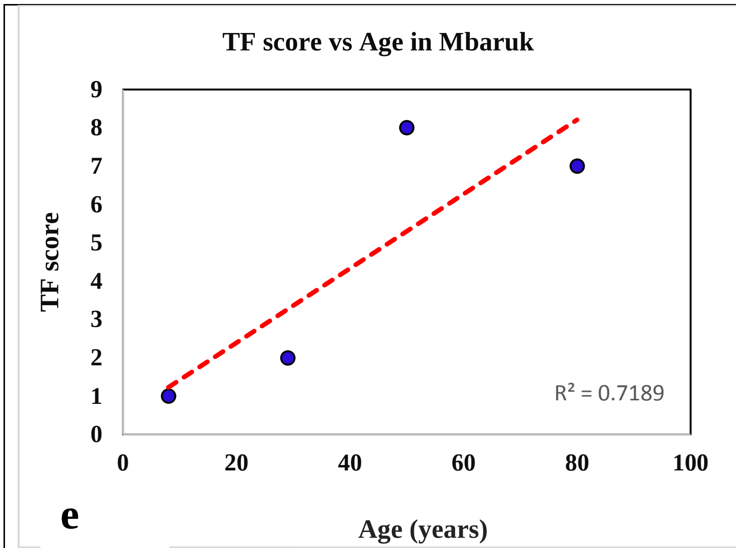


Figure 29 a-e. Linear regression graphs of fluoride severity vs age of the patients showing, negative correlation in Nakuru town area, no correlation in Gilgi, and positive correlation in Bahati, Rongai, and Mbaruk areas respectively.

The variation of severity and prevalence was then correlated with the two age groups, patients with developing dentition (below 14 years), and those with developed (above 14 years). There were 12 patients below 14 years, and only one had no signs of fluorosis making the prevalence of dental fluorosis 91.66%. Among 88 patients above 14 years, 13 patients had fluorosis making a prevalence of 85.56%. Average TF score for patients with developing dentition was 2.18 while for those with developed dentition was 3.77. Therefore, there was a higher prevalence in patients with developing dentition and a higher severity in patients with developed dentition.

Fluorosis increases with the duration of fluoride dosage in the body, therefore, adults have accumulated more fluoride due to the long duration of time of consumption compared to children (Fordyce, 2011). However, this is only applicable if the accumulation started during the early stages of teeth and bone development. This could possibly explain the positive correlation between age and TF score in Bahati, Rongai and, Mbaruk in Figure 29, and a higher severity in patients above 14 years. In a situation where both adults and children are introduced to high fluoride at the same time, children with developing dentition (below 14 years) tend to accumulate more fluoride than adults (Grimaldo et al., 1995; Kahama et a., 1997; Fordyce, 2011), therefore, can have higher fluorosis prevalence and severity. This could explain the negative correlation observed in Nakuru area (Figure 29a), and higher prevalence observed in patients below 14 years.

3.6.2.3 Fluorosis severity (TF score) and prevalence vs Sex

A comparative analysis was determined between the severity and prevalence of fluorosis, and sex of the patients. All male patients (n=45) had an average TF score of 3.88, while the 55 females had an average of 3.39. In 12 patients below 14 years, seven males had a TF score of 2.26, while five females had a score of 1.75. Among the 88 patients above 14 years, female patients (n=50) had an average severity of 4.00, while their male counterparts (n=38) had an average of 3.55. The prevalence of fluorosis was higher among male patients (91.11%) than in female ones (81.81%).

From these results, all male patients had a higher fluorosis severity than female patients. In the different age groups, males below 14 years still had a higher severity than their female counterparts, whereas, in patients above 14 years, females showed a higher severity. It should be noted that, although there were different scores observed, most of them were within 'mild fluorosis' group except in female patients above 14 years who had an average medium fluorosis (TF=4.0) while their male counterparts had mild (3.55).

3.6.3 Fluorosis records from Egerton University Njoro Dental Clinic

A total of 73 patients aged between 8 and 64 years participated in the study. Among them, 34 grew up outside the study area in different parts of Kenya with no similarity to the Rift Valley's geology and were therefore, not considered a good representative of the study area. This high number could be caused by the location of Egerton University, which has staff and other people running businesses around it who come from across the country. Data from the 39 patients (24 males and 15 females) who grew up in the study area were used in this analysis.

Among the patients, 20 came from the larger Njoro area, which includes Egerton where the university clinic is located, Njoro Center, Belgar, and Mauche, 17 came from Nakuru town area, and two from Rongai. There were 31 patients with dental fluorosis (TF>1), making the prevalence from the study areas 79.49%. Among the patients with no fluorosis, 7 came from Nakuru town area, and 1 from Rongai area. The prevalence of dental fluorosis in different regions of the study area was as follows; 58.82% (n=10) in Nakuru town area, 100% (n=20) in Njoro area, and 50% (n=1) in Rongai, which corresponds with the high fluoride concentrations found in these areas as shown in the spatial distribution map in figure 17. Among the patients with dental fluorosis, 61.29% (n=19) were male and 38.70% (n=12) were female. All patients (n=3) within the developing dentition age of 0-14 years had dental fluorosis making a 100 % prevalence in that age group. Among patients older than 14 years, 29 had dental fluorosis making a 79.38% prevalence.

These results from Egerton University-Njoro dental clinic indicate high prevalence of dental fluorosis in Njoro, Nakuru town area and Rongai, which corresponds to the high fluoride in groundwater shown in the spatial distribution map (Figure 17). The 100% prevalence in Njoro area corresponds with the high cases of dental fluorosis and even numerous cases of fractured bones, which are signs of skeletal fluorosis reported by a nurse in a clinic in Njoro center visited during fieldwork. High prevalence was also observed both in young patients between 6-8 years (100%) and in older patients (79.38%). Dental fluorosis prevalence was higher in male patients (61.29% %) than in female patients (38.70%).

From the general health investigation in the study area, the average fluorosis severity in patients from St. Mary's Hospital-Gilgil was 3.58, while the prevalence in patients from both dental clinics (St. Mary's Hospital-Gilgil and Egerton University-Njoro dental clinic) was in the range of 79.49-86%. These results show that, most of the local population suffer from mild dental fluorosis. There are several factors, however, which can affect the severity of fluorosis in an area despite the presence of high fluoride in groundwater. Nakuru and Gilgil towns have municipal water supply from river Malewa (Harper et al., 2013), which originates from the low fluoride Bahati escarpment, therefore, reducing fluorosis prevalence in population consuming piped water those towns. There are several physiological factors that affect the rate of fluoride absorption in the human body (Chen et al., 2012; James, 2016), which results in different levels of fluorosis in a population consuming the same amount of fluoride. Defluoridation of borehole water is practiced in Nakuru area (Akinyi and Kyende, 2013; Rutere, 2013), which reduces or prevents fluorosis amongst the population.

3.7 CONCLUDING REMARKS

The following is a summary of Chapter 3, which covers the case study involving studying the occurrence of fluoride in groundwater in the study area and its health implications through analysis and interpretation of borehole water and health study results:

- Nakuru area is located in the central Kenyan Rift Valley, with the Bahati and Mau escarpments in the east and south-west respectively, and the rift floor in the central part.
- Areas around the escarpments are mostly cold and humid and act as catchment areas, while the rift floor is mostly hot and humid. Ground and surface water flows radially from the escarpments to the floor.
- About 36% of the population, mostly in towns, have access to piped forcing most of the people in the area to rely on groundwater for domestic use.
- The area is dominated by late Quaternary Rift Valley alkaline volcanic rocks including various forms of trachytes, basalts, phonolites, tuffs, pumice, rhyolites, which can be intercalated, interbedded, or overlain by pyroclastics, lacustrine, and fluviatile sediments mostly in the rift floor.
- Fluoride rich minerals such as cordierite, muscovite, apatite, amphiboles, illite, kaolinite, and volcanic glass have up to 0.53 weight % fluoride.
- 4 aquifer groups were used in this study, which had high to low productivity, were found in fault-, fractured-, reworked sedimentary-, and weathered-zones of the different rock types.
- Water quality data from 32 boreholes covering these four aquifers show a dominant Na-HCO3 water type in the area, dominated by TDS, fluoride, sodium, bicarbonate, sulphate, carbonate, chloride, pH, calcium, magnesium, and potassium.
- Correlation analysis shows fluoride had a strong positive correlation with (in increasing order) potassium, magnesium, pH, chloride, sodium, carbonate, bicarbonate, TDS, and sulphate, and a weak negative correlation with (in descending order of association) depth and calcium. These correlations were consistent in the three analyses conducted; Pearson's Correlation, linear regression, and spatial analysis.
- Fluoride distribution in the area shows the highest concentrations in the rift floor area, and the lowest concentrations in the Bahati and Mau escarpment, in the east and south-west areas.
- High fluoride was observed in all the aquifer groups and the relative concentrations only varied with the location on the aquifers. Aquifers in the rift floor had the highest fluoride concentrations, while those close to the escarpments, had relatively lower concentrations.

- Dental fluorosis prevalence was studied in two dental clinics in the study area. Results show a prevalence range of 79.49 to 86%, and a severity of about 3.58 in one of the hospitals. This shows that, most of the population have mild dental fluorosis in Nakuru area.

CHAPTER 4: GENERAL CONCLUSIONS

4.1 LIMITATION FACTORS

It is worth noting that there are several limitations that must be taken into account in the case of the present study. The borehole data being secondary, is difficult to know which aquifer was sampled at the bottom of the boreholes, or if the boreholes were being pumped before sampled in an appropriate manner. The boreholes whose data was used to map fluoride concentration in the aquifers were different from those used by the patients who participated in the study, therefore were not the direct cause of the observed fluorosis cases. Although the main source of domestic water in the study area is groundwater, other sources of water such as piped municipal water, bottled water from outside the study area that can affect the prevalence and severity of dental fluorosis were not considered. This is a major factor particularly in Nakuru and Gilgil towns where, households, organizations, and institutions use municipal water supply. Another limitation is not considering other risk factors contributing to fluorosis such as diet, which varies with social status and the amount of daily water consumption, which varies from the hot and dry rift floor to the cool and wet escarpments areas.

4.2 CONCLUDING REMARKS

Despite the limitations mentioned above, the results obtained from this study show some meaningful and important trend. The following are the major findings of this study:

- The objectives of this study were to investigate the geogenic sources of high fluoride in groundwater in the study area, its occurrences and distribution in the aquifers, and prevalence of dental fluorosis in the local population. All these objectives were achieved through literature review of the local geology and hydrogeology, analysis of borehole data, and investigation of dental fluorosis in two hospitals in the area.
- Results from the geology studies of the study area show that, the dissolution of various alkaline volcanic rocks release the high fluoride in groundwater, whose concentrations in 87.50% of the boreholes studied, is higher than the WHO recommended value of 1.5 mg/l for safe drinking water.
- The results from both statistical and spatial analyses show a common trend of the nature and type of correlation between fluoride and the other dominant physico-chemical

parameters in groundwater. Fluoride had high positive association (in increasing order) with potassium, magnesium, pH, chloride, sodium, carbonate, bicarbonate, TDS, and sulphate, and a weak negative correlation (in descending order of association) with borehole depth and calcium. These correlations were consistent in the three analyses conducted: Pearson's Correlation, linear regression, and spatial analysis. From these correlations, it can be deduced that mineral dissolution and evaporative enrichment play part in fluoride release and concentration in groundwater in the area.

- There were high concentrations of fluoride in all the aquifer groups, and the variations only occurred with the location of the aquifers. Aquifers close to or in Bahati escarpment in the north-east area, and Mau escarpment in the south-west, showed the lowest fluoride concentrations, while aquifers in the rift floor had relatively higher fluoride concentrations. The fluoride hotspot was located between Nakuru town area and Njoro.
- The prevalence of dental fluorosis from both St. Mary's Hospital-Gilgil and Egerton University-Njoro dental clinics' study, was very high (>79%) and the average severity was mild (TF= 3.58) in St. Mary's Hospital-Gilgil. This means that, a high number of the local population suffer from mild dental fluorosis. A slightly higher prevalence was observed in patients with developing dentition, while older patients had a slightly higher severity. Fluorosis severity and prevalence did not show a considerable variation in male and female patients below 14 years. While older female patients showed a slightly higher severity than their male counterparts. High prevalence and severity of fluorosis was observed in most of the areas showing high fluoride in groundwater, signifying a positive correlation between fluoride concentrations in groundwater and the occurrence of dental fluorosis.
- This study, therefore, finds high fluoride concentrations in all aquifers in the study area, but the relative concentration was highest in aquifers in the rift floor, and reduces in aquifers located towards the escarpments. A high dental fluorosis prevalence (> 79%) observed in patients from the two hospitals, correlates with the high fluoride (> 1.5 mg/l) found in more than 80% of the boreholes used in the study.

4.3 SOME POSSIBLE RECOMMENDATIONS

A detailed mapping and productivity evaluation of aquifers close to or in the escarpments is required, as this study shows relatively lower fluoride concentrations in these aquifers, which can be exploited for safe domestic water. Borehole casing is suggested to boreholes with low fluoride concentrations, which occur close to those with high fluoride concentrations. There is a knowledge gap regarding the amount, duration, and timing of fluoride ingestion, water sources and nutrition among the population of the study area to establish the fluoride dose in drinking water and risk factor for dental and skeletal fluorosis for Nakuru area.

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APPENDIX 1. Borehole water quality table

WELL-ID	EASTINGS	NORTHIN(	PROJECT N	ELEVATIOI	DEPTH(M)	pH	F	Ca	Mg	Na	K	HARDNESS	Cl-	SO4	NO4	CO3	HCO3	TDS	ROCK
C364	177786.6	9968950	ST.MARYS	1854	126	7.4	1.4	3	0	94	10	12	7	16	1	1.2	260	258	TRACHYTE
D389	171505.2	9963968	HOPEWELI	1790	65	8.6	5.7	5	2	164	15	20	0.05	32	1	5.6	334	502	TRACHYTE
D359	180879.1	9981094	ALKIS CHA	2015	185	5.8	2	16	0.2	38	5	48	8	6	4	0	144	158	PHONOLIT
D399	175311	9967720	BILAL MUS	1830	100	8.7	30.2	3	7	430	11	34	72	56	0.9	22.4	1083	1206	TUFF/ VOL
D398	821963	9959236	CHEPTOROI SELF HEL		120	6.5	1.1	30	1	76	9	59	0.05	4	0.7	5.1	323	338	TRACHYTE
D439	179005.2	9937748	RERECUA \	1960	250	8.1	3.7	35	5	59	12	107	14	9	3	1.5	412	465	TRACHITES
D391	183675.4	9943744	ANDREW (	1850	170	7.6	7.1	16	8	181	11	73	35	29	1	4.2	465	614	TRACHITES
D390	193862	9923732	HOUSE OF PLENTY CH		200	7.8	13.1	17	2	258	16	52	109	103	0.2	1.5	600	908	TRACHITES
D342	828866.6	9965413	JENIFER N.	2135	150	7.3	2	14	0.7	42	6	37	48	5	3	5.9	100	223	TUFF
D510	183259	9978523	STEVEN KARIUKI		140	8.1	2.3	23	0.1	77	6	300	19	3	0.1	10	362	286	TRACHITES
D481	173099	9966737	DAVID GATONGI- MW		70	8.8	26.1	5	0.3	880	12	13	128	58	3.2	0.4	332	1814	PHONOLIT
D498	174944	9967145	BONDENI	1825	123	8.5	28.5	2	2	695	14	16	65	71	2.5	19.7	1505	2011	PHONOLIT
D430	190936.4	9985706	MARANA SELF-HELP (		120	8	1.9	4	4	13	6	28	10	12	0.2	3.3	128	122	PHONOLIT
D282	179951.3	9976944	DR. KELVII	1900	150	7.7	5.4	15	4.9	54.7	9.1	57	5.4	4.8	7.5	0.3	150	250	SANDS
D273	184127.8	9988472	BEREA THI	2200	70	7.4	0.5	9.9	2.1	26.6	11.4	33.2	9.8	0.1	0.5	0.4	381	233	TUFF
D251	174073	9967812	CDN MAIN	1820	120	9	72	2	0.58	869	18	7.4	72	281	2.5	78.9	1590	2210	TUFF
D220	180569.5	9981863	JOMO KEN	1960	220	8.3	2.3	12.3	0.6	68.6	2.2	33.1	3.9	3.5	0.7	1.7	210	260	TUFF
D214	179642.6	9973316	ST. ANTHC	1920	130	8.2	6.4	1.3	0.2	128.3	12.1	4.1	4.9	20.1	1	2.6	323	340	
D405	173979.9	9968642	RIFT VALLEY SPORTS (		125	9.1	22.5	2	3	414	8	15	30	62	0.6	34.5	649	762	
D308	176236.3	9984321	MIONDE-E	1830	160	8.7	11.1	2.5	0.1	107	5.9	6	11.6	16	4	12.1	599	328	TUFF
D178	180321.1	9989271	SOLAI SEC. SCHOOL		130	7.3	1	5.6	1.6	118.2	1.2	18	8	9	0	0	240	270	
D167	183086.1	9947003	ELEMENTA	1830	100	7.2	12.7	4	2.4	393	82.4	20	20	20	0	0.4	275	1200	TUFF
D166	168038.8	9963568	INGOBOR	1960	200	7.5	3.5	12.8	1.8	86.4	23.4	39.6	10.3	10.7	1.2	3.4	388	312	TUFF
D557	197832	9944335	LIFE WATE	1920	160	8.1	10	4	13	108	10	64	40	20	0.2	0.9	412	423	PHONOLIT
D562	167222.7	9971100	GRANDEPARK ESTATE		226	8	26.4	2	1	159	1	9	167	159	0.8	1.8	392	1243	PHONOLIT
D400	182335.8	9970120	RIARA FARM LTD		110	7.7	2	10	10	34	9	67	11	13	3	2.1	180	254	PHONOLTI
D285	192947.2	9994928	RHEINI VA	2020	160	6.9	2.9	7.7	9	64	15.8	56.4	5	4.2	1.7	0.1	220	310	VOLCANIC
D287	194347.6	9954200	SERVANTS	1777	140	8.5	9.3	3.2	3.2	230	13	21.1	32.6	8.8	3.1	4.4	640	610	TUFF
D260	824647.4	9939160	NJORO SPECIAL SCHC		125	7.2	2.1	11.5	4.2	55.9	11.7	45.9	17.6	11.7	1.9	0.1	171	308	
D1	192186.5	9941504	JOHN WACHIRA-STEI		130	7.6	7.1	16	8	181	11	73	35	29	1	0.9	465	614	
D2	231610.1	9928307	TENGECHA PRIMARY		130	7.6	6	6	37	16	15	230	18	20	1	0.5	279	173	
D288	173535	9967223	KASARANI POLICE LII		120	8.6	26.3	5	0.6	995	15	14	80	48	2	1.8	900	1920	TRACHITES

Appendix 2. Ethics Clearance letter from the University of Johannesburg

Faculty Ethics Committee
Faculty of Science
University of Johannesburg
Kingsway
Auckland Park Campus

Date: 20 November 2015

Protocol No: November 2015
Name: PK Gevera
Student No: 201517396

Researcher: Mr PK Gevera

Supervisor: Prof H Mouri

Department: Geology

Project Title: The occurrence of high fluoride in groundwater and its health implications in Nakuru County in the Kenyan Rift Valley.

Programme: MSc in Geology

APPLICATION FOR RESEARCH ETHICS CLEARANCE

Dear Mr Gevera

Thank you for submitting your proposal for ethics clearance.

The Faculty Ethics Committee of the Faculty of Science, University of Johannesburg reviewed and approved the application to use data obtained from the records of patients at the local health centres relating to the clinical traits of fluoride effects after informed consent has been obtained from the patients whose records will be used to obtain the required data and the relevant Health Authorities in Kenya.

Period of Study approval: 36 months

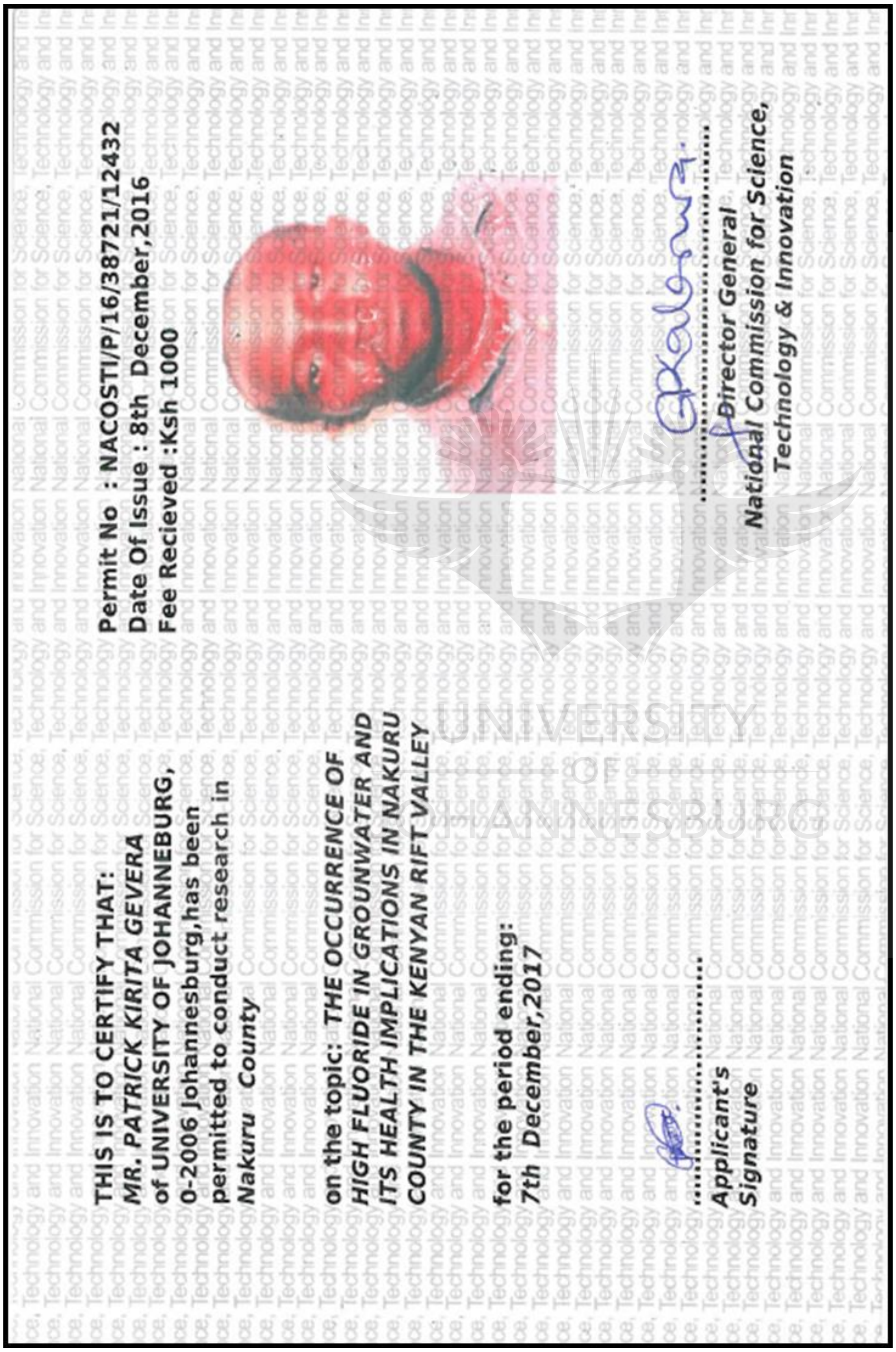
Sincerely

Chairperson: Faculty Ethics Committee
Faculty of Science

OFFICIAL ADDRESS | Cnr Kingsway and University Road Auckland Park
PO Box 524 Auckland Park 2006 | Tel +27 11 559 4555 | www.uj.ac.za
Auckland Park Bunting Campus | Auckland Park Kingsway Campus
Doornfontein Campus | Soweto Campus

UNIVERSITY OF JOHANNESBURG

Appendix 3. Ethics research permit from NACOSTI Kenya



THIS IS TO CERTIFY THAT:
MR. PATRICK KIRITA GEVERA
of UNIVERSITY OF JOHANNEBURG,
0-2006 Johannesburg,has been
permitted to conduct research in
Nakuru County

on the topic: *THE OCCURRENCE OF HIGH FLUORIDE IN GROUNWATER AND ITS HEALTH IMPLICATIONS IN NAKURU COUNTY IN THE KENYAN RIFT VALLEY*

for the period ending:
7th December,2017

....
Applicant's Signature

Permit No : NACOSTI/P/16/38721/12432
Date Of Issue : 8th December,2016
Fee Recieved :Ksh 1000

....
Director General
National Commission for Science, Technology & Innovation

Appendix 3. Informed consent Form

Informed Consent Form for dentists and dental technicians participating in the study: occurrence of high fluoride in groundwater and its health implications in Nakuru County in the Kenyan Rift Valley

Name of Principal investigator: **Patrick Kirita Gevera**

Name of Supervisor/ co supervisor: **Prof Hassina Mouri and Dr. Lydia Olaka**

School: **University of Johannesburg**

PART I: Information Sheet (information about the research)

Purpose of this investigation

This research is aimed to find the concentration of fluoride in the boreholes and map its concentration in the aquifers in Nakuru area. The effect of high fluorosis will be determined by investigating the occurrence and severity of fluorosis on the local population.

Why conduct this study?

Due to unreliability of rain water in the rift valley, most people have sort groundwater which is reliable for domestic, agricultural and industrial use. Unfortunately, contrary to common belief that groundwater is safe for drinking, groundwater in most part of the Rift Valley has high concentrations of fluoride which causes fluorosis (dental and skeletal) when consumed for a long period. This study is aimed to identify fluoride concentration in the aquifers and its health implications. This will help map out aquifers with high and low levels of fluoride which will aid in prospecting of clean and healthy groundwater.

Methodology

Water quality data was obtained from the CDN (Catholic Dioses of Nakuru) water program collected over a period of time in the area. The geochemical data was correlated to determine chemical controls of fluoride in groundwater and mapped on the aquifers of the area. The geochemical data shows higher concentrations of fluoride than the recommended 1.5 mg/l by WHO. This suggests a serious health problem exists in the area in form of dental and skeletal fluorosis caused by accumulation of fluoride in calcified tissues of the body such as teeth and bones. This results to stained teeth and brittle bones common in the area.

Therefore, we hereby request your cooperation in collecting clinical records on fluorosis affecting people residing within the Nakuru area.

Information required:

1. Fluorosis record (Deans and TF indices) of the about 100 first patients treated on the month of January 2017 in your dental facility.
2. Area of residence
3. Gender:
4. Age

Ethical consideration

The clinical information that we collect from this research will be kept confidential. Thus, any information about a patient (age, sex and geographic location) will not be made public or available to unauthorized individual. Anonymity of the data will be assured; this will be achieved by not recording patient name to protect the identity of the patient.

The knowledge that we get from this research will be shared with you.

If you have any queries in this regard, or any aspect of the research, please don't hesitate to contact any of the following: Patrick Gevera (pattygevera@gmail.com) (MSc candidate) or Dr. Lydia Olaka (lydiaolaka@gmail.com) (Co- supervisor of the project residing in Kenya).

Signature

Date:___________________

PART II: Certificate of Consent

I have read the foregoing information. I have had the opportunity to ask questions about it and any questions that I have asked have been answered to my satisfaction. I consent voluntarily to participate in this research.

Print Name of Participant___________________

Signature of Participant ___________________

Date ____________________________

Day/month/year

I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily. A copy of this informed consent form has been provided to the participant.

Print Name of Researcher/person taking the consent________________________

Signature of Researcher /person taking the consent__________________________

Date ___________________________

Day/month/year

Appendix 4. Clinical data collection forms

Fluorosis cases in Nakuru area recorded in St. Mary's Hospital/ Egerton University Dental Clinic

1. INTRODUCTION

This form is part of the research 'The occurrence of high fluoride in groundwater and its health implications in the Nakuru County in the Kenyan Rift Valley'. A short description of the study is contained in the informed consent form attached to this document. This part is intended to record the number patients treated in the clinic with visible fluorosis. Patients information will be filled in the last section as indicated. The TFI score below will be used for scoring fluorosis degree on the patients.

2. Thylstrup and Fejerskov Index- (TFI)

This TFI was proposed by Thylstrup and Fejerskov (1978) with the aim of overcoming the shortcomings of the Dean's index. Like the DI, the TFI is a tooth based scoring system that produces a maximum of 28 scores per subject. It is a **10-point** classification scale with numeric values from 0-9. This original index (with 10 categories involving description of all tooth surfaces) of fluorosis attempts to correlate clinical appearance with pathological changes in tissue. It therefore is a useful tool when evaluating dental fluorosis severity in epidemiological studies. However, it uses ordinal scale and therefore the scores should be considered only arbitrary points along a continuum of change. The index was later modified to be based solely on examination of facial tooth surfaces Score Criteria

- **0**- Normal translucency of enamel remains after wiping and drying of the surface
- **1**- Narrow opaque/white lines running across the tooth surface. Slight snow capping of cusps or incisal edges may also be seen.
- **2** -Smooth surfaces. More pronounced lines of opacity that follow the perikymata. Occasionally confluence of adjacent lines. Occlusal surfaces: Scattered areas of opacity

less than 2mm in diameter and pronounced opacity of cuspal ridges. Snow-capping is common.

- **3-** Smooth surfaces: Merging and irregular cloudy areas of opacity. Accentuated drawing of perikymata often visible between opacities. Occlusal surfaces: Confluent areas of marked opacity. Worn areas appear almost normal but usually circumscribed by a rim of opaque enamel
- **4-** Smooth surfaces: The entire surface exhibits marked opacity or appears chalky white. Parts of surface exposed to attrition appear less affected. Occlusal surfaces: Entire surface exhibits marked opacity. Attrition is often pronounced shortly after eruption
- **5-** Smooth surfaces and occlusal surfaces: Entire surface displays marked opacity Focal loss of outermost enamel (pits). Less than2mm in diameter.
- **6** -Smooth surfaces: Pits are regularly arranged in horizontal bands less than2mm in vertical height occlusal surfaces: confluent areas less than2mm in diameter exhibit loss of enamel marked attrition.
- **7-** Smooth surfaces: Loss of outermost enamel in irregular areas involving less than half of the entire surface. Occlusal surfaces: changes in the morphology caused by merging pits and marked attrition
- **8-** Smooth and occlusal surfaces: Loss of outermost enamel involving more than half of surface
- **9** -Smooth and occlusal surfaces: Loss of main part of enamel with change in anatomic appearance of surface. Cervical rim of almost unaffected enamel is often noted.

Appendix 5. Dental clinic records for St. Marys' Hospital-Gilgil

PATIENT	AGE (years)	GENDER	AREA OF RESIDENCE UP TO THE AGE OF 10 years	TF SCORE
1	40	Female	Bahati	7
2	11	Female	Bahati	3
3	15	Female	Nakuru Town	7
4	13	male	Nakuru Town	1
5	65	Male	Nyarate	6
6	16	Female	Bahati	1
7	50	Male	Rongai	3
8	6	Female	Nakuru town	0
9	6	Female	Rongai	3
10	20	Male	Gilgil	1
11	22	Female	Nakuru town	0
12	6	Male	Gilgil	6
13	36	Female	Kabaraki	0
14	48	Male	Nakuru town	2
15	65	Male	Nakuru town	1
16	35	Male	Naivasha	2
17	45	Male	Nakuru town	3

18	17	Male	Kagumo	7
19	35	Female	Gilgil	2
20	25	Male	Mbaruk	0
21	62	Female	Kikopey	8
22	5	Male	Naivasha	1
23	9	Male	Gilgil	3
24	29	Male	Nakuru	5
25	7	Male	Gilgil	2
26	26	Female	Gilgil	6
27	80	Female	Mbaruk	7
28	35	Female	Rongai	4
29	37	Female	Gilgil	8
30	8	Female	Mbaruk	1
31	24	Female	Naivasha	8
32	35	Female	Solai	0
33	34	Male	Gilgil	3
34	48	Female	Pipeline	7
35	45	Male	Gilgil	5
36	52	Female	Njoro	1
37	36	Female	Nakuru	0
38	64	Female	Bahati	8
39	18	Female	kikopey	6
40	41	Male	Free area	8
41	19	Female	Nakuru	1

42	64	Female	Ol Kalau	0
43	49	Male	Pipeline	3
44	10	Male	Nakuru	4
45	43	Male	Gilgil	3
46	23	Female	Naivasha	6
47	37	Male	Kikopey	8
48	26	Female	Laikipia	0
49	41	Male	Gilgil	1
50	28	Female	Nakuru town	8
51	32	Female	Greensted East of L.Nakuru	4
52	22	Female	Njoro	7
53	25	Female	Gilgil	0
54	47	Female	Flyover	5
55	33	Female	Narok	3
56	9	Male	Nakuru-town	3
57	24	Male	Mahi Mahiu	9
58	40	Female	Gilgil	4
59	62	Female	Pipeline	2
60	27	Female	Gilgil	1
61	22	Male	Karua	8
62	54	Male	Rongai	6
63	31	Female	Naivasha	9
64	35	Male	Gilgil	3

65	50	Female	Mbaruk	8
66	56	Male	Gilgil	4
67	74	Male	Nakuru-town	2
68	84	Female	Nakuru-town	0
69	52	Male	Nakuru-town	2
70	64	Female	Rongai	4
71	72	Female	Nakuru-town	1
72	32	Male	Nakuru-town	6
73	26	Female	Gilgil	8
74	18	Female	Kikopey	0
75	21	Female	Pipeline	4
76	31	Male	Naivasha	1
77	42	Female	Gilgil	6
78	35	Male	Gilgil	4
79	37	Male	Laikipia	2
80	40	Female	Nakuru-town	4
81	29	Male	Mbaruk	2
82	21	Male	Nakuru-town	0
83	26	Male	Gilgil	2
84	32	Male	Nakuru-town	8
85	40	Female	Gilgil	6
86	7	Male	Naivasha	1
87	19	Female	Nakuru-town	8
88	61	Female	Nakuru	2

89	22	Male	Shinners	4
90	21	Female	Nakuru-town	3
91	34	Male	Elbagon	1
92	83	Male	Naivasha	8
93	38	Female	Gilgil	4
94	23	Female	Nakuru-town	1
95	54	Male	Gilgil	0
96	47	Female	Molo	3
97	37	Male	Gilgil	0
98	23	Male	Ol Kalau	2
99	63	Female	Kariandusi	8
100	52	Female	Pipeline	3

Appendix 6. Dental clinic records for Egerton University-Njoro Dental Clinic

PATIENT	AGE	GENDER	AREA OF RESIDENCE UP TO THE AGE OF 10	PRESENCE OF FLUOROSIS?
1	22	Male	Belbar Njoro	Present
2	21	Male	Belbar Njoro	Present
3	48	Male	Nakuru town area	present
4	8	Male	Egerton	present
5	22	Female	Egerton	present
6	30	Male	Mauche Njoro	Present
7	29	Male	Egerton	Present
8	22	Male	Nakuru town area	Present
9	20	Male	Nakuru town area	Absent
10	21	Male	Thika	Absent
11	20	Male	Nakuru town area	Absent
12	21	Male	Thika	Absent
13	19	Female	Njoro	Present
14	20	Female	Nakuru town area	Absent
15	28	Female	Kisii	Absent
16	21	Female	Mombasa	Absent

17	30	Female	Kitui	Absent
18	17	Male	Mombasa	Absent
19	20	Female	Nakuru town area	Present
20	22	Male	Lodwa	Absent
21	37	Male	Njoro	Present
22	29	Female	Nakuru town area	Absent
23	19	Male	Kisumu	Absent
24	24	Male	Machakos	Absent
25	29	Male	Nakuru town area	Present
26	19	Male	Baringo	Absent
27	26	Male	Nairobi	Absent
28	25	Male	Kisumu	Present
29	20	Male	Kisumu	Absent
30	21	Female	Kisii	Absent
31	19	Male	Oyugis	Present
32	19	Female	Kisii	Absent
33	29	Male	Kericho	Present
34	9	Female	Egerton	Present
35	20	Male	Nakuru town area	Present
36	52	Female	Belbar Njoro	Present
37	21	Female	Njoro	Present
38	22	Male	Meru	Absent

39	18	Male	Njeri	Absent
40	19	Female	Bungoma	Absent
41	22	Female	Nandi	Absent
42	20	Male	Njoro	Present
43	6	Female	Egerton	Present
44	23	Male	Wajia	Present
45	21	Male	Belbar	Present
46	21	Male	Nakuru town area	Present
47	21	Male	Kisii	Present
48	21	Male	Mombasa	Absent
49	19	Female	Nakuru town area	Present
50	23	Female	Nakuru town area	Present
51	21	Male	Njoro	Present
52	21	Male	Nakuru town area	Present
53	17	Male	Rongai	Present
54	10	Male	Kisumu	Absent
55	23	Female	Nakuru town area	Present
56	27	Male	Rongai	Absent
57	23	Male	Njoro	Present
58	25	Male	Kericho	Absent
59	27	Female	Baringo	Absent

60	23	Male	Nakuru town area	Absent
61	64	Male	Egerton	Present
62	64	Female	Egerton	Present
63	24	Female	Baringo	Absent
64	18	Female	Nakuru town area	Absent
65	24	Male	Busia	Absent
66	26	Male	Eldoret	Absent
67	22	Male	Njoro	Present
68	17	Female	Nandi	Absent
69	20	Female	Nakuru town area	Present
70	22	Male	Baringo	Absent
71	21	Male	Kakamega	Absent
72	23	Female	Kericho	Absent
73	38	Male	Kitui	Absent