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HYDROCHEMICAL CHARACTERISTICS OF AQUIFERS IN MWINGI NORTH - KENYA

BY

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DECLARATION

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

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ABSTRACT

The arid to semi-arid area of Mwingi North, Kenya, suffers from low access to potable groundwater in part due to salinity, but also due to uneconomical development of groundwater because of the lack of understanding of the types of aquifers and knowledge of their distribution. The main objective of the study was to characterize the groundwater hydro-geochemical composition and also assess the problems caused by high salinity and fluorides in crystalline b*a*sement aquifers of Mwingi North. Groundwater sampling was carried out within the environment of Mwingi North for chemical analysis. 42 water samples collected from shallow depth wells (0-20 m), hand pumps (20 -100 m), and deep boreholes (Below 100 m and motorized) were analyzed using atomic absorption spectroscopy (AAS), ion-selective electrode, argentometric, turbidimetric, and titration methods. Parameters analyzed include cations such as potassium, sodium, calcium, magnesium, manganese and iron and anions such as carbonates, bicarbonates, nitrates, nitrites, sulfates, chlorides, and fluorides. Physical parameters that were analyzed included electrical conductivity, temperature, pH, turbidity, hardness, total alkalinity, color, free carbon dioxide and total dissolved solids. Electrical conductivity ranges from 362 µS/cm to 9379 µS/cm, temperatures ranges from 24ºC to 28ºC, and pH varies from 7.55 - 8.76. The concentration of Na^+ ranges from 3 - 800 mg/l distributed along E to W region while Mg^{2+} and Ca^{2+} have a spatial distribution pattern on an N to S region along the central areas with their concentrations ranging from 11.61 - 641 mg/l and 5.6 -592 mg/l respectively. Cl^- ranges from 3 -2320 mg/l with its spatial distribution pattern following N-S direction along the central areas while F^- registered minimal highs ranging from 0.26 - 4.65 mg/l. Using the median, concentrations of cations in groundwater increases in the order $Na^+ > Mg^+ > Ca^{2+} > K^+ > Fe^{2+} > Mn^{2+}$ while concentration of anions increases in the order $Cl^- > HCO_3^- > SO_4^{2-} > CO_3^- > NO_3^- > F^-$. EC, Na, Mg, Ca, Cl, and F are above WHO's maximum acceptable level in hand pumps and boreholes. Shallow wells have the least mineralized groundwaters while boreholes have highly mineralized groundwaters. Cation-exchange is the dominant rock-water interaction process. The relationship between Na^+ versus Cl^- for the majority of the groundwaters, suggests similar hydrochemical processes. Mivukoni and Ngomeni areas have poor quality groundwaters while Mumoni and south of Kyuso have potable groundwaters.

DEDICATION

I dedicate this report to my father Joseph Gogo Wadira.

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ACRONYMS AND ABBREVIATION

µs/cm	Micro-Siemens per centimeter
AAS	Atomic Absorption Spectrophotometry
APHA	American Public Health Association
ASAL	Arid and semi-arid land
AWWA	American Water Works Association
Bh	Borehole
EDTA	Ethylenediaminetetraacetic acid
EC	Electrical conductivity
GOK	Government of Kenya
pH	Potential of hydrogen
Eh	Redox potential
EU	European Union
FAO	Food and Agricultural Organization
GPS	Global Positioning System
GMT	Greenwich Mean Time
Hp	Hand pump
ISE	Iron Selective electrode
JICA	Japanese International Corporation Agency
KCIDP	Kitui County Integrated Development Plan
KEBS	Kenya Bureau of Standards
MAC	Maximum allowable concentration
$Meql^{-1}$	Milliequivalents per liter
MOWI	Ministry of Water and Irrigation
Mgl^{-1}	Milligrams per liter
NTU	Nephelometric Turbidity Units
PCO_2	Pressure of carbon dioxide
P-T-t	Pressure-Temperature-time
SPSS	Statistical Package for the Social Sciences
Sw	Shallow well
TDS	Total Dissolved Solids
UN	United Nation
USA	United States of America
WRA	Water Resources Authority
WHO	World Health Organization

CHAPTER ONE
INTRODUCTION

1.1 Introduction

This chapter presents the overall background of the hydrochemical characteristics of aquifers in Mwingi North – Kenya. It briefly discusses the impact of hydrogeochemistry globally, regionally and locally. It also outlines the research problems, main and specific objectives.

1.2 General Introduction

Groundwater is revered worldwide as the main water source for domestic, industrial and agricultural use (Hsan and Ansur, 2009). About a half of the global population use groundwater (Zheng et al., 2017). The increasing use of groundwater has mainly been realized in arid and semi-arid areas without surface water sources as well as in areas without piped water (Adams et al., 2001). Globally a third of the population depends entirely on groundwater for domestic use (Shivshankar et al., 2014). Consumption of groundwater without known hydrochemical composition has led to serious health problems such as dental fluorosis and kidney failures in humans (Young & Ishiga, 2011). It has also affected agricultural production and hence economy of a nation (Ochungo et al., 2019).

The primary source of salinity is due to the accumulation of mineral salts in the host rock material or groundwater (Attibu, 2014). Increasing salinity occurs from the weathering of soil and rocks which eventually lead to salt leachate from geologic marine sediments (Shiekhvanloo & Poorhasan, 2010). Secondary causes of salinity are anthropogenic, including addition of fertilizers to soil. During soil leaching, the infiltrated water dissolves these salts and percolates into the groundwater aquifers thus contributing to groundwater pollution. Secondary salinization is spreading rapidly mainly due to a steady rise in population and increased industrialized agriculture (Shiekhvanloo & Poorhasan, 2010). Further, salt accumulations in soils create an ionic imbalance in the soil thus inhibits plant growth (Attibu, 2014). Likewise, consuming water of high salinity has health hazards apart from compromising palatability (Attibu, 2014).

1.2.1 Global Hydrogeochemistry

Groundwater hydrochemistry is controlled by the geology, chemistry of rainwater, rivers and anthropogenic processes (Soler & Marcos, 2015). However, geology remains the main determinant in groundwater hydrochemistry (Kontis & Gaganis, 2012); thus, groundwater is composed of various hydrochemical elements depending mainly on rock-water interaction. In crystalline basement terrains, granitoid weathers down by hydrolysis to produce clay minerals while K, Na, and Mg ions are removed in solution leaving the relatively stable quartz. Likewise, in igneous areas, basalts weather out into clays and soluble ions of Na, Ca, and Mg; geochemical reactions of the resulting clay minerals with water releases ions into groundwater through weathering of primary silicates and secondary mineral phases (Pawar, 2016). Groundwater quality in crystalline basement aquifers is determined by rates of the geological and geomorphological processes acting on a particular area (Balakrishnan, 2020). Topography and the difference in hydraulic conductivities of rock units control the direction of ground and surface water flow (Adams et al., 2001). The excesses in the hydrochemical compositions of Cl^- and F^- resulting from the weathering of plagioclase and feldspars minerals are responsible for natural groundwater contamination (Appelo and Postman, 1996). Knowledge of the geogenic processes resulting in excess elemental concentrations in groundwater is essential in the development of strategic groundwater resources (Clark, 2015).

Salinity is sometimes a major issue in groundwater. It can be defined in a number of ways: (1) as the concentration of dissolved mineral salts in water and soils as a unit volume or weight basis (FAO, 1988; Ghassami et al., 1995); (2) by the chloride content (Hsan & Ansur, 2009); (3) by its total dissolved solid content (TDS in mgl^- or gl^-) (Hsan & Ansur, 2009), or (4) by its electrical conductivity (EC) (Vengosh, 2005). Groundwater salinity is also influenced by temperature and pH. The measure of pH refers to the H^+ and OH^- ions in water. According to Shiekhvanloo & Poorhasan (2010), waters of high temperatures experiences increased chemical reactions which reduces the solubility of gases resulting in a change in the taste and odor of water. Generally, the accumulation of salinity in both soils and water is determined by local topography, rate of evaporation, and vertical permeability (Adams et al., 2001). Water salinity varies from one place to another depending on the source of water, hydrochemistry of the environment, climate and geology of rock formation of the area (Avtar and Surjan, 2013). Saline water may have excess concentrations of anions such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) or cations, such as, chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), nitrate (NO_3^-) and trace minerals such as barium (Ba), strontium (Sr), lithium (Li), rubidium (Rb^+), iron (Fe), molybdenum (Mo), manganese (Mn) and aluminum (Al_3^+) in small concentrations (Young & Ishiga, 2011). The ratio of occurrence of these minerals in both surface and groundwater depends on the processes of rock-water interactions (Shiekhvanloo & Poorhasan, 2010).

Rainwater is the major recharge source for groundwater, and it is composed of some dissolved substances depending on the locality and time (Vengosh, 2005). As rainwater infiltrates and percolates the overburden, it undergoes several processes including adsorption, absorption, precipitation, and dissolution through rock-water interaction to modify the groundwater chemistry (Gibbs, 1967). Apart from the direct infiltration of rainwater, many groundwater systems receive considerable recharge from rivers, and also discharge into rivers during low flow periods (Vengosh, 2005); they are thus closely inter-linked. River water salinization depends on rainwater quantity and quality, evaporation, mineral weathering, topographic relief, vegetation cover and biological activity in a given area (Sharma & Subramanian, 2008).

The Piper diagram classification can be used to group water into NaCl, $NaHCO_3$, Ca $(HCO_3)_2$, $CaCl_2$, $CaSO_4$, and Na_2SO_4. $Ca(HCO_3)_2$ type waters (Adams et al., 2001). Further, Adams et al., (2001) noted that carbonate type waters are found on raised grounds of localized recharge while topographically lower grounds are associated with NaCl type waters. The presence of HCO_3 as the dominant dissolved ion in river water causes marginal acidity of water.

Groundwater pollution is a global phenomenon controlled by several factors. A study carried out by Gibbs (2019) found out that the three major factors that control world water chemistry are atmospheric precipitation, rock dominance, and evaporation–crystallization. Gibbs (2019) further observed that other minor factors that influence world water chemistry include relief, vegetation and composition of materials in the host rock. In the same study Gibbs (2019) also observed that the two end members characterizing world water chemistry are Ca-rich waters which represent the freshwater members and the Na-rich end which represents the highly saline waters. This study further noted that evaporation increases with salinity. Low saline groundwater is common in the tropics of Africa and South America. These are thoroughly leached, low relief areas that receive high rainfall throughout the year. In these areas, due to high rainfall, the rate of salt dissolution into the groundwater aquifers is low.

1.2.2 Regional Hydrogeochemistry

A study by Odoma & Umar (2014) in Nigeria established that groundwater quality in urban areas depends on the geology and geochemistry of the environment, rate of urbanization, industrialization, landfill/dumpsite, leachate, heavy metals, bacterial pollution, and climate. The study further suggests correctional measures such as preservation of water sources, better waste management, construction of sanitary landfills, control of all land use polluting activities and treatment of water before consumption. A similar study by Sharma & Subramanian (2008) of Narmada and Tapti Rivers in India also states that anthropogenic sources are an important means through which chemical pollutants find their way into the groundwater systems. Likewise, Tijani et al., (1996) in his study on the origin of saline water in the Ogoja area, Nigeria observed that the global water chemistry is generally a function of the rock weathering and, to a minor extent a product of anthropogenic processes.

The extensive Eastern Mozambique Belt Segment (EMBS) is associated with several episodes of metamorphism which gave rise to various ionic changes in the rocks, depending on the reactions which took place at different temperature and pressures (Nyamai et al., 2005). Past studies have indicated increased salinity in the groundwater aquifers of these areas (Nyamai et al., 2003 and Mathu, 2012). Regionally, the East African Rift System, which extends from Djibouti in the horn of Africa through Ethiopia, Kenya, Uganda, and Tanzania, has been distinguished as having increased concentrations of fluoride in water (Olaka et al., 2016; Wambu et al., 2014). The region has witnessed a lot of volcanic activity associated with chemical reactions at high temperatures and pressures. A study carried out in the rift found out that fluoride levels within the surface and groundwater of East Africa ranges from 0 to 180 mg/l (Olaka et al., 2016). Fluoride (F^-) concentrations are a necessity for human health if taken in required amounts and depending on age. Ingestion of lower amounts of fluorides (<0.4 mg/l) results in dental caries especially in young children with developing teeth while ingestion of excess amounts (>1.5 mg/l) of fluorides by older children or adults results in dental fluorosis (Pendrys & Stamm, 1990). Continued use of excess amounts of fluorides has been reported to result in serious health problems such as skeletal fluorosis, calcification of ligaments and neurological damage (Wambu et al., 2014). High fluoride concentrations in drinking waters have been observed to cause kidney failures (Young & Ishiga, 2011).

1.2.3 Local Hydrogeochemistry

Apart from the rift area, parts of Kenya are covered by arid and semi-arid (ASAL) lands. These areas are associated with erratic and poorly distributed rainfall, averaging 700 mm a year. Maximum temperatures are also high in the ASAL areas, averaging about 35˚C (Crowther, 1957; Mathu and Davies 1997). These very hot climatic conditions increase mineral dissolution and eventually, groundwater salinity. About 40% (25 million hectares) of the total soil area in Kenyan is saline (Mugai and Njue, 2011); out of this, between 80-83% is in arid and semi-arid lands, and about 30% of this area is located within the rift region which is known to be high in fluorides (Mugai and Njue, 2011). In such areas, primary salinity occurs due to the accumulation of mineral salts in the host soil and rock material as well as into the groundwater through leachate (Attibu, 2014). Secondary salinity occurs as a result of anthropogenic processes such as the use of fertilizers in agricultural areas, indiscriminate disposal of chemical substances, and improper disposal of radioactive minerals also modifies the groundwater hydrochemistry through chemical leachate. Secondary salinization is widespread due to industrialized agriculture (Shiekhvanloo & Poorhasan, 2010) and urbanization triggered by the increasing global population (Odoma and Umar, 2014). Apart from that, epidemiological evidence has associated a high intake of salts to hypertension in children and adults (Pathak, 2014).

1.3 Problem Statement

In Mwingi North constituency, groundwater has increasingly gained importance as the most reliable water source mainly due to lack of sufficient surface water sources as well as the scarcity and unreliability of piped water (Olago, 2019). Groundwater development in Mwingi North has been going on since the 1960s despite lack of knowledge on quality and quantity. Ochieng (2007) recorded fluoride concentrations of 2.47 mg/l at Jojo borehole in Mwingi. These high concentrations are a human health risk and as such calls for the assessment of groundwater quality.

Geologically Mwingi North area is characterized by sedimentary rocks such as kunkar limestone and metamorphic rocks of sedimentary origin whose principle rock type granitoids have plagioclase feldspars as the main source of sodium and calcium minerals (Crowther, 1957). Ngeani hills in the Mumoni area has huge deposits of limestone while kunkar limestone occurs as pockets along rivers Mumoni and Tharaka areas (Crowther, 1957). These limestone minerals are the sources of carbonates in the groundwater of Mwingi North area. Hornblende and mica minerals from amphibolite are the principal sources of fluorides in the groundwater of Mwingi North area (Coetsiers et al., 2009). These various minerals are dissolved overtime through the processes of water-rock reactions and eventually pollute the groundwater aquifers (Yousif et al., 2018).

The effects of these elements in excess quantities in groundwater have been both a medical challenge as well as an agricultural problem (Khan et al., 2011). Different plant species require a specific amount of ionic concentration in the soil for their normal development; therefore, salinity dictates the type of plants to grow in a particular environment making it a limiting factor since only salt-tolerant plants can be grown in saline environments (Vengosh, 2005).

The available groundwater sources of Mwingi North have experienced hydrogeochemical contamination. Some sources have been completely abandoned while a good number of sources are only being used by livestock due to unpalatability and health problems (Sklash and Mwangi, 1991). This has been an economic setback leading to serious financial losses (Mumma et al, 2011). A critical hydrogeochemical study within the Mwingi area is therefore necessary to underscore the problem and advise groundwater development partners as well as the community within the Mwingi North area. The present study, therefore, will help layout a design model of a groundwater development plan. The knowledge of contaminant distribution will act as guidelines to groundwater development planners on groundwater quality expectations in the available water sources within Mwingi North.

Given the above problems, the following research questions will be addressed:

1. What are the hydrogeochemical characteristics of the aquifers in Mwingi North?
2. What are the hydrochemical characteristics of groundwater of Mwingi North in relation to salinity, fluoride and nitrate levels?
3. How does geology, rock-water interaction, and human influence on the groundwater chemistry?
4. How is the groundwater quality index useful in groundwater planning and economic development?

1.4 Research Objectives

1.4.1 Main Objective

The main objective of the proposed project is to determine the hydrogeochemical characteristics of the aquifers in Mwingi North.

1.4.2 Specific Objectives

i. To determine the hydrochemical characteristics of the groundwater in Mwingi North and in particular its salinity, fluoride and nitrate levels.

ii. To evaluate the contributions of geology, rock-water interactions, and human influence on the groundwater chemistry.

iii. To develop a groundwater quality index map for groundwater development planning in Mwingi North.

1.5 Justification and Significance

1.5.1 Justification

Due to limited information on groundwater quality within Mwingi North there has been very little progress on groundwater development and economic planning. Information on groundwater hydrochemistry within an area assist groundwater development partners in planning and decision making (Olago, 2019). Excess or less of most ionic concentrations in drinking water is a health concern, knowledge of their distribution in the groundwater aquifers of a particular area assists in advising the community on safe and unsafe waters.

According to Government of Kenya (2007), Kenya aspires to reduce its water scarcity by increasing the development of high-quality water supplies. This development is planned to be realized through the initiation of projects involving water conservation, rain, and groundwater harvesting. With the projected increased supply of high-quality water, The Government of Kenya, (2007), also envisions an expansion of the agricultural sector through increasing the area under irrigation and drainage, rehabilitation of hydro-meteorological data gathering network as well as the construction of water and sanitation facilities.

1.5.2 Significance

Delineation of safe and unsafe water with respect to salinity, fluoride and nitrate will enable the County government of Kitui to better plan its groundwater resource use and development. An understanding of the geology and its relationship to groundwater chemistry will be essential in groundwater prospecting. Use of groundwater quality maps will reduce the time spent in groundwater development by avoiding trial drilling and avoiding areas with unacceptable ionic concentrated groundwater. This will eventually save on money spent in groundwater development as well us save human lives.

Groundwater is a key resource in the Mwingi North area that deserves a comprehensive quality study with projection measures on its development and use. This research project tries to address this problem by carrying out groundwater quality assessment that can be used in groundwater management and planning. Likewise, this research study strives to address the sustainable development goal no 6 and Vision 2030 on water and sanitation. Mwingi North being a rural area still lacks most basic services such as clean and safe water for domestic use. This research study is intended to help in increasing access to clean drinking water and sanitation to all. Also the current emergence of COVID -19 pandemic has demonstrated the importance of using safe and clean water for sanitation and hygiene, and for preventing and containing diseases.

1.6 Scope and Limitations of the Thesis

This research study presents an account of the hydrogeochemical analysis of groundwater within Mwingi North area in relation to salinity, fluorides and nitrates. Groundwater quality analysis was conducted to assess its potability. The study involved water sampling from shallow wells, hand pumps and boreholes, analysis and interpretation. Geological inferences were also made of representative rock units within the area. Due to logistical constraints this research study did not include bacteriological analysis which is a key factor in water quality determination. Further, this field study was limited only to areas that were accessible; more than half of Ngomeni ward (Kora National Reserve) and a great part of Kyuso ward were never accessed due to insecurity challenges.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter presents a critical analysis of previous studies carried out in the field of groundwater hydrochemistry and brings out the findings of past study works on groundwater salinity. It also tries to illustrate the areas which particular studies bypassed. These knowledge gaps are pointed out and some are addressed through the study objectives of this thesis. This chapter starts by bringing out the past studies carried out on groundwater hydrochemistry with particular focus on salinity, fluoride and nitrate. The review then delves in to the contribution of rock-water interaction to groundwater salinity in crystalline aquifers. Lastly, a brief overview is made of the groundwater quality and its importance in economic planning to development partners at the county and national levels.

2.2 Salinity, Fluoride and Nitrate Levels in Groundwater

Determination of salinity, fluoride and nitrate concentration in groundwater is essential in establishing safe drinking water (Hsan & Ansur, 2009). Groundwater with fluorides above 1.5 mg/l and below 0.4 mg/l is a human health problem (Monjerezi & Ngongondo, 2012). Groundwater salinity levels above the recommended levels makes groundwater unpalatable and also causes various health complications. Nitrate is the main pollutant in groundwater hydrochemistry. Its presence in groundwater in levels above 250 mg/l is both a human and plant health problem (WHO, 2016).

2.2.1 Groundwater Salinity

Soil and groundwater salinization was initially thought to be a preserve common only to arid and semi-arid areas (Kaushal, 2016). However, new research findings elsewhere have observed that man's influence on the environment greatly impacts soil and water resources thus leading to drastic quality shifts. Australia, China, and India are some of the countries in arid areas that have realized serious salinity challenges in their soil and water resource management (Vengosh, 2005). Studies have proved that the ever-increasing global population, alteration of freshwater flow, deforestation, irrigation, disposal of wastewater effluent, sea-level rise, storm surface, and application of de-icing salts are the main ways through which salinization increases (Franklin et al., 2015). Franklin et al. (2015) also observed that anthropogenic and climatic changes increase pressure on the available land and surface water sources, thus, disturbing the hydrogeological balance, and hence, rendering the soils and water resources prevalent to salinization.

Salinity is a global environmental phenomenon that has continued to affect water and soil quality degradation in arid and semi-arid areas (Vengosh, 2005). The effects have been realized in all spheres of both animal and plants' life. Both animals and plants require a specific amount of salt for their normal metabolism. Concentrations above these limits are a health problem to both plants and animals (Ochungo et al., 2019). Salinization of groundwater occurs through several processes. In coastal environments salinization of groundwater occurs due to seawater intrusion (Williams, 2001). Likewise, salinization can occur due to the intrusion of underlying or adjacent aquifers or the flow of saline water from adjacent or underlying aquifers as observed in the Floridian aquifers (Vengosh, 2005). Other processes include the mineralogical composition of the host rock and anthropogenic (Vengosh, 2005). Recharging groundwater derives almost its entire solute load through the dissolution of minerals along the flow path (Domico, 2011).

Salinity often refers to the concentration of chlorides in water or soils, however, chlorides form only a third of the total salinity percentage in a unit volume of water or soil (Franklin et al., 2015). The remaining volume is represented by other ionic compounds. Chlorides and fluorides often occur in association. Fluorides occur naturally or as fluorite in rock and mineral assemblages of the earth's crust. According to WHO (1986), global fluoride concentrations in soils occur in two different belts. The first belt runs from Syria through Jordan, Egypt, Libya, Algeria, Morocco, Ethiopia, Tanzania, Sudan, and Kenya. A second belt extends from Turkey through Iraq, Iran, and Afghanistan to India, Northern Thailand and China. Continents with the highest fluoride concentrations in soils include Asia, Africa and the USA (Czarnowski, 1996). Increased fluoride levels in soils have been observed in countries such as China, India, and countries along the East African Rift Valley (Wambu et al., 2014; Wang, 2002).

Groundwater salinity can be used to show land area prone to salinity risk (Shiekhvanloo & Poorhasan, 2010). Salinity classification is based on the depth of groundwater, the type of use of the water as shown in Table 2.1 and the effect of the salinity (Raper et al., 2014). Shiekhvanloo & Poorhasan (2010) further note that groundwater salinity is a spatially correlated phenomenon and its spatial analysis can be facilitated using the regionalized variables theory.

Table 2.1: Typical ranges for water salinity categories according to potential use (adapted from Shiekhvanloo and Poorhasan, 2010)

TDS (mg/L) EC	EC (µS/cm)	Water Description	Potential use for water supply
< 500	< 700	Fresh	Suitable for all purposes
500 – 1000	700 – 1500	Fresh	Suitable for most purposes
1000-1500	1500-2000	Partially brackish	Suitable for some purposes - the upper limit for drinking
1500-7000	2000-10000	Brackish	Suitable for only limited irrigation and most livestock
7000-15000	10,000-25000	Highly brackish	Some livestock (beef cattle, sheep)
>4500	>45000	Hypersaline	Ore processing, Brine production

2.2.2 Fluoride in Groundwater

Fluoride occurs commonly in plants, soils and phosphatic fertilizers (Madhavan and Subramanian, 2001). It is also a very important mineral needed by the human body in proportionate amounts. The body requires fluorides within the ranges of 0.4 mg/l-1.5 mg/l (Pendrys & Stamm, 1990). Less or more of it is a health concern. Excessive and longtime use of drinking water with high fluoride contents causes kidney failure as was observed in a study carried out by Young & Ishiga (2011) in Sri Lanka. The study which was carried out in the basement geology of central Sri Lanka also observed that fluoride concentration in groundwater has a direct relationship with pH and the concentrations of Na, Ca, and HCO_3^-. Further, groundwater fluoridation occurs because of longer time in water-rock reaction in aquifers within fractured crystalline rocks such as hornblende biotite gneiss and granitic gneiss (Karegi et al., 2019). Fluoride has a slow solubility rate, therefore, rock-water interaction though one of the contributing factors to groundwater fluoridation is aided by factors such as the amount of soluble and insoluble fluorides in source rock, soil temperature, rainfall and oxidation-reduction process (Ochungo et al., 2019). Likewise, areas of intensive agriculture are prone to shallow groundwater fluoridation associated with the leaching of fluorides due to irrigation practices (Young & Ishiga, 2011).

Various rock types have different concentrations of fluorides; basalt, 360 ppm; granites, 810 ppm; limestone, 220 ppm; sandstone and greywacke, 180 ppm; shale, 800 ppm; oceanic sediments, 730 ppm; and soils, 285 ppm (Madhavan and Subramanian, 2001). In volcanic areas, fluoride occurs as fluorite (calcium fluoride). This is a principal source of fluoride in igneous rocks; however, its solubility rate is very low. Fluoride as well occurs as a complex combination of minerals, the main one being apatite. In metamorphic regions like Mwingi North, fluoride occurs in amphibolites minerals such as hornblende, mica and other minerals (Karegi et al., 2019). In such minerals, fluoride undergoes a reaction to replace the hydroxide (OH) part of the mineral structure.

2.2.3 Nitrate in Groundwater and Its Effect to Human Health

Nitrate and nitrite are some of the known groundwater pollutants. They are generally present in the atmosphere and are considered a groundwater contaminant especially in agricultural areas. Unlike most elements, nitrate and nitrite are not derived from the minerals of the rocks which are found in groundwater (Driscoll, 1986). These chemicals instead enter groundwater from the hydrosphere and biosphere through bacterial fixation (Clark, 2011). Nitrate and nitrite are part of the nitrogen compounds which also includes ammonia. Nitrogen enters groundwater in several ways. Also, the chemical combustion of industrial plants emits nitrogen into the biosphere (Shao et al., 2018). Industrial chemicals also contain appreciable amounts of nitrogen which they disperse through waste disposal (Xu et al., 2019). Additionally, nitrogen is also dispersed into the groundwater system by decomposing plant debris, animal waste and fertilizer use (Hersi, 2003). The presence of nitrates above the recommended levels in some boreholes could be due to bacterial fixation (Lakshmanan & Kannan, 2007).

Consumption of groundwater with high concentration of nitrate affect human health. When nitrate is converted to nitrite in the stomach; it interferes with the blood's capacity to carry oxygen leading to a condition called methemoglobinemia, otherwise known as a blue baby syndrome in infants (Clark, 2011). Cattle are also prone to this disease where it results in low milk production (Fan, 2004). The high concentration of nitrates in surface waters is known to aid the development of algae and the growth of weeds (Clark, 2011).

2.3 Geology, Rock-Water Interactions, and Human Influence on Water Chemistry

Geologically, Mwingi North is part of the Mozambique belt which is described as a major superimposed structure traversing an expansive area along the eastern coast of Africa running from the Arabian Nubian shield in the north, southwards into the east of Antarctica (Mohammedyasin, 2017). According to scholarly works by Baker (1954), Saggerson (1957), Crowther (1957), Fairburn (1963), Biyajima et al. (1975), Mathu (1992), Mathu and Tole (1984), Mathu et al. (1991), and Nyamai et al. (2003), the geology of this sector is composed of rock units including amphibolite (plus or minus garnets), migmatites, granitoid gneisses, and granites, intrusive and meta-intrusive, mafic and ultramafic rocks that include diorites, gabbros, anorthosites, peridotites, and picrites. The ultramafic bodies are limited in comparison to the occurrence of the mafic gabbroic and anorthositic bodies. Associated minerals include mica (biotite, muscovite), hornblende schists and gneisses with the sporadic presence of staurolite, almandine garnet, kyanite, and sillimanite. According to a previous study carried out by (Karegi et al., 2018) in Mbeere South area, adjacent to the Mwingi North area, as outlined by Crowther (1957), the metamorphic geology of Mwingi North has groundwater mineralization in the order of Na^+> Ca_2^+> $Mg2^+$> K^+> Fe for the dominant cations and HCO_3^->Cl^->SO_4^{2-} >NO_3^->F^- for the dominant anions. Due to these hydrochemical variations the resulting water types in Mwingi North are expected to be Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-}, Ca^{2+}-Mg^{2+}-HCO_3^-, and Na^+-K^+-HCO_3^- water types (Karegi et al., 2018).

Naturally, groundwater quality is mainly affected by geomorphology, geology and hydrogeological setting of an area (Fantong et al., 2010). However, studies conducted by Avtar et al. (2013), Young and Ishiga (2011) and Taylor et al. (2003) are just but a few of the many scholars who have observed in their studies that groundwater quality has deteriorated over time due to both geogenic and anthropogenic causes (Vengosh, 2005). These are the main mechanisms that have accelerated surface and groundwater pollution over time.

A number of processes contribute to the chemical character of groundwater, and these include: rock mineralogy and lithology (Back & Baedecker 1989; Back et al. 1993); river water recharge (Sharma & Subramanian, 2008); and chemical weathering of rocks at the earth surface that may be accelerated by high temperatures (Soler & Marcos, 2015). During rock weathering, elements such as Ca^{2+}, $Mg^{2+,}$ K^+, Na^+, SO_4^{2-}, HCO_3^- and SiO_2^- among others are added to the water depending on the relative rock mineralogy (Hounslow, 1995). Rock-water reaction in lithology of variable mineralogy produces several reactions including dissolution, precipitation, ion exchange, oxidation-reduction, and sorption which can change water chemistry, producing chemical boundaries (Back & Baedecker, 1989). Recharge water chemistry and mineralogy therefore play significant roles in the overall chemical composition of the groundwater (Hounslow, 1995).

2.4 Groundwater Quality Mapping and Development Planning

Groundwater quality mapping has been used since ancient times in deciphering potable water. The bible records about sweet water (Lofrano et al., 2010 in Ochungo et al., 2019), a general term for potable water. In the ancient times civilization were situated around areas of potable water, likewise, the rise in urbanization relies mainly on the availability of safe water (Taylor and Francis, 1992). Man, in his quest to find safe water applied rudimentary techniques to solve his needs. However, due to lack of proper ways of storing groundwater information most of this knowledge were washed away. Some however, could not be translated due to technological gap. To solve this problem water quality index has been developed to characterize groundwater with the aim of assessing its suitability for specific use. Ochungo et al. (2019) used the water quality index method to assess the potability of groundwater within Langata Sub County, Nairobi, and concluded that the chemical parameters of groundwater in Langata Sub County are within permissible limits save for fluorides which need to be diluted with surface water.

Properly managed groundwater resources play a vital role in fostering social economic development in the rural areas of Sub-Saharan Africa, and it is the most preferred water source in arid and semi-arid areas due to its naturally high storage capacity, good quality, and affordability due to the limited infrastructure which is a common occurrence in most rural areas and thus needs proper management (Pavelic et al., 2012). Also, properly kept groundwater data help scientists in decision making processes and in determining best ways of aquifer protection (Mumma et al., 2011). Nevertheless, in Kenya, despite the numerous drilling carried out yearly, only about 15% of borehole completion records have water quality data (Ndiritu and Githae (2012). This deficit has hampered the proper production of representative groundwater maps of the whole country and this anomaly has been attributed by Pelvic et al. (2012) to lack of institutional management and responsibilities, inadequate resourcing, lack of technical expertise and lack of data-base retrieval systems.

Groundwater is vulnerable to contaminants such as salinity, nitrates and fluorides (Liggett & Talwar, 2009). The investigation and determination of these groundwater contaminants increases awareness in their presence in the aquifer of a particular area. As discussed by Olago (2019) aquifer characterization is necessary to avert the common occurrence of most development being undertaken without prior knowledge on the aquifer. Likewise, hydrological processes control chemical concentrations in groundwater (Olaka et al., 2016). The availability of water allows rapid flushing and the removal of all but the most insoluble compounds, such as iron and aluminum oxides. Olaka et al. (2016) further note that these processes can help in the development of strategies for sustainable use of shallow groundwater to minimize the health risk exposure to fluorides. F^- and Cl^- occurs in association, it is therefore not unusual to find both components being high.

The importance of water, sanitation and hygiene for health and development has been discussed in a number of international policy forums. Such forums have included health-oriented conferences such as the International Conference on Primary Health Care, held in Alma-Ata, Kazakhstan (former Soviet Union), in 1978. Also, they have included water-oriented conferences such as the 1977 World Water Conference, in Mar del Plata, Argentina, which launched the water supply and sanitation decade of 1981-1990, as well as the Millennium Development Goals adopted by the General Assembly of the United Nations (UN) in 2000 and the outcome of the Johannesburg World Summit for Sustainable Development in 2002. Most recently, the UN General Assembly declared the period from 2005 to 2015 as the International Decade for Action, “Water for Life” (WHO 2008). Locally, the enactment of Kenya’s 2010 constitution realigned the Kenya Water Act by the creation of the Kenya Water Act 2016 that established the Water Resources Authority (WRA), formerly Water Resources Management Authority (WRMA), with the sole mandate of formulation and enforcement of standards, procedures and regulation for the management and use of water resources, policy development, planning and issuing of water abstraction permits, and setting and collecting permits and water use fees (Langat et al., 2019). Developments in water supply and sanitation has faced major economic setbacks in most areas of the country, since the reductions in adverse health effects and health care costs prevailing over the costs of undertaking the interventions (Luedeling et al., 2015). Such involvement in improving access to safe water has favored the poor in particular, whether in rural or urban areas, and is an effective part of poverty alleviation strategies.

Within Mwingi North, knowledge on groundwater salinity in relation to fluoride and nitrate is still limited. The scale of investigations which has been carried out is marginal and only localized to single boreholes without aquifer characterization. Also, no similar studies have been carried out to clearly help scientists understand the process of rock water interaction and human influence within Mwingi North. Lastly, Water quality index maps have not been developed for the entire county so groundwater developers have very little inform to rely on.

2.5 Summary

Groundwater hydrochemistry is an essential parameter in groundwater development. Both quality and quantity of the available water resource is akin to groundwater monitoring. The need for healthy water does not discriminate, it is a right for both the poor and the rich, in rural or urban areas. However, in Kenya, despite the government's effort to create institutions to manage groundwater, information on groundwater quality is still scanty. Globally, several organizations are in a concerted effort to see that the available water is safe and economically viable. This section has noted the lack of knowledge on groundwater hydrochemistry with its particular focus on salinity, fluoride and nitrate in the crystalline aquifers of Mwingi North. Investigating the chemical variance in a particular aquifer can contribute to improved economic planning by reducing the number of abandoned boreholes, instituting objective use of water and realizing cost saving on health-related issues.

CHAPTER THREE
THE STUDY AREA AND METHODS

3.1 Introduction

This section presents a concise discussion of the study area and the various methods applied in realizing the objectives as set in section 1.5. A description is provided of the extent of the study area and its geographical location within Kenya. Likewise, brief accounts are given for climate and rainfall, vegetation and population, and general land use governing the study area. Further, this chapter outlines the general geology of the study area in relation to their hydrogeological importance and influence on groundwater quality. A detailed account is given of the fieldwork and sampling, and geochemical analysis methods used in studying the groundwater quality of Mwingi North. The section, also presents how computer software such as Golden Surfer, Statistics Package for Social Sciences (SPSS), Phree-QC and AquaChem have been used in data analysis.

3.2 The Study Area

3.2.1. Location

Mwingi North is located within Kitui County which is in the lower eastern region of Kenya. It is bounded by latitudes 0º 03´ and 1º 12´ south and longitudes 37º 47´ and 38º 57´ east, covering an area of 4,769.60 km². It is bordered to the south by Mwingi Central, to the west by Yatta, to the north by Embu and Tharaka Nithi Counties and to the east by Tana River County. Mwingi North is a sub-county of Kitui County. It has 5 wards, namely; Ngomeni ward, Kyuso ward, Mumoni ward, Tseikuru ward, and Tharaka wards. Figure 3.1 shows the location of Mwingi North, road network, and drainage pattern.

3.2.2 Climate and Rainfall

Mwingi North area experiences a tropical climate which is hot and dry most of the year. The area exhibits arid to semi-arid climate with unreliable and erratic rainfall. The mean annual maximum temperatures range between 24 °C and 26 °C, while the mean annual minimum temperatures range between 14 ºC and 22 ºC and the average annual temperature is 24 °C (Cassim et al., 2018). The coldest months are realized between April-November while the hottest months are realized from January–March. Annual rainfall received in the area ranges from 400 mm–800 mm while the average rainfall received is 600 mm (Cassim et al., 2018). The area has two rainy seasons, a long rainy season between March-April-May which is relatively unpredictable and a short rainy season between October-November-December which is rather reliable for food production (Cassim et al., 2018). The highlands of Mumoni receive more rainfall unlike the lowland areas of Ngomeni, Kyuso, and Tseikuru.

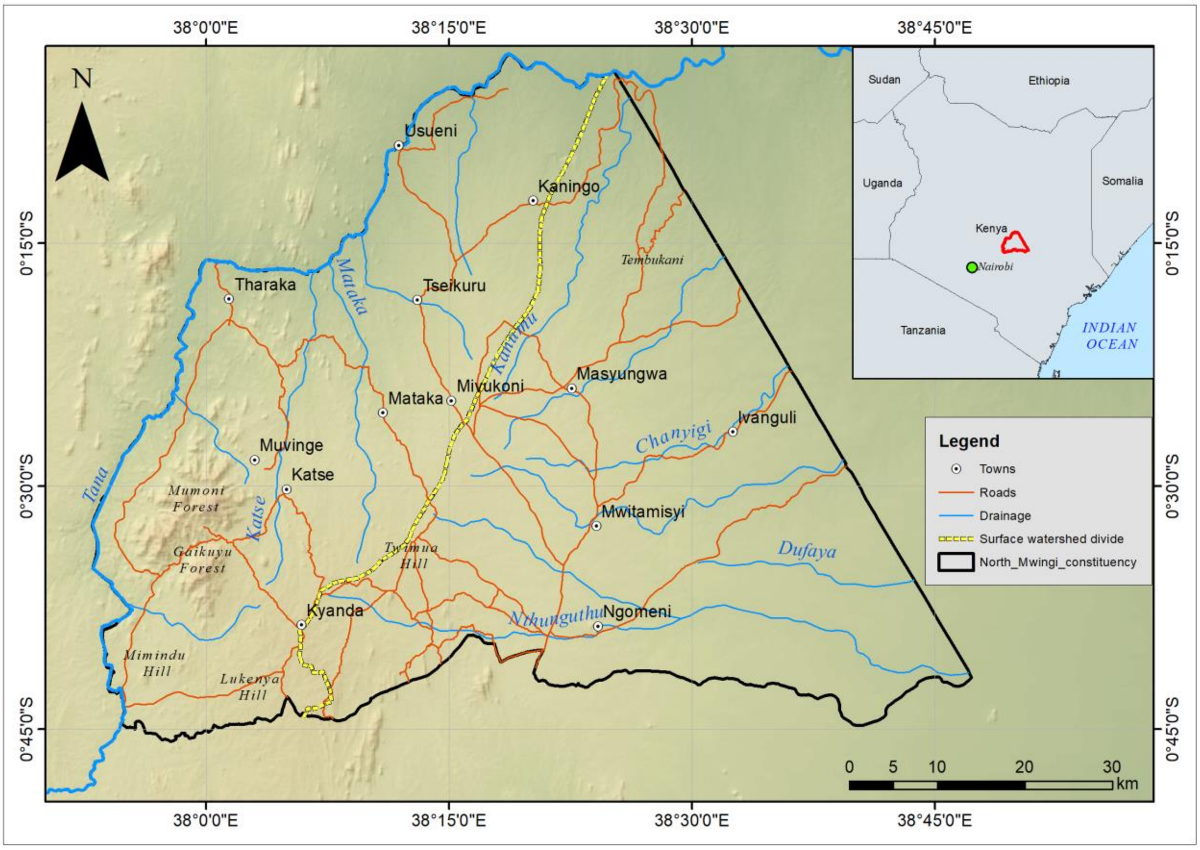

Figure 3.1: Location Map of Mwingi North showing the drainage pattern (edited from Crowther 1957 and Dodson 1953)

3.2.3 Vegetation

Mwingi North Constituency has diverse species of plants and animals most of which are concentrated on hilltops and along the river beds (Cassim et al., 2018). Acacia trees are the common trees in most of the area. Other trees include shrub trees same to tress in arid and semi-arid areas. The vegetation of Mwingi North is composed of indigenous trees that are drought resistant and have their distribution based on rainfall, the geology of the area and soil types. Most of the indigenous trees such as *Ficus spp*. and *Melia volkensii (Mukau)* are being depleted due to the increased search for timber and charcoal production (Wachira, 2012). Hilltop cultivation increases soil erosion thus a threat to the conservation of biological biodiversity.

3.2.4 Population and General Land Use

Cassim & Juma, (2018) in their study observed that the main livelihoods for the people of Mwingi North includes marginal mixed farming, mixed farming, and formal employment.

With the current population of Mwingi North standing at 117.738 (KNBS, 2019), about 51.9% of which practices mixed farming (Cassim & Juma, 2018). This involves the rearing of livestock mainly goats, cows, and sheep and growing crops. Due to harsh climatic conditions crops grown are limited to green grams, cowpeas, maize, millet, and sorghum. About 15.62% of the Mwingi North area is occupied by Mwingi National Reserve. This section is set aside by the government for the raring of both wild and domesticated animals. Other economic activities carried out in Mwingi North include brick making and sand mining (Cassim et al., 2018). Sand mining is being practiced indiscriminately along rivers Katse, Kataka, Chanyingi, Kamumu, Dufaya, and Nthunguthu (Crowther, 1957) .

3.2.5 Physiography and Drainage

The physiography of Mwingi North rises from an altitude of 666 m to 1747 m a.s.l. The elevation rises from Ngomeni peneplain area to the east towards Mumoni and Muvaroa hills to the west. Mumoni hills are the highest point within the study area, rising to an altitude of 1747 m above sea level (Crowther, 1957). Other notable high points within the study include Ngomeni rock (1702 m a.s.l.) which is an important rock catchment area supplying a greater percentage of the population to the southeast of the study area with water (Dodson, 1954).

Mwingi North area lies in an arid-semi arid eastern part of Kenya. (Crowther, 1957). The area does not have any permanent river. The seasonal rivers Katse, Mataka, Kamumu, Dufaya, Chanyingi, and Nthunguthu are the rivers in Mwingi North (Figure 3.1). These seasonal rivers are important in the hydrogeology of Mwingi North. Most water points are located along these river beds. The Tana River forms the northern boundary between Kitui County with Tharaka Nithi and Embu Counties. To the south and East, Mwingi North borders Garissa County while the western boundary borders Mwingi central constituency. Tana River is the only perennial river which through Tanathi Water Services Limited supplies the Mumoni ward with most of her water. However, the other four wards depend mainly on groundwater for their livelihood. 90% of the households in Mwingi depend on communal water points while only 10% of households are covered by piped water from Tanathi Water Services Company (Muiruri and Mutuku, 2016). The scarcity and unreliability of piped water make groundwater the only reliable drinking water source within Mwingi North. Over time, groundwater development in Mwingi North has been going on since the 1950s despite a lack of knowledge on quality and quantity.

3.2.6 Geological Setting

3.2.6.1 Geology of Mwingi North Area

Geologically Mwingi North area lies within sub-area II of the Eastern Mozambique Belt system (EMBS). This area has been intensively studied by several scholars at various times. According to scholarly studies by Crowther, (1957), the geology of this sub-area as shown in Figure 3.2 is mainly composed of quartzites, biotite, and hornblende gneisses on the highlands of Mumoni and Tharaka. Colluvial deposits and red soils in the low lying Ngomeni and Tseikuru areas. Sandstones occur as small pockets to the western parts of Tharaka. Alluvial sands occur along river beds and limestone occurs on Ngaaie hills in the Mumoni area as well as along river beds as sporadic outcrops of kunkar limestone. The rock units of the Mozambique belt can generally be called meta-sediments. Below is a brief description of the individual rock units plus their distribution.

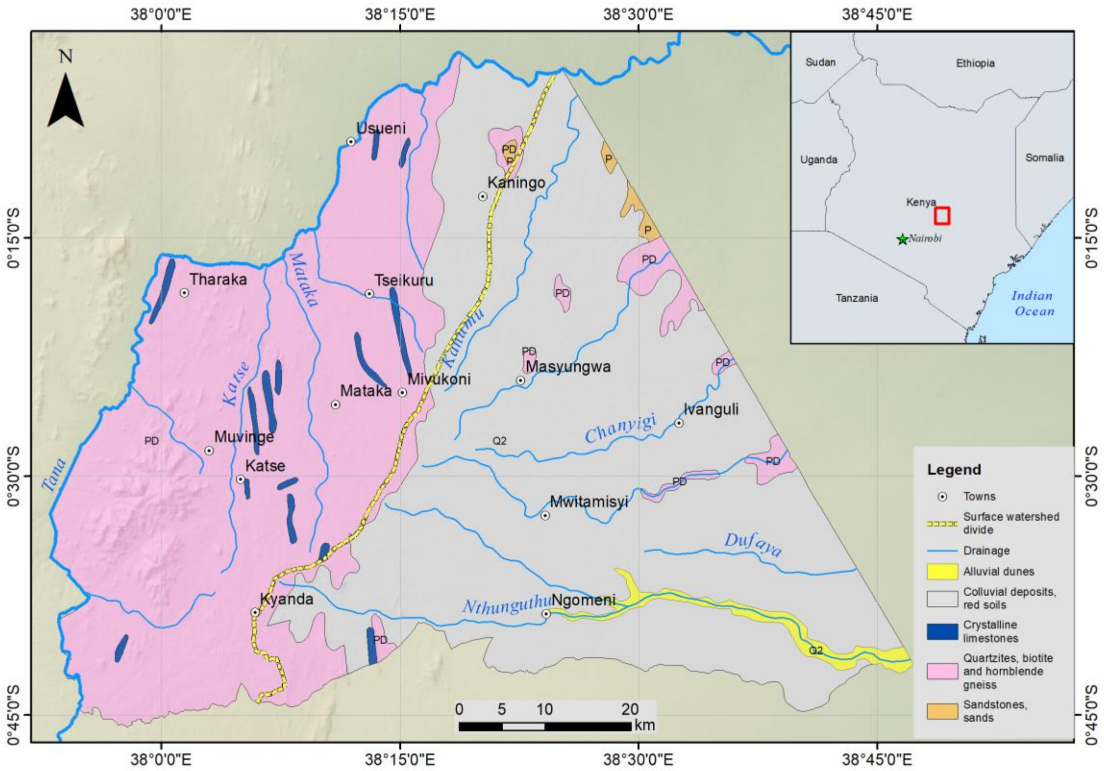

Figure 3.2: Geological map of project area edited from Crowther (1957) and Dodson (1954)

3.2.6.2 Brief Description of the Geological Units

Based on Crowther (1957), the rocks of Mwingi North predominantly consist of metamorphic and sedimentary rocks. Typical rocks in this region include alluvial dunes, sandstones, biotite gneisses, migmatites, granitoid gneiss, and limestone. These rocks in some places occur in association with intrusives of quartzites and pegmatites. Sands and sandstones are mainly found along the riverbeds. According to Crowther (1957), biotite gneiss represents the main pelitic and semi-pelitic rocks within the study area (plate 3.2) while migmatites occur within extremely deformed rocks often displaying obliterated foliations as observed on an outcrop at the foot of Ngomeni rock (plate 3.1).

Granitoid gneiss is the most widespread rock outcrop within the Mwingi North area (Crowther, 1957). It occupies the hilltops and raised grounds of most of the area, notably Mumoni hills (plate 3.2). The occurrence of granitoid on hilltops and raised ranges has been linked to their high competence to weathering processes (Mathu, 1980; Mutunguti, 2001). Marble outcrop is predominantly observed on the Ngaaie hills in the Mumoni area where it forms a massive outcrop covering a wide area. It occurs as vein fills or as crystalline calcite that appears to be fused with biotite gneiss or granitoid gneiss having an appreciable amount of magnesia (Crowther, 1957).

Quartzites and pegmatites occur as intrusive veins of various sizes in biotite gneisses, granitoid gneisses, or migmatites (Nyamai et al., 2003). Quartzites may occur as pure white, pinkish, reddish or brown depending on the host rock (Mathu, 1980). Pegmatites in the study area occur as highly granitised, coarse-grained meta-sediments with a general W-S trend. Plate 3.4 shows a quartz vein along river Katse with a width of about 30 cm wide (Crowther, 1957).

Plate 3.1: Typical migmatised granitoid gneiss at the foot of Ngomeni rock.

Plate 3.2: Granitoid gneiss on Mumoni hills

Plate 3.3: Biotite vein in quartzitic gneiss

Plate 3.4: Quartz pegmatite along river Katse

3.2.7 Geological Structures

The geological structures of the study area include both complex superimposed minor and major structures as outlined by (Crowther, 1957). These structures include faults, folds, and lineations. Figure 3.3 shows a sketch map of the geological structures within the study area. Following is a brief discussion of the major structures.

3.2.7.1 Faults

Dip faults are a common feature in most of the area. Most of them run northwest to southeast (Crowther, 1957). These faulting result in the host blocks having a general displacement to the right. The area has three major fault lines, one major fault line runs N-S through Wamwathi into Mwathya valley. This fault line is interrupted in Mwathya valley by two minor NW-SE running faults. The interruption of this major fault line in the Mwathya valley causes a major displacement around the Ngeeani area. The northward trend is however interrupted by another major fault running E-W (Crowther, 1957). Around Mumoni hills, a NE-SW trending fault has subjected the local overburden to a major rock displacement thus the Northern block has moved northwards. Lastly, a major fault occupies the eastern side of the Ngomeni area. The N–S trending fault also runs along a syncline from where the waters of Ngomeni rock flows into river Tseikuru.

Faulting in Mwingi North is identifiable by the linear vegetation pattern, abrupt change in altitudes and the linear trend in drainage within the area. Most of these faults are classified as normal faults that have undergone vertical movements of rock materials forming the hanging wall. The faults are deeply inclined and the angle ranges between 65° and 90° and dips to the east; the vertical movement is tens or sometimes hundreds of meters of the downthrow to produce cliffs or scarp features (Crowther, 1957).

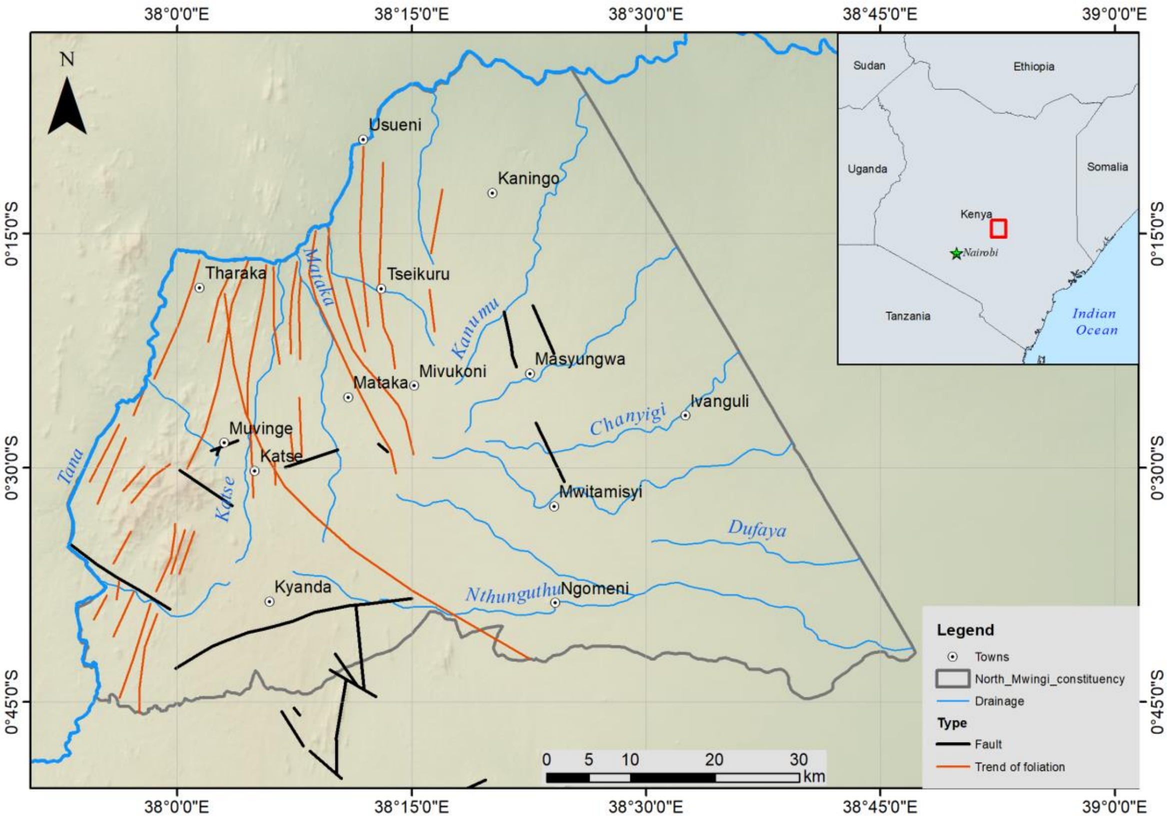

Figure 3.3: Sketch map of faults and folds in Mwingi North (edited from Crowther, 1957and Dodson 1954)

3.2.7.2 Folds

A study carried out by Nyamai et al. (1999) in an adjacent area of similar geology observed that the general outcrops of the area commonly display isoclinal, open, overturned and ptygmatic folds. Nyamai et al. (1999) in the same study further suggested that the orientation of the isoclinal fold axial plane is a result of compressive forces acting in a westerly direction. Mafic dikes are quite common in the surveyed area. Most of these dikes are of doleritic composition. These are believed to have been formed during a strong stress period as evidenced in the highly compressed leucocratic microfolds within them.

Within the Mwingi area, an anticlinal fold occurs near the Kiormo area trending north east-south west. North of Ngeeani area and south of Kimangao area another anticline with easterly and westerly dip directions suggests a ridge that drains into a synclinal valley to the east. The axis of this syncline trends north-north east through Kimangao into the Mumoni area as shown in Figure 3.3. The area east of Ngeeani has a pronounced ridge trending northward with its rocks dipping eastwards and westwards. This anticlinal ridge runs along the centre of the project area into the hills of the Tharaka area. Another anticlinal fold is found on the hills of Ngomeni. This folding display an anticline towards its southern parts with the northern and western sides display rather very steep dips.

3.2.8 Geological and Structural Evolution

The geological and structural succession of the Mozambique belt of Mwingi North can best be known by outlining its tectonic evolution history. Like the other parts of the Mozambique belt in Kenya, Key et al. (1989) observed three sequences of events that led to the tectonic evolution of the belt. The evolution started in about 820 Ma by plate tectonic collision which caused a tectonic-thermal event in the amphibolite-granulite facies producing major recumbent folds with ductile thrusting inter-fingered basement complexes, meta-sedimentary cover, and ophiolitic metavolcanic complexes. This deformation phase involved the emplacement of crustal melt granites and meta basic dykes. This was then followed by a post-collision green schist-amphibolite facies deformation between 620 Ma and 570 Ma. This collision phase produced regional uptight folds and vertical ductile strike-slip shear zones striking subparallel to the orogenic strike. This led to syntectonic granitic intrusions. Lastly, an uplift and cooling event dated between 500 Ma-480 Ma characterized by open folding and brittle shears marked the final tectonic orogenic event.

According to a study carried by (Nyamai, 1999) in Kangode area, an adjacent similar geological area observed that the structural trends in the Mwingi North vary from NNW-SSE to NW-SE with a general westerly dip. In the same study (Nyamai, 1999) also observed that the area experienced complex tectonic history in three documented deformation phases. He further observed that the predominant anorthositic rocks which are of moderate to thick sheets have intruded into the granitic gneiss and were boudinaged on a wide scale during the last evolution phase. (Nyamai, 1999) also noted the regional correlation of the mafic bodies within the Mozambique belt whereby N-S linear occurrence of anorthositic-gabbroic suites were observed within the belt from Mozambique to Tanzania. This general wide-scale structural trending was linked to the general mineralogical occurrence within the granulite facies

The geological evolution of the area is believed to have started by regional prograde metamorphism which later downgraded to the amphibolite and greenschist facies (Nyamai, 1999). This was followed by retrogression of the granulite facies into the amphibolite and greenschist facies. Mineralogical textures and associations indicated the development of coronas around the clinopyroxene crystals in the metadiorite and gabbroic rocks. Nyamai (1999) concluded that the acquisition of metamorphic facies due to variations in temperature and pressures suggested that metamorphism was related to tectonic thickening. He further explained that, the rare occurrence of the granulitic material in the cratonic areas and the Arabian-Nubian shield compared with their comparative occurrence in the Mozambique belt of East-Africa confirms the interpretation of continent-continent collision model which led to crustal thickening. Lastly, he observed that the occurrence of late temperature contact metamorphism led to granitic intrusions.

3.2.9 Hydrogeological Setting

Mwingi North being a rural area challenged by lack of piped water has realized rising groundwater development. Most of the area lacks permanent rivers and there exists inequitable distribution of piped water (Hope, 2015). The study area has both shallow and deep wells. Shallow wells are positioned along the riverbanks and are mostly non-saline. These shallow aquifers are in alluvial sands formed as a composition of recent sedimentary deposits along the river banks. Geologically the study area is mainly composed of crystalline rocks. Groundwater availability in crystalline geological terrains is confined in the weathered or fractured zones (Crowther, 1957). The nature and extent of weathering, especially in igneous and metamorphic rocks depend mostly on the existence of fracture systems (Nyamai, 1999). This is essential for groundwater accumulation.

3.2.10 Soils

Mwingi North constituency has loam sandy soils, red sandy soils, and pockets of black cotton soils (Crowther, 1957). Along the river valleys, there are sediments of alluvial soil which are in most cases agriculturally of moderate to high fertility. Generally, the soils of Mwingi North are of low fertility and are easily erodible (Cassim et al., 2018). Most hills are bare and only of shallow and stony soils unsuitable for crop farming (Crowther, 1957).

3.3 Methods

3.3.1 Research Design

This research was designed in a systematic way starting from desktop studies, field studies, data analysis and discussions stage. The first stage was preliminary or desktop stage from where the research concept was conceived after identifying a gap in groundwater quality within Mwingi North area. Gap identification was undertaken through critical analysis of available literature on the geology and hydrogeochemistry of the study area. The preliminary study was also used to understand the needed equipment's and tools that are necessary in seeing the deliverance of the research study. Fieldwork involved geological survey, water and rock sampling, and measurement of some physical groundwater parameters, such as, temperature, EC, pH, turbidity, hardness, total alkalinity, color, free carbon dioxide (CO_2) and total dissolved solids (TDS).

3.3.2 Objective 1 – Determination of the Hydrochemical Characteristics of the Groundwater

3.3.2.1 Desktop Studies

Before the fieldwork was carried out, preliminary information of the study area was undertaken. This involved desktop study of journals, reports, theses, topographical and geological maps to acquire information on the expected geology, topography, road network condition, expected climatic condition and hydrogeological conditions of the area. The information obtained from the study was then used in preparing a field map with approximate locations of sampling points.

3.3.2.2 Field Studies and Materials

The fieldwork was conducted from 30th January 2019 to 7th February 2019. Portable measuring equipments that were necessary for the project included a GPS and a Hanna Combo meter capable of taking measurements of temperature, pH, EC, and TDS. Forty-two water samples were collected from shallow wells, hand pumps and deep wells distributed as shown in Figure 3.4. Rock samples were for minerological identification. Sampling points were randomly distributed all over the project area to provide a general hydrochemical overview of the project area. Parameters such as EC, temperature, specific conductance and TDS were measured on-site. Total alkalinity was also measured at the time of sampling to avoid dissociation due to contact with air. These parameters were measured using Hanna Combo meter. This gadget was fitted with an electrode, a thermistor and a buffer solution necessary for calibration.

Representative water samples were collected using various methods to attain quality representation. Water from shallow wells were first purged to get representative sample. Water sample was then collected manually by scooping using an improvised bucket. Water from hand pumps was initially pumped out until clean free-flowing water was achieved. The water was then directly filled into the sampling bottle from the flowing water. Borehole water samples were collected near the head before entering the storage tanks, treatment plants, and pipes where they could be contaminated. Water samples were collected using half-litre polypropylene plastic bottles with screw caps.

The sample bottles were first rinsed in free-flowing sample water. Three water samples were collected per sampling point. Each sampling point was uniquely identified by initials i.e. Hp for hand pumps, Sw for shallow well and Bh for boreholes. After collecting water samples, the sample for determination of major anions was then preserved with 1 ml of HNO_3 acid in a 50 ml sample bottle as described by APHA (2005) and labelled A. Bottle labelled B was used for cations determinations while the third bottle was labelled C and was used as a reserve bottle for use in case of any loss or damage. All three bottles were then each marked with a sticker indicating the date of sampling, point number of sampling and source type. Upon completion of sampling, all the bottles were then packed in three separate boxes (boxes A, B, and C) for easy handling. The samples were then delivered to the Water Resources Authority Central Water Testing Laboratory in Nairobi for full chemical analysis.

Measured field results such as temperature, EC, pH, specific conductance and observations were recorded in a notebook. The information entered in the notebook included: date of sample collection, location name of site, sample number, temperature, pH, conductivity readings, and alkalinity titration results. Other information recorded which was important in reporting design included borehole depths, yield and date when the borehole was drilled, water use, and potential contaminants and GPS location. Fourty two water and eleven rock samples referenced by numbers were also entered in the field notebook.

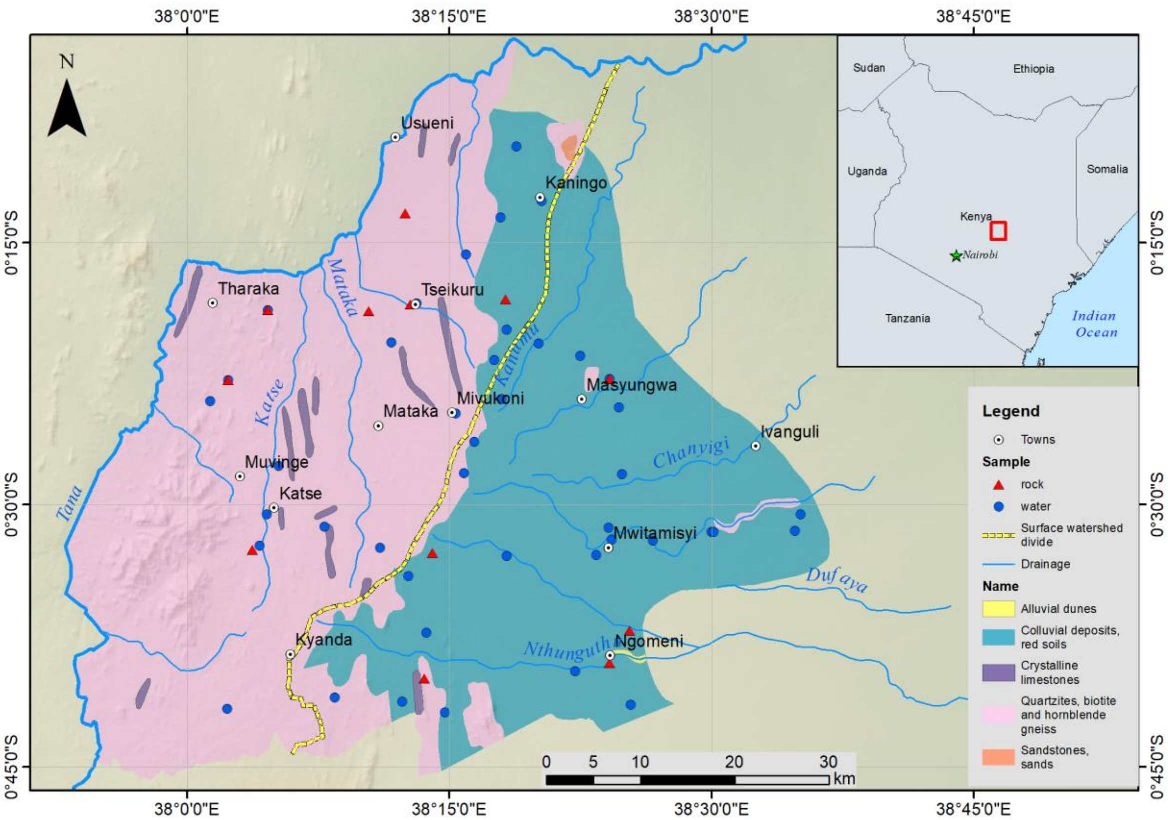

Figure 3.4: Sampling location map (edited from Crowther 1957 and Dodson 1954)

3.3.2.3 Laboratory Analyses

Laboratory analysis of the samples were carried out at Water Resources Authority Central Water Testing Laboratory in Nairobi. Major cations, Potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), manganese (Mn) and iron (Fe) were analysed using ion-selective electrode (ISE) and argentometric methods, while major anions (CO_3^-), nitrate (NO_3^-), nitrite (NO_2^-) sulphate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), total hardness and alkalinity were analysed using turbidimetric and titration methods. All these methods followed the "Standard Methods for the examination of Water and Wastewater" published by the American Public Health Association (APHA) and American Water Works Association (AWWA) (APHA & AWWA 2005). The laboratory analytical methods which were used include:

- *Ion-Selective Electrode (ISE) method*: This method was used to analyse Calcium, Nitrate, Fluoride, Sodium, and Potassium. This method involves an electrochemical sensor, based on thin films or selective membranes as recognition elements, and an electrochemical half-cell equivalent to other half cells of the zeroth. The electrodes which are used in this method are membranes that are fixed at each end of either glass or plastic tubes to select particular ions to which they are conductive. ISE uses electrodes whose body contains a reference solution having a constant mixture and when such an electrode is immersed in a solution it conducts electricity across the membrane.

- *Argentometric method*: This methodology was used to analyse chlorides and sulphates. Argentometric is a titrimetric method whereby the sample was titrated with standard silver nitrate using a potassium chloride indicator to produce a fine white precipitate of silver chloride. When all the free ions are complexed in this reaction, the silver nitrate acquires the bound chloride ions from the indicator to form blood-red silver chromate precipitate, marking the end of the titration (Hauser 2001).
- T*urbidimetric method*: This is a simple, sensitive, direct but rather rapid water laboratory analytical method. The turbidimetric method was used in the determination of sulphate ions. The method operates on the principle that sulphate ions react in acidic solution with barium chloride to form a suspension of uniformly sized crystals of barium sulphate. The method uses a turbidity meter. This instrument was calibrated using 80 NTU and 40 NTU standards. Sulphate, SO_4^{2-} standards were then prepared at an increment of 5.0 mg/l up to 40 mg/l in a 100 ml volumetric flask. The solutions were then transferred into 250 ml Erlenmeyer flask and 2.5 ml of sulphate buffer solution added to each and stirred. A spatula of $BaCl_2.2H_2O$ crystals of size 20 to 30 mesh was added to each solution while stirring at a constant speed for 1 minute. The turbidity of the standards was recorded and the calibration curve was obtained. The water samples and a blank were treated like the standards, turbidity values measured and the concentrations of sulphate present were read from the calibration graph.
- *Titration methods*: Titrations were used in the determination of total hardness, alkalinity, and bicarbonate ions. The determination of hard water is always done by analysing the nature of anions accompanying the metal cations (Robert, 1996). Determination of HCO_3^- was done by titrating the water samples with a standard sulphuric acid solution of 0.01N using cresol red and bromocresol green indicator. The carbonate alkalinity value expressed as $MgCaCO_3$ is taken as the carbonate ion content while the bicarbonate alkalinity values are considered to be equal to the bicarbonate ion concentration. In the determination of total hardness, water samples were titrated with Ethylene Diamine Tetra- Acetic Acid titrants. The amount of total hardness was then calculated from the volumes of titre and the sample using the below equation as expressed by (APHA, AWWA, WPCF, 1985):

Alkalinity Mg $CaCO_3$/L = A_x X N_x 5000/D - ***Equation 3.1***

Where: A - is the volume of titre EDTA

B -is $MgCaCO_3$ equivalent to 100 ml EDTA and

D - is the volume of the sample used.

3.3.2.4 Data Analyses

Several computer programs were employed in analysing the laboratory results. The data was first subjected to a charge balance test to check for data accuracy (Nordstrom et al., 1989). Charge balance calculation followed the following equation:

Equation 3.2

$$100 = \frac{\text{meq/L, cations} - \text{meq/L, anions}}{\text{meq/L, cations} + \text{meq/L, anions}}$$

The laboratory data were first subjected to charge balance error determination to assess the level of accuracy. Out of the 43 samples only one failed the charge balance. The data, therefore, passed the accuracy level. Discrepancies of charge balance above 10% were noted only in one site, Matooni shallow well 1 water sample, which had a charge balance of 13.27%. The rest of the samples were between 0-10% and were as such acceptable (Rademacher et al., 2001). The minimal error realized in Matooni shallow well water sample could have resulted due to sample handling.

The data were then subjected to statistical data analysis. Based on mineralization, groundwater sub-groups were determined using Principal Component Analysis (PCA). This was done by comparing average values and standard deviations for sub-groups which was later applied in evaluating whether different backgrounds and threshold values were needed for different subgroups. Most of the data were analysed using the computer software package called Statistics Package for Social Sciences (SPSS). Both multivariate and descriptive statistical methods were applied. Principal Component Analysis was used in classifying samples into recognizable clusters (Hans , 2003). These clusters were later used to produce associations among the hydrochemical variables according to their weights. The descriptive statistical analysis technique was aimed at identifying the chemical relationship between the water samples. Samples with similar physical and chemical characters have similar hydrologic records, recharge zones, infiltration pathways, and flow paths in terms of climate, mineralogy, and residence time (Guler et al. 2002).

Groundwater samples were later classified into chemical facies using ternary and piper trilinear diagrams (Piper 1944). The classification was done in such a way that the name of the cluster indicates the most concentrated anion and cation in the analysed sample. This analysis was done using Piper from the AQUACHEM program. Piper diagram is a commonly used graphical diagram that presents the relative concentrations of the major cations and anions on two separate trilinear plots, together with a central diamond plot where the points from the trilinear plots are projected. The central diamond field can be defined to represent water-type categories that form the basis for one common classification scheme for natural water (Back and Hanshaw 1965). Piper diagram was also used to illustrate the evolution pathways or mixing of different sources of water.

3.3.3 Objective 2 – Determination of Geological, Rock-Water Interactions and Human Influence on Groundwater Chemistry

3.3.3.1 Desktop Studies

Preliminary information was collected on the expected rock types, to understand the type of tools to assemble for rock sampling. Further information was also gathered from previous scholarly studies to understand the prevalent weathering mechanism within the project area. Also, borehole completion records were used to understand the available groundwater chemistry. As indicated in section 3.3.2.1 an understanding of the infrastructure was also considered in field work planning.

As can be deduced from Table 3.1 cation exchange occurs within the clay products. Ca^{2+} is a product of albite weathering and the dissolution of Fluorite (CaF_2). Oversaturation and near saturation occur when calcite is precipitated by the replacement of Na^+ (cation exchange) depending on temperature variation. High temperatures reduce (geothermal) the solubility of calcite.

Hounslow ratio cannot be used to carry out deductions with water samples of pH values between 5 and 6 since clay minerals dissolve releasing high silica. According to our water sample whose pH ranges from 7.95-8.76, the technique was quite applicable. The following Table 3.1 shows stepwise deductions of source rock using simple comparisons and ratios by Hounslow (1995).

Table 3.1: A Simplified analogy to studying the hydrogeochemistry of the groundwater in the area using simple comparison by Hounslow (1995)

Parameter	Value (Meq/L)	Conclusion
$Na^+ + K^+ - Cl^-/Na^+$ K^+ - C1$^-$ + Ca^{2+}	< 0.2 and 0.8 > 0.2 or 0.8	Plagioclase weathering possible Plagioclase weathering unlikely
$Na^+/Na^+ + Cl^-$	>0.5 = 0 < 0.5 TDS > 500 < 0.5 TDS < 500 > 50	Sodium source other than halite- albite, ion exchange Halite solution Reverse softening, seawater Analysis error Rainwater
$Mg^{2+}/Ca^{2+} + Mg^{2+}$ $Mg^{2+}/Ca^{2+} + Mg^{2+}$	$HCO_3^-/SiO_2 > 10$ =0.5 <0.5 >0.5 $HCO_3^-/SiO_2 < 5$ >0.5 <0.5	Carbonate weathering Dolomite weathering Limestone-dolomite weathering Dolomite dissolution, calcite precipitation, or seawater Silicate weathering Ferromagnesian minerals Granite weathering
Ca^{2+} / Ca^{2+} + $S0_4^{2-}$	Ca^{2+} / Ca^{2+} +S0$_4$ 2- = 0.5 <0.5 pH <5.5 <0.5 neutral >0.5	Gypsum dissolution Pyrite oxidation Calcium removal- iron exchange or calcite precipitation Calcium source other than gypsum-carbonates or silicates
TDS	>500 <500	Carbonate weathering or brine or seawater 2 Silicate weathering
Cl^- / sum anions	>0.8 TDS > 500 >0.8TDS< 100 <0.8	Seawater, or brine or evaporates Rainwater Rock weathering

3.3.3.2 Field Studies

The fieldwork was conducted from 30th January 2019 to 7th February 2019. Forty-two water samples were collected from shallow wells, hand pumps and deep wells as shown in figure 3.1. As well, eleven geological rock samples were collected representatively for hand identification.

Sampling points were randomly distributed all over the project area to provide a general hydrochemical view of the project area. Water sampling and measurements were as discussed in section 3.3.2.2 while measurements of geological structures carried out included the orientation and dips of lineaments and veins. The sample for the determination of major ions was dosed with nitric acid for preservation. Geological structures and rock lithologies were studied in the field and sampled for further studies in the office.

3.3.3.3 Laboratory Analyses

Analytical procedures used included Ion-Selective Electrode (ISE) method, Argentometric method, Turbidimetric method, and Titrimetric method as outlined in section 3.3.2.3.

3.3.3.4 Data Analyses

Comparative analysis of the possible origins of major elements was assessed using AquaChem and surfer programs. Deductions were then done using simple graphical methods. AquaChem program was used to produce box plots, Schoeller and trilinear diagrams. Alongside the graphical plot deductions source, rock references were made from ratios of reasoning adopted from the Hounslow (1995). Golden Surfer 16.6 was used to plot the spatial distribution of both physical and chemical parameters which were measured. These spatial distribution plots helped provide the extent to which the parameters are distributed within the project area. Also, PHREEQC software was used to calculate mineral-saturation indices.

3.3.4 Objective 3 – Groundwater Quality Index Map and Development Planning

3.3.4.1 Desktop Studies

Studies of past scholars were critically perused to provide an understanding on the quality of groundwater within Mwingi North. Further, studies of past work were also undertaken to understand how groundwater quality has affected economic development as well as human health within Mwingi North. Borehole completion records of past drilled boreholes were used to provide insight on the prevailing groundwater chemical constituents. Also, as mentioned in section 3.3.2.1, an understanding of the infrastructure was necessary to help in fieldwork planning.

3.3.4.2 Field Studies

Based on the outline on section 3.3.3.2, sampling points were randomly distributed all over the project area to provide a general hydrochemical view of the project area. Parameters such as EC, Temperatures, specific conductance and TDS were measured on-site. Total alkalinity was also measured at the time of sampling to avoid dissociation due to contact with air. Physical parameters were measured using Hanna Combo meter.

3.3.4.3 Laboratory Analyses

Parameters analysed included major cations, K, Na, Ca, Mg, Mn and Fe and major anions, CO_3^-, NO_3^-, NO_2^-, SO_4^{2-}, Cl^-, and F^-, total hardness and alkalinity. Water quality analysis procedures followed included those set in USDA Handbook 60 by Richards, 1954, FAO Soils Bulletin 10 by Dewis and Freitas1970 and APHA, 2005-the advanced edition of APHA (1790 Broadway). Groundwater quality parameters were analysed vis-à-vis existing acceptable limit set by WHO, and NEMA.

3.3.4.4 Data Analyses

Water quality index is a mathematical grading tool which has been developed to qualitatively and quantitatively compress large quantities of water samples by assigning them a single number (Ochungo et al., 2019). The development of WQI has made it easier to transform and pass on information on groundwater to the intended consumers. The methodology aims at determining the usability of a particular water sample for human consumption. WQI assigns a ranking system to easily decipher areas with potable and non-potable water such as excellent, suitable or unsuitable for human consumption (Gebrehiwot et al., 2011).

The calculation of WQI for the groundwater quality of Mwingi North has been done by considering the following 13 parameters including Potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), carbonates (CO_3^-), nitrates (NO_3^-), sulphates (SO_4^{2-}), chlorides (Cl^-), fluorides (F^-), pH, TDS (Tyagi et al., 2013). The WQI has been calculated by adopting the Weighted Arithmetic Index in a stepwise procedure as indicated below.

For calculating WQI each of the parameters was assigned a unit weight (w_1) depending on their strength of effectiveness in determining the overall quality of drinking water. The ranking was from 1-5, with 1 representing those parameters with least effectiveness and 5 representing those parameters with the greatest importance (Srinivasamoorthy et al., 2008).

Secondly, according to Brown et al. (1972) the weighted arithmetic is calculated using the equation:

Equation 3.3

$$W_1 = \frac{w1}{\sum_{i=1}^{n} w1}$$

Where: W1- is the relative weight

w_1 - is the weight of each parameter, and

n - is the number of parameters

Thirdly, the quality rating scale (Qi) for each parameter is obtained by dividing the observed concentration with its respective standard concentration as declared by KEBS. The sum is then multiplied by 100.

Equation 3.4

$$Q_1 = \left({}^{Ci}/_{Si}\right) x100$$

Where Q_i = quality rating

C_i = observed concentration of each parameter

S_i = KEBS drinking water standard for each physico-chemical parameter

In the fourth step, the water quality sub-index (SI) was first determined for each chemical parameter by:

Equation 3.5

$$SIi = Wi \times Qi$$

Where SIi – is water quality sub index of each parameter

Qi – is quality rating of each parameter

Lastly, WQI is calculated by

Equation 3.6

$$WQI = \sum SI\ 1\text{-}n$$

The calculations of WQI is usually graded into five classes: excellent, good, poor, very poor and unfit water for drinking purposes as in table 3.2.

Table 3.2: Water quality rating based on WQI

WQI	Water Quality Rating
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unsuitable for drinking

CHAPTER FOUR
RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter is divided into two sections; results and discussions. The first section presents the results of the physical and analytical tests that were conducted on the water samples collected from the Mwingi North area. The second section discusses the results that have been obtained in the context of the study's specific objectives. The results section is presented in three sub-sections, with each sub-section presenting one specific objective of the study. The three subsections of the results section are; hydrochemical characteristics, geology, rock-water interactions, and human influence on groundwater quality, and groundwater quality index and development planning. The discussion of the results has also been presented in three subsections according to the three specific objectives presented in the results section. The chapter then closes by presenting a summary of results and discussions.

4.2 Hydrochemical Characteristics

4.2.1 Physico-chemical Characteristics

4.2.1.1 Physical Characteristics (EC, pH, T, Turbidity, Alkalinity, Colour)

Physical parameters were analysed for 17 water samples from boreholes, 17 water samples from hand pumps, and 8 water samples from shallow wells within the Mwingi North area. Below is a short description of the quantitative occurrence of the parameters, EC, pH, temperature and total alkalinity, TDS, turbidity, and colour and Figures 4.1 a, b, c, and d shows box plots of physical parameters pH, TDS, Total hardness, and EC respectively.

a) Boreholes

The electrical conductivity ranges from 690-9379 µS/cm with a median of 3760 µS/cm, pH ranges from 7.95-8.76 with a median of 8.38, total alkalinity ranges from 168-600 mg/l with a median of 394 mg/l, TDS ranges from 427-5809 mg/l with a median of 2331 mg/l. Colour was noted to be > 5 mgPt/l in all the 17 water samples and as such negligible.

b) Hand pumps

The electrical conductivity ranges from 756 to 7710 µS/cm with a median of 2410 µS/cm, pH ranges from 7.55-8.53 with a median of 8.24, total alkalinity ranges from 150-664 mg/l with a median of 314 mg/l, TDS ranges from 484.84-4780 mg/l with a median of 1494.2 mg/l. Colour was noted to be >5 mgPt/l in all the 17 water samples and as such negligible.

c) Shallow wells

The electrical conductivity ranges from 362-2600 µS/cm with a median of 567 µS/cm, pH ranges from 8.21-8.61with a median of 8.46. Total alkalinity ranges from 160-350 mg/l with a median of 202 mg/l, TDS ranges from 228-1612 mg/l with a median of 395 mg/l. Colour was noted to be >5 mg Pt/l in 7 out of the 8 water samples and as such negligible. Only one shallow well registered colour of 30 mgPt/l, which is above the maximum acceptable limit of 15 mgPt/l.

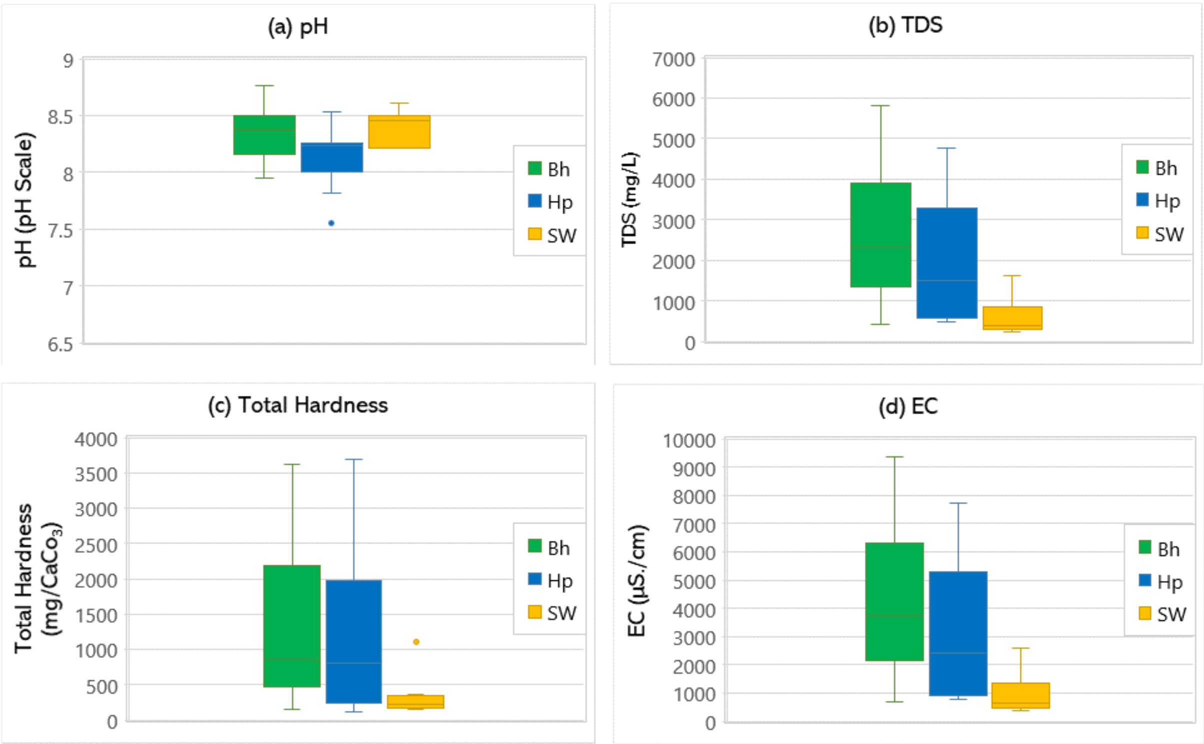

Figure 4.1: Physical parameters showing (a) pH levels with shallow wells having relatively alkaline waters (b) TDS with increasing trends from shallow wells to deep boreholes (c) Total hardness being relatively higher in boreholes and hand pumps and (d) Increasing electrical conductivity with depth (Sw through to Bh)

4.2.1.2 Chemical Characteristics (the Elements/Compounds)

Forty-two water samples were taken through full chemical analysis to determine their chemical constituents. The 42 water samples consisted of 17 water samples from hand pumps, 17 water samples from boreholes and 8 water samples from shallow wells. The categories were considered according to their depths. Boreholes water were those water points which were greater than 100 m deep and had submersible pumps installed, hand pumps were those which were fitted with hand pumps and had depths ranging between 20 and100 m, shallow wells were hand-dug with depths ranging from 0 to 20 m. A few shallow wells have been installed with submersible pumps especially those which are high yielding and on the river beds. The most notable one is Tharaka Women Users Association shallow well (Twa) which is used for water supply within Tharaka shopping centre and its environs. Table 4.1 shows the summarized statistical data of the resultant laboratory analysis in mg/l. The table also indicates sample identification numbers and site names. Figures 4.2 and 4.3 shows box plots of cations and anions respectively.

a) Boreholes

Characteristics of the borehole waters is as follows for cations: Na ranges from 90 to730 mg/l with a medium of 350 mg/l, Ca ranges from16 to 576 mg/l with a median of 152 mg/l, Mg ranges from 25.76 to 622.22 mg/l with a median of 136.13 mg/l, K ranges from 4.7 to 21 mg/l with a median of 10.1 mg/l, Fe ranges from 0.07 to 0.6 mg/l with a median of 0.1 mg/l, and Mn ranges from 0.01 to 0.14 mg/l with a median of 0.01 mg/l.

For the anions, the results were as follows: HCO_3 ranges from 146 to 3620 mg/l with a median of 860 mg/l, F ranges from 2.42 to 4.94 mg/l with a median of 2.05 mg/l, Cl ranges from 38 to 2200 mg/l with a median of 750 mg/l, and CO_2 ranges from 0 to 72 mg/l with a median of 14 mg/l.

b) Hand pumps

Characteristics of hand pump waters is as follows for cations: Na ranges from 15 to 500 mg/l with a median of 135 mg/l, Ca ranges from 5.6 to 480 mg/l with a median of 68 mg/l, Mg ranges from15.08 to 641.7 mg/l with a median of 135.59 mg/l, K ranges from 1.7 to 9.8 mg/l with a median of 5.3 mg/l, Fe ranges from 0.01 to 0.5 mg/l with a median of 0.1 mg/l, and Mn ranges from 0.01 to 0.18 mg/l with a median of 0.01 mg/l

For the anions, the results were as follows: HCO_3 ranges from 118 to 3700 mg/l with a median of 800 mg/l, F ranges from 0.58 to 2.63 mg/l with a median of 1.5 mg/l, and Cl ranges from 10 to 2320 mg/l with a median of 515 mg/l, while gaseous CO_2 had concentrations ranging from 0 to 160 mg/l with a median of 38 mg/l.

c) Shallow wells

Characteristics of shallow well waters are as follows for cations: Na ranges from 3 to 160 mg/l with a median of 65 mg/l, Ca ranges from14.4 to 224 mg/l with a median of 38 mg/l, Mg ranges from11.69 to 131.33 mg/l with a median of 31.37 mg/l, K ranges from 2.3 to 5.9 mg/l with a median of 4.3 mg/l, Fe ranges from 0.1 to 0.37 mg/l with a median of 0.1 mg/l, and Mn ranges from 0.01 to 0.14 mg/l with a median of 0.01 mg/l.

For the anions, the results were as follows: HCO_3 ranges from 144 to 1100 mg/l with a median of 224 mg/l, F ranges from 0.1 to 4.65 mg/l with a median of 1.06 mg/l, and Cl ranges from 4 to 640mg/l with a median of 40.5 mg/l, while gaseous CO_2 had concentrations ranging from 0 to 50 mg/l with a median of 0 mg/l.

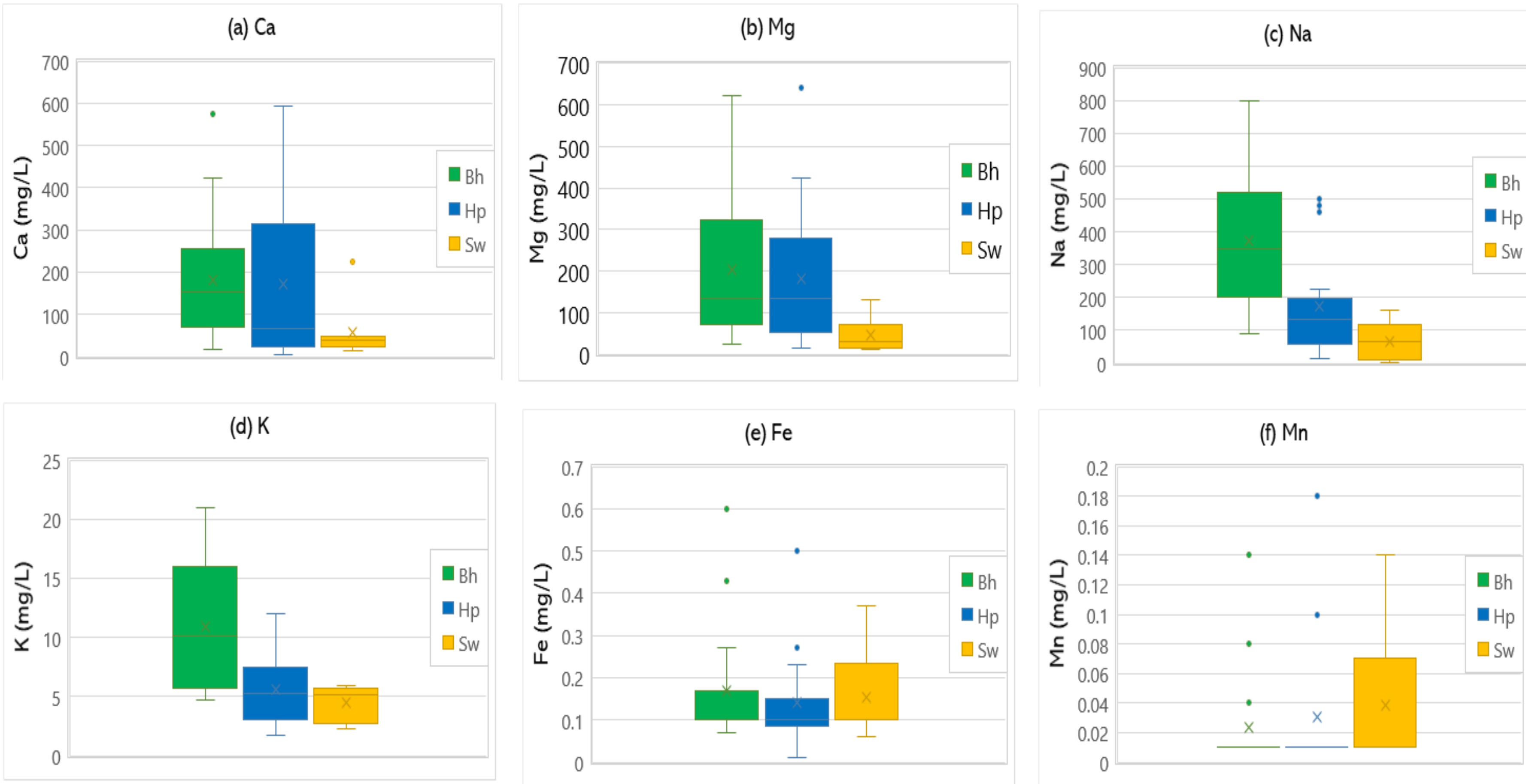

Figure 4.2: Chemical parameters showing cations (a) Ca (b)Mg (c) Na, and (d) K, levels shows increasing concentration in boreholes and hand pumps, (e) Fe shows shallow wells having high concentration, and (f) Mn shows high concentrations in shallow with HP and Bh having negligible concentrations

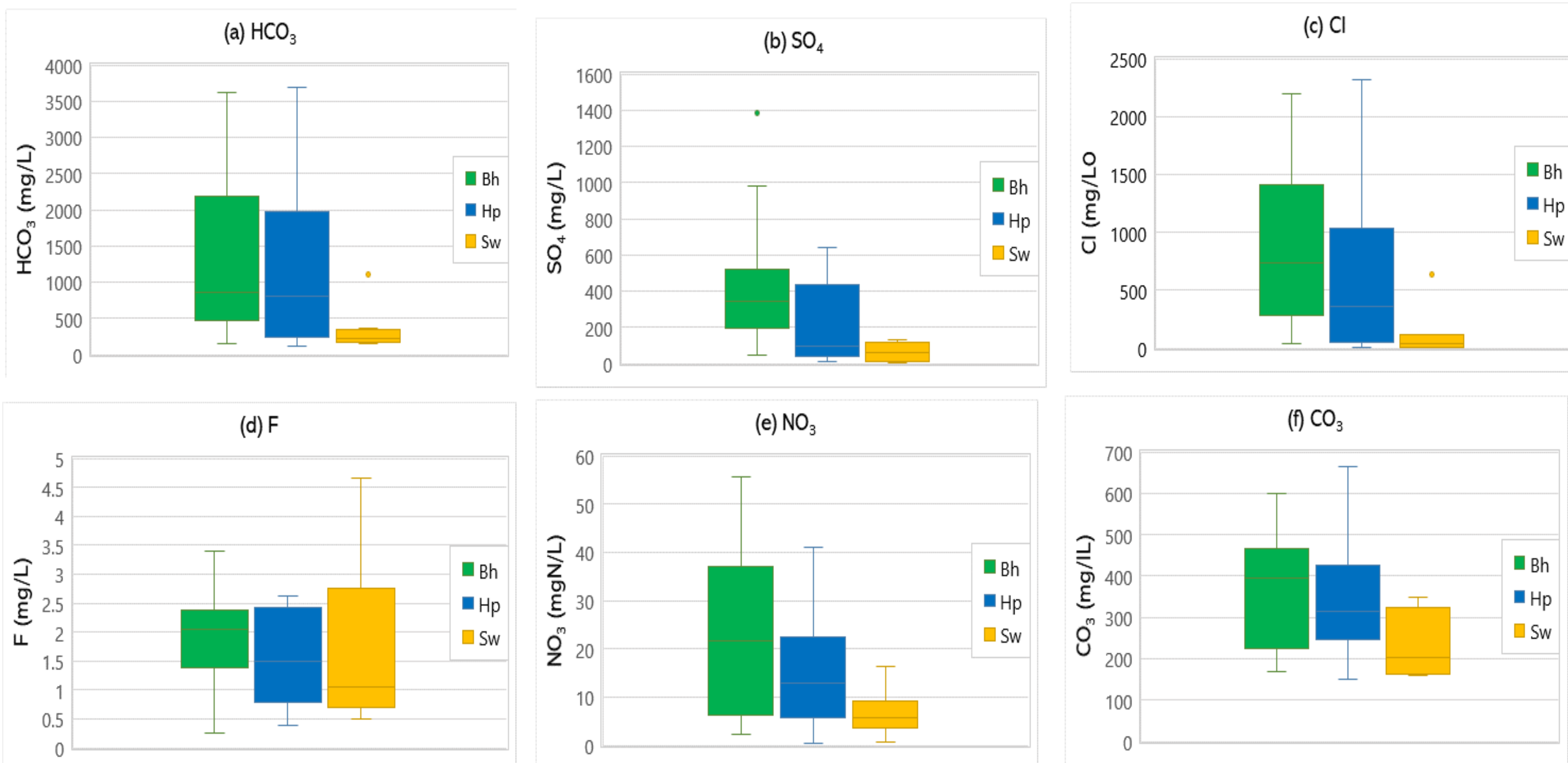

Figure 4.3: Chemical parameters showing anions (a) HCO_3, (b)SO_4, (c) Cl, and (e)NO_3 levels shows increasing concentration in boreholes and hand pumps, (d) F shows shallow wells having high concentration, and (f) CO_3 shows high concentration in shallow wells, hand pumps and boreholes

Table 4.1: Results for the physico-chemical parameters. Shaded cells show the parameters that are above acceptable limits for potable water (KEBS, NEMA, WHO).

	Hand pumps (February 2019)																				
No.	**Sample ID/Name**	**Code**	**pH**	**Col.**	**Turb.**	**EC**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**K**	**Hard.**	**Alk.**	**Cl**	**F**	**NO_3**	**NO_2**	**SO_4**	**CO_2**	TDS
1	Nzaalani HP	MN Hp/001	8.13	<5	1.38.00	2410.00	0.13	0.10	204.00	153.19	24.00	4.60	1140.00	200.00	270.00	0.00	8.28	0.037	70.00	132.00	1494.20
2	Wendo wa Kwiendea	MN Hp/023	8.26	<5	5.03	2220.00	0.07	0.01	68.00	153.1	135.00	7.70	800.00	260.00	355.00	2.45	13.16	0.01	288.10	16.00	1376.40
3	Twaathi Hp	MN Hp/024	8.24	<5	0.00	919.00	0.01	0.01	26.40	31.6.00	120.00	7.20	196.00	290.00	69.00	0.38	12.41	0.01	28.00	30.00	569.78
4	Makuka Hp	MN Hp/026	8.11	<5	1.27	7710.00	0.07	0.01	424.00	641.70	50.00	12.00	3700.00	422.00	2000.00	1.50	17.46	0.024	482.49	160.00	4780.20
5	Madongoi Hp	MN Hp/027	8.24	<5	1.76	4120.00	0.17	0.01	64.00	204.12	480.00	9.80	1000.00	400.00	760.00	2.59	33.71	0.013	431.20	36.00	2554.40
6	Kaliki Hp1	MN Hp/028	8.26	<5	0.58	782.00	0.10	0.01	22.40	15.08	124.00	2.40	118.00	314.00	10.00	1.55	12.78	0.01	12.45	26.00	484.84
7	Kwa Mutand Hp	MN Hp/029	7.92	<5	2.01	5610.00	0.10	0.01	480.00	311.27	138.00	6.60	2480.00	432.00	1250.00	1.39	40.93	0.071	443.60	38.00	3478.20
8	Kwa Ndingori Hp	MN Hp/030	8.24	<5	0.00	1370.00	0.13	0.01	32.00	135.59	15.00	5.60	638.00	450.00	72.00	1.83	24.54	0.029	43.14	80.00	849.40
9	Mitamisyi Sec Bh	MN Hp/031	8.04	<5	1.64	7350.00	0.10	0.01	400.00	379.25	500.00	5.30	2560.00	438.00	2030.00	2.42	20.41	0.011	258.11	66.00	4557.00
10	Nzaini Hp	MN Hp/032	8.27	<5	0.16	785.00	0.13	0.01	22.40	57.35	44.00	1.70	292.00	314.00	13.00	0.87	13.44	0.011	9.72	20.00	486.70
11	Ngomano Hp1	MN Hp/033	8.25	<5	12.94	4950.00	0.10	0.01	176.00	247.92	460.00	8.30	1460.00	664.00	700.00	2.42	25.59	0.01	644.00	46.00	3069.00
12	Ngomano Hp7	MN Hp/034	8.53	<5	0.49	927.00	0.10	0.01	21.60	41.32	110.00	2.70	224.00	360.00	30.00	1.89	5.73	0.01	36.72	0.00	594.94
13	Kwa Kaliya Bh	MN Hp/035	8.15	<5	7.38	2790.00	0.27	0.18	232.00	109.47	160.00	4.10	1030.00	150.00	825.00	0.58	5.73	0.01	47.67	54.00	1729.80
14	Twimnyua Bh	MN Hp/036	8.24	<5	20.08	2410.00	0.50	0.10	160.00	75.40	224.00	3.70	710.00	300.00	515.00	0.93	0.50	0.14	153.14	36.00	1494.20
15	Mbui Bh	MN Hp/038	7.55	<5	0.00	756.00	0.10	0.01	14.40	48.11	63.00	3.40	234.00	230.00	41.00	0.66	5.62	0.01	64.86	38.00	468.72
16	Kaundu Hp	MN Hp/040	7.82	<5	0.50	1228.00	0.07	0.01	5.60	58.31	163.00	2.80	254.00	280.00	137.00	2.63	6.04	0.018	98.14	14.00	761.36
17	Kamanga Catholic Bh	MN Hp/041	7.97	<5	2.42	7240.00	0.23	0.01	592.00	423.00	170.00	6.90	3220.00	224.00	2320.00	0.82	5.92	0.01	64.97	74.00	4488.80
Summary statistics		Min	7.55	-	0.00	756.00	0.01	0.01	5.60	15.08	15.00	1.70	118.00	150.00	10.00	0.58	0.50	0.01	9.72	0.00	484.84
		Max	8.53	-	20.08	7710.00	0.5.0	0.18	480.00	641.70	500.00	9.80	3700.00	664.00	2320.00	2.63	40.93	0.14	570.00	160.00	4780.20
		Median	8.24	-	1.38	2410.00	0.10	0.01	68.00	135.59	135.00	5.30	800.00	314.00	515.00	1.50	12.78	0.011	98.14	38.00	1494.20

	Boreholes (February 2019)																				
	Sample ID/Name	Code	**pH**	**Colour**	**Turb.**	**EC**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**K**	**Hard.**	**Alkal.**	**Cl**	**F**	**NO_3**	**NO_2**	**SO4**	**CO2**	TDS
1	Kathungu Bh	MN Bh/007	8.76	5	69.00	3480.00	0.43	0.01	80.00	68.08	580.00	5.90	480.00	300.00	670.00	1.88	7.33	0.01	433.51	0.00	2157.60
2	Ntumira Bh	MN Bh/008	8.54	<5	15.72	4830.00	0.27	0.08	104.00	131.26	730.00	10.90	800.00	600.00	740.00	2.11	6.18	0.01	700.00	0.00	2994.60
3	Kora Bh	MN Bh/009	7.95	<5	5.84	6610.00	0.13	0.01	576.00	282.18	310.00	17.00	2600.00	174.00	1760.00	0.84	35.48	0.02	471.57	44.00	4098.20
4	Masyungwa Bh	MN Bh/010	8.23	<5	3.29	6030.00	0.17	0.01	272.00	364.60	370.00	15.00	2180.00	394.00	1530.00	1.91	21.77	0.01	343.80	50.00	3738.60
5	Atoka	MN Bh/011	8.54	<5	1.09	5190.00	0.07	0.01	120.00	136.13	800.00	8.20	860.00	396.00	1300.00	1.14	38.78	0.01	215.34	0.00	3217.80
6	Ikathima	MN Bh/012	8.48	<5	2.69	1403.00	0.10	0.04	58.40	30.65	200.00	4.70	272.00	210.00	214.00	0.91	22.67	0.01	101.52	0.00	869.86
7	Kasaini Bh	MN Bh/013	8.48	<5	2.60	7040.00	0.07	0.01	248.00	384.00	590.00	10.10	2200.00	506.00	1600.00	2.91	39.72	0.27	573.86	50.00	4364.80
8	Mulangoni Bh	MN Bh/014	8.38	<5	1.75	3080.00	0.10	0.01	152.00	97.27	340.00	8.70	780.00	500.00	610.00	1.91	22.84	0.01	81.41	0.00	1909.60
9	Kathiani (Kawongo Bh)	MN Bh/015	8.18	<5	0.71	4130.00	0.10	0.01	152.00	272.20	245.00	17.00	1500.00	482.00	750.00	2.28	55.69	0.01	310.51	72.00	2560.60
10	Tito Nzuki Bh	MN Bh/016	7.95	<5	0.36	9370.00.	0.17	0.01	424.00	622.22	460.00	19.00	3620.00	450.00	2200.00	1.63	47.56	0.01	980.00	34.00	5809.40
11	Mwangea Bh	MN Bh/018	8.43	<5	0.77	1801.00	0.17	0.01	36.80	89.43	200.00	7.90	460.00	230.00	279.00	2.50	6.19	0.01	233.78	0.00	1116.62
12	Nziitu Bh	MN Bh/019	8.52	<5	0.91	690.00	0.10	0.01	16.00	25.76	90.00	5.60	146.00	220.00	38.00	2.05	5.33	0.01	43.45	0.00	427.80
13	Nzanzeni Sec Bh	MN Bh/020	8.48	<5	0.70	2440.00	0.10	0.01	40.00	75.34	370.00	10.10	410.00	420.00	279.00	2.12	10.80	0.01	344.76	0.99	1512.80
14	Kyenini Bh	MN Bh/021	8.13	<5	1.17	6850.00	0.10	0.01	264.00	452.00	390.00	21.00	2520.00	366.00	1100.00	3.39	10.80	0.01	1382.00	18.00	4247.00
15	Kaningo Bh	MN Bh/022	8.24	<5	0.54	3760.00	0.10	0.01	160.00	257.63	180.00	14.00	1460.00	450.00	710.00	2.39	28.05	0.01	302.66	24.99	2331.20
16	Ikaaie B Bh	MN Bh/036	8.12	5	18.98	1899.00	0.60	0.14	210.40	48.23	100.00	5.30	724.00	168.00	254.00	0.26	6.56	0.01	400.00	14.00	1177.38
17	Makuvuni Bh	MN Bh/042	8.24	<5	1.92	3550.00	0.07	0.01	168.00	141.00	350.00	4.70	1000.00	340.00	870.00	2.37	2.35	0.01	174.8	30.00	2201.00
Summary statistics		Min	7.95	-	0.36	690.00	0.07	0.01	16.00	25.76	90.00	4.70	146.00	168.00	38.00	2.42	2.35	0.01	43.45	0.00	427.80
		Max	8.76	-	69.00	9379.00	0.60	0.14	576.00	622.22	730.00	21.00	3620.00	600.00	2200.00	4.94	55.69	0.27	1382	72.00	5,809.00
		Median	8.38	-	1.75	3760.00	0.10	0.01	152.00	136.13	350.00	10.10	860.00	394.00	750.00	2.05	21.77	0.01	310.51	14.00	2,331.00

Shallow wells (February 2019)

No	sample ID/Name		**pH**	**Col.**	**Turb.**	**EC**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**K**	**Hard.**	**Alkal.**	**Cl**	**F**	**NO_3**	**NO_2**	**SO4**	**CO_2**	TDS
1	Kaghui SW	MN Sw/002	8.22	<5	4.31	2600.00	0.10	0.08	224.00	131.33	86.00	4.80	1100.00	250.00	640.00	0.50	3.86	0.03	117.87	50.00	1612.00
2	Katse Sw	MN Sw/003	8.48	<5	1.35	729.00	0.10	0.14	44.80	21.89	70.00	5.90	202.00	200.00	53.00	0.81	5.87	0.01	76.47	0.00	450.74
3	Katse River Sw	MN Sw/004	8.51	<5	16.06	455.00	0.27	0.01	46.40	13.15	23.00	5.40	170.00	20.40	10.00	0.65	5.88	0.01	18.84	0.00	282.11
4	Kwakiri Sw 1	MN Sw/017	8.21	<5	2.02	1323.00	0.10	0.01	26.40	72.42	130.00	5.60	364.00	350.00	102.00	4.65	10.35	0.03	113.42	16.00	820.26
5	Thangani SW (River)	MN SW/006	8.21	30	45.67	362.00	0.37	0.04	48.80	11.69	3.00	5.80	170.00	160.00	3.00	1.91	0.66	0.02	2.63	14.00	228.16
6	Matooni Sw1	MN Sw/024	8.44	<5	2.72	475.00	0.06	0.01	31.20	40.84	7.00	2.30	246.00	160.00	9.00	1.15	16.32	0.01	4.60	0.00	294.50
7	Malili Sw	MN Sw/039	8.48	5	1.58	1355.00	0.13	0.01	14.40	69.98	160.00	2.30	324.00	350.00	120.00	3.05	3.39	0.01	131.26	0.00	840.10
8	(Twwua)	MN Sw/005	8.61	<5	0.71	546.00	0.10	0.01	24.00	20.42	60.00	3.80	144.00	170.00	28.00	0.97	5.42	0.01	42.37	0.00	338.52
Summary statistics		Min	8.21	-	0.71	362.00	0.10	0.01	14.40	11.69	3.00	2.30	144.00	160.00	3.00	0.10	3.39	0.01	4.60	0.00	228.00
		Max	8.61	-	45.67	2600.00	0.37	0.14	224.00	131.33	160.00	5.90	1100.00	350.00	640.00	4.65	16.32	0.03	131.26	50.00	1,612.00
		Median	8.46	-	2.37	567.00	0.10	0.01	38.00	31.37	65.00	4.30	224.00	202.00	40.50	1.06	5.65	0.01	59.42	0.00	395.00

4.2.1.3 Spatial distribution of the Physico-chemical Parameters

Figures 4.4-4.6 are water quality maps showing the quantitative occurrence of the physical and chemical parameters. Physical parameters include pH, total hardness, electrical conductivity, and turbidity. Chemical parameters shown on the spatial maps includes cations such as iron, manganese, calcium, magnesium, sodium, and potassium. The anions shown on the spatial maps includes chloride, fluoride, sulphate and free bi-carbonate.

As shown in Figure 4.4 high EC are distributed on the eastern parts of the project area stretching along a N-S direction. Electrical conductivity ranges from 362 µS/cm to 9371 µS/cm. Highest electrical conductivities are in the far northern western areas of Tharaka, decreasing southwards towards the Kyuso area and again reaches another high point in Ngomeni areas to the southeast.

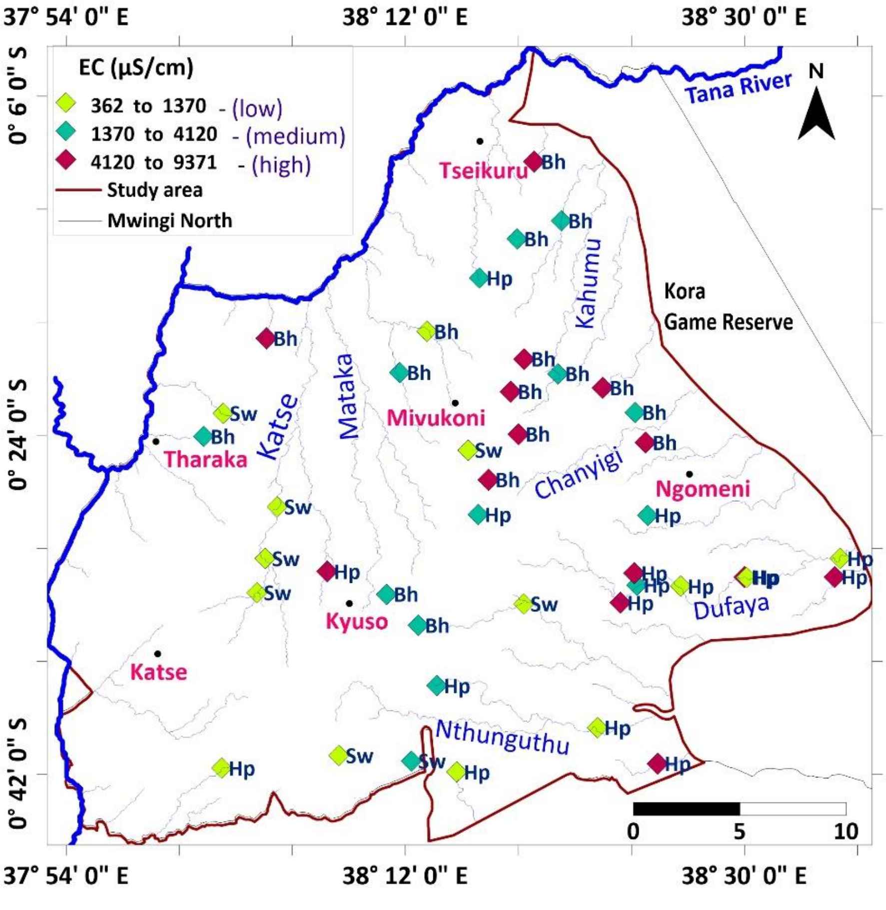

Figure 4.4: Occurrence and distribution of EC in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

The groundwater of Mwingi North ranges from weakly alkaline to alkaline (7.55 -8.76). The highest pH was recorded in the deep groundwater of the Tharaka area (8.76) to the west of the project area (Figure 4.5). From this peak point, pH decreases gradually northwards, eastwards and southwards reaching its lowest concentrations in the deep groundwater of the Mumoni area (7.55) to the southwest.

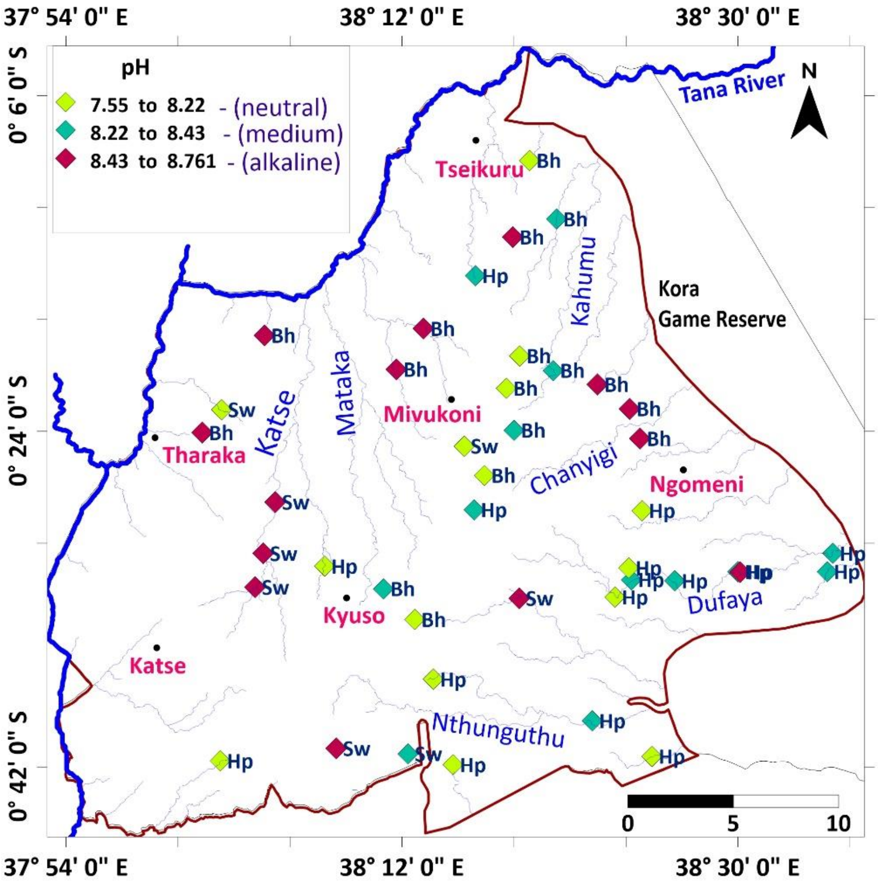

Figure 4.5: Occurrence and distribution of pH in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Turbidity is the cloudiness or haziness of a fluid caused by large number of particles invisible to the naked eye. According to WHO allowable levels of turbidity should be >5 NTU and < 1 NTU. Within Tharaka, turbidity values range from 1.38 NTU to 68.64 NTU and are highest in the western areas of Tharaka (Figure 4.6). It then decreases spatially eastwards, northwards and southwards with most areas of Mwingi North having groundwater with low turbidity. The most turbid water was realized in samples from shallow groundwater. Most shallow wells are along the river beds and tap their water from the alluvial sands deposited on the banks or along the river beds. Soil particles in these waters alter the expected clarity of the water. Water from boreholes and hand pumps are tapped further from the surface and are less turbid. Turbid waters occur to the west of the study area. Most of the groundwater around Kyuso area are less turbid as displayed in Figure 4.6. Turbidity was generally low in all the water samples of the study area.

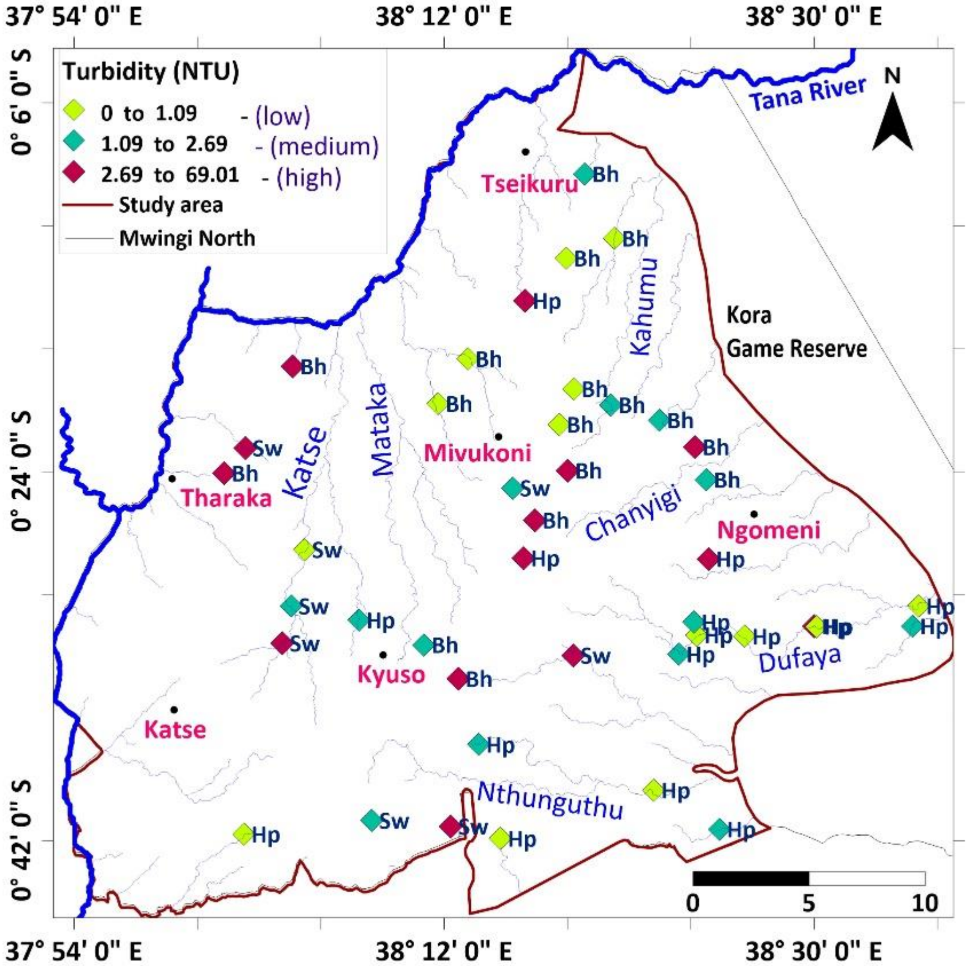

Figure 4.6: Occurrence and distribution of Turbidity in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Total hardness ranges from 118 mg/l to 3700 mg/l with a median of 752 mg/l (Table 4.1). As shown in Figure 4.7 total hardness is highest in the Ngomeni area to the southeast upwards along the central parts of the project area to the northern areas of Tseikuru. Other areas with high total hardness are the central parts of the study area, the Kyuso, and Mumoni areas. The southwest and east of the study area have the least concentrations of total hardness.

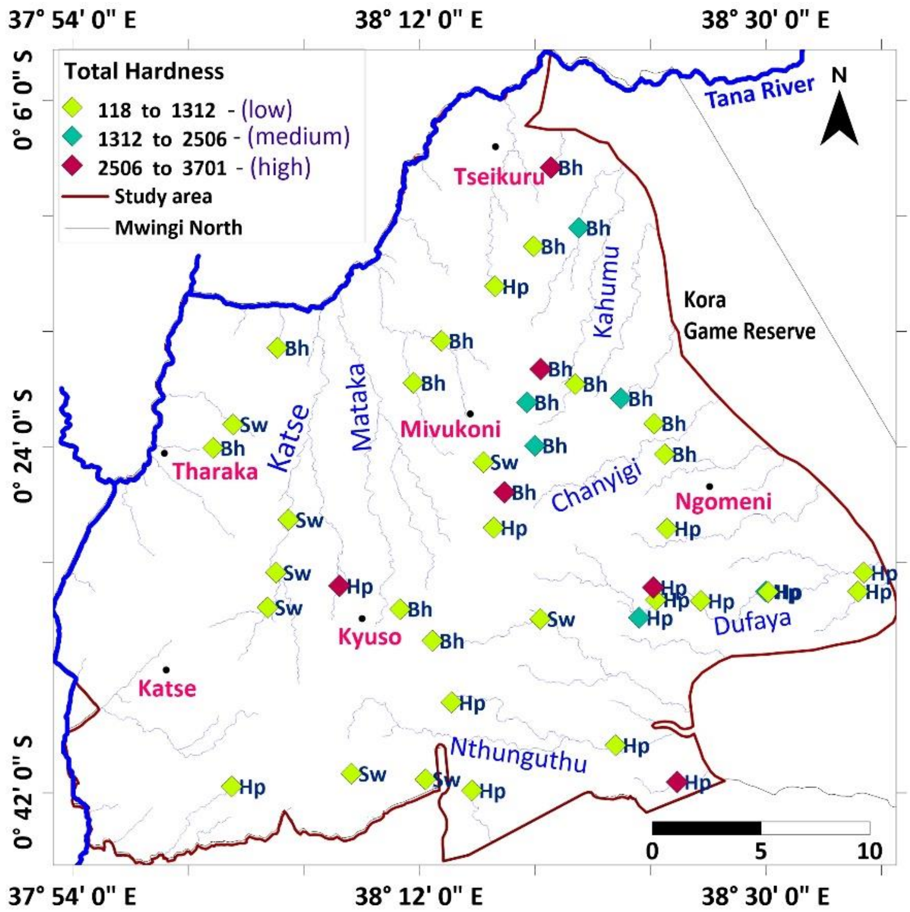

Figure 4.7: Occurrence and distribution of hardness in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Calcium concentration ranges from 5.6 -592 mg/l with a median of 92 mg/l. The spatial distribution of calcium in the project area is highest to the south towards the north while low in the highlands to the eastern and western areas of the study area as shown in Figure 4.8. The highest concentrations are at Makuka hp (424 mg/l), Kwa Mulandi hp (480 mg/l), Mitamsyi sec bh (400 mg/l), Kimangao catholic bh (592 mg/l), Tito Nzuki bh (424 mg/l) and Kora bh (576 mg/l

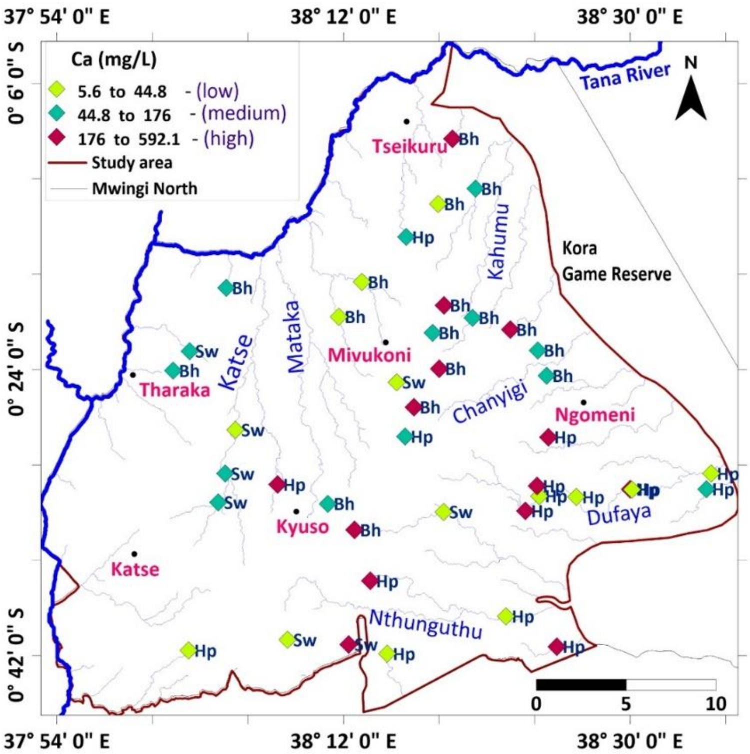

Figure 4.8: Occurrence and distribution of Ca in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Na is the most dominant cation within groundwater aquifers of Mwingi North. It ranges from a minimum of 3 mg/l to a maximum of 800 mg/l with a median of 161.5 mg/l. High sodium concentrations are in Tharaka highlands to the northwest of the study area and Tseikuru to the east of the study area. Low concentrations are to the west in the Mumoni area as well in the central areas south of the Kyuso market as shown in Figure 4.9. The allowable concentration limit of sodium in drinking water is 200 mg/l (WHO, 2008; NEMA, 2006). Several boreholes and hand pumps have sodium concentration above the allowable limits. While Shallow wells have a permissible level of sodium concentrations (Table 4.1).

Magnesium concentration ranges from a low of 11.69 mg/l to a high of 641.7 mg/l with a median of 153.1 mg/l. Magnesium highs are to the south and north of the study area while low to the western and eastern areas of the study area (Figure 4.10) The highest concentrations are notably at Makuka hp (641.7 mg/l), Kwa Mulandi hp (311.27 mg/l), Mitamsyi sec bh (379.25 mg/l), Kimangao catholic bh (423 mg/l), Masyungwa bh (364.6 mg/l) and Tito Nzuki bh (622.22 mg/l). The distribution of calcium and magnesium are positively correlated: an increase in calcium means an increase in magnesium (Figures 4.10). The concentration of calcium and magnesium are directly correlated for boreholes.

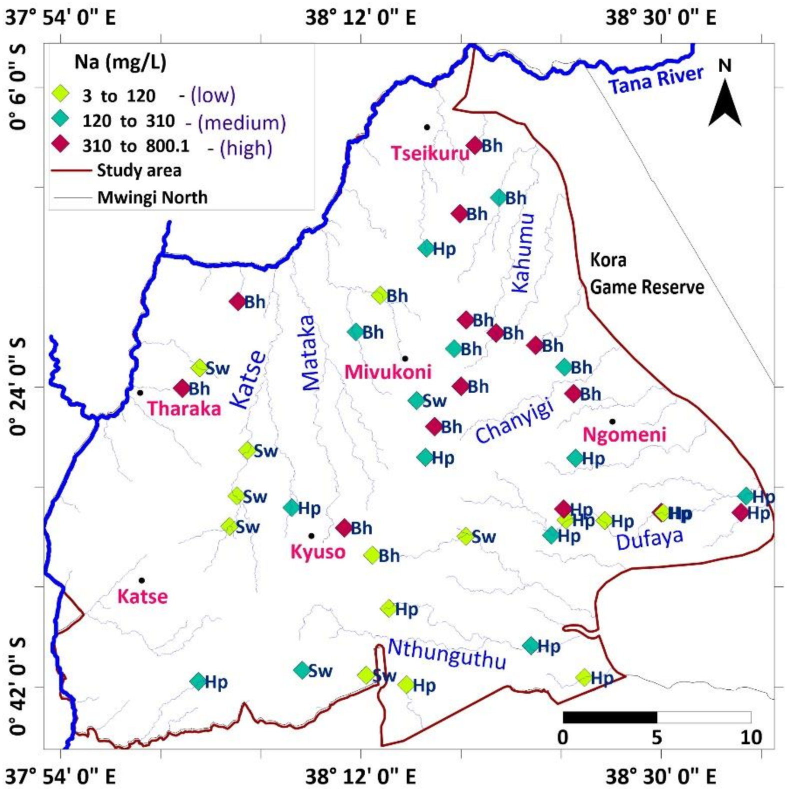

Figure 4.9: Occurrence and distribution of Na in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

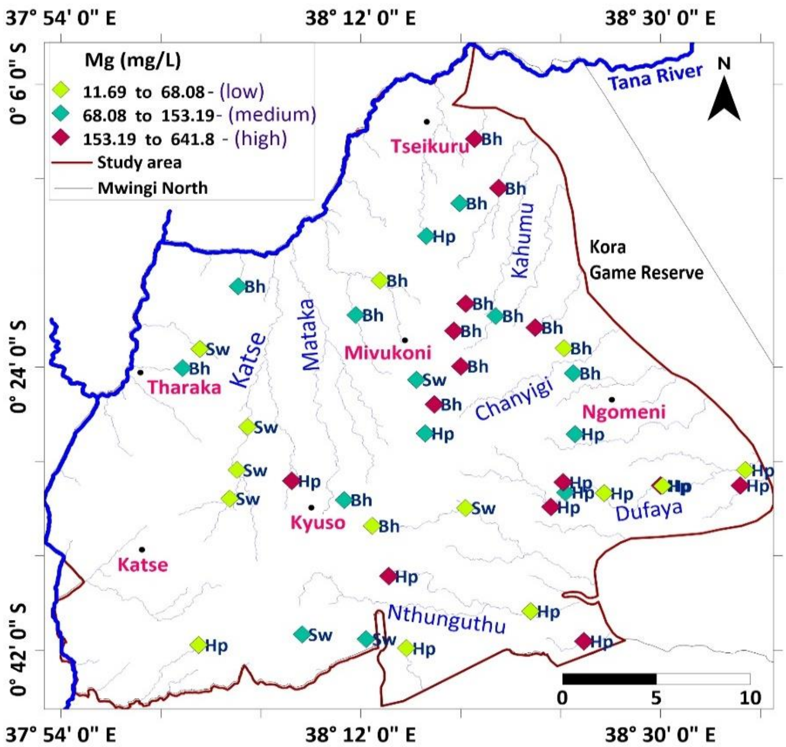

Figure 4.10: Occurrence and distribution of Mg shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Potassium occurs in all the groundwater of Mwingi North albeit in very low concentrations. Potassium ranges from 1.7 – 21 mg/l with a median of 5.85 mg/l. All the groundwater of Mwingi North has the concentration of potassium below the maximum allowable limits and therefore qualify as potable water (WHO, 2008; NEMA, 2006). As shown in Figure 4.11, potassium displays an even distribution within the study area.

The distribution of iron concentration ranges from 0.01- 0.6 mg/l with a median of 0.1 mg/l (Table 4.1). According to Table 4.1 some water points have concentration levels of iron above the WHO recommended limit of 0.3 mg/l. Figure 4.12 shows that iron is high in Tharaka areas in the north west and Kyuso areas within the centre of the study area while the northern and southern fringes have the least iron concentrated waters.

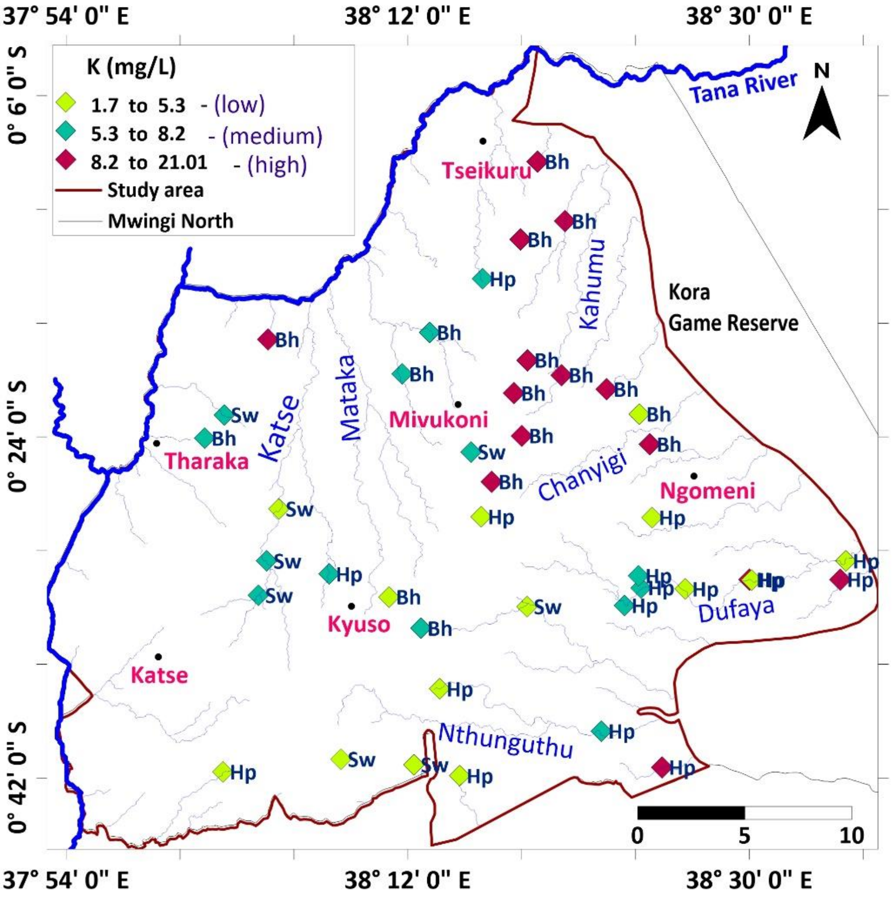

Figure 4.11: Occurrence and distribution of K shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

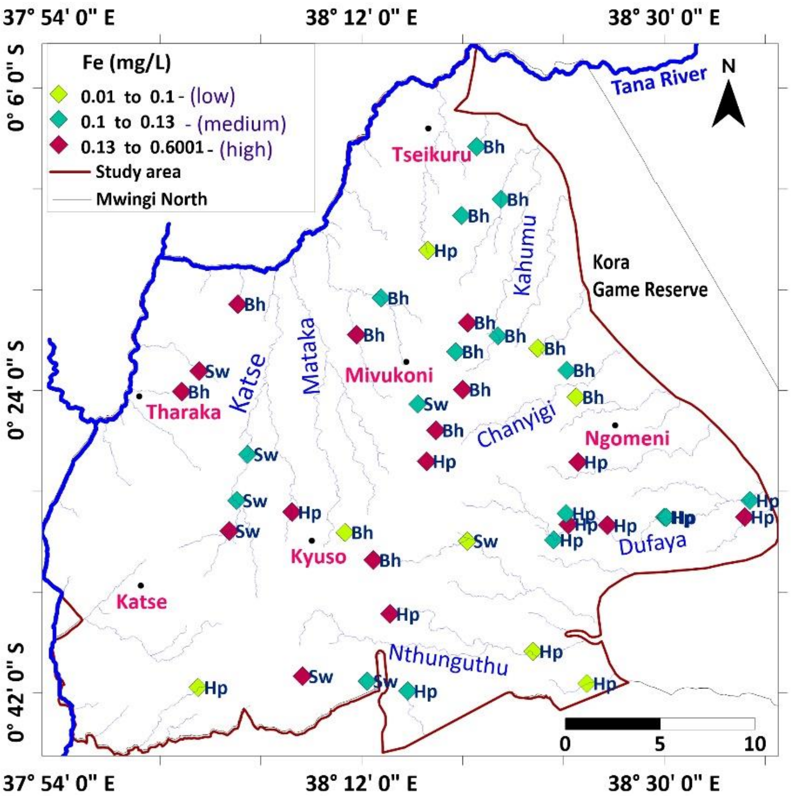

Figure 4.12: Occurrence and distribution of Fe in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

The concentration of manganese ranges from 0.01 mg/l to 0.18 mg/l as shown in Table 4.1, with a median of 0.01 mg/l. The distribution of manganese concentrations within shallow wells, boreholes, and hand pumps falls within WHO permissible limits of 0.5 mg/l. Manganese levels are within permissible limits. It is moderately high in the Ngomeni area in the southeast, and the Kyuso and Mumoni areas in the central and western parts of the study area as shown in Figure 4.13. Tseikuru and Tharaka areas to the north and northwest, respectively, have groundwater of low manganese concentrations.

The concentration of fluoride ranges from 0.26 mg/l to 4.65 mg/l with a median of 1.85 mg/l. Fluoride highs are in the centre of the study area north of the Kyuso ward and in the northern areas of Tseikuru (Figure 4.14). Areas low in fluoride concentrations are in the far south, east, and west of the study area. Water samples from shallow waters have the lowest fluoride levels, even though two shallow wells while Kwakiri sw (4.65 mg/l) and Malili bh (3.05 mg/l) notably recorded the highest fluoride levels. Waters from boreholes and hand pumps have the highest fluoride concentrations above the allowable limits.

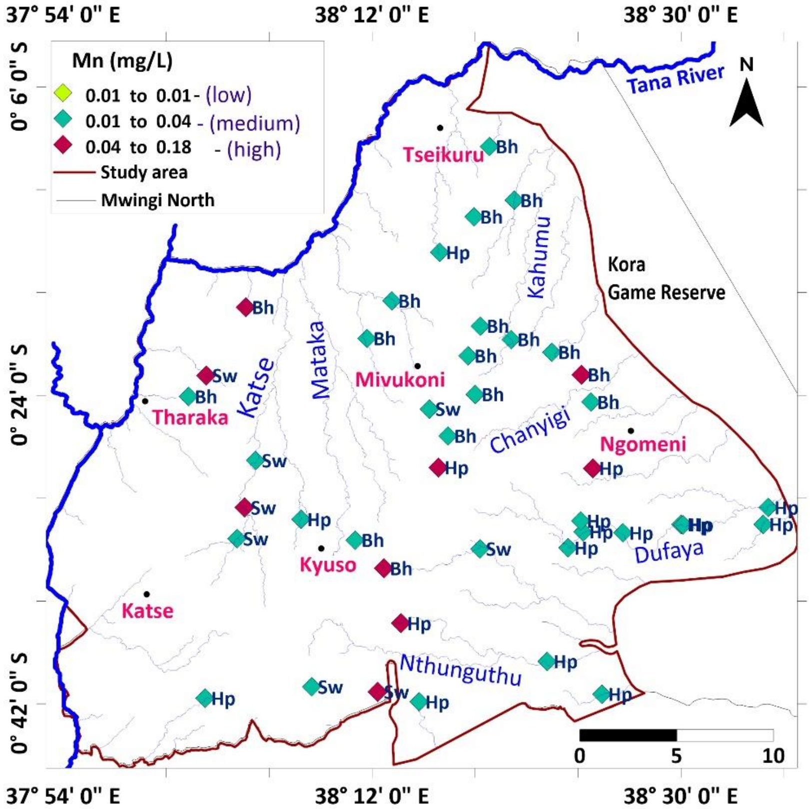

Figure 4.13: Occurrence and distribution of Mn in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

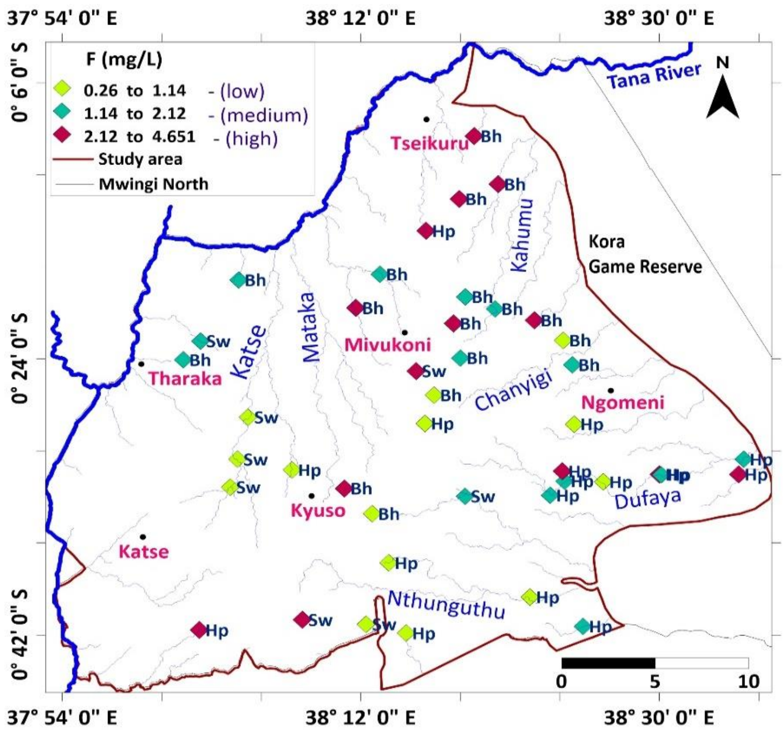

Figure 4.14: Occurrence and distribution of F in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

Chloride is the most dominant anion in the groundwater of Mwingi North. It is present in all waters of Mwingi North as shown in Figure 4.15. Its concentration ranges from 3 mg/l – 2320 mg/l with a median of 435 mg/l. High concentration of chloride are in Ngomeni area in the southeast, Kyuso area to the central areas and Tseikuru in the north of the study area. The concentration is notably low in the west and east of the study area. The least concentration of chloride was detected in Thangani sw within river Thangani (3 mg/l) while the highest concentration of chloride was recorded at Kimangao Catholic borehole Bh (2320 mg/l). Deep borehole waters have a median concentration of 548 mg/l while shallow waters recorded a median of 40.5 mg/l. According to the 250 mg/l limit (WHO, 2008; NEMA, 2006), all but one of the shallow wells are within safe limits. Kangui sw (640 mg/l) is the exception.

The concentration of sulphate anions in groundwater of Mwingi North ranges from 2.63 mg/l-1382 mg/l with a median of 163.67 mg/l. According to the maximum allowable limit of 250 mg/l (WHO, 2008) all shallow well waters are safe of sulphate contamination while deep waters are high in sulphate concentration with a median of 273.11 mg/l. However, according to (NEMA, 2006) declaration of 400 mg/l, only 8 water sources are high of sulphate, all of which are deep boreholes and are with Mavukoni and Ngomeni area (Figure 4.16).

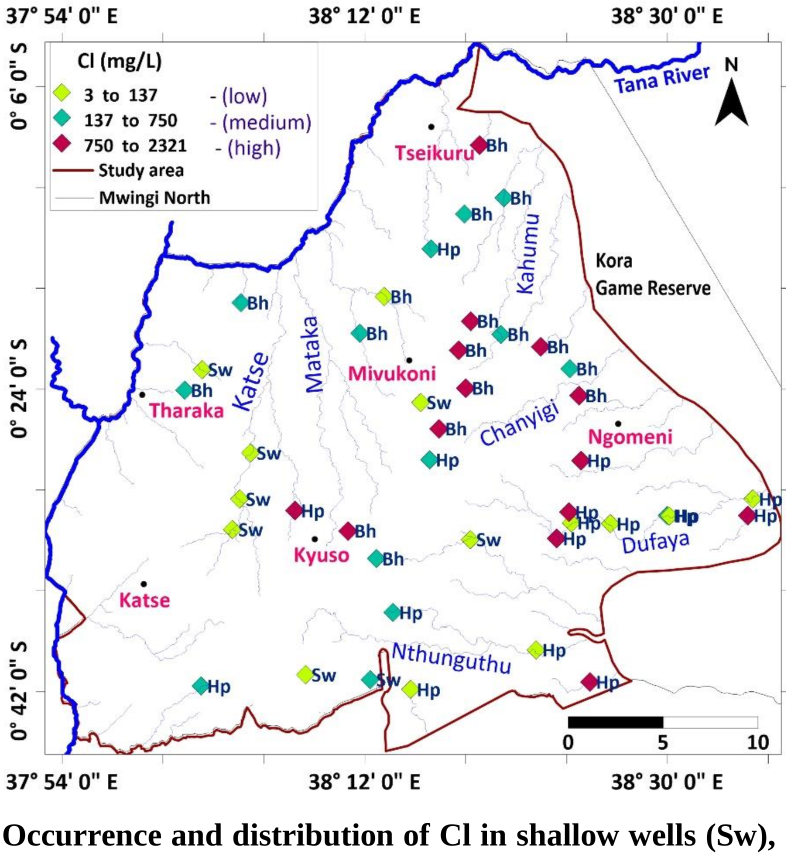

Figure 4.15: Occurrence and distribution of Cl in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

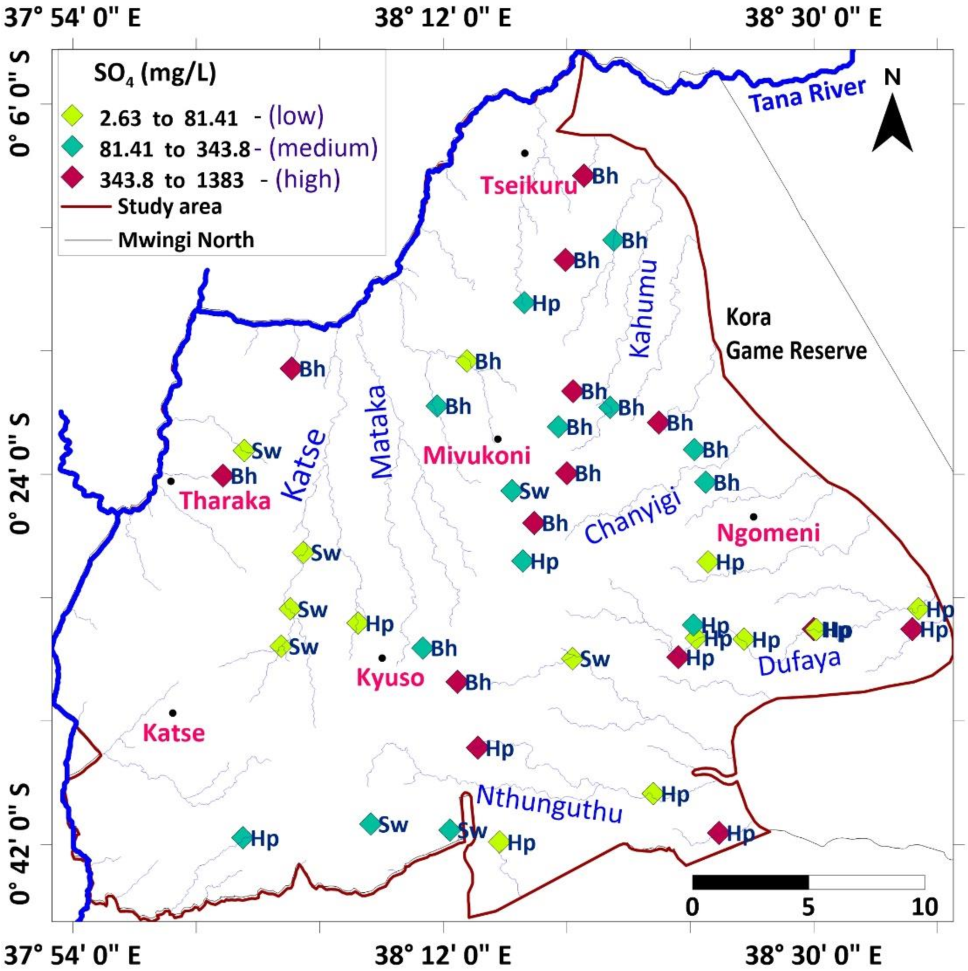

Figure 4.16: Occurrence and distribution of SO_4 in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

The concentration of bicarbonate ranges from 118 mg/l-3701 mg/l. According to Figure 4.17 bicarbonate highs are distributed north-south along the eastern border of the project site. Boreholes waters are the most concentrated followed by hand pumps waters with only one shallow well having high concentration of bicarbonates.

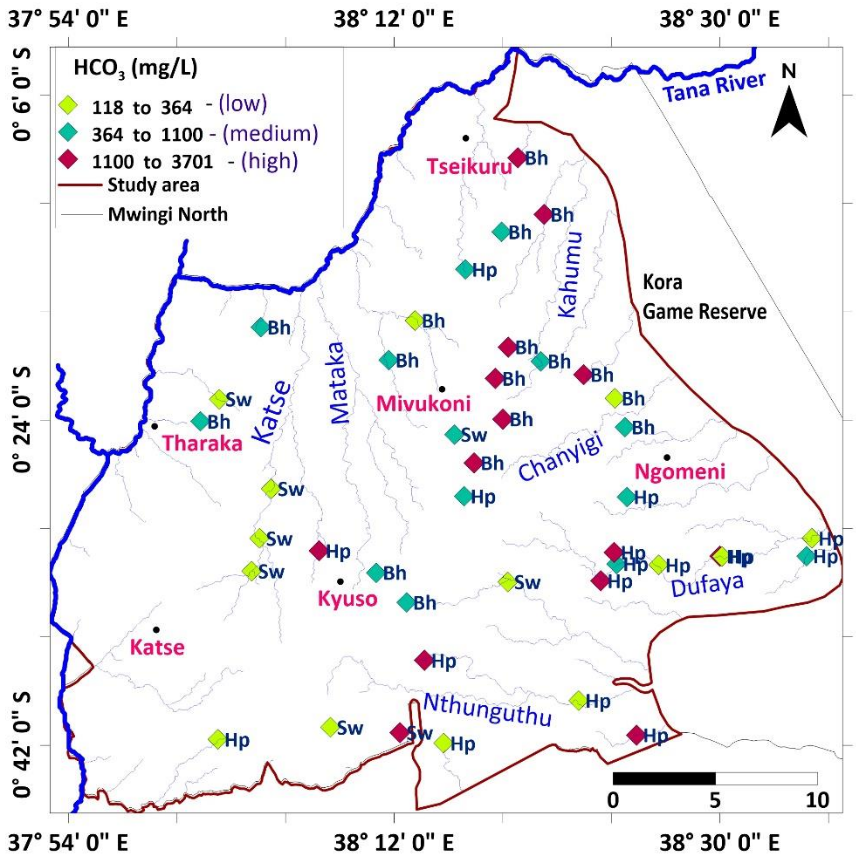

Figure 4.17: Occurrence and distribution of HCO_3 in shallow wells (Sw), hand pumps (Hp) and boreholes (Bh)

In conclusion, high EC values in boreholes are also associated with alkaline pH. Turbidity was generally low in both the shallow and deep groundwater of the study area with a few boreholes and hand pumps having hard water. The concentrations of Ca, Na, Mg, and K were observed to increase with depth, however, concentrations for Fe and Mn indicated reversed characteristics: low F occurred mainly in Bh and in Sw south of Katse; high Cl, SO_4, and HCO_3 were common in boreholes and hand pumps especially around Mivukoni location.

4.2.2 Hydrochemical Facies

The ionic composition of groundwater can be presented in several ways. Vertical bar graphs, hydrochemical facies evolution diagrams (HFE-D) and piper trilinear diagram, among others, are graphical techniques that have been developed to study the ionic composition of groundwater. For this particular study, Piper trilinear diagram has been chosen as the most comprehensive graphic method for the representation of the ionic composition of the groundwater in the study area. Piper analysis uses data in milli-equivalent per litre (meq/l).

The ternary diagram in Figure 4.18 shows that the general dominance of cations is in the order $Na^{+}>Mg^{2+}>Ca^{2+}>K^{+}>Fe^{2+}>Mn^{2+}$. Sodium ions form 41.7% of the total cations followed by magnesium at 29.5%, calcium at 27.5% and potassium at 1.3%. The presence of iron and manganese is insignificant. All hand pump waters have calcium as the dominant cation while sodium has a dominant presence in the borehole and shallow well waters (Figure 4.18). The general dominance of anions is in the order $Cl^{-}> HCO_3^{-}> SO_4^{2-}> CO_3^{-}>NO_3>F$. Chlorides form 47.8 % of the total anions followed by bicarbonates at 28.9% and sulphates at 19.8%. Other anions include carbonates forming 2.2%, nitrates forming 1.2% and fluorides forming 0.1%.

Figure 4.19 is a piper trilinear diagram indicating the ionic concentrations for a hand pump, borehole, and shallow well waters. According to the diagram, three primary water types are identified. Na-Cl, Na-CO_3 and Mg-CO_3 water types accounting for 61.8% of the total water type. Na-CO_3 waters are the dominant water type accounting to 23.8% followed by Na-Cl water type and Mg-HCO_3 water types each accounting to 19%. Other water types include Mg-CO_3 (11.9%), Mg-Cl (11.9%), Ca-cl (7.1%), Ca-CO_3 (4.8%) and Ca-HCO_3 (2.5%). Most borehole waters have high Na^{+} as the dominant cation. These ions evolve from CO_3 towards Cl^{-} concentrations.

Schoeller diagram is useful in determining the comparative changes in the concentrations and ratios of elemental concentrations in water quality. Figure 4.20 shows a Schoeller plot of all the 42 water samples from shallow wells (sw), hand pumps (hp), and boreholes (bh). The plot was generated using the AquaChem program. From the plot, it can be concluded that hand pumps and boreholes waters have the same source of bicarbonates as noted in their rather similar gradients. The other parameters, however, are derived from different sources.

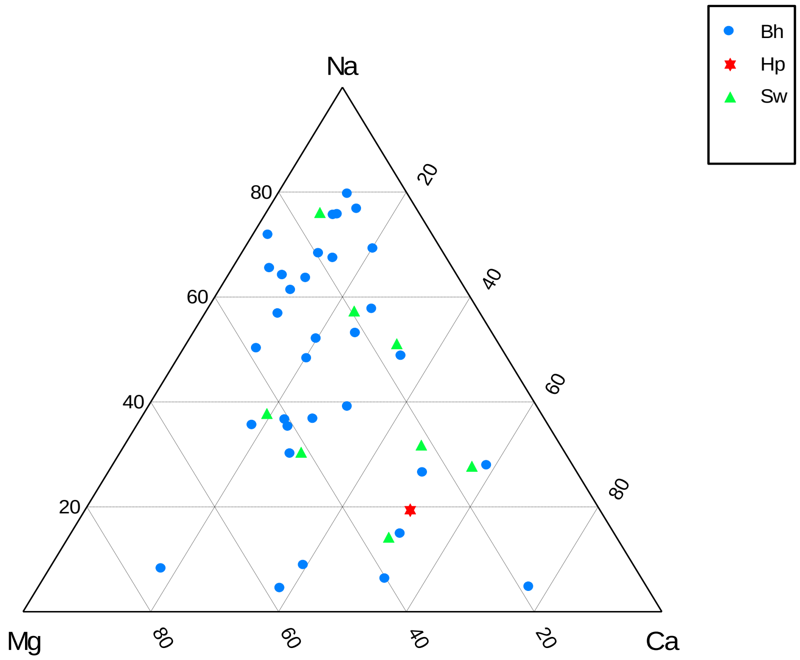

Figure 4.18: Ternary diagram showing dominant cations

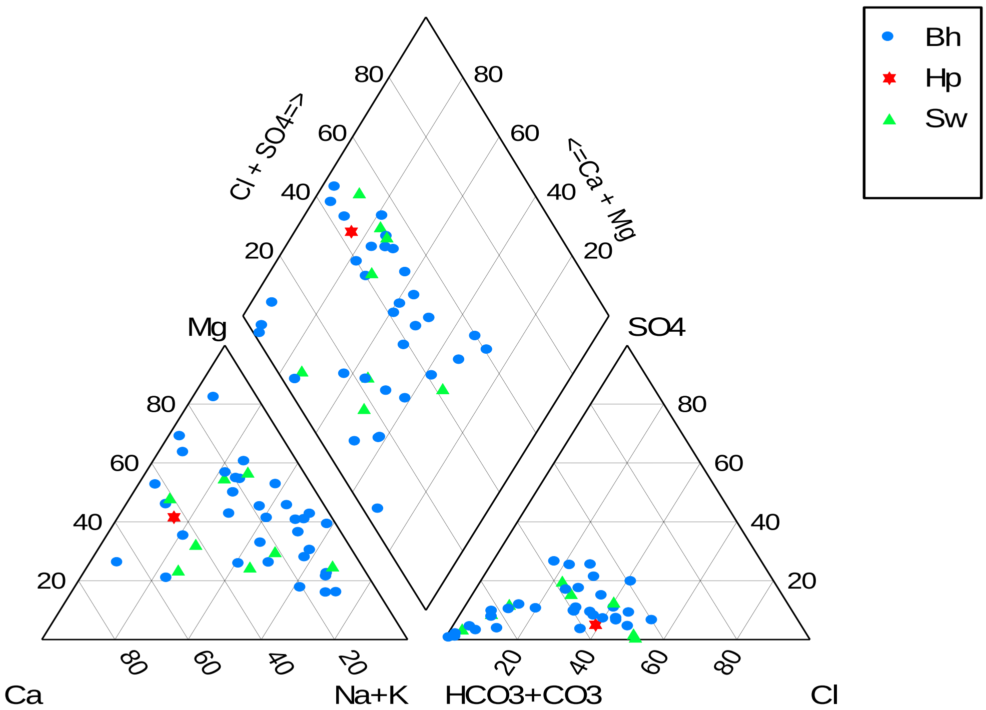

Figure 4.19: Piper diagram with indications of various ground water

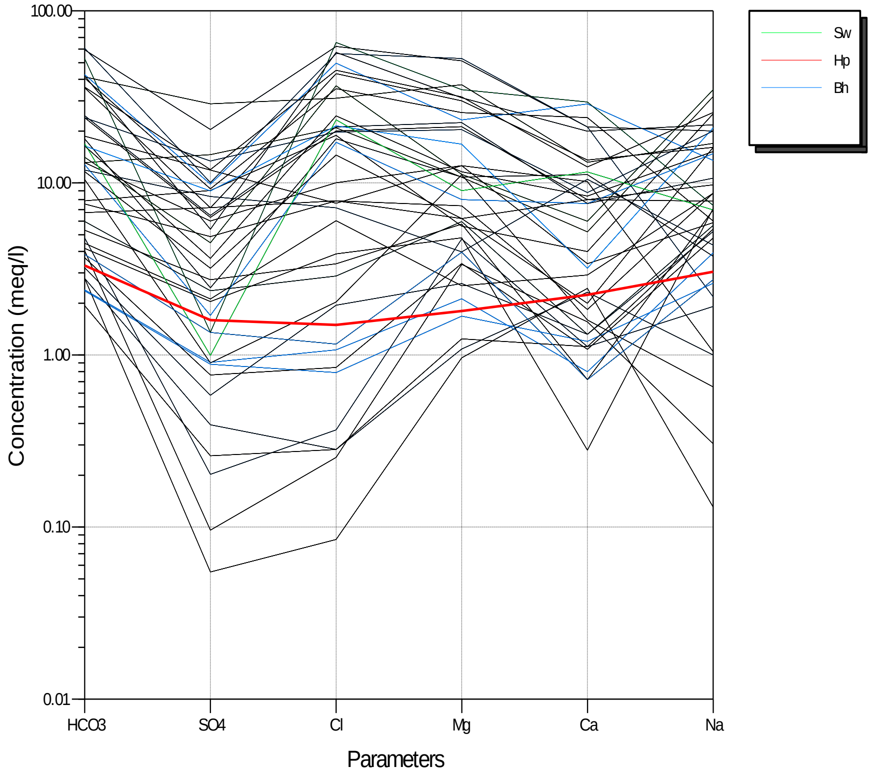

Figure 4.20: Schoeller plot for the groundwater parameters in the study area

4.3 Geology, Rock-Water Interactions, and Human Influence on Groundwater Quality

4.3.1 Contribution of Geology to Water Quality

Inferences were made of the rock samples against the prevalent ionic components in the groundwaters of Mwingi North. From the data on Table 4.1, Ca, Mg, Na, Fe and Cl, F, NO_3, and NO_2 are the prevalent ions in the groundwaters of Mwingi North. Using simple comparison by Hounslow (1995, shown on Table 3.1, we can be able depict the probable sources of the prevailing ions within the groundwater of Mwingi North. The concentration of dissolved ions in groundwater samples within the study area is controlled by the geology, nature of geochemical reactions and the solubility rate of the interacting rocks with atmosphere and the hydrosphere (Lakshmanan & Kannan, 2007). According to the data on Table 4.1, the concentration of some ionic parameters is high surpassing the recommended levels (WHO 2006 and KEBS 2016).

From the geological rocks sampled from various locations (Figure 3.4), Mwingi North has rocks that are highly resistant to weathering including granite (quartz and K-feldspars), gneiss (quartz, K-feldspars, plagioclase, amphibole), phyllite, schist (quartz, K-feldspars, biotite/muscovite, amphibole) and moderately soluble rocks such as limestone (calcite), marble (calcite) and rock gypsum (Crowther, 1957). The sampled rock sampled have been shown in Table 4.2.

Table 4.2: Rock units sampled with their mineralogical composition

Latitude	Longitude	Rock type	Mineralogy
-0.66632	38.22606	Granitoid gneiss	Feldspars and micas
-0.5461	38.16941	Limestone	Calcite
-0.54282	38.66222	Biotite gneiss	Feldspars, quartz, and biotite
-0.380591	38.038798	Kunkar limestone	Calcite
-0.37988	38.4034	Sandy soils	Fine sands
-0.3035273	38.3044158	Kunkar limestone	Calcite
-0.31506	38.1726	Banded quartz gneiss	Biotite, quartz
-0.30911	38.212793	Red brown soils	Red brown soils
- 0.22192	38.20785	Granitoid gneiss	Quartz, biotite, feldspars
- 0.65075	38.40257	Granitoid gneiss	Quartz, biotite, feldspars
-0.5093168	38.585030	Banded biotite gneiss	Biotite, quartz

The possible sources of calcium ions in groundwater of the study area could be from mica or ion exchange dissolution of precipitates of $CaCO_3$ and $(Ca\ Mg\ CO_3)_2$ during recharge (Lakshmanan et al., (2003). Magnesium ions is probably from mica, ion exchange dissolution of magnesium calcite and gypsum (Thivya et al., 2013). The dominant sodium cations are possibly from feldspars, ion exchange, weathering of plagioclase bearing rocks and overexploitation (Srinivasmoorthy et al., 2008). Potassium occurring in minimal quantities is from feldspars and ion exchange. Its low presence in the groundwaters of Mwingi North can be attributed to its fixation in the formation of clay minerals and weathering of feldspar from aquifer matrix (Vasanthavigar et al. (2010).

The occurrence of bicarbonates in the groundwater of Mwingi North is possibly from mineral weathering and action of CO_2 upon the basic material of soil and granitic rock (Vasanthavigar et al., (2010). The dominant chloride anion is possibly from rock salt, apatite, soil leachate and pollution (Srinivasmoorthy et al., 2008). Sulphate occurring in appreciable amounts may be from biological oxidations of reduced sulphur species (Shivshankar, 2014), dissolution of gypsum and anthropogenic activities (Subbarao et al. (1996 The occurrence of phosphorus may be from apatite and anthropogenic activities (Chidambaram et al., (2007b) while the contaminant nitrate infiltration into the groundwater could be possibly from indiscriminate waste disposal and poor sanitation (Srinivasmoorthy et al., 2009).

4.3.2 Rock-water Interactions and Groundwater Quality

Rock-water interaction was studied by understanding the differentiation that occurs during the chemical processes involved in mineral formation. These processes include dissolution/precipitation, ion exchange, oxidation and reduction. Hydrochemical composition of any groundwater is signature of rock-water interaction. Figure 4.21, demonstrates scatter plots of Na^+ versus Cl^- and Ca^{2+} + Mg^{2+}- SO_4^{2-}-HCO_3^- versus Na^+ + Cl^- respectively to help unravel the evolution of the dominant cations and anions of the groundwater of Mwingi North.

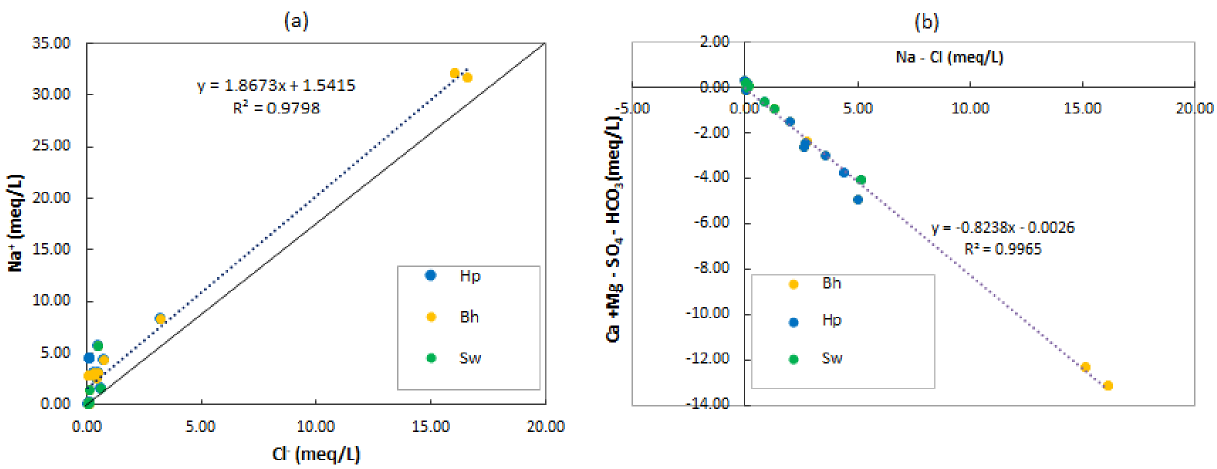

Figure 4.21 a) Plot of Na^+ versus Cl^- b) Plot of Mg^{2+}- SO_4^{2-} -HCO_3^- versus Na^+ + Cl^-

The relationship between Na and Cl was determined from the shallow wells, hand pumps and boreholes in the study area. The results revealed similar ratios of Na/Cl for the majority of the groundwater, suggesting similar hydrochemical processes leading to the release of Na and Cl ions in to groundwater. All the samples plotted above the 1:1-line indicating cation exchange processes leading to contribution of more Na than Cl ions. The average ratios of Na^+/Cl^-

indicated an increasing trend from the shallow well (4.98) to hand pump (8.59) to the deep boreholes (10.12). A plot of relationship between [Ca^{2+} + Mg^{2+}- SO_4^{2-} -HCO_3^- and Na^+ + Cl^- resulted in a linear relationship with a slope of -1 suggesting dominance of cation exchange (Fisher and Mullican, 1997).

4.3.2.1 Hierarchical Cluster Analysis (HCA)

Generally, as can be seen from the factor loadings on Table 4.3 and the dendrogram on Figure 4.22, the HCA categorizes the groundwater in the area in two groups. Group 1 comprises two clusters, cluster 1 and cluster 2, while group 2 consists of only one cluster (C3). Cluster 1 (C1), which forms 19.05% of all groundwater samples, comprises of groundwater of medium mineralization in the area and is characterized by high concentrations of SO_4 and NO_3. The groundwater samples in this cluster occur in Tseikuru and Ngomeni wards as is shown in Figures 4.16 and 4. While high increased SO_4 in groundwater can be linked to the use of fertilizers, farming activities was not common in the study area, and thus, the elevated concentrations in groundwater is due to dissolution of gypsum. Increased NO_3 levels in groundwater is linked to point pollution sources resulting from sanitation facilities in sub-urban Tseikuru and Ngomeni wards.

Cluster 2, which forms 21.43% of all groundwater samples, reflects the highly mineralized groundwater in the area characterized by high EC, Na, Mg, Ca, Cl, and HCO_3. Notably, this cluster had low F concentrations. The groundwater in this cluster occurs within the areas north-east of Kyuso and south of Tseikuru wards as shown in Figures 4.4, 4.8, 4.9, 4.10,4.15 and 4.17. The high EC, Na, Ca, Mg and HCO_3 is linked to carbonate weathering and dissolution into groundwater.

Cluster 3 represents the least mineralized groundwater in the area. This cluster accounts for 59.12% of the total groundwater sampled (more than half of all samples). As compared to clusters 1 and 2, F concentration is high in this cluster. This cluster is composed of all the shallow wells, most of which were along dry riverbeds of river Nthangani and Katse in the Mumoni ward. Other area includes Tharaka and Ngomeni wards. The evolution of groundwater of this cluster can be attributed to the modification to alkaline-mixed bicarbonates for hard calcium bicarbonates that increase the mobility of fluoride ions and hence its high concentration.

Table 4.3: Factor loadings for shallow wells, hand pumps, and boreholes in Mwingi North Constituency

Factor loadings									
	Sw			**Hp**			**Bh**		
	F1	F2	F3	F1	F2	F3	F1	F2	F3
pH	-0.512	-0.568	-0.460	-0.136	-0.213	0.499	-0.617	0.575	0.465
Cond	0.989	0.060	-0.104	0.978	0.171	-0.024	0.967	-0.021	0.226
Turbidity	-0.401	0.781	0.361	0.088	0.392	0.836	-0.287	-0.207	0.755
TDS	0.989	0.062	-0.102	0.978	0.171	-0.024	0.967	-0.021	0.226
Na	0.674	-0.526	0.353	0.478	-0.242	0.578	0.349	0.385	0.711
K	0.002	0.687	0.265	0.757	-0.196	0.025	0.855	-0.076	-0.172
Mg	0.969	-0.044	-0.077	0.943	0.115	-0.196	0.962	-0.025	-0.033
Ca	0.707	0.535	-0.437	0.829	0.452	-0.182	0.792	-0.488	-0.078
Mn	0.234	0.373	-0.397	-0.204	0.728	0.358	-0.345	-0.630	0.335
Fe	-0.431	0.702	0.393	-0.052	0.708	0.581	-0.323	-0.681	0.579
F	0.232	-0.355	0.889	0.299	-0.680	0.310	0.268	0.708	-0.014
Cl	0.895	0.279	-0.319	0.900	0.333	-0.135	0.922	-0.068	0.139
SO4	0.854	-0.329	0.187	0.650	-0.215	0.284	0.690	-0.149	0.339
HCO3	0.903	0.265	-0.277	0.935	0.261	-0.198	0.969	-0.196	-0.052
CO3	0.660	-0.427	0.554	0.499	-0.633	0.365	0.416	0.590	0.278
NO3	-0.126	-0.533	-0.162	0.539	-0.586	0.061	0.647	0.078	-0.207
Eigenvalue	*7.621*	*3.650*	*2.765*	*7.100*	*3.034*	*2.192*	*7.978*	*2.692*	*2.193*
Variability (%)	*44.830*	*21.472*	*16.263*	*44.375*	*18.963*	*13.697*	*46.927*	*15.834*	*12.902*
Cumulative %	*44.830*	*66.302*	*82.565*	*44.375*	*63.338*	*77.035*	*46.927*	*62.762*	*75.664*

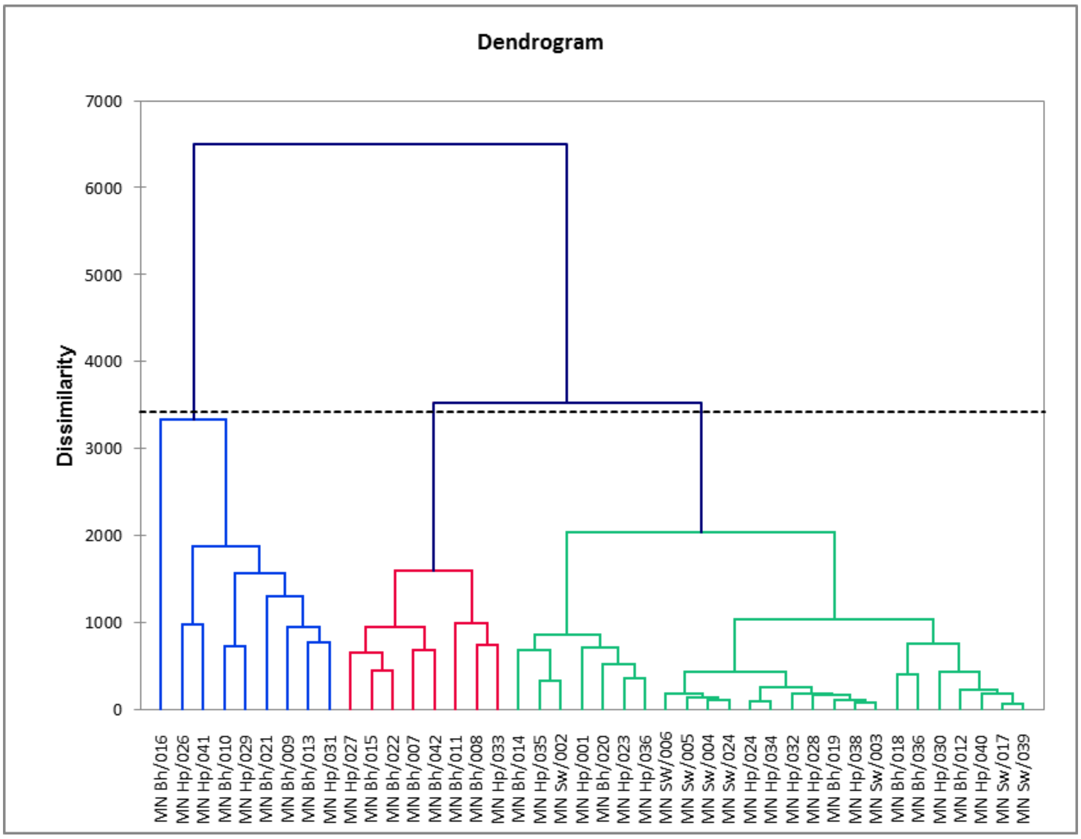

Figure 4.22: Dendrogram for the groundwater samples of the study area

4.3.2.2 Principle Component Analysis (PCA)

The evaluation of PC1 variables for shallow wells (Sw), hand pumps (Hp) and borehole (Bh) revealed similarities in the occurrence of EC, TDS, Na, K, Mg, Ca, Cl, F, SO_4, HCO_3, and CO_3 with positive loading on PC1, while pH and Fe were negatively loaded as shown in Figure 4.23 and Table 4.4. However, variations were observed in turbidity, Mn, and nitrate. Turbidity was negatively loaded on shallow wells and boreholes while positively loaded on PC1 for hand pumps. Manganese was positively loaded in shallow wells while it was negatively loaded in hand pumps and boreholes. NO_3 was negatively loaded on PC1 for shallow wells and positively loaded on PC1 for hand pumps and boreholes. Generally, PC1 reflects mineral dissolution and mineralization.

The evaluation of PC2 reflected similarities in the groundwater of shallow wells and hand pumps and those of boreholes. EC, Turbidity, TDS, Ca, Mn, Fe, Cl, and HCO_3 were positively loaded on PC2 for shallow wells and hand pumps while pH, Fe, CO_3, and NO_3 were negatively loaded. The reverse characteristic was observed in borehole samples. SO_4 was negatively loaded on the water samples of shallow wells, hand pumps and boreholes suggesting a similar source. K was negatively loaded in hand pumps and boreholes while positively loaded in shallow wells.

Table 4.4: Percentage distribution of components on PC1 and PC2 regarding Sw, Hp, and Bh

PCs	Shallow well (Sw)	Hand pump (HP)	Borehole (Bh)
PC1	44.83%	44.37%	46.93%
PC2	21.47%	18.96%	15.83%

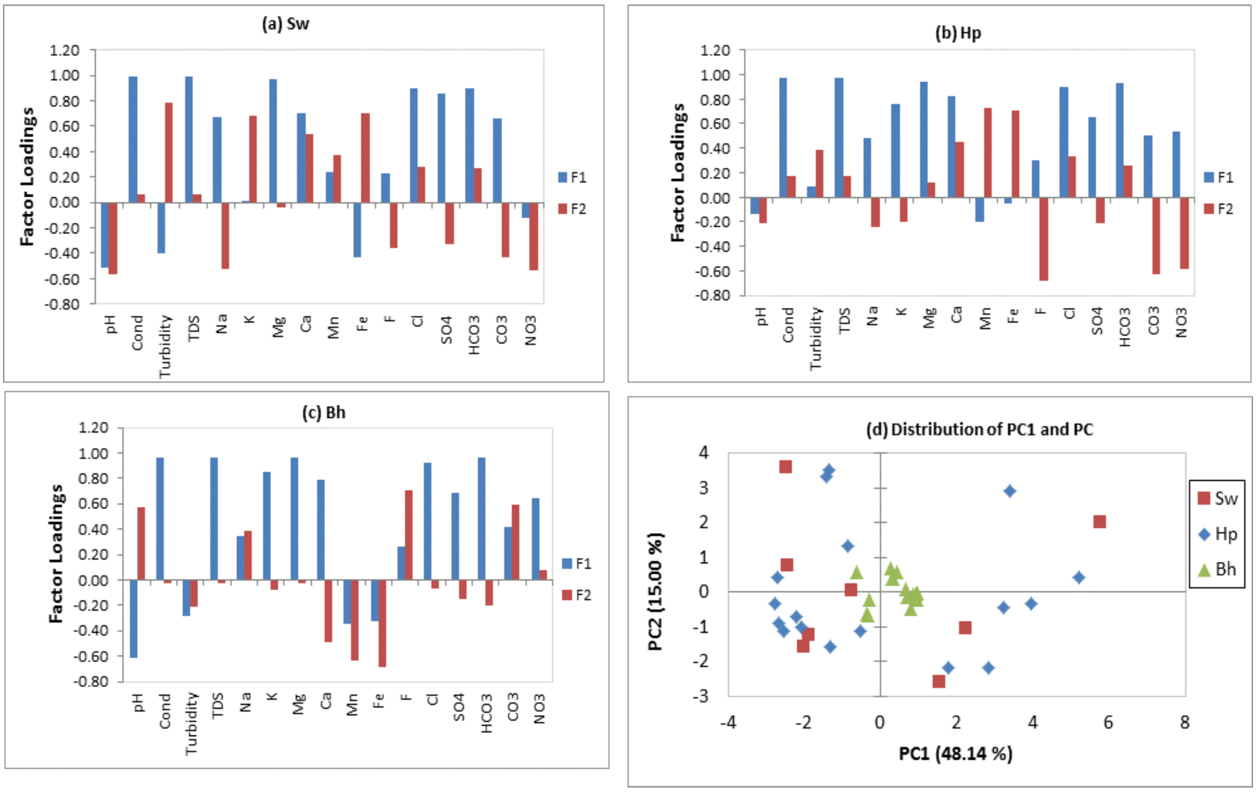

Figure 4.23: Factor loadings of the Chemical variables for (a) Sw (b) Hp (c) Bh and (d) spatial distribution of PC1 and PC2 for all the groundwater samples

4.3.2.3 Mineral Saturation Indices

The mineral saturation index shows that the groundwaters of Mwingi North are oversaturated in aragonite, calcite, and dolomite and undersaturated in anhydrite, fluorite, gypsum, halite, melanterite, pyrochlorite, rhodochrosite, and sylvite as shown in Figure 4.24. The groundwater of the area is as well undersaturated in shallow wells, but oversaturated in both hand pumps and boreholes in hausmanite, manganite and pyrolusite. Pyrolusite and siderite are negatively correlated with pyrolusite being undersaturated in shallow wells and oversaturated in boreholes and hand pumps, while siderite was oversaturated in shallow wells but undersaturated in boreholes and hand pumps. From the results as shown in Table 1 of appendix, it can generally be concluded that all groundwater of Mwingi North is oversaturated for carbonates. It was also observed that hausmanite, manganite and pyrolusite show high saturation in boreholes and hand pumps but low concentration in shallow wells.

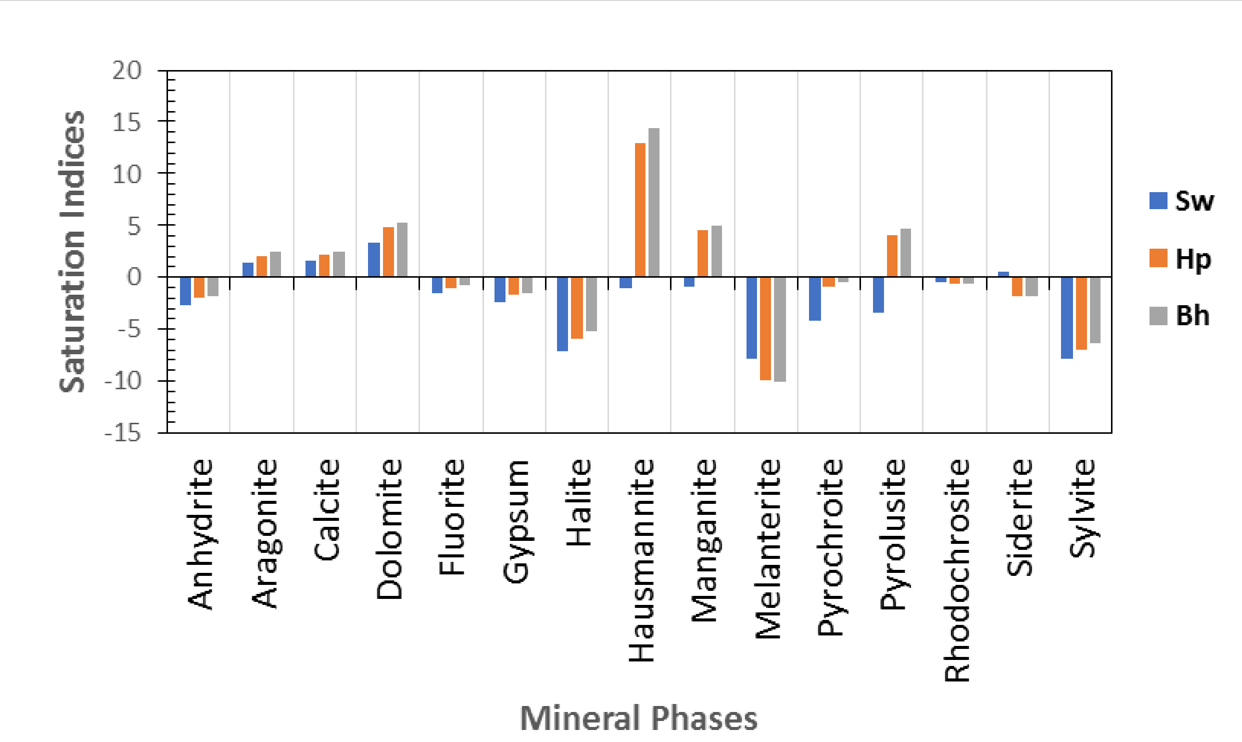

Figure 4.24: Mineral saturation indices of the groundwater samples

4.3.3 Human Influence on Groundwater Quality

The concentration of nitrate in boreholes ranges from 2.35 mg/l to 55.69 mg/l with a median of 21.77 mg/l, while that of nitrite ranges from 0.01 mg/l-0.268 mg/l with a median of 0.01 mg/l (Table 4.1). Boreholes with high nitrate levels are located to the west of the study area in Tharaka hills and east of the study area, south of Tseikuru. Nitrates are spatially distributed E-W. The highest concentrations are in Tseikuru and Ngomeni areas while low in Tharaka, Kyuso and Mumoni areas to the west of the study area as shown in Figure 4.25. The Maximum allowable limits (MAC) for Nitrate are 10 mg/l (NEMA, 2006) and 50 mg/l (WHO 2008). The MAC for nitrite is 3.0 mg/L (NEMA 2006). A few water points, therefore, do not pass the MAC for nitrates and are thus unsafe as potable water however as shown in Table 4.1, the nitrite levels in all the groundwater of Mwingi North are within permissible levels and are therefore safe for it. Borehole waters have the greatest concentration of nitrate followed by hand pump waters. As shown in Figure 4.25 the occurrence of nitrates in Mivukoni and Ngomeni areas stretches northwards from Mivukoni area and then southwards into Ngomeni area following an overturned u-shaped similar trend. The maximum concentration of nitrate was recorded in Kathiani Kamwongo hand pump (55.69 mg/l) while the lowest concentration was recorded at Timnyua borehole 0.5 mg/l. Possible sources of nitrates within Mwingi North area includes nitrogen based fertilizers, septic systems, animal feedlots and manure applied to land.

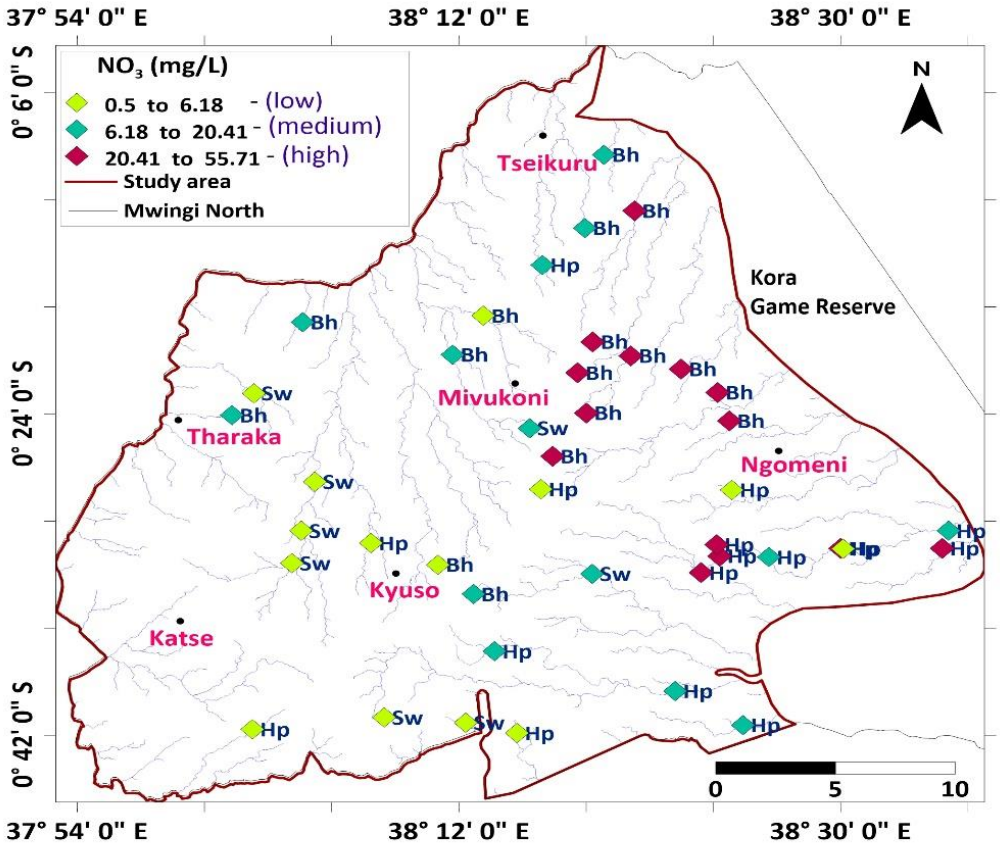

Figure 4.25: Occurrence and distribution of nitrates in shallow wells (Sw), hand pumps (Hp) and boreholes showing low concentrations (light green), medium (dark green), and high (deep red)

4.4 Groundwater Quality Index and Development Planning

4.4.1 Groundwater Quality Index Maps

Water Quality Index is a mathematical expression of the water quality results of a particular study area. According to the analytical results of the water samples from Mwingi North area, the following procedures were followed in the creation of the ground water quality index maps of the study area.

Thirteen physico-chemical parameters were selected for each of the 42 water samples collected from boreholes, hand pumps, and shallow wells. This resulted in 546 test results for analysis using the weighted arithmetic mean in a step wise procedure as outlined in section 3.3.4.4 (page 37).

Step 1. The Kenya Bureau of Standards on Drinking Water Quality's allowable limits as shown in Table 4.5, were used in derivation of the water quality index.

Table 4.5: Acceptable concentration levels according to WHO/KEBS

Parameter	pH	EC	Ca	Mg	Na	K	Fe	Mn	HCO_3	SO_4	Cl	F	NO_3	n=13
WHO/KEBS	8.5	1500	100	100	200	50	0.3	0.1	500	400	250	1.5	50	
Rating (wi)	4	4	2	2	3	1	3	5	3	3	3	5	3	∑wi = 41
Unit weight (Wi)	0.098	0.098	0.049	0.049	0.073	0.024	0.073	0.122	0.073	0.073	0.073	0.122	0.073	∑Wi = 1.001

Step 2: Weighting of the 14 parameters in order of their importance. The rankings were from 1-5, with 1 representing those parameters with least importance and 5 representing those parameters with the greatest importance. Computation of the relative weights was then carried out using equation 3.3 (Section 3.3.4.4-page 37).

Step 3: Data on Table 4.5 was then filtered, normalized, and used to calculate the relative water quality indices for each borehole using the formula shown in equation 3.4. The resulting data is shown in Table 4.6

Table 4.6: Water Quality Index Computation

Site Name	**Sample ID**	**Site ID**	**Coord. Latitude**	**Coord Longitude**	**Elevation**	WQI
Kathungu Bh	MN Bh/007	Stop 18	38.022	-0.401	587	129.623
Ntumira Bh	MN Bh/008	Stop 20	38.077	-0.314	514	164.214
Kora Bh	MN Bh/009	Stop 21	38.274	-0.440	784	238.409
Masyungwa Bh	MN Bh/010	Stop 22	38.300	-0.399	724	212.199
Ithoka	MN Bh/011	Stop 24	38.412	-0.407	654	180.883
Ikathima	MN Bh/012	Stop 25	38.403	-0.380	639	73.987
Kasaini Bh	MN Bh/013	Stop 26	38.374	-0.358	664	253.298
Mulangoni Bh	MN Bh/014	Stop 27	38.335	-0.346	644	120.607
Kathiani (Kawongo Hp)	MN Bh/015	Stop 28	38.293	-0.362	700	177.377
Tito Nzuki Bh	MN Bh/016	Stop 29	38.305	-0.333	685	324.376
Mwangea Bh	MN Bh/018	Stop 33	38.195	-0.345	592	84.227
Nziitu Bh	MN Bh/019	Stop 37	38.219	-0.308	572	48.242

Nzanzeni Sec Bh	MN Bh/020	Stop 38	38.299	-0.226	467	94.362
Kyenini Bh	MN Bh/021	Stop 42	38.314	-0.158	475	235.470
Kaningo Bh	MN Bh/022	Stop 44	38.338	-0.210	520	151.361
Ikaaie B Bh	MN Bh/036	Stop 91	38.211	-0.568	874	100.072
Makuvuni Bh	MN Bh/042	Stop 84	38.184	-0.541	851	126.419
Nzaalani HP	MN Hp/001	Stop 1	38.228	-0.621	826	103.980
Wendo wa Kwiendea Hp	MN Hp/023	Stop 45	38.267	-0.261	570	98.529
Twaathi Hp	MN Hp/024	Stop 52	38.370	-0.659	678	40.633
Makuka Hp	MN Hp/026	Stop 54	38.423	-0.691	651	261.078
Madongoi Hp	MN Hp/027	Stop 59	38.580	-0.525	535	161.677
Kaliki Hp1	MN Hp/028	Stop 60	38.585	-0.509	524	47.603
Kwa Mulandi Hp	MN Hp/029	Stop 69	38.390	-0.549	693	212.218
Kwa Ndingori Hp	MN Hp/030	Stop 75	38.405	-0.533	667	75.391
Mitamisyi Sec Hp	MN Hp/031	Stop 78	38.402	-0.522	669	250.850
Nzaini Hp	MN Hp/032	Stop 78	38.444	-0.534	636	45.067
Ngomano Hp1	MN Hp/033	Stop 74	38.500	-0.526	582	173.819
Ngomano Hp7	MN Hp/034	Stop 79	38.502	-0.526	586	51.254
Kwa Kaliya Bh	MN Hp/035	Stop 86	38.416	-0.471	654	125.813
Twimnyua Bh	MN Hp/036	Stop 88	38.264	-0.470	822	104.125
Mbui Bh	MN Hp/038	Stop 92	38.246	-0.698	769	32.947
Kaundu Hp	MN Hp/040	Stop 98	38.038	-0.695	928	60.758
Kimangao Catholic Bh	MN Hp/041	Stop 68	38.131	-0.521	776	243.415
Kaghui SW	MN Sw/002	Stop 4	38.206	-0.688	799	101.613
Katse Sw	MN Sw/003	Stop 8	38.076	-0.509	740	56.760
Katse River Sw	MN Sw/004	Stop 11	38.069	-0.539	792	37.304
(Twwua)	MN Sw/005	Stop 12	38.087	-0.463	678	37.790
Thangani SW (River)	MN SW/006	Stop 16	38.038	-0.381	561	46.094
Kwakiri Sw 1	MN Sw/017	Stop 32	38.255	-0.413	737	85.711
Matooni Sw1	MN Sw/024	Stop 50	38.305	-0.549	759	44.248
Malili Sw	MN Sw/039	Stop 96	38.142	-0.684	1024	70.830

Step 4: The Water Quality Index (WQI) indicated in row 7 of Table 4.6 is a summation of weighted quality value of the thirteen parameters for each borehole.

Step 5: As shown in Table 4.6, the Water Quality Index of Mwingi North can be studied by reading the maximum, average and minimum levels. The maximum water quality index is recorded by Tito Nzuki borehole (MN Bh/016), the minimum water quality index is recorded by Mbui hand pump (MN Hp/038), and the average water quality index is represented by Kwa Kaliya hand pump (MN Hp/035).

Step 5. The water samples of Mwingi North were then graded into five water quality classes as shown in Table 3.2. According to this ranking, the water quality indices were used to group the groundwater of Mwingi North as shown in Table 4.6.

Table 4.7: Grading scale of the water quality of Mwingi North

Water source	Excellent (0-25)	Good (25-50)	Poor (51-75)	Very poor (76-100)	Unsuitable for drinking (>100)
SW	0	4	2	1	1
Hp	0	4	2	2	9
Bh	0	1	1	2	13
Total	**0**	**9**	**5**	**5**	**23**

Step 6: The general water quality indices shown in Table 4.5 were used to graphically present the data on a map. Golden Surfer 16.6 Software was used to generate a general water quality index map of Mwingi North as shown in Figure 4.26. According to Table 4.6, it can be concluded that, within Mwingi North, boreholes have the least suitable groundwater accounting to about 31% of the total sampled groundwater. Shallow well water of Mwingi North presents the best potable water with only one sampled water point out of the eight sampled shallow well falling within the unsuitable drinking range (>100).

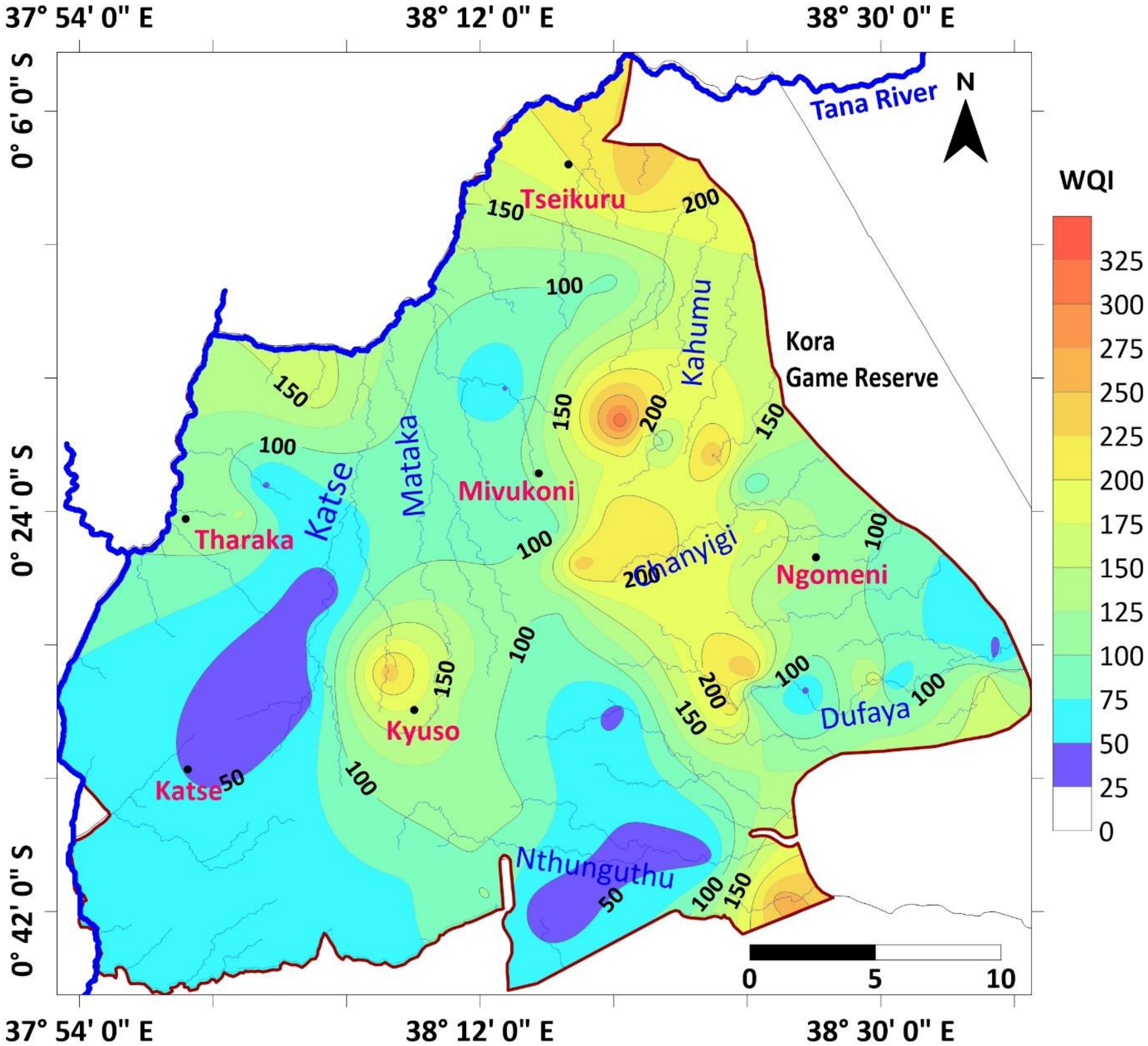

Figure 4.25: Water Quality Index map of groundwater of Mwingi North

4.4.2 Groundwater Development Planning

In this research study, the methodology applied in the development of groundwater planning involved the computation of concentrations from 42 water samples. The samples were from shallow wells, boreholes and hand pumps within Mwingi north. The Water Quality Index map on Figure 4.26 shows that suitable groundwater zones are concentrated to the southern and south-western areas of the study area while most of Tseikuru and Ngomeni areas have the most mineralized groundwaters. This zone of poor groundwater quality stretches from the north along the eastern peripheries towards the south east of the study area. Another zone of poor-quality groundwater branches from the east towards the central of the study area.

As illustrated in Table 4.6, site specific groundwater quality identification can be made. Together with the Water Quality Index map on Figure 4.26, groundwater development planners like hydrogeologist, geophysicists and scientist can easily employ it as a decision tool in enhancing their work thus ensuring increased development of quality groundwater.

4.5 Discussion

This section synthesizes and discusses the results. It also brings out systemically the specific objectives by framing it in a wider knowledge context. This section has been divided into subtopics that summarize the findings of the groundwater chemistry of Mwingi North.

4.5.1 Hydrochemical Characteristics

Mwingi North, located in a semi-arid area is affected by long dry periods and high temperature (24-26ºC). Most of the year (Cassim et al., 2018). Increased hydrochemical concentrations in the groundwater of this region is thus principally exacerbated by the temperature (24-26ºC) aiding evaporation and oxidation rates. The highlands of Tharaka and Tseikuru areas are characterized by alkaline water. As shown in Figure 4.5, the far northern and southern parts of the study area are of normal waters. This phenomenon can be attributed to the lateral intrusion of river water. River Tana flows on the northern frontiers of Mwingi North thus could alter the geochemical environment along its path. This phenomenon can as well indicate that the rocks along this path are permeable and allows for lateral infiltration of fresh river water. The Ngomeni rock to the south is an outcrop of granitoid rock with a moderately high pH of 8.35. Further south the water from the rock catchment has altered the geochemistry of the environment around Ngomeni thus normalizing pH. Likewise, intrusions of river Mumoni and Katse have normalized the pH of the environment within their paths. This analogy is confirmed by the statistical analysis shown in Figures 4.23 and 4.24. On a similar note, along the Nile delta in Egypt, Idris (1990) observed a considerable groundwater quality alteration due to the intrusion of river Nile water into the saline soils normalizing the pH thus making them useful to agriculture as well as for groundwater exploitation.

The hydrochemical changes in groundwater in both volcanic and metamorphic terrain results from the decrease or increase in the ionic concentrations in the groundwater, mobility of dissolved constituents and changes in the groundwater pH (Lakshmanan & Kannan, 2007). Most shallow wells are along the river beds and tap their water from infiltrations from the alluvial sands deposited on the banks or along the river beds. The short residence time realized in shallow wells means limited rock water contact thus limited geochemical alteration. Figures 4.25 and 4.26 shows that shallow wells are the least salinized groundwater within Mwingi North. These aquifers are prone to contamination by all kinds of organic matter. Soil particles in these waters alter the expected normal colorless property of water. Water from boreholes and hand pumps are tapped further from the surface and are less contaminated by organic matter. Turbid waters are concentrated to the western parts of Tharaka and Mumoni wards which has shallow wells along the alluvial sandy river beds. Most of the area to the east and central has less turbid water as displayed in Figure 4.6.

From Figure 4.8 and 4.10, groundwaters of Mwingi North are of the calcium-magnesium type. As shown in Table 4.1, all except one shallow well (Kaghui sw Ca-224 mg/l, Mg -131.33 mg/l) have soft water. Most boreholes and hand pumps have high contents of both calcium and magnesium or either of the two pointing to the increased occurrence of hardness with depth. Unlike the occurrence of calcium ions from igneous minerals in volcanic areas, in Mwingi North calcium presence in groundwater is mainly due to the dissolution of carbonates and feldspars. Within the Mt Elgon aquifers, the concentration of calcium and magnesium ions in groundwater ranges from 0.00 mg/l to 149.6 mg/l and 0.00 mg/l to 86.58 mg/l respectively (Kanoti et al., 2019). While in Mbeere calcium and magnesium ion concentrations in groundwater aquifer ranges from 80.0 to 430.0 and 3.0 to 330.0 mg/l respectively (Karegi *et al*., 2018). The study carried out in the Mt Elgon aquifer observed that groundwater mineralization is lower on the slopes of the mountain since rock water contact is limited but mineralization increases as the water enters the metamorphic rocks of the lower slopes where the residence time increases thus increased rock dissolution (Kanoti et al., 2019). The dominance of calcium ions can be attributed to the dissolution of aragonite, calcite, and dolomite minerals. Anhydrite which is another calcium bearing mineral rather has slow dissolution rate thus does not contribute much to the groundwater calcium ion content within the project area.

Magnesium highs were observed in more than 50% of the water samples. Most of the groundwater failed KEBS and NEMA (100mg/l) and WHO (50 mg/l recommended allowable limit. Water samples from Makuka hp (641.7 mg/l), Kwa Mulandi hp (311.27 mg/l), Mitamsyi sec bh (379.25 mg/l), Kimangao catholic bh (423 mg/l), Masyungwa bh (364.6 mg/l) and Tito Nzuki bh 622.22 mg/l) are just a few water points which do not qualify as potable water based on the magnesium content concentration. Magnesium mineralization occurs due to the chemical dissolution of ferromagnesian minerals such as olivine and pyroxenes which undergoes weathering faster than quartz.

Potassium ranges from 1.7 mg/l-21 mg/l with WHO maximum allowable limit being 50 mg/l. All the groundwaters of Mwingi North are therefore safe in terms of potassium concentration. Potassium ions presence in groundwaters in crystalline aquifers is mainly due to the dissolution of alkali feldspars (Srinivasmoorthy et al., 2012). Alkali feldspars are the principal components in granitoid gneisses which is the main rock type in the Mwingi North area. These potassium-containing rocks undergo chemical weathering following chemical equilibria. In this process, a reaction leading to mineral breakdown will proceed when materials are either added or removed from the system. According to Loughman (1969), in the alteration of potash feldspars to kaolinite, all the feldspars are lost in solution as shown in the equation 4.1 below:

$$2KAlSi_3O_8 + 3H_2O \rightarrow Al_2SiO_5(OH)_4 + 4SiO_2 + 2KOH. \quad \text{– Equation 4.1}$$

Potash feldspar water Kaolinite Silica potash

In case some potash is retained in the reaction then the resulting product will be illite and not kaolinite. As shown in the preceding equation.

$$3KAlSiO_8 + 2H_2O \rightarrow KA1_2(Al, Si_3)O_{10}(OH)_2 + 6SiO_2 + 2KOH \quad \text{– Equation 4.2}$$

Potash feldspar water illite silica potash

4.5.2 Geology, Rock-Water Interactions, and Human Influence on Groundwater Quality

4.5.2.1 Geological Influence on Groundwater Quality in Mwingi North

Water hardness is quantified by the content of $CaCO_3$ mg/l (Hem, 1970). Table 4.8 shows the Hems' classification of hardness. According to Hems' classification, the study area has no soft water. The best available water is at Kaliki hp (118 mg/l), which is the only groundwater classified as moderately hard water from the sampled water points. The next available batch falls in the hard water category. Tharaka Women Water Users Association sw (144 mg/l) and Nzitu bh (146 mg/l) are the only boreholes in this category. The rest of the groundwaters (about 93%) are classified as very hard water.

Table 4.8: Comparison of water hardness classification (Hem 1970)

Hardness range mg/1 of $CaCO_3$	Description
0 -60	Soft water
61 – 120	Moderately hard water
121-180	Hard water
Greater than 180	Very hard water

The human body tolerates appreciable amounts of chloride (>250mg/l) for its normal development. Geologically, chloride occurs as sodium chloride and apatite or sodalite (Roberts, 1996). Chloride evolves as evaporite minerals, connate water and brines. Chloride is as well commonly introduced into most groundwater systems as a disinfectant through chlorination. In this process, chlorine is added to water to kill bacteriological pathogens. Chloride concentration ranges from 3 mg/l – 2320 mg/l with a median of 435 mg/l in the study area. The Maximum allowable limit according to KEBS, NEMA, and WHO is 250 mg/l. Most groundwaters of Mwingi North do not therefore, qualify as portable water. The concentrations of bicarbonates as shown in Figure 4.6 (d) are spatially distributed from North of Tseikuru towards Kyuso, westwards into Mumoni and south-eastwards into the Ngomeni area. All these areas are characterized by granitoid gneisses. Chloride occurrence in the study area is therefore linked to chemical weathering of plagioclase minerals in granitoid gneisses, the host rock in the study area. The study also observed increased chloride levels in borehole and hand pump waters as opposed to shallow wells. This was realized to be a result of long residence time between rock-water interaction thus allowing full chemical weathering. Therefore, shallow waters of Mwingi North are low in calcium mineralization, unlike hand pump and borehole waters.

4.5.2.2 Influence of Rock Water-Interaction on Groundwater Quality in Mwingi North

The compositional feature of the identified water types in the project area shows two main contributing sources. They include reactions between meteoric water with rocks matrix along the flow path and mixing of the chemical evolving water with relatively inactive deep saline waters along the flow path. Mineral dissolution is the primary step in rock water interactions. Within Mwingi North area granites and gneisses form the bulk of the rock assemblages. These basement rocks consist of plagioclase and K feldspars with quartz and biotite/micaceous hornblende (Nyamai, 1999). Accessory minerals in these rocks include sillimanite and garnets. These crystalline rocks have fractures that form depending on the mineral components of the rocks and have been of interest in creating groundwater routes. These fractures undergo aging depending on the chemical content of the solute and duration with which they stay in contact. Water that flows through a newly formed crystalline fracture will be 40% plagioclase and 50% k-feldspars, the rest 10% will be composed of quartz. The solute that passes through these minerals along the pathway will possess feldspars as the dominant chemical signature in the waters. Due to the rock water contact, chemical reaction occurs on the fracture surfaces. This may result in the dissolution of minerals on the surface of the fractures which consequently result in secondary minerals covering the unstable primary rock matrix. The fracture surfaces ages with the rate of decrease in water-rock reactions. However, the major solutes and their relative proportion are contributed to by the dissolving unstable minerals.

Solutes such as Cl^- and SO_4^{2-} evolve from fluid inclusions in quartz that are opened by fracture formation, weather or other processes (Peters, 1986; Gascoyne and Kamineni, 1994). When crushed, granite rock will give total extractable Cl^- of 160 g/m^3. Fresh fractured granitic rock assemblage does not intersect much fluid inclusion in quartz as in freshly exposed reactive feldspars surfaces. Cl^- stored within the opened inclusions will get washed away by the first batch of water which wets the fresh fracture. In a counterview, the unstable feldspars will be exposed to water for a very long time continually undergoing feldspar hydrolysis thus maintaining its dominance in crystalline rocks.

The active development of $Ca\text{-}HCO_3$ in shallow good aquifers mainly along the river beds and close to the surface environments can be attributed to carbonate dissolution and plagioclase weathering. Many granites and gneisses contain secondary calcite, partially replaced feldspar and strongly altered ferromagnesium minerals. Massive calcareous limestone on Ngaaie mountain and sporadic outcrops of kunkar limestone along rivers, Katse and Nthunguthu are the main sources of carbonate evolution in shallow wells apart from the primary source which is the atmosphere. The composition of these shallow well waters with strong carbonates is an attestation that chemical alteration is continuing within the project area to date.

Plagioclase weathering is the most important process in near-surface environments which has contributed to chemical alteration in many areas dominated by crystalline rocks. Unlike calcite dissolution, plagioclase weathering acts over a longer period thus rock water interaction takes a longer time. The general reaction from anorthite is shown in Equation 4.3.

$$3H_2O + 2CO_2 + Ca_2Al_2Si_2O_8 \rightarrow Al_2Si_2O_5 (OH)_4 + Ca_2^{+} + 2HCO_3^{-} \quad \text{- Equation 4.3}$$

Anorthite Kaolinite

This reaction takes place in shallow aquifers in crystalline environments. Feldspars react with dilute meteoric water to form residual insoluble Al silicate mineral and Ca-HCO_3. The above process can proceed until saturation of calcite is reached, a state at which plagioclase weathering reaction and calcite equilibrium are at the same concentration as shown in equation 4.4.

$$3H_2O + 2CO_2 + Ca_2Al_2Si_2O_8 \rightarrow Al_2Si_2O_5 (OH)_4 + CaCO_3^{-} \quad \text{- Equation 4.4}$$

Anorthite Kaolinite Calcite

Plagioclase weathering produces calcite that precipitates within the fractures and cavities and is believed to be the source of Ca-HCO3for new generation meteoric waters. Secondary calcite occurs in fractures, veins, and cavities. The level of dissolution of Ca and HCO_3 in water depends on the amount of CO_2 available. CO_2 is found naturally from all plants and animals' matter. It is also found as a result of some bacterial activities within the soil. Calcite dissolution is the initial step in chemical water evolution. It is determined by the level of dissolution of CO_2 gas contributing to calcium and bicarbonate ions as shown in Equation 4.5,

$$H_2O + CO_2 + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^{-} \qquad \text{Equation 4.5}$$

The availability of CO_2 in recharge waters is the main source of bicarbonates and carbonates evolution in groundwater. High concentrations of CO_2 gas accelerate the water-rock reaction in crystalline basements. Scholarly studies by Garrels and Mackenzie (1967); Jones and Retting (1976) have observed that $NaCO_3$ results from selective silicate leachate.

Crystalline rocks, such as granites and gneisses have plagioclase as the main rock bearing Na and Ca minerals. The dissolution rates of quartz, K-feldspar, and albite are more than lower than that of anorthite (Garrels and Mackenzie, 1967). Accordingly, the rate of plagioclase dissolution strongly depends on its composition. The dissolution of plagioclase is fast, however, compared to K-feldspar and quartz even for plagioclase with low anorthite content (Garrels and Mackenzie, 1967). The high Ca waters within Mwingi North could be as a result of preferential weathering and dissolution of calcite (Garrels and Mackenzie, 1967).

According to a study by Markl and Bucher (1997), the dissolution rate constants of ferromagnesian silicates such as, biotite and hornblende are intermediate between anorthite and the other feldspars. Weathering of biotite, the most abundant Fe-Mg mineral in most granites and gneisses of the basement, and hornblende consequent Mg and K to the solute realm of the waters. The weathering process of biotite produces an insoluble Al-sheet silicate residue, typically chlorite or smectite that coats and covers fractures in the crystalline rocks.

Weathering of sulfide and its oxidation is the primary source of SO_4 in crystalline aquifers. The reaction generally involves pyrite dissolution, Fe oxidation and goethite precipitation as shown in the equation below.

$$2FeS_2 + 7H_2O + 7.5\ O_2 \rightarrow Fe\ (OH)_3 + 4\ SO_4^{2-} + 8H^+ \qquad \text{-Equation 4.6}$$

Pyrite goethite

The reaction process releases SO_4 and protons and in the process transferring Fe from one solid phase to another. As sulfide weathering precedes the resultant pH reduction catalyzes silicate weathering mainly from plagioclase. In sulfide weathering processes TDS and SO_4 often have a direct relationship and result in Ca-$HCO_3^-SO_4$ water types.

4.5.2.3 Anthropogenic Influence on Groundwater Quality Nitrate (NO_3) and Sulphate Nitrate

Nitrate concentration ranges from 0.5 mg/l – 55.69 mg/l. The maximum allowable limit according to WHO is 50 mg/l. Kathiani Kawongo borehole near Tseikuru shopping center of Mwingi North has the highest nitrate concentration of 55.69. mg/l. Other nitrate high areas are to the southwest in the Ngomeni area. Nitrite concentrations range from 0.05 mg/l-0.268 mg/l The nitrite maximum allowable limit according to WHO is 3.0 mg/l. All the ground waters of Mwingi North are therefore safe of nitrite. Nitrate is an oxidation product of nitrite and is mainly fixed into the ground from anthropogenic processes. Nitrate highs' concentration near the Tseikuru shopping center and Ngomeni area can be attributed to indiscriminate disposal of animal waste products that are washed into the groundwater aquifers. Nitrate highs to the southwest of the project area can be possibly due to agricultural activities along river Tana which then intrudes into the groundwater aquifers through the alluvial sands of the river Nthunguthu as shown in Figure 4.25. Also as was noted in Ghana by Anku et al. (2009) the slight increase in nitrate levels can be due to poor sanitary conditions around most boreholes, where aprons and troughs constructed around well heads are either destroyed or not kept clean and livestock take a longer time drinking and defecating and wading in the watering point. Further, within Mwingi North the cultivation of nitrogen fixing crops such as beans, cowpeas, peas and groundnuts, are common as sited in may farmlands. Cultivation is often done twice a year and in many instances involving the use of fertilizers. These continual fixing of small quantities of nitrates by crops and fertilizers eventually leaches into the ground thus contaminating the groundwater aquifers.

(a) Sulphate

Sulphate concentration ranges from 2.63 – 1382 mg/l. The maximum allowable limit is 400 mg/l (KEBS and NEMA). All shallow wells have normal sulphate concentrations while eight water samples including hand pumps and boreholes have sulphate levels above the recommended limits and are therefore unsafe. A notable water point is Kyenini Bh (1382 mg/l). Sulphate is one of the major anions occurring in natural waters (Hauser, 2001). It is important in public water supplies because of its cathartic effect upon humans when present in excessive amounts. In water sulphate occurs in equilibrium with hydrogen sulfide.

$$SO_4^{2+} \longleftrightarrow H_2S \qquad \text{Equation 4.7}$$

The direction of the equilibrium may shift according to the available oxygen in the water, and on pH (lower pH, more H_2S). In industrialized areas, increased concentration of sulphates may be due to industrial discharge contamination from tanneries, paper mills, and industries that use sulphate and sulfuric acid in their processes while in mining areas, mine drainage wastes and acid rain can increase the sulfate concentration of the water.

Sulphate in natural waters arise from the leaching of Sulphur compounds, either sulphate minerals such as gypsum or sulphide minerals such as pyrite (Kanda, 2010). Most natural waters have sulphate reduction as the most common redox buffer. Sulphate undergoes a redox reaction to produce sulfide due to its high solubility in normal water. Sulphate occurs as gypsum deposits in fractures and evaporitic horizons (Clark, 2011). It can as well be derived from the oxidization of pyrite (FeS). Another source of sulphate is also in high-salinity brines found in deep crystalline settings and deep sedimentary basins. The sulfide resultant of sulphate reduction, as either H_2S or HS^- at pH>7, is toxic to most organisms.

4.5.3 Groundwater Quality Index and Development Planning

The contribution of water quality and development planning has been prioritized in a number of international forums, including health-oriented conferences such as International Conference on Primary Health Care, held in Alma- Ata, Kazakhstan (former Soviet Union), in 1978. The importance of water sanitation, and health has also been prioritized in the Millennium Development Goal no 6, adopted by the General Assembly of the United Nations (UN) in 2000 and the outcome of the Johannesburg World Summit for Sustainable Development in 2002. Most recently, the UN General Assembly declared the period from 2005 to 2015 as the International Decade for Action, "Water for Life" (WHO 2008).

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

Groundwater quality in economic planning is often an afterthought despite the huge bearing that it holds in human health consideration. The international community and governments, have of late given it a priority in its economic planning. The quantity and quality of groundwater exploited has taken a central point both with the international and local organizations. The growing interest in groundwater quality in economic planning has seen a rise in methodologies for gauging the quality of water in both rural and urban areas. Locally, Kenyan government through WRA identifies actions necessary to contribute to an effective water resources management framework. This has been effected through stakeholder approach and capacity building, and by setting needs in the wider social and economic framework, and clearly recognizing the local hydrogeological, socioeconomic and institutional situation.

In many rural areas like Mwingi North, several people depend on groundwater as their primary water source. Many people collect water from hand-dug wells, most of which are along the riverbeds, on riparian lands and in areas with shallow aquifers. Most of these hand-dug wells are a health hazard due to the way they are being handled. Water pollution bacteriologically and chemically poses serious health problems (WHO, 2006). While bacteriological contamination is due to biological effects, chemical contamination is mainly a geological consequence. Other sources of chemical pollution include acid rain and anthropogenic sources (Srinivasamoorthy et al., 2014).

Naturally, water is saturated with several chemical elements. Groundwater in particular is saturated through water-rock interaction processes. It is saturated with the chemical derivatives from the weathering processes between the host rock and water action. Various bodies and organizations including NEMA (NEMA 2006), KEBS (KEBS, 2007) and WHO (WHO 2008), have carried out detailed analytical research in the field of water quality and have come up with maximum allowable concentration (MAC) or maximum permissible limits of elements in drinking water. Some limits, however, vary from one region to another depending on the available water source and perceived health effect.

According to the Water Quality Index map (Figure 4.26), within Mwingi North, quality water is concentrated to the southwest and south of the project area while poor quality groundwater runs N-S along the eastern boundary of the project area. This map can be used by groundwater developers to provide an insight on groundwater development (Ochungo et al., 2019). Further, Water Quality Index can be used to reduce the health risk associated with ingestion of poor-quality groundwater.

4.6 Summary

In summary, hand pumps and boreholes are highly mineralised unlike shallow well waters. The dominant cations and anions are sodium and chloride respectively. The resulting dominant water types are Na-CO_3, Na-Cl, and Mg-HCO_3. The major factors controlling the groundwater quality in Mwingi North includes hydrochemistry, geology and rock water interaction. Another minor factor is animal waste leachate occasioned by poor sanitation around animal watering points. Hydrochemically, the concentrations confirm that groundwater salinity within Mwingi North increases with depth. The order of concentrations are boreholes, hand pumps and shallow wells, with most boreholes showing greater salinity and shallow wells least salinity. The spatial dispersion of groundwater salinity as shown by the groundwater quality index map (Figure 4.26) shows potable water being concentrated to the south west and south of the study area while water of poor quality is concentrated in Tseikuru and Ngomeni area to the North southwards along the east of the study area.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATION

5.1 Introduction

This chapter presents conclusions of all the findings and scientific suggestions based on the research findings.

5.2 Conclusions

The main objective of this research was to evaluate the water quality and hydrogeochemistry of the groundwater in Mwingi North, Kitui County. The study was investigated using shallow wells (8), hand pumps (17) and boreholes (17). Chemical parameters determined include major cations and anions such as K, Na, Ca, Mg, Mn, Fe, CO_3, HCO_3, NO_3, NO_2, SO_4^{2-}, Cl^-, and F^-. Physical parameters that were analyzed included EC, temperature, pH, turbidity, hardness, total alkalinity, colour, CO_2, and TDS. Geological inferences were also made for cross relations of groundwater chemistry and geology.

Hydrochemically, the groundwaters in Mwingi North are mainly of three water types, Na-CO_3, Na-Cl, and Mg-HCO_3. Other water types include Mg-CO_3, Mg-Cl, Ca-Cl, Ca-CO_3, and Ca-HCO_3. The geochemical distribution shown in surfer plots points out that ground configuration plays a very important role in groundwater chemical evolution. Localized recharge resulting from short water-rock interaction is minimal within the study area. Only one water point at the Ikaaie community borehole is of Ca-HCO_3 water type.

On the contrary, Na-CO_3 and Na-Cl evolution on flat and low lying areas are mostly believed to be due to mineral leachate. Na-CO_3 water types are predominant in shallow wells and hand pumps along river Katse, Zanzeni, Nthunguthu, and Kaundu. These rivers have kunkar limestone outcrops from where CO_3 leachate evolves. On the other hand, Na-Cl water type is mainly realized in deep boreholes located in flat-lying areas. The formation of this water type is a result of precipitation, cation exchange and sulphate reduction.

Geologically, Mwingi North falls within the central sector of the Eastern Mozambique belt System (EMBS). The geology is mainly composed of crystalline rocks such as granitoids, gneisses, and amphibolite. Common minerals include sillimanite, garnet, and epidote. Hydrogeologically, crystalline rocks' value in groundwater development faces several challenges world over. Due to the effect of rock-water interaction over a long time, most of these aquifers are chemically saturated. These aquifers have witnessed the highest chemical pollution due to the action of temperature and pressure changes, thus complicating their development as portable water. Crystalline rocks are as well known for being compact and of low transmissivity; therefore, groundwater development in such rocks depends on proper and precise fracture delineation.

The increasing need for potable water within Mwingi North cannot be underestimated. A number of boreholes have been abandoned due to increased salinity, within Tseikuru and Ngomeni wards. Groundwater quality monitoring requires an open-minded approach by groundwater developers, taking into account the available scientific findings like water quality index maps and identifying the probable health risks associated with consumption of saline waters. Water quality Index map identifies areas with non-saline, and saline waters thus can be of economic benefit to scientist and groundwater developers.

In summary, geology and climatic conditions are the main factors that determine the hydrogeochemistry of aquifers within Mwingi North. Na, Mg and Ca, which are the dominant cations occur from plagioclase weathering. Chloride and bicarbonate, the dominant anions in shallow wells, hand pumps, and borehole waters have their sources in plagioclase and carbonate weathering respectively. 16 water points out of the 42 sampled, falls within the freshwater (non-saline) category (38%). The remaining 26 water points fall within the saline water category (62%) of the total sampled water points. The groundwaters of Mwingi North are therefore generally saline. Fluoride, which was initially thought to be the cause of groundwater salinity has very limited effect as only a few groundwater sources registered fluoride contents above 1.5 mg/l.

Nitrate contamination in the groundwater aquifers of Tseikuru and Ngomeni wards are probably from anthropogenic pollution. The surfer maps (Figures 4.4. to 4.17), as well as the groundwater quality index map (Figure 4.26), shows that hardness, Ec, K, Mg, SO_4, Ca, Cl and F follow the same distribution trend. These parameters are high in areas from far in the north of Tseikuru downwards along the middle of the project area and fans downwards forming an inverted 'Y' shape. At the same time, the eastern arm of the fan extends further outwards to the Ngomeni ward border. The western arm terminates in Tia fault line. The rest of the areas to the south and south-west have low concentrations and can be considered for groundwater development. This trend confirms that groundwater quality in Mwingi North is mainly influenced by geology. From this pattern, in Mwingi North poor quality water is in the N-S direction from Tseikuru downwards to the west of Kyuso area and south-eastwards in the Ngomeni area. Most of the area to the NW, including Tharaka areas, have soft water as well as the sites to the far west.

5.3 Recommendation

The following steps should be taken in place to ensure the protection and efficiency of the groundwater for the residence of Mwingi North:

- Several shallow wells, hand pumps and boreholes within Mwingi North have concentration levels of Na^+ and Cl^- ions surpassing NEMA, KEBS and WHO allowable limits despite their use as the only available water source. Groundwaters with such high levels of chemical constituents require softening to reduce the high concentrations of salts.
- Many people within this area depend on shallow wells for their domestic water, most of which are open. The mode of getting water out of these water points is prone to bacteriological contamination. This research study has delved into the hydrogeochemical aspect of a few boreholes, and an intensive confirmatory study needs to be carried out encompassing the bacteriological parameter.
- As observed, groundwater contamination is prevalent in Tseikuru and Ngomeni wards. Therefore, groundwater development should be concentrated in Mumoni, Kyuso and Tharaka wards which are less saline, while an alternative water source should be provided for parts of Tseikuru and Ngomeni wards. Construction of earth and rock catchment dams should be encouraged. A notable rock dam observed is Ngomeni rock dam which serves Ngomeni market and its environs.
- Proper groundwater development taking into account areas with known chemical saturations is essential. Use of Groundwater Quality Index maps should be encouraged to assist scientists in siting boreholes. Informed drilling should save money and protect human and ecosystem health.
- Point source pollution by nitrate can be avoided by initiating increased sanitation around animal watering points. This should involve rehabilitation of the cattle troughs to prevent leakage, preventing animals from wading into the water and allowing animals to take limited time at watering points, thus preventing them from defecating in water.

- Groundwater monitoring should be a continuous practice which should include water quality assessment, changes in water levels, recharging trends and the prevailing quality of drinking water. It entails water level drawdown and groundwater use, recharge relationships with rainfall and shape of the water table and groundwater directions. Water quality monitoring is the collection of water quality data over time and should involve the ambient trend, source and research in groundwater to ensure its safety.
- Implementation of low cost water treatment methods like biochar effectively treats the water from both chemical and biological contaminants. Biochar is a carbon-rich solid formed by pyrolysis of biomass The system uses locally available biomaterials making it useful to the rural communities. The technology has been used as a low cost soil and water quality reconditioner. It has been used to remove various contaminants in aqueous media from the soil by acting as an adsorbent. Other low cost water treatment methods such as sand filtration, boiling, solar disinfection and chlorination which are common mainly removes biological contaminants.

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APPENDIX

APPENDIX 1: SUMMARY OF STATISTICAL ANALYSIS OF MINERAL SATURATION INDICES

		(a)Boreholes			(b) Hand pumps			(c) Shallow wells		
		Max	Min	Median	Max	Min	Median	Max	Min	Median
Anhydrite	$CaSO_4$	-0.96	-2.87	-1.76	-1.12	-3.52	-1.97	-1.8	-1.79	-2.85
Aragonite	$CaCO_3$	-2.62	-1.22	2.39	2.72	-1.84	2.01	2.42	0.51	1.44
Calcite	$CaCO_3$	2.76	-1.08	2.53	2.87	-1.7	2.16	2.57	0.66	1.58
Dolomite	$CaMg(CO_3)_2$	5.6	-1.6	5.2	5.79	-3.22	4.83	4.98	1.41	3.28
Fluorite	CaF_2	-0.1	-2.07	-0.79	-0.14	-.2.32	-1.1	-0.39	-1.54	-1.5
Gypsum	$CaSO_4:2H_2O$	-0.66	-2.56	-1.45	-0.82	-3.21	-1.67	-1.5	-3.48	-2.38
Halite	NaCl	-4.65	-7.03	-5.16	-4.69	-7.81	-5.96	-5.89	-9.59	-7.165
Hausmanite	Mn_3O_4	19.17	-18.58	14.4	20.8	-24.01	12.92	18.98	-8.64	-1.06
Managanite	MnOOH	6.67	-7.55	5.04	7.27	-9.59	4.5	6.64	-3.78	-0.865
Melanterite	$FeSO_4:7H_2O$	-7.24	-12.66	-10.09	-7.52	-13.46	-9.88	-7.41	-11.73	-7.85
Pyrochlorite	$Mn(OH)_2$	0.99	-8.34	-0.54	1.4	-9.68	0.93	0.85	-5.93	-4.185
Pyrolusite	$MnO_2:H_2O$	6.9	-12.65	4.72	7.24	-15.39	4.01	6.54	-7.52	-3.455
Rhodochrosite	$MnCO_3$	0.43	-1.85	-0.6	0.44	-2.59	-0.57	0.6	-0.76	-0.525
Siderite	$FeCO_3$	1.11	-4.66	-1.87	0.78	-4.55	-1.84	1.18	-2.88	0.615
Sylvite	KCl	-5.66	-7.8	-6.32	-5.88	-8.79	-6.9	-6.7	-8.86	-7.9