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Assessment of Temporal and Spatial Variability of Groundwater in the Mbagathi River Catchment

MSc Thesis

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DECLARATION AND APPROVAL

This thesis is my original work. I also affirm that to the best of my knowledge; this has not been presented for a degree in any other university.

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ABSTRACT

Groundwater is increasingly an important source of water. Assessment of its variability helps in guiding decisions on exploitation. Groundwater varies over space and time. Groundwater contains multiple range of chemical parameters which influence its quality. This study entails indexing of groundwater quality parameters in Geographic Information Systems (GIS) based environment using Kriging geostatistical analyst. The study was conducted in the Mbagathi River catchment, a metropolitan area, Southwest of Nairobi, Kenya. Existing boreholes data was obtained from the regulator to provide yield and water rest level characteristics. Data on groundwater quality parameters were analyzed according to the KS EAS 12:2018 standard from sampled boreholes. Quality, yield and water rest level data was analyzed and modeled in ArcGIS 10.1 software geostatistical wizard for spatial and temporal variability. Prediction maps were generated from which it was deduced that spatial and temporal variability of groundwater in the study area exists. Temporal variability largely follows the rainfall patterns. Groundwater quality deteriorated with decrease in rainfall by 5% on average from wet to dry seasons. It was deduced that groundwater is mainly fair to good quality. There was no excellent or very poor groundwater quality observed. Spatial variability predominantly followed the river flow regime in the drainage basin. 57% of the boreholes had a good yield of at least 8.3m^3/hr. Modelling with associated prediction maps done on periodic basis is strongly recommended as a means of communicating groundwater characteristics. Smart level sensors, digital quality sensors and smart water meters are suggested as a means to collect and transmit data in a programmed manner over longer periods of time.

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LIST OF ABBREVIATONS AND ACRONYMS

ACA	Athi Catchment Area
BGRM	*Bureau de Recherches Géologiques et Minières*
BGS	The British Geological Survey
BH	Borehole
BNWPP	Bank-Netherlands Water Partnership Program
CGMW	Commission for the Geological Map of the World
CIWA	Cooperation in International Waters Africa
CoK	Constitution of Kenya
GIS	Geographical Information Systems
GW-MATE	Groundwater Management Advisory Team
hr	hour
IDW	Inverse Distance Weighting
IGRAC	International Groundwater Resources Assessment Centre
km^2	square kilometer(s)
KS EAS	Kenya Standard East Africa Standard
m	meter(s)
m^3	cubic meters
mbgl	metres below ground level
ME	Mean error
mg/l	milligrams per litre
QQ	Quantile-quantile
RMSSE	Root mean square standardized error
TBA	Trans-boundary Aquifers
UN	United Nations
UoN	University of Nairobi
WB	World Bank
WHO	World Health Organization
WHYMAP	World-wide Hydrogeological Mapping and Assessment Programme
WQI	Water quality index
WRA	Water Resources Authority

1 INTRODUCTION

1.1 BACKGROUND INFORMATION

Groundwater variability is the change in quantity and quality occurring over space and time. The variation is mainly influenced by natural processes. This is due to the fact that the ground water is formed through percolation of surface water and stays underground for a period of time. During this period, the water is in reaction with the dissolved chemical elements occurring naturally in the geological formation. Kenya is classified by the United Nations (UN) as a chronically water-scarce country. The country's natural endowment of freshwater is highly limited, with an annual renewable freshwater supply of about 647 cubic meters (m^3) per capita, significantly below the 1,000 m^3 per capita set as the marker for water scarcity (Mogaka et al., 2006). The current level of development of water resources in Kenya is very low. Only 15 percent (%) of the safe yield of renewable freshwater resources have been developed. This low level of development means that water supply storage per capita has declined from 11.4 m^3 in 1969 to about 4.3 m^3 in 1999 because of population increase (Mogaka et al., 2006).

Water is an economic and social right. The citizens are entitled to clean and safe water in adequate quantities. All actors in the water sector require to continually ensure that this right is realized not just for the current but future needs of the country (Constitution of Kenya (CoK), 2010). Groundwater is an important resource that supplements surface water sources. Groundwater varies in its spread and quality and requires experience to predict its variability (Li et al., 2015). Geostatistical models have been proposed as an alternative means of obtaining groundwater data through simulation rather than observation. The geostatistical models are used to derive aquifer hydrogeological properties (Peck et al., 1988). Through multiple studies researchers have attempted to compare groundwater variability in quantity and quality around the same areas (Furkuor et al*.,* 2013).

Groundwater forms part of the sources of water available for exploitation. It is important to enhance the understanding of groundwater variability to ensure its exploitation is in a sustainable manner. Knowledge in temporal and spatial groundwater variability is required for planning, controlling and monitoring groundwater sources. It guides sustainable harnessing and management of groundwater (Khairul et al., 2021).

1.2 PROBLEM STATEMENT

Water sources are increasingly deteriorating in quality and quantity. Groundwater as part of these sources, varies in quality and quantity (Li et al., 2015). Metropolitan area of Mbagathi River catchment experiences demand for water for various uses. Due to unmet water demand, groundwater is being exploited as an alternative source (Samantha, 2011). Exploitation of the groundwater continues with limited understanding of temporal and spatial variability. Without knowledge in temporal and spatial variability, authorities cannot effectively manage groundwater. Research in varied aspects of groundwater is hampered when knowledge in its temporal and spatial variability is limited. Effective management leads to sustainable groundwater sources. To achieve groundwater sustainability, proper planning, control and monitoring of current sources has to be done. Sustainability cannot be achieved without knowledge of temporal and spatial variability. To harness groundwater, there are capital and operational costs required. Lack of knowledge of the temporal and spatial variability, makes it difficult to undertake adequate cost benefit analysis for sustainable investment in groundwater exploitation. There is no study on temporal and spatial variability of groundwater in the Mbagathi River catchment area. There is need to fill this knowledge gap. This study proposes to obtain relevant data on groundwater quality and yield through sampling existing boreholes. Through geostatistical methods, the data shall be used to characterize temporal and spatial variability of groundwater in study area.

1.3 OBJECTIVE

1.3.1 Overall objective

To establish the temporal and spatial variability of groundwater in Mbagathi River catchment.

1.3.2 Specific objectives

The specific objectives of the research are as follows;

1. Characterize groundwater quality and groundwater yield
2. Establish temporal and spatial groundwater variability using applicable geostatistical models

1.4 SCOPE AND LIMITATIONS OF THE STUDY

The Mbagathi River catchment has been chosen for this study because of its relative continuous dependence of ground water for domestic, institutional, commercial, industrial and agricultural uses in the area. The study will cover the groundwater quality and quantity within the study area. It will attempt to determine the groundwater variability over space and time. Using the groundwater quality analysis results of the selected parameters, the data will be processed to generate prediction maps based on geostatistical analysis. Using the borehole drilling data, groundwater spatial distribution will be generated. Temporal and spatial maps will be compared for any trends.

The study is limited to an annual cycle for the weather changes within the area of study. The study is limited in determining the effect of the adjacent drainage basins on the groundwater variability. The study shall only rely on already stored data to explore the spatial variability.

2 LITERATURE REVIEW

2.1 OVERVIEW OF DEVELOPMENTS IN UNDERSTANDING GROUNDWATER VARIABILITY

The challenge of understanding groundwater resource is not new. Groundwater is water found in saturated zones beneath the earth’s surface. It is formed when the surface runoff from precipitation percolates to the ground as per the water cycle (Nelson, 2002). The upper surface of this saturated zone is the water table. Figure 2-1 shows the hydrological cycle typifying the natural processes of water including formation of groundwater.

Worldwide, various bodies exist that seek to enhance understanding of groundwater. These bodies carry out studies from which they produce various publications of their work. These bodies have attempted to explain groundwater variability at mainly national and continental level. The International Groundwater Resources Assessment Centre (IGRAC) formed in 2003 exists with a general objective of promoting sustainable ground water resources utilization and management by means of global exchange of knowledge. IGRAC promotes international sharing of knowledge, monitoring and information on groundwater development and resources. It also seeks to increase understanding of the Trans-boundary Aquifers (TBA) (https://www.un-igrac.org/who-we-are, 2018).

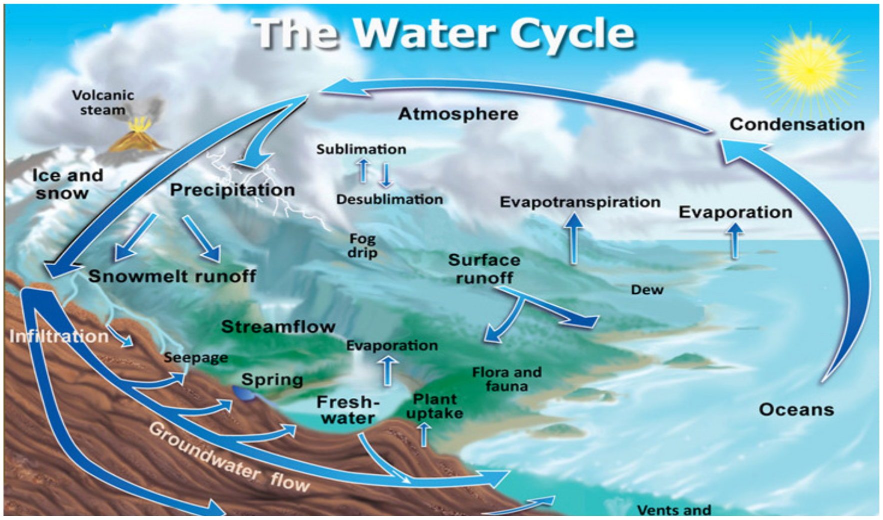


Figure 2-1The Hydrological (water) cycle adapted from https://en.wikipedia.org/wiki/Water_cycle, (2018)

In late 2000, efforts were made to increase understanding of the groundwater potential. The World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) was formed at the general assembly of Commission for the Geological Map of the World (CGMW). By late 2004, the first groundwater map of the world was produced. To date WHYMAP continues to offer insights into the global groundwater mapping. The extent to which the mapping of groundwater resources is undertaken indicates the significant level of importance placed on this resource (https://www.whymap.org/whymap/EN/Home/whymap_node.html, 2018).

In Africa, studies in groundwater date back to more than one century. The British Geological Survey (BGS), reports that it holds over seven thousand diverse publications on groundwater in Africa alone. This attests to the immense interest in groundwater in the continent. BGS has produced the groundwater atlas for Africa. The atlas gives a general view of the groundwater depth in metres below ground level (mbgl), depth of ground water storage and aquifer productivity (Barasa et al., 2018).

Bureau de Recherches Géologiques et Minières (BRGM) is the French geological survey. The BRGM hydrogeological map of Africa at a scale of 1:10 Million was first published in 2008. The development of the map incorporated two types of data. First aquifer type and second the available precipitation for the aquifer recharge. The map has been utilized as an important tool is identification of the aquifer potential on Africa according (http://www.brgm.eu/ , 2018)

The World Bank (WB) established the Cooperation in International Waters Africa (CIWA) in 2011 to promote the integrated and sustainable use of water resources including groundwater. Drawing from the WB experience on management of transboundary water resources CIWA is uniquely poised to provide neutral third party facilitation, technical support and critical analysis to better understand transboundary water issues and inform decisions (http://www.worldbank.org/en/programs/cooperation-in-international-waters-in-africa, 2018)

2.2 OVERVIEW OF GROUNDWATER IN KENYA

Kenya is grappling with a water crisis. This crisis is occasioned by droughts, forest cover depletion, floods, inadequate water supply and demand management, the contamination of water and rapid population increase. Some of the challenges are solvable. However, some like droughts and floods are strongly linked to climate change with a likelihood being exacerbated in the coming days (Samantha, 2011).

The lead agency in management of groundwater resources in Kenya is the Water Resources Authority (WRA). It was formed pursuant to the Water Act (WA) 2002 which was later amended to Water Act, 2016. WRA operates in the context of other actors in the water sector as illustrated in Figure 2-2 below.

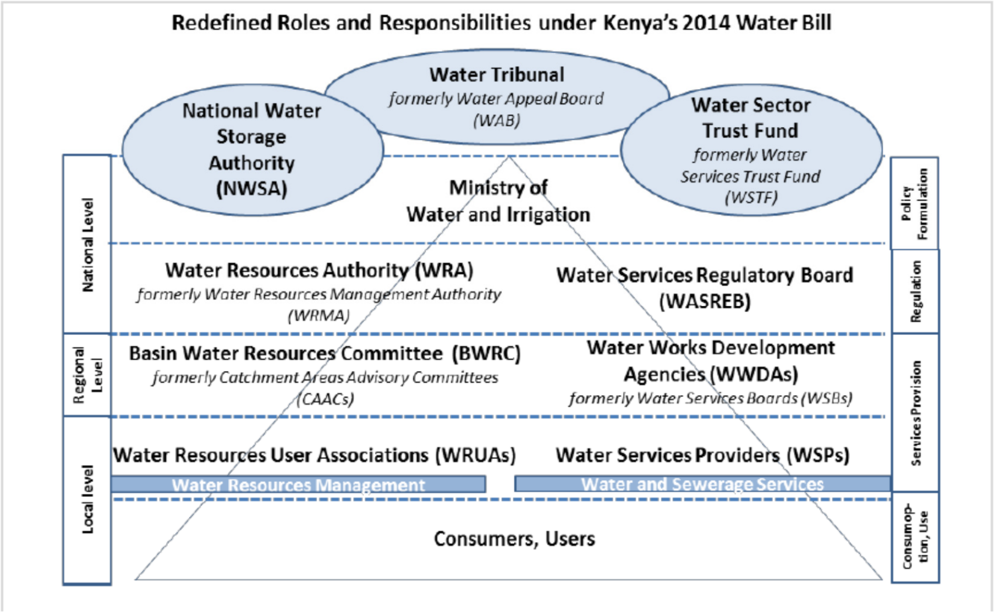


Figure 2-2 Water Sector in Kenya adapted from https://www.2030wrg.org/wp-content/uploads/2016/12/Understanding-the-Kenyan-Water-Act-2016.pdf

WRA's main role is protect, conserve, control, and regulate the use of water resources and flood mitigation through the establishment of a National Water Resource Strategy. WRA maintains groundwater database and information system through assessments, mapping and investigations. WRA safeguards groundwater resources from degradation through anthropogenic actions (Musonge et al., 2022). WRA works by delegation of its mandate to basin water resource committees. It regulates groundwater resources by developing guidelines, standards and codes of practice for sustainable groundwater development. (Musonge et al., 2022).

Knowledge in groundwater quantity and quality as a resource in Kenya is limited. Technologies and techniques for exploration and assessment are not only expensive but also complicated. The field data available is seldom satisfactory to produce projections that enhance in depth understanding of the groundwater resources (Li et al., 2015). This results in fragmented data thus limiting the integration for comprehensive assessment of groundwater resources. Groundwater regulation must go beyond the quality related issues and involve management of competition for the resource (Mogaka et al., 2006). Pollution, saline water intrusion and hydrogeological evolution as threats to the quality of groundwater resources. In their study, they note that groundwater is used for various purposes. In their opinion domestic use ranks highest. This is followed by agricultural use for crop production, livestock and fishing activities (Pavelic et al., 2012).

2.2.1 Management of groundwater

The most sustainable way of managing groundwater is by involvement of local communities. With proper mechanisms, self-regulation of abstraction, groundwater can be well managed. There is growing uncertainty in groundwater sustainability occasioned by effects of climate change and other anthropogenic factors. Groundwater sustainability is increasingly demanding highly innovative attention. Adaptive Management is proposed as a means of enhancing sustainability of groundwater sources by iterative approach. In this approach, systems and policies are continuously assessed using monitoring techniques that seek to enhance future management capacities (Thomann et al., 2020).

One of the recent developments in groundwater management is the Transboundary Aquifers (TBAs). TBAs are aquifers that transcend national boundaries. By their nature they are formed out of water cycle occurrence beyond one nation (Tamiru, 2010). TBAs are increasingly becoming critical to the management of the groundwater. TBAs sustainability is depended on the activities of interdependent ecosystems. It is strongly proposed that a harmonised all-inclusive approach is used to utilize the TBAs. Management of TBAs shall take into cognizance the existing frameworks. However, TBA management should evolve embracing flexibility and amalgamation of models (Villholth et al.., 2014)

2.3 VARIABILITY ON GROUNDWATER

2.3.1 Occurrence of groundwater variability

There exists variability of groundwater over space and time. The variability is influenced by the type of dissolved chemical elements found where the water exists. It is not easy to describe groundwater variability owing to the broad number of chemical, physical and biological indicators that can be tested (Babiker et al, 2006). Groundwater variability is strongly linked to linear increment with respect to its storage anomalies. Groundwater variability increases significantly with decrease in precipitation (Li et al., 2015).

The hydrochemistry of groundwater results from the type of the specific chemical elements and their contact time with groundwater. Factors such as temperature, water potential Hydrogen (pH), reduction and oxidation chemical reactions contribute to groundwater variability. The temporal variables of temperature, pH and redox potential have an effect on the chemical composition of groundwater because they affect the chemical reactions occurring in an aquifer. The chemical reactions result in differences in the taste and colour of groundwater from different wells. These are aesthetic parameters for drinking water. Water should be free from tastes and odours that are not acceptable to most consumers (Nelson, 2002).

Demand for groundwater is on the rise. This is partly due to the dwindling surface water sources. The main limitation of exploitation of groundwater within that area is its quality. It is difficult to describe the groundwater spatial variability if an effective monitoring system is lacking (Alexander et al., 2017)

Spatial variability in the groundwater quality parameters is strongly attributed to the geological formations. There exists temporal variability in the groundwater potential that is linked to the temporal factors such as rainfall patterns. The underlying geological formations strongly influence the quality of groundwater. In addition, there is a strong relationship between abstraction rates in the dry seasons and ground water quality than is the case during the rainy seasons (Mwamati et al., 2017).

2.3.2 Water Quality Index (WQI)

Water Quality Index (WQI) is synthesis of water quality parameters measures at different times and locations into a single number. The aim of indexing is to obtain quality data that is understandable and easy to use. Water Quality Index (WQI) was adopted to provide analysis into the quality of the groundwater. WQI helps to characterize the influence of every parameter on the overall groundwater quality. Development of WQI requires selection and weighting of each parameter. This is followed by determination of its relative weight based on the relative contribution to DWQ (Batabyal et al., 2015). The main factors that influence the confidence of the index estimation are the data quality and the nature of spacing of the sample points of the groundwater. When confronted with poor monitoring network of boreholes, employing analysis of data on exploratory basis is necessary (Alexander et al., 2017).

2.3.3 Relevance of chemical parameters in drinking water quality (DWQ)

Chloride is important to the human body for metabolism and physiological processes. However, it's concentration should not exceed proper levels. Groundwater sources tend to have elevated concertation of chlorides than surface water. Chloride anion attacks metallic pipes and structures when prevalent in high concentration. Chloride is formed from the solution of salts from by reaction of hydrochloric acid. Chloride generally occurs as table salt. Concentration of chloride should be at maximum 250 mg/l in DWQ (WHO, 2006).

Proper concentration of sodium in the human body is essential for prevention of diseases and complications. These include but not limited to hypertension, headaches and kidney diseases. Sodium is mainly consumed in form table salt by humans. It also occurs in groundwater. Surface fresh waters have less levels of sodium compared to the oceans and seas and salty water sources. WHO standards stipulates that the concentration of sodium for DWQ should not exceed 200 mg/1. Potassium is important to animals and plants. In human body it important to the well function of heart, regulation of blood pressure, muscle functionality, the nervous system and protein metabolism among other functions. Its deficiency can cause dysfunctionalities in the heart, muscles, protein dissolution among other complications. WHO recommends potassium should not exceed 12mg/l with respect to DWQ (Yirdaw et al., 2016).

Nitrates is a significant parameter that pose health risks. It causes particularly blue baby syndrome in infants besides other birth defects. Nitrate has potential to turn hemoglobin to methemoglobin affecting how blood caries oxygen. This causes weakness, high heart rate, dizziness and fatigue. Other possible risks of elevated nitrate levels in water are thyroid disease and colon cancer. The permissible levels of nitrate for DWQ should not exceed 5mg/l. Lack of calcium in adequate quantities in human beings causes rickets, bone fracture and poor blood clotting. On the contrary high levels of calcium contribute to increased risks of cardiovascular diseases (Yirdaw et al., 2016). Calcium contributes to the human physiology and bones. Calcium is stored in largely within the human bones and teeth. The permissible levels to meet DWQ should not exceed 75mg/l. Magnesium and calcium are the main elements that contribute to water hardness. Hardness has economic impacts in use of more soap and formation of scum and scale deposits in metallic pipes, staining of surfaces amongst other effects (WHO, 2006).

There is no notable effect of human health paused by sulphates. It is a parameter of aesthetic quality to water. WHO stipulates its concentration should not exceed 250mg/l in DWQ. High concentrations of fluoride increase the risk of dental fluorosis, while increasingly higher concentrations increase risk of skeletal fluorosis. The maximum permissible levels of fluoride to meet DWQ is 1.5mg/l (Linuz et al, 2021).

2.4 ASSESSMENT OF GROUNDWATER VARIABILITY

Assessment of groundwater variability can be undertaken using various models. The models have been employed to characterize variability in space and time. The models mainly involve statistical analysis.

2.4.1 Geographic information systems

Geographic information systems (GIS) have been used to study borehole exploration. GIS enhances understanding the characteristics of an aquifer. GIS can be used to categorize the degree of groundwater potential within a given area. After categorisation, areas that may require detailed study with respect to their groundwater potential can be identified. GIS approach is valuable to support groundwater development. GIS should not be used in isolation but be supported by other maps. In particular transmissibility and specific capacity maps should be explored in tandem with GIS to select areas for groundwater development. Various geostatistical methods can be employed to perform exploratory analysis of the groundwater data (Alexander et al., 2017). The analysis can provide pattern of variables, trend analysis and theoretical semivariagram fitting withing the Kriging geostatistical wizard with is a toolbox in GIS. The geostatistical analysis sheds light on the nature of distribution of the variables that were being analysed (Gyamfi et al., 2016).

2.4.2 Kriging

Kriging offers a way of interpolating different points with values even if those points were not physically mapped or sampled by utilizing already known data from a sample of points within the same area provided knowledge of underlying spatial relationship is known. This knowledge of the spatial relationship is provided by variograms. Kriging as an analysis tool is premised on the fact that there exists a relationship with respect to space for physically located sample points within a study area which can provide insight into the characteristic distribution of the variable factors on the surface (Said et al., 2017). This relationship can be expressed mathematically correlating the sample points in a defined area. Kriging involves various iterations at different stages. Kriging includes statistical analysis from exploratory approach and modelling of variograms (Naoumi & Tsanis 2004).

2.4.3 Inverse Distance Weighting (IDW)

This is a technique that attempts to spatially correlate values near to each other by insertion of weighting framework relative to their distance. As a computational method, IDW attempts to correlate factors during analysis in a manner that ensures that any factor analysed impacts the successive factor in the series to be analysed. The resulting spatial view of the analysed factors is expected to be smooth enough if graphically expressed. IDW as a computational method doesn’t make assumptions about the value of factors being studied except that there exists a spatial relationship between factors close to each other more than those far from each other.

IDW gives the user a degree of freedom to interrogate and control the significance level of the points that are already known to the point that hare unknown by using the distance between them from the output point according to (Augusto et al., 2016).

2.5 IMPLICATION OF LITERATURE

It is deduced from the publications by various authors that temporal and spatial variability of groundwater exists. The knowledge in variability is however limited. This limitation can be attributed to the generalized nature of the available knowledge at country and continental level. Therefore, it is necessary to establish the variability of groundwater in the study area. This will advance the knowledge from a generalized level to localized level and support groundwater exploration activities in the study area. Enhancing knowledge in spatial and temporal variability of groundwater requires data and analysis within a specific study area. Groundwater quality can be analysed using indexing. Data generated from indexing can be modelled to characterize the temporal and spatial groundwater variability in study area. The case for computational models has been strongly suggested by various authors. Kriging in GIS environment is one of such models. Kriging enhances the understanding of the variability by providing maps that enhance comprehension of the study area characteristics. In order to analyse groundwater quality, selected parameters from sample boreholes from the study area shall be tested. Detailed analysis using indexed data of the study area shall be evaluated in a GIS environment.

3 METHODOLOGY

3.1 STUDY AREA

The study area will be the Mbagathi River catchment. It falls in the Athi Catchment Area (ACA). ACA is one of the six drainage basins in Kenya. ACA oversees several counties. From the costal side of Kenya it covers Mombasa, Kilifi, Kwale and neighbouring Taita Taveta. On the Eastern part of Kenya it covers Kajiado, Makueni, Machakos and Kitui counties. ACA cover the capital city and county of Nairobi, parts of neighbouring Kiambu and further west county of Nyandarua.

The study area is parts of Kajiado and Nairobi counties. Each county has diverse conditions that are unique socially, economically, legally and administratively. The main physical features that are shared in these two counties are the Nairobi national park, the Mbagathi River and Magadi road. The two counties border each other along the Mbagathi River. Both areas grapple with population growth challenges that place demands on the existing services and infrastructure. Figure 3-1 shows the peri-urban location of the study area.

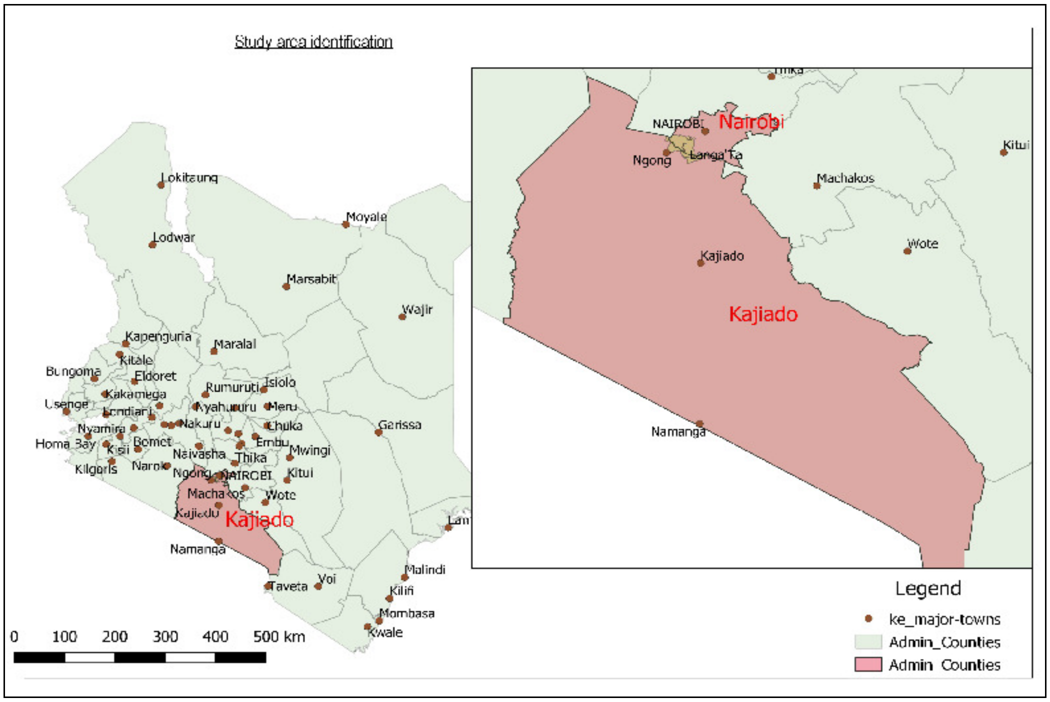


Figure 3-1Study area identification.

The greater part of the study area fall within Kajiado county. Kajiado County lies between 500m and 2,500m asl at Lake Magadi and Ngong Hills respectively. This county is characterised topographically in three ways. To the west, the dominant topography is the Rift valley. This comprises steep faults leading to plateaus, cliffs and grasslands.

At the centre is the defined by the central broken ground. This is an area between 20km to 70km wide, with altitudes between 1,220 to 2,073m above sea level (asl). Ngong Town is located within the Central Broken Grounds. To the south east it is defined topographically by the Athi Kapiti plains mainly constituting of gently sloping hills with altitudes between 1,580 to 2,460m asl.

The lesser part of the study area covers part of Karen suburb. This area is South-West of Nairobi Central Business District (CBD). It measures about 56 square kilometres (km^2). Its neighbouring towns are Ngong and Ongata Rongai from the Kajiado County, which are experiencing an upsurge in urbanization and population.

Mbagathi River is part of the larger Athi catchment ranging 1480m to 2160m asl. It drains into the Athi River which ends up in the Indian Ocean at the Kenyan coast. Figure 3-2 show the Mbagathi River catchment from the Upper Ngong-Karen in the Northwest to Rongai in the East.

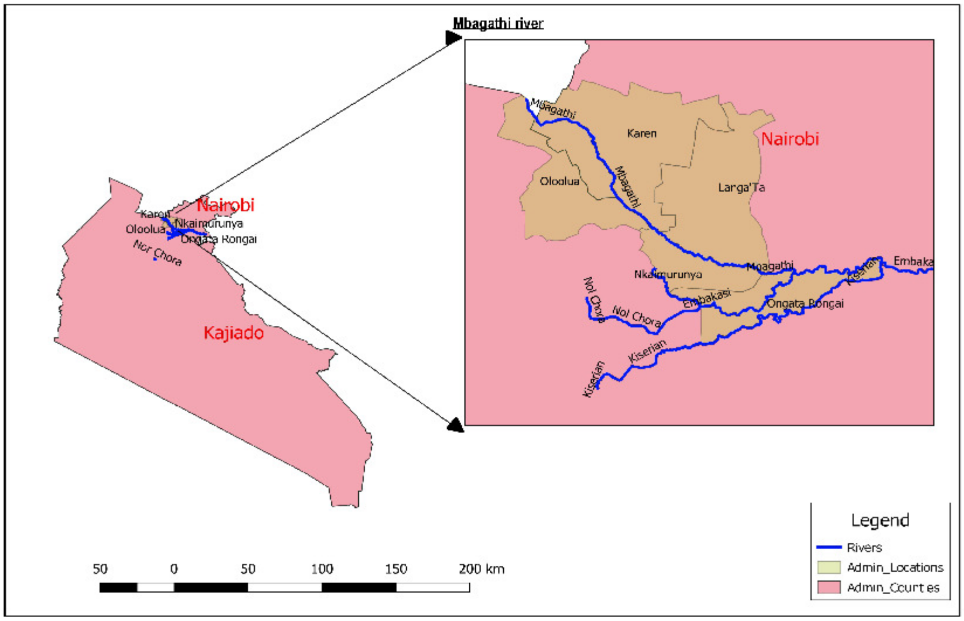


Figure 3-2 Mbagathi River Catchment.

The Mbagathi River originates from Ololua location traversing Karen and exits along the boundary of the two locations continuing along the boundary between Lang'ata and Nkaimurunya locations. It exits these two locations to discharge into Embakasi river in Ongata Rongai location. The catchment area has been delineated as per Figure 3-3 below

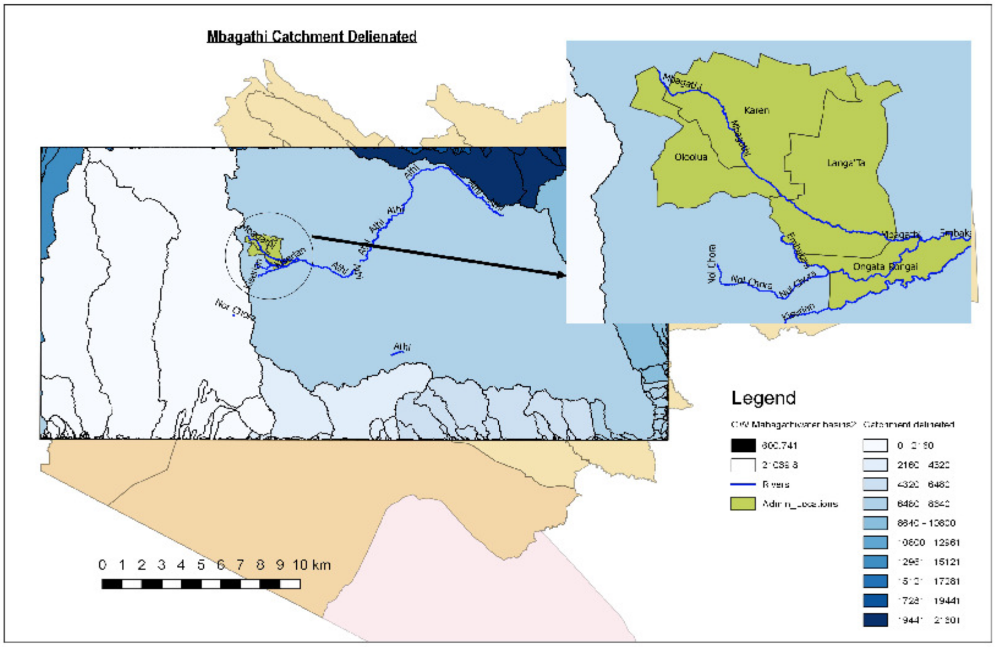


Figure 3-3 Delineated Mbagathi Catchment.

3.2 HYDROGEOLOGY OF THE STUDY AREA

Mbagathi River catchment area experiences high demand for water as it is home to people who work in the city. Surface water sources are inadequate to meet the water demand (Mulwa et al., 2005). Groundwater is exploited as an alternative to cover the deficit in surface water supply. The groundwater is conveyed to the residents by piping. Water vending by water trucks, water kiosks and hart carts was observed in the area.

Faulting, volcanicity and tectonic movements are the factors that have contributed to volcanic activity in the Ngong area. This has influenced the areas geological history and the geomorphological evolution (Saggerson, 1991). The typical rock formations are tertiary volcanic rocks. These rocks include Ngong basalts, Ol Doinyo Narok agglomerate, Limuru quartz trachyte, Kerichwa valley tuff, Nairobi trachyte, Nairobi phonolite, Mbagathi trachyte, Kandizi phonolite and Ol Esayeti phonolite (Saggerson, 1991). Kiserian-Matathia area is considered a water conservation zone to the east of Ngong hills. The water conserved is mainly determined by faulting affecting occurrence of groundwater in its distribution, flow and yield (Mulwa et al., 2005).

There is inconsistency in the hydrogeology of the Mbagathi river catchment caused by the varied lithological conditions. Weathering and fractured nature of the geological formations affect the hydrogeology contributing to this inconsistency (Mulwa et al., 2005). There are varied aquifers in the area. There are sands and sediment deposits interposed in tuff. Basalts, trachytes and turf rock strata with appreciable perviousness are also found in the area. The area also has connected rock formations such as basalts and turfs. Such connected rocks form aquifer that is fractured. Aquifers in fault zones have the highest groundwater yield. Basalt type of rocks influence at least 75% of the aquifer yields. Trachytes influence about 14% of aquifer yields. Weathered and jointed tuff influence about 6% of the aquifers (Mulwa et al., 2005).

3.3 DATA REQUIREMENT AND SOURCES

The data for the assessment of groundwater variability in the Mbagathi River catchment was as follows:

i) Groundwater quality data obtained from boreholes in the study area by sampling. From the identified sample boreholes, the parameters for study shall be fluorides, sulphates, nitrates, chlorides, sodium, calcium, magnesium and potassium.
ii) Borehole characteristics and drilling data for the identified sample boreholes obtained from WRA, borehole drillers and owners.
iii) Hydrogeology of the study area obtained from WRA and related publications.
iv) The rainfall and evapotranspiration data from rainfall gauging stations in the study area obtained from the Meteorology Department or other resourceful institutions.

3.4 DATA COLLECTION AND ANALYSIS

3.4.1 Collection of Groundwater Data

Groundwater quality data was tested from sample boreholes within the study area. Sampling was conducted from enumerated boreholes in Table 3.1 below

Table 3.1 Groundwater Sampled boreholes

Location Details of Sampled Boreholes				
No	Code	Location	Latitude	Longitude
1	B01	Matasia	-1.3946	36.6830
2	B02	Kiserian	-1.4432	36.6893
3	B03	Rongai	-1.3949	36.7347
4	B04	Kiserian	-1.4378	36.6825
5	B05	Rongai	-1.3927	36.7182
6	B06	Kiserian	-1.4265	36.6911
7	B07	Matasia	-1.3907	36.6729
8	B08	Rongai	-1.3961	36.7286
9	B09	Rongai	-1.3978	36.7245
10	B10	Rongai	-1.3965	36.7303
11	B11	Rongai	-1.3989	36.7255
12	B12	Kiserian	-1.4388	36.6888
13	B13	Rongai	-1.4069	36.7151
14	B14	Kiserian	-1.4557	36.7016
15	B15	Mericho	-1.3866	36.7063
16	B16	Kiserian	-1.4413	36.6905
17	B17	Rongai	-1.3845	36.7097
18	B18	Ngong	-1.3406	36.6835
19	B19	Ngong	-1.3340	36.6782
20	B20	Ngong	-1.3502	36.6601
21	B21	Ngong	-1.3719	36.6653
22	B22	Ngong	-1.3363	36.6715
23	B23	Ngong	-1.3510	36.6589
24	B24	Ngong	-1.3384	36.6785
25	B25	Mericho	-1.3914	36.6893
26	B26	Ngong	-1.3693	36.6571
27	B27	Ngong	-1.3388	36.6813
28	B28	Rongai	-1.4231	36.6858
29	B29	Ngong	-1.3591	36.6573
30	B30	Ngong	-1.3712	36.6597
31	B31	Rongai	-1.3894	36.7459
32	B32	Rongai	-1.3886	36.6769
33	B33	Ngong	-1.3513	36.6604
34	B34	Ngong	-1.3451	36.6651
35	B35	Ngong	-2.3569	36.6750
36	B36	Ngong	-1.2564	36.6731

The existing inventory of the boreholes in the area was acquired from the WRA regional groundwater office. Using the available inventory data, boreholes were sampled and prioritized on the basis of completeness of data. This borehole data was used to characterize the groundwater yield and water rest levels.

3.4.2 Demographic Data of The Catchment population

The catchment area was in Kajiado West sub-county which hosts Ongata Rongai and Ngong as the major towns. It also borders Karen area to the east. Censuses in Kenya have been carried out in 1897, 1948, 1962, 1969, 1979, 1989, 1999, 2009 and 2019 by the Kenya National Bureau of Statistics (KNBS). Based on the KNBS census and Kajiado County Integrated Development Plan and other related studies the catchment population was about 283,566 people giving an average density of 303 persons/km^2 and a population growth rate of 3.7%. This when projected will be about 1,186,485 persons by 2022 with an average density of 386 persons/km^2. The most populous town is Ngong as shown in Table 3-1 that gives the population in the catchment.

Table 3.2 Population of the Study area

Urban Centres	2009			2019			2022		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
Ongata Rongai	19,271	20,907	40,178	87,871	90,916	178,787	97,990	101,386	199,376
Ngong	52,453	51,620	104,073	62,804	64,992	127,796	70,036	67,397	137,433
Total	71,724	72,527	144,251	150,675	155,908	306,583	168,026	168,782	336,809

3.4.3 Groundwater Quality Data Analysis

Water from the boreholes sampled in the study area was analysed. The analysis was conducted from an accredited laboratory for purposes of determining the prevailing water quality that shall form a basis of analysis of water quality index. Historical water quality data from existing boreholes was obtained from some of the owners for comparative purposes.

The DR6000 Benchtop Spectrophotometer was the main equipment used to carry out the analysis. This spectrophotometer delivers top performance for routine laboratory tasks and demanding photometry applications. It offers high speed wavelength scanning across the UV and Visible Spectrum, and comes with over 250 pre-programmed methods, which include the most common testing methods. Samples were collected using labelled transparent one-litre bottles. Preprinted stickers were used to record sample details and label the bottles. Transportation of the samples shall be immediately to the lab for testing. Cool boxes were used to preserve the samples from adverse temperature changes. The selected parameters were tested according to the Standard operating procedures (SOPs) of the laboratory. The procedures were designed to ensure tests are carried out in conformance to the KS EAS 12:2018 potable water specifications standard.

The typical model for analysis was flowcharted as per Figure 3-4 below.

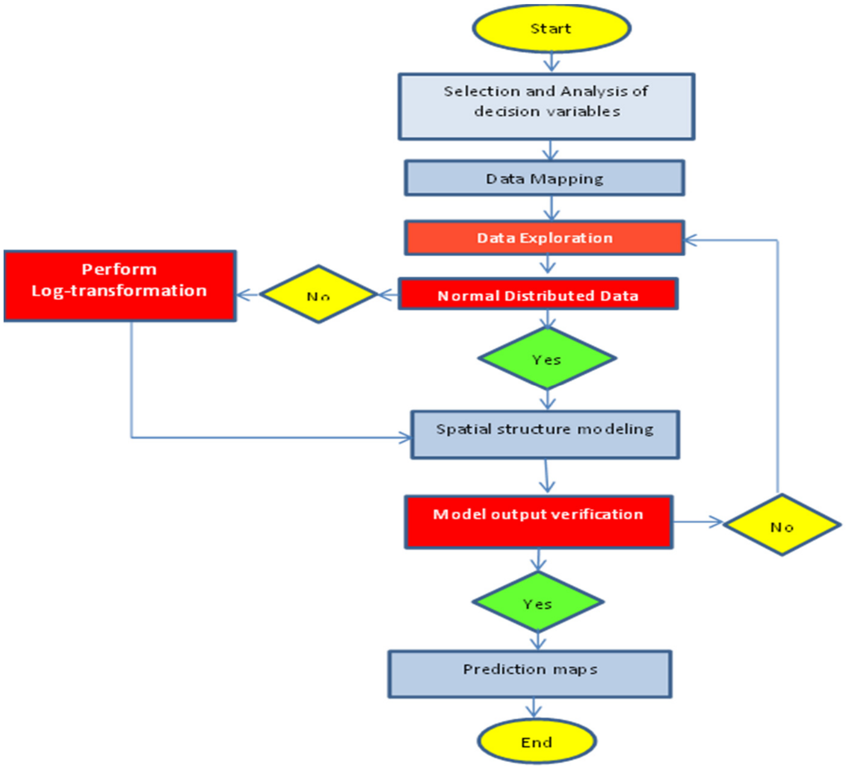


Figure 3-4 Flowchart of the data analysis, exploration and prediction maps

3.4.4 Groundwater Temporal and Spatial Variability Analysis

Using the WQI approach: -

Relative weight (W_i) of the chemical parameter was computed using the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad (1)$$

W_i refers to relative weight

w_i refers to weight of each parameter

n refers to number of chemical parameters in the analysis (Batabyal et al., 2015)

For each, relative weight (W_i) was computed as enumerated in table1 below

Chemical Parameters[a]	Kenyan Standard	Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
Fluoride	1.5	5	0.2381
Chloride	250	4	0.1905
Potassium	50	1	0.0476
Magnesium	100	3	0.1429
Calcium	250	3	0.1429
Sodium	200	2	0.0952
Nitrate	10	2	0.0952
Sulphate	400	1	0.0476
		$\sum wi$=21	$\sum Wi$ = 1.00

[a] chemical parameters in mg/l

In the third step, the quality rating was generated based on value of parameter concentration in every sample divided by the parameter respective value in the standard KS EAS 12:2018 and the result multiplied by 100.

$$q_i = \left(\frac{Ci}{Si}\right) * 100 \qquad (2)$$

q_i refers to the quality rating

C_i refers to the parameter concentration in every sample in mg/l

S_i refers to the Kenyan drinking water standard for each parameter in mg/l

The subindex (SI) for every parameter was calculated by multiplying the quality rating with its relative weight. The WQI was then calculated by summation the individual subindices for every sample (Batabyal et al, 2015). The formulas were

$$SI_i = q_i * W_i \qquad (3)$$

$$\text{WQI} = \sum SI_{\text{i-n}} \qquad (4)$$

SI_i is the sub index of i^{th} parameter;

W_i is relative weight of i^{th} parameter;

q_i is the rating based on concentration of i^{th} parameter, and n is the number of chemical parameters.

The quality data was subjected to statistical analyses using Microsoft Excel 2016 software. Correlation of the selected parameters was examined using IBM Statistical Packages for the Social Sciences (IBM SPSS) software. Correlation criterion as a statistical tool compares two variables to indicate if one variable can sufficiently predict the other by generating a correlation coefficient.

Spearman coefficient, $$\rho = 1 - \frac{6\sum d^2}{n(n^2 - 1)} \tag{5}$$

The Spearman coefficient was used to determine correlation between variables. This coefficient determines the extent of correlation of dependent variable (x) being only influenced by an independent variable (y) and vice versa. The correlation coefficient should lie between -1 and +1. Coefficient correlation values +0.7 or higher is very strong positive, +0.4 to +0.69 strong positive, +0.3 to 0.39 moderate positive, +0.2 to 0.29 weak positive, +0.01 to +0.19 negligible. Conversely, -0.7 or higher is very strong negative, -0.4 to -0.69 strong negative, -0.3 to 0.39 moderate negative, -0.2 to -0.29 weak negative. -0.01 to -0.19 negligible.

The GIS environment was used to perform spatial variability analysis in particular geostatistical wizard application in ArcGIS 10. The exploratory analysis was used to evaluate variable spatial distribution. Fitting the theoretical semivariogram was applied with distribution of variables done using Normal QQ plots. This aimed at characterizing whether the data follows a normal distribution. It was anticipated that the data shall have a normal distribution. Log transformation of the data was done in the absence of normal distribution or to improve the normal data. These methods give indication as to the nature of distribution of a variable under consideration. If skewness of a parameter was observed to be more than ±1 from the normal distribution then log transformation was performed on the data in order to realize a log-normal distribution. Mean, median and kurtosis statistics were examined from the data. Mean and median should to be close for a normal distribution. Kurtosis should be 3. From the data exploration, trends observed were analysed to determine presence of spatial variation (Gyamfi et al, 2016).

Semivariogram is a measure of the relation of data points within a particular variable to each other with respect to distance. This measure was used to assess the spatial dependency of the selected variables. Kriging assisted in generating distribution pattern from the parameters, trend analysis and fitting of the theoretical semivariogram. Kriging is designed to specially generate the models based on spatial variability.

Kriging is most appropriate when you know there is a spatially correlated distance or directional bias in the data. The general formula for Kriging is formed as a weighted sum of the data:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{6}$$

where:
$Z(s_i)$ = the measured value at the ith location
λi = an unknown weight for the measured value at the ith location
s_0? = the prediction location
N = the number of measured values

The analysis was based on the ArcGIS 10.1 geostatistical analyst model in particular ordinary Kriging. As a method of interpolation of data, Kriging is based on a statistical approach. It does weight based in specific values measured at the sampled locations. Kriging provides more than just predicted value of unsampled locations. There were additional statistical results to assist in interrogation of the data. The nugget and sill ratios of the semivariogram were used to describe the spatial dependency. Nugget/Sill ratio of < 0.25, 0.25-0.75 and 0.75 indicate strong, moderate and weak spatial structure respectively. Different semivariogram models were compared to determine the model with the best spatial structure based on the nugget and sill ratio. The best fitting model was selected based in the nugget/sill ratio formed the basis of generating the maps for predicting spatial variability using ordinary Kriging.

Mean Error (ME) and Root Mean Square Standardized Errors (RMSSE) are some of the statistical outcomes of a Kriging model.

$$\text{ME} = \frac{\sum_{i=1}^{n}\left(\hat{z}(s_i) - z(s_i)\right)}{n} \tag{7}$$

$$\text{RMSSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{\hat{z}(s_i) - z(s_i)}{\hat{\sigma}(s_i)}\right)^2}{n}} \tag{8}$$

where:
$\hat{Z}(S_i)$ = the measured value at the ith location

$Z(S_i)$ = the predicated value at the ith location
(S_i) = estimated standard error of mean of measured values
n = the number of measured values

ME is the mean difference between the measured and the predicted values. RMSSE enables to explore if the standard errors generated by the Kriging model are acceptable. For the errors to be acceptable, they should be close to 1 (Gyamfi et al, 2016). Whenever RMSSE falls below 1, most likely the variability prediction by the Kriging model is being overestimated. If RMSSE is more than 1, then the Kriging model indicates an underestimation of the variability so predicted.

Temporal variability was determined based on data collected for three seasons. The wet, moderate and dry in line with the bimodal rainfall patterns in the area. The temporal variability analysis was deduced from geostatistical analysis based on the identified seasons.

3.4.5 Selection of groundwater quality parameters

Kenyan Standard that specifies requirements, sampling and test methods for potable water intended for direct human consumption, domestic and industrial use (KS EAS 12:2018) was the basis of calculation of the WQI. Eight parameters shall be selected. These were Sodium, Fluoride, Chloride, Sulphates Calcium, Magnesium, Potassium and Nitrate. The parameters selected are part of the WHO DWQ guidelines. Groundwater is an important source of water within the Mbagathi River catchment. The concentration of the ions is largely influenced by the infiltration of water into the porous and permeable rocks during the rainy season (Mulwa et al., 2005).

The overall aim of the quality parameters selected was to provide insight of groundwater temporal variability. From the parameter test results and exploration of the quality data, it was possible to meet the study objectives. The selected parameters have varying impacts on human health according to WHO DWQ guidelines. Investigation into the prevalence of these parameters would enhance understanding the characteristics of the groundwater in the study area. The need to simulate data was considered. The chemical type of parameters were the only ones selected (Wu et al., 2011). This was to make it possible to simulate the data under the WQI model that was used. Other types of parameters such as bacteriological would pose a challenge to simulate with the chemical ones. The other criterion for parameter selection was its ability to be tested independently. This allowed the analysis of each parameter to be done without relying on outcome of any other parameter. In so doing it was possible to obtain data that can be indexed adequately. Selection of optimal number of parameters for testing was a consideration. This was to make it feasible to test and complete the study within time available. The parameters were considered to provide a good scientific basis for groundwater variability by simulation (Wu et al., 2011).

4 RESULTS AND DISCUSSION

4.1 GROUNDWATER SPATIAL VARIABILITY

Borehole records data within the study area was obtained from the Water Resources Authority (WRA). This data provided the recorded borehole yield besides other pertinent information. The average yield stood at 8.6m^3/hr based on the record of 140 boreholes obtained as per table in appendix 1. This presents a relatively fair yield given that 57% of boreholes permit are for domestic use. It underlines the relative importance in provision of domestic water supply. Other permits have been granted for institutional, commercial and agricultural uses. The drilled depth of boreholes averaged 171m. The average drilled depth provides indication of the capital investment required to develop groundwater in the study area. The observed water rest level (WRL) averaged 57m.

From the recorded borehole yield, a map of spatial variability was generated by geostatistical analysis in ArcGIS framework. Figure 4-1. Indicates groundwater yield which was observed to be higher in the central parts of Matasia and Nkoroi. Higher yield was also observed to the eastern parts of Ongata Rongai. Most of the aquifer yield is fair. The low yield observed in the North and North east area is likely due to Karen area being a discharge zone. The rate of water abstraction is greater than the rate aquifers are replenished (Mulwa et al., 2005).

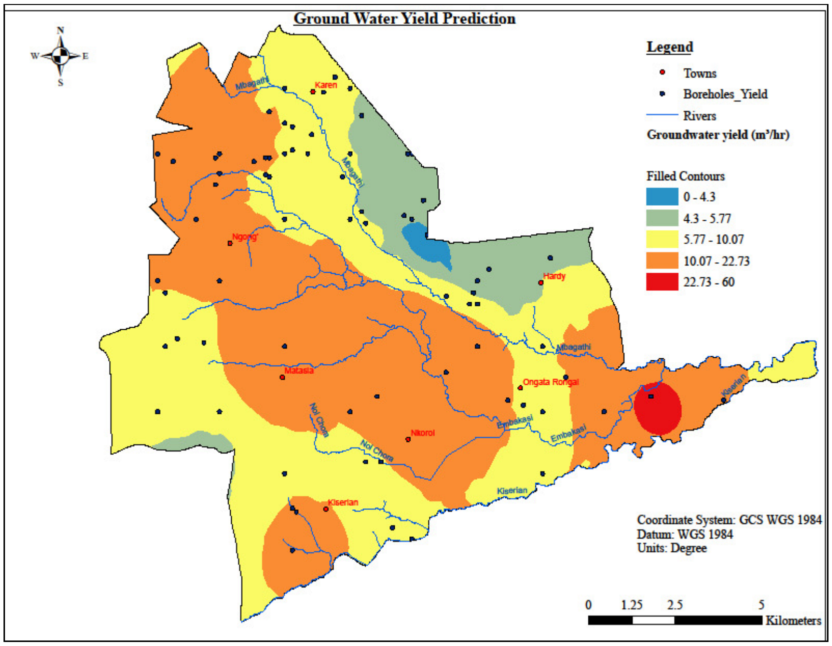


Figure 4-1Groundwater yield map and Water Rest Level of the study area

The groundwater rest level map in Figure 4-2 indicates flow is generally from the Northwest part of Ngong, Northern part of Karen and Northeast part of Hardy resting predominantly to Southwest parts of Kiserian. This strongly agrees with the altitude of the area. It was however not consistent with the yield.

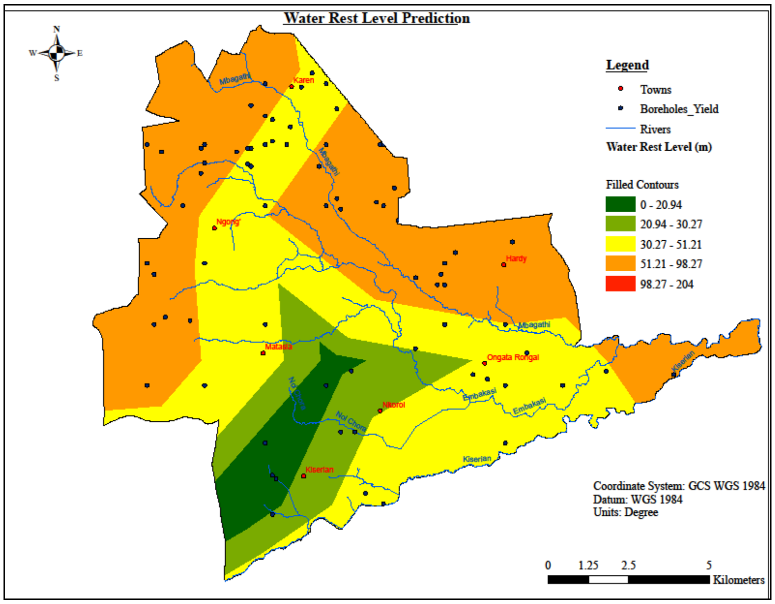


Figure 4-2 Water Rest Level map of the study area

Groundwater yield was observed to be segregated. It largely follows the river regime in the area with an exception of the North East parts. This agrees largely with Mulwa et al., 2005 who attributes the inconsistency to lithological conditions. This is further supported by the characterization of the fault lines Kiserian-Matasia area showed high water yield and rest levels. It is likely an area with high groundwater potential. The observation is consistent with Mulwa et al., 2005 who suggests that this area is a water conservation zone.

4.2 GROUNDWATER QUALITY ANALYSIS

Samples were collected from 36 boreholes and tested for Sodium, Fluoride, Chloride, Sulphates Calcium, Magnesium, Potassium and Nitrate. The tests covered three seasons wet, moderate and dry based on the bimodal rainfall patterns in the study area. The details of the water quality results for the tested parameters are in appendix 3 to appendix 5.

The basic statistics of parameters were summarized in Table 4-1. Fluoride was exceeding the permissible levels of KS EAS 12:2108 as per the Arithmetic Mean. It is typically the elevated parameter and most prevalent groundwater quality challenge in the study area. Fluoride, calcium and magnesium were exceeding the permissible levels in at least one sample as per the test results.

These combined parameters have the greatest impact on the groundwater. Calcium and Magnesium contribute to water hardness. Hardness was not covered in the scope of this study. There is marginal variability is groundwater quality over the three seasons. This informed the basis of variability prediction.

Table 4.1 Basic statistics for groundwater quality parameters

Parameters, mg/l		F^-	Mg^{2+}	Ca^{2+}	Cl^-	K^+	Na^+	SO_4^{2-}	NO_3^-
Wet	AM	1.6	29.0	53.1	106.1	15.7	16.9	8.2	0.8
	Max	3.3	99.1	163.4	243.7	25.3	43.7	28.4	2.5
	Min	0.7	2.4	12.3	36.9	6.6	6.7	2.2	0.2
Moderate	AM	1.7	25.1	46.6	102.0	15.6	18.3	8.0	0.7
	Max	3.3	94.5	116.2	211.0	24.0	49.0	30.0	2.4
	Min	0.6	0.7	11.4	38.0	5.0	6.5	1.0	0.2
Dry	AM	1.8	27.0	50.2	104.4	15.8	18.8	9.2	0.8
	Max	3.1	119.1	133.5	214.0	26.0	47.2	29.0	2.3
	Min	0.6	2.2	2.4	41.0	7.0	7.5	3.0	0.3
KS EAS 12:2018[a]		**1.5**	**100**	**150**	**250**	**50**	**200**	**400**	**10**
WHO Guidelines[a]		**1.5**	**100**	**250**	**250**	**12**	**200**	**400**	**10**

AM: Arithmetic Mean; Max: Maximum; Min: Minimum; [a]chemical parameters in mg/l

The wet season showed higher levels of calcium, magnesium and chloride. Calcium is the cation and fluoride is the leading anion with highest level of exceedance respectively.

4.3 EXPLORATION OF WATER QUALITY INDEX (WQI) DATA

The groundwater quality data was used to compute WQI which is indicated in Table 4-2. The WQI was computed using equation (1). The output as tabulated in Table 4.2 largely agree with the methods of Batabyal et al., 2015. The WQI was relied upon to perform variability analysis.

Table 4.2 WQI for the Wet, Moderate and Dry seasons

WQI for the Wet, Dry & Moderate Seasons			
BH Code	Wet	Moderate	Dry
B01	82.72	68.50	82.72
B02	47.95	37.79	44.05
B03	56.27	37.26	52.43
B04	92.25	46.30	71.73
B05	69.45	56.67	57.92
B06	79.99	53.93	63.97
B07	39.52	32.79	38.24
B08	64.80	49.03	51.12
B09	64.61	44.29	52.71
B10	58.75	46.80	48.92
B11	48.14	48.37	45.26
B12	56.44	46.90	44.15
B13	45.63	42.31	34.23
B14	56.07	46.06	45.24
B15	58.25	42.82	52.29
B16	65.10	50.36	53.70
B17	75.78	56.65	61.34
B18	54.42	43.90	44.58
B19	47.83	44.80	43.99
B20	56.26	41.40	40.30
B21	53.09	43.37	42.99
B22	45.78	33.81	35.94
B23	37.48	32.14	31.72
B24	64.64	44.28	43.81
B25	49.56	45.88	44.31
B26	30.42	22.70	24.66
B27	45.16	42.03	40.69
B28	85.54	45.20	45.60
B29	46.48	39.02	39.49
B30	46.63	40.03	39.71
B31	64.02	59.70	57.30
B32	34.07	27.76	30.28
B33	58.33	38.32	36.83
B34	61.77	61.27	54.19
B35	40.40	27.35	28.50
36	40.83	29.48	31.00

The mean, median and skewness were tabulated in Table 4-3 using the results from the ArcGIS geostatistical analysis. Under normal distribution, the mean and median should be close to equal, skewness should lie between -1 and 1 (Gyamfi et al, 2016), kurtosis should be 3. Skewness was 0.25, 0.38 and 0.98 for wet, moderate and dry seasons respectively. This was within acceptable range. The mean and median were not equal for all the seasons. The mean was closest to median for wet season but difference increased from moderate to dry seasons. Kurtosis was below 3 for wet season but above 3 for moderate and dry seasons. Log transformation was performed to determine if mean, median and kurtosis would comparatively improve.

Table 4.3 Statistics of Normal and Log-Normal data for WQI

Season	Statistic	Normal	Log-Transformed
Wet	Mean	44.18	3.76
	Median	43.68	3.78
	Skewness	0.25	-0.45
	Kurtosis	2.87	3.34
Moderate	Mean	44.19	3.76
	Median	43.48	3.77
	Skewness	0.38	-0.43
	Kurtosis	3.45	3.6
Dry	Mean	46.64	3.8
	Median	44.56	3.8
	Skewness	0.98	0.068
	Kurtosis	4.57	3.28

Mean and median improved and were equal in all seasons after log transformation to 3.8. Log-transformation methods agrees with Gyamfi et al., 2016 as a means of enhancing the geostatistical data to provide better results. Kurtosis improved for dry seasons upon log transformation from 4.57 to 3.28 becoming less leptokurtic. The marginal improvement in kurtosis was insignificant. Kurtosis however marginally deteriorated for wet and moderate seasons. In wet season, kurtosis moved from being less platykurtic to being more leptokurtic from 2.87 to 3.34. In the moderate season, kurtosis increase from 3.45.to 3.6 becoming more leptokurtic. The log transformed data for all seasons was observed to be leptokurtic indicating it will have relatively thick edges. The normal QQ plots for the normal and log-normal transformed data was explored for best fit. Figure 4-4 shows the wet and moderate seasons best of fit under normal data while dry season best fit was the log-normal transformed.

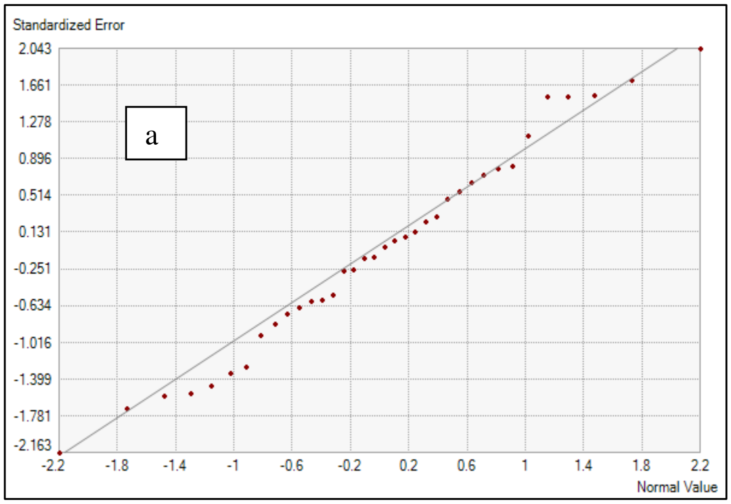


Figure 4-3 Fitted Normal QQ Plot for (a) Wet - normal distribution

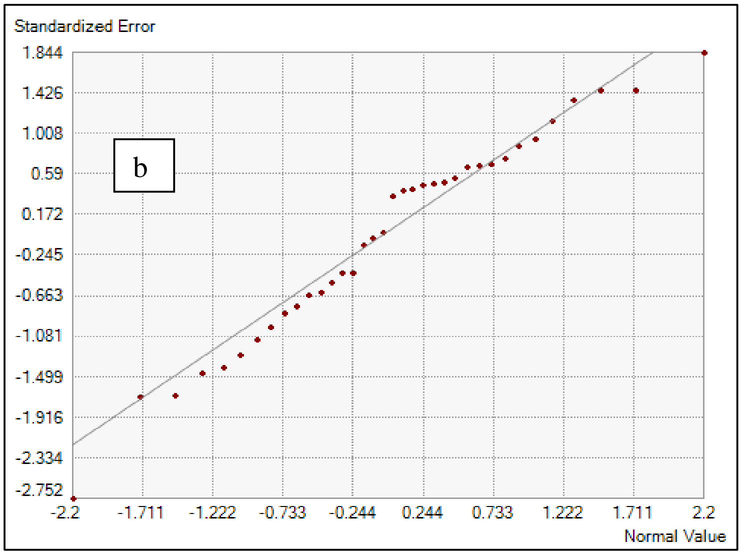


Figure 4-4 Fitted Normal QQ Plot for (b) Moderate season - normal distribution

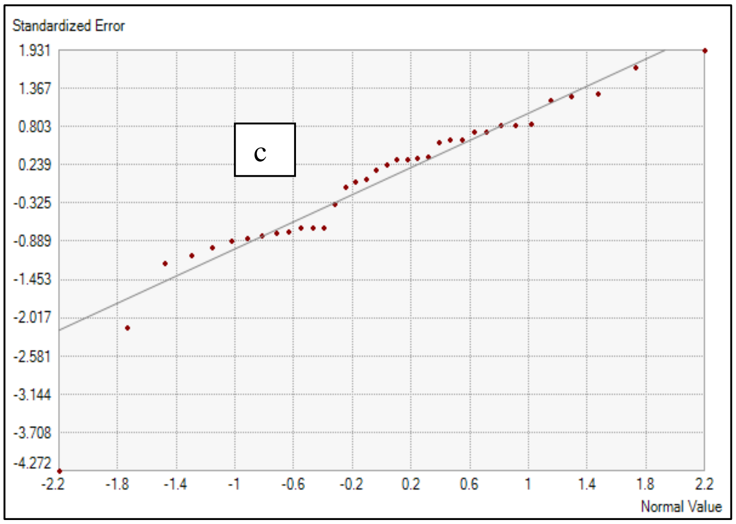


Figure 4-5 Fitted Normal QQ Plot for (c) Dry season - Log-normal distribution

The data was subjected to ordinary Kriging in ArcGIS to find the best fit model. Semivariogram models used were Stable, Gaussian, exponential, J-Bessel and spherical. The model predictions result in Table 4-4 showed the best fit model for wet season was the Exponential with nugget/sill ratio of 0. This also applied to moderate season with a nugget/sill ratio of 0.07. The nugget/sill ratio indicated a strong spatial structure dependency as displayed in Figures 4-7 and 4-8 for wet and moderate season respectively. Is selecting the semivariogram model, the approach for nugget/sill ratio concurs with Alexander et al., 2017.

Table 4.4 Summary of Normal data Semivariogram model comparison

Season	Statistic	Stable	J-Bessel	Gaussian	Exponential	Spherical
Wet	RMMSE	1.06	1.03	1.06	1.05	1.04
	ME	-0.07	-0.01	-0.07	-0.06	-0.07
	Nugget	40.11	41.90	40.11	9.36	23.61
	Sill	95.19	67.95	95.19	132.05	106.05
	Nugget/Sill ratio	0.42	0.62	0.42	0.07	0.22
Moderate	RMMSE	1.05	1.02	1.05	1.05	1.04
	ME	-0.05	-0.09	-0.04	-0.04	-0.06
	Nugget	26.00	24.72	26.00	0.00	8.74
	Sill	90.00	62.50	90.23	121.10	101.18
	Nugget/Sill ratio	0.29	0.40	0.29	0.00	0.09

RMSSE: root mean square standardized error; ME: mean error

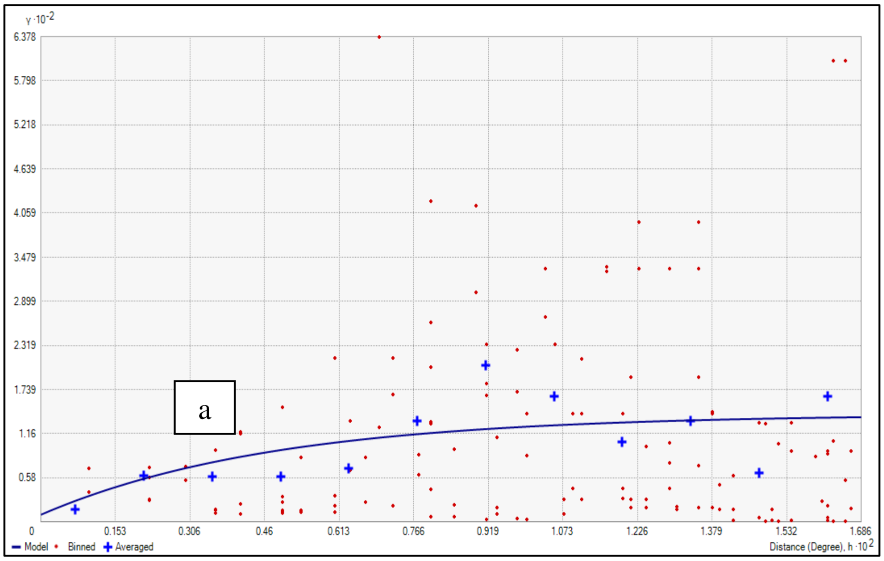


Figure 4-6 Exponential Semivariogram for (a) Wet season based on Normal data

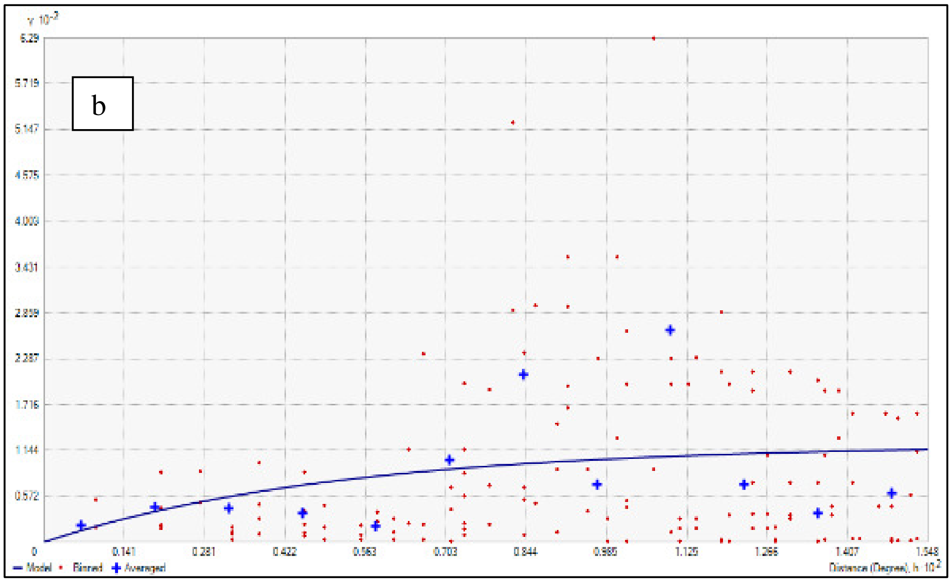


Figure 4-7 Exponential Semivariogram for (b) Moderate season based on Normal data

The best fit model for dry season was the Stable after Log-transformation with a nugget/sill ratio of 0 as shown in Table 4-5. The nugget/sill ratio indicated a strong spatial structure dependency as displayed in Figure 4-9 for the dry season.

Table 4.5 Summary of Log-Normal Semivariogram model comparison

Season	Statistic	Stable	J-Bessel	Gaussian	Exponential	Spherical
Dry	RMMSE	1.15	1.29	1.14	1.22	1.18
	ME	-0.02	-0.38	0.31	-0.19	0.19
	Nugget	0.00	0.01	0.04	0.02	0.03
	Sill	0.08	0.05	0.04	0.06	0.04
	Nugget/Sill ratio	0.00	0.19	1.09	0.34	0.71

It was anticipated that the nugget/sill ratio will be strong. This is because the groundwater quality parameters have an existing relationship. The relationship within the groundwater parameters is however complex. It is not easy to judge which parameters are more depended on others using the nugget/sill ratio. The nugget/sill ratio is generated from the data that has been indexed. It was therefore necessary to undertake further analysis to determine spatial dependency between parameters (Alexander et al., 2017).

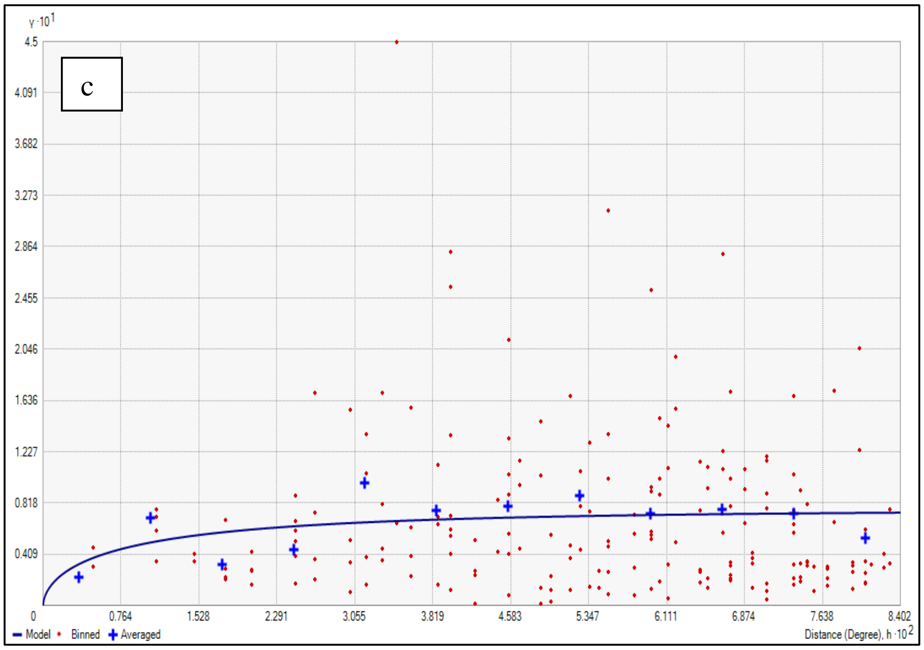


Figure 4-8 Stable Semivariogram (c) Dry season based on Log-Normal Data

The data from the sampling stations for sodium, fluoride, chloride, sulphate, calcium, magnesium, potassium and nitrate were correlated using the IBM SPSS . Spearman rho correlation coefficient was generated to determine nature of linear relationship among the parameters. Correlation of parameters is an approach that agrees with Alexander et al., (2017) and Batabyal et al., (2015) who also established the need to verify correlation of parameters used in indexing quality data. The degree of corelation informs reliability of the index data.

Table 4-6 shows in the wet season, parameters largely exhibited moderate, strong and very strong positive relationship. Chloride to sodium, calcium, magnesium, and fluoride had strong to very strong correlation. Fluoride had a moderately strong correlation with sodium, calcium, potassium and nitrate. Weak negative relationship existed between magnesium to fluoride and nitrate; fluoride to nitrate.

Table 4.6 Spearman rho correlation for wet Season

	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
Na^+	1	0.34	0.70**	0.92	0.37	0.26	0.37	0.35	0.53
F^-		1	0.64**	0.29	0.61**	0.95**	0.52	-0.21	0.62
Cl^-			1	0.98	0.22	-0.01	0.37	0.17	0.04
SO_4^{2-}				1	0.26	0.45	0.63	0.85**	0.57
Ca^{2+}					1	0.00	0.31	-0.01	0.02
Mg^{2+}						1	0.84**	0.07	0.01
K^+							1	0.59	0.87**
NO_3^-								1	0.52
WQI									1

**. Correlation is significant at the 0.01 level (2-tailed).

During the moderate season, table 4-7 indicates chlorine to sodium, fluoride calcium, magnesium and potassium had strong to very strong correlation. Fluoride had a moderately strong correlation with sodium, calcium, potassium and nitrate. Weak negative relationship existed between calcium to nitrate; and chloride to nitrate.

Table 4.7 Spearman rho correlation for moderate Season

	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
Na^+	1	0.338	0.7	0.916	0.367	0.26	0.366	0.347	0.526
F^-		1	0.642	0.285	0.61**	0.954	0.522	0.209	0.71
Cl^-			1	0.984**	0.221	0.01	0.366	-0.17	0.039
SO_4^{2-}				1	-0.26	0.451	0.626**	0.852	0.57
Ca^{2+}					1	0	0.308	-0.009	0.024
Mg^{2+}						1	0.836	0.069	0.005
K^+							1	0.59	0.873
NO_3^-								1	0.52
WQI									1

**. Correlation is significant at the 0.01 level (2-tailed).

The dry season exhibited strong to very strong correlation chloride to fluoride, sulphate, calcium, magnesium, and potassium from Table 4-8. Sodium had strong relationship with fluoride had a moderately strong correlation with sodium, calcium, potassium and nitrate. Weak negative relationship existed between magnesium to fluoride and nitrate; fluoride to nitrate.

Table 4.8 Spearman rho correlation for dry Season

	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
Na^+	1	0.848	0.384	0.678	0.535	0.912	0.664**	0.858	0.988
F^-		1	0.714**	0.716**	0.458	0.842	0.727	-0.018	0.590**
Cl^-			1	0.181	0.065	0.255	0.362	0.917	0.042
SO_4^{2-}				1	-0.129	-0.130	0.510**	0.817**	0.145
Ca^{2+}					1	0.000	0.398	0.384	0.007
Mg^{2+}						1	0.555**	0.220	0.001
K^+							1	0.909**	0.952
NO_3^-								1	0.005
WQI									1

** Correlation is significant at the 0.01 level (2-tailed).

4.4 TEMPORAL VARIABILITY BASED ON WQI

The groundwater prevalence based on WQI obtained from samples was presented using pie charts. There was no prevalence of very good groundwater quality present as per the analysis. The WQI indicated that groundwater deteriorated from the wet to dry seasons. The wet season exhibited 36% good quality as indicated in Figure 4-9, which was highest compared to 33% and 28% for moderate and dry seasons as indicated in Figure 4-10 and Figure 4-11 respectively. The fair groundwater quality remained the same at 58% for both the wet and moderate season but increased marginally to 61% in the dry season. The increase in the dry season can be attributed to the decline in good quality in the same season. The increase in the poor quality is noted from the wet to dry seasons. 6% of the sampled stations recorded poor quality in wet season. Poor quality increased to 8% in moderate and dry season. The dry season recorded very poor-quality water at 3%.

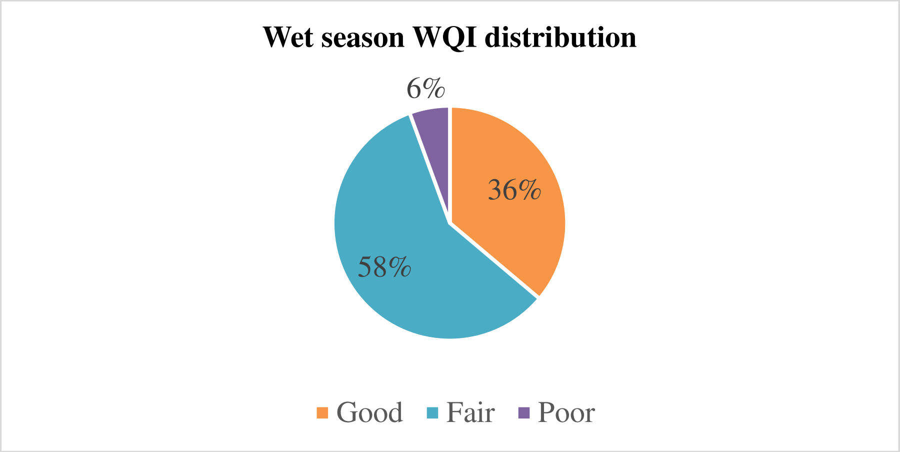


Figure 4-9 Wet season WQI

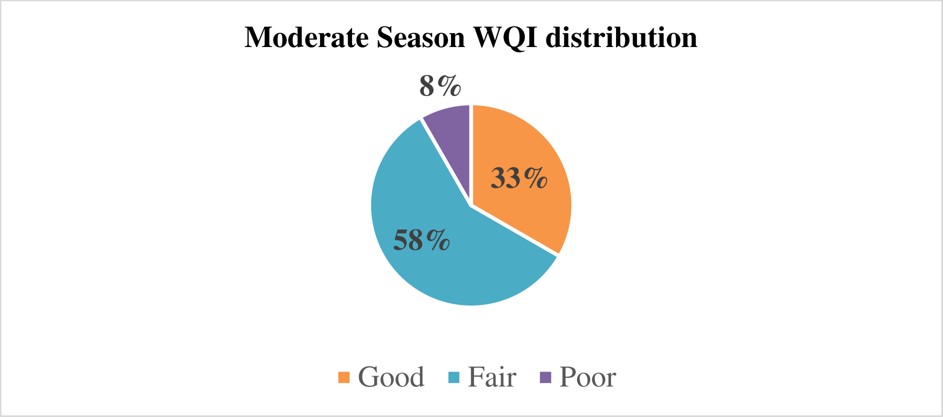


Figure 4-10 Moderate season WQI distribution

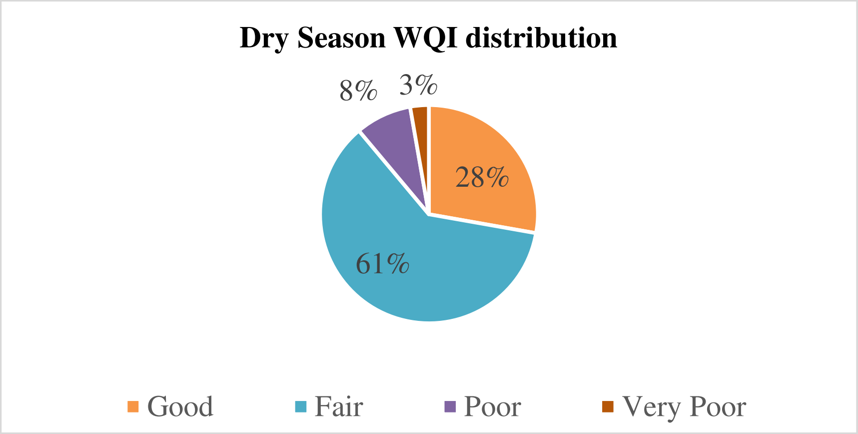


Figure 4-11 Dry season WQI distribution

The WQI temporal variability was mapped in ArcGIS during the three seasons and under combined condition as shown in Figure 4-13 to Figure 4-16. During wet season, the prevalence of the 58% fair quality was mainly in the south, central and eastern parts. This represented the Matasia, Kiserian and Nkoroi areas. Central and Southern parts had the highest recorded yield and highest water rest level.

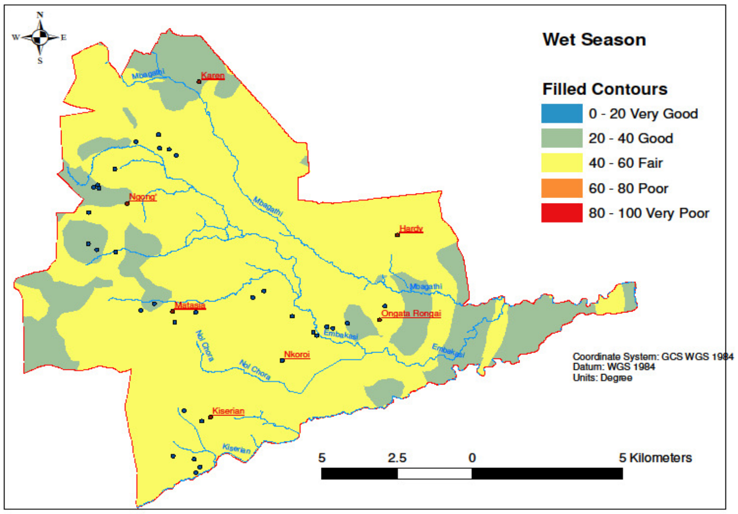


Figure 4-12 Temporal variability of sampled stations in wet season

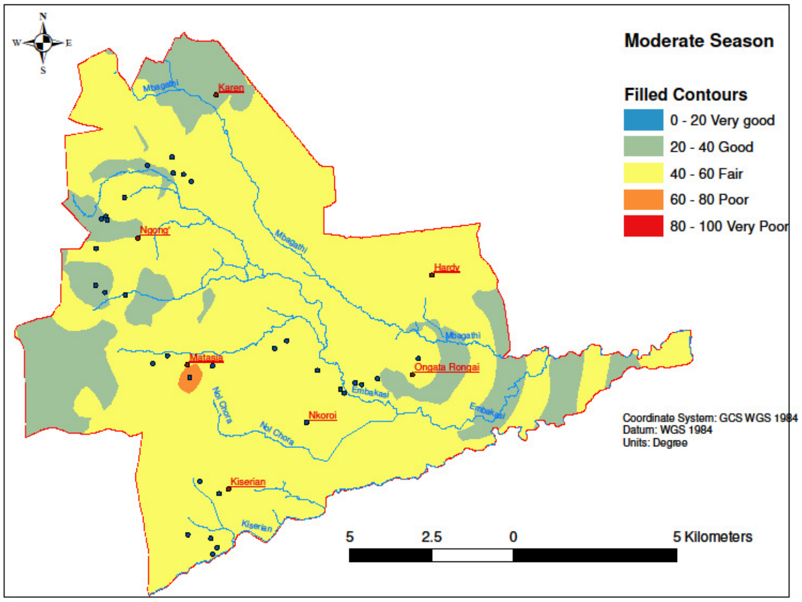


Figure 4-13 Temporal variability of sampled stations in Moderate season

Quality deteriorated marginally in the moderate season. Good quality in the south east dropped marginally increasing the poor quality in the central parts of Matasia. In the dry season there was an increase in poor and very poor-quality totalling to 11% of the sampled sites within the central to the southern parts. Good quality water was largely recorded in the North and West during the dry season.

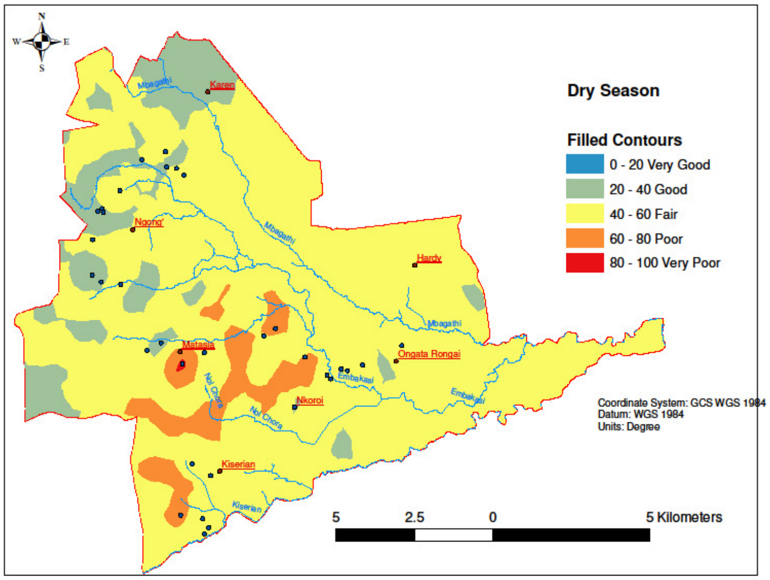


Figure 4-14 Temporal variability of sampled stations in dry season

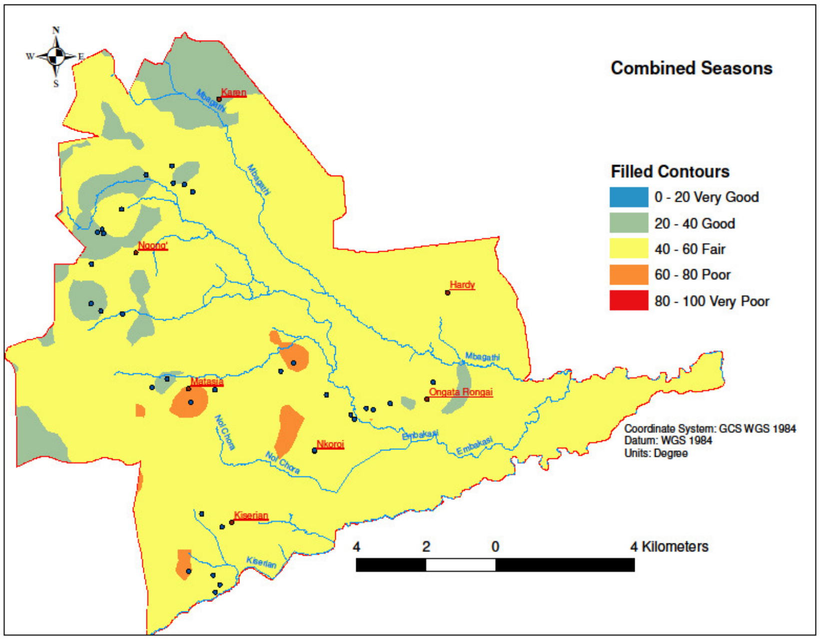


Figure 4-15 Temporal variability of sampled stations for combined seasons

4.5 MODEL VALIDATION

The WQI Kriging model was evaluated for credibility. Four sampling stations used in the calculation of WQI were randomly removed from data for the wet, moderate and dry seasons. The objective of removing the four sampling stations was to check how the model performed Which results they presented for the RMSSE and ME were used to evaluate the model performance. Removal of parameters randomly to test the model is an approach that agrees with Alexander et al., (2017). Gyamfi et al., (2015) approach relied on the nugget/sill ratio to justify the models used which differs from the apporach of this study that relies of removal of select parameters. Consequently reduction in the number of parameters in validating groundwater quality without much loss of information agrees with Hafizan et al., (2004).

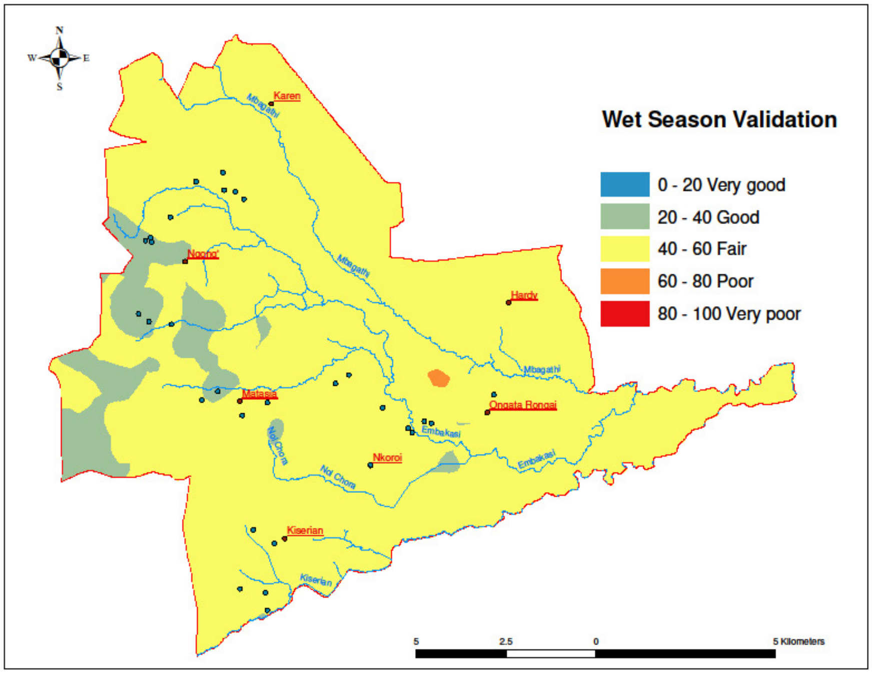


Figure 4-16 Model validation output for wet season

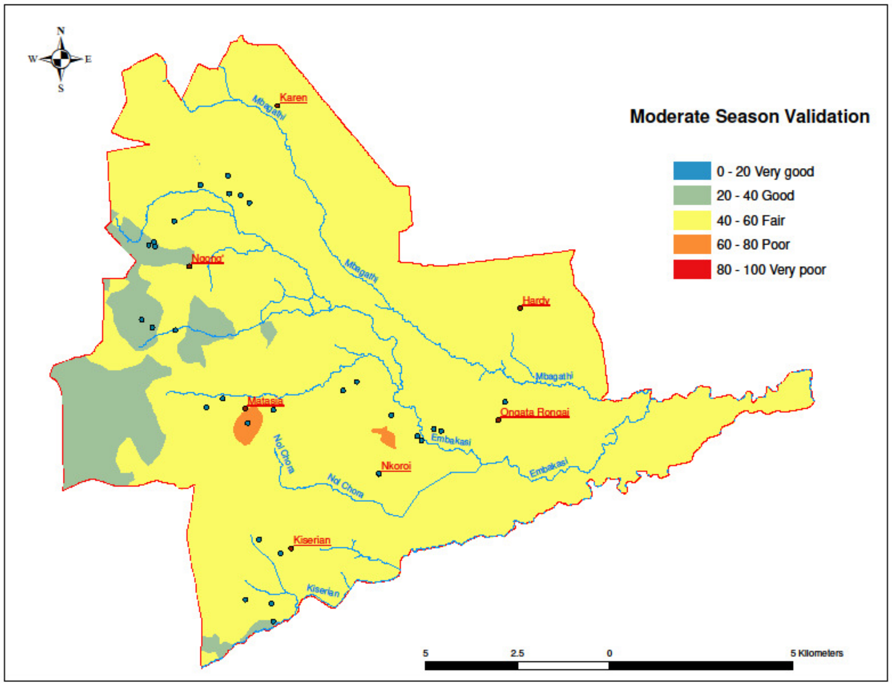


Figure 4-17 Model validation output for moderate season

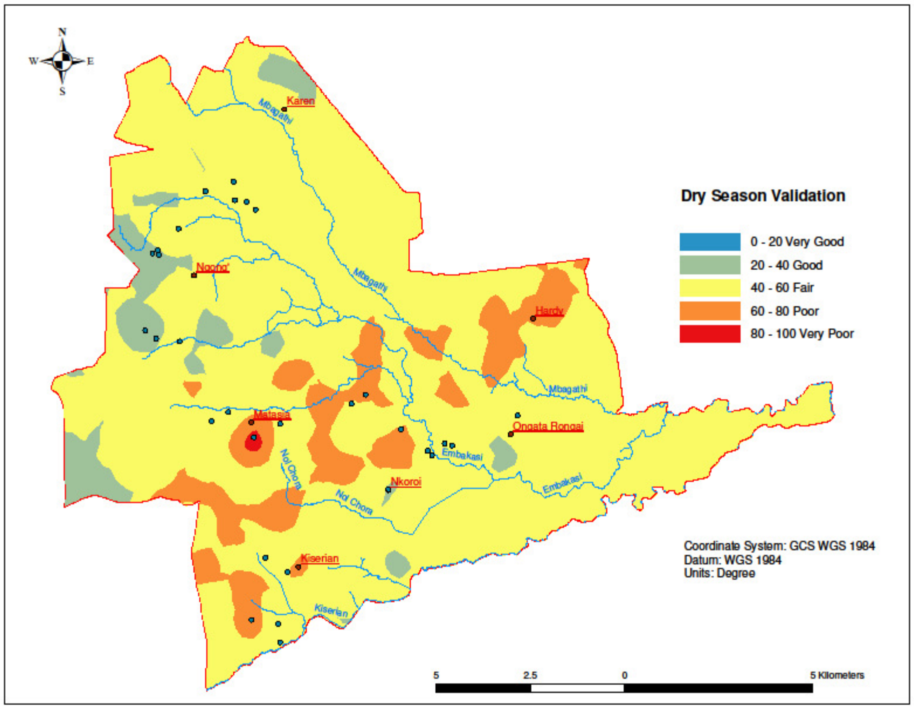


Figure 4-18 Model validation output for dry season

The validation model gave a fair result of RMSSE between 0.98 – 1.02 for stable and exponential semivariogram as displayed in Table 4-9. ME was between -0.04 to -0.08. Both cases the model was within the expected range of RMSSE and ME. The tests done have shown spatial and temporal distribution of groundwater in Mbagathi River catchment. The model has differentiated the areas with scarce water resources and those with high water resources.

Table 4.9 Summary statistics for the model validation

Season	Statistic	Stable	Exponential
Wet	RMMSE	1.02	1.00
	ME	-0.08	-0.07
Moderate	RMMSE	0.98	0.97
	ME	-0.06	-0.05
Dry	RMMSE	1.07	1.00
	ME	-0.06	-0.04

4.6 IMPLICATIONS OF RESEARCH FINDINGS

With dwindling surface water sources, there is increasing dependence on groundwater as an alternative source. Increased utilization of groundwater sources continues with little monitoring of quality and quantity. To harness the groundwater for various uses, understanding its variability in quality and quantity is vital for sustainable exploration of this important resource.

The characterization of the spatial variability of the groundwater yield shall enable abstraction management. WRA can use the results to recommend maximum allowable abstraction volumes for the boreholes licensed in the area. This will in turn enhance sustainable use of the scare groundwater resources. Using the findings, and if the aquifer characteristics can be established, though beyond the scope of this study, models such as decision support systems can be developed to assist is apportionment of maximum allowable abstraction volumes.

The outcome of this study shall be useful in assisting investments in the exploration of groundwater. Development of boreholes is financially demanding. Before someone considers to invest, advance information about the potential of groundwater will be helpful in anticipating the likely outcome of the investment. From an economic point if view, this study will greatly assist in guiding feasibility of the groundwater exploration in the area

The WQI has been useful in showing the quality of groundwater in temporal basis. It is therefore possible to know the anticipated groundwater quality impacts of abstracted water. In dry season, quality generally deteriorates. This will require that precautionary measures are put in place particularly for the affected areas to minimize the potential negative health impacts of the poor DWQ.

The study has revealed the prevalent high fluoride levels. The need to enhance water treatment using appropriate technologies should be prioritized. The water services regulatory board in conjunction with other relevant statutory agencies shall require to step up efforts in ensuring the unsuspecting public do not consume water that does not meet the required DWQ standards. Using the results of this finding it will be possible to identify the areas to focus on.

In the event of emergencies, groundwater has been shown to be a reliable option for water for public use (Takahiro, 2022). A case in point is during Covid-19, Athi Water Works Development Agency undertook a massive groundwater development especially in the low income and peri-urban areas of Nairobi city (https://www.awwda.go.ke/2020/04/30/ongoing-covid-19-water-interventions/ , 2022) . Using this study, potential areas for good groundwater yield can be identified faster in tandem with specific hydrogeological surveys.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In the study area, 57% of the boreholes have a good yield of 8.3m^3/hr able to cater for domestic purposes. The yield largely follows the rivers drainage regime in the basin. Groundwater yield is more available along the central and south east. From this study, it can be concluded that there exists temporal and spatial variability of groundwater. Wet seasons are likely to have better groundwater quality than the dry and moderate seasons. Groundwater quality can be deduced to deteriorate with decrease in rainfall.

Use of WQI and geostatistical tools in a GIS framework enabled synthesis of different quantity and quality parameters into an understandable format. WQI is a good approach that can be used to characterize temporal groundwater variability. Geostatistical tools provide a platform to model and view the data. This agrees with Alexander et al., 2017 and Gyamfi et al., 2016. Kriging in particular is a reliable geoprocessing and modeling tool with which temporal and spatial variability can be predicted. It further provides relevant statistical bases of not only predicting but also verifying the model reliability.

Spatial variability was established using the borehole yield and water rest level data obtained from the WRA records as at the time of drilling. Spatial variability was observed, with the Northwest and Southwest parts of Ngong, Matasia and Ongata Rongai respectively recording good and fair quality. From the study, it is possible to identify the areas with low groundwater yield and poor quality for further investigations.

The decline of 5% in groundwater quality during wet to dry seasons in sample stations indicates the temporal variability of the groundwater. This decline in quality agrees with Nyakundi et al., 2015, who also noted the decline in groundwater in dry weather. The decline implies poor DWQ occurs with relative decline in rainfall. Such decline is detrimental to human health if the water is consumed without proper treatment. For portable DWQ, temporal variability as characterised, reveals the need for close monitoring of abstracted water. Deteroriation in DWQ should be addressed by treatment of the groundwater.

The central parts of Matasia and Kiserian are seen to harbour the greatest decline quality. These same parts have relatively high yield and water rest levels. It is likely that the deterioration in quality can be associated with the flow of groundwater beneath the earth surfaces. Groundwater in the study area can be termed as 36% - 28% good, 58% - 61% fair, and 6%-11% poor for drinking based on its hydrochemistry barring the elevated fluoride content in some areas.

The best fit semivariogram was the exponential and stable models. There is observed strong spatial dependency for all the three seasons. Using correlation analysis there was strong to very strong similarities.

5.2 RECOMMENDATIONS

A noticeable declining groundwater quality trend is observed from wet to dry seasons. Elevated groundwater quality deterioration in areas with higher yield and water rest level was also observed. Additional biological and physiochemical parameters can be added to the analysis and with longer periods of sampling to generate more models.

Despite the successful use of these geostatistical tools to predict the variability of groundwater, more sampling stations and longer periods of monitoring would enhance the prediction. Using the maps generated, at 95% confidence, quality within a given area can be estimated. This shall inform groundwater development options before drilling.

It is necessary for the public to be informed of the risks associated with the decline in water quality. Water Service Provider and Water Services Regulatory Board can work together to realize this objective.

It will be beneficial for WRA to have a real time monitoring framework. Smart level sensors, digital quality sensors and smart water meters can be used to collect and transmit data in a programmed manner over longer periods of time. This can be done from existing sample monitoring boreholes in the study area.

The temporal and spatial variability of groundwater should continue beyond the period of this study. Periodic studies over longer timeframes shall be of great contribution to deepening the understanding of the variability in the study area. This will require to consistently perform groundwater quality analysis for similar parameters over a period of time. To increase the chances of this recommendation being realized, a knowledge sharing platform of published studies shall be of great benefit.

Modelling continues to inform innovations. I recommend other applicable models to be used to establish temporal and spatial variability of groundwater in the study area. Other models of indexing data can be explored to provide data that can be modelled to establish the temporal and spatial variability in the study area.

This study can be complimented by other related studies. I suggest that if studies such as aquifer characteristics variability can be done, they can complement the findings from this study area and beyond.

REFERENCES

Alexander A. C., Ndambuki J., Salim R., 1 and Manda A., (2017). Assessment of Spatial Variation of Groundwater Quality in a Mining Basin, *Journal of Sustainability*, 9, 823; doi:10.3390/su9050823

Athi Catchment Area (ACA) – Machakos (06/11/2018 05:24:26AM) http://www.wra.go.ke/athi-catchment-area-aca-machakos/

Augusto F., O., Soares, W. and Fernandéz, C.I. (2016) Mapping of the Water Table Levels of Un-confined Aquifers Using Two Interpolation Methods. *Journal of Geographic Information System*, *8,* 480-494. http://dx.doi.org/10.4236/jgis.2016.84040

Babiker, I.S.; Mohamed, M.A.; Hiyama, T. (2007). Assessing groundwater quality using GIS. *Water Resour. Manag*., 21, 699–715. doi:10.1007/s11269-006-9059-6.

Barasa M, Crane E, Upton K, Ó Dochartaigh BÉ and Bellwood-Howard I. (2018). Africa Groundwater Atlas: Hydrogeology of Kenya. British Geological Survey. Accessed 31/10/2018 02:59:36PM. http://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Kenya

Batabyal A. K. & Chakraborty S. (2015). Hydrogeochemistry and Water Quality Index in the Assessment of Groundwater Quality for Drinking Uses *Water Environment Research*, *87(*7) doi:10.2175/106143015X14212658613956

Constitution of Kenya, 2010

Forkuor G., Pavelic P., Asare E. & Obuobie E. (2013) Modelling potential areas of groundwater development for agriculture in northern Ghana using GIS/RS, *Hydrological Sciences Journal*, 58:2, DOI: 10.1080/02626667.2012.754101

Gyamfi C., Ndambuki J. M., Diabene P. Y., Kifanyi G. E., Alexander A. and Githuku C. R. (2016). Using GIS for Spatial Exploratory Analysis of Borehole Data: A Firsthand Approach towards Groundwater Development *Journal of Science and Technology*, *36*(1) http://dx.doi.org/10.4314/just.v36i1.7

Hafizan J., Sharifuddin M. Z., Mohd E. T., Mazlin M., Hasfalina C. M., (2004). Application Of Artificial Neural Network Models for Predicting Water Quality Index *Jurnal Kejuruteraan Awam* 16(2): 42-55

Hashemi H., Berndtsson R., Kompani-Zare M., and Persson M., (2013). Natural vs. artificial groundwater recharge, quantification through inverse modelling *Journal of Hydrology and Earth System Sciences*, *17*, 637– 650, www.hydrol-earth-syst-sci.net/17/637/2013/

https://www.awwda.go.ke/2020/04/30/ongoing-covid-19-water-interventions/

https://www.unigrac.org/sites/default/files/resources/files/GWMATE%20briefing%20notes%20-%20Resource%20Management.PNG

http://www.worldbank.org/en/programs/cooperation-in-international-waters-in-africa

Thomann, J. A., Werner, A. D., Irvine, D. J., Currell, M. J., (2020) Adaptive management in groundwater planning and development: A review of theory and applications, *Journal of Hydrology*, *586*, https://doi.org/10.1016/j.jhydrol.2020.124871.

Kenya National Bureau of Statistics. (2009). Population and Housing Census. Nairobi: Government Printer.

Kenya National Bureau of Statistics. (2019). 2019 Kenya Population and Housing Census: Volume I, Nairobi: Government Printer.

Kenya's Giant Aquifer Highlights Groundwater's Critical Role (31/10/2018 02:59:36PM) https://news.nationalgeographic.com/news/2013/10/131002-kenya-aquifer-lotikipi-groundwater/

Khairul, H., Sondipon, P., Tareq, J. C., & Antipova, A., (2021). Analysis of groundwater table variability and trend using ordinary kriging: the case study of Sylhet, Bangladesh *Applied Water Science*, 11:120 https://doi.org/10.1007/s13201-021-01454-w

Kourgialas N. N. & Karatzas G. P. (2015) Groundwater contamination risk assessment in Crete, Greece, using numerical tools within a GIS framework, *Hydrological Sciences Journal*, 60:1, 111-132, DOI: 10.1080/02626667.2014.885653

Li, B., Rodell, M., Famiglietti, J. S., (2015). Groundwater variability across temporal and spatial scales in the central and northeastern U.S. *Journal of Hydrology* 525

Linuz A., & Mattias O., (2021). Effect of fluoride on drinking water *Journal of Political Economy*, *129*(2)

Llamas, M. R. and Martínez-Santos, P., (2005). Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts *Journal of Water Resources Planning and Management*, ASCE editorial, S7 - 342

Mogaka H., Gichere S., Davis R. and Hirji R. *Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management* World Bank Working Paper No. 69, 2006

Mulwa, J.K., Gaciri, S.J., Barongo, J.O., Opiyo-Akech, N. And Kianji, G.K. (2005). Geological and Structural Influence On GroundwaterDistribution And Flow In Ngong Area, Kenya *African Journal Of Science And Technology (AJST) Science And Engineering Series 6*(1),

Musonge P., Matere C., Dierker K & Delaire C., (2022). Kenya Institutional Framework for Water Supply www.Globalwaters.org/real-water

Mwamati F T., Kitheka J U. and N Peter G., (2017) An Assessment of the Spatial and Temporal variations of Groundwater quality in Yatta Plateau in Kitui County, Kenya *Journal of Environment and Earth Science.7*(1), ISSN 2225-0948

Naoum S. & Tsanis I.K. (2004) *Ranking Spatial Interpolation Techniques*

Nektarios N. Kourgialas & George P. Karatzas Groundwater contamination risk assessment in Crete, Greece, using numerical tools within a GIS framework, *Hydrological Sciences Journal, 60*(1), DOI: 10.1080/02626667.2014.885653

Nelson D., (2002). Natural Variations in the Composition of Groundwater. *Groundwater Foundation Annual Meeting Report*.

Nelson, N. L., Nemerow, Franklin, J. A., Patrick S., and Joseph A. S., (2009) *Environmental Engineering: Water, Wastewater, Soil and Groundwater Treatment and Remediation* (6th Ed.) John Wiley & Sons

Niranjannaik, M.; Kumar, A.; Beg, Z.; Singh, A.; Swarnkar, S.; Gaurav, K., (2022) Groundwater Variability in a Semi-Arid River Basin, Central India. *Hydrology 9(*222). https://doi.org/10.3390/

Pavelic, P.; Giordano, M.; Keraita, B.; Ramesh, V; Rao, T. (Eds.). 2012. *Groundwater availability and use in Sub-Saharan Africa*: A review of 15 countries. Colombo, Sri Lanka: International Water Management Institute (IWMI). 274 p. doi: 10.5337/2012.213

Peck A., Gorelick S., Marsily G., Foster S. & Kovalevsky V., (1988) *Consequences of spatial variability in aquifer properties and data limitations for groundwater modelling practices* International Association of Hydrological Sciences (IAHS), Publication No. 175

R.M. Nyakundi, M. Makokha, J.K. Mwangi & C. Obiero (2015) Impact of rainfall variability on groundwater levels in Ruiru municipality, Kenya, *African Journal of Science, Technology, Innovation and Development*, *7*(5), DOI: 10.1080/20421338.2015.1085157

Saggerson, E.P., (1991). *Geology of the Nairobi area.* Rep. No.98, Geol. Surv. Kenya.

Said N., Ronald C., Graham H., David M., Abdul M. M., (2017) *Delineation of Soil Management Zones for Variable-Rate Fertilization: A Review,*

Samantha Marshall (2011), The Water Crisis in Kenya: Causes, Effects and Solutions, *Global Majority E-Journal*, 2(1)

Takahiro, E., Tomoki, I., Hitomi, K., & Nahoko, H., (2022). Groundwater as emergency water supply: case study of the 2016 Kumamoto Earthquake*, Japan Hydrogeology Journal* 30

Tamiru, A. A., (2010). An overview of the transboundary aquifers in East Africa, *Journal of African Earth Sciences*, 58(4), https://doi.org/10.1016/j.jafrearsci.2009.10.003.

Understanding-the-Kenyan-Water-Act-2016.pdf (25/09/2018, 9:28:PM) https://www.2030wrg.org/wp-content/uploads/2016/12/Understanding-the-Kenyan-Water-Act-2016.pdf

Vaux, H. (2011). Groundwater under stress: the importance of management. *Environ Earth Sci 62*. https://doi.org/10.1007/s12665-010-0490-x

WHYMAP and the Groundwater Resources Map of the World 1:25,000,000 (31/10/2018 03:05:57) http://www.springerlink.com/index/10.1007/978-90-481-3426-7_10/
World Health Organization. *Guidelines for drinking-water quality [electronic resource]:*

Wu, S., Hu, Y., Zuo, D., (2011) Discussion on Parameter Choice for Managing Water Quality of the Drinking Water Source*, Procedia Environmental Sciences* 11

Yirdaw, M., & Bamlaku, A., (2016). Drinking water quality assessment and its effects on residents' health in Wondo genet campus, *Ethiopia Environ Syst Res 5*(1)

APPENDICES

Appendix 1: Boreholes data from the study area obtained from WRA

Boreholes Data from WRA

	ID	CODE	X	Y	TDEPTH	M_WSL	WRL	YIELD
1	1368	C1368	36.866	-1.65	183	34	24.4	1.62
2	10053	C10053	36.808	-1.29	252	228	114	4.2
3	10375	C10375	36.733	-1.366	256	252	97.3	6.48
4	9775	C9775	36.833	-1.5	200	108	55.2	3
5	10082	C10082	36.679	-1.334	100	80	58	7.2
6	6215	C6215	36.675	-1.335	160	30	5	11.8
7	6208	C6208	36.678	-1.334	140	60	32	12
8	6484	C6484	36.679	-1.339	120	30	33	12
9	6524	C6524	36.683	-1.325	134	128	88	13.2
10	10615	C10615	36.683	-1.254	179	156	105	10
11	10236	C10236	36.733	-1.372	250	205	90.4	5.46
12	3337	C3337	36.766	-2.066	138	137	62	4.98
13	11361	C11361	36.745	-1.3983	150	108	112	3.96
14	9005	C9005	36.119	-2.057	200	186	45	15.9
15	10339	C10339	36.625	-1.25	250	162	86.2	3
16	56	C56	36.666	-1.3	73	66	11	10.8
17	10057	C10057	36.679	-2.525	200	120	57	4.38
18	6094	C6094	36.679	-1.322	138	68	65	4.2
19	10001	C10001	36.685	-1.326	212	142	61.6	4.38
20	11045	C11045	36.685	-1.332	182	140	30.2	3.36
21	10137	C10137	36.689	-1.333	115	84	24.3	9
22	10235	C10235	36.69	-1.328	202	140	43.8	10.1
23	11246	C11246	36.693	-1.317	202	162	19.7	5.54
24	10928	C10928	36.696	-1.301	200	156	30.2	7.62
25	7396	C7396	36.696	-1.313	104	96	28	12
26	10056	C10056	36.698	-1.339	212	92	63	8.28
27	20	C20	36.7	-1.316	98	0	78.7	6.78
28	891	C891	36.7	-1.3	58	41	15	7.32
29	900	C900	36.7	-1.316	152	141	85.9	9.6
30	83	C83	36.7	-1.333	108	106	87	1.86
31	2489	C2489	36.7	-1.35	138	130	82	4.08
32	10200	C10200	36.703	-1.323	249	136	98	4.38
33	10580	C10580	36.703	-1.348	300	276	74.4	2.22
34	10129	C10129	36.715	-1.333	180	112	86	7.2
35	10524	C10524	36.716	-1.333	118	40	19.5	9.54
36	41	C41	36.716	-1.333	149	104	73	4.5
37	173	C173	36.716	-1.316	141	121	64	0.66
38	10075	C10075	36.719	-1.305	227	95	18.3	10.5
39	6064	C6064	36.719	-1.345	200	171	108	1.98
40	9951	C9951	36.725	-1.37	301	260	103	2.4
41	10055	C10055	36.732	-1.369	240	228	74.8	2.64
42	10432	C10432	36.733	-1.333	183	158	72.2	4.5
43	10201	C10201	36.75	-1.348	210	126	88	7.92
44	10752	C10752	36.763	-1.332	305	236	127	3.12
45	10302	C10302	36.828	-1.345	250	100	98.3	7.56
46	10625	C10625	36.704	-1.351	270	98	69	8.4
47	2254	C2254	36.7	-1.333	179	170	15.9	7.8

48	2443	C2443	36.683	-1.3	61	51	19	10.9
49	2248	C2248	36.733	-1.35	123	121	85	13.6
50	2205	C2205	36.7	-1.316	131	70	35	1.38
51	7220	C7220	36.714	-1.349	324	300	95	3.3
52	9983	C9983	36.716	-1.35	198	152	76	3.48
53	9062	C9062	36.718	-1.322	177	150	86.5	0.84
54	1126	C1126	36.633	-1.3	216	207	204	1.14
55	3576	C3576	36.683	-1.416	137	17	0	0.48
56	4867	C4867	36.683	-1.416	102	76	15	10.8
57	1259	C1259	36.685	-1.436	142	16	9	20.4
58	4199	C4199	36.685	-1.425	270	192	30	21.4
59	4863	C4863	36.686	-1.426	94	64	15	4.86
60	5161	C5161	36.7	-1.4	150	43	24.8	9
61	9727	C9727	36.704	-1.413	90	87	29.5	10
62	10439	C10439	36.707	-1.396	94	56	16.2	12.6
63	10521	C10521	36.755	-1.486	100	74	33	6.3
64	11267	C11267	36.764	-1.497	150	136	22	13.3
65	10741	C10741	36.704	-0.704	156	146	74	19
66	10328	C10328	36.72	-1.354	280	267	102	2.28
67	11355	C11355	36.726	-1.342	250	188	104	6.6
68	9647	C9647	36.729	-1.355	300	264	104	3.3
69	10931	C10931	36.729	-1.168	210	148	94.3	6.6
70	10551	C10551	36.731	-1.372	250	208	45.5	7.2
71	10696	C10696	36.733	-1.366	315	108	113	6
72	10002	C10002	36.736	-1.353	135	126	103	3.3
73	10581	C10581	36.736	-1.363	320	228	98	1.02
74	9980	C9980	36.747	-1.341	200	102	97	5.28
75	12814	C12814	36.747	1.3564	310	305	125	10.2
76	10919	C10919	36.752	-1.36	262	244	127	5.46
77	10250	C10250	36.754	-1.336	280	140	92.6	8.76
78	11360	C11360	36.76	-1.1033	325	102	106	2.29
79	10960	C10960	36.753	-1.353	190	96	109	0.84
80	4575	C4575	36.633	-1.35	196	0	122	4.8
81	2294	C2294	36.65	-1.333	155	149	16	14.1
82	5117	C5117	36.65	-1.35	117	21	9	10
83	6099	C6099	36.65	-1.366	166	124	40	13.4
84	6377	C6377	36.65	-1.366	200	52	0	3
85	9423	C9423	36.654	-1.335	140	128	23	11
86	9953	C9953	36.655	-1.381	89	88	76	6.06
87	3937	C3937	36.66	-1.35	260	225	3	35.7
88	6979	C6979	36.662	-1.382	161	141	80.1	5.76
89	10003	C10003	36.665	-1.334	131	106	10.9	7.02
90	6650	C6650	36.666	-1.338	30	16	10.1	1.2
91	1294	C1294	36.666	-1.433	182	21	9	0.2
92	4123	C4123	36.666	-1.333	255	22	36	31.6
93	6216	C6216	36.666	-1.4	265	145	145	2.7
94	5500	C5500	36.666	-1.333	148	80	36.5	22.5
95	6081	C6081	36.666	-1.366	174	128	117	4.98
96	833	C833	36.683	-1.316	55	49	14	10.4
97	1429	C1429	36.683	-1.333	101	75	10	18.9
98	1648	C1648	36.7	-1.333	104	91	37	2.16
99	588	C588	36.683	-1.35	79	56	53	9.06
100	2500	C2500	36.654	-1.355	252	152	21	8.22

101	1166	C1166	36.633	-1.316	237	217	174	4.08
102	8881	C8881	36.652	-1.369	114	78	63.7	3.96
103	8238	C8238	36.665	-1.341	120	66	34	3.3
104	7372	C7372	36.7	-1.4	113	52	23	10.5
105	10967	C10967	36.711	-1.43	80	65	48.2	2.88
106	7296	C7296	36.8	-1.366	150	83	57	8.16
107	9689	C9689	36.65	-1.366	100	74	18.9	9.3
108	4201	C4201	36.683	-1.383	155	104	16	32.7
109	4881	C4881	36.7	-1.35	137	80	52	13.5
110	10026	C10026	36.827	-1.52	102	72	50.7	1.98
111	4024	C4024	36.833	-1.5	67	60	30	24
112	93000	C93000	36.834	-1.437	200	164	80.1	2.1
113	10261	C10261	37.667	-2.367	95	93	40.9	3.9
114	10670	C10670	36.711	-1.452	126	76	80	0.84
115	6269	C6269	36.583	-1.383	80	36	30	12.9
116	4624	C4624	36.7	-1.35	230	210	33	3.12
117	10769	C10769	36.708	-1.413	82	68	35	5.1
118	5423	C5423	36.716	-1.433	112	42	17	12
119	3886	C3886	36.733	-1.383	260	225	59.1	6.75
120	5042	C5042	36.733	-1.383	150	112	29	5.04
121	10132	C10132	36.741	-1.397	75	56	34	6.6
122	11129	C11129	36.748	-0.386	154	116	40	4.6
123	4713	C4713	36.75	-1.383	150	138	43	13.6
124	4843	C4843	36.75	-1.416	132	35	35	9.64
125	5368	C5368	36.75	-1.383	125	100	46	6.6
126	6322	C6322	36.75	-1.4	133	62	35	4.02
127	6325	C6325	36.75	-1.4	151	110	66	5.46
128	6318	C6318	36.75	-1.4	200	100	20.5	5.52
129	5369	C5369	36.75	-1.383	51	42	29	10.4
130	5418	C5418	36.756	-1.391	83.4	72	31.8	5.7
131	6321	C6321	36.766	-1.4	201	182	26	6
132	5009	C5009	36.783	-1.383	154	103	45	6.72
133	10932	C10932	36.797	-1.397	120	93	65.4	9
134	7336	C7336	35.85	-1.566	150	120	19	5.4
135	6494	C6494	36.65	-1.366	160	77	6	26.4
136	5798	C5798	36.65	-1.4	140	68	48.8	7.48
137	11131	C11131	36.652	-1.383	160	74	112	6.6
138	2592	C2592	36.778	-1.396	323	0	0	60
139	2639	C2639	36.724	-1.389	234	0	0	60
		Average			**171.34**	**114.37**	**56.20**	**8.56**

APPENDIX 2: Dry season ground water quality test results and WQI

Dry Season Quality Test Results and WQI									
BH Code	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
B01	0.93	38.77	7.64	0.09	15.49	20.72	4.16	0.17	87.97
B02	0.81	22.57	8.32	0.05	4.83	0.91	5.98	0.09	43.56
B03	1.34	37.32	3.90	0.05	1.26	0.93	6.76	0.04	51.61
B04	0.63	39.06	9.98	0.31	10.25	8.02	2.08	0.09	70.42
B05	0.84	31.39	5.10	0.12	11.06	7.77	5.46	0.11	61.86
B06	0.78	44.12	6.50	0.06	0.28	1.69	3.90	0.22	57.56
B07	0.69	20.11	5.10	0.05	4.41	3.97	5.72	0.04	40.08
B08	0.35	27.20	9.26	0.22	2.98	5.28	2.08	0.06	47.41
B09	0.67	37.03	2.81	0.03	3.22	4.65	2.86	0.08	51.34
B10	1.02	15.33	5.30	0.16	12.36	16.90	5.98	0.09	57.15
B11	0.84	26.47	4.78	0.06	9.47	1.90	4.68	0.03	48.24
B12	0.54	22.42	9.41	0.04	5.17	1.90	1.82	0.04	41.35
B13	0.37	11.57	7.85	0.05	5.88	5.35	4.94	0.05	36.07
B14	1.04	26.04	7.85	0.09	2.06	0.45	5.46	0.06	43.05
B15	0.79	18.81	5.41	0.09	11.06	19.01	3.64	0.04	58.84
B16	0.74	22.42	11.13	0.12	13.08	4.44	3.64	0.05	55.60
B17	1.09	29.52	4.63	0.13	10.84	15.63	5.20	0.08	67.11
B18	0.33	25.21	4.21	0.15	6.89	4.73	5.72	0.09	47.33
B19	0.36	27.71	6.40	0.06	2.54	1.10	3.38	0.04	41.59
B20	0.57	20.11	5.10	0.18	6.38	5.73	3.90	0.07	42.04
B21	0.74	22.76	3.22	0.12	9.07	7.53	2.60	0.08	46.12
B22	1.01	9.21	7.90	0.06	8.50	7.48	5.20	0.09	39.46
B23	0.34	21.15	2.70	0.05	2.05	1.59	3.38	0.06	31.33
B24	0.79	27.86	5.30	0.04	2.26	1.79	1.82	0.13	40.00
B25	0.41	24.20	4.26	0.09	6.92	5.97	4.94	0.09	46.87
B26	1.79	10.99	4.78	0.10	1.52	1.31	3.12	0.06	23.67
B27	2.05	23.67	5.62	0.09	2.74	2.05	2.34	0.03	38.58
B28	1.06	27.14	5.10	0.08	5.72	1.67	4.68	0.12	45.56
B29	0.54	20.07	4.06	0.05	11.48	3.36	3.90	0.11	43.56
B30	0.79	28.24	3.38	0.03	1.54	0.39	2.60	0.09	37.06
B31	1.19	44.04	2.18	0.12	2.41	0.62	5.46	0.07	56.08
B32	0.57	16.59	4.58	0.15	3.33	0.92	5.20	0.03	31.37
B33	0.52	25.29	3.59	0.14	1.52	0.43	3.64	0.07	35.21
B34	0.96	40.42	3.43	0.08	2.40	0.64	3.90	0.06	51.88
B35	0.57	17.13	2.44	0.09	4.15	1.31	4.16	0.08	29.93
B36	1.48	18.80	2.13	0.14	4.34	1.28	3.90	0.09	32.16

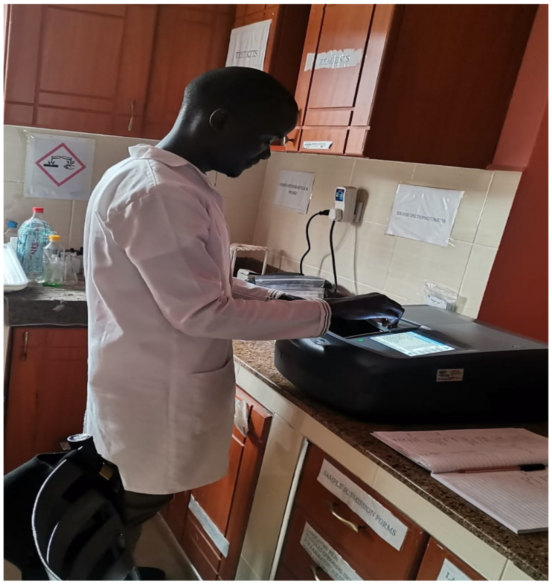
APPENDIX 3: Moderate season ground water quality test results and WQI

Moderate Season Quality Test Results and WQI									
BH Code	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
B01	17.3	2.1	153.0	2.0	116.2	94.5	14.0	1.6	72.5
B02	16.9	1.2	155.0	4.0	32.0	9.4	20.0	0.4	37.4
B03	27.9	1.7	70.0	3.0	12.0	0.7	24.0	0.2	37.5
B04	11.4	1.6	190.0	30.0	34.0	20.6	5.0	0.2	42.7
B05	18.9	2.0	97.0	11.0	88.1	53.4	21.0	1.6	60.3
B06	18.8	2.1	123.0	4.0	48.0	29.1	15.0	2.4	52.1
B07	15.2	1.1	95.0	4.0	28.0	17.0	22.0	0.6	34.1
B08	7.1	1.8	168.0	19.0	40.0	24.3	8.0	0.3	46.6
B09	13.2	1.9	57.0	1.0	48.0	29.1	11.0	0.6	45.2
B10	20.1	1.2	106.0	14.0	104.1	63.1	23.0	0.8	53.6
B11	17.3	1.9	93.0	5.0	60.1	38.9	18.0	0.2	51.0
B12	18.4	1.6	184.0	8.0	36.0	21.9	7.0	0.4	43.7
B13	6.5	1.4	150.0	1.0	41.2	25.1	19.0	0.3	42.8
B14	26.0	1.8	150.0	6.0	16.0	9.7	21.0	0.5	44.1
B15	16.7	1.1	101.0	6.0	100.1	60.7	14.0	0.8	48.1
B16	16.6	1.3	211.0	9.0	76.1	46.1	14.0	0.2	51.4
B17	22.0	2.1	89.0	11.0	92.1	55.8	20.0	0.9	61.2
B18	8.2	1.7	80.0	14.0	50.5	30.6	22.0	0.8	46.4
B19	9.5	2.0	122.0	2.0	16.8	10.2	13.0	0.3	42.3
B20	12.3	1.5	94.0	16.0	54.9	33.3	15.0	0.7	43.1
B21	14.8	1.6	59.0	6.0	72.1	43.7	10.0	0.8	46.1
B22	24.1	0.7	114.0	7.0	75.3	45.6	20.0	0.9	38.4
B23	6.8	1.5	49.0	6.0	16.0	9.7	13.0	0.7	31.6
B24	19.4	1.9	106.0	2.0	18.0	10.9	7.0	1.3	40.4
B25	8.3	1.8	84.0	9.0	60.1	36.4	19.0	0.8	48.5
B26	40.2	0.6	94.0	7.0	12.8	7.8	12.0	0.6	21.8
B27	49.0	1.7	106.0	9.0	20.0	12.1	9.0	0.2	39.7
B28	22.0	1.9	88.0	8.0	48.7	9.9	18.0	1.2	45.4
B29	12.5	1.4	74.0	5.0	97.9	20.0	15.0	1.0	43.2
B30	19.0	2.0	61.0	4.0	11.4	2.3	10.0	0.8	37.4
B31	28.0	3.2	42.0	9.0	18.0	3.7	21.0	0.6	58.2
B32	10.0	1.0	88.0	11.0	27.0	5.5	20.0	0.2	29.1
B33	14.0	1.8	69.0	10.0	12.6	2.6	14.0	0.7	36.5
B34	24.0	3.3	62.0	6.0	18.6	3.8	15.0	0.6	58.3
B35	12.0	1.1	49.0	7.0	38.4	7.8	16.0	0.7	29.1
B36	33.0	1.2	38.0	11.0	37.5	7.7	15.0	0.9	30.9

APPENDIX 4: Wet season ground water quality test results and WQI

Wet Season Quality Test Results and WQI									
BH Code	Na^+	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	NO_3^-	WQI
B01	17.6	2.1	140.1	4.8	119.3	72.4	15.2	1.7	68.2
B02	16.2	1.1	147.1	4.3	34.0	20.6	21.7	0.7	36.8
B03	26.7	1.2	67.7	3.8	20.0	12.1	25.3	0.3	31.8
B04	11.8	0.7	178.3	28.4	163.4	99.1	6.6	0.6	57.0
B05	17.3	2.2	137.3	10.6	102.5	62.2	22.2	1.5	66.6
B06	16.8	1.1	174.6	4.8	93.7	68.0	15.9	2.5	51.4
B07	14.1	1.1	135.9	4.3	30.0	56.8	23.3	0.5	42.4
B08	6.9	1.7	243.7	18.8	52.1	18.2	8.5	0.5	48.1
B09	12.9	1.3	78.2	2.2	48.1	31.6	11.6	0.7	36.2
B10	19.9	1.5	146.5	15.6	110.1	29.1	22.9	0.8	52.5
B11	16.7	1.8	130.3	5.9	54.1	66.8	17.9	0.2	55.0
B12	14.0	1.7	170.4	5.6	32.0	32.8	7.0	0.4	43.7
B13	6.9	2.1	140.5	2.8	36.0	19.4	18.9	0.4	48.7
B14	22.7	1.8	140.5	6.5	20.0	21.9	20.9	0.5	44.4
B15	15.9	1.0	95.7	6.5	110.1	12.1	13.9	0.6	38.5
B16	15.2	1.2	198.4	9.3	44.0	66.8	13.7	0.3	48.1
B17	21.4	2.3	83.1	10.7	101.5	21.9	19.5	0.8	57.3
B18	7.1	1.7	75.2	13.1	52.9	34.0	21.5	0.8	46.0
B19	8.1	2.0	114.4	3.7	18.1	26.7	12.7	0.3	43.7
B20	11.6	1.5	89.6	15.4	55.6	33.6	14.6	0.7	41.9
B21	14.4	1.6	56.5	7.9	74.2	44.1	9.8	0.8	45.3
B22	21.5	0.7	124.2	6.1	80.2	48.3	19.5	0.9	39.9
B23	6.7	1.6	47.2	5.1	17.5	10.3	12.7	0.6	32.0
B24	17.0	2.1	97.1	2.8	19.6	11.6	6.8	1.3	40.6
B25	8.0	1.9	77.5	7.9	64.2	38.5	17.7	0.8	48.9
B26	37.0	0.7	86.8	7.5	13.4	8.0	11.2	0.6	21.5
B27	43.7	1.8	99.9	7.9	21.5	12.5	8.4	0.2	38.7
B28	21.0	2.0	86.8	7.0	50.6	10.2	16.7	1.2	44.9
B29	11.3	1.4	71.0	4.7	101.8	20.6	14.0	1.0	43.1
B30	16.9	2.1	58.8	3.3	12.3	2.4	10.2	0.9	37.1
B31	25.1	3.3	39.2	9.3	19.4	3.8	21.5	0.7	57.6
B32	10.5	1.1	82.2	11.7	28.6	5.7	20.5	0.3	29.4
B33	11.8	1.9	64.4	10.7	13.3	2.7	14.3	0.7	36.0
B34	20.9	3.3	59.8	6.1	19.9	3.9	15.3	0.6	56.7
B35	11.4	1.2	44.8	7.0	39.6	8.1	16.4	0.8	29.3
B36	30.5	1.3	36.9	11.2	39.2	7.9	15.3	0.9	31.2

APPENDIX 5: DR6000 Benchtop Spectrophotometer (left) and collected groundwater samples in a cooler box (right)



Source: Aquatreat Solutions Ltd laboratory.