GROUNDWATER VULNERABILITY ASSESSMENT AS A STRATEGY FOR PROTECTING AGAINST GROUNDWATER POLLUTION: A CASE STUDY OF MID RIVER NJORO CATCHMENT, KENYA

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Groundwater Vulnerability Assessment as A Strategy for Protecting Against Groundwater Pollution: A Case Study of Mid River Njoro Catchment, Kenya

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DECLARACTION

This thesis is my original work and has not been submitted for a degree in any other University

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DEDICATION

To my late mother, Mrs. Dansoye Halake, for instilling good virtues and strong habits that have never faded even in her absentia. For the good parentage, I owe you this academic fulfilment. To my loving father Mr. Halake Rendilicha, for standing with me all through my studies. To my siblings, Galm Halake, Shakata Halake, Dokatu Halake, Somo Halake and My brother-in-law, Jirm Wako for the encouragement and support throughout my academic life.

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LIST OF ABBREVIATIONS AND ACRONYMS

APHA	American Public Health Association
ASALs	Arid and Semi-Arid Lands
CI	Contamination Index
EC	Electrical Conductivity
DRASTIC	Depth, Recharge, Aquifer, Soil media, Topography, Impact of Vadose zone, Conductivity
DO	Dissolved Oxygen
GIS	Geographical Information System
GPS	Geographic Positioning System
GQI	Groundwater Quality Index
GVI	Groundwater Vulnerability Index
IDW	Inverse Distance Weighted
KALRO	Kenya Agricultural and Livestock Research Organization
KARI	Kenya Agricultural Research Institute
KEBS	Kenya Bureau of Standards
MS	Microsoft
NH_3	Ammonia
NO_3	Nitrate
NACOSTI	National Commission of Science, Technology and Innovation.
NWWA	National Water Well Association
TP	Total Phosphorus
UNICEF	United Nations International Children’s Emergency Fund
WHO	World Health Organization

ABSTRACT

Groundwater pollution is becoming a major concern worldwide. The impact of polluted groundwater resources is three-fold: artificial water scarcity, human health problem and an impediment to economic development. Mid River Njoro catchment has experienced numerous human settlements and intensive agricultural activities over the years, threatening the quality of water from wells and boreholes. This study assessed the groundwater quality, the land-use types and the vulnerability of groundwater resources to surface pollution within Mid River Njoro catchment, Kenya, using a modified DRASTIC model in a GIS environment. Groundwater samples were collected from boreholes and analyzed for pH, temperature, electrical conductivity, dissolved oxygen, nitrate, ammonia, and total phosphorus to calculate the Groundwater Quality Index (GQI). The land-use map was prepared from a high-resolution Google earth satellite imagery of 2015. The vulnerability zones developed using parameters such as depth to water table, net recharge, aquifer media, topography, impact of vadose zones, hydraulic conductivity and land use types. Validation nitrate values were compared to the calculated DRASTIC index to assess the efficacy of the modified DRASTIC model. From the results, the GQI range from 68.38 to 70.92, suggesting fairly good groundwater quality. The major land-use types identified include agricultural land, built-up areas, forests and agroforestry areas. The agricultural land dominated the study area, followed by built-up areas, forests and agroforestry areas. The study area is characterized by three vulnerability zones: very low (6.1%), low (87.4%) and moderate (6.5%). The validation results obtained from Pearson's correlation (0.49) and chi-square values (5.01), revealed a positive relationship between the modified DRASTIC index and nitrate values. The area with moderate vulnerability overlapped built-up areas and those with very low vulnerability had deeper water table depths and forest covers. The land-use types impacted negatively on the groundwater quality and vulnerability of the study area. This study reveals the importance and potential application of vulnerability assessment in protecting and controlling groundwater pollution. To mitigate further contamination in the moderate vulnerability zones, the study recommends protective and recovery measures to be put in place.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Groundwater is an important, valuable and renewable natural resource which constitute about 95% of the freshwater supply available for mankind, making it essential to human life and economic development (Foster et al., 2013). In many countries with limited sources of surface water, groundwater is the only source of water supply for domestic and other uses. Over the past 50 years, the use of groundwater has significantly increased and is expected to rise higher in the near future due to population growth and frequent droughts (Foster et al., 2013). Other reasons why the demand on groundwater resources continue to rise are: its general good quality and generally its modest costs of development (Calow et al., 2010; Kumar, 2018).

In the recent past, the world is facing enormous challenges in meeting the human and ecological needs for water. Increase in human population, industrialization, urbanization and rising standards of living across the globe put water resources under increasing stress, while at the same time environmental degradation, poor waste management and climate change reduce freshwater availability. Nonetheless, the use of groundwater has increased agricultural growth across the world, especially in India, the United States and China, accounting for over 50% of global groundwater abstraction (Adelana and MacDonald, 2008).

In Africa, groundwater is the main source of drinking water and its use for irrigation is expected to increase substantially to combat the challenges of food insecurity (Adelana and MacDonald, 2008). Vörösmarty et al. (2005) stated that, the water use in Africa is set to increase remarkably over the next few decades due to population growth, urbanization and planned increases in irrigation to increase food security. According to Adelana and MacDonald (2008), about 300 million people in Africa do not have access to safe and clean drinking water and many of whom are amongst the poorest and most vulnerable in the world. The only alternative to address the problem of the water scarcity is by increasing and developing groundwater supplies throughout Africa (Giordano, 2009).

In Kenya, about 17 million people living in the arid and semi-arid lands (ASALs) meet their water demands from the groundwater sources (Mumma et al., 2011). Groundwater is of considerable importance, because about 43% of rural and 24% of urban households in Kenya rely on a spring, well, or borehole as their main source of water. Groundwater has other advantages such as: the speed with which it can be developed, the relatively low capital cost of development, its drought resilience, and its ability to meet water needs, that make the water suitable for exploitation (Mumma et al., 2011). Other uses of groundwater in Kenya are: garden irrigation, commercial greenhouses, flower cultivation, residential houses and major hotels in urban Kenya (Foster et al., 2013).

Despite its importance, groundwater has not received enough attention when it comes to its protection against surface pollution, especially in Kenya (Mumma et al., 2011). Just like surface water system, the groundwater system is vulnerable to pollution from environmental degradation and wastewater caused by anthropogenic activities. Intense agricultural activities, fertilizer applications and release of industrial and municipal wastes have resulted into groundwater contamination (Mishra et al., 2014). This menace of pollution has become a critical issue to deal with.

The biggest challenge with polluted groundwater systems is the remedial process, which is very expensive, time consuming and requires advanced technologies which may not be available in a developing country like Kenya (Yin et al., 2013). Moreover, contamination of groundwater can result in poor quality of water, health risks and high cost of treatment. The risks of polluted groundwater are; artificial water scarcity, economic hardship, damaged ecosystems and health hazards (Dams et al., 2008). As such, it is very important to prevent and protect groundwater resources from surface pollution to secure clean and continuous supply of groundwater for future generations. And groundwater vulnerability assessment to surface pollution constitutes a major step towards attaining sustainable groundwater resources development.

The concept of groundwater vulnerability assessment arose from the needs to prevent groundwater pollution (Aller et al., 1987) and sustainably promote groundwater management, to assure a predictable supply of clean groundwater for future generations. It came into existence back in the 1970s, to address artificially induced groundwater pollution in France (Albinet, 1970). The fundamental principle of a groundwater vulnerability assessment is to explain why some land areas are easily polluted than others. The purpose of groundwater vulnerability assessment is basically to subdivide an area according to the vulnerability index (Vrba and Zaporozec, 1994). The vulnerability map provides the necessary information from which land use and related human activities could be planned and controlled as an integral part of an overall policy of groundwater protection at national, regional and catchment level (NRC, 1993).

The past few years have seen the development of groundwater contamination modelling and increased knowledge of groundwater pollution. Environmental managers have shown interest in evaluating the groundwater vulnerability to surface pollution and the likelihood of contaminants concentration exceeding acceptable levels in some areas compared to others (Vrba & Zaporozec, 1994). Many approaches have been developed to assess the groundwater vulnerability to pollution, such as process-based methods (Leone et al., 2009), statistical methods (Burkart et al., 1999) and overlay and index methods (Aller et al., 1987). The choice of method that is suitable to generate a groundwater vulnerability map for certain areas depends on number, distribution and reliability of the data (Massimo, 2010). Overlay and index methods have been the most widely used in building the groundwater vulnerability map because of the availability of data as compared to the other two approaches (Massimo, 2010). The groundwater vulnerability map is therefore, an environmental tool that should be integrated into land-use planning scheme for any order and degree of any administrative boundary.

1.2 Statement of the Problem

Groundwater pollution destroys the groundwater systems and the process of cleaning up the polluted groundwater is costly, time-consuming and requires advanced technologies. Kenya has incidences of groundwater pollutions in some areas such as Juja, Kisauni, Kitale, Mombasa, Marsabit and Wajir (Mumma et al., 2011). In these areas, the sources of pollutions were leakages from septic tanks, agricultural fertilizers, industrial chemicals, domestic wastewater discharge and saltwater intrusion (Mumma et al., 2011). The potential of groundwater contaminations in the country is very high from sources such as industries, agricultural fertilizers, seepage from septic tanks and domestic wastewater (Mumma et al., 2011).

The pollution in the Mid River Njoro catchment where this study is based has reached alarming rate (Kundu et al., 2003), thereby threatening the quality of the groundwater in the catchment. High population, intensive agricultural activities, industries and urbanization are potential sources of groundwater contamination in the catchment (Kithiia, 2012). Unless proper strategies are put in place to control groundwater pollution, there will be artificial water scarcity and adverse health effects in the near future. Groundwater vulnerability assessment is a general planning and decision-making tool, which helps in directing the regulatory, monitoring, educational and policy development efforts to those areas where they are most needed for the protection of groundwater quality.

1.3 Objectives

1.3.1 Main objective

The main objective of this study was to assess the vulnerability of groundwater resources of the Mid River Njoro catchment, Kenya, using modified DRASTIC model and GIS techniques.

1.3.2 Specific objectives

The specific objectives of this study were to:

1) Determine the groundwater quality index of Mid River Njoro catchment using GIS techniques.
2) Evaluate the influence of land-use types on groundwater quality and vulnerability of Mid River Njoro catchment.
3) Develop the spatial groundwater vulnerability zones for the Mid River Njoro catchment using a modified DRASTIC model.

1.4 Research questions

This study sought to answered the following research questions:

1) How does the groundwater quality index of the Mid River Njoro catchment vary spatially?

2) How do the land-use types of the Mid River Njoro catchment influence the groundwater quality?
3) How do the groundwater vulnerability index values vary spatially within the Mid River Njoro catchment?

1.5 Justification of the Study

Kenya is a water-scarce country and an opportunity to sustainably manage groundwater resources is very important (Adelana et al., 2008). Besides, once the groundwater is polluted, the clean-up process is costly, time-consuming and requires advanced technologies that are not found in developing countries like Kenya (Panagopoulos et al., 2006). Groundwater pollution destroys groundwater systems, create artificial water scarcity and impede economic growth. The main potential sources of groundwater pollutions are industrial wastes, agricultural fertilizers, seepage from septic tanks and domestic wastewater (Mumma et al., 2011). Mid River Njoro catchment, where this study is based, is mainly served by groundwater sources. The mainstay of the economy in this Njoro area is agri-based industries, and light manufacturing industries (WHO, 2011). The Njoro area also, experienced a high population growth (Shivoga et al., 2007; Yillia, et al., 2008; Olang, 2011), resulting into an alarming proportions of surface pollution for two decades (Kundu et al., 2003). It is therefore very important to regularly monitor and manage the groundwater resource in this catchment through groundwater vulnerability and quality assessment to ensure secure and clean water for future generations. Often the purpose of groundwater vulnerability assessment is to differentiate between areas that need protection from potential contaminating activities, and areas where such activities would constitute a minor threat to the groundwater.

1.6 Scope and limitation of the study

The study was conducted in the Mid River Njoro catchment in Nakuru County, Kenya. It focused on the groundwater quality and vulnerability index assessment, especially overlay and index methods. The impacts of land-use types on the final groundwater quality index and DRASTIC index was also evaluated. The modified DRASTIC model applied in this study has limitations. The ranking and weight of the parameters used were from the original DRASTIC model established by the committee of experts, hence subjectivity can never be ruled out. There was also the challenge of accessing privately own boreholes to collect water samples and measure the depths. This study does not deal with the hydrogeology of the entire Njoro river catchment.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Overview

This chapter entails the previous studies which are relevant to the groundwater resources, threats to groundwater pollution and groundwater vulnerability assessment. It presents the various methods used for groundwater vulnerability assessment such as processed-based methods, statistical methods and overlay and index methods. The literature on the advantages, limitations and validation of these methods were reviewed and the research gap identified.

2.2 Overview of Groundwater Resources and Associated Threats

Groundwater is water stored below the earth's surface in the soil and porous rock aquifers after some portion of precipitation water infiltrate through the surface and into the ground (Todd, 1980). It is the most valuable and freshwater resources especially in the arid and semi-arid areas of the world. It contributes about 95% of the freshwater we have on our planet Earth, making it essential to human life and economic development (Foster et al., 2013). In many countries with limited sources of surface water, groundwater is the only source of water supply for domestic and other uses. Over the past 50 years, the use of groundwater has significantly increased and is expected to rise higher in the near future due to population growth and frequent droughts (Arabgol et al., 2016). Other reasons why the demand on groundwater resources continue to rise are: its good quality and generally modest costs of development (Calow et al., 2010; Kumar, 2018).

Over a billion people in the world rely on groundwater as their primary source of drinking water (Alley et al., 2002), while more than half of irrigation water supplies come from the underground sources (Siebert et al., 2010). Groundwater also acts as the key strategic reserve in times of drought (Famiglietti et al., 2011), particularly in the developed countries such as the United States, northeastern Brazil and Australia.

In Kenya, about 17 million people living in the arid and semi-arid lands (ASALs) meet their water demands from the groundwater sources. Groundwater is of considerable importance, because about 43% of rural and 24% of urban households in Kenya rely on a spring, well, or borehole as their main source of water (Mumma et al., 2011). Groundwater has other advantages that make it suitable for exploitation such as the speed with which it can be developed, the relatively low capital cost of development, its drought resilience, and its ability to meet various water needs (MacDonald et al., 2008). Other uses of groundwater in Kenya are garden irrigation, commercial greenhouses, flower cultivation, residential houses and major hotels in urban Kenya (Foster et al., 2013)

Groundwater resources in many part of the world have been at risk of depletion and pollution (Langrudi et al., 2016). The main risks emanate from industrial wastes, agricultural chemicals and fertilizers and municipal wastes in many countries of the world (Liang et al., 2016). In Africa, groundwater resources are increasingly facing the threats of pollution from urbanization, industrial development, agricultural and mining activities, and poor sanitation practices and over-exploitation due to increasing demand from human and agricultural activities (Gaye & Tindimugaya, 2019). Kenya, one of the first developing country in Africa, is already experiencing the pollution in some of the important groundwater aquifers at the coast, central and northern parts of the country (Adelana et al. 2008). Intensive agricultural activities, urbanization, high population and industrial development are potential threats to the existing groundwater aquifers. This is further accelerated by insufficient management, poor groundwater quality monitoring and uncontrolled human activities (Mumma et al., 2011).

Therefore, it is very crucial to take precautionary measures to prevent groundwater pollution, rather than dealing with the impacts (Todd & Mays, 2005). One such precautionary measure is the establishment of a groundwater monitoring system that allows researchers to conduct groundwater vulnerability assessment of a given aquifer. This then allows proper land-use zoning to avoid groundwater vulnerable zones and recharge areas.

2.3 Groundwater Vulnerability Concept

Since the early 1970s, there was a growing awareness of the risks associated with polluted groundwater ranging from artificial water scarcity to public health. In the interest of human welfare and the need to utilize groundwater resources sustainably, the groundwater vulnerability assessment concept was developed in the late 1960s by French hydrogeologist (Margat, 1968), as a useful tool for environmental planning and decision-making (Dassargues, 2000).

Studies on groundwater vulnerability to contamination provides a better understanding of groundwater sensitivity against pollution with respect to geological, hydrological and meteorological conditions. It is the tendency of or likelihood for, contaminants to reach a specific position in the groundwater system after introduction at some location above the uppermost aquifer (Vrba et al., 1994). The likelihood of pollutants reaching groundwater aquifers depends on intrinsic hydrogeological properties of groundwater systems as well the characteristics and the amount of the introduced pollutants (Fijani et al., 2013).

The vulnerability concept explains why groundwater aquifers maybe more vulnerable to surface contaminations than others. Groundwater vulnerability assessment studies categorize an area into a weaker and stronger region, which forms the bases for limited resources allocation for protection of groundwater resources. The final result of a groundwater vulnerability assessment is the groundwater vulnerability maps showing zones with different vulnerability indices (El-Naqa et al., 2006). The groundwater vulnerability assessment is broadly classified into two mainly categories namely intrinsic vulnerability and specific vulnerability. The intrinsic vulnerability assessment describes the inherent geological and hydrogeological characteristics of sub-surface that provide some measure of protection against external contamination. It does not consider the properties and nature of pollutants but rather takes into account contribution of the geological and hydrogeological characteristics of an area (Entezari et al., 2016). Specific vulnerability considers the vulnerability to one or more contaminants and contribution of external factors are also taken into account (Haiyang et al., 2017).

2.3.1. Groundwater Vulnerability Mapping Methods

There are three methods for mapping groundwater vulnerability zones namely process-based, statistical, overlay and index (Tesoriero et al., 1998). Over the years, several models have been developed under each category and used at regional and national scale to achieve sustainable groundwater development in many developed countries of the world (Awawdeh et al., 2010; Alwathaf et al., 2011; Diodato et al., 2013; Huang et al., 2013; Yin et al., 2013; Stevenazzi et al., 2017). The choice of the methods and models to apply mainly depends on the availability of data, the scale of applications, accuracy of the results and the local conditions (Massimo, 2010). The vulnerability mapping methods generate a map showing area that are more susceptible to contamination from anthropogenic sources. This makes it a useful tool for groundwater resource management and land use planning. However, vulnerability mapping provides only preliminary evidence of groundwater pollution potential, which can be used to supplement detailed investigations. It is considered to be an appropriate preventive strategy for controlling groundwater pollution, if conducted with accurate and reliable input data.

The groundwater vulnerability map can be used as an effective preliminary tool for the planning, policy, and operational levels of the decision-making process concerning groundwater management and protection. The objective of vulnerability assessment is to direct regulatory, monitoring, educational and policy development efforts to those areas where they are most needed for the protection of groundwater quality. Often the purpose of groundwater vulnerability assessment is to differentiate between areas that need protection from potential contaminating activities, and areas where such activities would constitute a minor threat to the groundwater.

2.3.1.1 Process-Based Methods

These methods require analytical or numerical solutions to mathematical equations that represent coupled processes governing contaminant transport. Simulation models are used to predict the flow of contaminants and the data required must be obtained by indirect techniques (Lindström, 2005). The method requires analytical solutions to sets of mathematical equations that represent the processes governing solute transport. The methods range from the simplest indices based transport model to complex three-dimensional transport models (Lindström, 2005). Unlike other approaches, the process-based methods attempt to predict contaminant transport in both space and time (Jawed et al., 2012). The process-based models provide the most accurate results in predicting susceptibility as compared to statistical and overlay methods. However, the disadvantage of this approach is that it needs a large volume of data (Jawed et al., 2012). Also, it is limited by spatial scale and the difficulties in quantifying the sources of uncertainty (Focazio, 1984).

2.3.1.2 Statistical Methods

The statistical method correlates contaminant occurrence within a given area with response variables (intrinsic properties of aquifer systems), in an attempt to predict the probabilities of contamination (Masetti et al., 2009). Statistical methods having a contaminant concentration or a probability of contamination as the dependent variable form the basis for these methods. These methods incorporate data on known areal contaminant distributions and provide characterizations of contamination potential for the specific geographic area from which data were drawn (Masetti et al., 2009). These models identify parameters which influence groundwater contamination and produce a correction between the explanatory parameters and the contaminant concentration (McLayR et al., 2001). The logical regression model is the most popular statistical model which compares the uncontaminated status and contaminated status of soil sections to assess the groundwater vulnerability based on its probability of contamination (Mair and El-Kadi, 2013). Statistical techniques are not generic as they are mostly used in the assessment of groundwater where similar contaminants are present. Statistical methods are sometimes used by regulatory agencies that have the regional databases on ground water contamination needed to develop models. Their disadvantages are insufficient water quality observations, data accuracy and careful selection of spatial variables.

2.3.1.3 Overlay and Index Methods

overlay and index methods are based on the assumptions that a few major hydrogeological parameters largely control groundwater vulnerability, and that these parameters are known and can be evaluated. These methods are, in general, based on limited basic data, used in regional studies, and usually cover extensive areas (Lindström and Scharp, 1995). The groundwater vulnerability evaluated is qualitative and relative. Scoring, integrating or classifying to produce an index, rank or class of vulnerability, interprets the information. Overlay and index methods are the most widely used methods because of the availability of data, simple procedures and large application areas (Kumar et al., 2015). These methods combine layers of different physical and hydrogeological parameters that to control pollutants movement through the unsaturated zone until they reach the water table and spread (Aller et al., 1987). The parameters are assigned relative scores and weights established by a committee of experts (NRC, 1993). It is usually supplemented with field visits to produce reliable results. However, the overlay and index methods have been criticized due to the fact that the rates and weights assigned to the parameters are opinions from experts which may introduce subjectivity in judgment (Frind et al., 2006). Also, the linear relationship between the vulnerability and the parameters are assumed in some studies while others show non-linear combination (Kumar et al., 2015). The most commonly used of these methods, DRASTIC (Aller et al., 1987), uses a scoring system based on seven hydrogeological characteristics of a region. Several other overlay and index systems for groundwater vulnerability exist. Examples of these methods are GOD (Foster, 1987), SINTACS (Civita, 1994) and EPIK (Doerfliger et al. 1999). Table 2.1 shows the different types of overlay and index methods and their advantages and limitations.

Table 2.1: The Limitations of Overlay and Index Methods Applied in Different Studies.

Models	Parameters used	Limitations
GOD (Foster, 1987)	Groundwater occurrence, lithology of the Overlaying layers, Depth to the groundwater,	Limited number of parameters (three) which is inadequate in giving sound judgement. Does not consider the effect of saturated zone/aquifer medium.
DRASTIC model (Aller et al., 1987)	Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity	Considers several parameters influencing groundwater movements and recharge quality, giving sound judgement. Use weighing and rating factor techniques to balance and enhance importance of each parameter. The model can be used in extensive regions due low cost of application and easy to collect data.
Aquifer Vulnerability Index (Van Stempvoort et al., 1993)	Thickness of each uppermost aquifer (D), hydraulic conductivity (K) of each of these sedimentary layers.	Limited number of parameters used which does not give adequate and sound scientific judgement. Does not consider the effect of saturated zone/aquifer medium.
SINTACS (Civita, 1994)	Water table depth, effective infiltration, unsaturated conditions, soil media, aquifer hydrogeological characteristics, hydraulic conductivity and topographic slope	Considers seven parameters almost similar to DRASTIC model parameters The model was derived from the DRASTIC model adapted to Mediterranean conditions.
EPIK (Doerfliger et al., 1999)	Epi karst, the Protective cove, Infiltration conditions, Karst network development.	Model use less parameters as compared to DRASTIC and SINTACS models Only adaptable to karst aquifers.

2.4 DRASTIC Vulnerability Model

DRASTIC model is one of the most widely used overlay and indexing techniques for assessing intrinsic groundwater vulnerability of an area (Aller et al., 1987). It was developed in the USA through a collaboration between the US Environmental Protection Agency (EPA) and the National Water Well Association (NWWA). Its main purpose is to help environmental managers, land-use planners and administrators in land-use planning. The model consists of two major components namely: the hydrogeological component and the ranking system called DRASTIC index (Aller et al., 1987).

The hydrogeological component is based on the following seven parameters: depth to groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). These parameters are assigned some ratings and weights established by the committee of experts using the Delphi technique (Aller et al., 1987). The hydrogeological parameters are those believed to influence groundwater flow (recharge) and movement in the subsurface. The recharge is the vehicle that moves contaminants from the surface, through the unsaturated zone into the groundwater aquifers (Aller et al., 1987).

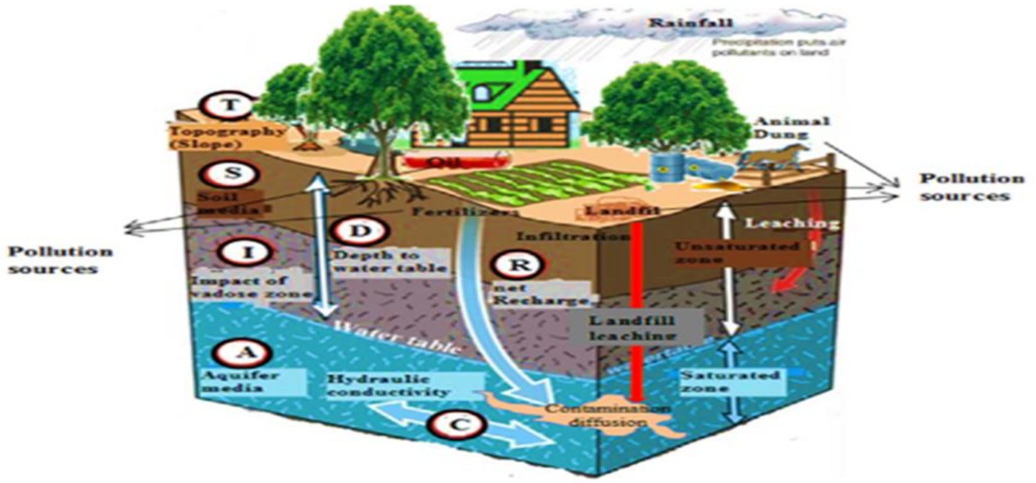


Plate 2.1: Hydrogeological Parameters for DRASTIC MODEL (Source: http://frakturmedia.net/oswp/drastic/)

The Plate 2.1 shows the hydrogeological parameters that interact with the recharge from the time surface water enters the ground surface up to the time it reaches the groundwater table. Aquifer media and hydraulic conductivity parameters determine the extent the recharge would spread within the aquifer boundary. The recharge carries all sorts of pollutants from the groundwater surface into the groundwater aquifers. These pollutants can lead to degradation of the groundwater quality in the aquifers. Aquifer contaminations may be partially mitigated by natural processes that take place between the recharge and these hydrogeological parameters. However, some conservative substance may be very difficult to remove from the recharge. Other times, continuous inflow of contaminated recharge may subdue the decontamination capacity of the subsurface environment, thereby causing groundwater pollution (Aller et al., 1987).

The relative ranking scheme uses a combination of weights and ratings to produce a numerical value called DRASTIC INDEX, which describes the vulnerability of the groundwater systems (Aller et al., 1987). The final DRASTIC index (DI) is a summation of the seven-weighted-rated parameters as shown in Equation 2.1 (Aller et al., 1987).

$$DI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \tag{2.1}$$

Where D, R, A, S, T, I, and C are the seven parameters, r is the rating value and w is the weight associated to each parameter. The vulnerability index calculated from Equation 2.1 is dimensionless and measures the susceptibility to pollution and regions with higher DRASTIC index value are more vulnerable to pollution than those with the low index value. The rates, weights and ranges of the original DRASTIC model were used in this study, as shown in Table 2.2.

Table 2.2: Standard DRASTIC Weights and Ratings System Used for Calculating DRASTIC Index

Depth to water		**Net Recharge**		**Aquifer Media**		**Soil Media**		**Topography**		**Impact of Vadose zone**		**H. conductivity**	
Range(m)	**Rating**	**Range (mm/yr.)**	**Rating**	**Range**	**Rating**	**Range**	**Rating**	**Range (%)**	**Rating**	**Range**	**Rating**	**Range (m/day)**	**Rating**
0 – 1.5	10	<50	1	Massive shale	2	Thin/absent, gravel	10	0 - 2	10	Confining layer	1	<4	1
1.5– 4.5	9	50 – 100	3	Metamorphic/igneous	3	Sand	9	2 – 6	9	Silty/clay	3	4 - 12	2
4.5-9	7	100 – 175	6	Weathered metamorphic/igneous	4	Peat	8	6 – 12	5	Shale	3	12 - 30	4
9-15	5	175 – 250	8	Glacial till	5	Shrinking/ aggregated clay	7	12– 18	3	Limestone	6	30 - 40	6
15-22	3	> 250	9	Bedded sandstone, limestone, shale	6	Sandy loam	6	>18	1	Sand, bedded sandstone	6	40 – 80	8
22-30	2			Massive sandstone, limestone	6	Loam	5			Sandstone, shale., sand, gravel	6	>80	10
>30	1			Sand and gravel	8	Silty clay	4			Metamorphic/igneous	7		
				Basalt	9	Clay loam	3			Sand/gravel	8		
				Karst limestone	10	Muck	2			Basalt	9		
						Non-shrinking/non-aggregated clay	1			Karst limestone	10		
Weight = 5		Weight = 4		Weight = 3		Weight = 2		Weight = 1		Weight = 5		Weight = 3	

From the weights and rates assigned to these parameters, reclassified raster layers were created and final vulnerability index calculated by linearly combining them using a spatial analyst extension of ArcGIS software. Table 2.3 represents the ranges for DRASTIC indices adapted from Civita and De Regibus (1995).

Table 2.3: Criteria for Assessing the Degree of Vulnerability of Groundwater

Calculated Index value	Vulnerability class
< 80	Very low
80 – 120	Low
120 – 160	Moderate
160 - 200	High
>200	Very high

The DRASTIC model has been developed using four major assumptions includes the contaminant is introduced at the ground surface; the contaminant is flushed into the groundwater by precipitation; the contaminant has the mobility of water, and the areas evaluated using DRASTIC model should be 40.5 hectares or more (Aller et al., 1987).

2.5 DRASTIC Model Input Parameters

2.5.1 Depth to water table

Depth to the water table (D) is the vertical distance that contaminants must travel from the ground surface to the top of the saturated zone, in the aquifer. It is considered one of the most important parameters with the highest weighting value of 5 (Aller et al., 1987). The potential of the contamination increases with the decreasing values of depth. This means that the deeper water tables have less chances of contamination when compared to shallow water tables. The depth of wells and boreholes can be measured directly using the Dipper-T water level meter or obtained from the geological report (Aller et al., 1987).

2.5.2 Net Recharge

Net recharge (R) is the total amount of recharge water that reaches the water table and it is the main driving force for transferring contaminants from the surface to the aquifers. In addition, the quantity of water available for dispersion and dilution of contaminant in the vadose zone and in the saturated zone is controlled by this parameter. Recharge quality is very critical to the groundwater quality, a reason for assigning a higher weight of 4 (Aller et al., 1987). The more the net recharge, the higher the probability for contamination to occur in the groundwater system. In the Mid River Njoro catchment, infiltration from the precipitation is considered the main contributing factor to the net recharge because wastewater application and irrigation return in the area is unaccounted for. The net recharge might be estimated from the drilling logs and pumping test for the drilled boreholes or from rainfall infiltration and absorptions wells for shallow wells.

2.5.3 Aquifer Media

An aquifer is a rock formation which yields a sufficient amount of water for use. The consolidated and unconsolidated materials (sand, gravel or limestone) which make up these rocks are called aquifer media (Aller et al., 1987). These materials control the flow path, length and movement of contaminants. The aquifer medium also influences the amount of the effective surface area of materials with which the contaminant may come into contact within the aquifer. Large sediment size, higher permeability and lower attenuation capacity of aquifer materials mean more vulnerability of the aquifer to pollution. Weighting value assigned to the aquifer media is 3 (Aller et al., 1987).

2.5.4 Soil Media

The top weathered portion of the unsaturated zone represents the soil media and significant biological activities occurs in this zone (Aller et al., 1987). Soil media properties determine the pollution potentials of an area by influencing the decontamination processes. Other factors such as clay type, grain size and shrinkage indicates the vulnerability of aquifers. It is the less significant parameter with a weighting factor of 2.

2.5.5 Topography

The slope of the land (topography) controls the runoff of the contaminants. Topography determines the probability of the contaminants to remain on the surface for long for infiltration to occur or runoff down into streams and rivers and flushed away into the water bodies. The steeper slopes mean that the runoff containing contaminants does not have time to infiltrate into the ground hence lower chances for contamination to occur. This parameter is least significant with a weight value of 1 according to the original DRASTIC system.

2.5.6 Impact of Vadose Zone

The vadose zone is commonly defined as the geologic media spanning from the land surface to the groundwater table of the first unconfined aquifer (Stephens, 2018). The natural attenuation processes which filter out the contaminants from the recharge occurs in this zone. Therefore, its properties and texture also determines the time of travel of the contaminant. The vadose zone can be prepared from the lithology of the drilling logs and sub-surface geological survey. It is the most significant parameter, just like depth to the water table, with the highest weight value of 5.

2.5.7 Aquifer Hydraulic Conductivity

Hydraulic Conductivity (C) is the ability of the aquifer to transmit water containing contaminants (Babiker et al., 2005). The pumping test results and lithology of a region are used to construct the hydraulic conductivity map. The region with higher hydraulic conductivity indicates a greater potential for contamination because contaminants can move easily through the aquifer. The parameter was assigned a weight value of 3.

2.6 Modification on DRASTIC Model

In spite of its popularity, the DRASTIC model has some shortcomings, which prompted some researchers to modify it, in order to achieve more accurate results and improve its applicability. The major drawback of DRASTIC model is the subjectivity in the assigning of weights and ratings plus the doubt regarding the selection of some parameters and exclusion of others (Panagopoulos et al., 2006). Other reasons why DRASTIC model, just like other types of overlay and index methods, was criticized were: disregards to the impact of regional characteristics by assigning uniform rates and weights; lack of standard method of validation and qualitative selection of the model parameters rather than quantitative approaches. Many researchers have attempted to modify the model to address these shortcomings as shown in the Table 2.4.

Table 2.4::Modifications on DRASTIC Model in Various Studies

Modification	Description	Reference
DRASTIC-LU	Modified by introducing land use as an addition parameter to generate vulnerability of Indo Gangetic plains of India	Khan et al. (2010)
DRASTIC-sensitivity analysis	Applied DRASTIC model along with sensitivity analysis to assess groundwater pollution risk of Kakamigahara Heights, Gifu Prefecture, central Japan.	Babiker et al. (2005)
Pesticide DRASTIC-LU	Assessed groundwater vulnerability to non-point source pollution under conflicting land use pattern, using pesticide DRASTIC-LU in in a Mediterranean coastal zone, Turkey. Results showed a significant association between high groundwater NO3-- concentration and distance between LULC types.	Guler et al. (2013)
DRASTIC-geo-statistical techniques	Modified DRASTIC model using simple geo-statistical techniques. Land use and correlation coefficient with the nitrates concentration included as additional factor. Results was an improved correlation coefficient between groundwater pollution risk and nitrates concentration.	Panagopoulos et al. (2006)
DRASTIC-Fm	Modified version of DRASTIC of fissured hard-rock aquifers. The fractured was derived from the map of tectonic lineaments density.	Denny et al. (2007)

Various techniques have been used to develop and modify the DRASTIC model algorithm. These techniques include: weight adjustment technique, rate adjustment technique and addition/omission and substitution technique.

2.6.1 Weight Adjustment Techniques

The weight adjustment techniques involve modifying the weight factors in order to meet the specifications of the study area (Mair et al., 2013; Neshat et al., 2014; Sinha et al., 2016). Different methods have been used to modify the original weight of the DRASTIC parameters: sensitivity analysis (Ismail et al., 2018); weights of evidence (Daneshfar and Benn, 2002); correspondence analysis (Pacheco and Fernandes, 2013) and analytical hierarchy process (Saaty, 1988). Among these weigh adjustment techniques, sensitivity analysis is the widely used method (Neshat et al., 2014; Sadat-Noori and Ebrahimi, 2016; Sinha et al., 2016)

2.6.1.1 Sensitivity Analysis

DRASTIC model is a combination of seven parameters which some researchers believed to could control uncertainties on the final groundwater vulnerability assessment (Rosen, 1994). Other researchers believed that the same results could be obtained by integrating less parameters, and cutting on ease of obtaining the data and cost (Barber et al., 1993). There are others also who emphasized on using more than the seven parameters to improve the model performance (Khan et al., 2010). To avoid this confusion, sensitivity analysis could be used to evaluate the required DRASTIC model parameters. There are two types of sensitivity analysis: map removal sensitivity analysis (Lodwick et al., 1990) and single parameter sensitivity analysis (Napolitano and Fabbri, 1996). Equation 2.1 computes the sensitivity of vulnerability map to removing one or more DRASTIC layers.

$$S = [(V / N - V' / n)] / V * 100 \tag{2.1}$$

where S is the sensitivity index, V and V' unperturbed and perturbed vulnerability indices, respectively; N and n are the number of parameters used to compute V and V'. The calculated vulnerability index obtained by using seven parameters is considered an unperturbed while the vulnerability computed using a lower number of parameters was considered as a perturbed one (Babiker et al. 2015).

The single parameter sensitivity analysis is used to calculate the effective weight of each parameter using Equation 2.2. It examines the significance of each parameter in vulnerability index.

$$W = ((P_r * P_w) / V) * 100 \tag{2.2}$$

where W refers to 'effective' weight of each parameter, Pr and Pw rating and weighting values of each parameter and V is unperturbed vulnerability indices.

2.6.2 Rate Adjustment Techniques

The rate assigned to DRASTIC parameters determines the accuracy of the final groundwater vulnerability assessment (Assaf and Saadeh, 2009). In order to calibrate the rate assigned to the parameters, some methods have been developed: Wilcoxon rank sum non-parametric statistical test (Wilcoxon, 1945) and probabilistic based statistical model, frequency ratio (Neshat and Pradhan, 2015).

2.6.2.1 Wilcoxon rank sum non-parametric statistical test

The rates assigned to the DRASTIC parameters can be modified using the Wilcoxon rank sum non-parametric statistical test. This is achieved by using the nitrate concentration as a main factor in rate adjustment through correlation processes. However, to adjust rates using this method, the following requirement need to be met: contaminant distribution should be relatively uniform in the area; area should be dominated by agricultural activities and precipitation should be main cause of flushing of contaminant into the groundwater. Table 2.5 summarizes some of the studies that have used Wilcoxon rank sum non-parametric statistical test to adjust the initial DRASTIC model ratings.

Table 2.5: Wilcoxon Rank Statistical Test for Adjusting the Rating Values of DRASTIC Model.

Studies	Reference
Optimization of the drastic method for groundwater vulnerability assessment via the use of simple statistical methods and gis. The correlation coefficient between groundwater pollution risk and nitrates concentration was considerably improved and rose to 33% higher than the original method.	Panagopoulos et al, (2006)
Modification of drastic model to map groundwater vulnerability to pollution using nitrate measurements in agricultural area. The results showed that the modified DRASTIC is better than the original method for nonpoint source pollutions in agricultural areas	Javadi et al. (2011)
Estimating groundwater vulnerability to pollution using a modified drastic model in the Kerman agricultural area, Iran. The results revealed that the modified DRASTIC model performs more efficiently than the traditional method for nonpoint source pollution, particularly in agricultural areas	Neshat et al. (2014)
Groundwater assessment of Halabja Saidsadiq basin, Kurdistan region, ne of Iraq using vulnerability mapping.	Abdullah et al. (2016)
Groundwater vulnerability assessment in agricultural areas using a modified drastic model. The results showed that the coefficient of determination between the point data and the relevant vulnerability map increased significantly from 0.52 to 0.78 after modification.	Noori and Ebrahimi (2016)

2.7 DRASTIC Model Review Critique

Researchers who modified the weights and ratings of the original DRASTIC model considered the differences in regional characteristics which tend to influence the groundwater movement and hence, contamination. However, the original weights and ratings were assigned to factors and media which remain the same from place to place (Napolitano and Fabbri, 1996). Spatial distribution of measured nitrate concentrations were mostly used to modify ratings of the original DRASTIC parameters but what if there is no nitrate contamination due to other preventive measures put in place? Instead, the modification of the original DRASTIC model should look into redundancy of some parameters which have the same hydrological properties, such as impact of vadose zone and aquifer materials. The impact of human activities in manipulating the soil medium parameter (which was considered because of its biological properties thereby contributing to decontamination process), especially in agricultural areas should be considered as a parameter rather than potential source of contaminants. Human activities, which are manifested in the type of land use practiced in an area, not only generates more pollutants, but also increases the amounts of recharge, and therefore the possibility that contaminants will reach the groundwater resources is greater. Thus substituting the soil media, in areas where intensive agricultural activities is dominant, with land use types, will only make specific vulnerability more meaningful. Besides, the vulnerability assessment was limited to shallow aquifers of water-table depth less than 30 m and this implies that deeper aquifers are not vulnerable to contaminations, which might not be true in some areas (Aller et al., 1987).

2.8 DRASTIC Model Validation

Validation process ensures that the model performs as expected and the results explained scientifically in order to approve its applicability. This is done mostly by assessing the correlation between observed nitrate concentration and the final vulnerability index. The reason to use observed nitrate concentration was because this compound is not naturally present in groundwater system but since it is highly soluble, it can easily reach aquifers after its application on the surface (WHO, 2011). In addition, it is the main contaminant that human activities can introduce into the environment which therefore affects the groundwater quality (US EPA, 1985). Many researchers have used measured nitrate concentration from wells to validate the performance of the final vulnerability indices (Baalousha, 2011; Javadi et al., 2011; Yin et al., 2013; Iqbal et al., 2015; Sahoo et al., 2016).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Description of the Study Area

The study area covered Mid River Njoro catchment, located at southwestern part of the Rift Valley region, Kenya. The total land area covers approximately 55.10 km^2. The study area is located between latitudes 0º 30’ S and 0º 18’ S and longitudes 35º 46’ E and 35º 55’ E. Figure 3.1 shows the location and boundary of the study area in Nakuru County. The area experiences a trimodal precipitation pattern with long rains occurring from April to May, short rains occurring from November to December, and an additional short rainfall season occurring in August (Mainuri and Owino, 2014).

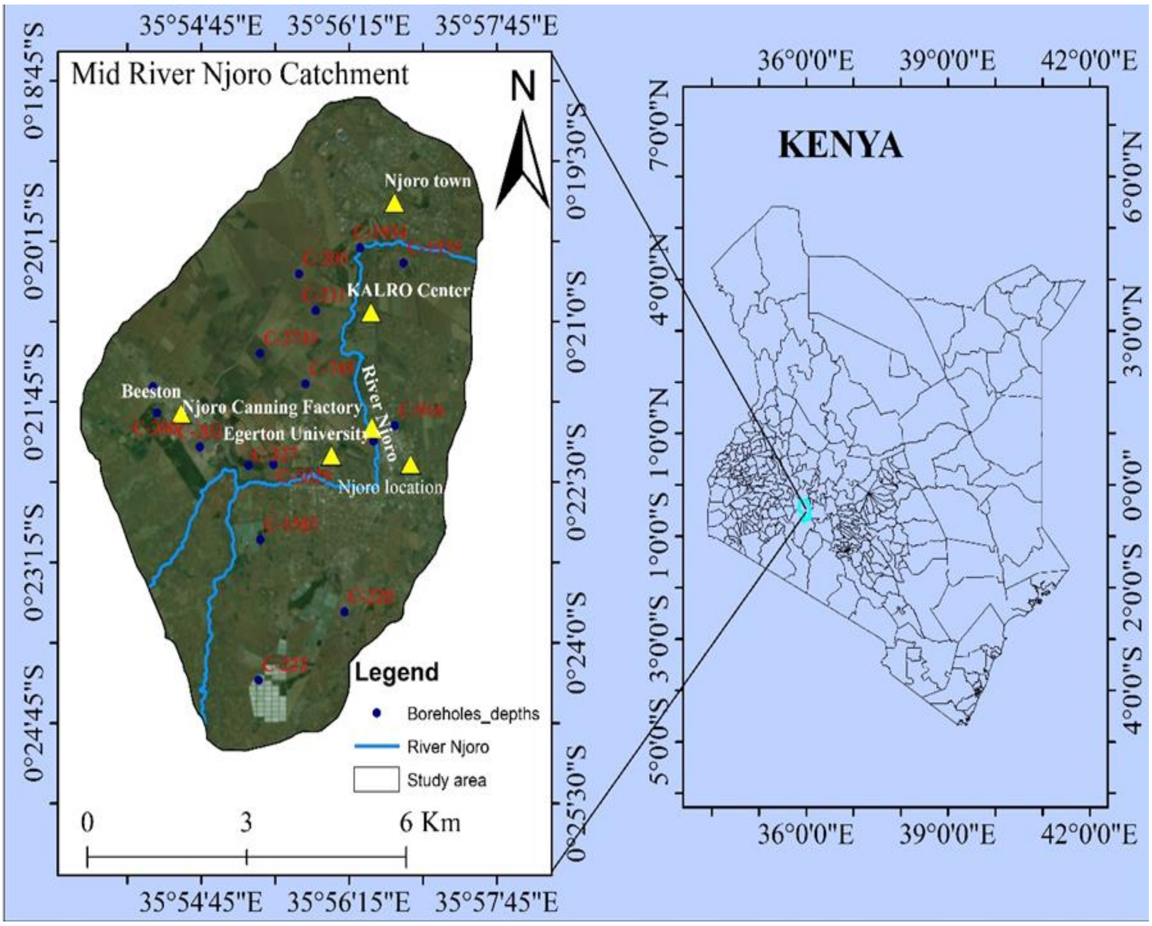


Figure 3.1: Location of Mid River Njoro Catchment

The rainfall ranges from 800 mm to 1700 mm and potential evaporation is in the ranges of 1200 mm to 1500 mm. Average annual minimum and maximum temperatures are 9ºC and 24ºC respectively (Mainuri and Owino, 2014). The study area is dominated by various agricultural activities with extensive application of fertilizers in farms. The rest of the land is covered by settlements, patches of forests and rivers. Based on topographical maps, the highest ground elevation is 2377 m and the lowest is 2133 m above the sea level, resulting in a difference of elevation of 244m. Within the study area river Njoro and its tributaries flows from south to east. The primary supply of drinking water in the area comes from boreholes that have watertable depth ranges between a few meters to 240 m below the surface (Kanda and Suwai, 2013)

3.1.1 Geological and Hydrogeological Characteristics

The geology comprises a succession of Miocene–Pleistocene volcanic, primarily phonolites, trachytes and basalts, with pyroclastics and intervening lacustrine beds being more widespread in occurrence during the Pleistocene (McCall, 1967; Baker, 1986). Much of the rift floor area is draped by Holocene pyroclastic, basalt flows, and volcanic soilsgrid faults that occur in this section of the rift (Baker, 1986; Schlüter, 1997; Woldegabriel et al., 2016) are masked by the superficial materials. As assessment of borehole geo-logs in the study areas indicate that the top brown soils and sediments are on the order of 10 m thick or more. Below them are lava flows of rhyolites, basalts, trachytes or phonolitic trachytes, with varying thicknesses, from thin (10 m or less) to thick (sometimes 30–40 m), that alternate with consolidated pyroclastic materials such as tuffs, agglomerates, ashes and their derivatives comprising loose tuffaceous sands or pumiceous gravels. These also comprise thin layers (5 m or less) to thick (>50 m). This series occurs up to depths exceeding 200 m (Mogaka, 2010). The mid River Njoro catchment is within the bigger rift valley aquifer with the static water levels being shallower than the depth at which water was initially struck suggesting the presence of confined shallow aquifers (Isaac & Janet, 2013). The depth at which groundwater samples were collected ranged from 22 m to 126 m. Aquifer lithological studies identified three types of aquifer media; sediments (including volcaniclastics), trachyte and tuffs. Sediment units intercalated in the volcanic formation forming the main sources of groundwater.

3.1.2 Land Use Patterns

Over the years the area has experienced drastic land-use changes from forest cover to intensive agricultural fields. Important centres such as Kenya Agricultural and

Livestock Organization (KALRO), formerly Kenya Agricultural Research Institute (KARI), Njoro Canning Industry and Egerton University are found within the study area. The main economic activities in the study area are agricultural-based industries including vegetable and milk processing, large-scale wheat and barley farming. Light manufacturing industries such as timber milling and quarrying are also a mainstay of the local economy(Olang, 2011).

3.2 Groundwater Quality Assessment

3.2.1 Location of Groundwater Sampling Boreholes

The sampling locations (See Figure 3.2) and corresponding elevations of the sampling points above sea level were recorded using a handheld Garmin 64 GPS receiver. These were subsequently transferred and organized in MS Excel and then imported to ArcMap for spatial analysis. The sample locations shapefile were linked to the attribute table of groundwater quality data. The water level data were also collected at each borehole using Dipper-T water level meter as shown in Plate 3.1.

Plate 3.1: Measuring Groundwater Depth Using Dipper-T Water Level Meter

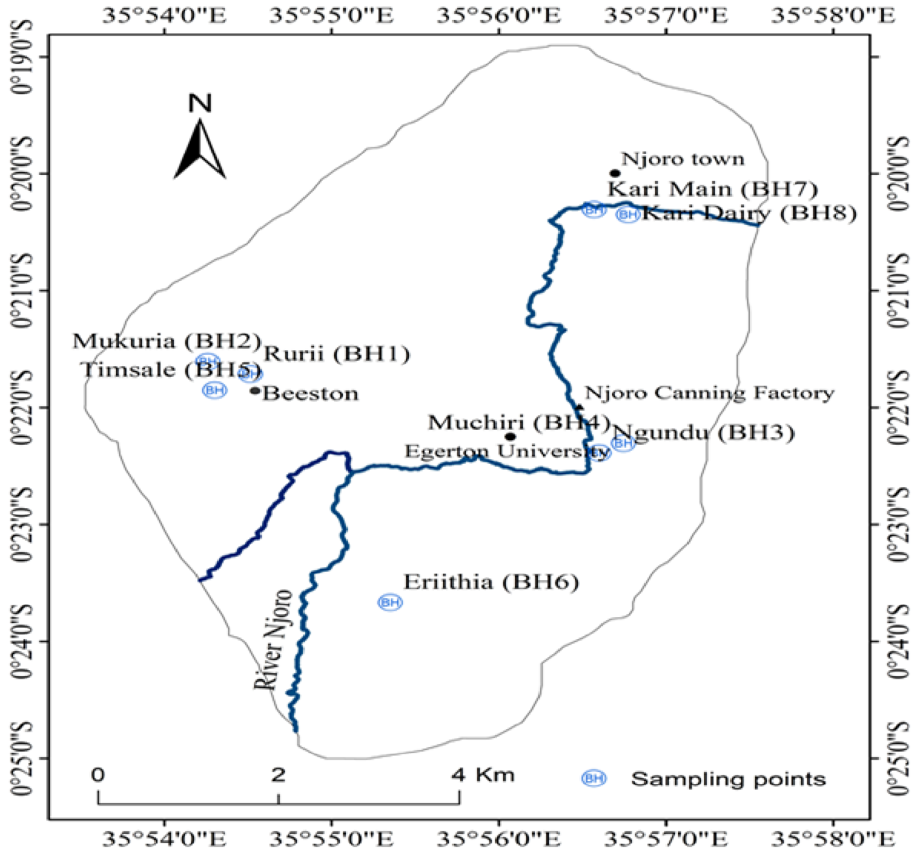


Figure 3.2: Location of Groundwater Sampling Points in the Study Area

3.2.2 Collection of Groundwater Samples for Quality Analysis.

Groundwater samples were collected in the period between October and December during short rains of 2017 from eight (8) boreholes located in the study area. The groundwater samples were collected in a pre-washed and rinsed sampling bottles and closed immediately. A total of 168 groundwater samples were collected. Three replicates were run for each sample for a period of seven (7) weeks as shown in the Plate 3.2. Extra samples were carried in cooler, preserved as prescribed in America Public Health Association manual (APHA, 1998) and taken to laboratory for chemical analysis.

Plate 3.2: Field and laboratory analysis of the groundwater samples

3.2.3 Groundwater Quality Analysis in the Field and Laboratory

The groundwater samples were analyzed for pH, temperature, electrical conductivity, dissolved oxygen, nitrate, ammonium, and total phosphorus. These seven parameters were selected from the list of Kenya Bureau of Standards (KEBS, 2010) standards and World Health Organization (WHO) guidelines for drinking water (WHO & UNICEF, 2014). The pH, water temperature, electrical conductivity (EC) and dissolved oxygen (DO) of the sampled water were measured in-situ by Hach HQ40D portable multi meter, as shown in Plate 3.1. The NO_3-N and NH_3-N were determined using the sodium-salycilate method (APHA, 1998). The TP was determined using the ascorbic acid method (APHA, 1998).

3.2.4 Computation of the Groundwater Quality Index

Seven groundwater quality parameters were selected to prepare the groundwater quality index (GQI) map. These groundwater parameters include pH, water temperature, electrical conductivity (EC), dissolved oxygen (DO), nitrate, ammonia and total phosphorus (TP). The pH and temperature are important water quality parameters which influence the chemical composition of the groundwater. The EC estimated the concentration of dissolved salts and indicate the chemical contaminants while the pH, temperature and DO influence the chemical composition of the groundwater. The Nitrate, Ammonia and TP are chemical parameters derived from human activities and nutrient content of manure used in agriculture, hence indicators of possible contaminations from the surface. The results obtained were compared with the standard values prescribed in KEBS (2010) and guidelines from WHO (2011).

Groundwater quality index (GQI) provides a way to summarize overall water quality conditions in a manner that can be clearly communicated to different audiences, can help to understand whether overall quality of groundwater body poses a potential threat to various uses of water. GQI is easy to calculate using the threshold values of different groundwater quality parameters. In addition, the results obtained from GQIs are very convenient to interpret. GQI method adopted in this study was proposed by (Babiker, et al., 2005), and it involved the following five steps:

3.2.4.1 Preparation of Groundwater Quality Maps

Maps representing the spatial distributions of groundwater quality of the study area were prepared. The boreholes location data obtained using Garmin GPs were linked to the groundwater quality data generated after field and laboratory analysis. Using the IDW (Inverse Distance Weighted) interpolation method of spatial analyst tools in ArcGIS, concentration maps of the seven selected groundwater quality parameters were developed. IDW is mostly suitable for interpolating areas with few data points and hence the reason why it was applied. The concentration maps become raster format of the original point data of groundwater quality parameters. The raster format is usually preferred because it provides a simple data structure and provides easy and efficient overlay analysis as compared to vector format.

3.2.4.2 Normalizing Concentration Maps

The concentration maps were transformed to a common scale for ease of integration in GIS. The grid cell value in the primary concentration map was transformed using normalized difference index as shown in Equation 3.1. The CI values in the resultant normalized difference map range between -1 and 1.

$$CI = (X' - X)/(X' - X) \qquad (3.1)$$

Where:

CI = Contamination Index;

X’ = Measured/Observed Concentration;

X = KEBS and WHO Maximum Desirable Concentration Guidelines.

3.2.4.3 Derivation of Rank Maps

The normalized difference map was further transformed into a rank map to remove the negative values using the polynomial Equation 3.2 (Babiker et al., 2005). The rank map rates the CI values from 1 to 10 and rank 1 indicates minimum impact on groundwater quality, while 10 indicates the maximum impact. The minimum contamination index level (−1) was set equal to1, the median level (0) was set equal to 5 and the maximum level (1) was set equal to 10.

$$r = 0.5 * CI^2 + 4.5 * CI + 5 \qquad (3.2)$$

Where:

CI = Contamination index value for each grid cell in the normalized map;

r = Corresponding ranking value

The rate 1 indicates least impact on groundwater quality and the rate 10 indicates the highest impact.

3.2.4.4 Assigning of Weights to the Rank Maps

A relative weight (w) of the parameter which corresponds to the "mean" rating value (r) of each rank map (1–10) and to the "mean r + 2" ($r \leq 8$) in the case of parameters that have potential health effects (e.g. nitrate) was assigned to each parameter. The weights indicate the relative importance of each parameter to groundwater quality (Babiker et al., 2005). The parameters with high mean rate impact more on groundwater quality as compared to those with low mean rate and therefore, are assumed to be more important in evaluating the overall groundwater quality index (Babiker et al., 2005). For the pH, temperature, dissolved oxygen and total phosphorus, the average rank value was used as weight, while for nitrate, a value of two was added to the mean rank value because of the potential risk posed by the nitrate. A value of two was also added to the mean rank value of electrical conductivity because this parameter as a cumulative effect of chemically derived contaminants.

3.2.4.5 Calculation of the Groundwater Quality Index.

The final step in calculation of GQI indices and map is the linearly combination of the relative weights and the corresponding rank maps using raster calculator of the spatial analyst tools of ArcGIS 10.1 using Equation 3.3.

$$GQI = 100 - \{(r_1 w_1 + r_2 w_2 + r_3 w_3 + ... r_n w_n) / N\} \qquad (3.3)$$

Where:

r = the rate of rank map (1-10);

w = the relative weight of the parameter which corresponds to the “mean” rating value (r) of each ranking map (1-10;

N = total number of parameters used;

100 = reflection of high-water quality and those values close to 100 reflect high quality of water and those far below 100 reflect low quality of water.

3.3. Land Use Classification

The Google Earth satellite provided high-resolution images that were used to create a land-use map of an area. In this study, Google earth satellite imagery of 2015 was used to generate land use map of the study area. The Google earth digitizing tools such as polygons, lines and points were utilized to construct the various land use types present in the study area. Several polygons were constructed for built-up areas, forests and agroforestry areas. These polygons were then imported into ArcGIS software and converted into layers. The layers were joined using the union tool of ArcGIS software. The joined layer was then erased from the study area using the erase tool of ArcGIS software and the remaining area assigned to the agricultural land. These four major land-use types formed the land use map of the study area. This map was employed to assess the impact of land use types on groundwater quality as well as a parameter of modifying the original DRASTIC model. The impact of land-use types on groundwater quality was assessed using an GIS technique. The polygons of each land use type were overlaid on the GQI map and using the spatial analyst tools (zonal statistics) of ArcGIS software, the mean and the standard deviation of the GQI values within each land use type were calculated and compared.

3.4 Determination of Groundwater Vulnerability Index

The Groundwater Vulnerability Index (GVI) describes the level of susceptibility as a function of hydrogeological factors and anthropogenic effects (Panagopoulos et al., 2006). To generate GVI, seven thematic layers were created and each layer reclassified using the rating values of the standard DRASTIC rating system. The weight factor, based on standard DRASTIC system, was then assigned to each thematic layer and final modified DRASTIC index calculated using Equation 3.4. Figure 3.2 show a GIS model for calculating a modified DRASTIC index.

$$mDI = D_r D_w + R_r R_w + A_r A_w + T_r T_w + I_r I_w + C_r C_w + LU_r LU_w \qquad (3.4)$$

Where: D_rD_w is the rate and weight assigned to watertable depth (D) parameter,

R_rR_w is the rate and weight assigned to net recharge (R) parameter,

A_rA_w is the rate and weight assigned to the Aquifer medium (A) parameter,

T_rT_w is the rate and weight assigned to the topography (T) parameter,

I_rI_w is the rate and weight assigned to the impact of vadose zone (I) parameter,

C_rC_w is the rate and weight assigned to the hydraulic conductivity (C) parameter,

Lu_rLu_w is the rate and weight assigned to the land use (Lu) parameter.

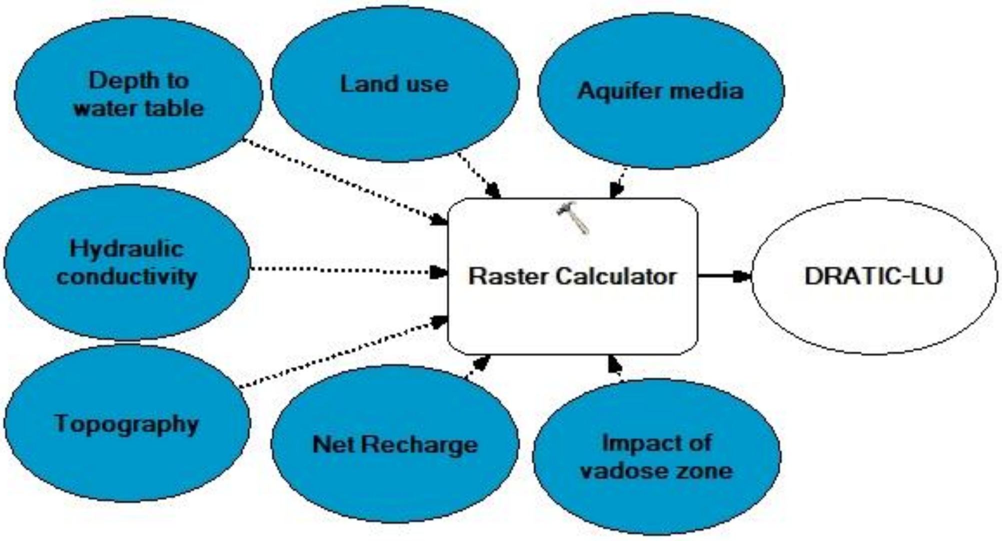


Figure 3.3: A GIS Model for Calculating a Modified Drastic Index

3.4.1 Measurement of Watertable Depth

Groundwater table depths were mainly measured using Dipper-T water level meter. Additional data on watertable depths were obtained from geological report no. 86 of the Molo area. Groundwater table map was constructed from the point data using mainly Kriging interpolation. Unlike other point interpolation methods Kriging is built on a statistical method. The Kriging method performs a weighted averaging on point values where the output estimates equal the sum of product of point values and weights divided by the sum of weights. The weight factors in Kriging are determined by using a user-defined semi-variogram model based on the output of the spatial correlation operation. The original rating values (See Table 2.2) of the DRASTIC model were used in reclassification process. The final depth to water table map was then used as an input to the modified DRASTIC model.

3.4.2 Determination of Net Recharge

The net recharge data was obtained from the Borehole Completion Report (BCR) and hydrogeological survey reports. The point net recharge data was then interpolated using ordinary Kriging method and reclassified according to original DRASTIC model rating values, using ArcGIS spatial analyst tools. The reclassified net recharge map provided an input date needed for vulnerability assessment.

3.4.3 Determination of Aquifer Media

The aquifer media were determined by digitizing geological map of the Molo area, and clipping the study area, using ArcGIS 10.1. The aquifer media classes were reclassified and rated using the original value of DRASTIC model and reclassification tool of ArcGIS software. Reclassification means assigning a value of cells to a new information. A relative weight of 3 was assigned to the rated aquifer media map and used in calculating the final vulnerability map.

3.4.4 Determination of Topography

The topographic map was derived from the Shuttle Radar Topography Mission (SRTM) 30 metres image of Kenya and slope percentage calculated using the Spatial Analysts Tools of ArcGIS 10.1. The slope map was then divided into five classes of the range 0 to 2 percent and rating assigned according to the original DRASTIC model. The reclassified slope map was assigned a rating of 1 and used to calculate the final vulnerability index of the study area.

3.4.5 Determination of Impact of Vadose Zone

The impact of vadose zone data was obtained from digitizing geological map of the Molo area using geo-referencing tool of ArcGIS 10.1. Different rock formations were further digitized and reclassified. The original DRASTIC model weight and rating were used in building this layer. The layer generated formed an input into the modified DRASTIC model for determining groundwater vulnerability index.

3.4.6 Determination of Hydraulic Conductivity

Hydraulic conductivity map was created from the pumping test result obtained from BCR and hydrogeological survey reports of available boreholes. The point hydraulic conductivity data was then interpolated using ordinary Kriging method and reclassified according to original DRASTIC model rating values, using ArcGIS spatial analyst tools. The reclassified hydraulic conductivity map was then assigned a weight of 3 and used as input to the modified DRASTIC model to obtain final vulnerability map of the study area.

3.4.7 Determination of Impact of Land Use Type

Google earth satellite imagery of 2015 was used to generate land-use map of the study area. This map was then employed to calculate the modified DRASTIC method by substituting the soil medium parameter of the original DRASTIC model. This was necessitated by the fact the top soil has been manipulated over the years due to human settlements and agricultural activities thereby losing its biological properties to control groundwater pollution. As shown in the Plate 3.3, the top soil layer has been mechanically disturbed and its biological properties removed. This renders the soil parameter in original DRASTIC method redundant and its application in vulnerability assessment misleading. The inclusion of the impact of land use activities is therefore justified.

Plate 3.3: A Section Mid River Njoro Catchment showing Mechanical Manipulation Top Soil.

The rating values and the weight of this parameter were adapted from Secunda et al., (1998) and Panagopoulos et al. (2006). The rating values and their weights are shown in the Table 3.1.and Table 3.2.

Table 3.1: Land Use Type Rating for Modified DRASTIC Index

Land use category	Rating	Land use category	Rating
Site-specific land usage		Natural areas or reserves	1
Toxic-waste disposal	9	Citrus orchards	7
Oil spillage	8	Orchards of other fruit	6
Industries	7	Pasture or other land unsuitable for agricultural use	5
Solid-waste disposal (regional)	6	Uncultivated land	5
Domestic-waste disposal (local)	5	Temporarily uncultivated land	5
Effluent irrigated fields	4	Vineyards	5
Effluent reservoirs	3	Olives	5
Extensive land usage		Quarries	5
Cotton	10	Non-irrigated field crops	4
Built-up areas	8	Avocados	2
Irrigated field crops	8	Forests	1
Greenhouses/tomatoes	8	Dune sands – Open areas	1
Reservoir	7		

Table 3.2: Land-Use Type Rating for Modified DRASTIC Index

Land use type	Typical rating.
Complex cultivations	10
Farm-residence	10
Principally agricultural land	4
Agro-forestry areas	3
Olive groves	5
Sclerophylous vegetation	1
Mineral extraction sites	2
Moors and heathland	2
Mixed forest	1
Broad-leaved forest	1
Coniferous forest	1
Continuous urban fabric	10
Discontinuous urban fabric	9
Natural grassland	3
Non-irrigated arable land	4
Transitional woodland/shrub	2

3.5 Validation of the Modified DRASTIC Method

Validation provided an insight into the existence and spatial distribution of groundwater pollution. Therefore, as the validation of the vulnerability maps on contaminants datasets collected on-site from boreholes distributed in the study region. This is usually done using the concentrations of nitrates in the collected samples. To validate the performance of the modified DRASTIC method result, a Pearson's Correlation

Coefficient and Chi-square value were used to compare the nitrate concentrations and the resultant modified DRASTIC index map.

3.5.1 Validation Using Pearson’s Correlation Coefficient

The linear dependence between the modified DRASTIC index and the observed nitrate concentration was analyzed by calculating the Pearson’s correlation coefficient (r) of the two variables. For this purpose, the groundwater vulnerability index at each borehole were extracted using GIS technique. The graph of vulnerability index values and observed nitrate at each borehole was plotted and Pearson’s correlation coefficient (r) determined.

3.5.2 Validation Using Chi-Square Value

The spatial relationship between the modified DRASTIC vulnerability map and nitrate concentration map was calculated as an area cross-tabulation, one map being in rows and the other in columns. An area cross-tabulation table summarizes the overlap of all possible combination of the two input maps. The chi-square test is a quantitative measure of the degree of association between two maps and the calculations are based on the number from the area cross-tabulation. The area table between the two maps (say A and B) becomes the matrix T, with elements Ti, j, where, i is the number of classes in map B (rows of the table) and j is the number of classes in A (columns of the table). The marginal total of T is the sum of i-th (Ti) rows and j-th(Tj) columns (Graeme et al., 2014). The expected area (Tij*) is given by the product of sum of the rows (Ti) and columns (Tj), divided by marginal total (T), as shown Equation 3.4:

$$T_{ij}^{\ *} = \frac{T_i - T_j}{T} \tag{3.4}$$

Then, the chi-square statistic is given by Equation 3.5:

$$X^2 = \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{(T_{ij} - T_{ij}^{\ *})^2}{T_{ij}^{\ *}} \tag{3.5}$$

Equation 3.5 is a classical chi-square equation (observed-expected)^2/expected expression, which has lower limit of 0, in case the observed areas equals the expected areas (Graeme et al., 2014). The chi-square value increases as the difference between the observed areas and expected areas increases in magnitude up to an upper limit variable. The overall value of chi-square represents the overall association between the modified DRASTIC model index and the observed nitrate concentration, hence validating its performance.

For this purpose, the observed nitrate values at the borehole locations were interpolated using the ordinary Kriging interpolation of ArcGIS10.1 and classified into seven classes. The nitrate concentration map was then reclassified using the Spatial Analysts Tools of ArcGIS 10.1. The obtained modified DRASTIC vulnerability map was also classified according to criteria proposed by Civita and De Regibus (1995) and Corniello et al. (1997). The area cross tabulation table of the reclassified nitrate concentration and the final vulnerability map was obtained using available ArcGIS tools. Then, chi-square table was calculated using Equation 3.5.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Groundwater Quality Assessment

Groundwater quality describes the state of the water that is located beneath the Earth's surface. Millions of people worldwide depend on the groundwater either for domestic use or irrigation. Depending on the use, the quality of groundwater must meet certain standards for it to be fit for certain purposes. Groundwater quality assessment is an exercise to determine whether the groundwater quality has met the set standards or not, for it to be declared safe for certain purposes. The present study assessed the groundwater quality and mapped the spatial variation of groundwater samples in terms of suitability for drinking purpose. Assessment of groundwater quality in the aquifer has therefore become vital to ensure the availability of safe water for human uses and ecosystem support. The results of the groundwater quality parameters analyzed from 161 groundwater samples of Mid River Njoro catchment is presented in Table 4.1. Table 4.2 displays the basic statistics of the groundwater quality of the study area.

Table 4.1: Laboratory Analytical Results of Groundwater Quality for the Study Area

Location	**pH**	**EC (µS/cm)**	**DO (mg/l)**	**Temp. (^{0}C)**	**NO_3 (mg/l)**	**NH_3 (mg/l)**	**TP (mg/l)**
Rurii (BH1)	8.47	766.00	5.49	20.43	0.44	0.0910	0.08
Mukuria (BH2)	7.53	538.00	3.34	21.07	1.99	0.0713	0.11
Ngondu (BH3)	8.70	623.00	5.85	24.5	0.05	0.0305	0.06
Timsales (BH4)	7.94	902.00	9.01	17.58	1.72	0.0883	0.05
Eriithia (BH5)	7.78	389.50	7.8	19.4	1.15	0.1248	0.02
KALRO Main (BH6)	7.71	591.50	4.67	22.75	3.56	0.1003	0.10
KALRO Dairy (BH7)	7.96	501.50	1.53	23.65	60.86	0.0927	0.11

Table 4.2: Basics Parameter Statistics Used in Calculating GQI for the Study Area

Parameters	KEBS	Min	Max	Mean	Std. Dev
pH	7.5	7.53	8.70	8.01	0.43
EC (µS/cm)	1500	389.50	902.00	631.19	153.49
DO (mg/l)	4	1.53	9.01	5.38	2.41
Temperature (^{0}C)	25	17.58	24.50	21.34	2.56
NO_3 (mg/l)	10	0.05	60.86	9.14	22.29
NH_4 (mg/l)	0.5	0.03	0.12	0.09	0.03
TP (mg/l)	2	0.02	0.11	0.08	0.03

From the results the observed pH readings varied from 7.53 to 8.70, with the overall mean value of 8.01. The maximum pH value of the study area exceeds the KEBS and WHO recommended value of 8.5. Since the mean pH is more than the neutral value of 7, the groundwater of the study area can be described as ‘slightly’ alkaline. This result concurs with the previous results of Emily, (2012), who studied the influence of anthropogenic activities on the surface and groundwater quality of lake Nakuru basin, Kenya, and concluded that the groundwater of the region as alkaline. The author attributed the alkalinity to the weathering and infiltration water through the geological formation, especially the carbonates, that make up the unsaturated zone of region, Mid River Njoro catchment included. The recent studies conducted by Muraguri, (2016) and Kirianki et al. (2018), in Nairobi county and Njoro sub-county, respectively Kenya, are also comparable to the finding of this study.

The EC of the study area ranged from 389.50 µS/cm to 902.00 µS/cm, with a mean value of 631.19 µS/cm. The observed EC is below the threshold value of 2500 µS/cm set by KEBS standard and WHO guidelines. Nonetheless, high levels of EC are not desired in drinking water because it makes water unpleasant for human consumption. Previous studies carried out on the groundwater quality in the region observed relatively similar EC value (Wamalwa & Mutia, 2014; Kirianki et al. 2018).

All the groundwater samples had observed DO vary between 1.53 mg/l to 9.01 mg/l, with overall mean of 5.38 mg/l. This value slightly exceeds the maximum desired threshold of 4 mg/l recommended by KEBS and WHO. Water samples with DO greater than 0.5 mg/l are considered ‘oxic’ and those with DO less than 0.5 mg/l are considered ‘suboxic’, according to the geochemical classification system (Canfield & Thamdrup, 2009). Based on this classification, the groundwater of the study area is ‘oxic’ in nature. According to Rose and Long (1988a), the DO concentration is important in determining groundwater quality of an area because it regulate the valence state of metals and constrain the bacterial metabolism of dissolved organic species. M’Erimba et al. (2017) and Kirianki et al. (2018), assessed the groundwater quality of Njoro area, Kenya and found out that the observed DO concentration were 6.39 and 6.2 respectively. These values are closed to the finding of this research work.

The temperature readings varied between 17.58 °C to 24.50 °C. The overall mean was 21.34 °C, which is below the threshold of 24 °C recommended in KEBS standard and WHO guidelines. However, temperature fluctuation is not desired because it triggers changes in physical, chemical and microbial processes, which in turn affects the groundwater quality (Hahnlein et al., 2013).

Nitrate concentration range between 0.05 mg/l to 60.86 mg/l. Except for KARLO dairy borehole (which showed extremely high nitrate value of 60.86 mg/l) the observed nitrate values in other boreholes were lower than maximum acceptable level of 10 mg/l recommended in the KEBS standard. Low nitrate concentrations have also been reported by other studies (M’Erimba et al., 2017; Kirianki et al., 2018). The extremely high level of nitrate in KALRO dairy borehole could probably because of point-source contamination from the fecal matter of the dairy animals. Nitrate accumulation occurs when surface run-off collects fecal wastes into water source. A point-source pollution of groundwater of Kargi area, Marsabit County, Kenya by high level of nitrate concentration, was the causes attributed to the death of over 1000 animals in the year 2000 (Aquasearch Ltd. 2010; Bulle et al., 2012).

The observed ammonia concentration in the study area was between 0.03 mg/l to 0.12 mg/l. The observed values are below the maximum desired limits of 0.5 mg/l for safe drinking water. Ammonia is very toxic even at a very low concentration (Fadiran & Dube, 2009). The occurrence of the ammonia in groundwater is an indicator of anthropogenic impact and agricultural activity (Lingle, 2013). Fadiran and Dube, (2009) conducted a study on the relative levels and factors in the analysis of total ammonia nitrogen in some surface and groundwater bodies in Swaziland and the measured ammonia concentration from 15 boreholes was in the range of 0.11 to 0.43 mg/l, which is comparable to this study.

The total phosphorus concentration ranged between 0.02 mg/l to 0.11mg/l and the overall mean concentration was 0.08 mg/l. Compared to the desired value of 2 mg/l (KEBS, 2010), the observed concentration lower than maximum acceptable level. The low concentration of total phosphorus in groundwater is because of the adsorption to soil and aquifer sediments surface as well as its immobile nature (Holman, et al. 2008). The sources of the total phosphorus to the groundwater resources include soil layers, aquifer media mineral dissolution, agricultural chemicals, animal wastes and leakage from septic tanks (Fuhrer et al. 1999). The observed total phosphorus levels in this study concur with previous studies on groundwater quality of river Njoro watershed, (M'Erimba et al., 2017; Kirianki et al., 2018).

4.2 Development of Groundwater Quality Index

Groundwater quality assessment is important because it ensures sustainable and safe use of groundwater resources. Describing the overall water quality condition is difficult due to the spatial variability of multiple contaminants and the wide range of indicators (chemical, physical and biological) that could be measured. Babiker et al. (2007), proposed a GIS-based groundwater quality index (GQI) which synthesizes different available water quality data by indexing them numerically relative to the World Health Organization (WHO) standards. This study adopted a five-step procedures of Babiker et al. (2007) to develop a groundwater quality index (GQI) of the Mid River Njoro catchment. The process involved the generation of representations for the spatial variability of the originally point data and the multiple transformations of groundwater quality data into a corresponding index rating value related to groundwater quality.

4.2.1. Spatial Variations of the Groundwater Quality Parameters

4.2.1.1 Spatial Variations of pH

The values of the pH ranges from 7.53 to 8.7, (Figure 4.1), which indicates the alkaline nature of groundwater of the study area. As per the (WHO, 2011) standards, all the samples fall within the recommended limit of the range 6.5 to 8.5 for human consumption, except in Ngondu borehole. The Ngondu groundwater borehole is located directly in the Egerton university community, in operation since the 1950's, and probability this is the cause of high pH. The spatial concentration map of pH (Figure 4.1) shows an elevated level in the eastern part of the study area, where Njoro canning factory and Egerton university community are located. The elevated pH levels in this area is probably attributed to decay of organic matters from Njoro canning factory and Egerton university community. The pH levels slightly exceed the desired range of 6.5 to 8.5 set by KEBS standards and WHO guidelines. The pH is a master variable due to its participation in most of the chemical reactions in groundwater (Deutsch, 1997). This result concurs with the previous results of Emily, (2012), who studied the influence of anthropogenic activities on the surface and groundwater quality of lake Nakuru basin, Kenya, and concluded that the groundwater of the region as alkaline.

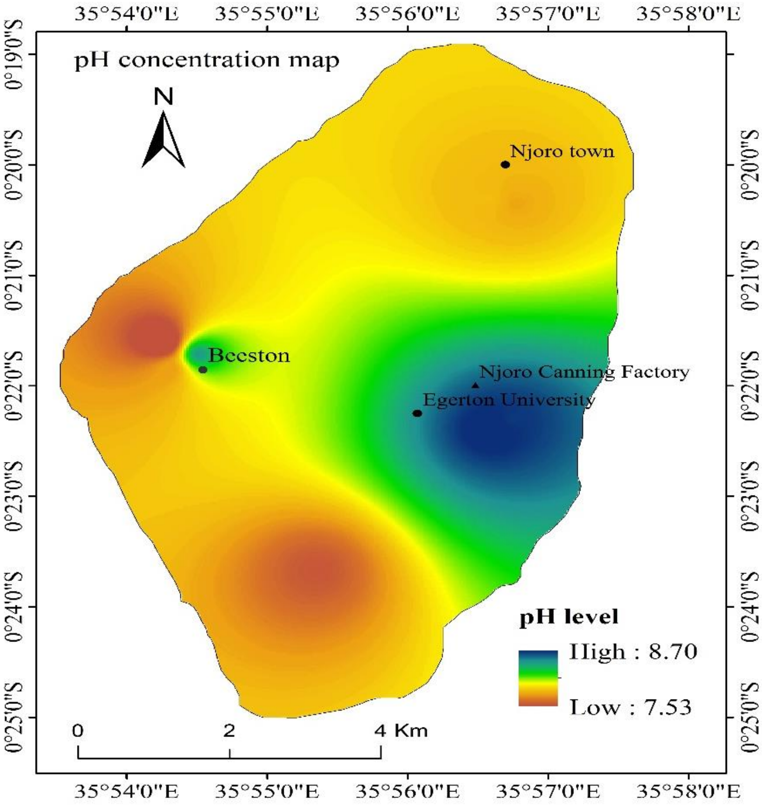


Figure 4.1: Spatial Variations of pH in the Study Area

4.2.1.2 Spatial Variations of Temperature

The spatial distribution of the underground water temperature is presented in Figure 4.2. Groundwater temperature of the study area vary slightly (depending on the depth to watertable) and range from 17.58 °C to 24.50 °C. The groundwater temperature falls in the eastern part, area around the Njoro canning factory and Egerton university community, is high as compared to the south west area. This temperature distribution seems to be affected by the depth to the groundwater table, since the area with low temperature had high groundwater tables as compared those areas with high temperature. Groundwater temperature is a physical parameter which is widely used in hydrogeological investigation. High potable water temperature may impart undesirable taste and odor as well as the corrosive ability of the water (WHO, 2011).

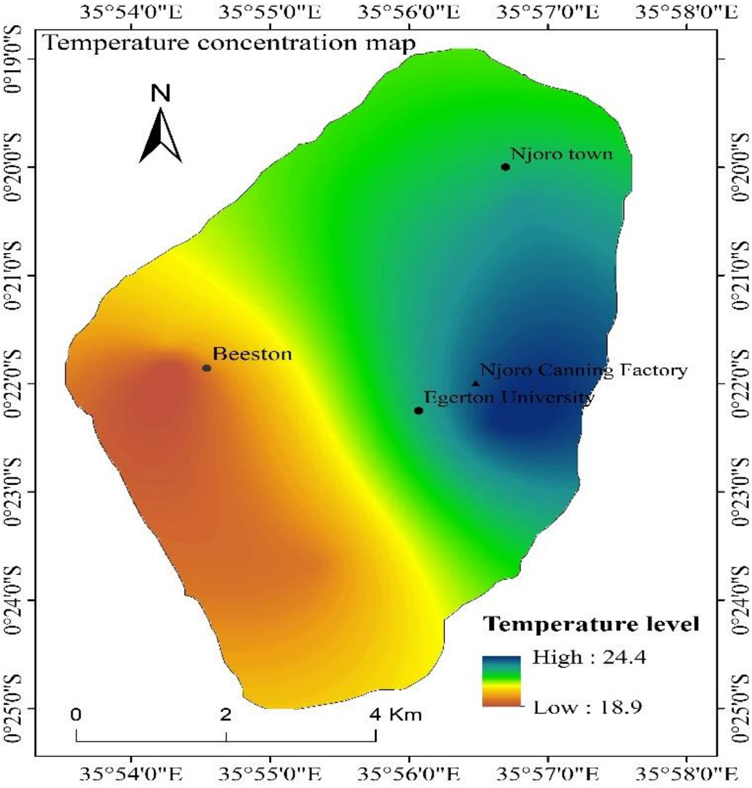


Figure 4.2: Spatial Variations of Temperature in the Study Area

4.2.1.3 Spatial Variations of Electrical Conductivity

Electrical conductivity is a measure of water capacity to convey electric current. In the study area, the EC of the groundwater is varying from 389.50 µS/cm to 902.00 µS/cm with an average value of 631.19 µS/cm. High EC values at some sampling locations is likely caused by the high salt composition contained in groundwater. An elevated level of electrical conductivity is observed in the Beeston village and Egerton university community. The study area generally depicted a medium level of EC. This parameter is highly and spatially variable in the study area as shows in the Figure 4.3. The spatial variability is seen in the built up areas, around Njoro town, Beeston village and Egerton university community. The EC can be categorized into three types, namely (I) type with a low salt content (value of EC <1.500 µS/cm); (II) type with medium salt level (value of EC 1.500 and 3.000 µS/cm); (III) type with high salt content (value of EC > 3.000 µS/cm). Water sample from study area is 100% classified as the first category with a low salt content. This may be due to the study area are within the volcanic region (McCall, 1967; Baker, 1986) and too far away from the shore line, therefore the levels of sodium chloride accumulation in groundwater tends to be low.

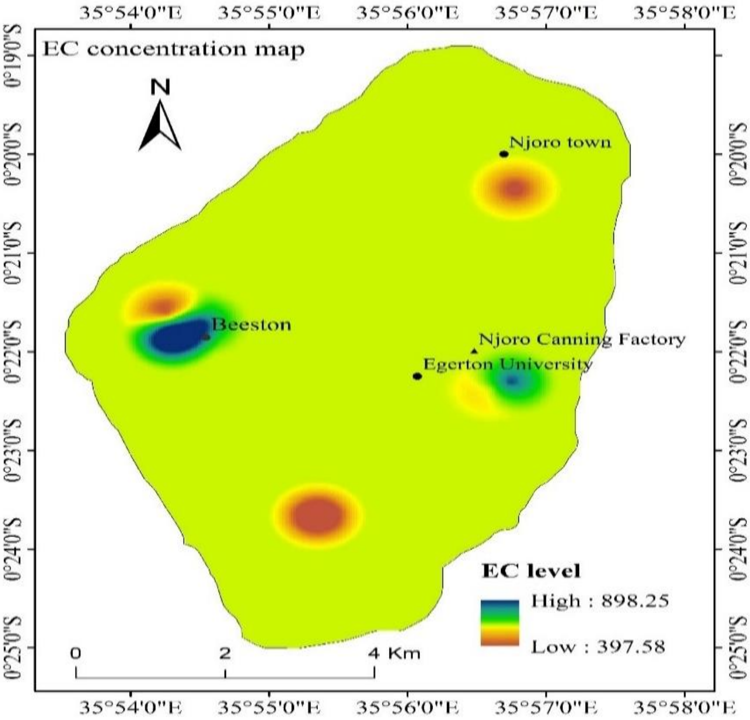


Figure 4.3: Spatial Variations of Electrical Conductivity in the Study Area

4.2.1.4 Spatial Variations of Dissolved Oxygen

The spatial distribution of dissolved oxygen is presented in Figure 4.4. The observed dissolved oxygen varied from1.53 mg/l to 9.01 mg/l, with overall mean of 5.38 mg/l. The mean value slightly exceeds the maximum desired threshold recommended by KEBS and the WHO guidelines of 4 mg/l. The southern part of the study area has high dissolved oxygen concentrations as compared to the areas around the Njoro town and this is probably because of the different groundwater levels, which is very low in the north as compared to south. According to Rose and Long (1988a), the DO concentration is important in determining groundwater quality of an area because it regulate the valence state of metals and constrain the bacterial metabolism of dissolved organic species. M’Erimba et al. (2017) and Kirianki et al. (2018), assessed the groundwater quality of Njoro area, Kenya and found out that the observed DO concentration were 6.39 mg/l and 6.2 mg/l, respectively. These values are closed to the finding of this research work.

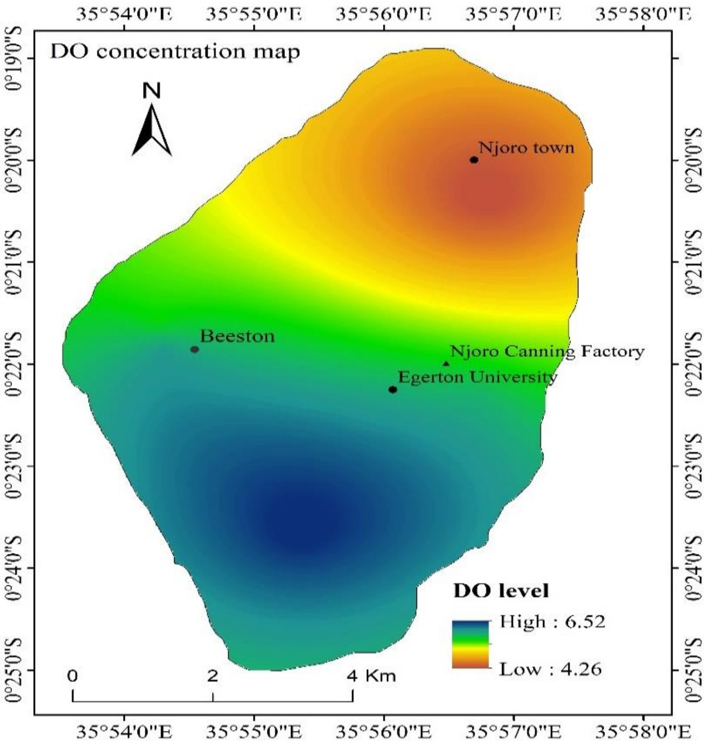


Figure 4.4: Spatial Variations of DO in the Study Area

4.2.1.5 Spatial Variations of Nitrate

Nitrate spatial concentration map is presented in Figure 4.5. The northern part of the study area where Njoro town and KALRO are located has high levels of nitrate as compared to the southern area. There is an extreme value nitrate is observed in the KALRO dairy borehole and this is probably because of point-source pollution from the fecal matter of the dairy animals. Nitrate presence in groundwater is a direct indicator of groundwater contaminations from human activities (Fuhrer et al. 1999; Baalousha, 2011). Nitrate concentrations in groundwater can be derived from faulty septic tanks, sewage discharge, oxidation of organic materials, farming and/or agricultural processes.

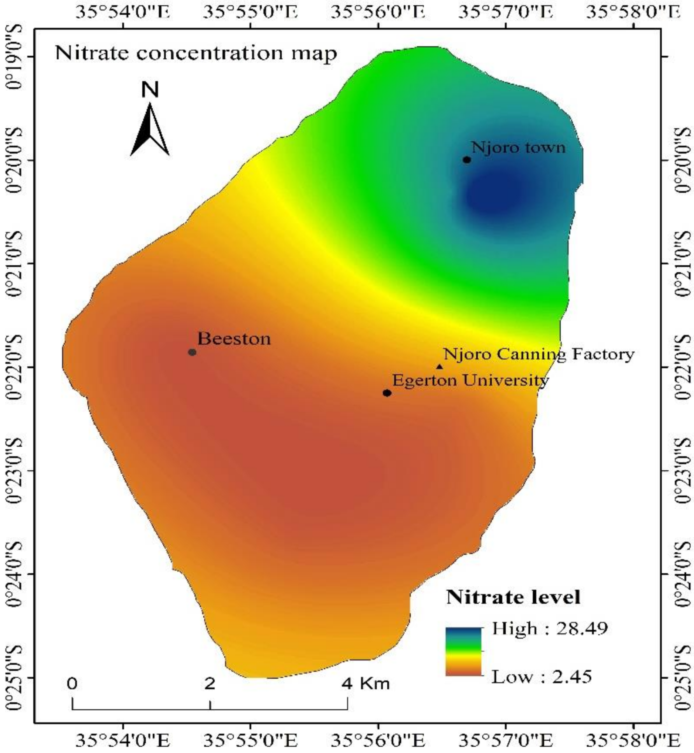


Figure 4.5: Spatial Variations of Nitrate in the Study Area

4.2.1.6 Spatial Variations of Ammonia

The spatial distribution of ammonia is shown in the Figure 4.6. The ammonia is highly variable in the study area, varying between 0.02 mg/l to 0.12 mg/l. Low levels of ammonia are observed in Njoro canning factory and Egerton university community areas, where pH and temperature are also high. Ammonia is found in groundwater naturally as a result of anaerobic decomposition of organic material (Bohlke et al., 2006). Ammonia is toxic to organisms at concentrations exceeding 0.5 mg/L (WHO, 2011). Ammonium can also oxidize to nitrate, which can lead to decreased levels of dissolved oxygen. Ammonia in sediments typically results from bacterial decomposition of organic matter that accumulates in sediment Moreover, a major concern with ammonia in drinking water is nitrification associated with the formation of nitrites and nitrates.

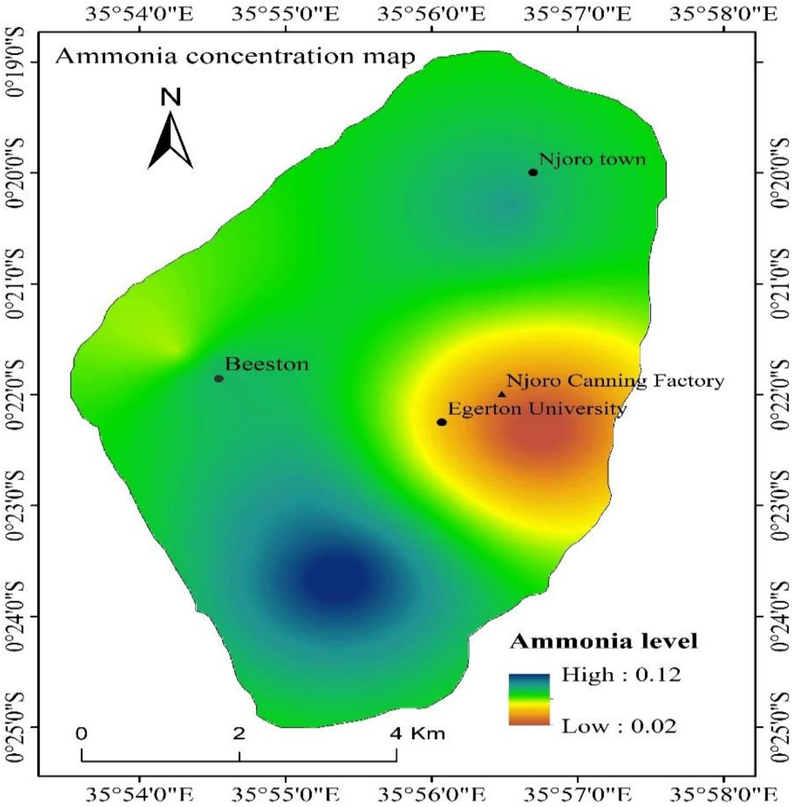


Figure 4.6: Spatial Variations of Ammonia in the Study Area

4.2.1.7 Spatial Variations of Total Phosphorus

The spatial variations of TP is depicted in the Figure 4.7. The highest concentrations occurred in boreholes located in northern part of the study area around Njoro town as compared to the southern area. There are three possible sources for the TP found in groundwater of the study area: anthropogenic sources such as domestic wastewaters, a natural source in the soil or aquifer sediments, or a combination of both. However, the concentrations of TP in groundwater generally low because phosphorus tends to sorb to soil and aquifer sediments and is not readily transported in groundwater (Holman et al. 2008).

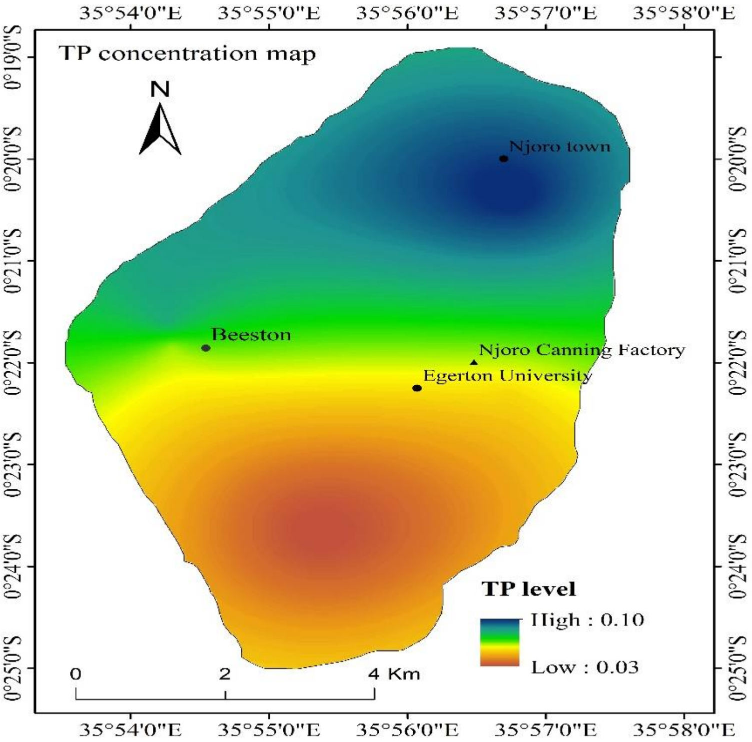


Figure 4.7: Spatial Variations of Total Phosphorus in the Study Area

4.2.2 Contamination Index Levels in the Study Area

Determination of contamination index for each parameter using normalizing difference index equation (Equation 3.1) is the second step to calculate GQI. Contamination index describes the difference between the observed concentration of physico-chemical parameters measured in the field and the maximum desired limits set by KEBS standards and WHO guidelines. The contamination index is a factor of single component that exceeds the maximum permissible concentration of groundwater quality parameters and reflects the contamination levels of each groundwater quality parameter (Singh et al., 2015). The spatial distribution of exceedance factor (CI) of the groundwater quality parameters is similar to their observed concentration levels. The contamination index values for the parameters whose concentrations are below the maximum desired limits are negative and those which exceed the maximum limits are positive. The contamination index spatial distribution maps show the contamination levels per pixels of the study area in the range of -1 and 1. Thus, contamination index (CI) becomes the ratio between the measured concentration of contaminant and the prescribed maximum acceptable contaminant level, with fixed upper and lower limits. The contamination index distributions maps are shown in Figure 4.8 to 4.14. The contamination index maps are similar to the concentration maps, except that the contamination index maps give the standard deviation from the maximum acceptable level for each parameters, hence estimating the level of contaminations.

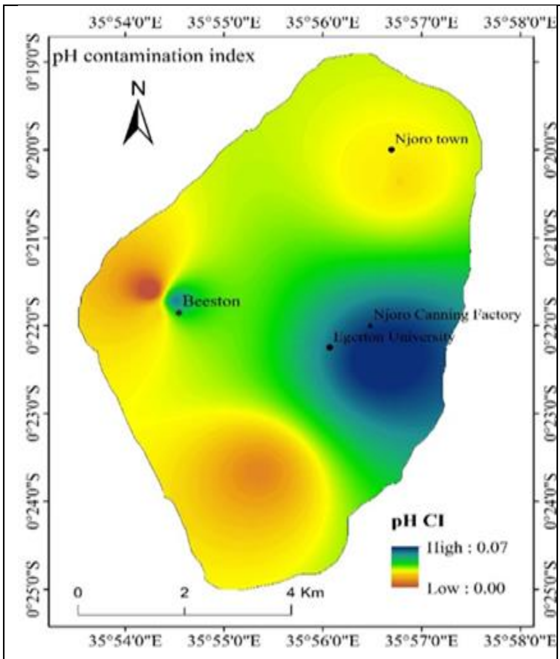


Figure 4.8: pH Contamination Index Levels

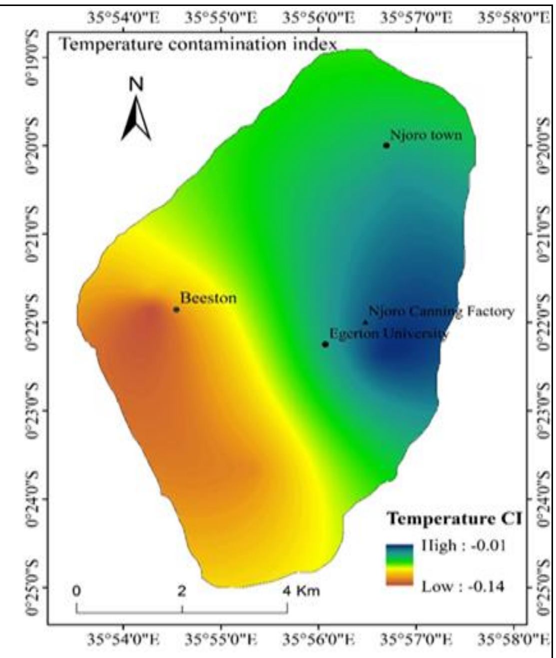


Figure 4.9:Temperature Contamination Levels

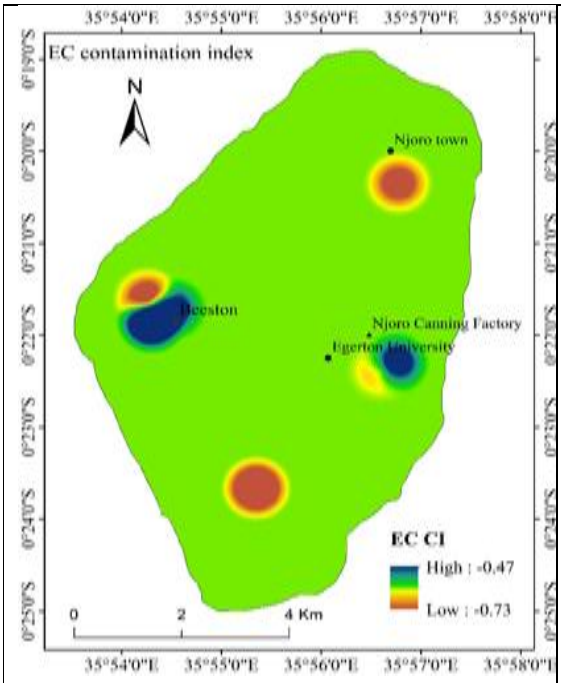


Figure 4.10: EC Contamination Index Levels

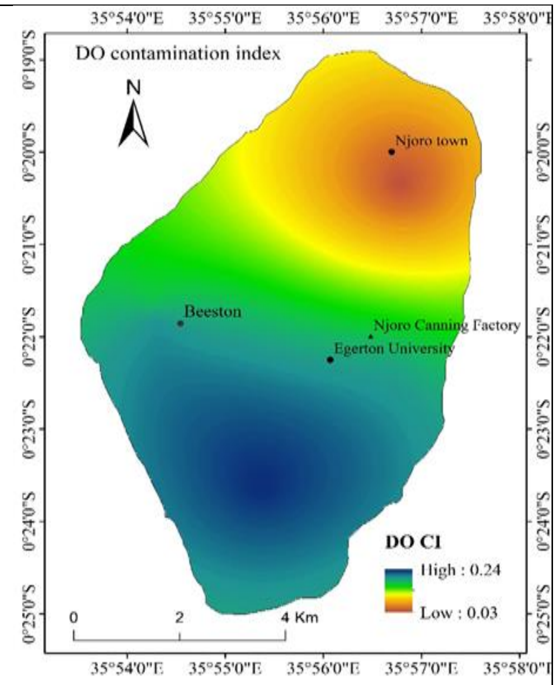


Figure 4.11: DO Contamination Index Levels

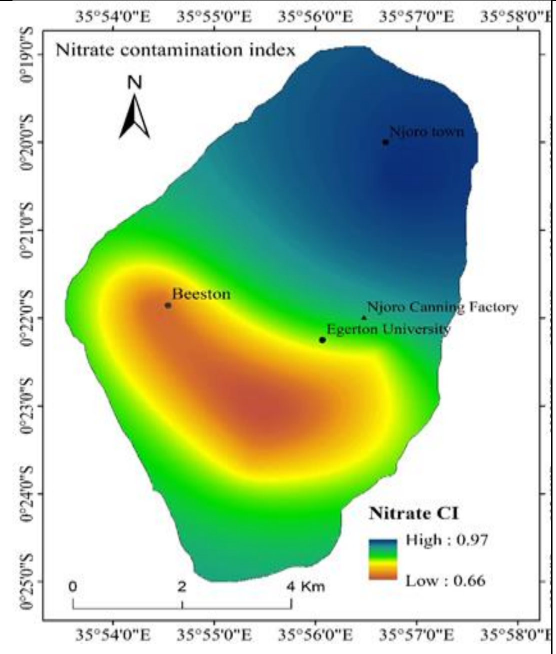


Figure 4.12: Nitrate Concentration Index Levels

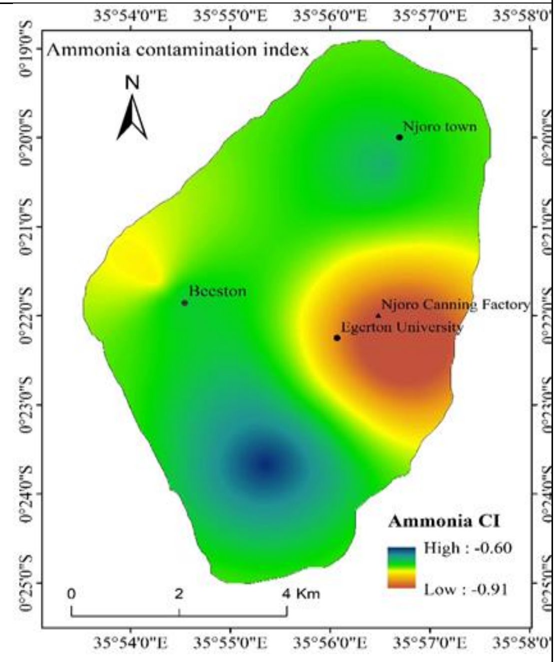


Figure 4.13: Ammonia Concentration Index Levels

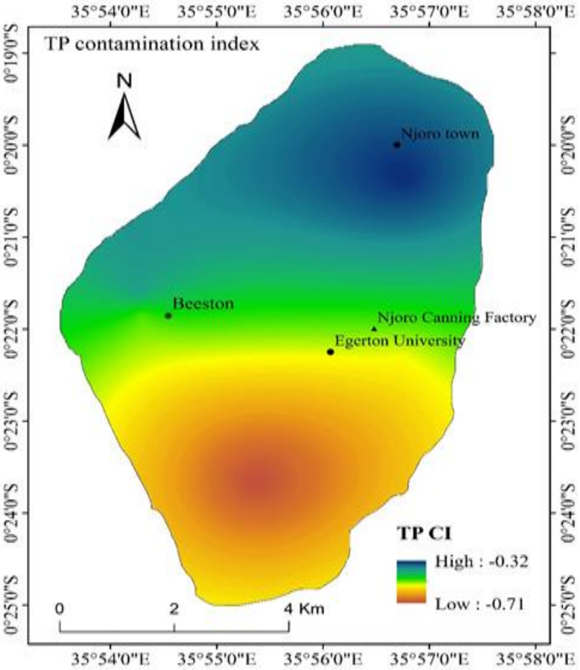


Figure 4.14: TP Concentration Index Levels

4.2.3 The Ranking of Contamination Index Levels

The contamination index levels calculated for each parameter in the previous step, is rated using polynomial Equation 3.2. The statistics (Table 4.3) of the seven rank maps (parameters) used to compute the GQI, indicate that parameters such as nitrate, pH, and DO dictate the spatial pattern of groundwater quality portrayed in Figure 4.22 due to their high mean rank value. The nitrate has the highest-ranking levels between 8.19 to 9.81 while the ammonia has the least ranking levels between 1.31 to 2.48. The rate 1 indicates least impact on groundwater quality and the rate 10 indicates the highest impact. Therefore, the nitrate parameter has the highest impact on the groundwater quality and ammonia has the least impact of the groundwater quality of the study area.

Table 4.3: The ratings and weights of groundwater quality parameters

Parameters	**Ratings**	**Weights**
pH	5.00 – 5.33	5.17
EC	4.00 – 4.99	4.50
DO (mg/l)	5.14 – 6.11	5.63
Temperature (°C)	4.38 – 4.96	4.67
Nitrate (mg/l)	8.19 – 9.81	9.00 (+2)
Ammonia (mg/l)	1.31 – 2.48	1.90
Total phosphorus (mg/l)	2.44 – 3.62	3.03

Figure 4.15 to 4.21 display the spatial ranking maps for the seven parameters used in calculation of GQI of the study area. The spatial distribution of CI in the study area is rated per cell. The pH, DO and nitrate concentration determine the overall groundwater quality of the study area, based on the ranking factor. The importance of these parameters in determining overall water quality are emphasized in a book chapter on water quality parameters reviewed by Nayla, (2019). pH is considered one of the most important water quality parameters because heavy metals dissolve in highly acidic water (Nayla, 2019), and some chemicals such as ammonia becomes poisonous in alkaline water (Nayla, 2019). DO, as earlier discussed, determines groundwater quality because it regulate the valence state of metals and constrain the bacterial metabolism of dissolved organic species (Rose and Long, 1988). The nitrate is poisonous at a concentration level more than 10 mg/l (APHA, 2005).

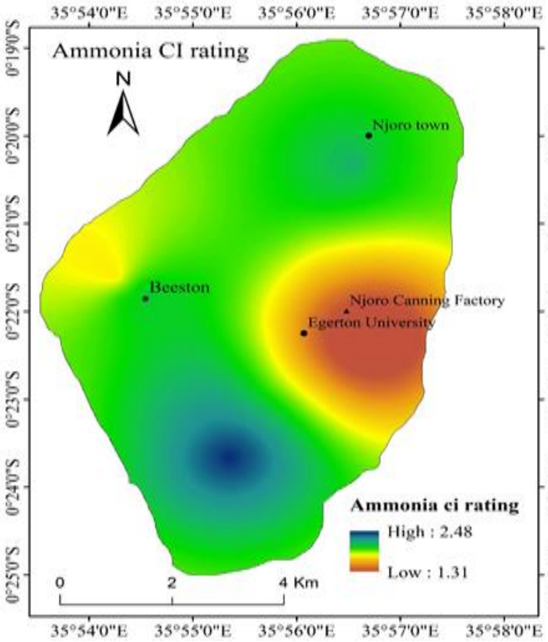


Figure 4.15: Ammonia Ranking Levels

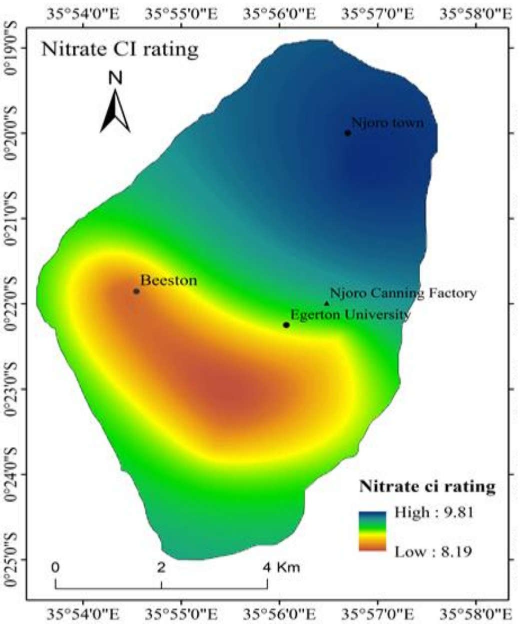


Figure 4.16: Nitrate Ranking Levels

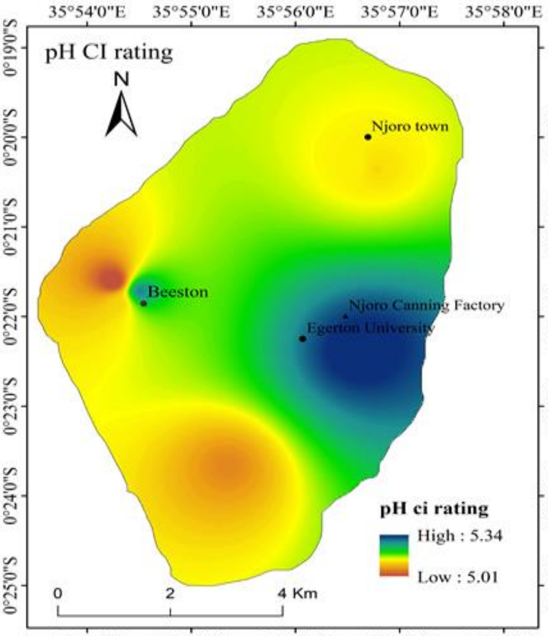


Figure 4.17: pH Ranking Levels

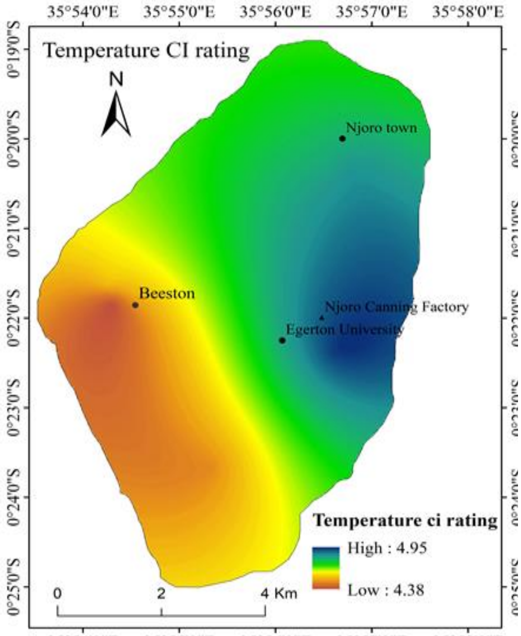


Figure 4.18: Temperature Ranking Levels

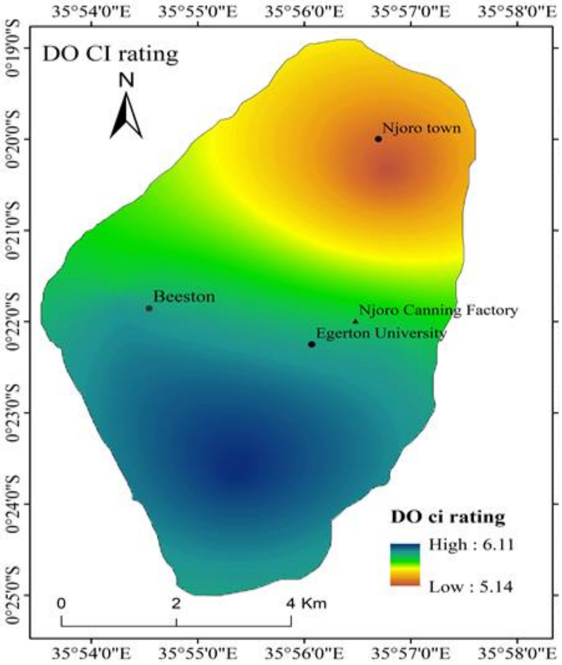


Figure 4.19: DO Ranking Levels

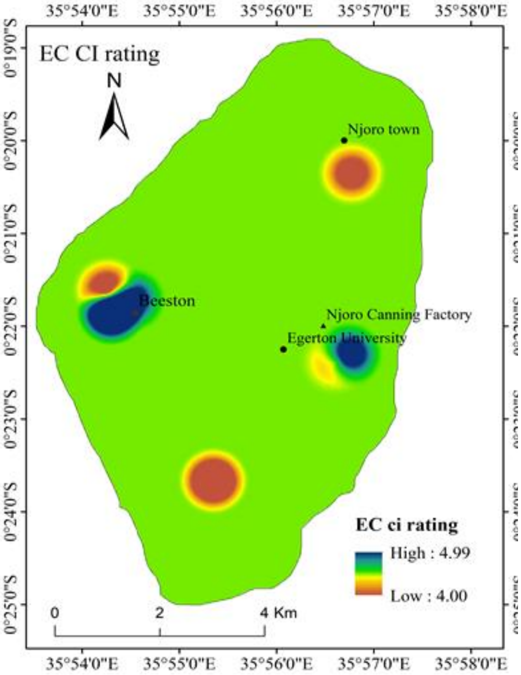


Figure 4.20: EC Ranking Levels

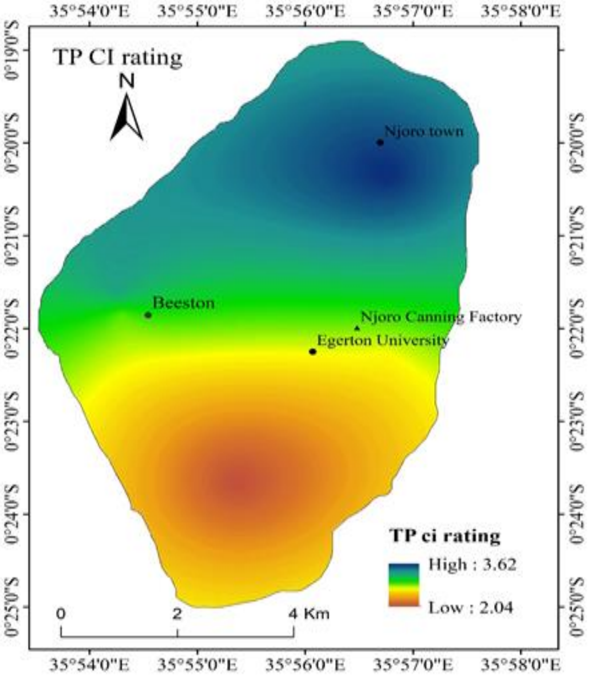


Figure 4.21: TP Ranking Levels

4.2.4 Calculation of Groundwater Quality Index

The spatial pattern of groundwater quality index (GQI) of the Mid River Njoro catchment is shown in the Figure 4.22. The GQI indicated that the groundwater quality of the Mid River Njoro catchment, relatively good, ranging from 68.38 to 70.92, with spatial mean of 69.65. It also displayed the parameters, which reflected lower groundwater quality (high mean rank value) such as nitrate, pH and DO. The blue shade shows high GQI value, which corresponds to good groundwater quality as compared with the greenish shade, which represents the low GQI value. The northern part of the Mid River Njoro catchment, shows low values of GQI, corresponding to relatively low quality of groundwater when compared with the central part, which has high GQI values. In addition to that the upper northern part of the Mid River Njoro catchment is characterized by a very high population density which increases the chance of anthropogenic contamination.

The land use type seems to also control the spatial distribution of the groundwater of Mid River Njoro area, since the areas which depicted high GQI values are favored by the existence of patches of forest covers and agro-forestry practices. The influence of anthropogenic such land use type and population density on the spatial distribution of groundwater was noted in earlier study conducted by Babiker et al. (2007). Contrary, Khan et al. (2017), revealed that the spatial variability of groundwater of the alluvial aquifer in the western Ganges basin was not controlled by land use patterns. However, it is very difficult to certainly determine the influence of land use types on the groundwater quality, especially in areas with diffused nature of different land use patterns.

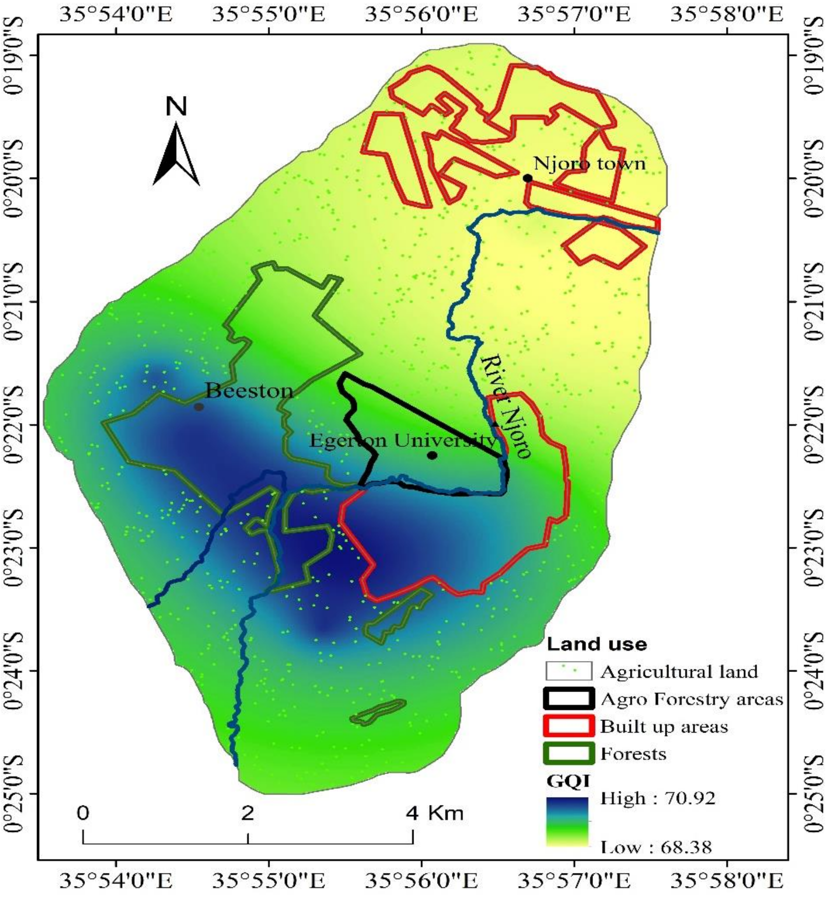


Figure 4.22: Groundwater Quality Index in the Mid River Njoro Catchment

4.3 Impact of Land Use on Groundwater Quality

Generally, land use has bearing on the quality of groundwater and the intensity of it depends the type of land use. Land use change is an important factor affecting the groundwater recharge and water quality, especially in agricultural regions (Scanlonet al., 2005). Even though the groundwater quality assessment is done at specific locations (boreholes), it is usually influenced by the type of land use in the immediate surroundings and the potential catchment area of the boreholes, especially in relatively flat terrains. Figure 4.23 represents the land use map of the study area developed using Google Earth Imagery of 2015.

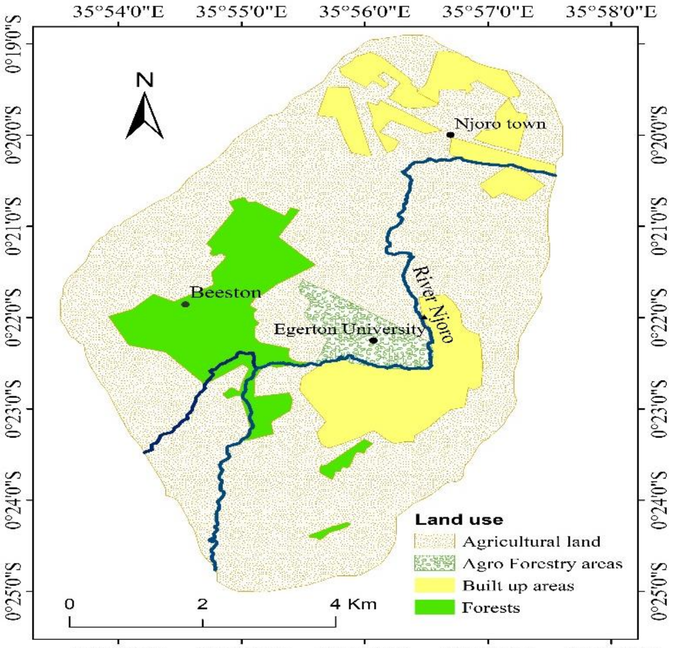


Figure 4.23: Land Use Classification of the Mid River Njoro Catchment

The land-use types listed here are those that are capable of polluting the groundwater resources. Figure 4.24 displays the percentage area of the land use classes. The agricultural land (72%) dominated the study area, followed by built-up areas (14%), forests areas (11%) and agroforestry areas (3%).

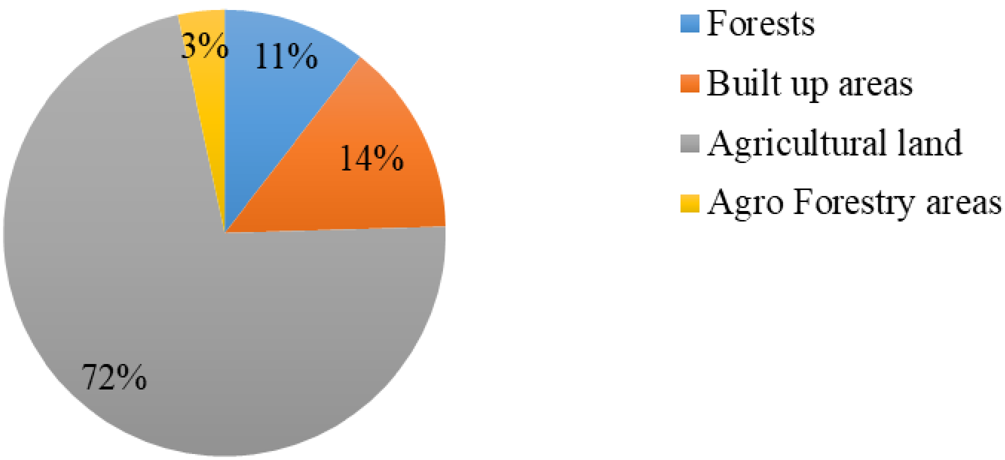


Figure 4.24: Percentage Area for Each Land Use Type in the Study Area

Table 4.4 represents the mean and the standard deviation of the GQI values within each land use type.

Table 4.4: GQI Statistics for Each Land Use Type

Land use type	Groundwater quality index	
	Mean	Std. dev.
Forest areas	70.82	0.40
Agricultural land	69.15	0.68
Built-up areas	68.48	0.34
Agroforestry areas	70.03	0.44

From the statistics it is evident that the mean GQI value varies among the different classes of land use present in the study area (See Table 4.4). The forest areas have high GQI value, and the built-up areas have low GQI value. This suggests that the groundwater in the study area is experiencing the adverse effect of land use conditions. This is probably because the agricultural land is profusely spread over the entire study area.

Also, a higher standard deviation is seen in agricultural land, suggesting a greater spatial variation of groundwater quality. This could be attributed to the systems of farming and intensity of agricultural chemicals used in farming activities. Such a great spatial variation of groundwater quality and overall contamination index is not desired since this has a tendency to lower the groundwater resource sustainability (Khan et al., 2017).

According to the recent study conducted by Mainuri (2018), on the impact of human settlement (built-up areas) on land use/land cover changes in the mid River Njoro Sub Watershed, Kenya, the human settlement increased by 121% and forest cover reduced by 43%. The same result was obtained in an earlier study conducted by Shivoga et al. (2005), which reported a forest loss of 20% between 1986 and 2003. The forest areas were converted into mixed-small scale agriculture and human settlements. Moreover, the main economic activities in Mid River Njoro catchment is intensive agriculture which rely on fertilizers and other agricultural chemicals that impact negatively on the surface water quality and by extension groundwater quality (Kirianki et al. 2018). These studies' findings are in line and support the results of the present study.

4.4. Estimation Modified DRASTIC Model Input Parameter Maps.

The modified DRASTIC index was calculated from the seven thematic layers constructed from six hydrogeological parameters and one anthropogenic factor, using ArcGIS 10.3. The rates and weight were assigned to each thematic layer and final modified DRASTIC Vulnerability Index calculated as a raster summation of all the seven thematic layers.

4.4.1 Depth to Groundwater Table Parameter (D)

Groundwater level depths (D) is the first parameter of the original DRASTIC method for assessing groundwater vulnerability. Groundwater table depth in this study was taken as the distance between the ground surface to the level at which water is first encountered or sensed (strike water level) by the Dipper. It actually determines the thickness of the vadose zone and hence, the distance the contaminants must travel before reaching the aquifers (Aller et al., 1987).

Figures 4.25, 4.26 and 4.27 represent the groundwater table spatial variation, reclassified groundwater table depths and the rating assigned to each class. The depths at which water were encountered ranged from 7.63 m to 126.55 m below the surface. The large percentage of the study area had a water depth above 30 m, which correspond to a rating value of 1, according the original DRASTIC method. The deepest levels were recorded towards the northern part of study area. In this region, therefore it takes longer time for contaminants to reach groundwater table unless there is a porous gate or even faults. The areas around Beeston village, Egerton university and south of the study area had high groundwater table, hence more likely to be contaminated as compared to the northern region.

The large percentage of the study area has groundwater depths which make it resilient to groundwater pollution. The groundwater depths are deep enough to provide enough time for elimination of contaminants through natural processes. This is reflected in the rating value of 1 assigned to water table depth beyond 30 m by the original DRASTIC model (Figure 4.27).

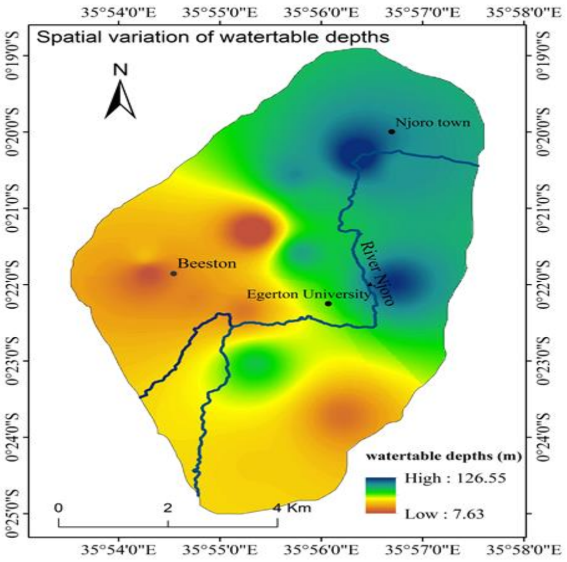


Figure 4.25: Spatial Variation of Watertable Depths

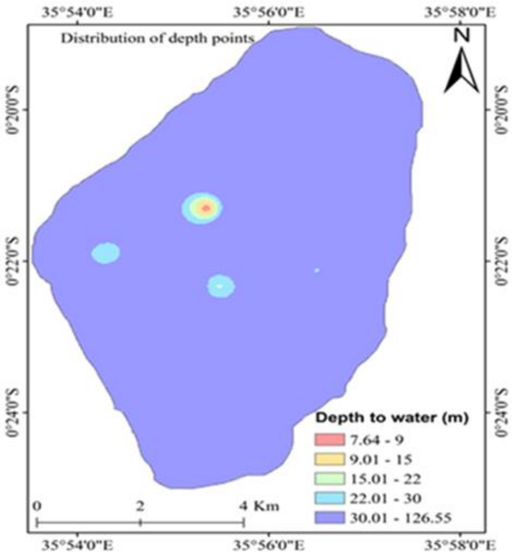


Figure 4.26: Reclassified Water Table Depths

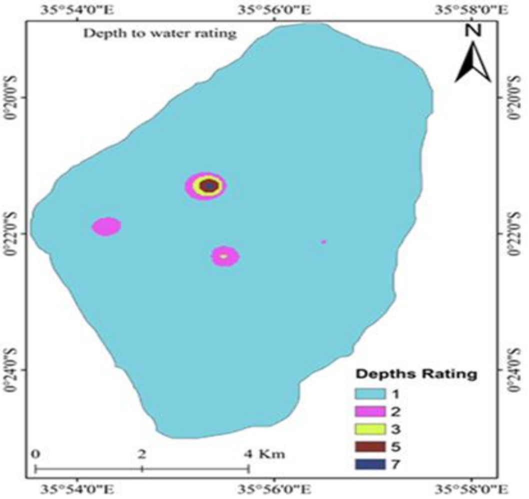
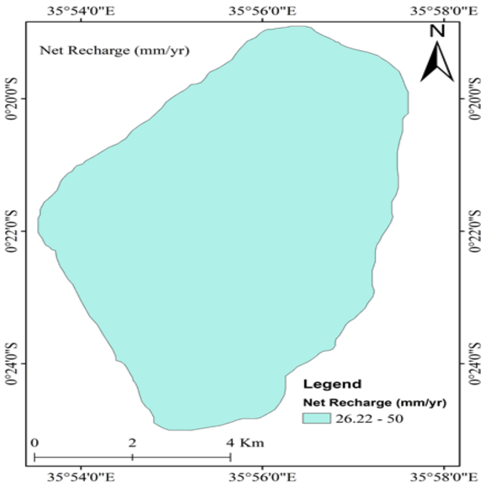


Figure 4.27: Assigning of Rating to Each Class

4.4.2 Net recharge parameter (R)

Net recharge is the amount of water per unit area of land which enters the ground surface, infiltrate through the soil and vadose zone and finally reaches the water table. Figure 4.28 and 4.29 represent the spatial distribution of net recharge and rating assigned net recharge parameter of the Mid River Njoro catchment. From the hydrogeological reports of the boreholes in the study area, the net recharge range between 26 mm/year to 27 mm/year. The study area is classified into a single class with rating value of 1 according to the original DRASTIC model. This means the vulnerability of the study area minimally influenced by the net recharge.



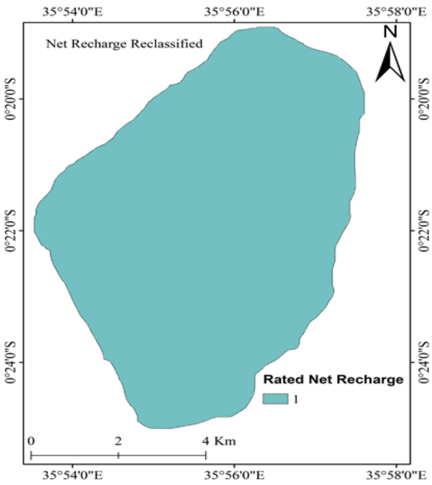


Figure 4.28: Spatial Variation of Net Recharge in the Study Area

Figure 4.29: Rating Assigned to the Net Recharge in the Study Area

4.4.3 Aquifer Media Parameter (A)

Aquifer material plays a critical role in groundwater contamination because of its characteristics related to hydraulic conductivity and porosity of the water-bearing formations. Depending on these aquifer properties the contaminants might spread both horizontally and vertically within the aquifer or restricted to just point of introduction. Figure 4.31 and 4.32 display the aquifer media and rating assigned to various aquifer media found in the Mid River Njoro catchment. Basically aquifer media composed of sediments, pumice, black ashes and eutaxitic welded tuffs. The sediments are unconsolidated and loose materials categorized as sandstones while the pumice are extremely porous rocks similar to sand. The black ash is a volcanic ash with fine-grained size, also called black sand. The tuffs are consolidated igneous rocks. The aquifer media of the Mid River Njoro catchment is therefore, classified into three classes: sand, sandstones and igneous rock. The aquifer map was then reclassified based on the rating value assigned to sand (8), sandstones (6) and the igneous rock (4).

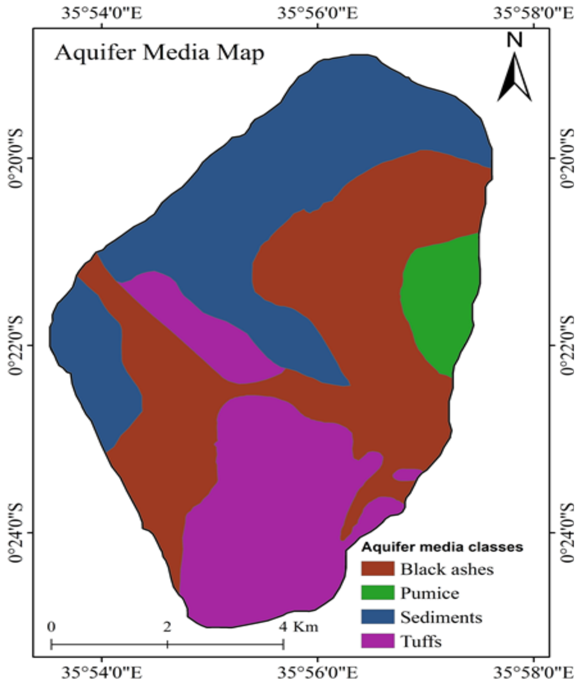


Figure 4.30: Aquifer Media in the Study Area

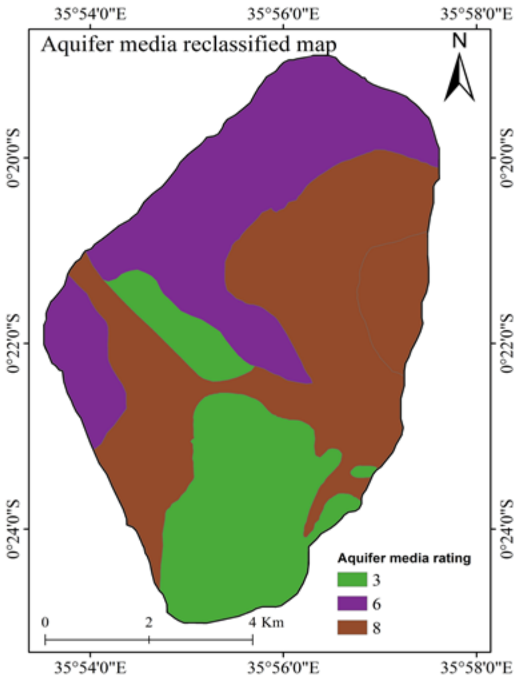


Figure 4.31: Aquifer Media Ratings

4.4.4 Topography Parameter (T)

Figures 4.33 and 4.34 display percentage slope and the ratings assigned to different class of slope percentage of Mid River Njoro catchment, respectively. The topography of the study area is for most part, a flat plain and gently undulating category covering 44.36%, followed by closely by rolling class occupying an area of 40.02% and high slope of about 15.62% towards the southern area. The first two classes increase percolation time from the ground surface to water table, hence high chance of groundwater pollution.

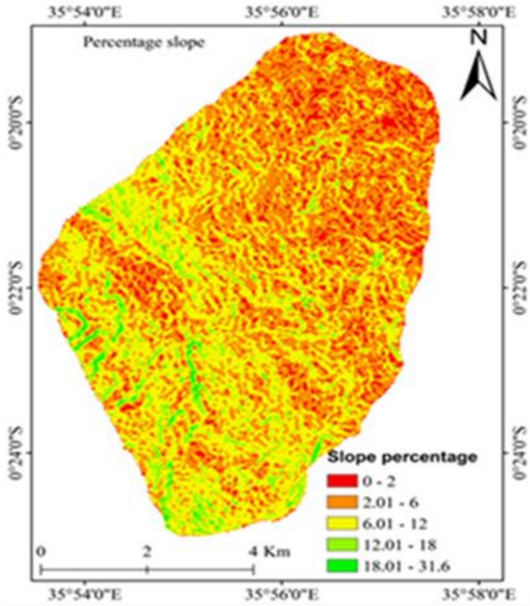


Figure 4.32: Slope Percentage in the Study Area

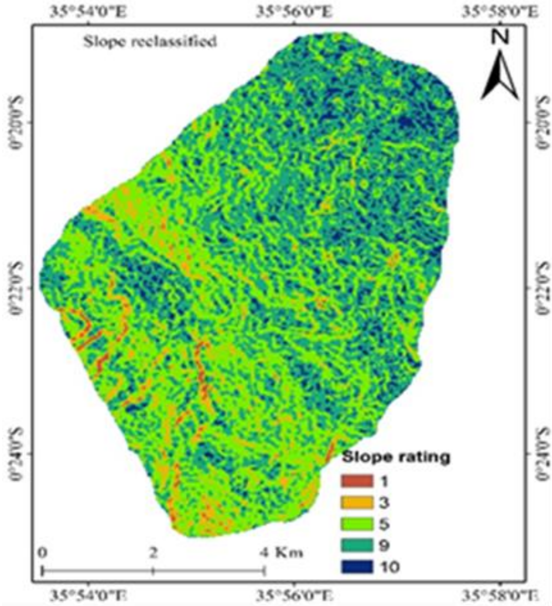


Figure 4.33: Slope Percentage Ratings

According to Maina and Raude (2016), the highest area percentage of Njoro catchment, Kenya, fall under flat to gently undulating landscape covering 52.98%, which is in close in agreement with the finding of this study. Such flat areas allow run off to collect for long time (Maina and Raude, 2016) thereby increasing the infiltration of contaminants into groundwater table.

4.4.5 Impact of Vadose Zone Parameter (I)

The vadose zone plays an important role in controlling groundwater pollution because it controls infiltration rate and the environment for attenuation of the various type of contaminants (Arrey, 2019). Within the vadose zone, pollutants may be biodegraded, mechanically filtered, chemically reacted, volatilized and dispersed and this decrease with increase depth to the water table (Arrey, 2019).

Figure 4.35 and 4.36 display the vadose zone map and reclassified vadose zone map of the study area.

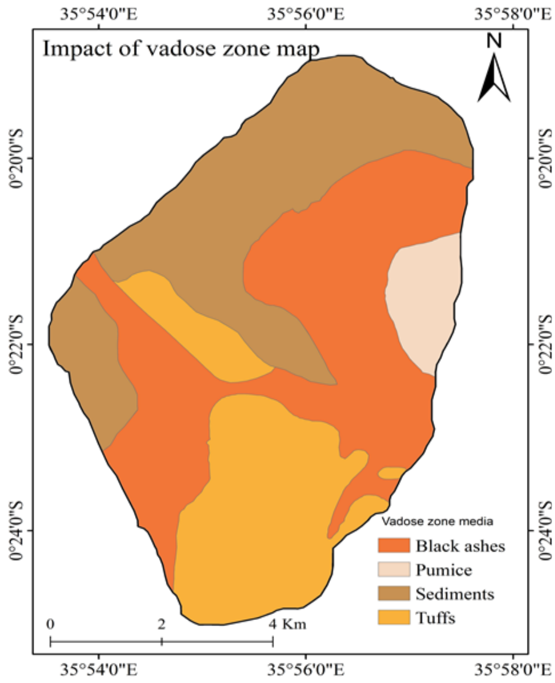


Figure 4.34: Vadose Zones Distribution in the Study Area

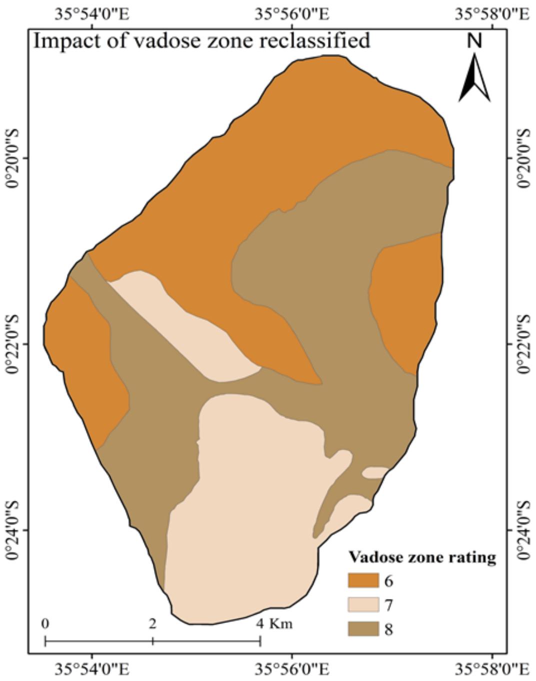


Figure 4.35: Impact of Vadose Zone Ratings

The geology of the study area comprises of black ashes, eutaxitic welded tuffs, pumice and pyroclastic and sediments rocks. The eutaxitic welded tuffs covered an area of about 24.35%, the black ashes about 38.50%, pumice about 4.86% and the pyroclastic/sediments occupied 32.29% of the study area. The rating value assigned to each geological class is shown in 4.34. The age of the eutaxitic welded tuffs and black ashes range from early tertiary to recent time, while the pumice and the pyroclastic and sediments are quaternary and recent formations.

According to the hydrogeological study of Njoro area (Odero and Peloso, 2000), the geology comprises of volcanic and sediments. The sediment (black ashes) units intercalated in the volcanic rocks (pumice and tuffs) forming the main source of groundwater. On the west to northeast side, there are a series of welded-vitreous to pumice Mau tuffs in the Njoro-Rongai area and lower Menengai vol-canics which include vitreous tuff and phonolite trachytes (Macdonald et al., 2011).

4.4.6 Hydraulic conductivity parameter (C)

Figure 4.37 and 4.38 show the spatial distribution of hydraulic conductivity and the rating assigned to different class of hydraulic conductivity found in the study area.

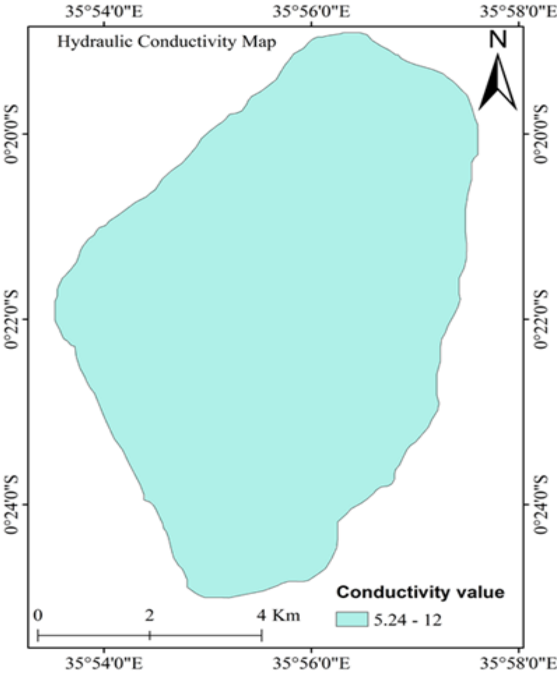


Figure 4.36: Conductivity Distribution in the Study Area

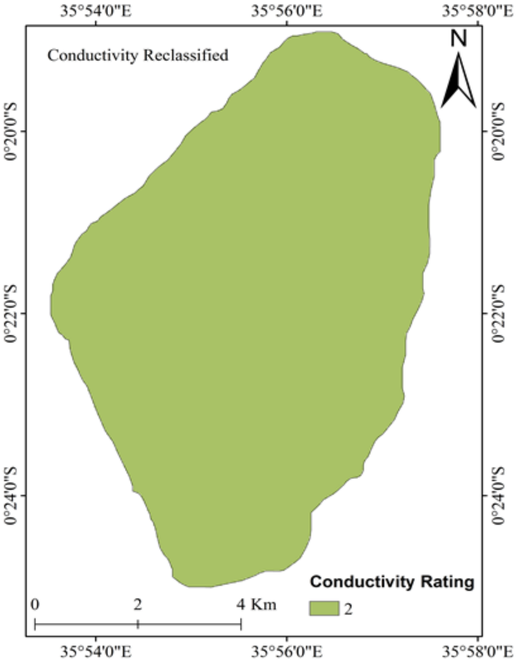


Figure 4.37: Conductivity Rating

The hydraulic conductivity here is for the aquifer materials but not the various strata above the groundwater table. The study area exhibits single hydraulic conductivity class with low rating value of 2 according to the original DRASTIC system. Hence, this parameter's contribution to the vulnerability of the groundwater to pollution is also low. Janet (2012), assessed the vulnerability of groundwater pollution in the lake Nakuru Basin, Kenya using the Protective Cover (PC) and Infiltration Condition (IC) method and found out that the resulting groundwater vulnerability map indicates low vulnerability of groundwater to pollution in most parts of the study area due to high protection offered by the overlying layers and the depth of most of the groundwater aquifer.

4.4.7 Impact of Land Use Type Parameter (Lu)

Figure 4.39 and 4.40 represent the major land use types and the ratings assigned to the different class of land use types found in the study area. These land use types are those that have potential influence on the groundwater recharge quality.

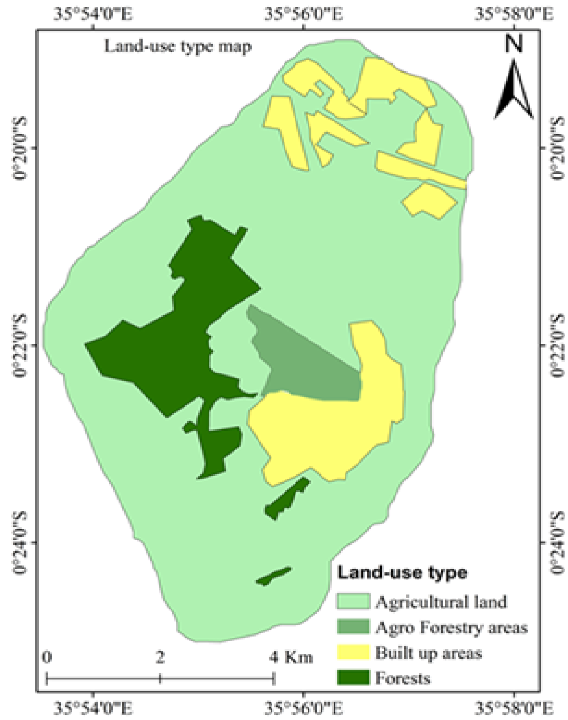


Figure 4.38: Land Use Types in the Study Area

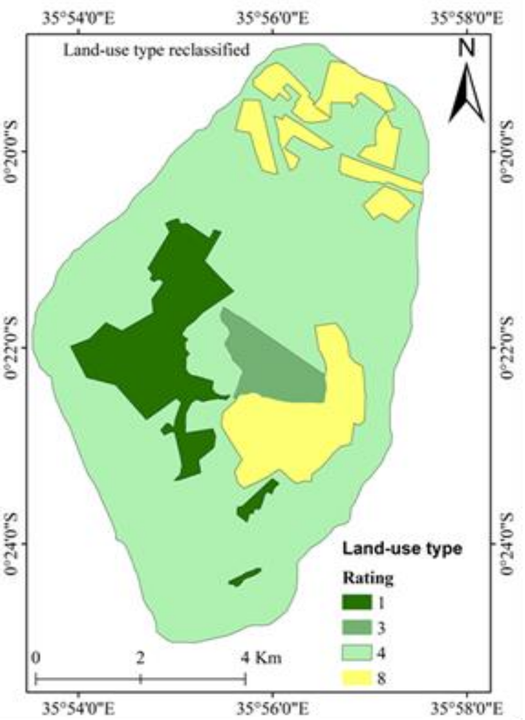


Figure 4.39: Land Use Type Ratings

The study area is dominated by the agricultural activities covering 72%, followed by the built-up areas occupying about 14%, forest cover about 11% and agro-forestry about 3% as shown in Figure 4.24. The built-up areas were given high vulnerability rating of 8 because they generate high recharge and contribute both point and non-point sources of contaminants (Wakode et al., 2018). This is followed by the agricultural land because of the agricultural chemicals that are applied to improve crop yield (Mishra et al., 2015). The agro-forestry and forest covers have least influence on the quality of groundwater hence low vulnerability rating.

According to the recent study conducted by Mainuri, (2018), on the impact of human settlement (built-up areas) on land use/land cover changes in the Mid River Njoro Sub Watershed, the human settlement has increased by 121% and forest cover reduced by 43%. The same result was obtained in an earlier study conducted by Shivoga et al. (2005), which reported a forest loss of 20% in the period between 1986 and 2003. The forest areas were converted into mixed-small scale agriculture and human settlements. Moreover, the main economic activities in Mid River Njoro catchment is intensive agriculture which rely on fertilizers and other agricultural chemicals that impact negatively on the surface water quality and by extension groundwater quality (Kirianki et al. 2018). The findings from these studies are in consistent with the results of the present study.

4.5 Modified DRASTIC Index – DRATIC-Lu

The computed modified DRASTIC (DRATIC-Lu) indices identify areas which are more vulnerable to groundwater pollution. A high index value reflects high groundwater pollution potential while low index value indicates low groundwater pollution potential area. Figure 4.41 and 4.42 represent the spatial distribution of groundwater vulnerability indices developed using modified DRASTIC model and the vulnerability of the Mid River Njoro catchment. The study area is characterized by three vulnerability zones: very low (6.1%), low (87.4) and moderate (6.5%). Based on the vulnerability map, Mid River Njoro catchment is dominated by low vulnerability classes, hence low potential for groundwater contamination. The areas with moderate vulnerability overlapped built-up areas and those with very low vulnerability had deep watertable, forest covers and agroforestry practices.

This result is comparable to the previous work of Janet, (2013), who determined spatial intrinsic variability of groundwater vulnerability to pollution in Lake Nakuru basin applying Protective cover and Infiltration condition (PI) method which is a GIS-based approach. According to the author, the vulnerability map indicates low vulnerability of groundwater to pollution in most parts of the study area due to high protection offered by the overlying layers and the depth of most of the groundwater aquifer.

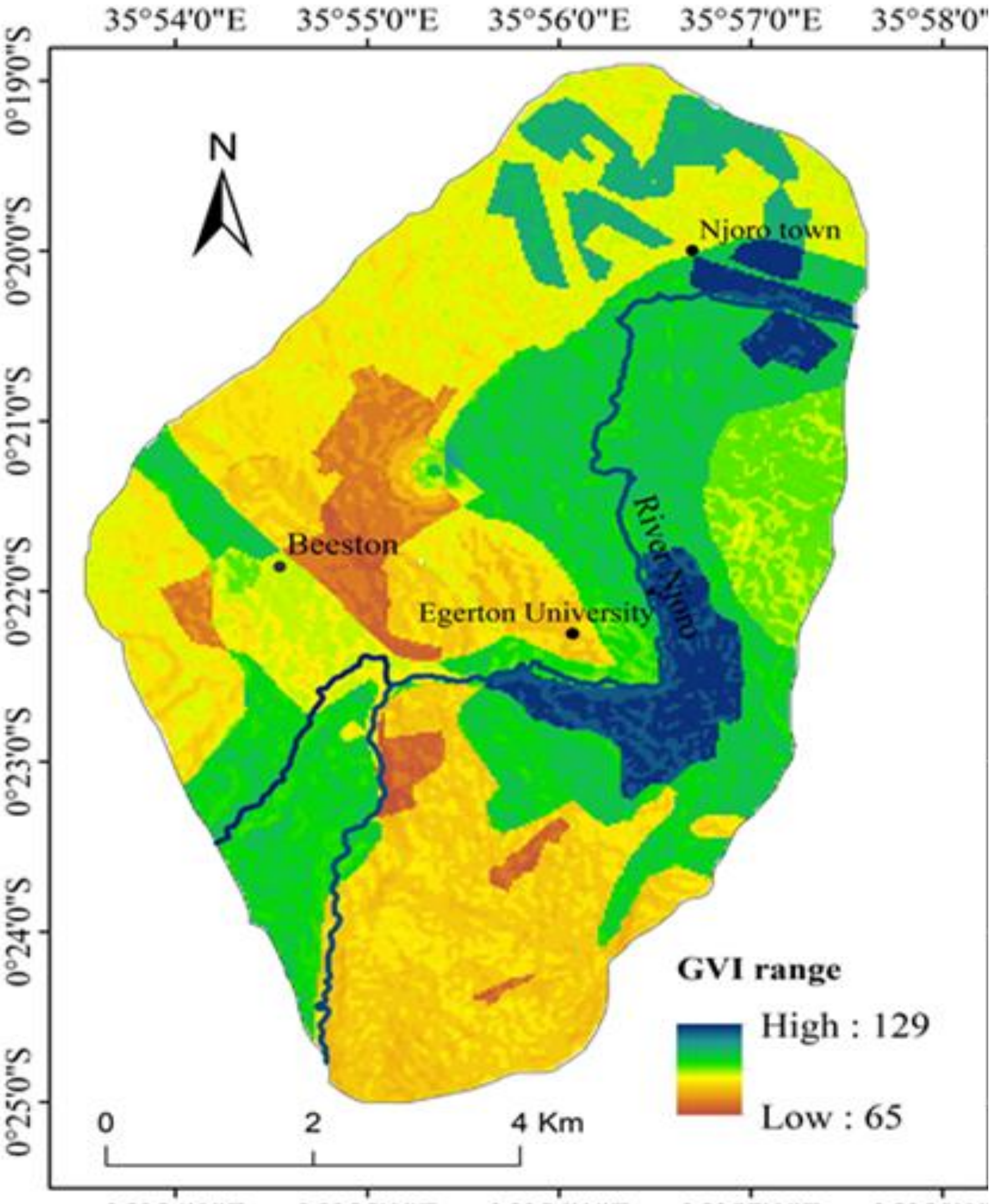


Figure 4.40: Modified DRASTIC (DRATIC-Lu) Indices

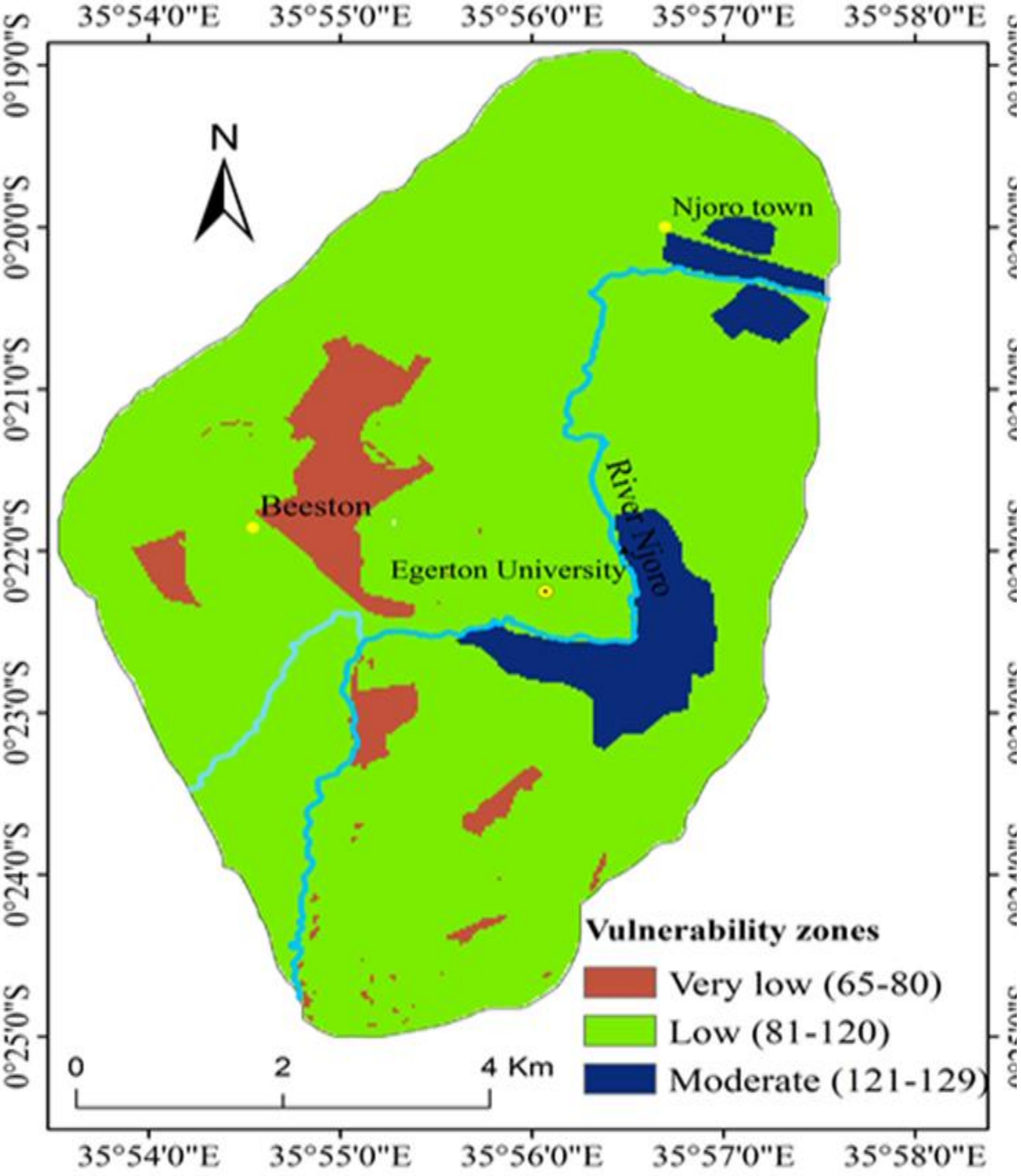


Figure 4.41: Groundwater Vulnerability Zones of Mid River Njoro Catchment

4.7 Validation of Modified DRASTIC Model

Validation is an essential process to ensure the model performs accurately and reliably, so that scientific inference can be desired from it (Kumar & Krishna, 2016). Table 4.5 represents the measured nitrate and modified DRASTIC index values at each borehole. Figure 4.43, shows the Pearson’s correlation coefficient ‘r” of the relationship between the nitrate concentrations and the modified DRASTIC values.

Table 4.5: Nitrate Concentration and Modified DRASTIC Index per Locations

Borehole locations	Nitrate levels	Modified DRASTIC Indices
C-200	1.58	98
C-201	1.62	109
C-202	1.56	93
C-205	2.09	88
C-211	2.07	104
C-220	1.64	84
C-223	1.67	84
C-327	1.58	69
C-745	1.84	104
C-916	1.91	128
C-1585	1.55	69
C-1934	2.31	104
C-1935	2.33	108
C-2745	1.81	107
C-5029	1.82	108
C-6032	1.61	88
r'		0.48

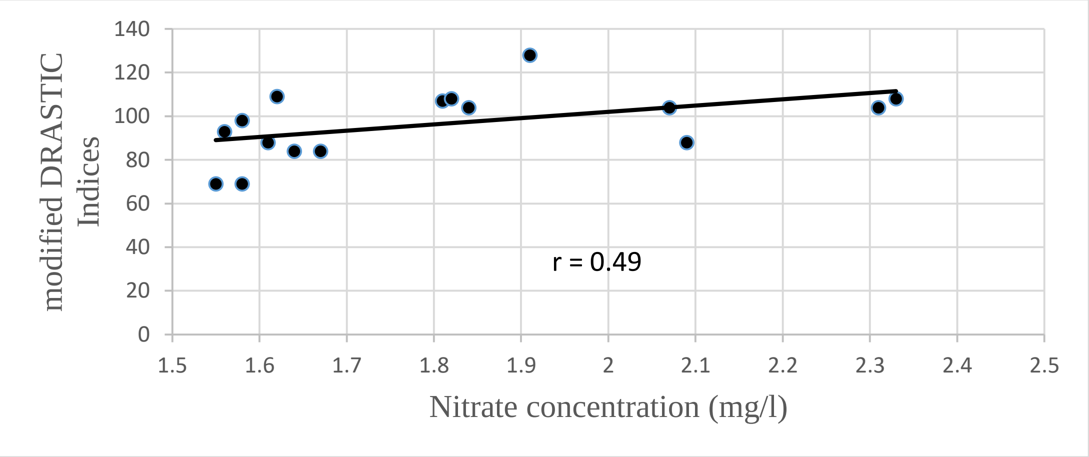


Figure 4.42: Validation of Modified DRASTIC Indices with Nitrate Levels

The Pearson's correlation coefficient, 'r' was found to be 0.49, which indicates a positive relationship between the nitrate concentration and the obtained groundwater vulnerability index values, thereby confirming the validity of the obtained results.

Chi-square test was also carried out to test association between the modified DRASTIC index map and the nitrate concentration map. Figure 4.39 and 4.40 show the interpolated and reclassified nitrate concentration maps, respectively. The area cross-tabulation analysis between the reclassified nitrate concentration map (Figure 4.44) and the modified DRASTIC Indices (Figure 4.45) was carried out using spatial analyst tools of ArcGIS 10.3 and the result presented in Table 4.7.

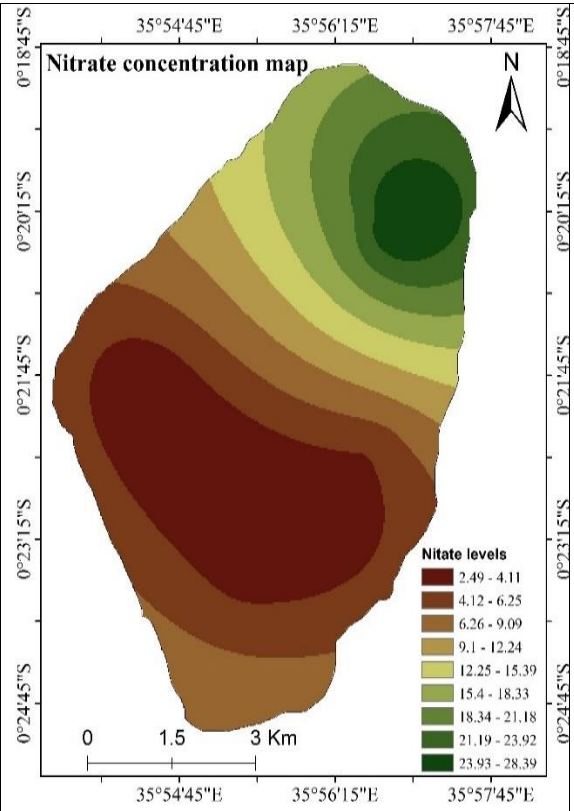


Figure 4.43: Spatial Distribution of Nitrate in the Study Area

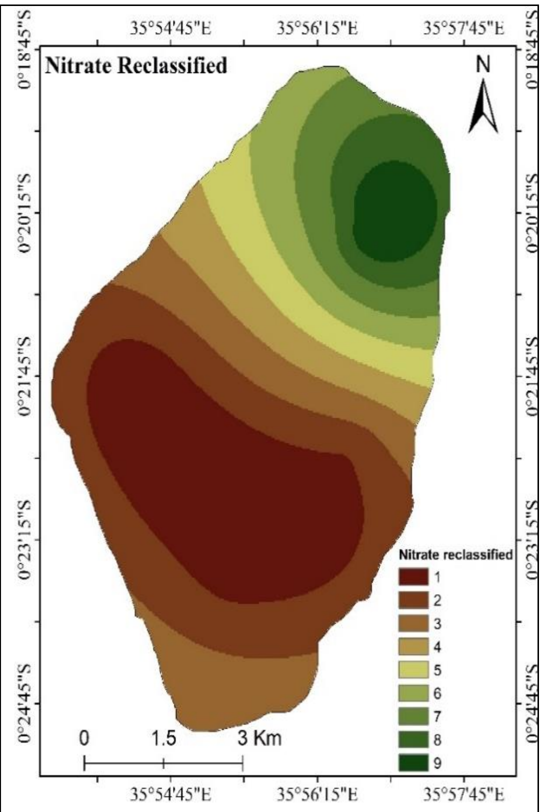


Figure 4.44: Assigned Ratings to Different Levels of Nitrate

Table 4.6: Area Cross-Tabulation Between Modified DRASTIC and Nitrate (Km^2)

Mdi Classes	**Nitrate class1**	**Nitrate class2**	**Nitrate class3**	**Nitrate class4**	**Nitrate class5**	**Nitrate class6**	**Nitrate class7**	**Nitrate class8**	**Nitrate class9**	**Total**
Class VL	1.71	0.70	0.53	0.42	0.04	0.00	0.00	0.00	0.00	3.40
Class L	12.88	10.31	4.08	2.31	3.19	3.46	5.12	5.04	1.69	48.08
Class M	0.28	1.09	0.48	0.57	0.13	0.00	0.00	0.66	0.36	3.58
Total	**14.88**	**12.10**	**5.10**	**3.29**	**3.36**	**3.46**	**5.12**	**5.71**	**2.05**	**55.06**

Table 4.7: Chi-Square Values for the Modified DRASTIC Index Classes and Nitrate Level Classes

m-DI Classes	**Nitrate class1**	**Nitrate class2**	**Nitrate class3**	**Nitrate class4**	**Nitrate class5**	**Nitrate class6**	**Nitrate class7**	**Nitrate class8**	**Nitrate class9**	**Total**
Class VL	0.69	0.00	0.15	0.23	0.14	0.21	0.32	0.35	0.13	2.21
Class L	0.00	0.01	0.03	0.11	0.02	0.06	0.09	0.00	0.01	0.34
Class M	0.48	0.12	0.07	0.58	0.04	0.22	0.33	0.23	0.39	2.47
Total	**1.17**	**0.13**	**0.25**	**0.91**	**0.20**	**0.50**	**0.74**	**0.58**	**0.52**	**5.01**

From Table 4.8 the chi-square value was found to be 5.01 (See Appendix 1). The Chi-square value increases as the difference between the observed areas and expected areas increases in magnitude up to an upper limit variable. Therefore, the small value (5.01) of chi-square value in this correlation means that the two maps are related though the relationship is very minimal. The chi-square result may be affected by the observed extreme value of nitrate concentration at KALRO dairy borehole.

Statistical spatial relationship between the modified DRASTIC maps and nitrate map were tested using Pearson’s correlation coefficient and chi-square. Pearson’s correlation coefficient of 0.5 and chi-square value of 5.01 were calculated as a relative measure to define the spatial dependency between two maps. The validation results (Pearson’s correlation coefficients and chi-square) obtained, demonstrated that the modified DRASTIC vulnerability map represent contamination situation in the Mid River Njoro catchment.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Based on studies discussed in this thesis, the following conclusions can be derived:

a. The GQI indicated that the groundwater quality in the Mid River Njoro catchment, Kenya, is generally good ranging from 68.38 to 70.92 on a scale of 0 to 100.
b. The land-use types of the Mid River Njoro catchment seem to be a major threat to the future of groundwater use since moderate vulnerability zones are found in built-up areas while low vulnerable areas are in forest cover. The major land-use types that influence water quality and vulnerability in Mid River Njoro catchment are: agricultural land (72%), built-up areas (14%), forests (11%) and agroforestry (3%).
c. The groundwater resources of the Mid River Njoro catchment has a low potential of contaminations because of the natural protection offered by the hydrogeological parameters. The study area is characterized by three vulnerability zones: very low (6.1%), low (87.4%) and moderate (6.5%).
d. This study reveals the importance and feasibility of vulnerability assessment in preventing and controlling groundwater pollution.

5.2. Recommendations

For future studies on groundwater vulnerability assessment the following recommendations can be proposed:

a. For better predictions of the vulnerability, it is suggested that modifications on weights and ratings values be done to fit this region.
b. Measures to prevent surface contaminations and excessive use of agricultural chemicals need to be in place.
c. Groundwater vulnerability assessment is recommended for all groundwater catchment areas to prevent groundwater pollutions

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APPENDICES

Appendix 1: Summary of Field and Laboratory Results of Groundwater Quality in the Study Area

Groundwater quality analyis for dry season													
	Date	**Location**	**Date**	**Source-ID**	**Rep**	**pH**	**EC (µS/cm)**	**DO (mg/L)**	**Temp (° C)**	**TSS (mg/L)**	**Nitrate-N (mg/L)**	**Ammon-N (µg/L)**	**TP (µg/L)**
1	24-Oct-17	Beeston	24-Oct-17	Rurii BH	1	8.65	667.00	6.53	20.50	3.33	0.01	48.00	44.29
	24-Oct-17	Beeston	24-Oct-17	Rurii BH	2	8.64	694.00	6.64	20.20		0.00	45.00	35.71
	24-Oct-17	Beeston	24-Oct-17	Rurii BH	3						0.05	41.00	38.57
						8.65	680.50	6.59	20.35	3.33	0.02	44.67	39.52
1	24-Oct-17	Beeston	24-Oct-17	Mukuria BH	1	7.62	504.00	3.31	24.00	3.33	0.09	17.00	94.29
	24-Oct-17	Beeston	24-Oct-17	Mukuria BH	2	7.60	514.00	3.34	23.20		0.10	17.00	94.29
	24-Oct-17	Beeston	24-Oct-17	Mukuria BH	3						0.16	25.00	92.86
						7.61	509.00	3.33	23.60	3.33	0.12	19.67	93.81
1	24-Oct-17	Ngondu	24-Oct-17	Ngondu BH	1	8.72	618.00	5.72	24.50	3.33	0.01	23.00	40.00
	24-Oct-17	Ngondu	24-Oct-17	Ngondu BH	2	8.68	628.00	5.85	24.50		0.02	21.00	52.86
	24-Oct-17	Ngondu	24-Oct-17	Ngondu BH	3						0.01	31.00	58.57
						8.70	623.00	5.79	24.50	3.33	0.01	25.00	50.48
1	24-Oct-17	Ngondu	24-Oct-17	Muchiri BH	1	8.64	739.00	6.83	24.50	3.33	1.10	17.00	61.43
	24-Oct-17	Ngondu	24-Oct-17	Muchiri BH	2	8.63	737.00	6.80	24.80		0.07	23.00	55.71
	24-Oct-17	Ngondu	24-Oct-17	Muchiri BH	3						1.10	15.00	51.43
						8.64	738.00	6.82	24.65	3.33	0.76	18.33	56.19
2	31-Oct-17	Beeston	31-Oct-17	Rurii BH	1	8.30	878.00	4.42	21.20	2.50	0.10	8.00	77.14
	31-Oct-17	Beeston	31-Oct-17	Rurii BH	2	8.29	825.00	4.36	21.20		0.17	0.00	80.00
	31-Oct-17	Beeston	31-Oct-17	Rurii BH	3						0.09	3.00	74.29
						8.30	851.50	4.39	21.20	2.50	0.12	3.67	77.14
2	31-Oct-17	Beeston	31-Oct-17	Mukuria BH	1	7.42	529.00	3.35	20.40	2.50	0.00	6.00	82.86
	31-Oct-17	Beeston	31-Oct-17	Mukuria BH	2	7.43	533.00	3.31	20.30		0.00	7.00	82.86
	31-Oct-17	Beeston	31-Oct-17	Mukuria BH	3						0.01	13.00	84.29
						7.43	531.00	3.33	20.35	2.50	0.00	8.67	83.33
1	31-Oct-17	Njoro	31-Oct-17	KALRO BH 1	1	7.92	471.00	3.69	24.80	5.00	0.81	4.00	101.43
	31-Oct-17	Njoro	31-Oct-17	KALRO BH 1	2	7.74	501.00	3.65	24.70		0.89	5.00	98.57
	31-Oct-17	Njoro	31-Oct-17	KALRO BH 1	3						0.73	7.00	94.29
						7.83	486.00	3.67	24.75	5.oo	0.81	5.33	98.10
3	7-Nov-17	Beeston	7-Nov-17	Mukuria BH	1	7.56	579.00	3.45	19.20	0.00	0.14	107.00	90.00
	7-Nov-17	Beeston	7-Nov-17	Mukuria BH	2	7.57	569.00	3.28	19.30		0.17	98.00	97.14
	7-Nov-17	Beeston	7-Nov-17	Mukuria BH	3						0.16	99.00	94.29
						7.57	574.00	3.37	19.25	0.00	0.16	101.33	93.81
1	7-Nov-17	Beeston	7-Nov-17	Timsales BH	1	7.85	905.00	7.70	17.60	2.50	0.31	98.00	45.71
	7-Nov-17	Beeston	7-Nov-17	Timsales BH	2	7.85	906.00	7.69	17.60		0.31	101.00	40.00
	7-Nov-17	Beeston	7-Nov-17	Timsales BH	3						0.36	98.00	41.43
						7.85	905.50	7.70	17.60	2.50	0.33	99.00	42.38
1	7-Nov-17	Njokerio	7-Nov-17	Erithia BH	1	7.78	382.00	7.80	19.40	2.50	0.26	100.00	21.43
	7-Nov-17	Njokerio	7-Nov-17	Erithia BH	2	7.78	397.00	7.80	19.40		0.28	102.00	18.57
	7-Nov-17	Njokerio	7-Nov-17	Erithia BH	3						0.24	105.00	27.14
						7.78	389.50	7.80	19.40	2.50	0.26	102.33	22.38
2	7-Nov-17	Njoro	7-Nov-17	KALRO BH 1	1	8.23	480.00	5.72	22.90	2.50	1.23	115.00	105.71
	7-Nov-17	Njoro	7-Nov-17	KALRO BH 1	2	8.21	481.00	5.67	23.00		1.32	112.00	90.00
	7-Nov-17	Njoro	7-Nov-17	KALRO BH 1	3						1.37	110.00	111.43
						8.22	480.50	5.70	22.95	2.50	1.31	112.33	102.38
3	14-Nov-17	Njoro	14-Nov-17	KALRO BH 1	1	7.96	502.00	1.61	23.90	2.50	12.03	74.00	107.14
	14-Nov-17	Njoro	14-Nov-17	KALRO BH 1	2	7.96	501.00	1.53	23.40		13.49	72.00	114.29
	14-Nov-17	Njoro	14-Nov-17	KALRO BH 1	3						15.79	82.00	112.86
						7.96	501.50	1.57	23.65	2.50	13.77	76.00	111.43
1	14-Nov-17	Njoro	14-Nov-17	KALRO BH 2	1	7.19	701.00	5.02	22.60	5.00	0.25	50.00	65.71
	14-Nov-17	Njoro	14-Nov-17	KALRO BH 2	2	7.19	705.00	5.00	22.50		0.24	53.00	115.71
	14-Nov-17	Njoro	14-Nov-17	KALRO BH 2	3						0.41	53.00	115.71
						7.19	703.00	5.01	22.55	5.00	0.30	52.00	99.05
4	14-Nov-17	Beeston	14-Nov-17	Mukuria BH	1	7.97	490.00	3.09	22.20	0.00	1.03	135.00	145.71
	14-Nov-17	Beeston	14-Nov-17	Mukuria BH	2	7.95	499.00	3.04	20.60		1.05	136.00	148.57
	14-Nov-17	Beeston	14-Nov-17	Mukuria BH	3						1.02	134.00	151.43
						7.96	494.50	3.07	21.40	0.00	1.03	135.00	148.57
2	14-Nov-17	Beeston	14-Nov-17	Timsales BH	1	8.02	899.00	10.34	17.50	0.00	0.45	62.00	48.57
	14-Nov-17	Beeston	14-Nov-17	Timsales BH	2	8.02	898.00	10.29	17.60		0.47	66.00	48.57
	14-Nov-17	Beeston	14-Nov-17	Timsales BH	3						0.43	58.00	52.86
						8.02	898.50	10.32	17.55	0.00	0.45	62.00	50.00

Appendix 2: Calculation of Chi-Square Values Between the Modified DRASTIC Class and Nitrate Class

Observed										
Mdi Classes	Nitrate class1	Nitrate class2	Nitrate class3	Nitrate class4	Nitrate class5	Nitrate class6	Nitrate class7	Nitrate class8	Nitrate class9	Total
Class VL	1.71	0.70	0.53	0.42	0.04	0.00	0.00	0.00	0.00	3.40
Class L	12.88	10.31	4.08	2.31	3.19	3.46	5.12	5.04	1.69	48.08
Class M	0.28	1.09	0.48	0.57	0.13	0.00	0.00	0.66	0.36	3.58
Total	14.88	12.10	5.10	3.29	3.36	3.46	5.12	5.71	2.05	55.06
Expected										
Mdi Classes	Nitrate class1	Nitrate class2	Nitrate class3	Nitrate class4	Nitrate class5	Nitrate class6	Nitrate class7	Nitrate class8	Nitrate class9	Total
Class VL	0.92	0.75	0.31	0.20	0.21	0.21	0.32	0.35	0.13	3.40
Class L	12.99	10.57	4.45	2.88	2.94	3.02	4.47	4.98	1.79	48.08
Class M	0.97	0.79	0.33	0.21	0.22	0.22	0.33	0.37	0.13	3.58
Total	14.88	12.10	5.10	3.29	3.36	3.46	5.12	5.71	2.05	55.06
Chi-square value										
Mdi Classes	Nitrate class1	Nitrate class2	Nitrate class3	Nitrate class4	Nitrate class5	Nitrate class6	Nitrate class7	Nitrate class8	Nitrate class9	Total
Class VL	0.69	0.00	0.15	0.23	0.14	0.21	0.32	0.35	0.13	2.21
Class L	0.00	0.01	0.03	0.11	0.02	0.06	0.09	0.00	0.01	0.34
Class M	0.48	0.12	0.07	0.58	0.04	0.22	0.33	0.23	0.39	2.47
Total	1.17	0.13	0.25	0.91	0.20	0.50	0.74	0.58	0.52	5.01

Appendix 3: A Section of Mid River Njoro Catchment Under Farming

Appendix 4: Groundwater Samples Being Analyzed in the Egerton University Laboratory