HYDROGEOLOGIC CHARACTERISATION OF GROUNDWATER SYSTEMS IN RIVER NJORO WATERSHED, KENYA

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A Thesis Submitted to Graduate School in Partial Fulfilment for the Requirements of the Master of Science Degree in Natural Resources Management of Egerton University, Njoro, Kenya

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DECLARATION

This Thesis is my original work and has not been presented for the award of degree in any university or institution of learning and that all the sources used herein have been acknowledged.

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DEDICATION

This thesis is dedicated to my wife, Eglah and children, Baruch and Berenice who mean the world to me. Also to my blessed mom, Sarah for her constant prayers.

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ABSTRACT

Groundwater is increasingly becoming an important source of water in regions with rapidly growing population. This water is critical particularly in degraded regions that have inadequate surface water. Such is the case of the River Njoro Watershed (RNW) where output from groundwater has declined significantly in the recent years. This study was carried out to characterise the hydrogeologic system in the RNW utilizing both qualitative and quantitative aspects of groundwater dynamics. A generalised hydrogeologic characterisation of the watershed was based on secondary information sourced from lithologic logs and water levels from boreholes in the watershed. The exercise dealt with aquifer characterisation, estimation of groundwater recharge and flow regimes. Recharge was estimated using chloride mass-balance (CMB) and water-table fluctuation (WTF) methods while groundwater flow regimes and water table trends were based on the potentiometric measurements. The results show that the watershed is a multi-layered aquifer system. The aquifer is considered complex and spatially variable since all the aquifer types (perched, unconfined and confined) were observed in the watershed. The main aquifer formation found is the weathered and/or fractured volcanic lava flows composed mainly of tuffs and trachytes. Pyroclastic sediments also constituted aquifer formation in some cases. Water table levels, water struck levels and the total borehole depths generally indicate an increasing trend since 1940. The geologic structures particularly faults were found to affect groundwater occurrence by producing fissures that enhance recharge or act as conduit for water seepage. It was also established that groundwater flow was controlled by the faulting system of the rift valley. However, the groundwater flow largely conformed to the region's topography. The watershed recharge varied markedly from 115.2 mm yr^{-1} (lower section of the watershed) to 364.3 mm yr^{-1} (upper section of the watershed) representing 14.7% and 34.1% of the annual rainfall. Though the chloride mass balance (CMB) and water table fluctuation (WTF) methods used showed some variation in amount and space, the recharge trends were comparable. Variability in recharge was attributed to variation in precipitation (784 to 1069 mm) within the watershed as well as type and condition of the geologic formation(s). Groundwater potential areas were mapped on the basis of aquifer transmissivity as determined by potentiometric contours. The areas within Egerton University have many boreholes concentration that tend to lessen the groundwater reserves. The information from this study could therefore be used in establishing sustainable groundwater development in River Njoro Watershed.

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LIST OF ABBREVIATIONS AND ACRONYMS

asl	Above sea level
BH	Borehole
Cl^-	Chloride ion
CMB	Chloride mass-balance
°C	Degrees centigrade
DEM	Digital elevation model
GIS	Geographic information system
GPS	Global positioning system
KARI	Kenya Agricultural Research Institute
KWS	Kenya wildlife service
μm	Micron
RVIST	Rift Valley Institute of Science and Technology
S_y	Specific yield
T	Transmissivity
TIN	Triangulated irregular network
UTM	Universal transverse mercator
WRMA	Water Resource Management Authority
WTF	Water table fluctuation

DEFINITION OF TERMS

Aquifer

This is a body of rock that is sufficiently permeable to conduct groundwater and to yield significant quantities of water to wells. The term can also be referred to as ground water reservoir.

Aquitard

A confining bed that retards but does not prevent the flow of water to or from adjacent aquifers. It does not readily yield water to wells or springs, but may serve as a storage unit for groundwater.

Borehole total depth

The depth between land surface and bottom of the borehole. Also referred to as the total depth to which a borehole is drilled.

Confined aquifer

An aquifer bounded above and below by impermeable beds. It is also defined as a formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations.

Equipotential line

A line in a two-dimensional groundwater flow field such that the total hydraulic head is the same for all points along the line.

Eutaxitic

Banded structure of certain extrusive rocks, which results in a blotched appearance.

Fissure

A crack, joint, fault or other break in rocks caused by mechanical failure.

Formation

A body of rock strata that consists dominantly of a certain lithologic type or combination of types.

Groundwater system

Groundwater defined by similar natural features and characteristics.

Head

Energy contained in a water mass, produced by elevation, pressure or velocity.

Hydraulic conductivity

A coefficient of proportionality describing the rate at which a specific fluid can move through a permeable medium.

Hydrogeology

The science that deals with occurrence, distribution, movement and geological interaction of water in the earth's crust.

Ignimbrite

Rock formed by the widespread deposition and consolidation of ash flows.

Lithology

The description of rocks in hand specimen and in outcrop, on the basis of such characteristics as colour, mineralogic composition, and grain size.

Paleosoils

A buried soil or soil of the past often preserved after being buried by lava.

Perched aquifer

Special case of unconfined aquifer where the groundwater body is separated from the main groundwater by a relatively impermeable stratum of small extent.

Permeability

The capacity of a porous rock, sediment or soil to transmit a fluid. It is a measure of the relative ease of fluid flow under unequal pressure.

Porosity

The ratio of the aggregate volume of interstices in a rock or soil to its volume.

Potentiometric surface (piezometric level)

An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a well.

Recharge

The quantity of water that is added to a groundwater reservoir from areally distributed sources such as the direct infiltration of rainfall or leakage from an adjacent formation or from a watercourse crossing the aquifer.

Specific yield

The ratio of the volume of water that a given mass of saturated rock will yield by gravity to the volume of that rock. This is the property of an aquifer to absorb or yield water.

Transmissivity

The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer

An aquifer containing unpressurised groundwater, having an impermeable layer below but not above it.

Water rest level

The level at which water stands in a borehole. The term also refers to the depth below ground level where water stands in a borehole when not being pumped.

Water struck level

The depth below ground level where water is encountered when drilling a borehole.

Water table

A surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure. The top of the water surface in the saturated part of an aquifer.

Welding

Induration of a rock by the action of heat and pressure from the weight of overlying material.

Yield

The volume of water provided by a well or borehole, measured in m^3

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Groundwater is that part of the subsurface water that is in the zone of saturation (Bates and Jackson, 1984). Freeze and Cherry (1979) defined it as subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated. The nature and distribution of aquifers in a geologic system are controlled by the lithology, stratigraphy, and structure of the geologic deposits and formations. Groundwater accounts for about two-thirds of the freshwater resources of the world. When limited to utilizable freshwater, groundwater accounts for about 98% (Hiscock, 2005) and therefore illustrates the importance of this water resource. This is because more than 2 billion people globally depend on groundwater for their daily supply (Kemper, 2004).

Hydrogeologic studies provide an understanding on groundwater occurrence, reliability, how it can be protected and utilised. Knowledge and understanding of aquifer characteristics is necessary in support of management and protection of the local groundwater resources (Wei *et al.*, 2009). Such knowledge is important to River Njoro Watershed (RNW) since groundwater is a major source of water supply to an estimated half million human inhabitants in this area. On broad perspectives, groundwater is of fundamental importance in meeting the water requirements of the rapidly expanding urban, industrial, and agricultural water needs (De Vries and Simmers, 2002). Therefore, an understanding of the spatial distribution of recharge is necessary for modeling water resources and protecting such areas from contamination. Recharge is a vital parameter required in the successful development of groundwater resources, since the rate of recharge determines the amount of water that can be abstracted safely from boreholes in a particular aquifer (De Silva, 2004). It is particularly important to define groundwater inputs and especially direct recharge (Conrad *et al.*, 2004). De Vries and Simmers (2002) state that the quantification of groundwater recharge is a prerequisite for efficient and sustainable groundwater resource management.

Hydrogeological studies such as the present one hold immense potential in the planning and execution of measures in watershed development programmes. Groundwater storage, movement and recharge are dependent on the hydrogeological characteristics of the host rock and other features comprising the physical system (geological, geomorphological and hydrological nature) of the watershed (Pakhmode *et al.*, 2003).

1.2 Statement of the problem

An understanding of the hydrogeology of a watershed is a prerequisite for the management of problems related to decline in quantity and quality of groundwater. A significant decline in groundwater output has been reported within the RNW in recent years. Similarly, the River Njoro only empties into Lake Nakuru during seasons of heavy precipitation because of reduction of precipitation. However, the causes of drying up of some boreholes within the watershed are not known. Hydrogeological site characterisation is therefore necessary in the overall understanding of the hydrogeology of the RNW, an area whose surface water supplies are inadequate to meet the growing demand by educational institutions, intensive farming activities and an ever increasing population. Such an understanding will serves as background information for planning sustainable exploitation and management of the water resources in the study area.

1.3 Main objective

The main objective is to characterise the hydrogeologic system(s) in the River Njoro Watershed using qualitative and quantitative aspects of groundwater dynamics as an aid to sustainable utilisation.

1.3.1 Specific objectives

i. Characterise the hydrogeology as a determinant factor of occurrence and availability of groundwater and changes over time.
ii. Characterise geologic structures and their influence on groundwater system.
iii. Characterise the groundwater flow regimes.
iv. Quantify the amount of recharge in the aquifer system(s).

1.4 Research questions

i. What are the hydrogeologic characteristics of the aquifer systems?

ii. What types of geologic structures exist and what is their influence on groundwater system?

iii. What are the groundwater flow regimes in the watershed?

iv. What are the recharge quantities in the aquifer system(s)?

1.5 Justification

The decrease in surface water due to over abstraction and degradation of the resource base has lead to an urgent need for a change in water resource development strategy. For this reason groundwater plays an important role in sustaining water supply in the River Njoro Watershed.

The area served by the watershed has a rapidly increasing human population, for example the population of Njoro Division and Nakuru Municipality has almost doubled since 1999 from 124,430 to 205,445 and 212,162 to 224,743 respectively(Kenya National Bureau of Statistics, 2010). This increase in human population, the need for production of basic food and increased growth of industries are some factors that are exerting pressure on the water resources from the watershed. However, groundwater development strategies alone are not the ultimate solutions because of the interrelationships with surface water. Groundwater mining over time lowers the water table, depletes or even dries up wells, and reduces the ability of an aquifer to hold sufficient groundwater for development. The current study provides an insight on groundwater characteristics and dynamics, which can be used to develop groundwater management strategies for the River Njoro Watershed.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Hydrogeological characterisation

Characterisation of geological materials is important for conceptual understanding of the hydrogeological processes operating in any region. Information on characteristics of the rock matrix can be determined reliably by using core samples taken from drilling or from surface exposures (Cook, 2003). Hydrogeologic characteristics are defined by the aquifer properties, namely; porosity of the aquifer, which controls how much water is in storage; the storage coefficient (storativity), which controls how much water can be removed; transmissivity (hydaulic conductivity), which governs how readily that water can move through the permeable formations to wells and natural outlets, and the presence and position of hydraulic properties (Price, 1996). According to Erdelyi and Galfi (1998), geologic time is an important factor in the hydrogeologic properties particularly for volcanic rocks. For instance porosity and permeability tend to decrease with geologic time with pre-Cenozoic volcanic rocks being generally poor aquifers.

The hydraulic conductivity of pyroclastic deposits depends on the degree of consolidation and welding. Typically non-welded tuffs have porosities between 30% and 40%. Welded tuffs are formed at high temperatures by the fusion of rock fragments and have low porosity and very low conductivity. The porosity of welded tuffs ranges between 10% and 20% (Wood and Fernandez, 1988). The hydraulic properties of tuffaceous rocks based on degree of welding and fracture are shown in Table 1.

Table 1: Hydraulic properties of different types of tuff

Rock type (Tuffs)	Transmissivity (m/day)	Permeability (m^2)
Densely welded (matrix)	$T < 10^{-6}$	$< 10^{-18}$
Densely welded(fractured)	$10^{-6} – 10^{1}$	$< 10^{-18} – 10^{-11}$
Non-welded	$10^{-3} – 10^{-2}$	$10^{-15} – 10^{-14}$

Source: Maidment (1993)

Pyroclastics associated with lava flow are generally porous but not very permeable because of poor sorting and an abundance of fine material. Volcanic ash beds of large extent may form semi-horizontal barriers to water movement. However, sedimentary deposits intercalated with volcanic rocks may increase the average porosity of large volumes of rocks. Alluvial deposits, lacustrine sediments and pyroclastic deposits provide storage space for water which makes them important aquifers.

Rock matrix porosity and permeability may help determine the extent to which fractures are likely to dominate groundwater flow. Where matrix permeability is low, fracture permeability is likely to exceed matrix permeability, and fractures will dominate groundwater flow (Cook, 2003). Fractured volcanic rocks are more permeable since they connect the storage rocks and thereby providing recharge from the surface (Erdelyi and Galfi, 1998). Water bearing properties of rocks are believed to be dependent on the extent of weathering and occurrence of fractures. The deeper the weathered zone, the greater the amount of water (Alemayehu, 2006).

2.2 Hydrologic conditions in fractured-rock systems

All aquifers contain some degree of heterogeneity. In many cases, the degree of heterogeneity is relatively low for consideration in groundwater investigations. However, when aquifer heterogeneity is pronounced, it could have profound implications on groundwater processes. The fundamental characteristic of fractured rock aquifers is extreme spatial variability in hydraulic conductivity, and hence groundwater flow rate (Cook, 2003). Fractured rock aquifers comprise a network of fractures that cut through a rock matrix. In some cases, fractures become filled with minerals or clay deposits but when they remain open, they can form channels for groundwater flow.

Most recharge through the unsaturated zone occurs rapidly along discrete, permeable fractures, which may become saturated during rain events, even though the surrounding micropores remain unsaturated. Thus, water levels in fractures may rise while most of the formation remains unsaturated. When this is the case, the specific yield would be equal to the fracture porosity. This situation is most likely to occur in response to large rainfall events where the matrix permeability is very low. In this situation the rate of rise in water-level would be very rapid, as would the rate of subsequent water-level decline (Healy and Cook, 2002).

2.3 Determination of recharge – discharge areas

Recharge has been defined as the entry of water into the saturated zone made available at the water-table surface, together with the associated flow away from the water table within the saturated zone. Discharge is defined as the removal of water from the saturated zone across the water-table surface, together with the associated flow toward the water table within the saturated zone (Freeze and Cherry, 1979). Recharge is simply the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (De Vries and Simmers, 2002). Generally, groundwater levels within all aquifers appear to follow the topography. Flow occurs from the recharge areas, which are on the high ground, to the discharge areas, which are low-lying (Price, 1996).

To understand recharge effectively in a groundwater system, one must consider the processes that control the rate of recharge. The factors that control the rate of recharge are related to the hydrologic landscape of the aquifer system and include climate, topography, and the geologic framework (Sanford, 2001). Rainfall supplies the land surface with water, the soil allows the water to infiltrate to the water table, and the deeper geologic framework provides the permeability necessary for deeper flow. The permeability of the geologic formation controls recharge in any given area if the rate of infiltration is not limited by the climatic and soil conditions. This situation produces a relatively shallow water table due to a higher storage of water underground due to high infiltration. Consequently, a deeper water table would result in the case of a saturated zone transmitting more recharge than provided by the climatic and soil conditions. These surface or subsurface types of control on recharge can also in general be correlated with a region's rainfall and topographic relief.

2.4 Groundwater recharge estimation

Accurate quantification of recharge rates is imperative to proper management and protection of valuable groundwater resources. The amount of groundwater resources is determined by the average annual recharge and discharge circulating into and out of the watershed system (Eakin, 1962). As a result, estimates of natural recharge and discharge for an entire watershed is of importance to decision makers (Dettinger, 1989). This requires determination of safe yield of an aquifer underlying a watershed, which can be quantified effectively by a reliable estimate of groundwater recharge. The two methods used to quantifying recharge in the study area, that is chloride mass-balance (CMB) and water-table fluctuation (WTF) are discussed below.

2.4.1 Chloride mass-balance method

Many methods can be used to estimate groundwater recharge, such as direct measurements, water-balance methods, Darcian approaches, and tracer techniques (Lerner *et al.,* 1990). Environmental tracers such as chloride (Cl^{-1}) are produced naturally in the earth's atmosphere and are used to estimate recharge rates (Allison and Hughes, 1978; Scanlon, 2000 and Phillips, 2002).

The CMB method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface (Beekman and Xu, 2003). The chloride ion is used in chemical recharge studies because of its inert nature (Ting *et al.***,** 1998). It is also regarded as effective because atmospheric deposition is the only source of chloride to groundwater (Edmunds *et al.,* 2002). Tracer methods have several advantages over physical techniques. One advantage is that the precision of a recharge estimate does not decrease as the moisture flux to groundwater decreases (De Vries and Simmers, 2002). The chloride mass-balance method yields ground water recharge rates that are integrated spatially over the watershed and over times of tens to thousands of years. The method, which is inexpensive, requires only knowledge of annual precipitation, chloride concentration in that precipitation, and chloride concentration of ground water of the aquifer of interest (Bazuhair and Wood, 1996). Mechanisms of recharge and recharge rates can also be considered crucial in the assessment of vulnerability of groundwater resources to pollution (Beekman and Xu, 2003).

2.4.2 Water-table fluctuation method

Techniques that are based on groundwater levels are among the most widely applied methods for estimating recharge rates. This is due to the abundance of available groundwater-level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of groundwater levels (Healy and Cook, 2002). The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Scanlon *et al.,* 2002). This method assumes that all recharging water goes immediately into storage, that the net subsurface flow to the bore is balanced by flow away from the bore, and that there is no evapotranspiration from the water table. Water table fluctuations due to other processes are generally much fewer than that caused by recharge (Healy and Cook, 2002), therefore this method provides good recharge estimates (Cartwright *et al.,* 2007).

2.5 Groundwater flow regime

Movement of groundwater takes place whenever there is a difference in pressure heads (potential energy head) between two points (Driscoll, 1986). Measurements show that groundwater flows from topographic high areas towards the topographic lower areas where the discharge sites are located (Wilkes *et al.,* 2004). Therefore, as surface water flow is downhill and perpendicular to topographic contours, the direction of ground water flow is also downhill and perpendicular to the water table contours. Groundwater is assumed to flow at right angle to the lines of equal water-table elevations (equipotential lines) and the flow occurs on the premise of the potential energy head difference in the path of least resistance due to gravity.

2.6 Potentiomentric surface

The elevation to which water rises in a well represents potentiometric level especially with confined aquifers (Driscoll, 1986). This surface corresponds to the water table in an unconfined aquifer. A potentiometric map of an aquifer provides an indication of the directions of groundwater flow in the aquifer (Freeze and Cherry, 1979).

A potentiometric surface map is a contour map that shows the groundwater elevations in an aquifer (Fetter, 1994). The contour lines illustrate the potentiometric surface much like the contour lines of a topographic map represent a visual model of the ground surface.

A potentiometric surface map is very similar to a water table map in that both show the horizontal direction and gradient of groundwater flow. The maps are shown as contour map with lines of equal elevation derived from groundwater level measurements.

2.7 Research study gaps

The important role that groundwater plays in sustaining water supply in the watershed cannot be overemphasised due to decrease in surface water and increase in demand. In Kenya, a lot of effort has been directed towards providing remedies to existing and potential groundwater related problems resulting from reduction in production and seeking alternate source locations rather than understanding the groundwater systems. A preliminary groundwater characterisation study by Kimani *et al.* (1991) in Lake Nakuru Catchment was based on limited historic data; while the analysis of groundwater potential by Kiptanui (2006) was only based on the middle section of the River Njoro watershed. However, hydrogeologic characterisation of groundwater dynamics has not been undertaken in the River Njoro Watershed. The basis of this research therefore, is on the need to undertake detailed hydrogeologic studies of the watershed groundwater system to provide basic information on the behaviour of these systems that would guide in the management of groundwater resources.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study area

The study area is situated in Nakuru District, Rift Valley Province, Kenya. It comprises part of the central Rift Valley flanked to the west by the Mau Escarpment and Rift Valley floor to the east marked by Lake Nakuru, degree sheet 35 SW quarter of Survey of Kenya. It covers an area of approximately 250 Km^2 to the west of Nakuru Town lying between latitudes 0°15"S and 0°25"S and longitude 35°5"E and 36°5"E (Figure 1).

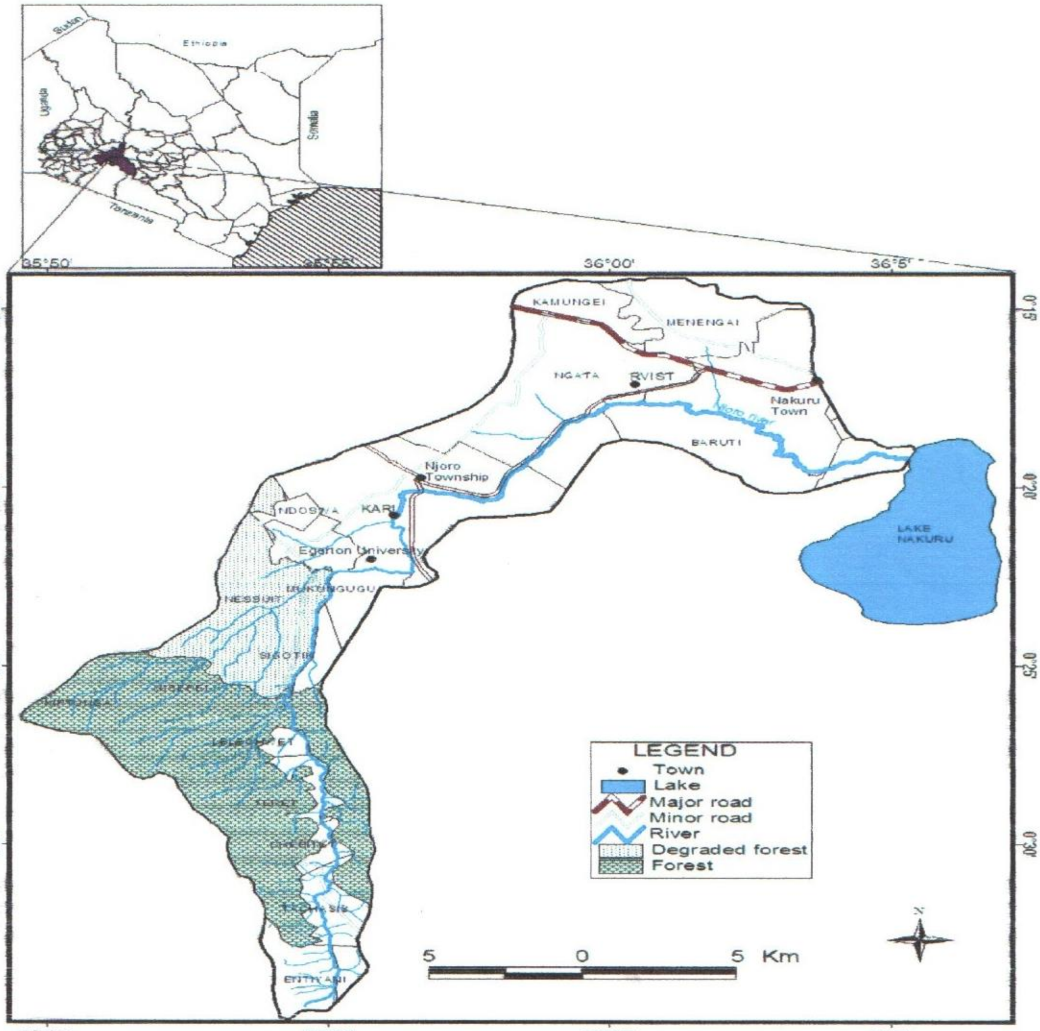


Figure 1: Map of the study area

3.2 Physiography and climate

The major topographic feature is the Rift Valley floor in the eastern lower section of the watershed area hosting Lake Nakuru (1760 m a.s.l), the volcanic Menengai crater (2273 m a.s.l) within Nakuru Municipality, and Mau Escarpment covering the western part of the watershed. Mau Escarpment forms the largest portion of the watershed and lies at an average altitude of 2500 m a.s.l. The River Njoro has cut a channel through highly weathered tuffaceous lithologic unit overlying unconsolidated pumice and ash running over hard upper surface of black ash. The river follows a zigzag course generally in the line of north-south fault zones and cutting eastwards across the area between the fault zones (McCall, 1957). It loses its water in porous or fissured zones to the extent that great volume of water never reaches the Lake Nakuru on the surface; the bulk of its flow entering to the water table below Lake Nakuru (McCall, 1967).

The climatic conditions are strongly influenced by altitude and physical features. River Njoro Watershed lies within ecological zones II and III (Pratt and Gwynne, 1977) with an altitude between 1800 and 2400 m a.s.l and receives rainfall of between 760 mm and 1270 mm per annum. However, the lower section of the watershed drainage system is within ecological zone IV in the Rift Valley floor with an altitude ranging from 1520 m to 1890 m a.s.l and receiving rainfall less than 760 mm annually. The wet months are March to May (long rains) while June to August period is moderately cool and wet. The short rains occur from September to October, while the months of December to February are the driest part of the year. The maximum temperature is about 30°C with December to March as the hottest months while July is the coldest with the mean annual temperatures of 23°C.

3.3 Geology of River Njoro Watershed

The area is covered with volcanic rocks (Figure 2) intercalated with Recent sediments in a few locations. The oldest of these rocks are the Tertiary volcanics, which are made up of the Mau tuffs while the youngest are the Recent volcanics. The Mau Escarpment and area west of Njoro Township is covered with yellow pumiceous tuffs. This rock decomposes into a clayey aggregate on contact with water (McCall, 1967). The Mau tuffs grades to ignimbrite rock to the north of the River Njoro and are composed of streaky brownish glass flowing around fragments of well crystallized trachyte. To the South of the River Njoro it grades into a porous purplish tuff and to a spongy welded tuff composed of brownish glass in form of coalesced fragments.

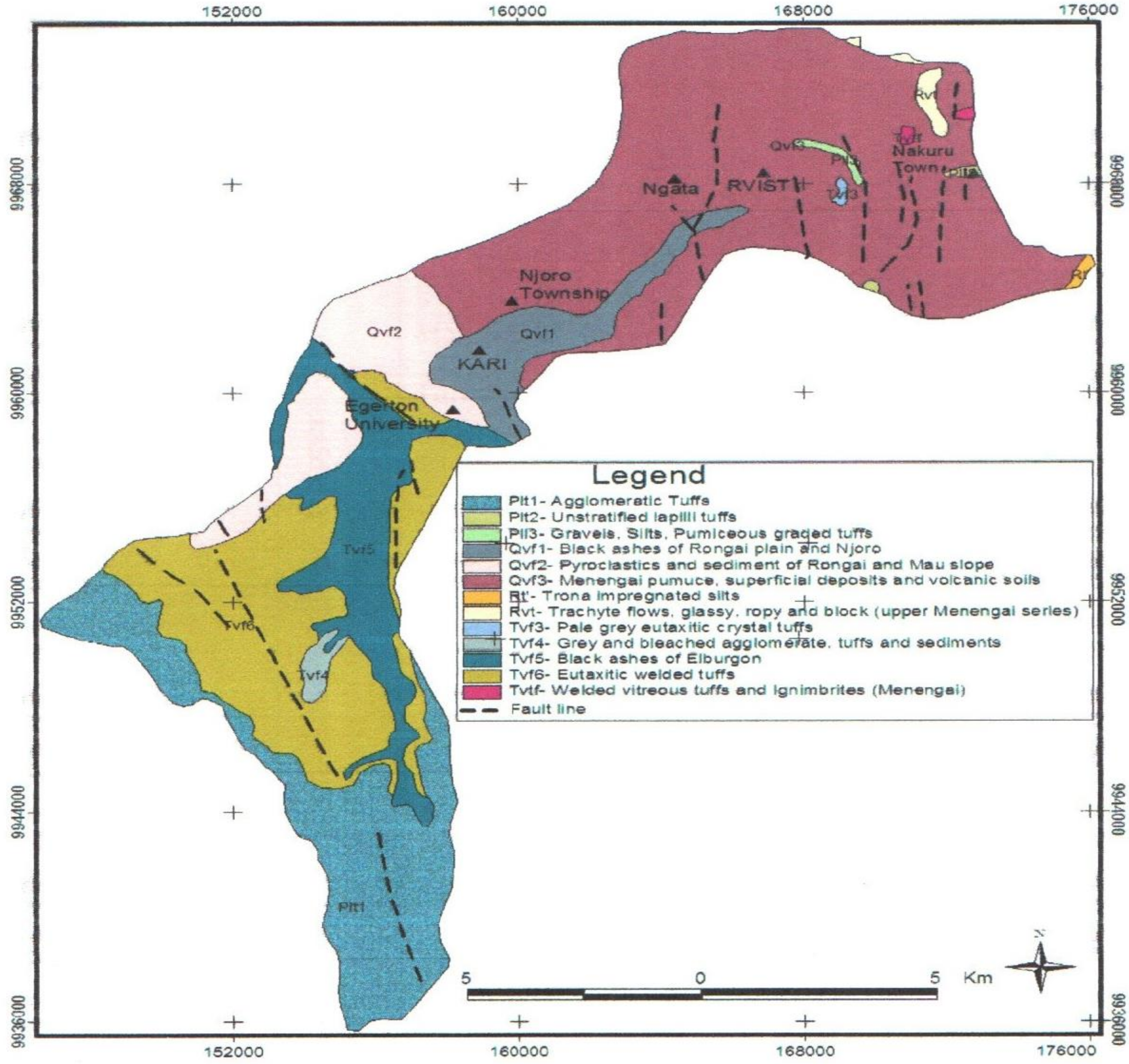


Figure 2: The geology of River Njoro Watershed

The youngest formations covering the watershed are the Menengai pumice, the pyroclastics and sediments of Rongai plain and Mau slopes, and the black ashes of Rongai plain and Njoro, all of Quaternary age (Figure 3). The unconsolidated Menengai pumice overlies much of the lower section of the watershed from Ngata towards Nakuru Town. The pumice is glistening pale green grey or silver grey in colour and occurs in roughly equidimensional lapilli (Jennings, 1971). The area from Egerton to Nakuru runs a strip on both sides of the Mau–Nakuru road of the pyroclastics and sediments of Rongai plain and Mau slopes. This constitutes the recent deposits represented by well-bedded, glistening grey unconsolidated pumice. A small portion around Egerton University extending towards Ngongongeri and some parts of Nessuiet is covered by the black ashes of Rongai plain and Njoro. This formation is overlain by the later silver-grey pumice beds and is characterised by distinctive black ashes with glassy bombs that are widely spread in Menengai area with Menengai crater being its probable source.

Quaternary	Recent		The Upper Menengai – trachyte lava – scoria The black ashes of Rongai Rongai pyroclastic sediment
			Makalia lacustrine sediment
	Pleistocene	Upper	Tuffs and sediment Larmudiac sediment of Nakuru basin
			Menengai pumice
		Middle	Agglomeratic tuff
		Lower	Ronda lacustrine sediment Ronda phonolites and trachytes
Tertiary	Upper		Mau tuffs – pumiceous tuff intercalated with phonolite

Source: McCall (1967)

Figure 3: Lithostratigraphy of the study area

To the west of Egerton University towards Teret lies the eutaxitic welded tuffs grouped under a series of welded pyroclastics, which falls under the Tertiary pyroclastics of upper Mau. The coarse grained series is found around Nessuiet in the south-east of the Molo area. This formation overlies the black ashes of Elburgon. The other pyroclastic rocks of the upper Molo are the black ashes of Elburgon. These rocks overly the grey eutaxitic welded tuffs, the yellow tuffs and agglomerates of which Mau is composed. The porous textured formation covers portions of Nessuiet extending in a north-east direction, outcropping near Egerton University as shown in Figure 2.

3.4 Hydrogeology of the study area

The geologic formations are limited to the Cenozoic volcanic rocks (Tertiary–Quaternary) and sedimentary deposits mainly of lacustrine origin. The volcanic formations consists of phonolitic trachytes and trachyte flows together with, intercalated tuffs and reworked tuffs containing abundant water rounded fragments. Welded tuffs are also extensive in the area.

Sikes (1934) stipulated that the old land surface between the lava flows provided the main aquifers within the volcanic formations. However, the principal aquifers are the sedimentary formations composed of well-rounded volcanic grits and diatomaceous material with red clays. The aquifers in the study area are described as sedimentary intercalations in faulted lava flows, old land surfaces separating by lava flows, fissures within the body of lava flows and welded formations and lacustrine sediments deposited subsequent to the major fault.

The sedimentary intercalations comprise 90% of the aquifers (McCall, 1957). The volcanic grit horizons form ideal media through which water flows and the clay horizons providing impervious aquicludes that prevents water from further down movement. In Nakuru area, lacustrine sediment formations have produced abundant supplies of groundwater. The conditions of occurrence are similar to those of the sedimentary intercalation formation other than the diatomaceous content. The old land surface formation act as an aquifer forming in restricted weathered zones separating lava flows. This has reddened material that is devoid of water-rounded fragments and is limited in extent. Lava flows are essentially impervious but the upper highly weathered, scoracious and broken up zones are permeable and allow water to pass through. Extensive faulting and fissuring in Rift Valley provides fissured aquifers within the main body of the flows, but they are limited in occurrence since the fissures are widely spaced and steeply inclined.

3.5 Research design

The study started with a compilation of existing information in order to develop hydrogeologic database for the watershed. In addition, field surveys were conducted to update existing data for borehole water levels. Data collection and analysis included:

- Defining geologic features that affect the aquifer system. Features included structures such as faults and lithology of hydrogeologic units.
- Determination of groundwater movement direction using water level difference over space.
- Determination of groundwater recharge based on chloride mass balance (CMB) and water table fluctuations (WTF) methods.

The watershed was divided into three segments on the basis of altitude for the purpose of aquifer characterisation. However, two sites (lower and upper section of the watershed) were selected for the purpose of recharge analysis on the basis of rainfall regime and location of weather station locations.

3.6 Methodology

3.6.1 Hydrogeological characterisation

The geological data obtained from previous drilling investigations were reviewed. The data included details of important geological and hydrogeological information such as rock types, aquifer types, and yields. A ground truthing geologic survey was carried out. This comprised checking the condition of the surface geology and taking photographs. The ground survey features of interest included the state of weathering and fracturing of the geologic formation. The information obtained was combined with results from previous studies to provide cumulative data on the known geology of the area. This study also endeavoured to describe the basic geology of the River Njoro Watershed.

Cross-sectional illustrations were developed based on the geologic surface maps and lithologic information recorded on the driller's logs for selected boreholes. The Universal Transverse Mercator (UTM) coordinates for each of the boreholes were imported into an ArcGIS and plotted on a contoured surface. The lithologic changes identified in the driller's logs were interpreted using knowledge of the local geology provided by previous studies (McCall, 1967; Jennings, 1971) and combined with information obtained from the field study. The stratigraphy between the boreholes along selected cross section line was assumed using the basic principles of stratigraphic relations of the boreholes. The boreholes selected to represent the cross section of the study area was based on the major geologic representation and their structural conditions such as state if weathering and faulting.

3.6.2 Borehole monitoring within the study area

A monitoring network of boreholes within the watershed was established. At least four (4) boreholes in each segment of the watershed were selected for monitoring which largely depended on the existence of a functional airline. Boreholes chosen for observation were designed to provide data that represents the various topographic, geologic and climatic environments (Taylor and Alley, 2001). It is on this basis therefore that the segmentation of the watershed was made, that is the upper, middle and lower section of the watershed. This involved three months of measurements, in addition to existing borehole data from Rift Valley Water Resource Management Authority (WRMA) in Nakuru Town. Water levels in the boreholes were measured using flat tape water level meter (a dipper). The monitoring was carried out on a weekly basis, setting the days to the convenience of the borehole (BH) owners.

The BH casings were marked to ensure that every reading was consistently measured from the same point on the BH. The elevation and location of each BH was measured using GPS equipment with a Universal Transverse Mercator (UTM) system. Water level readings were taken during the monitoring period after which the water level data were entered into a spreadsheet.

3.6.3 Potentiometric surface map of River Njoro Watershed

The month prior to the monitoring of water level reading was free of a major rainfall event. All pumps were shut down at least one hour (1 h) prior to measurement to allow for recovery of any drawdown. A potentiometric surface map was made using groundwater level obtained from the driller's log record. Existing water level data were used to plot the trend since 1940.

3.6.4 Recharge estimation

3.6.4.1 Application of chloride mass balance (CMB) method

Groundwater recharge was quantified using a mass-balance of conservative chloride ion (Cl^-). Chloride ion was used as the principal variable because it remains inert during the recharge process (Edmunds *et al.*, 2002). The mass-balance utilizes three parameters namely; the concentration of chloride ions dissolved in precipitation, the volume of precipitation, and the concentration of chloride ions dissolved in groundwater. The three parameters were obtained from the precipitation gauges and groundwater samples collected from boreholes segmented into upper and lower section of the watershed. Samples were taken on an event basis from rain gauges set approximately 1 m above the ground surface. The collection bottles were set below ground to avoid evaporation. These measurements were carried out during the short rains season in October to December.

Two samples from each selected borehole were collected in plastic bottles. The chloride ion concentration in both rain and groundwater samples were determined using argentometric titration method based on standardised silver nitrate titrant.

3.6.4.2 Application of Water table fluctuation (WTF) method

The WTF method requires a good knowledge of the potentiometric (piezometric) level throughout the entire basin (Marechal *et al.*, 2006). For this technique, groundwater recharge was estimated from the product of specific yield and the average rate of water level change over time from bore hydrographs. However, specific yield is extremely difficult to measure reliably (Sophocleous, 1991).

Groundwater level measurements were carried out on a weekly basis for one year using flat tape water level meter. Subsequently, groundwater hydrographs were prepared from data collected from the boreholes located in the upper and lower section of the watershed. Two sites in each segment were selected based on location of the weather stations. The Egerton University site was designated to represent the upper section of the watershed (>2000 m a.s.l) whereas the Nakuru station was designated to represent the lower section of the watershed (<1900 m a.s.l). Within each segment, the boreholes tested were selected based on the workability of the airline.

3.7 Data analysis

3.7.1 Hydrogeological characterisation

The geologic map of the area was scanned and an on screen digitisation was carried out using Arc GIS (Ormsby *et al.*, 2009). The lithologies were presented as geo-referenced polygons in ArcView. Digital Elevation Models (DEM) for the area were obtained, then imported in to ArcView and contours generated. The contoured surfaces were overlain by the digitized polygons representing the lithologies.

3.7.2 Groundwater flow direction

Groundwater levels were plotted using data collected from boreholes. The location of each borehole was geo-referenced based on the UTM positioning system. Locations, surface elevation, depth to the groundwater and borehole identification were entered into Arc-Map GIS software. Contour lines were then generated using the surface analysis function in spatial analyst. The groundwater level contour interval was set at 100 m. These contours were analysed to determine groundwater flow direction. It is on the basis flow direction that recharge and discharge areas in the watershed was established.

3.7.3 Recharge estimation

3.7.3.1 Chloride mass balance method

The chloride ion concentration in groundwater relative to that in rainfall was used to calculate the mean annual recharge for the watershed. For the purpose of recharge calculation, average values were used for the chloride ion concentrations in bore and rainwater (Cook, 2003).

$$\mathbf{R = Cl_P P/Cl_R} \quad \ldots\ldots 1$$

Where R represents recharge to groundwater, P is precipitation, while $\mathbf{Cl_P}$ and $\mathbf{Cl_R}$ represent chloride ion concentrations in precipitation and groundwater respectively.

The use of CMB to determine annual groundwater recharge for a watershed requires a minimum of one year of data collection. Data in this study was therefore collected from January 2007 to December 2007. Data collection for groundwater recharge determination was conducted as dictated by the parameters shown in Equation1: annual precipitation volume (P), chloride ion concentration in precipitation (Cl_p) and groundwater (Cl_R). Rainfall was measured and sampled promptly following a precipitation event. Borehole water samples for chloride ion were taken twice based on the bimodal rainfall pattern (March to May and October to November) of the study area. For the watershed, the annual mean chloride ion concentration, Cl_p, was determined averaging the seasonal chloride ion concentrations of precipitation to corresponding seasonal precipitation volumes based on the nearest precipitation collection point. Groundwater chloride ion concentrations (Cl_R) were obtained by averaging over the season to produce an approximation of chloride ion concentration in groundwater at each location.

3.7.3.2 Water table fluctuation method

Groundwater recharge based on the groundwater hydrographs were estimated using water table fluctuation (WTF) analysis as per Delin *et al.*, (2007).

$\mathbf{R = S_y \Delta h / \Delta t}$**……………………………………………………………………………………2**

Where $\mathbf{S_y}$ is specific yield, **h** is water-table height, and **t** is time. The theory assumes that changes in the rate of water level are due to vertical changes in the specific yield as the water rises through different strata (Bekele *et al.*, 2003).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Hydrogeologic characterisation results

4.1.1 Description of major hydrogeologic units

The nature of the geologic unit informs the hydrologic characterisation as conditioned by the geologic processes of formation. This essentially influences the character of aquifer formation such as the porosity, transmissivity and storativity. The major hydrogeologic formations in the study area consist of Quaternary pyroclastic deposits and, Tertiary tuffeous and trachytic formations. These hydrogeologic units include; the Menengai pumice (Qvf3), Mau pyroclastic sediment (Qvf2), black ashes of Njoro and Rongai (Qvf1), eutaxitic welded tuffs (Tvf6), black ashy tuffs (Tvf5) and bleached agglomeratic tuffs and sediments (Tvf4) (Figure 3).

4.1.1.1 The Quaternary pyroclastic deposits

The Menengai pumice (Qvf3) consists of unconsolidated mantle (lapilli) which covers a large area especially east of Njoro Township (Figure 2). This formation has roughly equidimensional particles that vary spatially in size ranging from 1–10 mm. The coarser fragments occur closer to the source that is the eastern margin of the watershed towards Menengai, while the finer lapilli lie closer to Njoro. The mantle is banded horizontally into remarkably uniform layers of fragments ranging from 0.15 m to 0.16 m in depth.

Pyroclastic sediments of Mau (Qvf2) are well bedded recent deposits of grey unconsolidated pumice. These sediments grade from beds of fresh glistening grey pumice to decomposed weathered pumice beds. This gives in to ash-fall deposits that constitute bedded clays and soils that retain to a large extent a sandy texture. The pumice sediments are medium grained to the east and grade to much finer gained clays and sandy soils produced by weathering of finer ash to the west on the slopes of Mau escarpment.

The black ashes of Njoro (Qvf1) comprise uncompressed pumice fragments that are coarsely vesicular with a fine grained black porous matrix. It has friable texture and is therefore prone to erosion. In some cases the deposit is composed of little compacted close-packed, light coloured grit sized lava fragments with angular black glass chips of up to 5 mm. Angular fragments of trachytic lava of 3 mm were part of the pyroclastic sediment. It also had a high proportion of glass bombs composed of porphyritic black glass with 5 mm feldspar fragments. These bombs had vesicles several centimetres long that are varied in size, shape and distribution.

4.1.1.2 The Tertiary tuffs

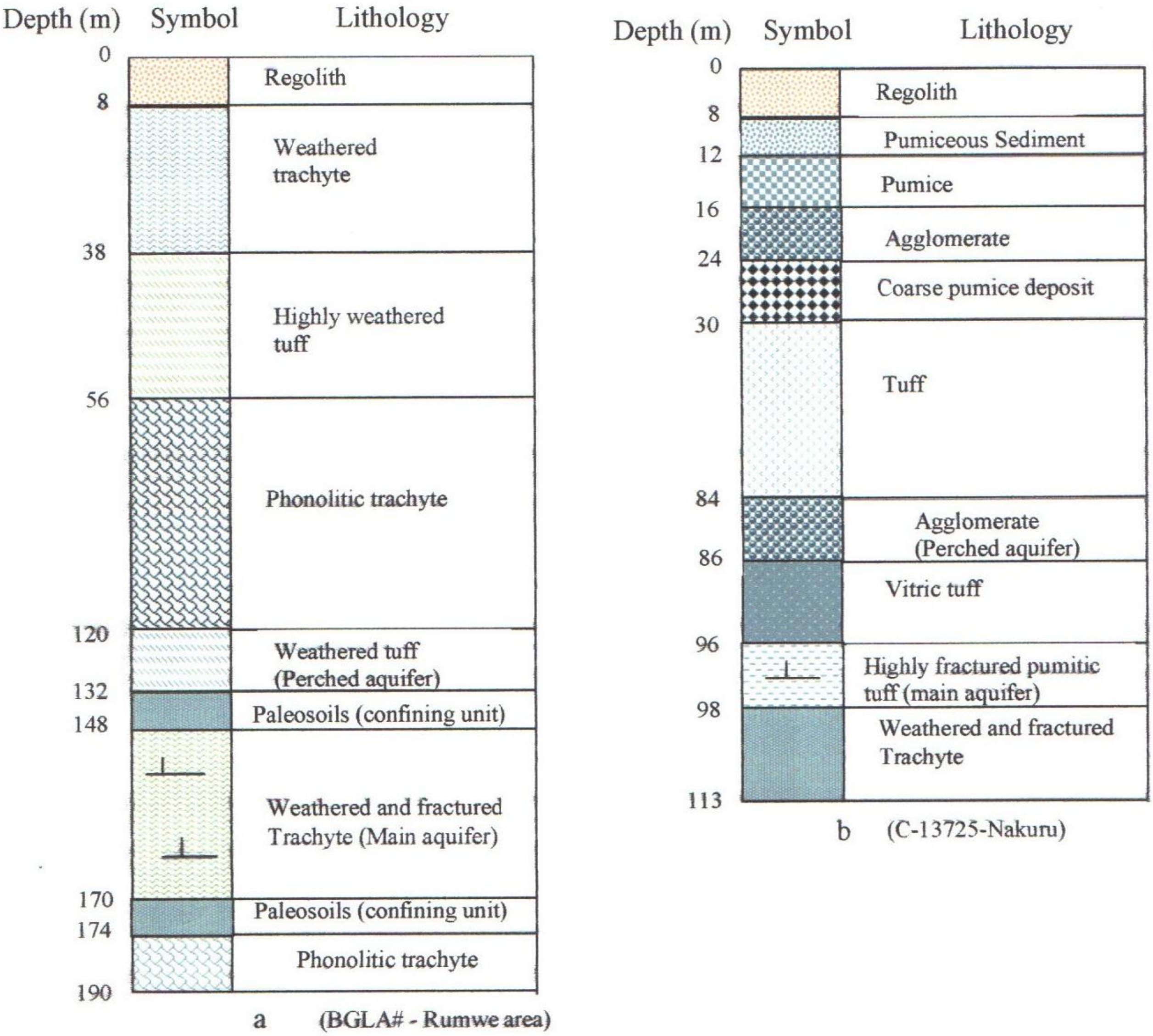
Eutaxitic welded tuffs (Tvf6) are pyroclastic rocks characterised by varying texture, colour, degree of compaction and the pumice content (Figure 2). Two varieties exist in the study area; the fine grained grey tuffs and the coarse grained eutaxitic welded tuffs. The latter comprise up to 30 mm devitrified pumice fragments held in grity ash matrix, while the former is composed of the fine grained grey base packed with grit-sized particles of phonolitic and trachytic lava. The fragments occasionally exist as irregular obsidic or pumitic particles of up to 3 mm.

The black ashy tuffs referred to as the black ashes of Elburgon (Tvf5) are porous tuffs formed from coalesced fragments that sometimes fracture producing friable, gritty base up to 4 mm in size. These rocks were found to weather readily because of the soft nature. The rocks are compressed to a limited extent with obsidic groundmass particles.

The agglomeratic tuffs are also known as the grey and bleached agglomerates, tuffs and sediments (Tvf4). These rocks are soft and disaggregate to agglomerate, tuffs and clayey sediments. The agglomerates consist of fine grained ashy base with generally uncompressed pumice fragments that are varied in size and proportion.

4.1.1.3 The Tertiary trachyte/phonolite

The phonolitic trachyte appears rarely as bedrock in the study area but common as one of the hydrostratigraphic unit (Figure 5a). This rock formation grades into trachyte in some sites. The trend towards trachytic composition is well-defined on the upper layers of the lava flow and is commonly fissile and banded. In some areas the formation grades into streaky vitreous trachyte.



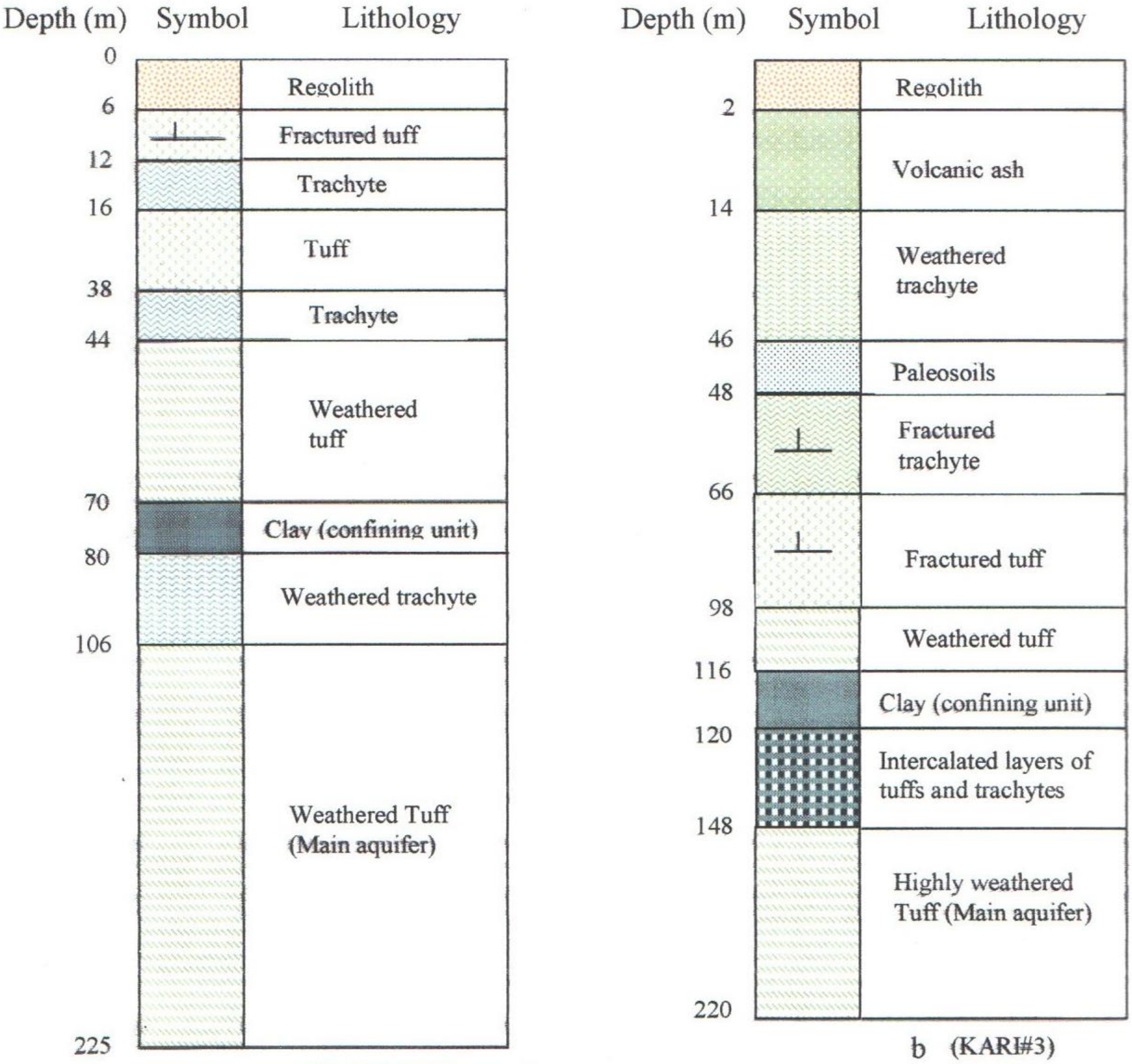
a (BGLA# - Rumwe area)

b (C-13725-Nakuru)

Figure 4 (a, b): Well log showing the aquifer condition for BH BGLA# and C-13725

4.1.2 Aquifer characteristics

The hydrogeologic information was sourced from lithological logs, pumping test data and water level data from borehole records. The watershed has different groundwater potential that is associated to the type of geologic formation and structures, the geomorphology, as well as the rainfall distribution. The groundwater potential variability is indicative of a generally localised aquifer system that is dominated by highly fissured and weathered volcanic and lacustrine sediments intercalated with old land surfaces particularly in the volcanic formations (Figures 5 and 6).



a (C-14463-Egerton)

b (KARI#3)

Figure 5 (a, b): Well log showing the aquifer condition for BH C-14463 and KARI#3

The watershed is characterised by three aquifer classes identified based on the rock types. There is the old land surface in which groundwater is stored in weathered zones and in older formations between lava flows. The groundwater is interconnected through fissures and porous materials that are partly contained in the old land surface deposits or paleosoils buried in the rift valley.

The second aquifer class is made up of fractures and fissures especially within the major fault lines which are predominant in the watershed. The fissures normally modify or act as groundwater storage within the lava (trachytic and phonolitic) formations. The fault planes may be filled with impermeable materials especially clay which acts as a groundwater movement barrier. But in absence of infilling material, the fault acts as conduit for water movement from the aquifer therefore draining out of the watershed or as surface water. The third and most productive aquifer within the watershed is the sediments constituted system, which exhibits an occurrence of volcanic grits and lacustrine sediments (Plate 1).

Plate 1: Pyroclastic sediment observed in the lower section of the watershed

The groundwater system in the watershed is characterised by a multi-layered aquifer system where there are more than one water-bearing layers (Figure 5a). This is exemplified by groundwater struck at multiple levels in more than 75% of the boreholes that had well logs analysed. Multi-layered aquifers are not unique to River Njoro Watershed as this is reported in other regions covered by similar volcanic formations as reported by Ayenew (2008) in a study of the Ethiopian aquifers. The upper layer of this water bearing geologic unit is under perched groundwater condition. In some cases, water drains from the perched aquifer to the deeper underlying groundwater bearing stratum. Water draining to the deeper levels is demonstrated by C–8515 and C–10797 boreholes (Figure 4). Their groundwater level increased from 80 m to 102 m and 60 m to 113 m respectively from the water struck level to the piezometric level. Such conditions also signify the presence of leaky (semi-confined) aquifers underlain by a semi-pervious aquitard which permits downward flow. The seepage of this magnitude is most likely caused by a fissured or highly weathered underlying confining layer. Such an occurrence is supported by the presence of fault lines that are running south–north direction along the area where borehole C-8515 is located with one fault line tapering towards C-10797.

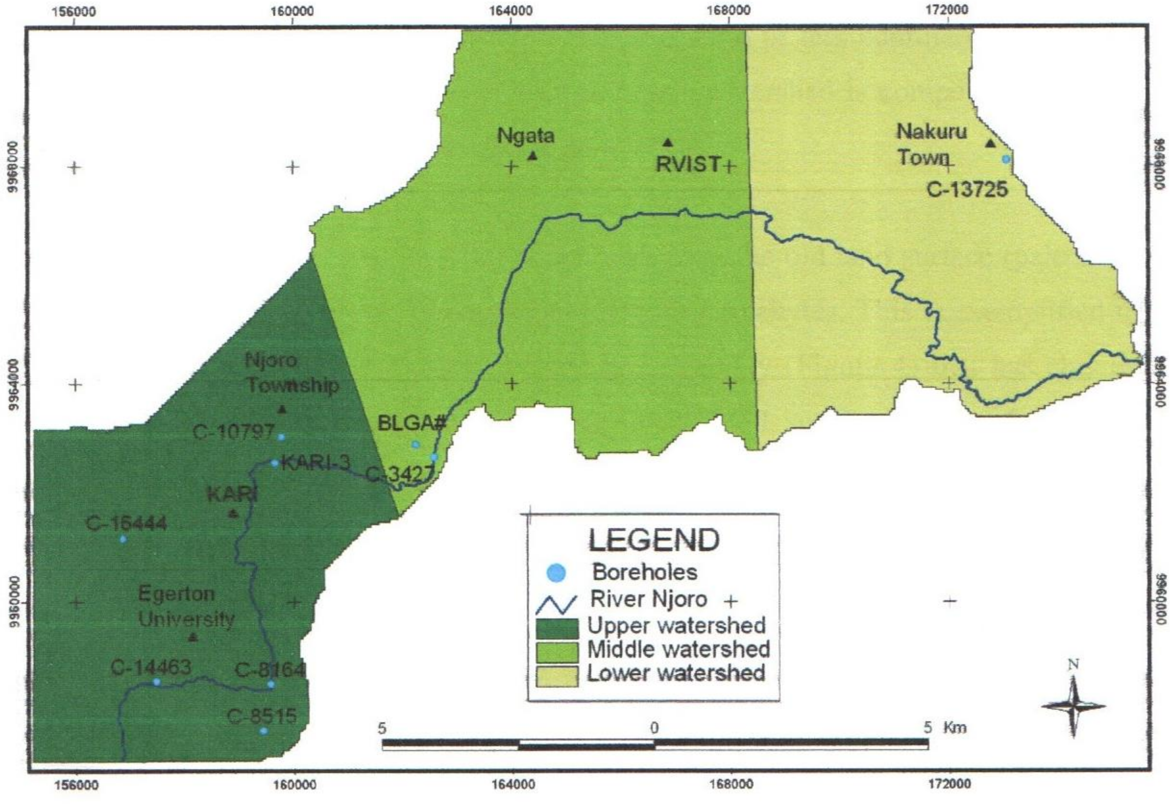


Figure 6: Location of cited boreholes

The complexity of the aquifer system in the area is due to the high spatial variability of the geologic units such that incidence of all the aquifer types as observed in the watershed, are easily encountered within short distances. Perched aquifers that are mainly set above the main aquifer occur due to presence of geologic lenses that constitute old land surface (paleosoils) strata that are relatively impervious. The study area has old land surface that is interbedded with successive lava flows and the impervious material appear to form the local perched groundwater. The perched aquifer seems to be occurring predominantly as a small layer yielding either temporary or little quantities of water. However, there are boreholes particularly within Njoro vicinity that are under perched condition and have yielded high quantities of water (11.4 m^3/h) which is within the area's range of main aquifer production as reported by McCall (1957).

The groundwater system in the upper section of the watershed (areas covering between Njoro and Highland nurseries) is generally under confined condition since most of the boreholes' piezometric level rise above the top of the aquifer formation which is represented by the water struck level. The regional mean water struck level which is generally confined, is at 146.6 m below the ground surface. The middle section of the watershed is also covered to a large extent by a confined aquifer that lies about 146.9 m indicating more or less continuous water bearing geologic unit. On the other hand the upper section of the watershed is composed of weathered trachytic formation which is fractured as well in some areas.

The confining units are either clay material which constitute the old land surface (paleosoils) or welded tuffs and in some situations unweathered phonolitic trachytes. This is exemplified in the study area by borehole C–14463 located at Egerton University (Figure 4) that has clay as the confining formation between 70 m to 80 m below the land surface (Figure 5a). The clay formation is most likely derived from the disaggregation of tuffeous formation. A similar scenario is represented in borehole KARI#3 (Figure 5b) located about 5 km north of borehole C–14463 though at different depth. In the two boreholes the confining clay formation resides between weathered tuffs with the lower formation being the main aquifer as is illustrated in the geologic log of the respective borehole. The lithostratigraphic column in the two sites bears similar characteristics with a slight variation in the magnitude of fissuring/or weathering and depth.

Since the area's aquifer is multi-layered, the upper minor aquifer is spatially variable over the middle and upper section of the watershed. This is attributed to the variability of the geologic unit which is overlain by Quaternary to Recent pyroclastics and Tertiary volcanics for the upper and middle section of the watershed respectively. Secondly the upper section has most of its boreholes close to the River Njoro which may cause seepage of water to the groundwater through the fissured and highly weathered rock units.

Table 2: Mean aquifer depths in the watershed sections

Watershed Section	1st (minor aquifer)	2nd (main aquifer)
	Water struck level (m)	
Upper	78.6	146.6
Middle	103.2	146.9
Lower	85.3	115.1

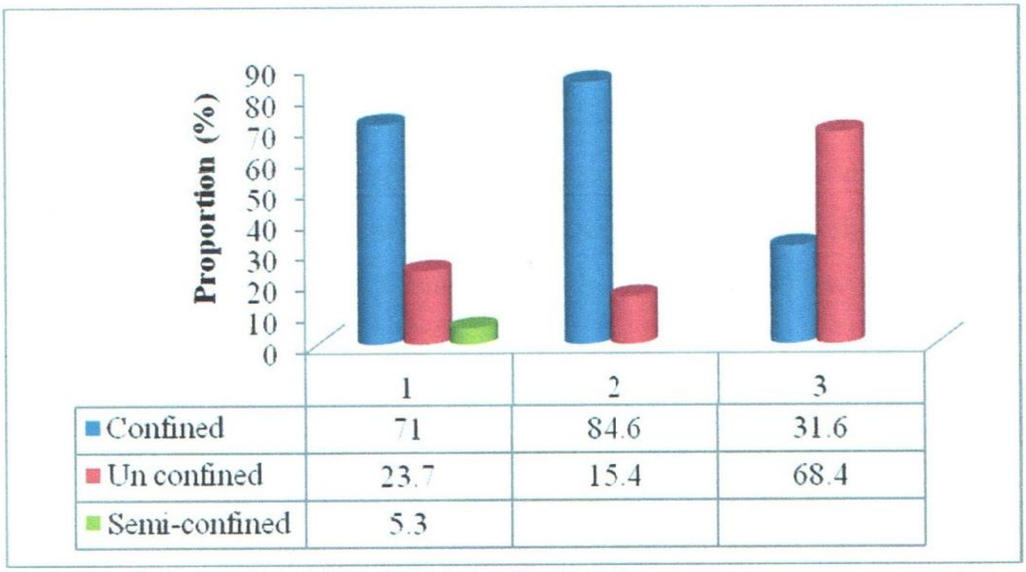
The lower section of the watershed shows some degree of variation from the other two segments in the main aquifer depth and character. The groundwater system in the lower section of the watershed is mainly characterised by groundwater levels that are at water table which is an indication of an unconfined aquifer condition. The lithostratigraphic column reveals a series of interbedded layers of pyroclastic sediments that have absence of confining material. This is demonstrated by the well log information for borehole C–13725 (Figure 6b) situated at the centre of Nakuru Town which marks the eastern end of the watershed. The borehole record show that the aquifer formation which is embodied by the water struck level is at the same elevation with the water rest level and therefore, affirming the unconfined condition of the aquifer system. The area has also a higher water table (Table 3).

Table 3: Mean borehole depth characteristics in the watershed

	Total depth (m)	WRL (m)	Yield (m^3/h)
Upper watershed	191.9	84.7	9.1
Middle watershed	177.4	116.9	6.6
Lower watershed	150.3	95.3	9.6

WRL: Water rest level

This would be expected in a phreatic condition because it is overlain by loose pyroclastic materials that include pumiceous volcanic sediments and agglomerate (Plate 1) that normally has a high water transmitting and holding capacity. This is in agreement with MacDonald and Davies (2000) assertion that porosity within volcanic ashes and agglomerate provides significant groundwater storage. The area underlain mainly with the Menengai pumice that constitutes roughly equidimensional lapilli is located in the lower section of the watershed which covers the area between the Rift Valley Institute of Science and Technology, Nakuru town and Lake Nakuru. The pumice mantle vary in grain size (1-10 mm) spatially with increasing coarseness towards the eastern margin of the watershed resulting in increased porosity in space with enhanced grain size. This partly explains the fairly good aquifer occurrence that is unconfined to the lower section of the watershed (Figure 7).



	1	2	3
🟦 Confined	71	84.6	31.6
🟥 Un confined	23.7	15.4	68.4
🟩 Semi-confined	5.3		

1: Upper watershed
2: Middle watershed
3: Lower watershed

Figure 7: Percentage of aquifer distribution in River Njoro Watershed

This would also explain the decreased yield of groundwater in the middle section of the watershed as the overlying finer pumice mantle reduces the porosity hence lowers water potential. This middle section is also underlain by tuffaceous materials that have low permeability and whose water holding capacity is enhanced with increased weathering. This collaborates with Chilton and Foster (1995) in that the processes of weathering and disaggregation can enhance both porosity and permeability. It is also consistent with Domenico and Schwartz (1998) assertion that volcanic rocks are susceptible to weathering that develops secondary porosity, opens pre-existing fractures and produces pathways that are more pervious. The area to the west of Njoro Township is underlain with pumiceous tuffs which disintegrate easily on contact with water thereafter enhancing porosity of the formation that would otherwise be a low aquifer potential locality. Since the area is located in the Rift Valley it follows as stated by Hagos (2006) that the thick pyroclastic deposits and volcanic rocks within structural discontinuities in the rift and the escarpment provide the good aquifers.

4.1.3 Borehole characteristics

A constructed database from the existing boreholes was made from 104 drillers' logs that constitute representative of the existing boreholes. The boreholes distribution is spatially varied with the highest density located in the upper section of the watershed especially within Egerton University main campus but density decreases down the lower section of the watershed (Figure 8).

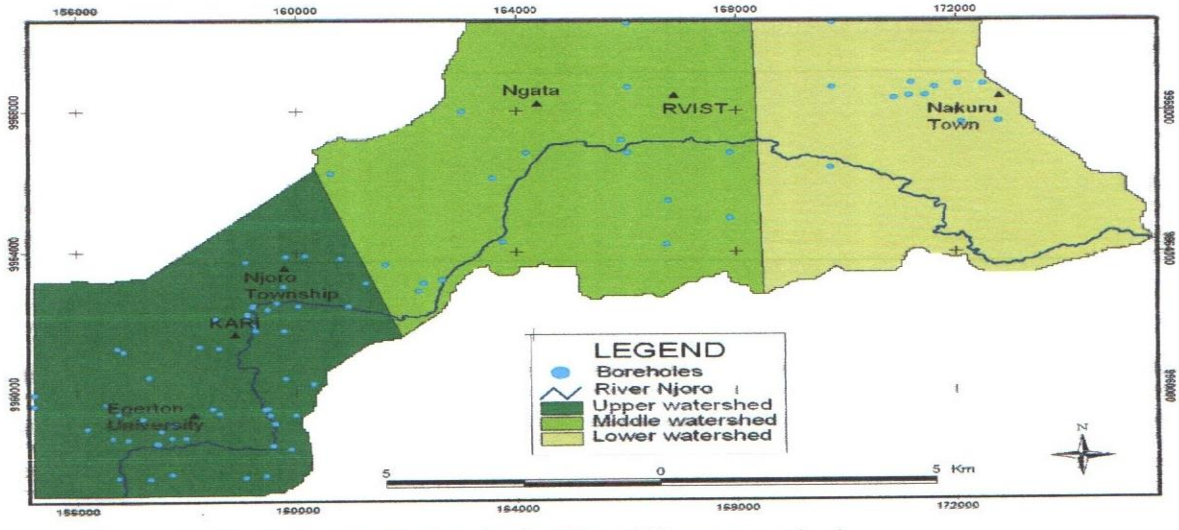


Figure 8: Borehole distribution in the River Njoro watershed

Within the entire watershed however, the general distribution of boreholes tend to be clustered along the Njoro River.

Egerton University is the single institution in the watershed that has the highest concentration (17) of boreholes and in some cases the radius between the boreholes is less than the recommended 800 m. In one case, two boreholes are at a radius of less than 50 m apart. The same applies in the neighbouring Njoro Canning Factory with boreholes spaced about 100 m. In the eastern part of the watershed, the relatively clustered boreholes are those developed for industrial purposes located north east of Nakuru Town.

Although the distribution of the boreholes varies greatly, the depths differ depending on the stratigraphic type and thickness in relation to the water bearing layer. The deepest boreholes are generally sited in the volcanic rock formations that constitute the tuffs and trachytes. The shallower boreholes are in the eastern and lower section of the watershed overlain by the unconsolidated pyroclastic formations. The boreholes have a depth ranging from 73 m to 250 m below the land surface with a median depth of 178 m. Borehole depths to a large extent provide indications of the likely depth to a region's aquifer. The areas with boreholes that have the deepest depths are expected to have the greatest water table depths while those with shallow boreholes will equally have shallow water table depths.

The changes in depth since 1940 when groundwater was first developed in the study area were assessed based on the borehole total depth, water struck level and water rest level. Trends in these water depth parameters indicate that there has been a generalised increase in depth over the years since 1940 (Figure 9).

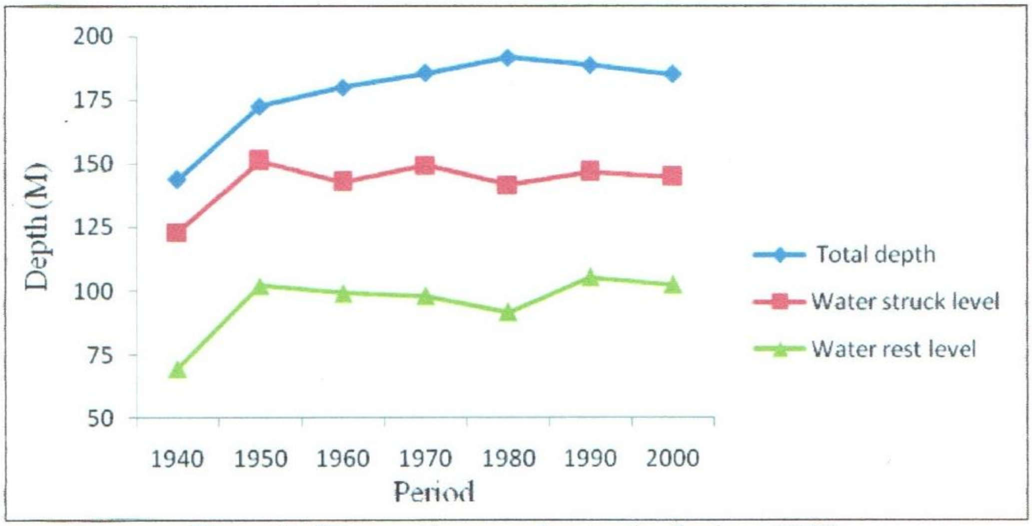


Figure 9: Changes in groundwater depth since 1940

The steady increase in water depth could be attributed to increased groundwater withdrawal as a result of increase in water demand and reduced surface water seepage levels. Reduction in quantity of surface water seepage has been due to land degradation especially the Mau catchment area in the recent past. The increase in demand for water has exacerbated groundwater withdrawal resulting in decline in water levels. This is consistent with the increased depth of the water rest level. The water struck level followed the same trend as the total depth and water rest level while the slight change in water struck level is because of the position of water bearing layer that remains invariable over the same aquifer system. The implications of increase in total depth would imply increased costs of groundwater development in terms of drilling and pumping. Ultimately this would lead to drying of existing boreholes and failure of water strike in new bores.

4.2 Influence of geologic structures on groundwater

Groundwater systems are influenced by the geomorphology and geologic structures that exist in the area. In the study area, the main hydrogeologic structures are those created by the faulting system associated with the formation of the Rift Valley. These faults showed a northwest–southeast orientation characterised by normal faulting. The faulting occurred in three episodes that produced precipitous terrain in some areas conforming to the fault direction. The subsequent faulting modified the hydrogeological characteristics of different lithologies producing fissures that have enhanced the permeability of the rock units (Plate 2).

Plate 2: Fractured phonolitic trachyte observed in eastern part of River Njoro Watershed

This is exemplified by several borehole logs in the watershed that show highly weathered and fractured volcanic formations. Such fractures generally act as conduit to groundwater movement thus increasing the rock permeability and hence aquifer productivity. The high groundwater yield in the lower section of the watershed (Table 3) in spite of the low rainfall regime could be attributed to preferential flow of water through the numerous fault lines within the study area. The upper section of the watershed has considerably reduced borehole water levels in a number of locations especially in the vicinity of Egerton University. This is largely attributed to water loss through seepage as a result of the several faults in the area with one main one running NW–SE through Ngongongeri farm. Failure of groundwater strike because of faults was established during the drilling of borehole C–16444 (Figure 4) on the first attempt as it was sighted along a fault line. However, a shift of site yielded a high (22.5 m^3/h) quantity of water in sited of its closeness and comparable bore depth. Failure of groundwater strike due to fault incidence causing deep piezometric level was also noted in borehole C–3467 (Figure 4) near River Njoro 2 km north east of Njoro Township (McCall, 1957).

The geomorphic features manifested by the faulting in the study area formed alternating steep scarps and gentle terrain because of the different episodes of faulting. The fault orientation delineates the river course as it also determines the topography. The fault line is a conduit for seepage of water from the river to the groundwater system and which enhances the water potential of the aquifer in the vicinity of the River Njoro. The link between the fault and groundwater system is well established as reported by McCall (1957, 1967) and Jennings (1971). This collaborates well with findings observed in borehole C–8164 (Egerton BH 12) showing significant changes in groundwater levels because of periodic difference in rainfall (Figure 10).

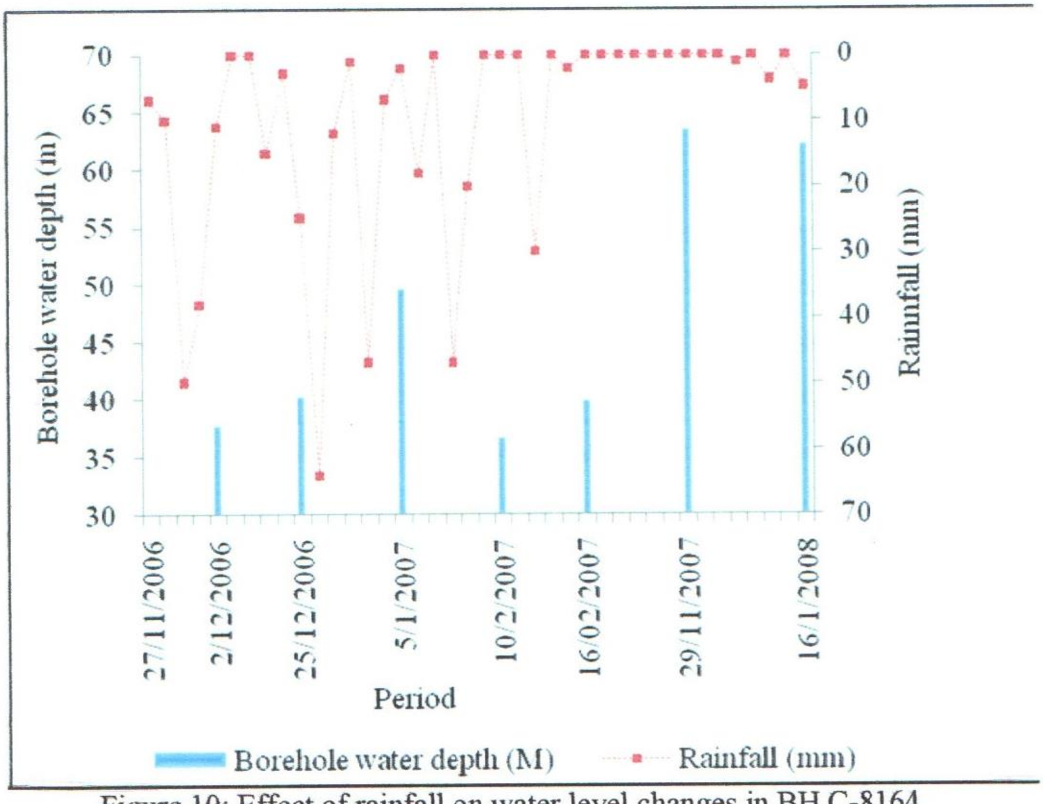
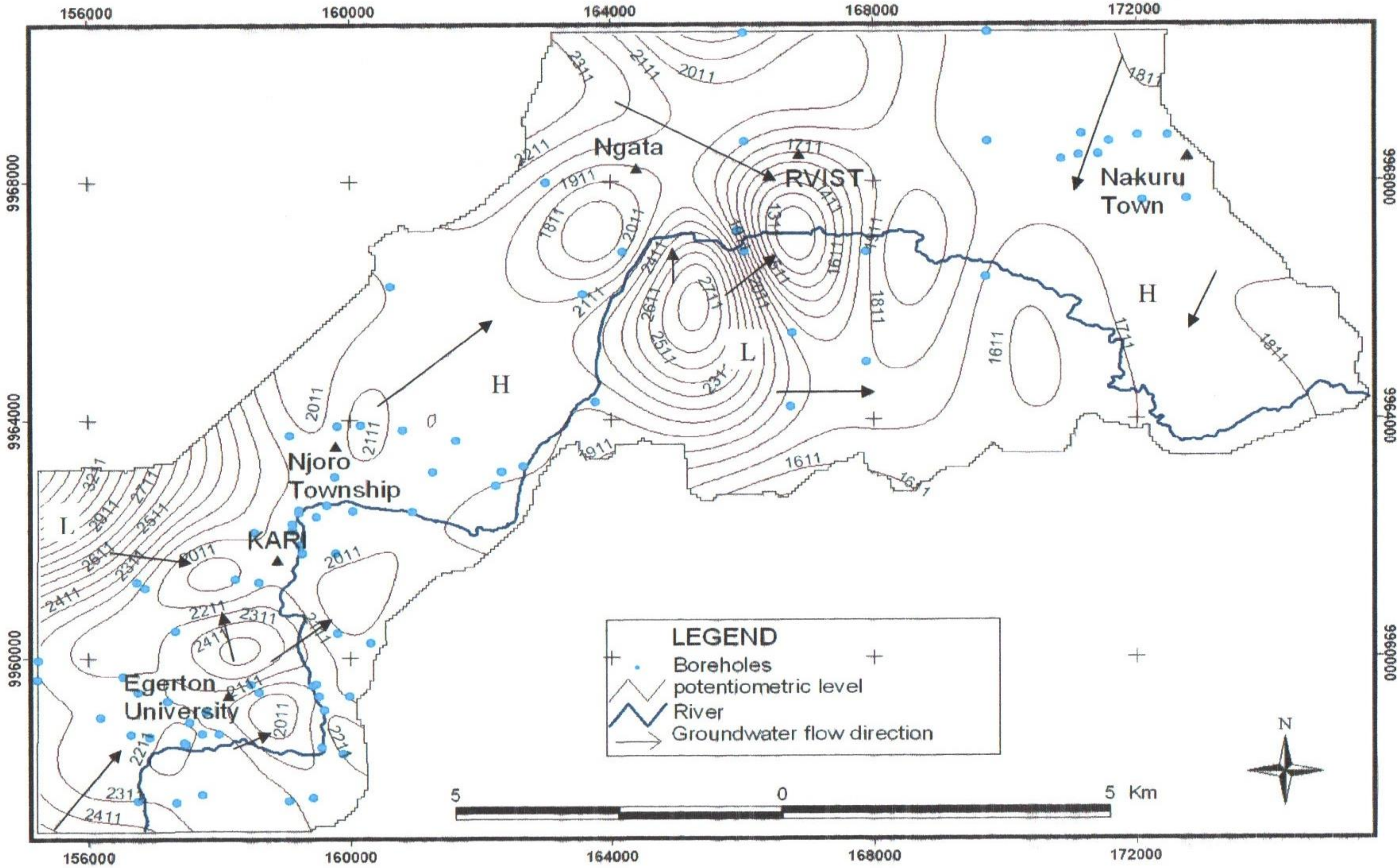


Figure 10: Effect of rainfall on water level changes in BH C-8164

4.3 Direction of groundwater flow

The direction of groundwater flow was determined using groundwater level elevations. This was plotted as contours showing lines of equal water elevation. Groundwater movements through the aquifer system indicate flow from areas of higher hydraulic head to the areas of lower hydraulic head and the direction of water flow is perpendicular to the groundwater contours. Groundwater flow within the watershed appears to follow the topography of the area and moves from high altitude towards lower altitude regions. The areas with higher water elevation also indicate areas of recharge whereas the lowest water elevations points to discharge zones. The groundwater flow direction has also a vertical component which moves downward to the aquifer through the overlying geologic layers.

The groundwater contour map (Figure 11) shows the flow through the volcanic aquifer. The flow indicate that the groundwater originate from the Mau escarpment. The Mau escarpment represents a high–altitude area located west of the watershed and it acts as the main recharge zone. The other recharge zone, though much smaller in extent, is the Menengai Hill that lies north of Nakuru town and eastern end of the watershed. The groundwater flow is largely controlled by these geomorphic features that define the watershed topography and are also forested recharge areas. The primary recharge is from infiltration of precipitation through the volcanic formations which overly the watershed. These geologic formations range from the highly permeable unconsolidated mantle due to their relative uniformity, to fractured and weathered volcanic rocks. The downward groundwater movement to the aquifer is also enhanced by the faulting system that is extensive in a number of the sites.



H: Areas of high groundwater potential
L: Areas of low groundwater potential

Figure 11: Potentiometric surface map indicating groundwater flow direction.

Spatially the lateral groundwater flow down-gradient is generally on a southwest–northeast direction from the Mau escarpment. This is controlled by geomorphological ridges created by the Rift Valley faulting system that forms a series of steep gradients and gentle surfaces. It is this topographic outline that determines the groundwater hydraulic gradient and therefore the contour structure. In the watershed, potentiometric surface map is closely spaced south of Egerton University at the edge of Mau escarpment. Similar close contour spacing is evident at scarp running along the western end of Lake Nakuru through Rift Valley Institute of Technology lapsing to the north of the watershed. The propinquity of groundwater contour signifies the aquifer transmissivity values (Brassington, 2007). The close and wide contours represent low and high transmissivity respectively. The two sections in the watershed with close contour line spacing reflect the steep hydraulic gradient indicative of low transmissivity. Such aquifers would be regarded less permeable than the areas with spaced contour lines. These widely spaced contours represent areas of groundwater discharge while the closely packed contour lines are indicative of recharge sites since a sharp hydraulic gradient is favourable for downward movement of water through an aquifer. Those areas of the watershed that have close potentiometric contours also represent low hydraulic conductivity sites that have smaller aquifer thickness (Kresic, 2007). The sections of the watershed that have groundwater contours widely spaced (H) are good potential sites for initiating new boreholes, while the contrary is true for areas (L) that have closely spaced contours (Figure 11).

4.4 Recharge estimation

4.4.1 Chloride mass balance method

4.4.1.1 Precipitation (P)

Average rainfall used was collected from the nearest rain gauge to the sampled borehole. Rainfall data was taken from the Egerton University weather station (site I) in the upper section of the watershed, Kenya Wildlife Services (KWS) – Nakuru Town station (site II) and Water Resource Management Authority (WRMA) – Nakuru Town station (site III) respectively representing the lower section of the watershed (Table 4). For the purpose of comparative analysis site I was taken to represent the upper watershed while site II represented the lower watershed since site III is also located in the lower watershed.

Table 4: Mean monthly precipitation (mm), 2007

Month	Site[a]		
	I	II	III
January	56.7	56.1	24.6
February	146.8	44.0	89.3
March	19.5	23.9	21.2
April	64.5	113.8	107.4
May	84.1	78.1	119.6
June	168.2	125.7	134.7
July	131.6	99.3	97.7
August	208.0	70.9	156.4
September	93.6	65.9	100.2
October	73.1	68.8	65.2
November	14.1	35.2	56.3
December	9.1	2.3	9.7
Total	1069.3	784.0	982.3

Site[a] I: Egerton University
II: Kenya wildlife service, Nakuru Town station
III: Water resources management authority, Nakuru Town station

A difference in quantity and period of precipitation received was observed during the study period over the three sites. Precipitation received at the Egerton University Station (upper section of the watershed) was about 27% greater than that at the KWS-Nakuru station (lower section of the watershed) of the study area. The monthly trend in precipitation for all the three stations were similar though the lower watershed receives generally precipitation. The minimum monthly precipitation occurs in December in all stations while August represents the highest amounts of precipitation received in site I and III, and June for station II respectively. Generally the precipitation level increased with rise in topographic elevation.

4.4.1.2 Chloride ion concentrations (Cl_p and Cl_R)

The average chloride ion concentrations recorded in precipitation in the upper section of the watershed (I) was 6.95±0.92 mgl^{-1}, while that in the lower section of the watershed (II) was 12.53±1.37 mgl^{-1}. The maximum chloride ion concentrations were 7.9 mgl^{-1} and 13.8 mgl^{-1} respectively (Table 5). In general, higher chloride ion concentrations were recorded in the lower section of the watershed than in the upper section (higher altitude) of the watershed. The regional precipitation chloride ion concentrations variability is attributed to differences in topography and intensity of precipitation. Decreased values of chloride ion concentrations were recorded with rise in elevation while it is inversely proportionate to the precipitation intensity.

Table 5: Precipitation chloride ion concentrations (mgl^{-1})

	Site[a]		
Month	I	II	III
April	5.9±0.83	13.5±1.29	17.0±0.49
May	7.9±0.78	13.8±1.23	17.3±0.34
October	7.5±1.10	11.9±1.45	16.4±0.45
November	6.5±0.96	10.9±1.51	16.5±0.41
Average	6.95±0.92	12.53±1.37	16.8±0.42

Site[a] I: Egerton University
II: Kenya wildlife service, Nakuru Town station
III: Water resources management authority, Nakuru Town station

A minimum of 19.8 mgl^{-1} and a maximum of 109.1 mgl^{-1} groundwater chloride ion (Cl^-) concentration were recorded with a range of 89.3 mgl^{-1} and mean of 64.3 mgl^{-1}. Chloride ion levels in groundwater showed a high spatial variation with a peak in the lower section of the watershed (low elevation areas). The spatial coefficient of variation (CV) within the watershed was estimated at 68.1%. This variation in concentrations also indicated a temporal trend with higher values recorded in the period before and during the onset of precipitation, while concentrations decreased during the wet seasons. Highest groundwater chloride ion concentrations occurred at site III with a mean value of 108.1 mgl^{-1} and the lowest at site I with mean of 20.4 mgl^{-1} respectively. The results obtained indicate a direct relation between chloride ion concentration in precipitation and groundwater recharge rate (Tables 5and 6).

Table 6: Groundwater chloride ion concentration (mgl^{-1})

	Site[a]		
Month	I	II	III
April	20.45±0.49	65.48±0.93	109.1±0.78
May	20.25±0.52	63.51±0.78	107.6±0.74
October	19.80±0.55	63.97±0.81	107.4±0.81
November	21.10±0.59	64.50±0.87	108.2±0.87
Average	20.4±0.54	64.4±0.85	108.1±0.76

Site[a] I: Egerton University
II: Kenya wildlife service, Nakuru Town station
III: Water resources management authority, Nakuru Town station

4.4.2 Groundwater recharge estimates from chloride mass balance

The groundwater recharge rate estimates using CMB were calculated based on the average annual rainfall and concentration of chloride ion in both rainwater and groundwater. The estimated annual recharge in site I was 364.3 mm yr^{-1} representing 34.1% of the annual rainfall in the area. However, the recharge in the lower section of the watershed (site II) was 152.5 mm yr^{-1} representing 19.5% of the annual rainfall received in the area (Table 7).

Table 7: Recharge estimates using chloride mass balance method

Site[a]	Rainfall (mm)	Recharge (mm yr^{-1})	Percentage (%) recharge to rainfall
I	1069.3	364.3	34.1
II	784.0	152.5	19.5
III	982.3	152.7	15.5

Site[a] I: Egerton University
II: Kenya wildlife service, Nakuru Town station
III: Water resources management authority, Nakuru Town station

This method largely present recharges flowing to groundwater at the area of sampling (Marechal *et al.*, 2009). There is considerable recharge range of 211.6 mm yr^{-1} in the watershed (152.5 mm yr^{-1} to 364.3 mm yr^{-1}) with a mean of 258.4 mm yr^{-1}. The coefficient of variation of 57.96% could be attributed to both the high variability in altitude (1600– 2350 m a.s.l) and the distance from Lake Nakuru which is saline. Calculated percentage average annual recharge rate was 23%, with a minimum of 15% and maximum of 34% of the annual rainfall. These recharge estimates compare well to those in areas with similar conditions in Ethiopian highlands that have recharge rates ranging from 100 mm yr^{-1} – 400 mm yr^{-1} (Ayenew *et al.*, 2008).

4.4.3 Groundwater recharge estimate using water table fluctuation method.

Groundwater level data for water table fluctuation method were plotted as shown in Figures 12 and 13. The rise of water table (Δh) is defined and measured by a horizontal line extrapolated from the lowest groundwater level. The specific yield (S_y) of 0.12 used was set as an average estimate for volcanic aquifers (Hahn *et al.*, 1997). The choice of the specific yield used compares well with the findings from the area (0.11) derived from pump test analysis (Kiptanui, 2006). Recharge calculations for the watershed were carried out with the groundwater table data collected from selected boreholes near a rain gauge site stations. Data from two representative sites (Table 8) that were easily monitored were selected; one each in the upper and lower sections of the watershed was used.

Table 8: Monthly water rest levels in the monitored boreholes

	WRL (m)[a]	
Month	Egerton	Nakuru (KWS)
Jan	93.97	57.74
Feb	93.59	58.91
Mar	93.42	58.5
Apr	93.62	58.42
May	95.87	58.54
Jun	94.02	59.12
Jul	93.58	59.21
Aug	94.04	59.15
Sep	94.12	59.18
Oct	94.47	58.18
Nov	93.13	58.97
Dec	93.65	58.52

WRL[a]: Water rest level

The groundwater recharge (R) based on water table fluctuation (WTF) method for each of the sites was calculated based on equation 2. Since an inventory period of one year (Δt =1 year) was used, the recharge results were obtained by multiplying the water rise level (Figures 12 and 13) with the specific yield value of the aquifer formation. Recharge for site I (upper watershed) was:

$$\begin{aligned}\text{Recharge (R)} &= \text{Specific yield } (s_y) \times \text{Water-level rise } (\Delta H)\\ &= 0.12 \times 2600\text{mm}\\ &= 312 \text{ mm yr}^{-1}\end{aligned}$$

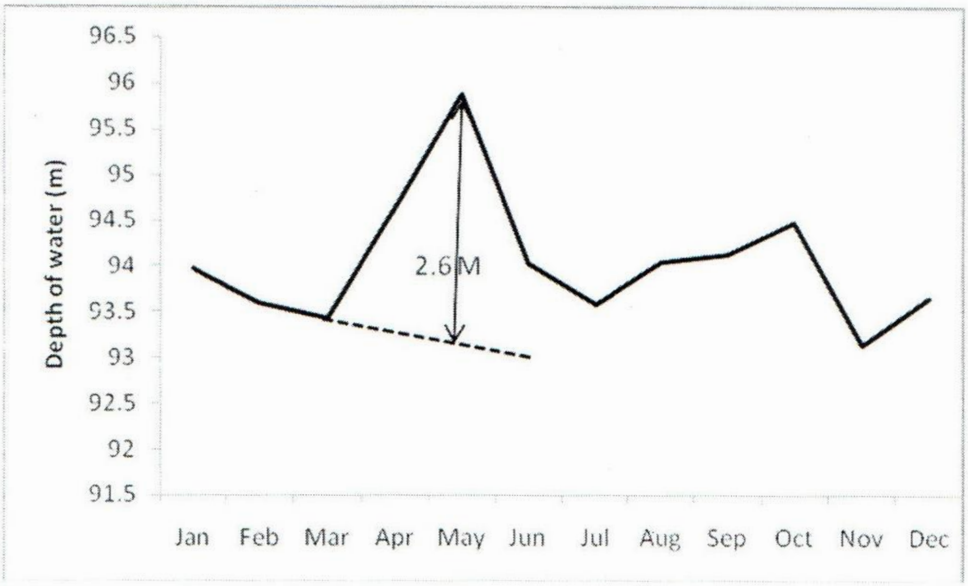


Figure 12: Groundwater recharge in site I (Egerton University) based on WTF method.

Groundwater recharge at site II (lower watershed) based on the same method was:

$$\text{Recharge (R)} = \text{Specific yield } (s_y) \times \text{Water-level rise } (\Delta H)$$
$$= 0.12 \times 960\text{mm}$$
$$= 115.2 \text{ mm yr}^{-1}$$

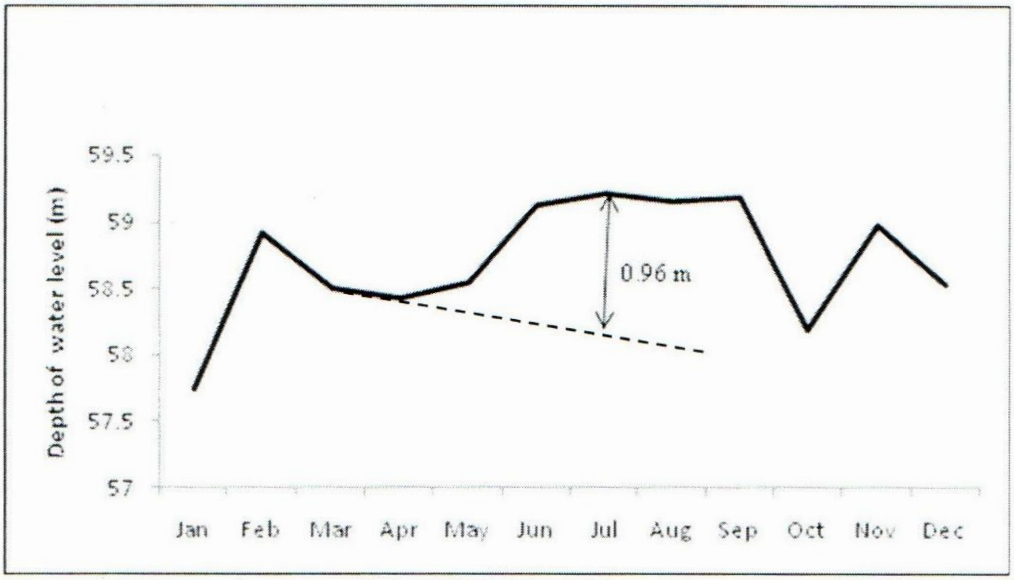


Figure 13: Groundwater recharge in site II (Nakuru Town) based on WTF method.

The recharge values as a percentage of rainfall were calculated using total rainfall for the monitoring period. The average rainfall for the study period were 1069.3 and 784 mm for sites I and II respectively. Using specific yield (S_y) value of 0.12, the recharge rates in the watershed were between 115.2 and 312 mm yr^{-1}. This gives a mean of 213.6 mm yr^{-1} with a coefficient of variation (CV) of 65.2% representing 14.7% and 29.2% (mean of 21.95%) of rainfall respectively. Though the recharge estimates depend to a great extent on the S_y values of the aquifer, the volcanic geologic units in the area are generally similar, thus the average value used is unlikely to be much higher than the estimated. However, the high coefficient of variation could be attributed to the variation in precipitation intensity in the two study sites. This collaborates well with studies that indicate variability in recharge in relation to change in climatic regimes within a watershed (e.g. Chilton and Seiler, 2006).

The mean variation in percentage of recharge estimates calculated using the two methods used in this study was 4.9 and 4.8 for CMB and WTF respectively (Table 9). This shows consistency in recharge change and hence reliability in spatial recharge difference. There was a higher recharge rates in the upper section of the watershed than in the lower section. Recharge spatial variability could be attributed to the rainfall differential. The main groundwater recharge in the area occurs in the highlands (upper sections of the watershed) where annual rainfall is above 1000 mm, while the lower section of the watershed (about 700 mm of annual rainfall) which forms the rift floor acts mostly as a discharge area. There is also a possibility of preferential recharge through the faults which are prevalent especially in the lower section of the watershed. This may account for the high annual recharge percentage to rainfall received. The faults may also increase the rate of groundwater loss from the aquifers. This has been reported in some boreholes within the watershed which could partly explain the enhanced spatial recharge variability.

Table 9: Recharge estimates in the watershed

	Method[a]				
	CMB	WTF	CMB	WTF	
Area	Recharge (mm yr^{-1})		Recharge (% of rainfall)		Variation
Upper watershed	364.3	312.0	34.1	29.2	4.9
Lower watershed	152.5	115.2	19.5	14.7	4.8
			14.6	14.5	

Method[a]

CMB: Chloride mass balance
WTF: Water table fluctuation

Estimates of the amount of groundwater recharge using the two methods show similar trends although not the same amounts and distributions of groundwater recharge. These methods also give a high spatial variability in recharge with coefficients of variation of 58% to 65%. The high variability has been attributed to spatial differences in rainfall, geomorphology, lithology and regional structures. This is consistent with Ayenew *et al.,* (2008) who reported that there are differences in recharge between the rift floor, escarpments and highlands. Therefore, single point measurements of recharge are not good indicators of regional recharge rates. Recharge estimates for the watershed were between 14.7% and 34.1% of annual rainfall. Estimates using the CMB method gave higher estimates of recharge; therefore this method should only be used to estimate annual values. The chloride ion deposition (C_p), which determines the recharge estimates, is controlled by the origin of rainfall that is recycled from land or straight from the ocean. Geology and land use practices have secondary influence. On the other hand, the WTF method can show the magnitude of event recharge and its relationship with rainfall, the residence time of groundwater in the aquifer and the total annual recharge but it is heavily reliant on the selected value of the specific yield.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The study aimed at understanding the hydrogeology in terms of occurrence of groundwater, recharge and water movement in River Njoro Watershed. This knowledge is fundamental for developing and managing groundwater resources.

- The geologic material overlying the study area ranged from Recent pyroclastic deposits to Tertiary volcanic rock grades of trachytes, tuffaceous and pyroclastic formations.
- The principal aquifers comprise weathered and fractured tuffs and trachytes. The area has a multi-layered aquifer system with different hydrogeologic characteristics whereby all aquifer types (confined, semi-confined and unconfined) are established. The unconfined aquifers are prevalent in the lower section of the watershed which forms the floor of the Rift Valley and is overlain by thick unconsolidated pyroclastic deposits. The confined aquifer sited in upper section of the watershed is mainly made of lava flow formations of trachytes and tuffs intercalated in some sections by old land surface or clay sediments derived from highly weathered tuffs.
- Groundwater movement is controlled by the hydraulic head, where the water flow direction follows the topography. The groundwater contours determine the aquifer transmissivity which is useful in mapping potential areas for groundwater development.
- It was also established that total borehole depth, water struck level and water rest level appear to have increased over the last 40 years indicating increased groundwater withdrawal.
- Recharge rates showed a high temporal variability. The amount of recharge appears to be influenced to a large extent by the amount and distribution of rainfall, the type of geologic formation, degree of weathering, and secondary structures such as faulting. Recharge estimates using the CMB method were 364.3 mm yr $^{-1}$ and 152.5 mm yr^{-1} whereas those using the WTF method were 312.0 mm yr^{-1} and 115.2 mm yr^{-1} for the upper and lower sections of the watershed respectively. These estimates of recharge

represent 34.1%, 29.2%, and 19.5%, 14.7% of the total precipitation in upper and lower sections of the watershed.

- The information presented could therefore be useful as a guide to enacting water use policies in RNW such as water extraction regulation based on established recharge rates.

5.2 Recommendations

a. Based on the results of the study

- Groundwater contours suggest that areas within Njoro Township and some areas in the lower part of Nakuru Town have high groundwater potential. These sites could be considered for new borehole exploration and development. However, the area starting from Ngata to Rift Valley Institute of Science and Technology should have fewer boreholes than they currently hold because of the low groundwater potential.
- A monitoring programme of groundwater resources be instituted as a policy for the purpose of understanding the changes in water level. This could aid in establishing water extraction regulations. There is therefore, a need for installing monitoring piezometers especially in Egerton University which has boreholes that are closely spaced. It is also recommended that the standard radius between boreholes (800m) need to be adhered to when licensing development of new boreholes.
- Although groundwater recharge requires more than one method to enhance the confidence of the estimates obtained, the chloride mass balance method is recommended as a relatively good method for estimating annual recharge rates. It is also a simple method to use.

b. Recommendation based on knowledge gap

Further research to enhance the water resource manager's knowledge on groundwater systems for management of this vital resource is recommended.

- Assess specific site groundwater occurrence and water movement based on specific lithologic units. Borehole pumping tests with observation wells be carried out to ascertain actual field conditions because of their variability with depth and lateral space.
- Studies be instituted to assess the climatic impacts on recharge over time.

- Studies on groundwater quality are necessary to enact measures to prevent the resource from potential pollution from increased industries, flower farms and other farming activities.

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APPENDICES

Appendix I: The upper River Njoro Watershed borehole records and the associated parameters

BHNo	GRIDX	GRIDY	ALT	COMPDATE	TDEPTH	1st WSL	Main-WSL	WRL	AQUIFER CONDITION	YIELD
C-10704	827879	9957047	2302	9/20/1993	190	112	140	70	C	9.8
C-11426	825286	9957560	2346	7/16/1996	204	68	184	67.3	UC	8
C-227	824693	9957581	2377	6/17/1943	167	115	143	63	C	6.72
C-8515	827366	9957635	2257	8/10/1989	158	40	80	102	SC	4.26
C-1749	825678	9957698	2311	4/10/1952	175	69	134	85	P/C	5.46
C-8164	827509	9958489	2248	5/11/1989	142	72	124	100	P/C	32
C-8163	824870	9958667	2308	2/18/1989	136	60	112	54	SC	33
C-6515	824872	9958674	2309	8/29/1985	170	36	36	36	UC	16
C-8162	824585	9958710	2308	1/16/1989	136	61	103	51	C	8.24
C-4785	825681	9958726	2273	10/1/1980	202	52	148	52	UC	11.1
C-4917	824130	9958994	2318	3/1/1981	184	90	164	28	C	8.16
C-3490	825735	9959087	2282	5/2/1968	193	92	134	107	P/C	7.86
C-5206	827551	9959118	2215	11/18/1982	220	34	158	34	UC	16.62
C-4517	825142	9959273	2312	5/30/1978	188	104	180	97	C	16.88
C-916	827928	9959343	2219	7/8/1949	213	156	175	117	C	3.66
C-6968	827470	9959344	2212	2/28/1986	240	30	189	97	P/C	8.76
C-327	824694	9959418	2286	10/27/1944	137	30	105	35	UC	8.5
C-3243	824694	9959418	2273	6/8/1963	189	73	177	85.4	C	10.92
C-5029	827376	9959524	2212	8/3/1982	210	30	138	88	P/C	3
C-6032	827428	9959550	2214	2/28/1985	240	31	188	70	P/C	3.12
C-8161	826430	9959555	2294	12/9/1988	202	134	176	93	C	11.16
C-6271	824469	9959686	2306	1/1/1985	200	130	164	88	C	5.3
C-6206	823185	9959964	2335	2/19/1985	173	32	102	35	C	12.06
D436	828256	9960250	2195	7/1/2007	210		180	164	C	4
C-10807	827748	9960402	2194	4/6/1995	200	92	172	166	P/C	5.29
C-4669	825270	9960449	2248	10/1/1979	214	14	116	21	UC	15.68

C-16444	824814	9961170	2270	7/25/2005	174	54	154	93	P/C	22.5
D-435	827175	9961892	2193	7/1/2007	176	110	164	88	C	8
C-1934	827436	9962368	2179	1/15/1953	198	122	195	97	C	2.58
C-6070	827158	9962436	2172	5/20/1985	250	140	160	129	C	22.12
C-1935	827985	9962462	2178	3/14/1953	184		128	122	C	4.08
C-4206	827153	9962478	2171	5/17/1976	250	130	242	100	C	25.4
KARI-3	827589	9962548	2176	11/26/2003	220	106	170	105	UC	10.2
C-10797	827714	9963021	2189	5/16/1994	200	40	60	113	SC	5.4
C-211	826544	9961266	2179	2/18/1943	135		93	90	UC	1.8
C-4413	826478	9962102	2196	10/14/1977	137	42	131	68	P/C	6.9
C-8297	827069	9962137	2174	2/14/1989	252.5	108	164	104	C	8.52
C-9065	827057	9962237	2170	7/22/1990	198	146	186	105	C	8.58
KARI-4	827209	9961755	2174	1/4/2004	220	33	160	90	P/C	7.2
				Average	**191.25**	**78.714**	**146.5526**	**84.7**		**9.064**

BH: Borehole
ALT: Altitude
TD: Total depth
WSL: Water struck level
WRL: Water rest level
C: Confined aquifers
UC: Unconfined aquifer
SC: Semi-confined aquifer
P/C: perched and confined aquifer

Appendix II: The middle River Njoro Watershed borehole records and parameters

BHNo	GRIDX	GRIDY	ALT	COMPDATE	TDEPTH	1st WSL	Main-WSL	WRL	AQUIFER CONDITION	YIELD
BLGA #	830178	9962878	2137	1/23/2008	190	124	124	129	C	6
C-2745	824694	9961266	2346	12/18/1957	178	109	171	92	P/C	9.78
C-11844	830232	9961484	2140	6/24/1996	180	153	173	112	C	3.6
D185	828894	9962450	2145	4/1/1999	180		135	120	C	3.6
C-3559	830250	9963110	2148	4/2/1969	199	146	164	104	P/C	4.56
C-5403	828405	9963113	2168	1/21/1984	175		124	113	C	19.62
C-1491	830266	9963113	2118	7/28/1951	162	107	151	85	C	10.32
C-1125	830593	9963205	2115	6/24/1950	125		108	80	C	13.02
C-4506	829559	9963644	2166	7/15/1978	149	76	130	122	P/C	9.78
NPT#	827018	9963730	2162	3/8/2006	215	80	173	108	P/C	14.4
D393	828748	9963826	2159	4/1/2004	145	80	115	104	P/C	1.8
JW#	828748	9963826	2159	2/1/2006	170	101	155	132	P/C	3.4
C-13598	827751	9963901	2174	11/15/2001	180	120	160	114	P/C	3.2
D166	166727	9964200	1920	10/1/1998	100		50	60	UC	7.2
C-1028	167884	9964950	1960	1/31/1950	229	117	223	167	P/C	6.6
C-10516	166767	9965447	1970	6/20/1993	208	145	186	185	UC	6.78
C-11500	828575	9966232	2153	4/3/1996	200	92	151	138	C	3.6
C-11845	169704	9966379	1845	7/9/1997	200	145	170	134	C	6
C-2670	166022	9966797	1981	4/15/1957	192		181	167	C	2.82
C-8167	166022	9966797	2050	8/30/1988	105		97	92	C	9.6
C-1362	832117	9966798	2057	4/14/1951	200	45	195	175	P/C	4.56
C-4670	833867	9967156	2005	9/1/1980	223		170	170	UC	3.96
C-11501	830949	9967961	2156	5/4/1996	180	90	143	92	C	2.5
C-214	166022	9968646	1981	2/28/1943	121		64	55	UC	2.94
C-993	166022	9968646	1920	11/18/1949	198	115	124	112	C	4.08
				Average	**175.5833**	**107.563**	**146.375**	**118**		**6.5717**

BH: Borehole
ALT: Altitude
TD: Total depth
WSL: Water struck level
WRL: Water rest level
C: Confined aquifer
UC: Unconfined aquifer
SC: Semi confined aquifer
P/C: Perched and confined aquifer

Appendix III : The lower River Njoro Watershed borehole records and parameters

BHNo	GRIDX	GRIDY	ALT	COMPDATE	TDEPTH	1st WSL	Main-WSL	WRL	AQUIFER CONDITION	YIELD
C-306	173455	9963114	1789	6/28/1944	73	18	70	19	UC	13.5
C-7949	172100	9967650	1830	5/14/1988	81		65	66	UC	7.92
C-13218	172771	9967677	1845	4/14/2001	120		54	65	UC	11.4
D444	173520	9968315	1838	8/1/2007	104		95	75	UC	8
C-7455	170860	9968351	1846	9/1/1987	201		124	90	C	11.28
C-7729	171128	9968416	1852	1/1/1988	201		156	95	C	10.14
C-7628	171426	9968431	1848	10/1/1987	120		90	89	UC	17.46
D405	174188	9968447	1843	9/1/2006	120	80	110	80	UC	14
C-13725	173962	9968629	1848	12/19/2002	113	84	96	84	UC	11.5
C-805	169732	9968647	1855	12/20/1948	166	112	161	113	UC	8.1
C-7376	171593	9968647	1835	6/1/1987	167		65	64	UC	8.1
C-2278	173454	9968647	1874	10/2/1954	123		105	102	UC	10.92
C-13535	172030	9968741	1879	3/2/2002	170	115	125	93	C	10.8
C-11456	172490	9968744	1878	10/26/1996	200	103	178	101	C	11.8
C-7448	171168	9968772	1854	2/3/1988	232		110	97	C	10.26
D414	173545	9969770	1889	6/1/2006	131		105	112	UC	1.2
C-1246	173453	9969780	1890	10/21/1950	128		116	107	C	9.12
C-855	166021	9970483	1981	4/25/1949	189.8		184	182	UC	4.5
C-1535	169732	9970484	1938	9/28/1951	189		178	177	UC	4.92
				Average	**150.2192**	**85.3333**	**115.10526**	**95.32**		**9.5746**

BH: Borehole
ALT: Altitude
TDepth: Total depth
WSL: Water struck level
WRL: Water rest level
C: Confined aquifer
UC: Unconfined aquifer
SC: Semi-confined aquifer
P/C: perched and confined aquifer