REGIONAL GROUNDWATER FLOW SYSTEMS IN THE KENYA RIFT VALLEY

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February, 2017

SUPERVISORS:
Drs. Robert Becht
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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources and Environmental Management

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ABSTRACT

With the growing industry and economic development in Kenya, the demand for groundwater increases due to its great potential and availability in most parts of the country. But there is need to institute proper management of water resources for sustainable development using scientific tools and information. The understanding of the various factors affecting groundwater exchange with surface reservoirs is critical and can be achieved through modelling. Previous studies described groundwater flow patterns around Lake Naivasha and presented quantified groundwater interactions using detailed water budgets. Researchers speculate that flow from Naivasha is towards Lake Elementeita to the north and Magadi to the south. But natural and anthropogenic factors that influence groundwater flow in the Kenya Rift Valley are yet to be properly understood making the projected utilization of groundwater resource untenable. The main objective of this study is to model and describe groundwater flow in the study area. However, there is no single method that can be used to provide all the necessary data sufficient to explain groundwater flow and that is why there is need for an integrated approach. The methods employed in this study include updating the conceptual model on the basis of integrating geology, isotope chemistry observations and morphology of the lakes. The study aimed also to integrate data and assess water budgets of the eight lakes in the Kenya Rift Valley through finite difference modelling with MODFLOW 2005 in the iMOD environment. A six layer system was designed with coarse grids of 1000m and the selection of appropriate boundary conditions to simulate steady state conditions with emphasis on the lake package. Using satellite derived meteorological data, the model was calibrated to observed lake areas/levels. Based on the resulting hydraulic heads and water balances, groundwater flow paths were simulated by iMODPATH providing insight into the direction and extent of flow and possible interaction between the lakes and groundwater. The simulated flow patterns were categorized into two to represent regional and local fluxes. Regional groundwater flow patterns originate from Lake Naivasha and indicate major outflow areas to the south and to the north. The simulated extent of flow from Lake Naivasha northwards reached Lake Baringo which acts as a groundwater sink to regional groundwater flow. But Lake Baringo's freshness implies that it also has an underground discharge. Flow southwards reached Lake Magadi and flow simulation from Lake Baringo failed due to insufficient structural data about faults which act as conduits that convey water to Kapedo springs. Each lake was assessed separately to simulate local fluxes attributable to local aquifer and recharge zones. A final integrated matrix of local and regional fluxes was derived and presented to contribute to existing literature and offer opportunity for further research.

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Whereas I humbly accept responsibility for the work and time leading to this thesis, the contribution of many others who helped me to do my best by trusting that I was able must be saluted. I thank God for them all

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DEDICATION

This Thesis is dedicated to My Father

The late John Aggrey Fuchaka

Wakati wa Mola ulipofika
Mwito wake ukaitika
Ukatuwacha tukisikitika
Na kuomboleza
Kuwa ni yako zamu

Matunda yako si haba
Na sifa yako kuifika
Sio rahisi kwa hakika
Mashariki mwa Afrika
Na kwingine utasifika

Tumejitwika juhudi na ari moyoni
Japo umeondoka
Daima utasikika
Milele utasifika
Kwa yako kazi

Jana imepita na majuto
Babangu tabasamu
Safiri salama
Ukifika nisalimie waliotangulia
Umsalimu pia Maulana

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LIST OF ABBREVIATIONS

ArcGIS	Arc Geographic Information System
C	Conductance
CKR	Central Kenya Rift
DTM	Digital Terrain Model
E	Evaporation
EARS	East African Rift System
GHB	General Head Boundary
GIS	Geographical Information System
GPS	Geographical Positioning Systems
GUI	Graphical User Interface
ILWIS	Integrated Land And Water Information System (ITC GIS Package)
Lake Package	Processor For Lake Transience Used With Modflow
LAK7	Lake package of MODFLOW
LNROA	Lake Naivasha Riparian Owners Association
Ma	Million Years
MAE	Mean Absolute Error
Mamsl	Metres Above Mean Sea Level
MCM/Y	Million Cubic Meters/Year
ME	Mean Error
MODFLOW	Finite Difference Groundwater Flow Model
NA	No Available Data
PEST	Parameter Estimation
RMS	Root Mean Square Error
S	Storativity/Storage Coefficient (Also Used For Lake Stage)
Sensan	Sensitivity Analysis Program
SRTM	Shuttle Radar Topography Mission
T	Transmissivity
USGS	United States Geological Surveys
WRAP	Water Resource Assessment Project

1. INTRODUCTION

1.1. Background

The interaction between groundwater and surface water is very complex and varies in complexity from place to place. This complexity is particularly evident in the Kenya Rift Valley where a cascade of closed basin lakes alternate with volcanic centres exuded above a severely faulted Rift floor. The hydrogeology within the Kenyan Rift Valley is complex due to the potential influence of faults and porous volcanic and volcanoclastic media on groundwater flow(Lydia Atieno Olaka, 2011). Hydrogeology is important in formulating sustainable development of groundwater resources which requires estimation of this 'unseen' resource necessary to maintain an equilibrium between surface and groundwater resources. Sadly, studies on the regional groundwater in the study area have not received much attention. As a result, there is insufficient data to quantify groundwater flow and influence on the Rift Valley lakes.

A few studies have adopted a traditional approach to avoid the problem of subsurface water flow by assuming that the input of groundwater is equal to the outflow into the lakes. According to this approach, groundwater flow can be considered to be balanced out and must not to be included in hydrological modelling and paleoclimate studies(Bergner, Trauth, & Bookhagen, 2003) But there are cases where significant groundwater flow exists in the Rift Valley lakes that cause significant unaccounted for water in the water balance calculations if this assumption is adopted. The freshness of Lake Naivasha for instance, as a surficially closed lake, is thought to be a result of groundwater discharge out of the lake(G. Darling, Allen, & Armannsson, 1990). The unaccounted for water from Lake Naivasha budgets is suspected to be discharge into groundwater and is estimated at 50 MCM per year(Becht, Mwango, & Muno, 2006).

Currently, there exists a knowledge gap in the dynamics of lake-groundwater flows and inter-basin transfer for the adjacent basins in the study area. This makes it necessary to investigate the hydrodynamic and hydrogeological properties of the subsurface to map groundwater flow and surface-groundwater interaction within the Kenya Rift Valley. In order to understand the complex nature of the surface-subsurface dynamic interaction, a multi-faceted approach must be undertaken to integrate knowledge on the climate, regional geology, permeability of the underlying rocks and the structures governing the occurrence and movement of groundwater. Among the approaches adopted is groundwater modelling as a tool used to simulate the behavior of groundwater in response to natural or artificially imposed stresses.

This thesis aims to contribute to the knowledge on regional groundwater regimes and groundwater balance for sustainable development of water and geothermal resources in Kenya. It also provides a basis for further studies. Characterizing lake level and lake area variability and assessing the dominant processes affecting these levels will aid in understanding regional groundwater flow. A regional groundwater model has been developed and used to investigate possible groundwater flow systems in the Kenyan Rift Valley. The model can best be used for broad-scale predictions and can also be used to provide a general sense of groundwater to surface water and groundwater to groundwater impacts in the Rift Valley basins. Since groundwater is a crucial link in the hydrological cycle, its estimation spatially and temporally is prerequisite for sustainable groundwater management. Quantitative estimation is necessary to observe if the groundwater reservoir in a state of dynamic equilibrium over a period of time(Yihdego, Reta, & Becht, 2016). Morphological nature of the lakes, long term water balances, isotope information and observed flow patterns will form basis of this study.

1.2. Problem Definition

Describing groundwater flow regimes in the Rift Valley is one of the most difficult tasks in hydrogeology due to complex geology tied to the area's dynamic evolution and its volcanic systems(Muno, 2002). The study area forms part of the East African Rift System (EARS) which is characterized by a cascade of lakes occupying an extremely faulted graben with geothermal manifestations and volcanic centers. Natural and anthropogenic factors that influence groundwater flow in the Rift Valley are yet to be properly understood making the projected utilization of the resource a mirage. The underlying geology and geological structures in the Kenyan Rift Valley(also known as the Gregory Rift), recharge zones, lake levels in the Rift lakes, aquifer geometry, transmissivity and specific capacity of the aquifers change in time and space. Secondly, only lake Naivasha has been studied extensively due to its economic and ecologic importance as a fresh water source. Other Rift Valley lakes have not received much attention yet they are important indicators in regional groundwater flow systems. Lastly, there is lack of a tool that can be used to provide technical basis for policy formulation on groundwater utilization activities in the region for sustainable development. Such a tool can be useful in making predictions about future demands of groundwater resources and how to prepare for them.

Water is defined as an essential resource to support the development activities planned under the Kenya Vision 2030 – Kenya's development blueprint(Nippon Koei, 2013). But groundwater in the Rift Valley which constitutes a larger percentage of fresh water has not been properly assessed to cope with increasing water demands for irrigation, domestic and industrial use. The Olkaria geothermal power project (generating about 47% of electricity in Kenya) is a major electricity-producing enterprise in Kenya that depends on recharge from the deep seated groundwater flow(ESI Africa, 2016). Therefore, there is need to better understand the dynamics of groundwater flow and describe the role of lakes in this flow. A thorough understanding of the causes of lake level dynamics in the Kenyan Rift Valley can help water authorities to be not only prepared for extreme events but also to manage long-term water abstraction regimes and inform continued development of geothermal energy. To achieve this, studies must be undertaken to estimate spatial distribution of groundwater and possible flow paths for optimal utilization.

1.3. Objectives and Research Questions

1.3.1. Main Objective

The main objective of this research is to investigate groundwater flow systems in the Kenyan Rift Valley.

1.3.2. Specific Objectives are:

1. To develop and calibrate a 3D steady state groundwater numerical model for the Kenya Rift Valley
2. To describe the South and North general extent of groundwater flow with respect to Lake Naivasha.
3. To simulate observed flow paths from lake Baringo
4. To simulate both local fluxes around respective lakes and regional flow paths

1.3.3. Research Questions are:

Based on the above objectives, the research questions will be as follows:

1. Can the hydrogeology of the Kenya Rift Valley be transformed to a numerical model which is capable to simulate the observed conditions and interactions of the lakes and aquifer systems?
2. Which Rift Valley lakes are the groundwater sources and sinks in the study area?
3. How do the local fluxes around the aquifer/lake system help in the understanding groundwater flow patterns in the area?

1.4. Hypothesis

In order to achieve the main objective set, the following hypothesis is formulated and tested at the end of this study.

- The groundwater flow is discontinuous in the Kenya Rift Valley due to surficially closed lake basins, impervious volcanic centres and high pressure geothermal cells.

1.5. Novelty of the study

The findings of this study will augment the existing data and will contribute to the understanding of regional groundwater flow in the study area by including the following novelty works;

1. **Application of tool that was not used before in the study area**
   In this study, a new tool - Interactive MODFLOW (iMOD) has been used to simulate the groundwater flow in the study area. This approach allows for 3D interactive modelling that is capable of generating models of any sub-domain within the area covered by the data set. The new Lake package LAK 7 available in the iMOD environment has been used extensively

2. **Use of data from new, additional boreholes and geothermal well information that had earlier not been used to constrain the model**
   Boreholes drilled in the recent past and additional geothermal wells drilled in the study area will provide more information required to describe the flow of groundwater and lithology in the area.

3. **Application of a numerical Model to simulate groundwater flow for the entire Kenya Rift Valley**
   No complete 3D groundwater models have been developed for the whole Kenya Rift Valley area but a few models for smaller regions exist.

1.6. Research Approach

To arrive at the above stated research objectives, the following steps have been undertaken to a satisfactory level;

1.6.1. Review of Scientific Literature

Existing scientific literature about the Kenya Rift Valley area by credible authors was reviewed under the following topics: Existing models, Satellite data for hydrologic modelling, Pathline simulations and particle tracking, Isotope chemistry information, Geomorphological setting of the Rift Valley lakes, Bathymetric and Hypsometric characteristics of Rift valley lakes and Regional groundwater modelling approaches

1.6.2. Fieldwork and Data Collection

Required data for the study was collected in two stages; before fieldwork and after fieldwork. Data used by other scientists and previous MSc. students in their theses were assessed before fieldwork to identify areas of data gaps and data inconsistencies. Assessment was also necessary to avoid duplication of data or measurements. During fieldwork, missing data and new datasets were collected and verified. Meteorological data was collected from the Kenya Meteorological Department (KMD) while hydrological measurements were collected from the Water Resources Management Authority (WRMA)

1.6.3. Data Integration and Modelling

In order to develop a model, a wide variety of data is pre-processed and integrated before being converted into a simple conceptual model. Collected satellite data and in-situ measurements from sub catchments within the study area were integrated to generate a conceptual model from the geomorphological setting of the Rift Valley. The conceptual model was then transformed into a numerical model. Quality assessment of the model input files was performed. Calibration, validation and sensitivity analysis were also performed. Figure 1 below shows how the integration of data led to development of a conceptual model.

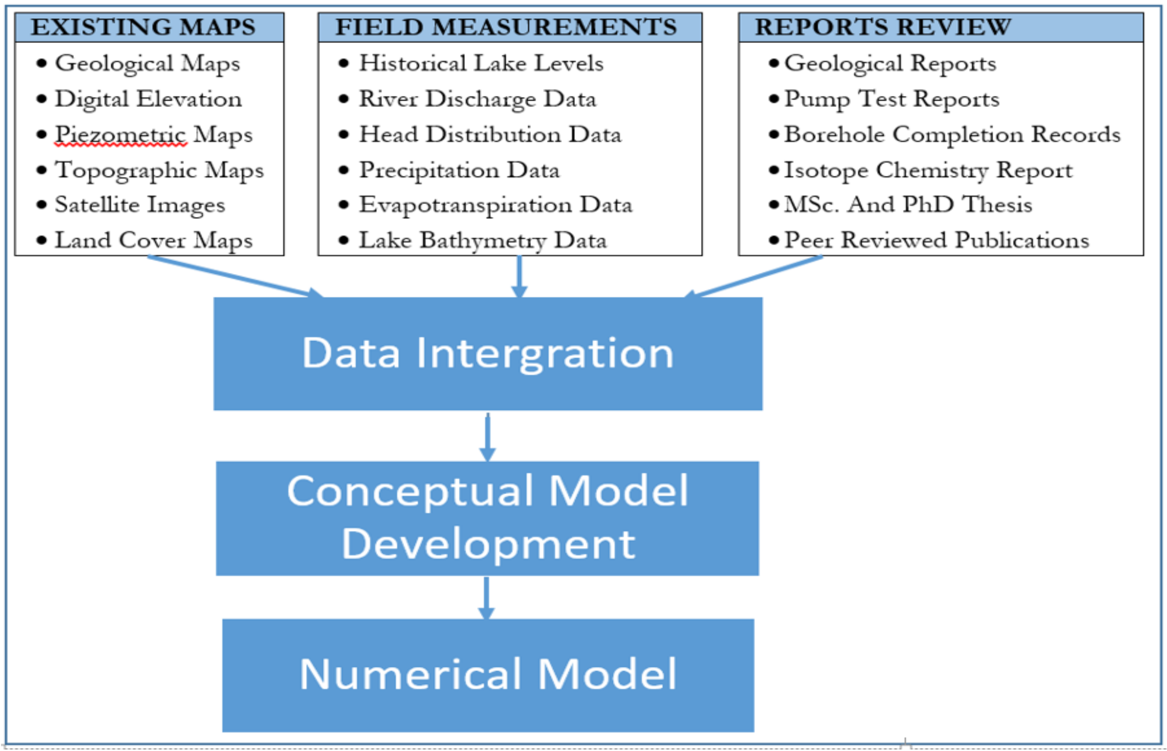


Figure 1: Data sources and data integration for conceptual model development

1.7. Structure of the Thesis

This thesis is composed of six chapters.

- Chapter one discusses the introduction to the study, objectives and research questions to be answered at the end of the research.
- Chapter two details the description of the study area, location, rainfall patterns, climate, hydrogeology and observed lake levels in the study area
- Chapter three elaborates the method employed in this study; literature review, data acquisition, data processing and research methods.
- Chapter four outlines the conceptualization of the model and numerical modelling setup and parameterization.
- Chapter five discusses the results
- Chapter six summarizes the discussion, conclusion and recommendation of the study

2. DESCRIPTION OF THE STUDY AREA

2.1. Location

The study area is part of the East African Rift System (EARS) which has two branches, the eastern (Gregory Rift) and the western arms (Albertine Rift) that crosscut Eastern and Central Africa, beginning at the triple junction of the Red Sea (Lydia A. Olaka, Odada, Trauth, & Olago, 2010). The EARS comprises a series of rift zones stretching more than 3000km from the afar triple junction in the North to the Zambezi River in Southern Africa(Kuria, 2011). There are 23 major lakes in the EARS; 8 in central Ethiopia, 8 in Kenya and 7 in Tanzania(Becht, Odada, & Higgins, 2005). All of these lakes are uniquely in endorheic basins.

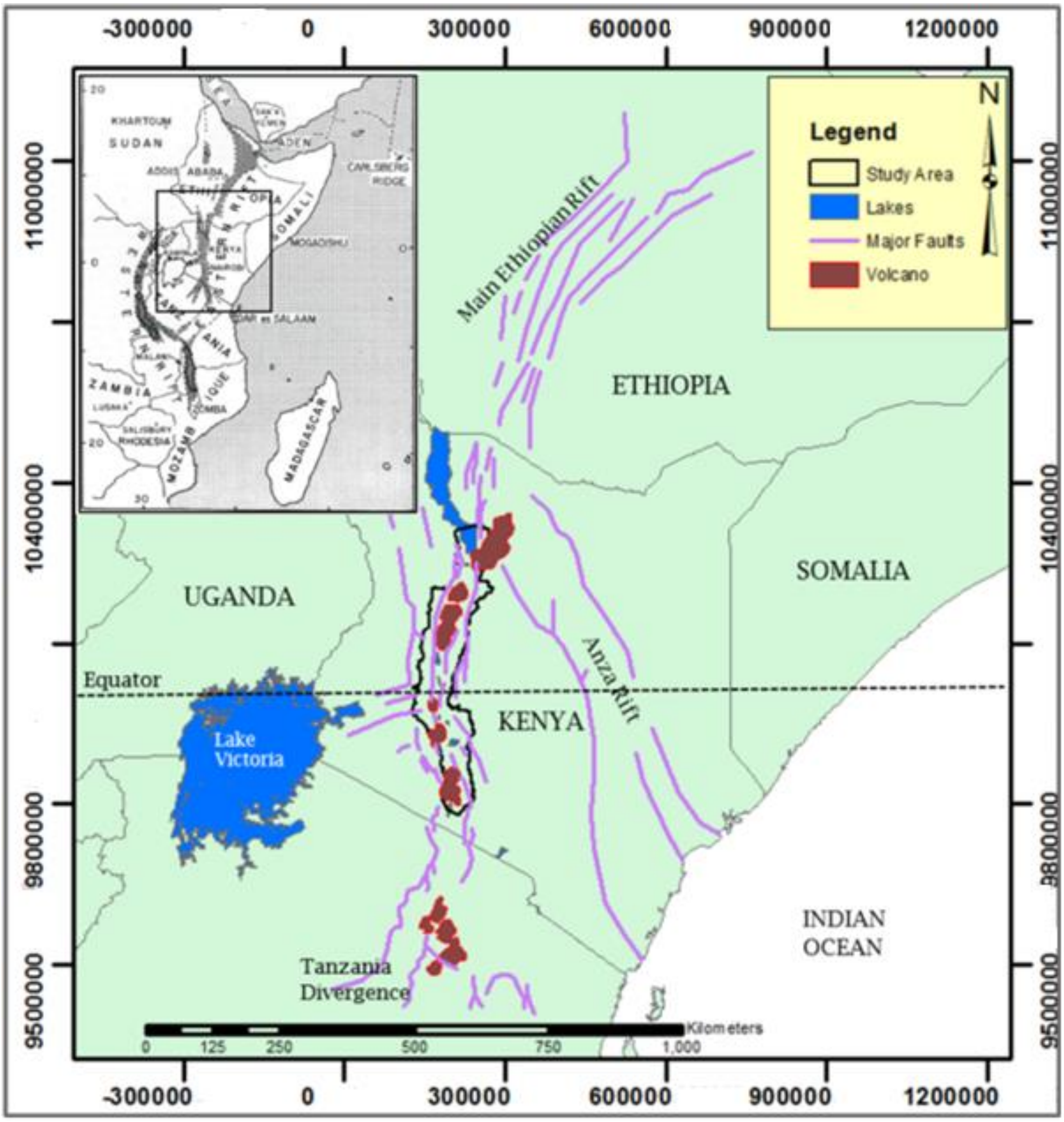


Figure 2: Map of the Kenyan Rift Valley showing the location of the study area

The eastern branch or Kenya Rift Valley system harbours eight lake basins that together form the extent of my study area. These lakes vary in size as well as hydrological setting (Alemayehu, Ayenew, & Kebede, 2006). The existence of these lakes is at least partly due to the numerous Late Quaternary central volcanic structures, which often separate the lakes from each other(W. G. Darling, Gizaw, & Aruse, 1996). The Kenyan Rift Valley lake basins from North to South are: Turkana, Logipi, Baringo, Bogoria, Nakuru, Elementeita, Naivasha and Magadi. Being located in the tectonically active region, the hydrogeology of the study area is quite complex due to the disruption of lithologies by faults and the variability and lateral discontinuity of the aquifers as well as the unknown effect of geothermal cells. The aquifers within rift valley include: Turkana aquifer, Baringo-Bogoria aquifer, Nakuru aquifer, and Magadi aquifer.

The Kenya Rift Valley area (130,452 Km^2) is an area of internal drainage discharging into Lake Turkana in the north and Lake Natron to the south(Olago, Opere, & Barongo, 2009). However, this study does not encompass the entire Kenyan Rift Valley but only a part of it. The study area is approximately 35,206 Km^2 bounded by coordinates extending from latitudes 5^0 N to 2^0 S and longitudes 35^o 50' to 36^o 42' E. The study area is defined by Northings 9770000 – 10320000 and Eastings 172000 - 280000 UTM zone 37. Elevation ranges from about 280 -3200m above sea level. Figure 2 above shows the study area within the Kenyan Rift Valley.

Some parts of the study area are accessible by major roads from Nairobi to Western Kenya yet most parts are only accessible via minor roads. Naivasha and Nakuru areas are also accessible by railway but far flung areas like Turkana are best accessed by road or light aircrafts

2.2. Climate

Rainfall is not evenly distributed in the Kenya Rift. Other climatic conditions vary with response to differences in elevation and land cover. According to the Kenya Meteorological department data (1931-1980), mean annual rainfall is fairly low 430 mm around Lake Magadi area rising to 627 mm around Lake Naivasha and rising further to 981 mm around Lake Nakuru. Rainfall amounts begin to decrease when descending the rift floor northwards. The rainfall regime is influenced by the rain shadow from the surrounding highlands of the Nyandarua range to the east, and the Mau escarpment to the west(Muno, 2002). A schematization of the hydrological cycle in the Lake Naivasha basin is shown in Figure 3. Throughout the Kenyan Rift Valley, relative humidity is low. Lake Naivasha area registers less than 75% humidity while Lake Magadi area records an average of 60% humidity. Mean annual temperature ranges from 8^0C to 30^0C according to records available. Maximum daily temperatures around Lake Naivasha area is 25^0C and minimum daily temperature is recorded as 9^0C. At Lake Magadi area, the maximum daily temperature is 35^oC and minimum is 23^oC

Annual potential evaporation rates over the lakes are generally at least three times the rainfall that these lakes receive. Potential evapotranspiration is lower at higher altitudes than lower ones and during the wet months the PET is even lower at respective altitudes. Over the Rift escarpment, evapotranspiration is averaged at 1400 mm while Naivasha catchment records as much as 1525 mm in the dry months

2.3. Rainfall Patterns

Generally, the Rift Valley rainfall patterns vary with respect to relief. See Figure 26. Some 33 rainfall stations in the study area were used to demonstrate this as shown in Figure 4. Clearly in Rainfall intensities are much higher on the Rift escarpments. The rainfall recorded on the Rift floor is far much less compared with regions with higher altitude. The rift flanks receive up to four times more rainfall (2400 mm/year) than the rift floor (600 mm/year) according to McCann, 1974. Besides the spatial variation in rainfall, there is also a temporal variation according to the records and satellite data. The study area receives bimodal rainfall with long rains being recorded in April and May and part of June; sometimes these rains begin in March. The short rains begin in December and January, occasionally start in November.

Appendix 2 shows clearly the seasonal variation in rainfall patterns across the study area. From the figure, it is evident that rainfall patterns for all stations follow a typical trend of two rainy seasons. It is important to note that these patterns result from taking averages of rainfall for five years. Therefore, the actual yearly pattern may vary significantly from the long-term average.

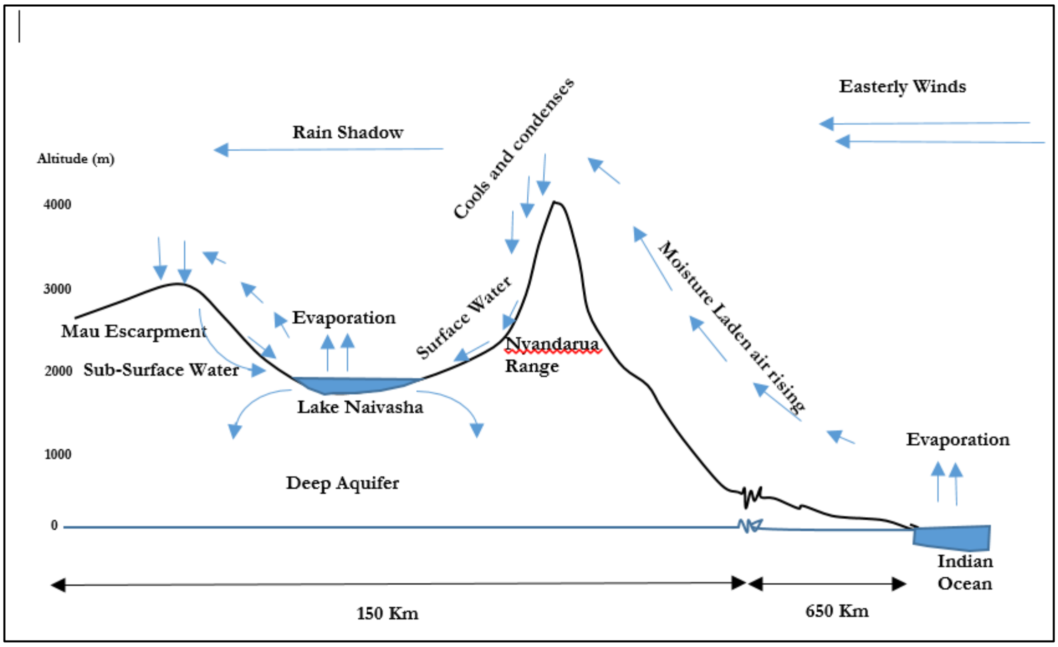


Figure 3: Hydrological cycle of the Lake Naivasha basin; Edited from (Everard & Harper, 2002)

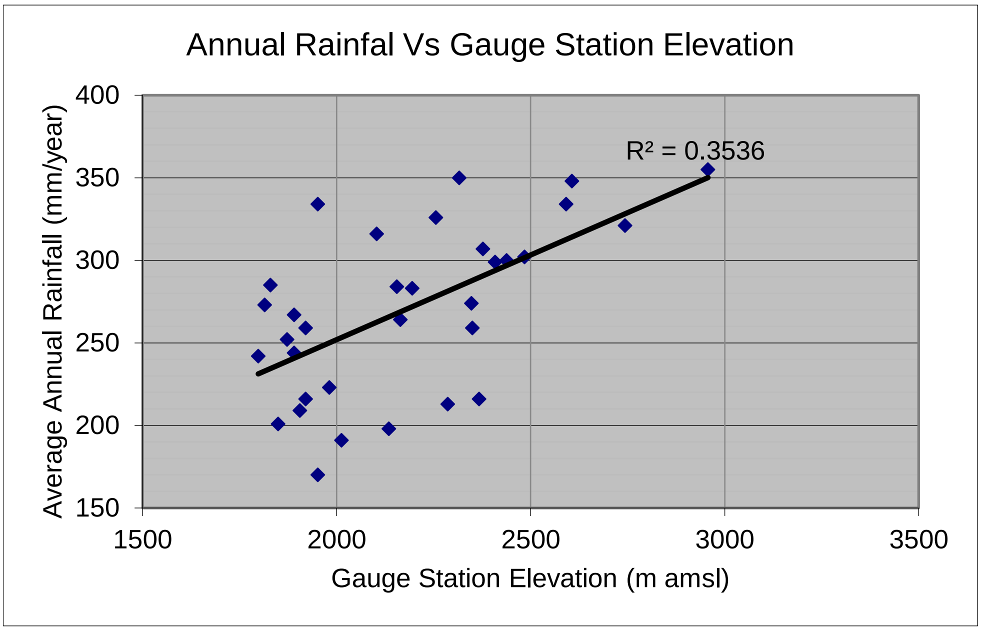


Figure 4: Graph showing the relationship of Rainfall and Altitude in the study area

2.4. Physiography and Land use

The topography of the Kenyan Rift is highly undulated. The elevation of the Rift floor is highest in the central segment between Lake Nakuru and Lake Naivasha where it is almost 2000 m amsl and decreases in northwards towards Lake Turkana (300 m amsl.) and southwards towards Lake Magadi (600 m amsl). Due to this considerable differences in altitude and landforms, there is a variation in the climate within the Rift Valley. The topography and cross-sections throughout the Rift Valley are showed in Figure 5

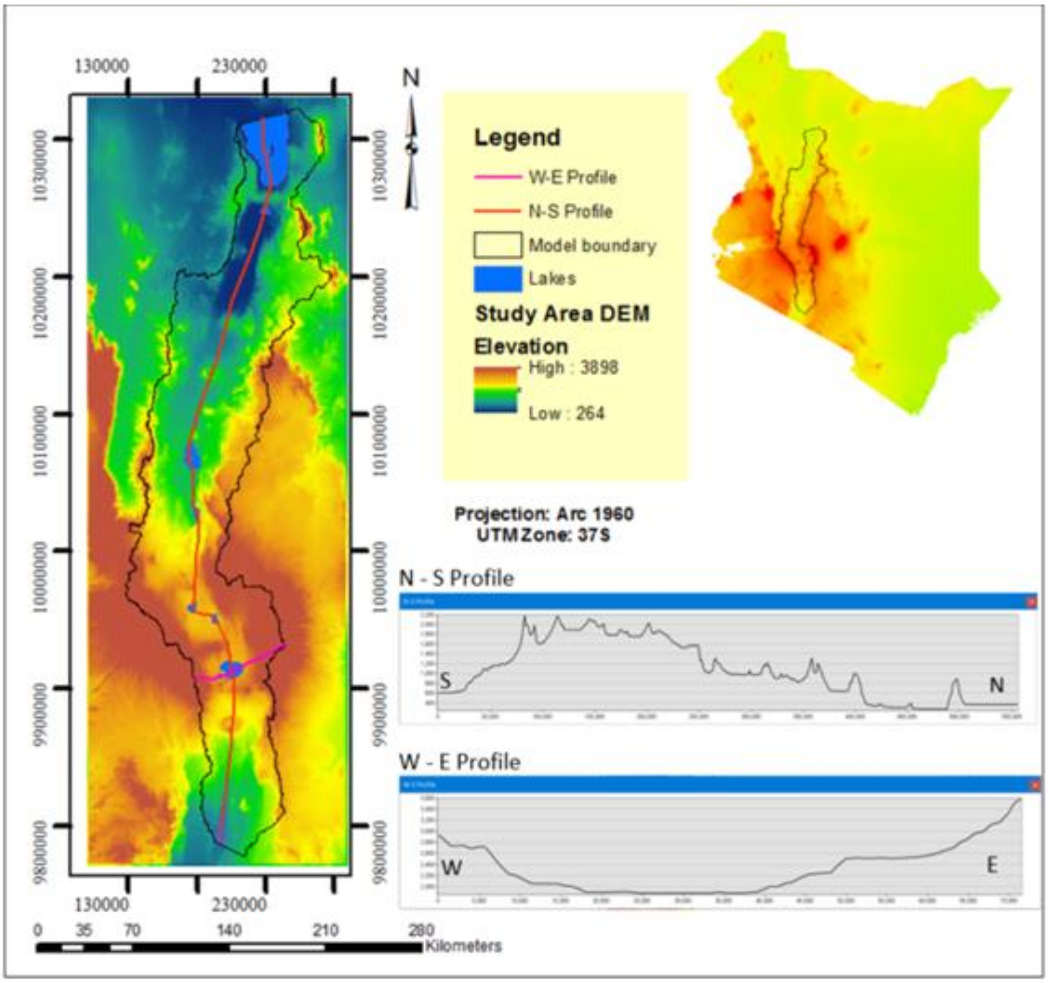


Figure 5: Map and cross-sections showing the highly undulating topography of the Kenyan Rift

Land cover in the low lying regions of the Kenya Rift Valley is primarily grasslands, bushlands with some acacia and cactus trees. These shrubs and grassland savanna are ideal habitat for wildlife and pastoralism. On the rain fed slopes, agriculture and irrigated crop farming is practiced. Important crops include; maize, beans, potatoes, vegetables, fruits, wheat among others. Harper et al., (1990) documented the presence of ephermal papyrus colonies covering Lake Naivasha shores and rafts of Salvinia molesta which cover some parts of the lake surface. But these vegetation do not thrive in Lake Nakuru and Elementeita due to highly saline waters. Commercial irrigation is also practiced around Lake Naivasha where flowers for export are grown.

It is worth noting that population densities are higher around townships than in rural areas. This means pavements and tarmacking and similar land cover types associated with urbanisation are restricted to very few townships.

2.5. Geology

The Kenyan Rift Valley (Gregory Rift) corresponds to the Kenyan dome and comprises a succession of late Quaternary and Tertiary volcanics but some areas have lacustrine sediments and alluvium of reworked volcanic debris. See Figure 6. The Rift Valley floor is obscured by the late Quaternary volcanic piles such as Longonot and Suswa, and by lower and middle Pleistocene sediments around Magadi and between Naivasha and Nakuru (Muno, 2002). The volcanic pile along the flanks of the Rift Valley is over 2000 m thick in places, and the succession in the Rift floor is considered to be significantly thicker than this, perhaps reaching 3000 to 4000 m (Baker, 1972). The lowest altitudes are recorded at the Turkana-Omo lows, with significantly lower (250 m asl) elevations and no pronounced rift shoulders.

The doming of the Ethiopian and the Kenyan domes preceded the Rifting in the EARS. This morphotectonic evolution contributed significantly to creating important orographic barriers and environmental changes(Lydia A. Olaka et al., 2010). Late Cenozoic tectonic activity in the EARS commenced with southward propagation of rifting with magmatic activity and gradual formation of faulted troughs in the entire rift, in which lakes have formed. The evolution of the Gregory Rift is marked by the initial formation of the full graben morphology between 12 and 3.7 Ma (Baker, 1972) and modifications caused by subsequent tectonic and three associated major volcanic events that caused the separation and closing up of the Nakuru-Elementeita and Naivasha basins: first, the Eburru volcano (2820 m asl) divided the two basins at ca. 400 kyr BP, next, the Olkaria volcanic complex (2440 m) closed the Naivasha basin to southwest at ca. 320 kyr BP and finally, the Menengai Caldera (2278 m) closed Nakuru-Elementeita basin to the north at ca. 180 kyr BP (Clerke, Woodhall, & Darling, 1990).Volcanic and tectonic activity is on-going.

Smith & Mosley, (1993) subdivided the Kenya Rift into segments he noted as overlaying the Precambrian basement. The topography of the basement is uncertain and is a subject of continuing geophysical research (Muno, 2002). Archean Basement gneisses are the oldest rocks which outcrop near the Nguruman Escarpment in the south-west (Baker, 1958). Younger volcanics overly the basement and Pliocene basalts. The composition of these younger volcanics include basalts, phonolites, trachytes and mugerarites at the Aberdare range and basalts, trachytes, phonolites and nephelinites at the Oloregesailie, Ol Esayeti and Ol Esakut volcanos. Other rock types in the study area include rhyolitic lavas and tuffs from numerous volcanic centres. It is very difficult for geologists to differentiate between air-fall pyroclastics and reworked sediments composed of pyroclastic material in some areas.

Lacustrine sediments are found in the vicinity of the Rift lakes these sedimentary deposits are basically thin layers of reworked volcanic debris in the study area. The Olorgasaile lakebeds comprises of diatomaceous clay of the middle Pleistocene while the Kedong Valley sediments are largely fine sand stones and clays forming conglomerates that are poorly sorted. At Magadi, there are evaporate deposition series while diatomaceous sediments of the upper middle Pleistocene age exist around lake Elementeita. But the most widespread sediments were deposited during Gamblian Pluvial period towards the end of the Pleistocene epoch (Muno, 2002). It is important to note that during the Gamblian Pluvial period, Lake Naivasha basin was joined with Lake Nakuru basin, when the respective levels were 122 m and 120 m higher than at present.

Linear feature manifestations include faults bisecting eruptive centres, aligned, volcanos and linear river sections (Strecker, Blisniuk, & Eisbacher, 1990). There are many faults that characterise the Rift Valley most of which are parallel or sub-parallel to the main rift axis. The Nguruman and Mau Escarpments in the west, and the Kikuyu, Nyandarua and Bahati Escarpments in the east form some of the major faults in the Kenyan Rift. The rift boundary in the south East is less well defined due to a succession of smaller escarpment faults with smaller faults between them. The geology of the study area is showed in Figure 6 below

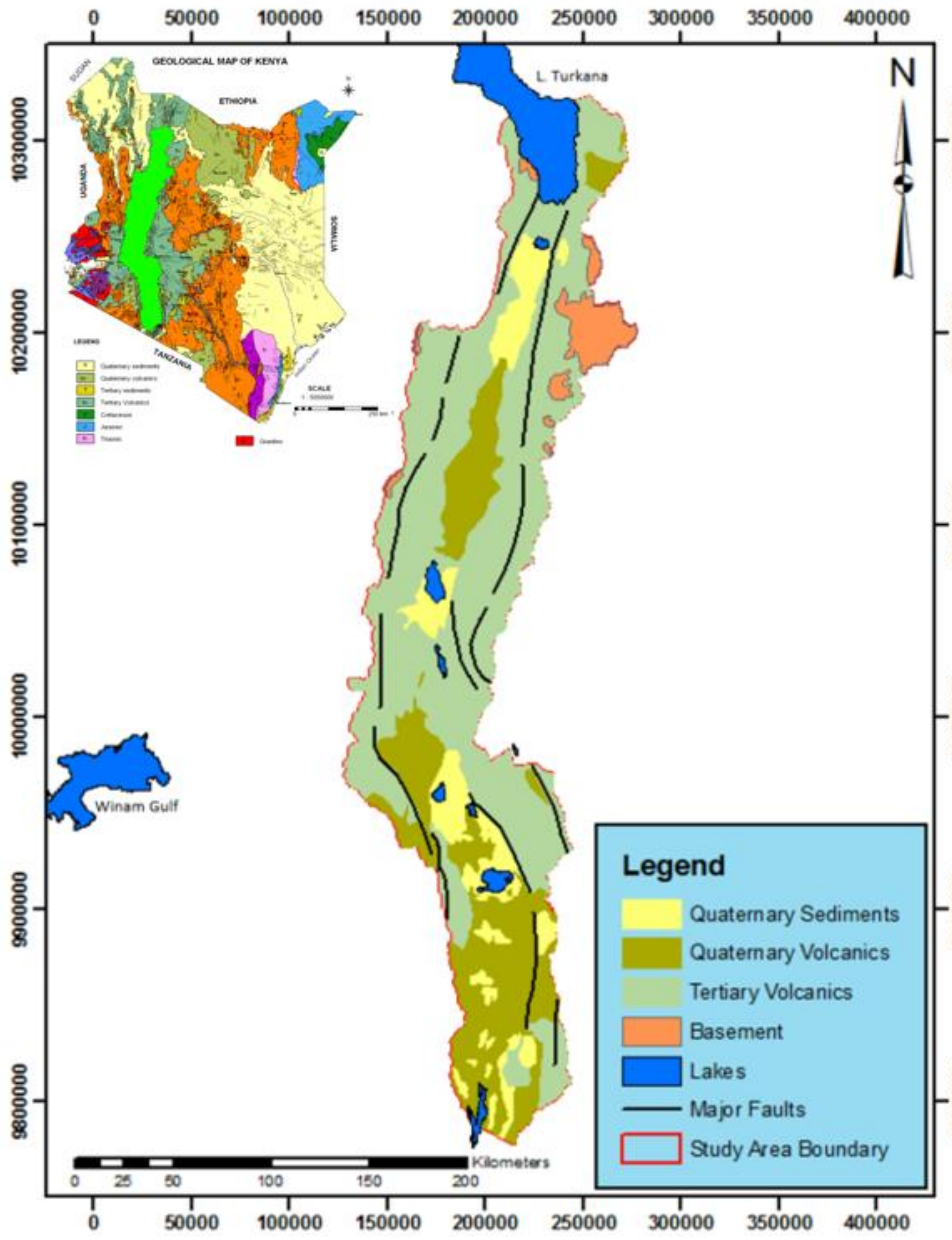


Figure 6: Geological Map of the study area in the Kenya Rift Valley

Satellite images from google earth show that linear structures representing fault lines appear to be continuous from the area around Lake Bogoria to the area around Lake Magadi except for the central rift where volcanic activity has covered and obliterated these linear manifestation. See Figure 7 and Figure 8. This information clearly shows that the expansive linear structures spanning from North to South were only interrupted in recent geologic time by younger volcanics. The structures can be used to infer the connection of groundwater flow in the rift valley

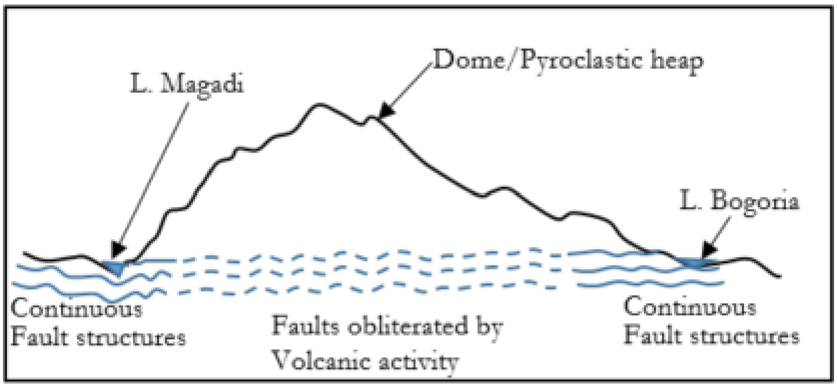
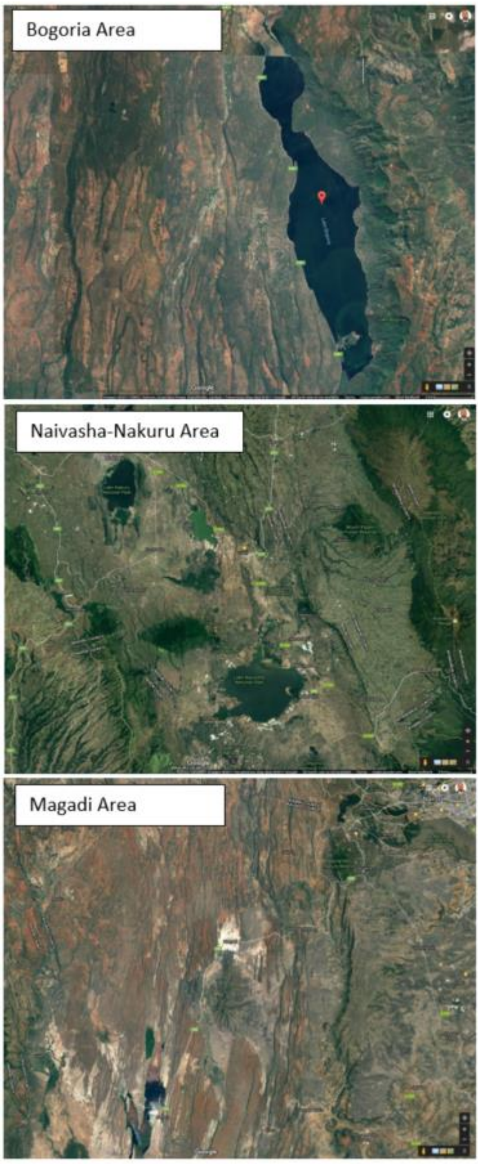


Figure 7: Figure showing a schematization of fault discontinuation in the central rift. See also Figure 8 below



North-South oriented linear structures clearly visible

North-South oriented linear structures are obliterated or covered by volcanic heap

North-South oriented linear structures clearly visible

Figure 8: Google Earth images showing discontinuation of linear structures due to interruption by younger Volcanics

2.6. Hydrogeology and Drainage

The hydrogeology of the study area is defined by aquifers within the volcanic and lacustrine deposits around the lakes where water tables range in depths from 1 m around lake Naivasha to about 250m on the flanks of the rift or on volcanoes (Clerke et al., 1990). Rift Valley aquifers are often confined or semi-confined and their storage coefficients are likely to be low. Areas covered by the lakes have aquifers with relatively high permeabilities. They are often unconfined and will have relatively high specific yields. Deeper aquifers recharge the geothermal reservoirs and maintain geothermal steam production by the geothermal company at Olkaria, Eburru and at Menengai. Shallower aquifers are ideally exploited for domestic use and irrigation as the cost of exploiting them is fairly manageable.

Each of the eight sub-catchments is unique in relation to the surface hydrology through the observed drainage patterns. Some of the major rivers in the study area include; Turasha, Gilgil, Malewa Mereroni Karaiandushi, Mbaruk, Njoro, Ngosur, Larmudiac, Nderit among others Figure 9 shows all the sub catchments defined by this study and the rivers that drain them

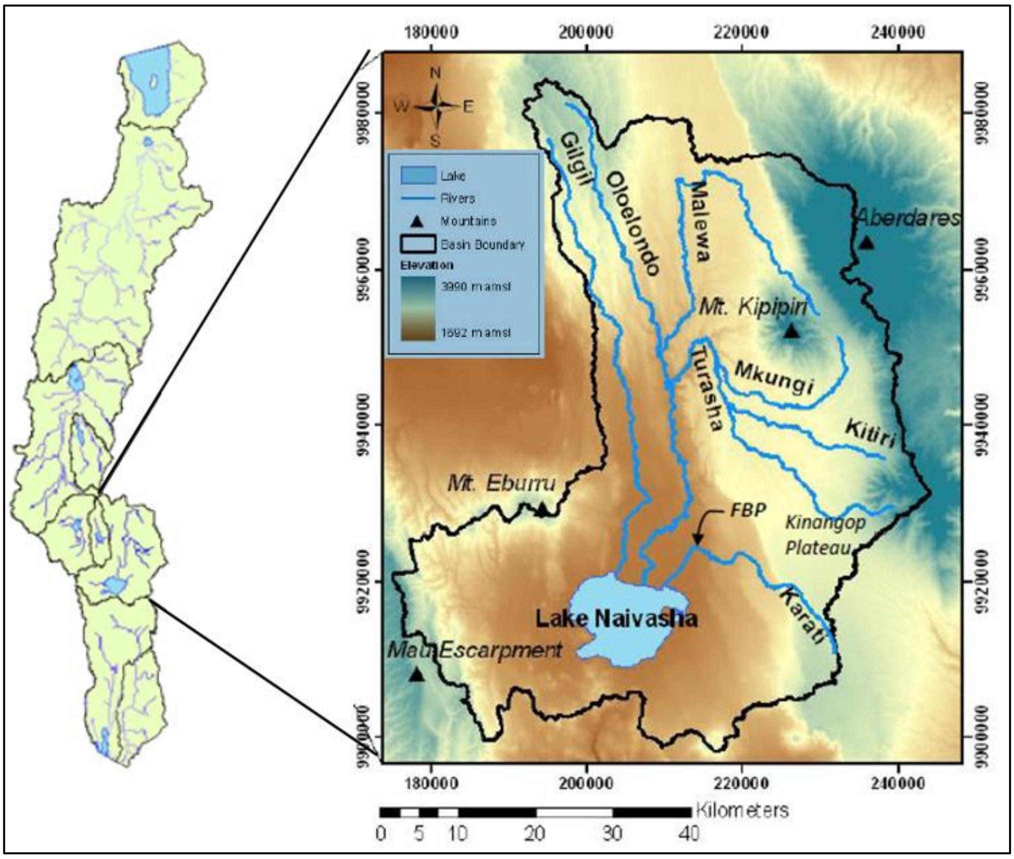
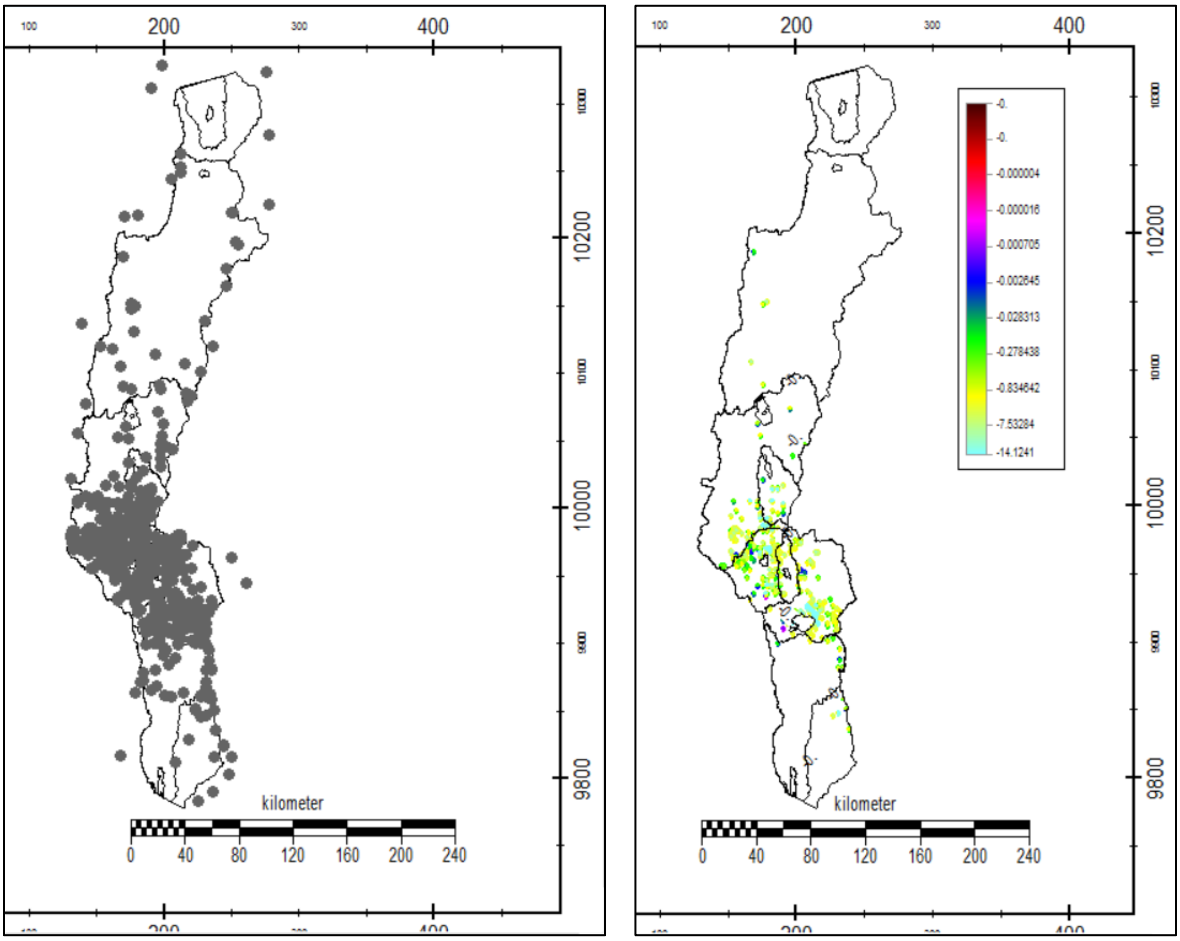


Figure 9: Lake Sub-catchments and the respective drainage patterns. Inset: Naivasha sub-catchment

There are 795 registered wells in the study area although the number could be higher since unregistered wells also exist. Information about these wells were acquired from the National Water Resource Management Authority of Kenya (WRMA) and the National Water Master Plan 2013. Borehole monitoring and borehole abstraction data is not properly kept. But tested borehole yields and transmissivities near the lakes are higher than further away (McCann, 1974). See Figure 2. The piezometric map in the central Kenya rift is showed in Figure 11 below. Using this map flow of groundwater from the flanks to the rift floor can be confirmed



Map A **Map B**

Figure 10: Map A showing locations of drilled boreholes and Map B showing tested yields of the wells from archived records

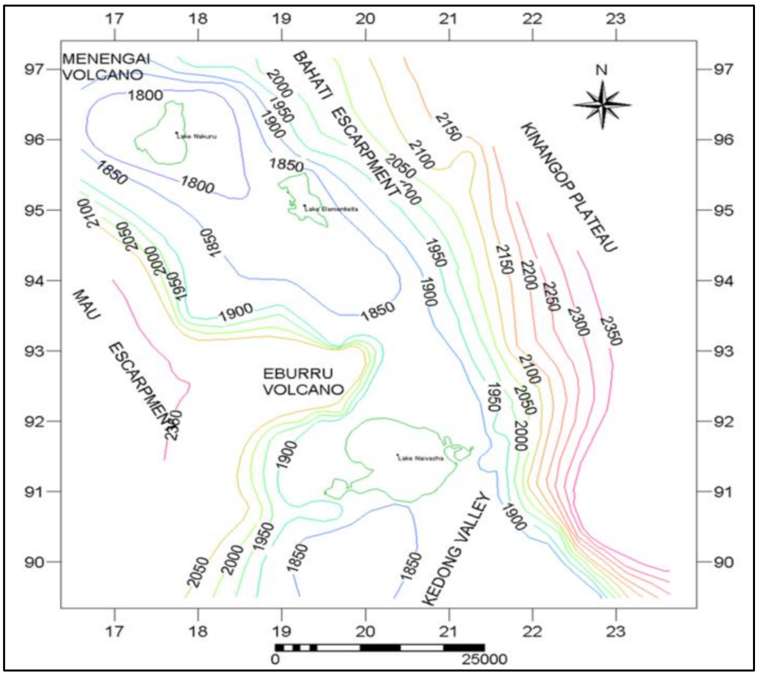


Figure 11: Piezometric Map of the Central Kenya Rift (Source: Muno, 2002)

2.7. Lake level fluctuations

There is a long history of lake level monitoring for some of the lakes. Records about Lake Naivasha Levels date back to 1900 for instance. Sikes, 1936 included some of these early records in his "Notes on the hydrology of Lake Naivasha". Although seasonal and annual water level fluctuation of lakes is a common phenomenon in every lake, long term averages can be used to characterize each lake and its response to stresses. Annual fluctuations are usually due to the differences between precipitation and evaporation at specific season. Historical lake levels for three lakes in the study area are showed in Figure 12 below. Virtually all the lake level data used in the study were historical and already digitally archived after reconstruction by (Mmbui, 1999).

The reconstructed lake are useful when plotted together as they allow us the opportunity to observe any trends with time. Consequently, the observed and reconstructed lake level series were inspected for evidence of significant abrupt and gradual trends.

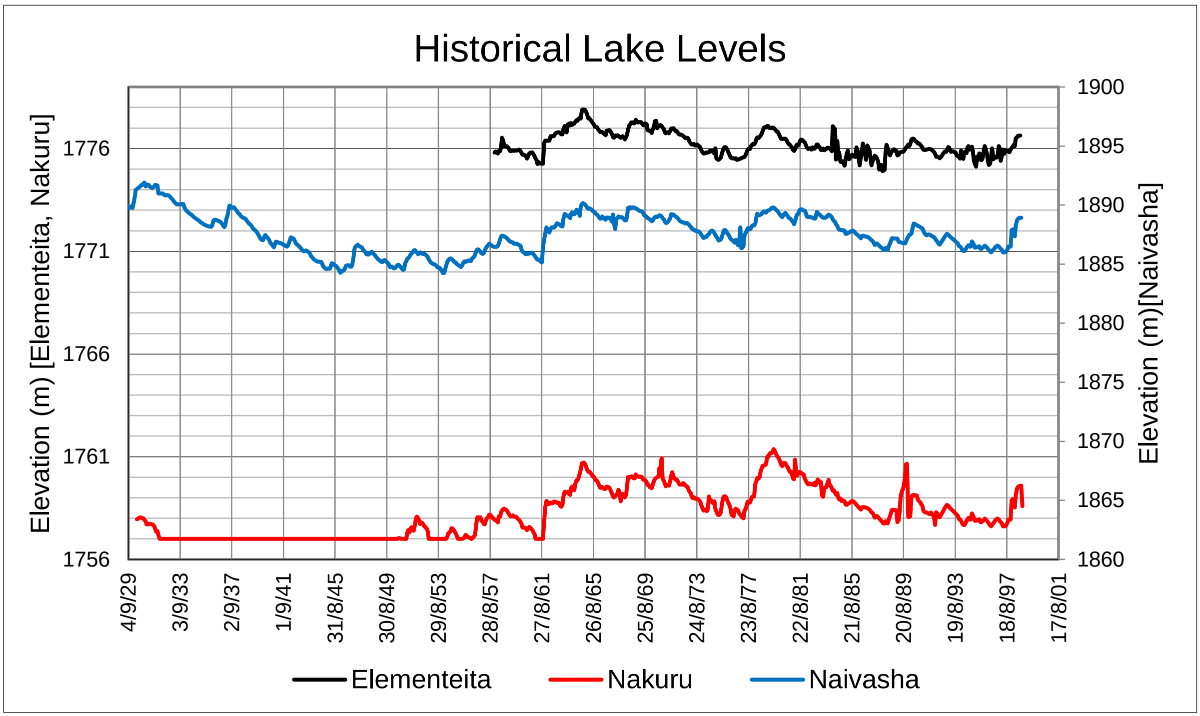


Figure 12: Graph showing reconstructed lake levels for Nakuru, Elementeita and Naivasha

3. METHODOLOGY

3.1. General Approach

In order to investigate the regional groundwater flow systems, the hydrological nature of the Kenya Rift Valley lakes and their morphological characteristics, long-term water balances and analysis of water level records must be assessed and modelled. Since lakes are arguably groundwater outcrops especially in their adjacent vicinity, the water level records of these eight Kenya Rift Valley lakes indicate their hydrological stability in terms of water level dynamics and their controlling factors to inform us on regional flows. All lakes were fundamentally treated similarly as terminal lakes in closed hydrological basins. Since the overall purpose is to investigate possible groundwater flow patterns in the Rift Valley, the need to carry out a detailed hydrogeological inquest into the inter-basin hydrological connectivity became critically important. Therefore the significance of the methods employed here is to answer the question 'how closed are closed-basin lakes in the Kenya Rift Valley?'

A multidisciplinary approach to properly simulate steady state conditions was developed to integrate geomorphological information, climatical data, hypsometry and bathymetry, time-series analysis, and modelling of all eight lake basins in the Kenyan Rift Valley. First, the inputs and outputs of every studied lake were estimated in order to derive the long term water balances based on characterising lake level regimes(Szesztay, 1974). The second approach as suggested by (Litinskaya, 1970) is based on lake geomorphology. The third approach is to analyse isotopic evidence using existing data from other studies. All these approaches will borrow a lot from digital terrain analysis, geologic information and remote sensing data during data processing.

Overaly, existing literature was reviewed extensively and more data was acquired through fieldwork then processed and integrated into usable file formats for the chosen Modelling code. Using Modflow 2005 in the iMOD environment, the model was set up and calibrated to observed lake levels and lake areas before using it to predict possible groundwater flow patterns. Figure 15 shows the schematization of the main stages involved in doing this research. These stages are discussed below

3.2. Literature Review

3.2.1. Regional Groundwater studies

Lake level and area variations are sensitive to regional climate changes and can be used to indirectly estimate water balances of lakes(Zhang, Xie, Yao, & Kang, 2013). Ten of the greatest lakes in China were studied for changes in lake level and area derived from satellite data (ICESat and Landsat) recorded between 2003 and 2009. Results showed a strong correlation of lake level and lake area in six lakes and weak only in one. Characterization of Water Level Variability of the Main Ethiopian Rift Valley Lakes(Belete, Diekkrüger, & Roehrig, 2016) is another similar regional study where the geomorphology and water balances of many lakes were extensively used

Other regional groundwater modelling approaches related to this study include the Groundwater modelling for the Mekong Delta, Vietnam using iMOD. iMOD stands for Interactive MODelling and facilitates an easy-to-use modelling environment to engage stakeholders and stimulate participation in active groundwater management(P. Vermeulen, Hong, Dinh, & Nam, 2013). iMOD compared to conventional modelling tools, allows generic geo-referenced datasets and images that may contain files with unequal resolutions and that can be used to generate sub-models at different scales and resolutions applying up- and downscaling concepts(P. Vermeulen et al., 2013). Also, due to the computational limitations of the CPU memory to handle large numerical MODFLOW-grids of regional models, a model builder is often made choose between (1) building a model for a large area with a coarse grid resolution or (2) build a model for a small area with a fine grid resolution but iMOD easily resolves resolutions internally and provide results in the finest scale available of the sub model. This advantage using iMOD is becomes powerful in this study since available data for the catchment vary in resolution and spatial extent within the model domain area. Lastly, iMOD has a powerful Pathline simulation capability.

3.2.2. Existing Models

Many hydrogeological models exist and have been used in different studies to produce fairly reliable results. Some models used are lumped (empirical or conceptual) while others are distributed(H. V. Gupta, Sorooshian, & Yapo, 1998). Distributed models are more useful compared to lumped models(Muleta & Nicklow, 2005) as they take into account the heterogeneity of environmental factors such as topographic features, land use, soil type and weather parameters. A given modelling protocol is adopted to provide guidance that promotes realistic groundwater conditions. (Anderson & Woessner, 1992) argues that a modelling protocol includes code selection, model design, calibration, sensitivity analysis and prediction. Table 1 shows details of some modelling protocols that have been attempted for the lake Naivasha sub catchment

Table 1: Overview characteristics of existing models for the Naivasha sub-catchment.

	Van Oel et al. (2013)	**Owor (2000)**	**Yihdego (2005) (Yihdego and Becht, 2013)**	**Legese Reta (2011)**
Type of model	Water balance	Groundwater	Groundwater	Groundwater
Computer code	MS Excel	PMWIN + MODFLOW	GMS + MODFLOW	GMS + MODFLOW
Spatial scale	Lumped	500 grid	500 grid	500 grid
Conceptual layering	Lumped (groundwater cascade)	50 unconfined 10 confined	3 layers of varying thickness	60 unconfined 100 confined
Lake representation	Lumped (lake cascade)	Lake Package	'High K' method	Lake TINs
Calibration	Manual Curve fitting	First manual, then PEST on steady-state model	PEST on steady-state model	PEST on steady-state model
Calibration parameters	Hydraulic conductance of aquifer	Hydraulic conductivities of zones, recharge	Hydraulic conductivities of zones	Hydraulic conductivities of zones
Validation	None, curve fitting only	None, sensitivity analysis only	None, sensitivity analysis only and checking for water balance closure	None, sensitivity analysis only
Performance (95% confidence interval)	0.5	0.5	n/a, steady state only	n/a, not given

Most of the existing models in the study area are both transient and steady state focusing on Lake Naivasha and its interaction with regional groundwater. Muno, 2002 modelled four lakes in the central Kenya Rift; Magadi, Naivasha, Elementeita and Nakuru using spreadsheets. Few other researcher modelled the relationship of Lake Naivasha and Elementeita. A summary of findings from these modelling attempts are given in Table 2 below

Table 2: Summary of findings from previous studies for Lake Naivasha catchment. Source:(Reta, 2011)

Parameters	Author	Estimated Values
Evapotranspiration	Ase, 1986	1865 mm/year
Aquifer transmissivity	Hermandez, 1999	1-500 m^2/day
Storage Volumes	Owor, 2000	6.9 MCM/month
Aquifer storativity	Hermandez, 1999	0.1-0.15
Lake water outflow	Sikes, 1936	43 MCM/year
	Ase, 1986	46-56 MCM/year
	Clerke A., D. Allen, 1990	50 MCM/year
	Mmbui, 1999	50 MCM/year
	Becht & Harper,2002	50 MCM/year
Lake water inflow	Viak, 1975	1.8 MCM/year
	Owor, 2000	2.64 MCM/year
Abstraction (Lake and Aquifer)	Goldson, 1993	43 MCM/year
	Hermandez, 1999	6 MCM/year
	Owor, 2000	6-9 MCM/year
	Kibona 2000	5.1 MCM/year

3.2.3. Water Balance Assessments

The balancing of a water budget in space and time is very necessary in hydrological modelling(S. K. (Sushil K. Gupta, 2011). Most water models use a water balance approach involving changes in water fluxes; the difference between input and output over the surface area. The water balance has not only helped to understand water fluxes but also the relationship between climate, hydrological cycle and water resources(S. I. Khan et al., 2010). For simulating pathlines, the water balance model for the watersheds of the lake systems are first calculated under a GIS environment(Singh, 2016). The mass balance equation can be used to derive possible subsurface outflow of groundwater from lakes whose outlets are not known (Becht, Mwango, & Muno, 2006). The areas over which processes related to the water balance occur may range from several meters to thousands of square kilometres making it an ideal strategy for regional studies.

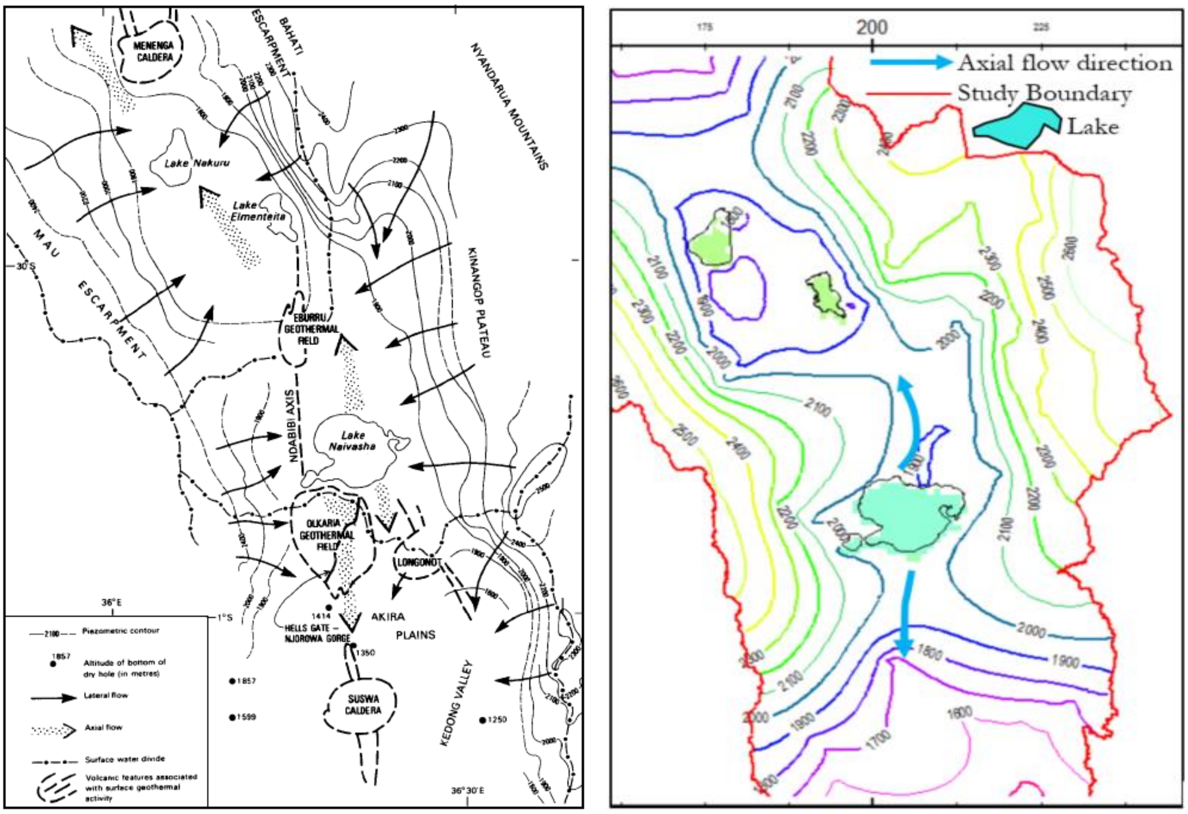
Several studies have been undertaken to derive water balances of some individual lakes. Sikes in 1936 made the first attempt to statistically estimate monthly and annual water budgets for Lake Naivasha which is one of the sub-catchments of this current study. His methods were not well documented but he estimated that water was seeping out of the lake at the rate of 43 mcm/year. Clerke, Woodhall, & Darling, (1990) used two methods to determine water flow by 1) water balance and 2) application of Darcy's law of groundwater flow. They estimated that 50 MCM/year flow out of Naivasha catchment which represents 20% of total recharge.

3.2.4. Observed Groundwater Flow Patterns

The freshness of Lake Naivasha had puzzled scientists who knew the Rift Valley lakes. It is recorded that Thompson of the Royal Geographical Society of England concluded that the freshness of the lake water and attributed it to being either of recent origin or the lake having an underground channel (LNROA, 1993). Many studies have concluded that Lake Naivasha is a critical source while others are sinks or not directly connected to the flow from Naivasha. Gregory (1992) suspected that the freshness of Lake Naivasha was due to undiscovered groundwater outlet.

Equally interesting is the assertion by Nilsson (1938) that the freshness of the lake resulted in water entering and leaving the lake by underground seepage. But based on lake water chemistry, Gaudet and Melack (1981) concluded that there is a subsurface outflow from Lake Naivasha. But with regard to flow directions, (Ojiambo, Poreda, & Lyons, 1992) concluded from piezometric surfaces that the subsurface outflow from Lake Naivasha emanates from the southern shores of the lake, and then flows southerly and south-westerly toward Olkaria Geothermal complex. (Ojiambo et al., 1992) also concluded that the main lake outflow fluxes ranges from 18 and 50 mcm/yr.

Other studies have found that water flows out of the lake Naivasha to the North via Gilgil and under Eburru volcanic centre. The studies also have predicted a southerly flow following the hydraulic gradient towards Lake Magadi, but no evidence at all suggests that the water ever reaches the lake. Conclusively, it appears from all studies that groundwater flows on either side along the rift ridge axis from lake Naivasha. The estimated amount contributed to groundwater flow by the Lake Naivasha is 50 to 60 mcm/yr(Becht et al., 2006). As indicated in Figure 13 below, the groundwater flow has two flow patterns; lateral flow pattern and axial flow pattern.



Map A **Map B**

Figure 13: Map A showing piezometric map of the CKR(Source; Yihdego & Becht, 2013) and Map B showing modelled equipotential lines depicting axial flow gradients and possible flow directions.

3.2.5. Geomorphological setting of the Rift Valley Lakes

The East Africa Rift System is a classical example of continental rifting with similarities to mid ocean rift systems. The rift extends from the Afar triple junction through the Ethiopian highlands, Kenya, Tanzania and Malawi to Mozambique in the south(Omenda, 2005). Important to note is that the Kenyan (Gregory) Rift corresponds to the Kenyan dome. The Rift Valley floor is highest in the central portion between Lake Nakuru and Lake Naivasha where it is almost 2000 m asl and decreases in elevation northwards towards Lake Turkana (300 m asl.) and southwards towards Lake Magadi (600 m asl)(Muno, 2002).

Basic morphometric features such as volume, surface area, and mean depth, as well as information related to hypsographic curves, are increasingly being used to describe limnological changes that occur as lake volume changes (Lydia Atieno Olaka, 2011). These bathymetric and hypsometric characteristics are crucial in understanding the hydrology within the Rift Valley. Rift valley lakes at high elevations like Naivasha and Awassa in Ethiopia are both characteristically fresh closed basin lakes meaning they discharge water into the ground. See Figure 14 below.

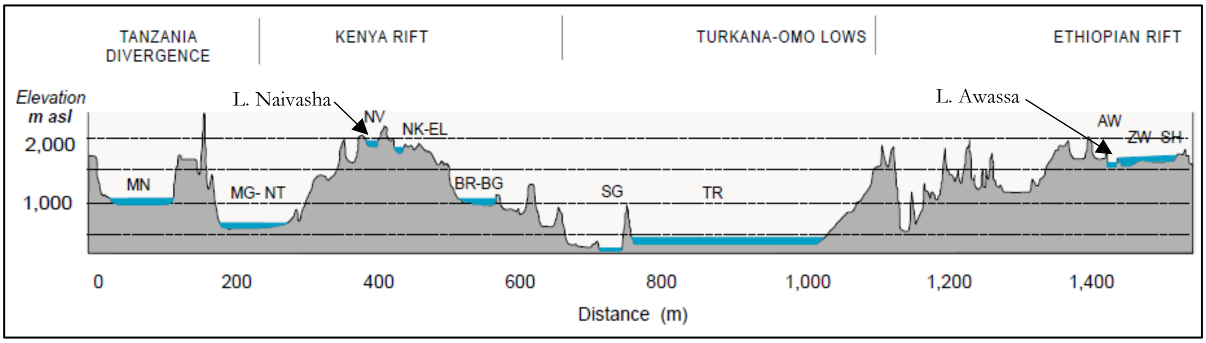


Figure 14: Topographic section through rift valley lakes from Ethiopia to Tanzania. Awassa and Naivasha are fresh(Source: Lydia Atieno Olaka, 2011)

3.2.6. Isotope chemistry information

Darling et.al (1990) and others were able to determine the direction, quantity and character of the underground flows in and out of Lake Naivasha. They used stable isotopic composition of the fumaroles steam from volcanic centres in the areas to infer groundwater composition. Using simple modelling methods they were able to trace the outflow from the lake up to 30km south. Lake water has been detected in Olkaria steam. The work confirmed that of Allen (1989) that most of the water leaving the lake exits in-between Olkaria and Longonot, while a smaller portion flows northwards between Eburru and Gilgil. Their estimates of the outflow agreed broadly with the earlier researchers like Sikes, McCann and Ase.

Water quality is equally important. Due to the saline nature of the rift valley lakes, there have been fewer studies about the hydrogeology of the area on a regional scale. Many researchers and their financiers prefer to put their money in fresh water resources. With the exception of Lake Naivasha and Lake Baringo, all the other six lakes covered by this study are saline to hypersaline in nature.

3.2.7. Satellite data for hydrologic modelling

Satellite data is crucial in hydrogeological modelling. Khan et al., 2011 emphasizes the need to undertake modelling studies involving accurate spatial and temporal information on climatological and hydrological variables. Many other scientists have advocated for the usefulness of remote sensing data for hydrological modelling siting a number of advantages. Gupta, 2011 and Montzka et al., 2008 have argued the following advantages; 1) reliable geospatial data, 2) availability of data even for remote areas, 3) ability to save time and energy, 4) good spatial and temporal resolution and 5) cost effectiveness.

Remote sensing techniques discussed in this study are based on the interaction of matter and the electromagnetic radiation. The images derived can then be interpreted using a variety of techniques although dedicated computer programmes are most ideal. Many aspects of hydrology and hydrogeology that may be mapped include soil, geomorphological units, land cover, slope, vegetation, drainage patterns, water bodies like lakes, lineaments, geological structures and man-made structures

The development of satellite observed precipitation and potential evapotranspiration (PET) for instance, has helped to overcome the challenges of temporal and spatial resolution of rainfall events as well as spatial coverage of the same phenomena(You, Liu, Wang, & Cao, 2011). Other remote sensing products like the digital elevation models (DEM) are important in delineating geomorphological features and catchment basins. Moreover, satellite acquired data are indispensable in retrieving land uses within the catchments and vegetation regeneration at various stages.

The variation in the volume of lakes can be calculated through water inputs such as groundwater recharge, precipitation over the lake and river inflow and outputs such as groundwater seepage, river outflow and evaporation from the lake. But direct measurement of these parameters at hydrological stations is usually difficult. Remote sensing has proved to be a powerful and efficient tool for monitoring these lakes(Zhang et al., 2013).

3.3. Data Acquisition

3.3.1. Pre Fieldwork

Literature review preceded data collection which was undertaken through fieldwork in September 2016. Data collection was not only through the fieldwork but also by retrieving from previous works by other scientists. Previous studies indicated that there exists many boreholes in the CKR and that this record is kept by the National Water Resource Management Authority of Kenya (WRMA). I looked at some existing borehole information in the databases and saw the record includes well depth and yield, depth to water table, casing length, water strike levels and water rest levels, well use and location. Using this information, estimating groundwater heads, transmissivities and other hydrogeological variables was possible. A review of existing maps, reports and notable publications by respected scientists was done during this desk study

3.3.2. Fieldwork

To achieve the objectives of this study, necessary primary as well as secondary data had to be collected and analysed. The Water Resources Management Authority- Nakuru, Kenya Electricity Generating Company- Naivasha, Kenya Meteorological Department-Nairobi and Ministry of water Development are some of the organisations that were visited to retrieve data. A visit to three of the study lakes and some of their rivers was done to check the gauges, verify general hydrology and confirm GPS coordinates.

Fieldwork was done in Kenya for three weeks of from 6th – 26th September 2016. Some of the data sets that were retrieved include; water abstractions from surface and groundwater sources, Precipitation data, Bathymetric data of the lakes, other meteorological data, remote sensing data and GPS survey data. Verification of some of the data collected was done during the fieldwork

3.3.3. Post Fieldwork

After the fieldwork, the collected data was checked for consistency with information from previous studies. Also, the data was analysed to see possibility of data gaps and whether indeed the collected data sets were adequate for the scope of this study.

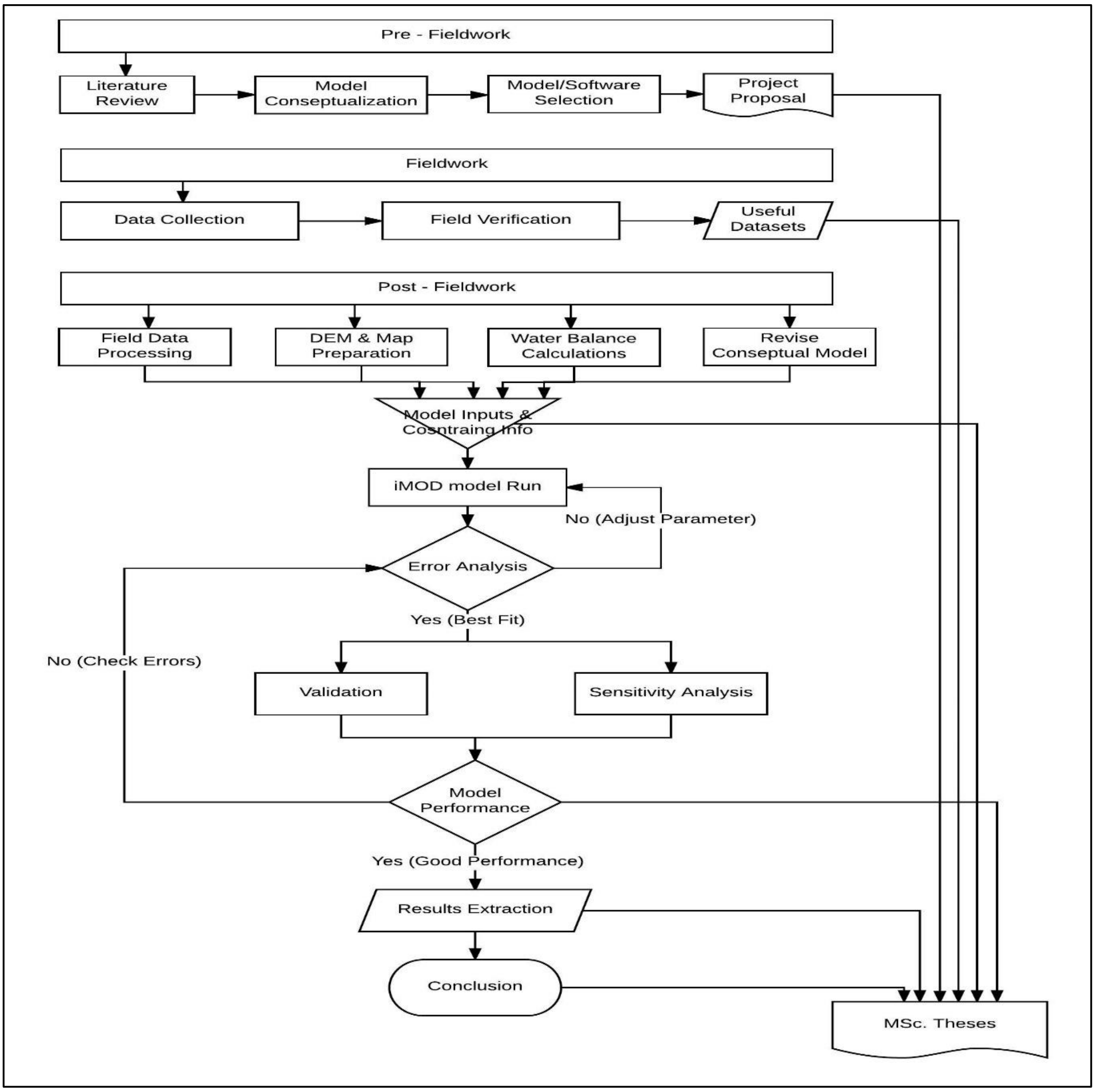


Figure 15: Schematization of the Data collection and modelling process

3.4. Data Processing

In order to properly simulate hydrological phenomena, modelling approaches employ a large variety of data from different information sources. The lake package LAK 7 under the iMOD environment requires four key hydrological variables as inputs required. These are namely; precipitation on the lake surface, evaporation from the lake, runoff from the catchment flowing into the lake and withdrawal/abstraction volumes from the lake for anthropogenic use. Other datasets that required processing for this research include; lake levels, geology, bathymetry, hypsometry, aquifer thicknesses and geometry, faults and lineation orientations, observations from borehole networks and aquifer characterization. Information about these variables was treated as insitu ground measurements or remote sensing measurements and for either case was processed into a usable form for the model. Data currency was adopted in order to enable simulation using more recent data.

3.4.1. Processing of Ground Measurements

Data processing was conducted to deal with gaps/missing data, errors, outliers, statistical analysis, interpolation, extrapolation and use of data cleaning methods. The adopted model environment has a GIS capability that was used to process all raster files required to run the model. iMOD also has processing capabilities that were useful in generating bathymetry files for all lakes as shown in Figure 16. ILWIS and spreadsheets were other tools that were used in data processing

Since iMOD uses IDF files (iMOD Grid Files), all images required were converted into IDFs. See Figure 26. Precipitation and potential evaporation were prepared from satellite products and are discussed in section 3.4.2 below. Other maps were prepared in various GIS environments and analysed to be used during modelling. The DEM was imported into iMOD as an ASCII file.

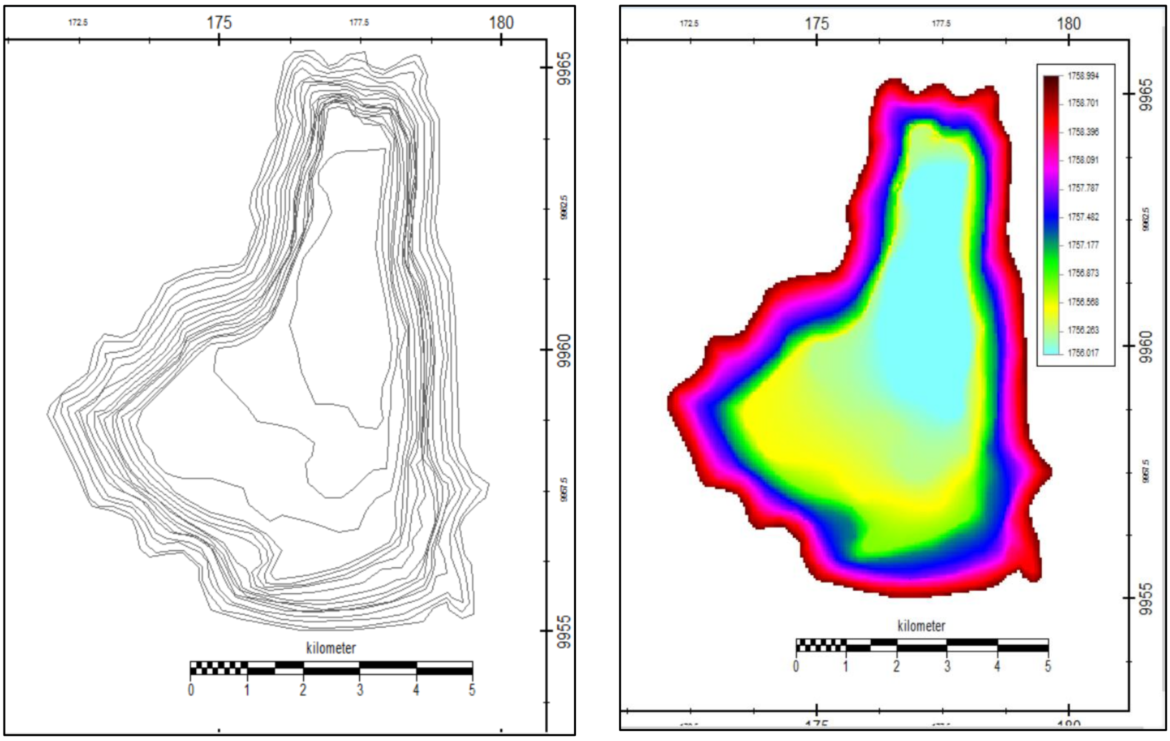


Figure 16: Sketch of Lake Nakuru's bathymetry and how it was interpolated into an IDF

3.4.2. Runoff Estimation

Runoff was estimated using the runoff coefficient method. The coefficient normally ranges between 0.1 and 0.5(Will, Klaus. Siegert, & Chapman, 1991). The fact that the threshold rainfall has first to be surpassed explains why not every rainstorm produces runoff (Fink et al. 1979). This is important to know when assessing the annual runoff-coefficient of a catchment area. Under natural conditions the runoff threshold amounts to a few millimeters for crusted soils in low intensity rainfall areas. In Turkana, (Finkel 1987) no runoff is produced at rainfall below 10 mm and in Baringo 8 mm was said to be required to produce runoff (MoALD 1984). See Figure 17 below. With reference to the study 'Hydrology Across Scales: Sensitivity of East African Lakes to Climate Changes (Lydia Atieno Olaka, 2011),I used the established geomorphological ratios and indices to further refine the runoff estimates in each sub-catchment. This approach follows a recent study on Hypsometric control on surface and subsurface runoff (Vivoni, Di Benedetto, Grimaldi, & Eltahir, 2008)

It was assumed for this study that lake withdrawal volumes for anthropogenic use was infinitesimal to affect the equilibrium of the regional model. Secondly, the withdrawal if any will occur only in the two fresh water lakes and not have a significant effect on the regional model dynamics

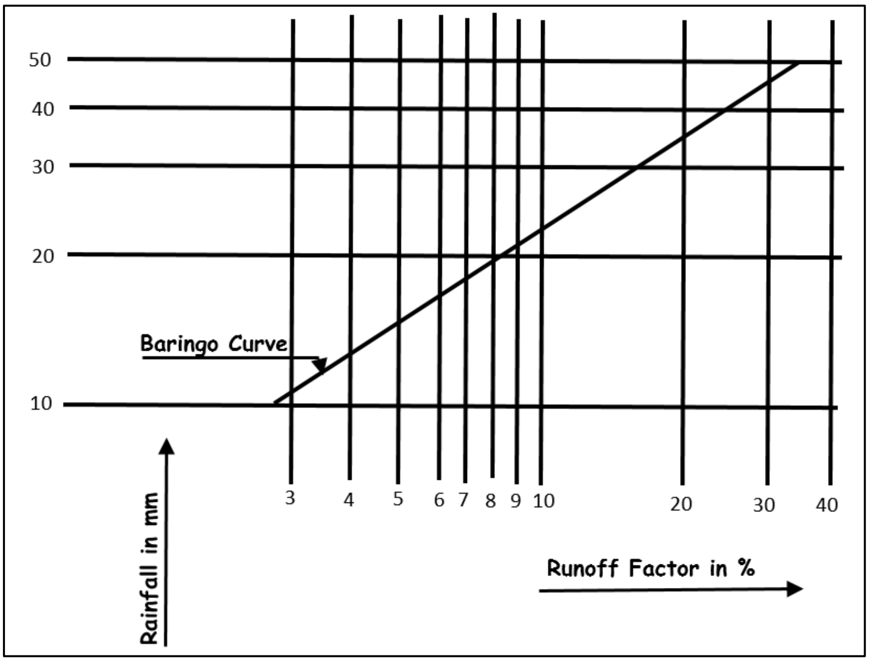


Figure 17: Rainfall-Runoff relationship in the Baringo Sub-catchment. (Source: Finkel 1987)

3.4.3. Processing of Remote Sensing Data

The use of modern remote sensing systems provided a detailed, up-to-date information for hydro-meteorological data enabling a full potential for the investigation of water balances through modelling. Earth observation products (digital elevation model (DEM) and climatological data) were processed in various GIS environments. Although climatological measurements by conventional weather stations provide relatively accurate estimates especially near the station location, insitu measurements were not adopted for this study due to relatively low weather station density in the study area. In the absence of reliable insitu measurements, rainfall and evaporation by remote sensing becomes an indispensable approach since rainfall in the study area is highly variable in space and time.

Satellite time series data on rainfall estimates (RFE) and potential evapotranspiration (PET) were acquired from the Famine Early Warning System Network (FEWSNET) of the United States Geological Survey (USGS) from January 2010 to December 2014. The USGS Data Portal provides access to geo-spatial data, satellite image products, and derived data products in support of FEWS NET drought monitoring efforts throughout the world.(USGS, n.d.) PET are estimates of climate parameter data that is extracted from the Global Data Assimilation System (GDAS) analysis fields(S. I. Khan et al., 2010).

Long term distribution of satellite rainfall estimates and potential evapotranspiration in 5 years (2010-2014) from FEWSNET were analysed. The data was downloaded on daily basis and used to observe intra-seasonal rainfall variability of all eight lake basins for the same period. . The aim was to understand the precipitation disparities observed per season and per sub-catchment. Appendix 2 illustrates these rainfall patterns. The sources of the satellite products that were used in this study are given in Table 3 below.

In total, 1826 images of RFE and 1826 images of potential evapotranspiration (PET) were downloaded, resampled and masked to match the size and resolution of the model input files. Further, the estimates derived were averaged on a monthly basis for all the five years. Using map statistics in GIS environment, the long term averages of RFE and PET were computed and rasterized as shown in Figure 18 below. Satellite rainfall distribution is illustrated in Figure 27.

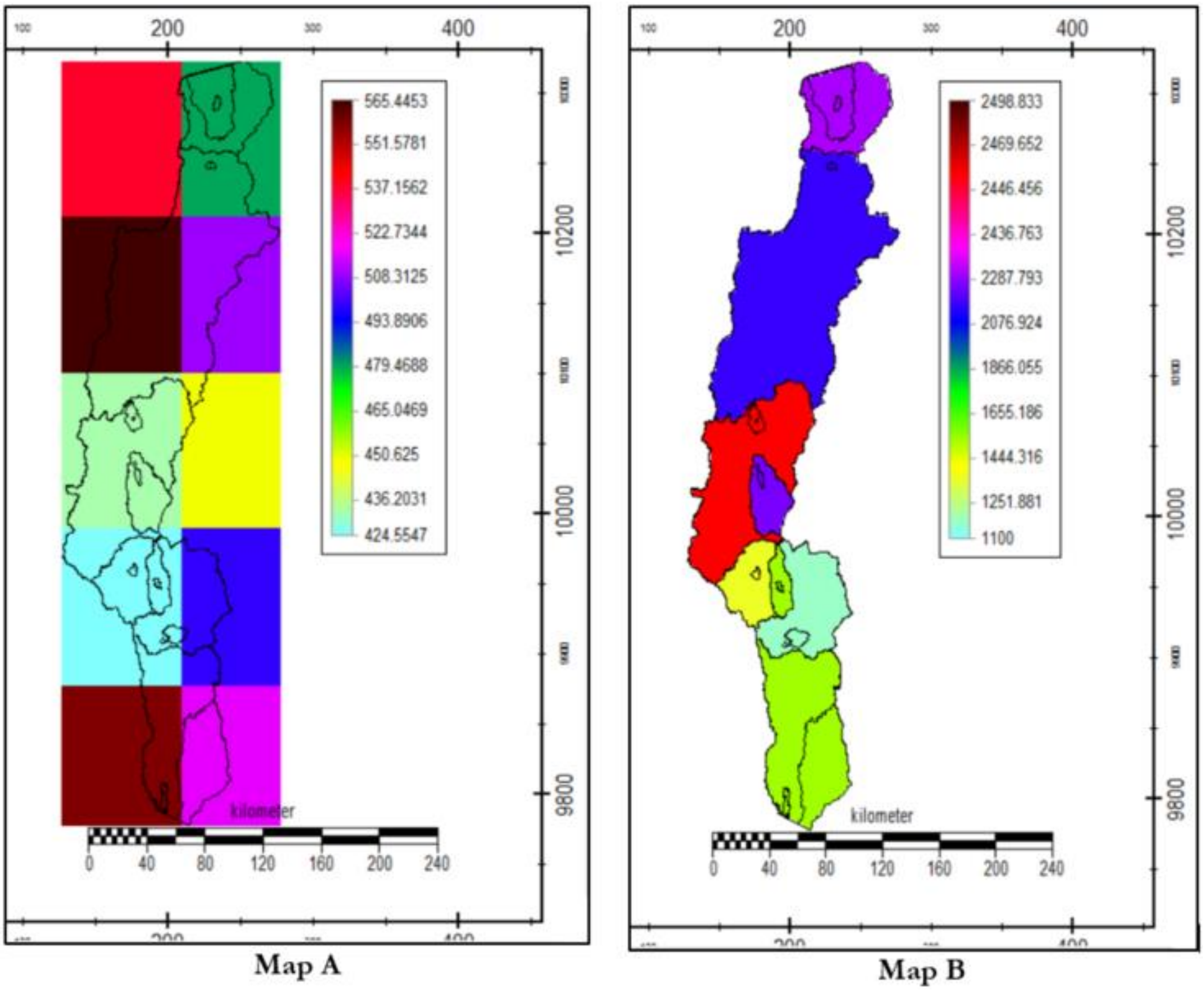


Figure 18: Map A showing a sample of PET Satellite product and how it was averaged to long–term average estimates per sub-catchment in Map B

Table 3: Sources of Satellite data used in the study

DATA	**SOURCE**
FEWSNET RFE	http://earlywarning.usgs.gov/fews/datadownloads/Continental%20Africa/Dekadal%20RFE
FEWSNET PET	http://earlywarning.usgs.gov/fews/datadownloads/Continental%20Africa/Dekadal%20PET
SRTM DEM	https://earthexplorer.usgs.gov

In order to prepare the input data files for the model, the use of ILWIS, ArcGIS, iMOD and other geographic information systems and internet-based tools were combined to provide support for (1) delineation, parameterization and characterization of the basin; (2) pre-processing of data; (3) set-up and calibration of model; and (4) visualization and analysis of model results.

3.5. Research Methods

3.5.1. Water Balance Approach

The knowledge of water balance of lakes and reservoirs is an essential component of water management(Singh, 2016). Simple calculations of the water balance components using individual lake parameters can be used to assess a lake's interaction with regional groundwater system. See Figure 19. Changes in lake volume may be calculated through differences in water inputs such as; precipitation over the lake, river inflow, groundwater recharge and outputs such as; evaporation from the lake, river outflow, and groundwater seepage. However, direct measurement of these parameters at hydrological stations is usually difficult (Zhang et al., 2013). Also, absolute groundwater inflow and outflow cannot be distinguished because only the net flow is computed(Muno, 2002). Water balance components for all lakes were systematically examined and results integrated into the regional hydrologic balance.

Input and output components of a water balance of any lake or reservoir always depends on the physical dimension of the water body and also on the climatic, hydrological and geological factors affecting the water body and its surrounding areas(Singh, 2016). Equating Inflow to Outflow is the basis of water balance estimations. Szesztay,(1974) suggested that inflow factors, outflow factors and the aridity factors are critical in classifying lakes according to their hydro-climatic characteristics. The general water balance equation for a lake can be written based on the mass conservation law as in the equation below.

$$\Delta V = P - E + SW_{in} - SW_{out} + GW_{in} - GW_{out} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq 1}$$

Where P is precipitation on the lake, E is lake evaporation, SW_{in} & SW_{out} are surface water inflows and outflows respectively, GW_{in} & GW_{out}, are the inflows and the outflows of groundwater, respectively, ΔV is the change in the amount of water stored in the lake during the simulation period.

Using the equilibrium area of the given lake, Eq 1 above can be rewritten to solve for the quantification of the interaction between the lake and groundwater. Based on Eq 2 below, it is observed that for Lake Naivasha, volumetric inputs into Lake Naivasha outweigh volumetric losses in terms of evaporation. The difference in the two is discharge to groundwater which is estimated at 50MCM/year. Similarly, due to the large surface area to volume ratio of lake Elementeita that is exposed to evaporation, the lake would have already dried up if not for the groundwater inflow. But this method can only work for lake basins where PET and Actual ET have been distinguished numerically. Appendix 4 tabulates some data that may be used in this approach.

$$A_B(P_B - E_B) = A_L(P_L - E_L) + Q_g \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq 2}$$

Where; $\mathbf{A_B}$ is the area of the Basin, $\mathbf{P_B}$ precipitation falling in the basin, $\mathbf{E_B}$ actual evaporation from the basin, $\mathbf{A_L}$ equilibrium area of the lake, $\mathbf{P_L}$ Precipitation on the lake, $\mathbf{E_L}$ Evaporation from the lake and $\mathbf{Q_g}$ is the net groundwater flux

In iMOD, the calculations are not simple because they take many factors into consideration as explained in section **4.4.1.** Additional information; Lake level–surface area and lake level–volume relations are calculated for each lake based on bathymetric data within the model environment. For estimating lake areas, remote sensing has proved to be a powerful and efficient tool for monitoring these lakes (Gong & Peng, 2012). Basically, precipitation and evaporation are multiplied by the average lake surface area (Long term average). Figure 20 below shows how the model presents calculated water budgets after a successful simulation attempt.

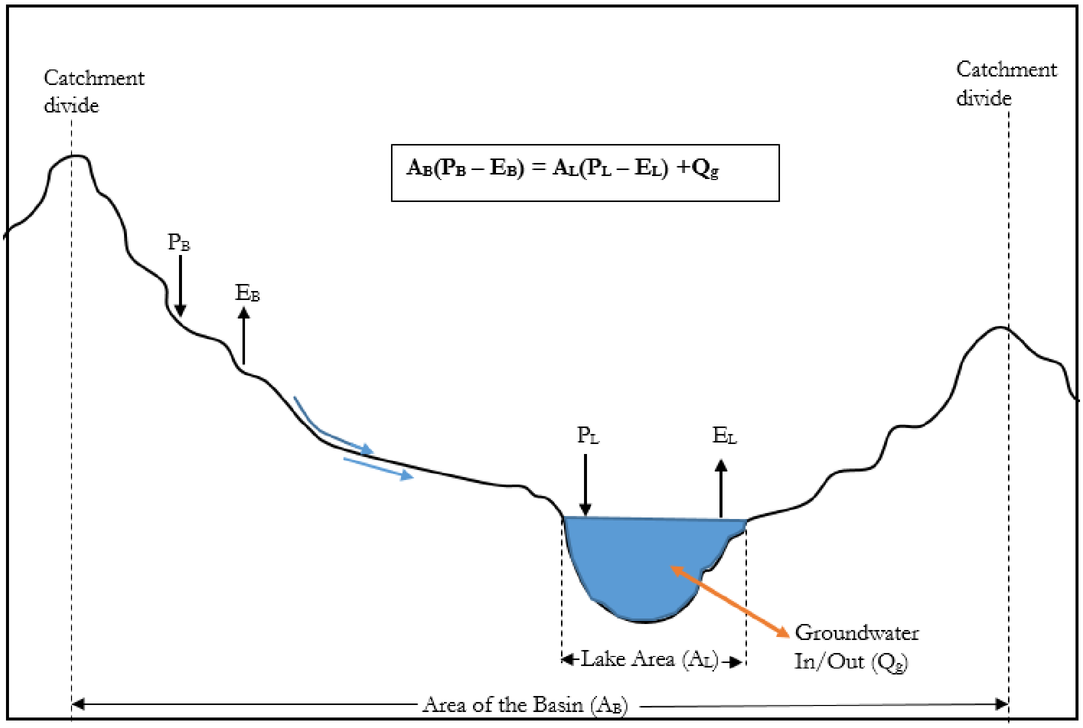
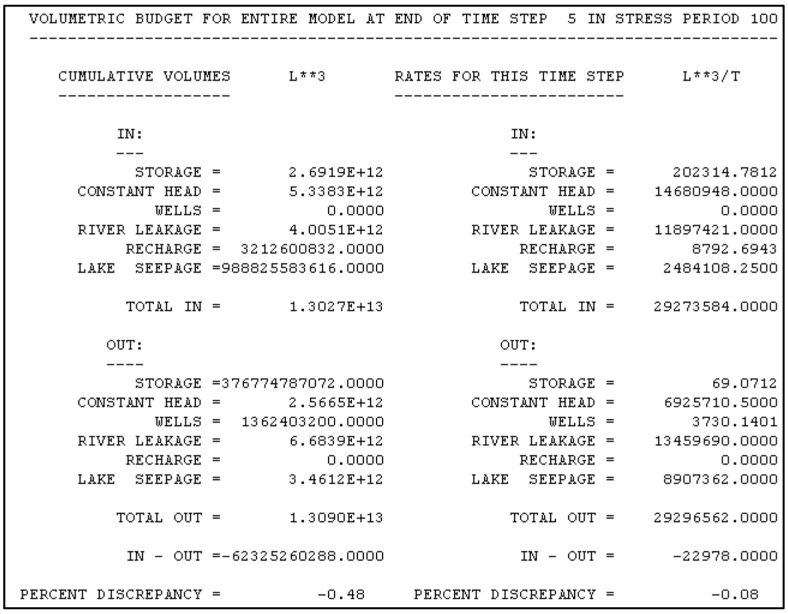


Figure 19: Graph showing components of a simple water balance assessment method



```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  5 IN STRESS PERIOD 100
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                   IN:
          ---                                   ---
            STORAGE =        2.6919E+12            STORAGE =     202314.7812
      CONSTANT HEAD =        5.3383E+12      CONSTANT HEAD =   14680948.0000
              WELLS =            0.0000              WELLS =          0.0000
      RIVER LEAKAGE =        4.0051E+12      RIVER LEAKAGE =   11897421.0000
           RECHARGE =   3212600832.0000           RECHARGE =       8792.6943
      LAKE  SEEPAGE =988825583616.0000      LAKE  SEEPAGE =    2484108.2500

           TOTAL IN =        1.3027E+13           TOTAL IN =   29273584.0000

         OUT:                                  OUT:
         ----                                  ----
            STORAGE =376774787072.0000             STORAGE =         69.0712
      CONSTANT HEAD =        2.5665E+12      CONSTANT HEAD =    6925710.5000
              WELLS =   1362403200.0000              WELLS =       3730.1401
      RIVER LEAKAGE =        6.6839E+12      RIVER LEAKAGE =   13459690.0000
           RECHARGE =            0.0000           RECHARGE =          0.0000
      LAKE  SEEPAGE =        3.4612E+12      LAKE  SEEPAGE =    8907362.0000

          TOTAL OUT =        1.3090E+13          TOTAL OUT =   29296562.0000

           IN - OUT =-62325260288.0000            IN - OUT =     -22978.0000

PERCENT DISCREPANCY =             -0.48     PERCENT DISCREPANCY =          -0.08
```

Figure 20: Sample of water balance output for the whole study area by the iMOD model

3.5.2. Geomorphological Approach

The lake basins in the Kenyan Rift Valley are encompassed by high relief escarpments and mountains that influence orographic rainfall distribution and in turn exerts control on runoff routing that creates large variations in the water balances from one lake to another despite their spatial proximity. Therefore, regardless of the processes that led to lake formation, the lake's altitude, surface shape, surface area, bathymetry and the irregularity of their shoreline have a major impact on their interaction with groundwater and surface runoff. Importantly also, the nature of the Kenyan dome where the topographic highs within the rift create a hydrological gradient that facilitates local and regional groundwater flow must be considered. This information was important in developing the conceptual model and investigating the inter-basin, hydrological connectivity among the lakes.

Hypsometric analysis describes the elevation distribution across an area of land surface, therefore it is an important tool for assessing and comparing geomorphic evolution of various landforms, irrespective of factors such as tectonics, climate, and lithology, which may be responsible for their creation (Lydia A. Olaka et al., 2010). Using the hypsometric integrals and the ratio of catchment area with lake surface area, the potential of the lakes to naturally regulate the surface runoff inflowing from their watersheds was assessed. Strong topographic differences and morphological shapes of the lakes have helped to inform on the general directions of gravity driven groundwater flows. Figure 23 shows these topographic differences across the study lakes. Groundwater heads and the flow direction were analysed to show the hydraulic gradient information. The natural groundwater flow in the Kenya Rift Valley was inferred from water rest levels of boreholes in the local aquifers.

From previous studies, the hydrogeological patterns in the Rift Valley also helped to map out groundwater flow paths. This entailed hydrogeological, structural and geophysical data and reports of the area. Notably, the rocks in the Rift Valley floor and margins are faulted and fractured extensively thereby enhancing secondary porosity and permeability in the study area. Consequently, these fault manifestations enhance groundwater flow and also provide paths that rivers selectively follow. Inherent inhomogeneity caused by these fractured rocks and the existence of volcanic centres, have provided critical information that was used to restrain the model. The surface expression of these fractures can be seen in linear river sections and alignments of volcanoes. Lineament influences on the hydrological features such as river path direction were mapped and spatially correlated with groundwater depths.

Table 4 shows the morphological characteristics of individual lakes in the Rift Valley Basin.

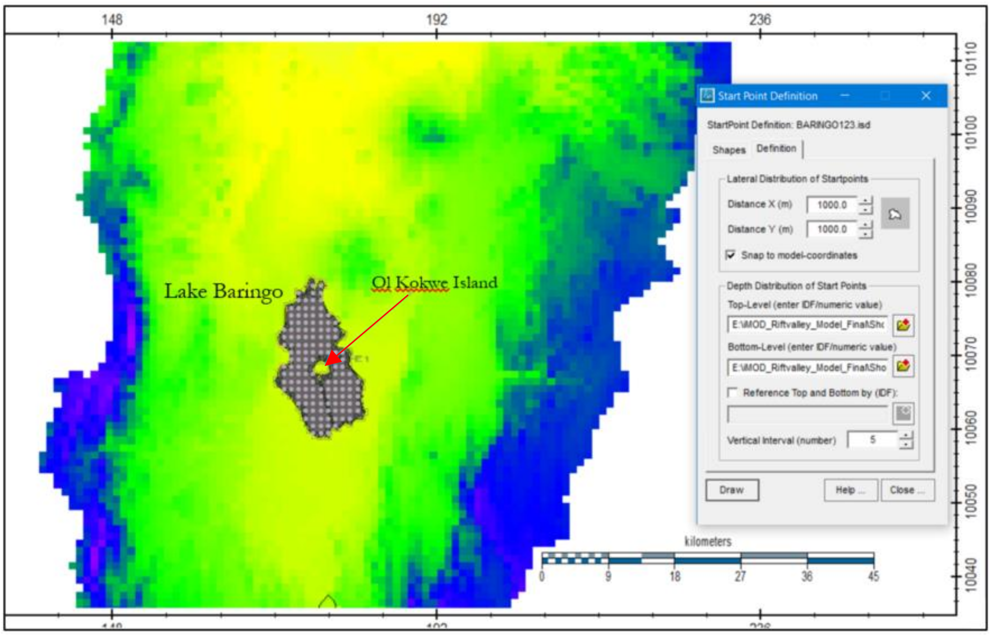
Table 4: Morphological characteristics of the Kenya Rift Valley lakes (Source: Various)

	Lake	**Elevation (m.a.s.l)**	**Max Depth(m)**	**Mean Depth(m)**	**Volume (Km^3)**	**Surface Area(Km^2)**	**Watershed Area(Km^2)**	**References**
1	Turkana	375	114	35	237	7500	130860	(Yan, et al.2002)
2	Logipi/Suguta	275	5	3	-	80	12800	(Lydia A. Olaka et al., 2010)
3	Baringo	975	8	2.5		160	6820	(Onyando, et al. 2005)
4	Bogoria	960	10	5.4	-	34	1110	(Olago et al., 2009)
5	Nakuru	1759	2.8	2.3	92	45	1360.4	(Ayenew & Becht, 2008)
6	Elementeita	1776	1.2	0.9	40	21	829.4	(Ayenew & Becht, 2008)
7	Naivasha	1886	11.5	4.9	4600	139.2	3387.8	(Ayenew & Becht, 2008)
8	Magadi	600	4	2	-	440	10930(Incl. Natron)	(Muno, 2002)(Lydia A. Olaka et al., 2010)

NOTE: Lake Area and depth is highly variable both seasonally and inter-annually; Max and Mean values based on various time slices

3.5.3. Pathline Simulation and Particle Tracking

The need for water balance assessments cannot be over emphasized especially as basis for simulating pathlines. Groundwater flow system patterns and direction were analyzed on the basis of the simulated hydraulic heads in the entire model domain. iMOD offers the possibility to trace particles throughout the model extent when the starting locations (startpoints) for the particles is properly defined. See Figure 21 below.



StartPoint Definition: BARINGO123.isd

Distance X (m) 1000.0

Distance Y (m) 1000.0

☑ Snap to model-coordinates

Top-Level (enter IDF/numeric value) E:\iMOD_Riftvalley_Model_Final\Shc

Bottom-Level (enter IDF/numeric value) E:\iMOD_Riftvalley_Model_Final\Sho

☐ Reference Top and Bottom by (IDF):

Vertical Interval (number) 5

Figure 21: Location and particle definition necessary to simulate flow lines from Lake Baringo

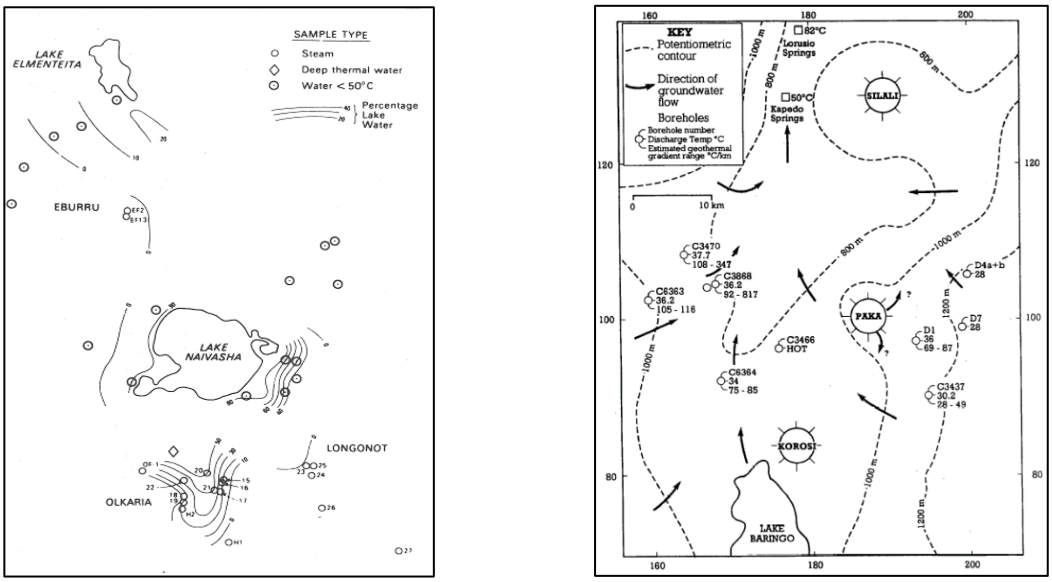
The IMODPATH function enables computation of flowlines based on the budget terms that result from the simulation. The particles are assumed to be transported by advection and can be tracked either forward in time or backward in time. Another advantage with iMOD is that the particles can be simulated in normal 3D-coordinates (x,y,z) at model trace time. See Figure 39. Cross-sections in 2D showing directions of fluxes in the aquifers is also possible. In this thesis, particle tracking analyses in the iMOD environment have particularly been useful for delineating flow patterns in the Kenyan Rift Valley.

3.5.4. Isotopic Evidence

Previous studies conducted in the study area where isotope chemistry was employed were reviewed in order to shed more light on observed flow system information that can be used to inform the modelling process (Figure 22). The isotopic tracing can only be observed and interpreted to solve some hydrogeological problems on the basis of the general knowledge of isotope variation in nature.

Isotopic tracing using oxygen and hydrogen, the chemical elements which constitute the water molecule are, in a certain sense, ideal geochemical tracers of water because their concentrations are not subject to changes by interaction with the aquifer material(Muno, 2002). During phase changes, the ratio of the heavy to light isotopes in the molecules in the two phases changes. Heavier water isotopes (^{18}O and ^{2}H) become enriched in the liquid phase during condensation of vapour while the lighter isotopes (^{16}O and ^{1}H) tend toward the vapour phase. Due to this, it is possible to distinguish the source of ground water based on isotope chemistry. Also, isotopes are ideal geochemical tracers of water because their concentrations are not subject to changes by interaction with the aquifer material. The topographic variation in the study area also makes it likely that the observed changes in altitude enables the analysis of groundwater flow by isotopic composition of rainfall possible.

Analysis of samples collected from the hot springs at the southern shore of Lake Elementeita and the hot springs around Lake Magadi was carried out at the Centre for Isotope Research University of Groningen, in the Netherlands(Muno, 2002). According to (W. G. Darling et al., 1996) these samples and those from around Lake Baringo were prepared for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ analysis by the methods of Epstein and Mayeda and Coleman et al., respectively. Results and conclusions of that study are summarized in chapter five.



Map A **Map B**

Figure 22: Map A showing sampling points around L. Naivasha and geochemical evidence from wells, springs and fumaroles (Source Allen 1990) and Map B showing groundwater potentiometric contours and flow directions from Lake Baringo to Kapedo springs (Adapted from Allen and Darting, 1992).

4. MODELLING

4.1. Model Purpose

Groundwater models are developed as tools which help to understand groundwater flow systems and to guide and support the decision making process on water resources management (Lubczynski & Gurwin, 2005). A model's purpose is also to predict the behaviour of a system under a management regime(Yihdego & Becht, 2013). This prediction is important since lakes, aquifers, rivers and the climate that affects them are complex environmental systems and their sustainable management requires advanced hydrological techniques to forecast natural and anthropogenic impacts. Modelling approaches can be used for evaluating the sensitivity of lakes in their response to different controlling factors, to infer past fluctuations in precipitation from historical variations in Lake water level, or to predict the response to climate and artificial changes in the regime of streams, lakes, and groundwater basins. So, modelling may be used to provide scientific basis and argument for institutional policy support incorporating a groundwater dimension into planning and management of Kenya's Natural resources.

Usually, groundwater modeling begins with a conceptualization of observed groundwater information. The next step in modeling is translating the conceptual model into mathematical terms(Kumar, 2015). To quantify the change in storage of the aquifers in response to groundwater flow systems and regimes, modelling is carried out using dedicated computer software programmes. Recent research focuses on the development and application of computer models which have the capacity to internally handle surface-groundwater interactions, so called integrated models(Zehairy, 2014). This is necessary because water resources management is moving towards integration, where groundwater, surface water and related aquatic ecosystems are considered as one management unit(Mehreteab, 2015).

4.2. Conceptual Model

The focus of this study was the zone above the cap rock that seals off high temperature and high pressure geothermal cells. These cells exist in the central rift below the caprock at approximately 700m in most locations. A regional-scale groundwater model was developed depending on the general conceptual understanding of the hydrogeological setting in the Rift valley. However, many details of the hydrogeological environment were sparse relative to the large modelling domain. Another bottleneck for building a robust hydrogeological conceptual model of the study area was the lack of sufficient drilling logs, pumping test data and information on static groundwater levels. Despite this limitation on hydrogeological data in some parts of the study area, a simple conceptual model of the regional groundwater flow was developed, making a number of simplifying assumptions that were necessary for a useful numerical model.

A simplified conceptual model is shown in Figure 23 below. Previous studies have concluded that groundwater flows on either side along the rift ridge axis from Lake Naivasha. Flow to the south is suspected to be deeper than flow to the north. Solid lines show flow confirmed by isotope chemistry while dotted lines show suspected flow directions yet to be confirmed

Flow to the south and north of Lake Naivasha is possible because the rocks in the Rift Valley floor and margins are severely faulted and fractured extensively thereby enhancing secondary porosity and permeability in the study area. Groundwater is therefore always flowing and the direction of flow is always from location of higher hydraulic heads to low hydraulic heads.

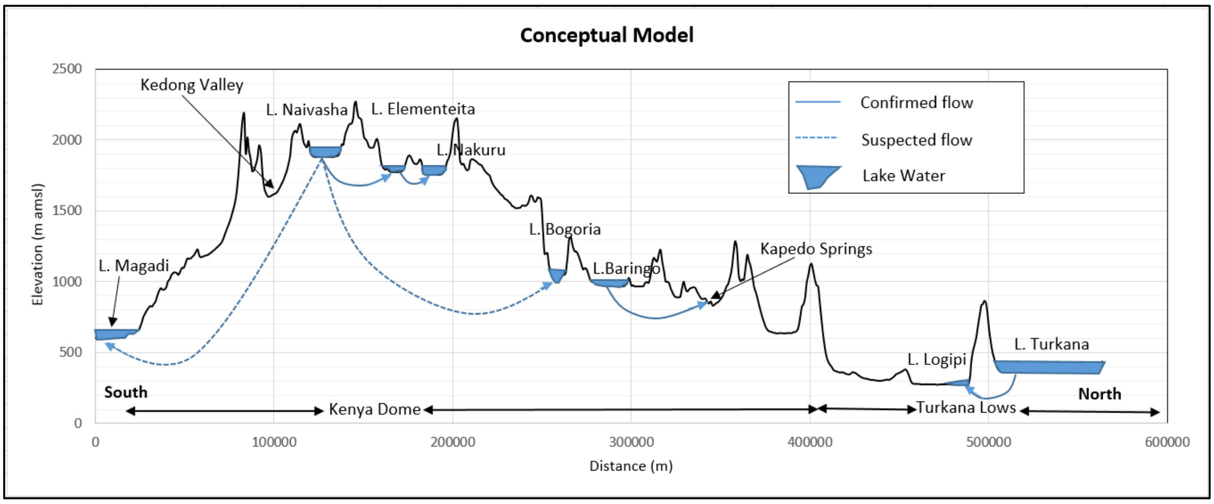


Figure 23: A North-South topographical profile of the rift valley floor showing the conceptual model

According to reviewed literature, lake sediments have a thickness ranging from approximately 15m in areas of low thickness (thins out towards the scarps) to over 50m beneath the lake. See Figure 28. They consist of thin and low permeability clay, silt interbedded with thicker layers of sand and coarser material.

4.3. Numerical Model

4.3.1. Model Selection

MODFLOW-2005 under iMOD environment was applied to simulate the interactions between surface water and groundwater systems. MODFLOW is a three dimensional (3D) finite difference groundwater model for flow simulation(McDonald & Harbaugh, 1988). The code is used to describe and predict the performance of groundwater systems. Three-dimensional incomprehensible groundwater flow through porous material is governed by the partial-differential equation (McDonald & Harbaugh, 1988)

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad \text{……………………………………………..…..….. } \mathbf{Eq\ 3}$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinates axes, which are assumed to be parallel to the principal directions of hydraulic conductivity; h is the hydraulic head; W is the discharge per unit volume, S_s is the specific storage of the porous material; and t is time. The equation above together with the boundary and initial conditions constitutes a mathematical representation of groundwater flow system. With this conditions together with initial conditions for head, MODFOW uses discretized, algebriac form of the equation to solve for potentiometric head at every model cell at time steps within each simulated period.

iMOD (interactive MODFLOW) approach has the advantage as a modelling tool that allows gathering of available input data to be stored at its finest available resolution(P. Vermeulen et al., 2013). The data does not have to be clipped to any pre-defined area of interest or pre-processed to any model grid resolution. Resolutions of parameters of interest can differ and the distribution of the resolution of one parameter can also be heterogeneous. This is illustrated in Figure 24 below. In addition, the spatial extents of the input parameters do not have to be the same. iMOD can perform up- and down scaling(P. T. M. Vermeulen, Heemink, & Valstar, 2005) whenever the resolution of the simulation is lower or higher than that of the available data. This among other factors make iMOD completely different from methodologies that are used in other conventional software packages. iMOD can therefore be used by many modellers to build one more versatile and indispensable model that can be used to study hydrogeology in the rift valley.

MODFLOW-2005 works with different packages to simulate different processes such as; lake/stream/river leakage into groundwater, recharge, groundwater fluxes, stream flow, etc. Applications of the conceptual model approach using the Lake Package LAK7 in iMOD environment were extensively explored in this study.

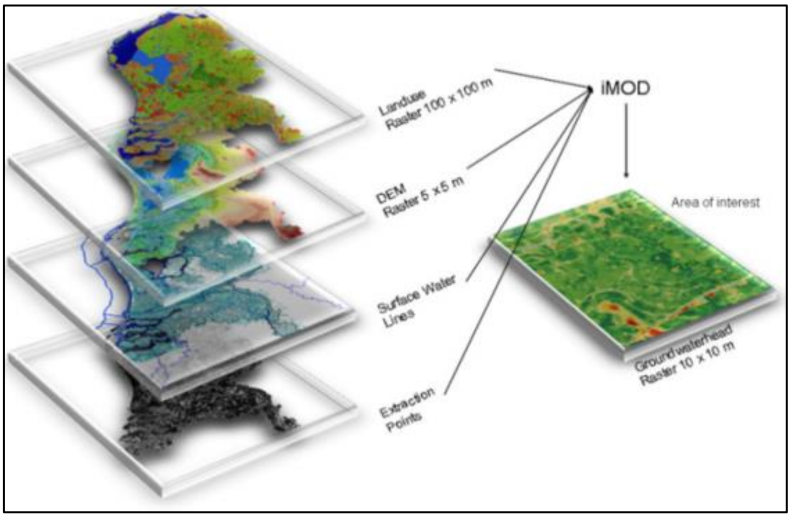


Figure 24: The iMOD approach: Resolutions of parameters can differ and the distribution of the resolution of one parameter can also be heterogeneous.

4.3.2. Model Set Up

In numerical modelling, groundwater flow can be simulated by two methods; steady-state and transient flows. For this study, time invariant steady-state model was achieved by running transient for a long time. Ten year time steps were used for one hundred stress periods.

Grid Design

The main model covers an area of 130,452 Km^2 with agrid definition of 560 rows and 190 columns, each 1000m by 1000m. Figure 25 elaborates how the model was set up in iMOD. The sub-model has a refined grid of 500m by 500m. Finer grids give more accurate water balance estimates but at the expense of increased computational time

Boundary Conditions

The boundary conditions were defined and simulated on conditions observed as well as inferred groundwater flow patterns. These boundaries were categorized into internal and external model boundary conditions in tandem with the respective physical and hydrological boundaries of the basins. The external model boundary conditions were simulated through the no-flow and constant head boundary. The entire eastern and western rift margins were simulated as no flow boundaries while constant head boundaries were designated at locations which cross-cut lakes Turkana and Magadi in the north and south respectively.

Model Layers

The modelled area extended to a depth of 700m covered by six layers. Multiple layers were required to simulate vertical flow but the depth was limited to less than 700m to avoid the high pressure-high temperature geothermal zone. The surface of the model top (digital elevation model (DEM)) was used to define all other layers by subtracting model thicknesses. Layer 1,2,3,4 and 5 were assigned 100m thicknesses while layer 7 was assigned 200m thickness. Layer 7 is thicker than the rest because it coincides with the caprock which is between 500 -700m below the ground surface according to geothermal logs. This layer definition approach was used due to unavailability of spatially variable lithologies.

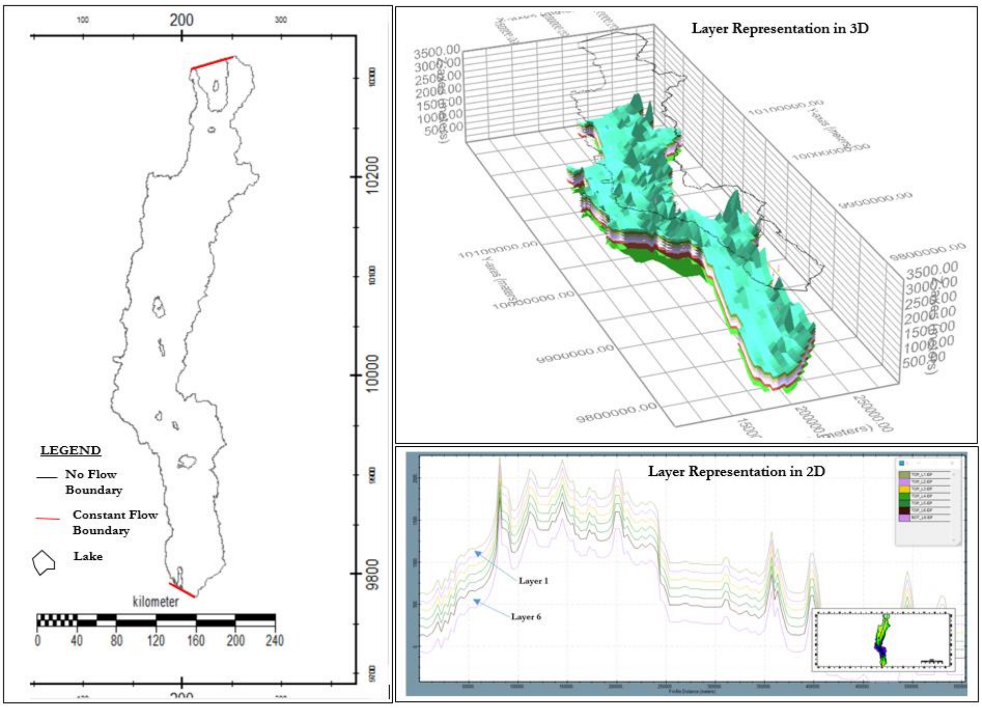


Figure 25: Model Set Up: Boundary conditions and layer definition in the iMOD environment

4.3.3. Model Inputs and Packages

Besides running the basic MODFLOW package [BAS] in the iMOD environment, other packages were also enabled. These included the river package, recharge package, constant head boundary package, well package and the lake package. Horizontal flow boundary (HBF) was used initially but due to lack of resistance data about the faults, it was switched off. Data about wells in the modelled area was prepared as an iMOD point file (IPF) while information about the stage of rivers and lakes, bed resistance and bathymetry of the lakes was prepared as iMOD grid files (IDF). Climatological inputs were also prepared in the form of IDFs. Figure 26 below shows samples of some of the input files that were used in the model.

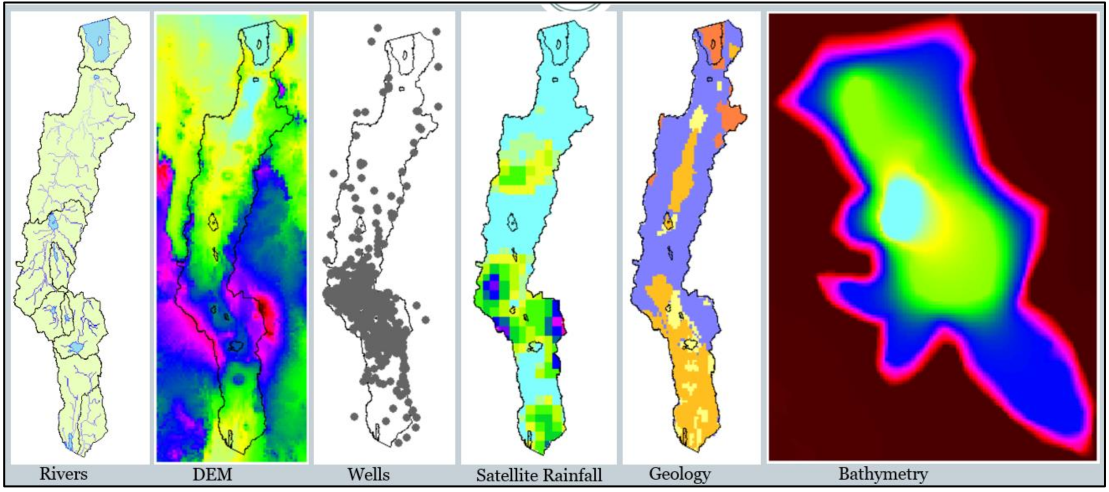


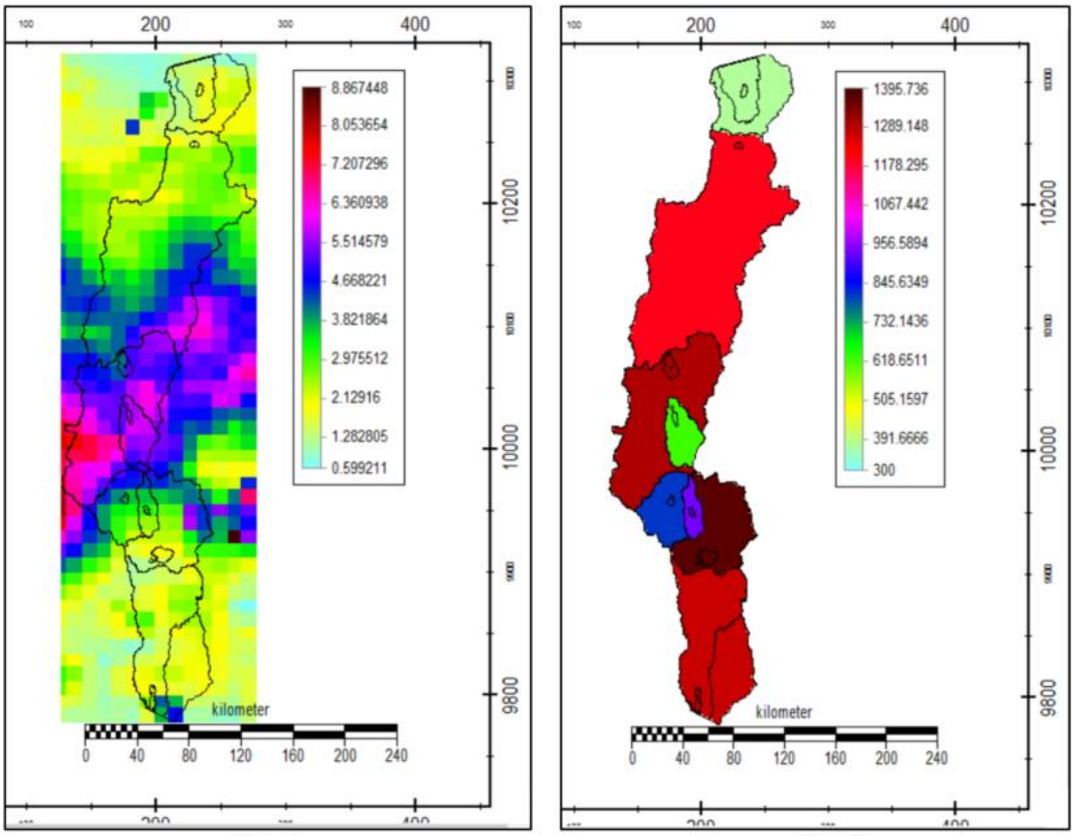
Figure 26: Sample of model inputs that were used in iMOD as grid files (IDF) or point files (IPF)

4.3.4. Initial Conditions

The initial conditions considered for this model were as lake levels, river flows and water rest levels in wells. The initial lake levels have been derived as a long-term average value from 1928 to 2001 for some lakes. The initial groundwater levels were assumed to be ten meters below the digital elevation model over the study area. This assumption was adopted because lake levels within this duration relate to the natural stresses that were impinging on the system then and lack of enough data to correctly describe the piezometric surface at the start of the simulation period.

4.3.5. Driving Forces

Precipitation is usually the main driving force in groundwater modelling and determines the model output. The number and type of model driving forces may differ from one type of model to the other depending on the intended purposes. In this study, where modelling using the lake package was critical, the model driving forces were precipitation, runoff, lake withdrawal and potential evapotranspiration (PET). Information that was used about these driving forces for each respective sub-catchment is tabulated in Appendix 1. Figure 27 below shows how daily satellite precipitation was averaged into long-term precipitation per catchment.



Map A **Map B**

Figure 27: Map A showing a sample of satellite daily rainfall and how it was averaged to long–term average estimates per sub-catchment in Map B

4.3.6. System Parameterization

Estimates of initial model input values were required before the first run. These values must be adjusted to within reasonable range for the model to converge appropriately. System parameterization can be achieved from an assessment of good quality geology data as well as hydrological, geomorphological and climatic data. The core calibration parameters were: lake bed resistance, horizontal permeability (KHV) and vertical anisotropy (KVA). The estimation and adjustment of these initial parameters and others ensured converging of the first run that paved way for actual calibration. The solver head tolerance was also adjusted to 0.01m using the Preconditioned Conjugate-Gradient solver

Parameterization of the lake package component involved assigning the initial stage, minimum and maximum levels allowed for each lake. The initial lakebed resistance values were also assigned for respective lakes. River stage, river bottom, river conductance and infiltration factors were assigned for all lakes draining into the lakes

4.3.7. State Variables

These are system characteristics which show different values in time and space and therefore can be used as calibration targets. Often they include; groundwater heads from piezometers, lake levels, well discharges, stream discharges and soil moisture of an unsaturated zone. Normally, the state variables are simulated by the model to enable comparison with observed measurements. In this study, the state variables were groundwater heads, lake levels and lake areas. Calibration of the model is usually based on the one or two state variables

4.4. Modflow Lake Package

4.4.1. Lake-Aquifer Interaction

Lake-groundwater interactions require codes that dynamically integrate groundwater, the unsaturated zone and flux estimations. The new lake package (LAK 7) is one such code which is supported by other packages of MODFLOW-2005, MODFLOW-NWT and iMOD to function properly. The lake is represented as a volume of space within the model domain consisting of active cells. The lake cells exchange water with the adjacent aquifer at a rate determined by relative heads and by lakebed resistance which is based on cell dimensions, hydraulic conductivities and user defined leakance distribution. The direction and magnitude of seepage between lake cells and the aquifer depends on the relationship between the lake stage and hydraulic head in the aquifer. Figure 28 shows a schematization of the lake interaction with the aquifer and important components required for the lake package.

Quantification of the rate of seepage between the aquifer and lake is calculated through Darcy's Law.

$$q = K \frac{h_l - h_a}{\Delta l} \qquad \text{.......} \quad \textbf{Eq 4}$$

Where;
Q = seepage rate (L/T)
K = hydraulic conductivity (L/T)
h_l = lake stage (L)
h_a = aquifer head (L)
Δl = is the distance (L) h_l and h_a

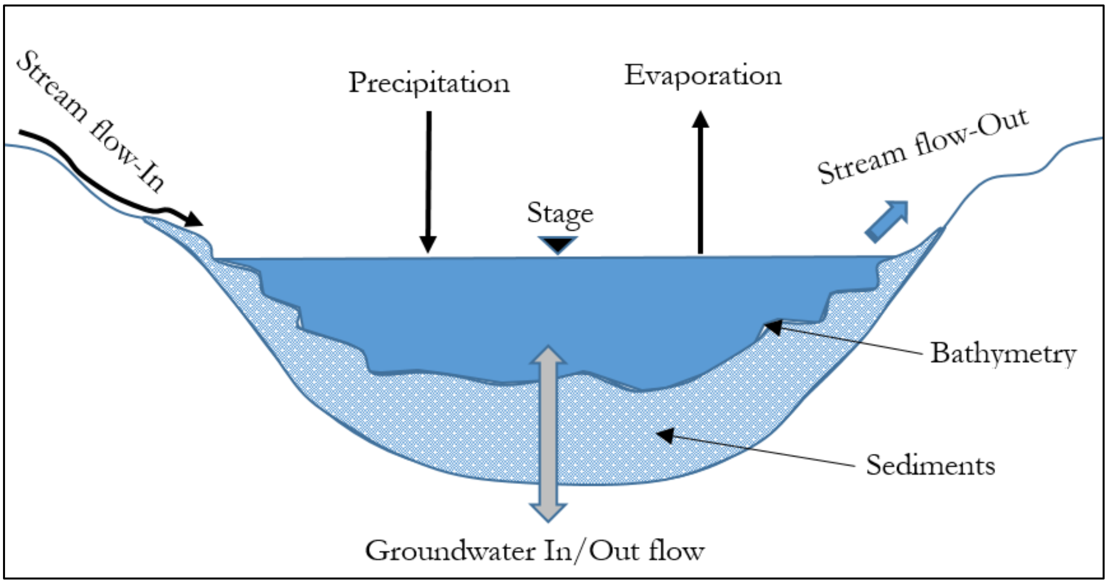


Figure 28: Sketch of the lake - aquifer interaction showing components required in the lake package

The algorithm after (McDonald & Harbaugh, 1988) and Prudic (1989) simplifies this interaction and flow over a grid cell with a validity condition that groundwater head and lake level are higher than the bottom of the lakebed sediments.

$q_i = COND_i(S - h_{ijk})$ ………………………………………………………………………. **Eq 5**

Where;

q_i - seepage rate (L/T)

$COND_i$ – Lakebed conductance

S – Lake stage

h_{ijk} – Groundwater cell in space

Three other validity types are used to cater for the wetting capability in the event the cell falls dry. They are;

I. The groundwater table is below the lakebed bottom and the lake is full (Max Seepage)

$q_i = COND_i(S - BOT_i)$ ………………………………………………………..………………... **Eq 6**

BOT_i – Lakebed bottom of flow cell

II. The lake cell is empty and the lakebed bottom is above groundwater table

$q_i = 0$ …………………………………………………………………………………….………. **Eq 7**

III. The lake cell is empty but the groundwater table is above the lakebed bottom

$q_i = COND_i(BOT_i - h_{ijk})$……………………………………………………………..……… **Eq 8**

Lakebed conductance is calculated as follows;

$$COND_i = \frac{KA}{TOP_i - BOT_i}$$ ……………………………...……………………………..……….... **Eq 9**

Where;

A – Lake cell surface area (On a horizontal plane)

TOP_i – Top of Lake Cell

K – Hydraulic conductivity of the lakebed

4.4.2. iMOD Lake Package (LAK 7)

One of the advantages of MODFLOW 2005 under the iMOD 3.5 environment is the possibility of using the lake package (LAK 7) to simulate lake-groundwater interaction. Generally, MODFLOW simulates both steady state and non-steady model (transient) flow by assuming that exchange of the water with the aquifer occurs only vertically through the bottom of the lake. Lake bathymetry is also accommodated in the iMOD lake package. In this study lake bathymetry was defined by manually sketching the lakebed terrain following the work of the (Muno, 2002) for some of the lakes. The Preconditioned Conjugate-Gradient Package in iMOD is recommended as the solver of choice since it is very sensitive to the "head change criterion" and converges easily.

Sadly though, there is a disclaimer from Dutch developers of iMOD- Deltares about stability issues when running the beta version in steady state. The Graphical User Interface (GUI) for the iMOD 3.5 is still under development and is scheduled for official release in February 2017. This affected the processing of my model data in steady state. The developers were not able to help arrest the problem by the time of finalizing this thesis. In the meantime I have managed to use the beta version curtesy of the developers from Deltares But since transient simulation is a robust way of achieving steady state results – after a long time, the approach was used to deliver steady state results. Consequently, the model was run for 100 stress periods with time steps of 10 years each. Steady state was achieved after about 822 years using the storage coefficient of 0.0003. Figure 29 below shows how transient simulation was used to achieve steady state lake level of Lake Naivasha.

Each lake was simulated by defining its average water level, minimum stage and maximum stage. Precipitation falling on the lake surfaces and evaporation thereof were also defined for each lake. Runoff from respective catchments into the lakes were estimated but withdrawal from the lakes for anthropogenic utilization were assumed to be negligible. The river package is used to rout streamflow to these closed basin lakes. Detailed information about these driving forces that were used in the simulations for each respective sub-catchment is tabulated in Appendix 1

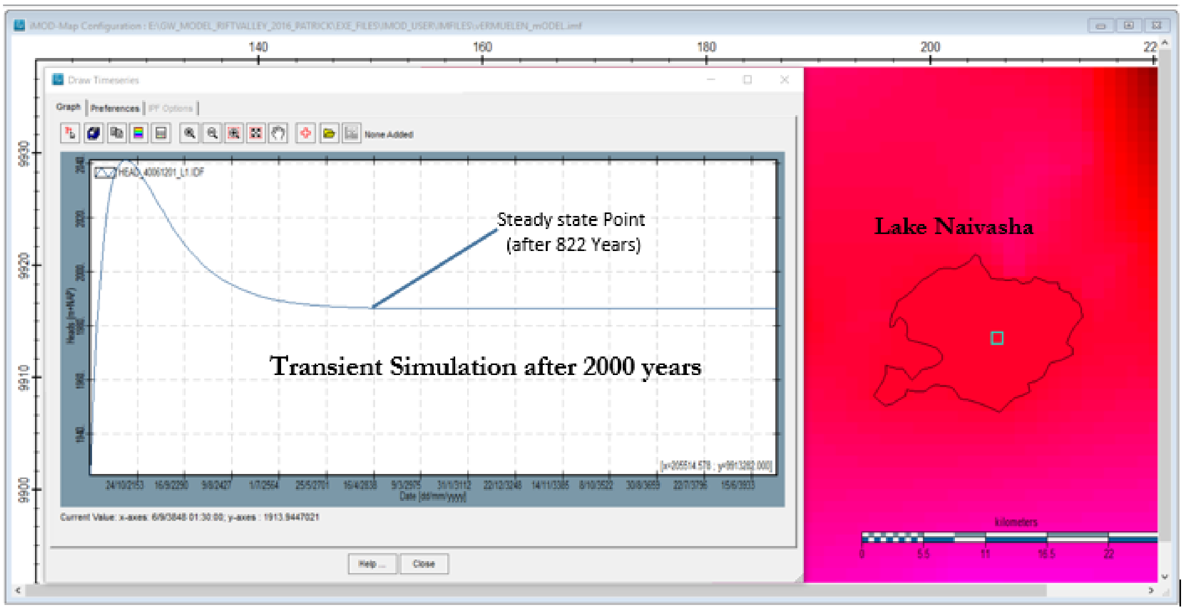


Figure 29: Using transient simulation to achieve steady state results

4.5. Model Calibration

Calibration is one of the processes that is undertaken to adjust the model such that the model can as closely as possible represent observed field measurements. Optimum values of key parameters are determined by minimising the error terms between observed measurements and simulated measurements. Therefore the process of calibration culminates in parameter data sets that best represents field measured conditions. Calibration of the model was carried out by comparing lake levels and surface area of the study lakes with field observations.

A series of manual calibration procedures have been attempted to obtain an optimal set of model parameters for the whole of the Rift Valley as well as selected sub-catchments. Due to the complexity of regional groundwater flow systems in the study area and the sparsity of available data sets, calibration exercise has been plagued by problems of insensitivity, non-uniqueness, and instability leading to trial-and-error calibration. To achieve this, values of hydraulic conductivity, lake bed resistance and recharge were manually modified until the differences between the observed and calculated aquifer head values were reduced to an acceptable level. Calibration targets were both the groundwater level heads and the lake area and or stage. The mean square root error was used for lake stage calibration while the discrepancy value was used for the water balance

4.6. Sensitivity Analysis

Uncertainty exists in modelling because of spatial and temporal variation of parameters, boundary conditions, subsurface heterogeneity and initial conditions. It is therefore necessary to evaluate the effect of uncertainty on these parameters using a sensitivity analysis. The criteria for error analysis were done using the root mean square as shown in Eq 10 below. Parameters evaluated in the sensitivity analysis were lakebed resistance, vertical anisotropy and hydraulic conductivity. Sensitivity analysis was done by varying one parameter while holding other parameters fixed to test their response on lake levels. The most sensitive parameters will be the most important parameters causing the model to match the observed values

The purpose of this exercise was to examine the trend model follows when its input data is adjusted from that on which it is calibrated. Linearity of the model was also tested during this exercise when a variable was increased or decreased by a factor of two, for instance, to see if the response will decrease or increase by the same factor.

$$RMSE = \sqrt{\frac{\Sigma(H_{obs.}-H_{calc.})^2}{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq 10}$$

4.7. Model Validation

Model protocol requires that before any scenario simulation is made, the model should be validated or verified. Validation is the use of the model to reproduce similar results using a second set of field data. The purpose of validation is usually to fairly demonstrate a genuine relationship between the behaviour of the model and reality so that we have confidence that it will make accurate predictions. In this study, the model has been validated against independent climatological data of the same sub-basins following the study by Lydia Olaka (Lydia Atieno Olaka, 2011). The data used for validation is tabulated in Appendix 1

5. RESULTS AND DISCUSSION

The final results of the diverse approaches that were employed in this study have revealed the regional flow patterns in the Kenyan Rift Valley. These results compare well to the results obtained by previous researchers and observations made in the field. Results derived from the calibrated model with the lake package and pathline simulation thereof have been graphically presented to demonstrate the model's capabilities to simulate groundwater flow. The entire Rift Valley model has been simulated on a coarse scale of 1,000 meter, by a simulation network of 190 columns and 560 rows and 6 model layers.

Groundwater flow system patterns and directions were analyzed on the basis of model simulated heads at steady state. iMOD offers the possibility to trace particles throughout the model extent when the starting locations (startpoints) for the particles are properly defined. The combined groundwater flow patterns in the Kenyan Rift valley is illustrated in Figure 48. Evaluation of the model used and other results are presented under the following sub-headings.

5.1. Evaluation of the Model

5.1.1. Steady State Calibration

In iMOD the model residuals (the difference between simulated and observed values) are generated by the iPEST module. The model was not calibrated automatically through inverse modelling but through a trial and error approach. The results of the modelling showed that the observed and simulated lake stage agree to acceptable limits considering that this is a regional model. This is illustrated by the fairly good correlation between the two measurements resulting from good calibration process as shown in Figure 31A below. The actual values for observed and simulated lake areas and stage are as summarised in Table 5

The model had 14 hydraulic conductivity zones with values ranging from 0.08 – 68m/day. Higher values of permeability are found in the volcanics and sediments around Lake Naivasha area. On the rift escarpments, the permeabilities of different rock types are uniformly low. Permeability values also fall with depth mainly as a result of the closure of fissures by the overburden stresses. Recharge zones were catchment based and all had less than 1mm/Year. The calculated recharge value for the whole model was 0.047658 mm/year. Lake bed resistance was from 4 -10.5 days. Lower lake bed resistance values were assigned to lakes that allow flow through regimes like Naivasha and Elementeita

However, it was not possible to obtain the desired level of agreement between the modelled and simulated aquifer heads and lake stage. Notably, when the lake stages were calibrated, a scatter plot of observed against simulated water rest levels in wells exhibited a poor correlation. See Figure 31 B. Every lake was taken as an observation point hence only eight points of observation for the lake for comparison purposes

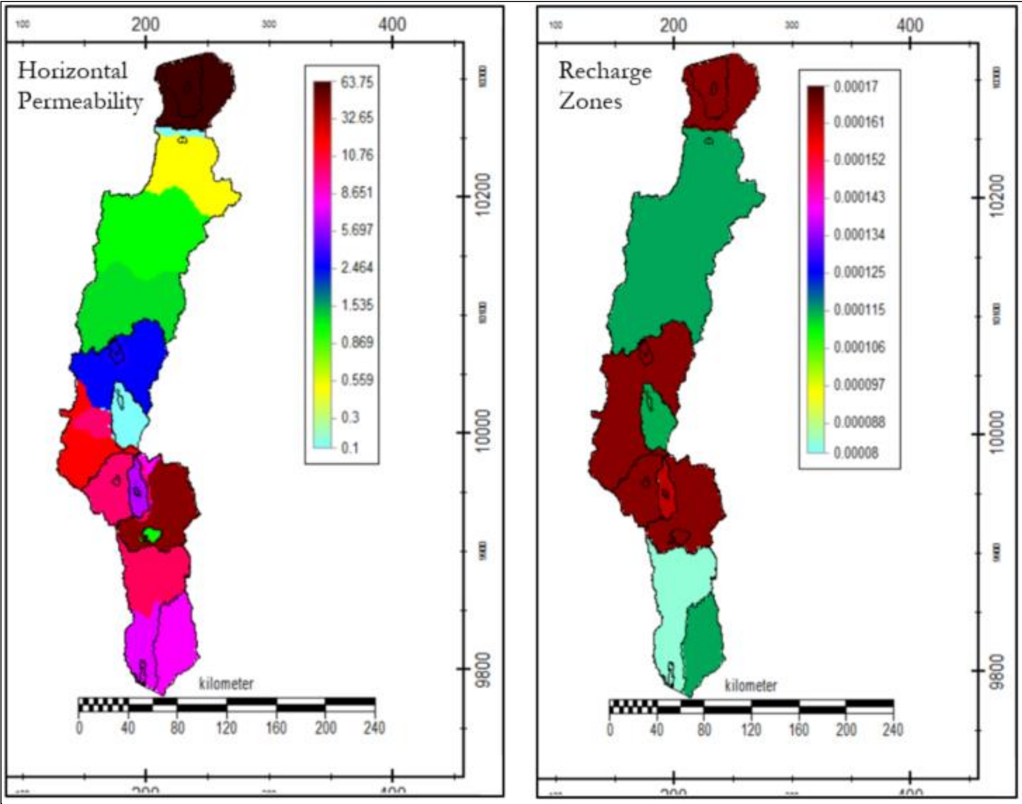
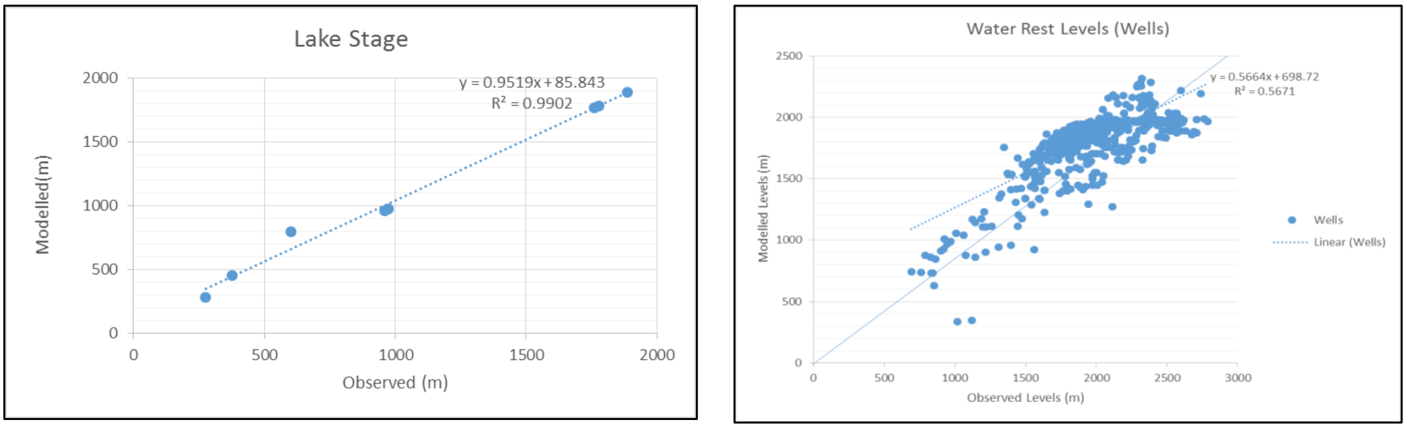


Figure 30: Figure showing calibrated results of horizontal permeability and recharge



Graph A

Graph B

Figure 31: Scatter plot showing the relationship between observed and simulated lake stage (Graph A) and water rest levels in wells (Graph B).

Table 5: Comparison between observed and simulated parameters

	Lake	**Lake Stage (m)**		**Lake Area (Km^2)**	
		Observed	Modelled	Observed	Modelled
1	Turkana	375.0	450.0*	6405.0	1119*
2	Logipi/Suguta	275.0	279.5	10 - 18	25
3	Baringo	975.0	974.05	168.0	151.0
4	Bogoria	960.0	957.9	34.0	33
5	Nakuru	1759.0	1761.5	45.0	33.0
6	Elementeita	1776.0	1779.4	18.0	24.0
7	Naivasha	1886.0	1884.9	139.0	127.73
8	Magadi	600.0	793.2*	100.0	93.0*

Note: Values with asterisk belong to incomplete lake and catchment parameters

5.1.2. Sensitivity Analysis on Model Parameters.

The sensitivity analysis was based on the root mean square error and the overall error is large due to the contribution of two incomplete lakes and their catchment parameters. Results showed that the model responds highly to changes in lakebed resistance, vertical anisotropy and hydraulic conductivity. The model is particularly sensitive to a decrease in lakebed resistance than when an increase is affected. This is reasonable because lower lakebed resistance values trigger increased flow through regimes. But hydraulic conductivity exhibits a more symmetrical relationship. The model is also very sensitive to an increase in vertical anisotropy. Figure 32 shows the outcome of the sensitivity analysis. The values that were used in deriving the curves are given in Table 6.

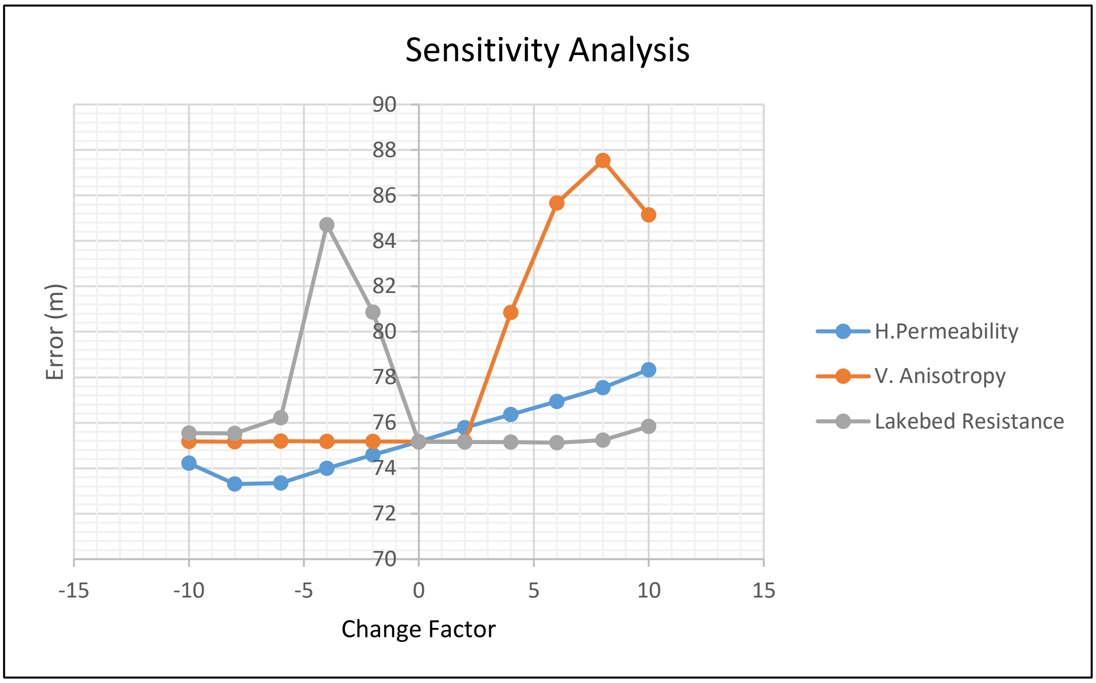


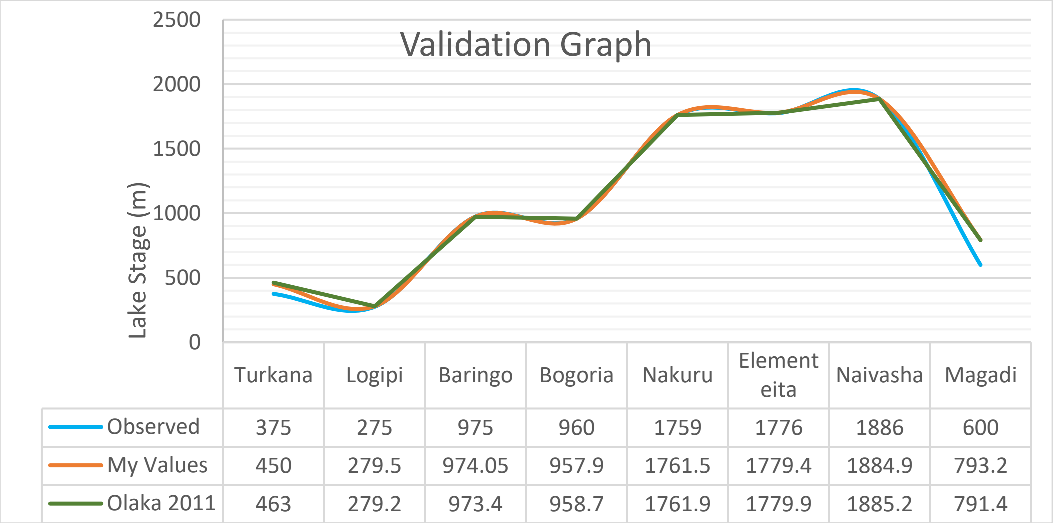
Figure 32: Figure showing the sensitivity analysis of various parameters on simulated lake stages

Table 6: The root mean square error analysis on various parameters

Change Factor	H. Permeability	V. Anisotropy	Lakebed Resistance
10	78.3385	85.15045	75.8385
8	77.53785	87.5321	75.23549
6	76.94381	85.66976	75.12143
4	76.36506	80.85192	75.14931
2	75.78159	75.17322	75.14757
0	75.16799	75.16799	75.16799
-2	74.5874	75.17332	80.86292
-4	73.99795	75.18044	84.71388
-6	73.3505	75.18718	76.21651
-8	73.30471	75.17047	75.53549
-10	74.22559	75.1734	75.54448

5.1.3. Validation

Validation using Lydia Olaka (Lydia Atieno Olaka, 2011) meteorological data showed a slight increase in the lake stage due to a slight increase in values of precipitation in all except two lakes. This is true because the variation in the two input datasets were very small. Consequently, there is a very small difference between the observed stage and using the two separate data sets. It is likely that Olaka used satellite data spanning around the same period as my input data sets. A good trend is observed since the two datasets are very close. See Figure 33 below.



	Turkana	Logipi	Baringo	Bogoria	Nakuru	Elementeita	Naivasha	Magadi
Observed	375	275	975	960	1759	1776	1886	600
My Values	450	279.5	974.05	957.9	1761.5	1779.4	1884.9	793.2
Olaka 2011	463	279.2	973.4	958.7	1761.9	1779.9	1885.2	791.4

Figure 33: Validation results using separate meteorological data showed little variation on the simulated lake levels

5.1.4. Main Model Water Budget

Water budgets for this model are based upon the long term averages of components of the water balance. These components include; runoff inflow from rivers, rainfall on the lake surface, evaporation from the lake surface and abstraction from the lakes which was assumed to be zero in all lakes. The lake level– area–volume relationship is built into the model and allows the calculation of the all water budget components and water seeping in to and from the lake to the aquifer. The lake package LAK 7 calculates this effortlessly using the MODFLOW codes.

A groundwater budget has been prepared reflecting all water flow in to and out of the regional aquifer. Table 7 shows the overall water budget of the study area at the end of the simulation time. The tabulated water budget indicates that the lakes are not in equilibrium with long term a long term average inflows. The flow in minus out (groundwater budget for the whole model) was calculated as -22978.0m^3/day. This represents a percentage discrepancy of -0.08. It is worth noting that because a transient approach was used to arrive at steady state, storage terms cannot be wished away if the water balance is to register closure. Consequently, storage has been deliberately included in the water balance to show the exact output of the model's water balance

The discrepancy is fairly high because Lake Turkana and Lake Magadi's input data may be inaccurate due to area incompleteness in the model domain. The error is also attributable to possible computational errors resulting from the evaluation of long-term runoff to the lakes. Also, Lake levels are sustained during time periods when the total inflow (consisting stream inflow, runoff and rainfall) exceeds the total outflow (consisting lake seepage, abstraction and evapotranspiration). These periods which are linked to consistent inflow volumes possibly occur during the high rainfall seasons. Nonetheless, a discrepancy value around 1% or less is usually accepted(Anderson & Woessner, 1992).

Table 7: Groundwater budget estimates for the entire model

Flow Components	Inflow (m^3/day)	Outflow (m^3/day)
Storage	202314.7812*	69.0712*
Constant Head Boundary	14680948.0	6925710.5
Wells	0.0000	3730.1401
River Leakage	11897421.0	13459690.0
Recharge	8792.6943	0.0
Lake Seepage	2484108.25	8907362.0
Total	29273584.0	29296562.0
In - Out	-22978.0	
Percentage Discrepancy	-0.08	

Note: Storage values have an asterisk because a transient approach was used to arrive at steady state

5.1.5. Sub-Model Water Budget

The budget estimates for a smaller region of the model were also computed. The entire model domain was the region of interest while the area comprising Lake Naivasha, Lake Elementeita and Lake Nakuru formed the area of interest (Sub-model) See Figure 34. The sub-model was simulated at a finer resolution of 500 x 500 meters and the results are shown in

Table 8. Similarly, storage terms have been included in the water budget because a transient approach was used to arrive at a steady state.

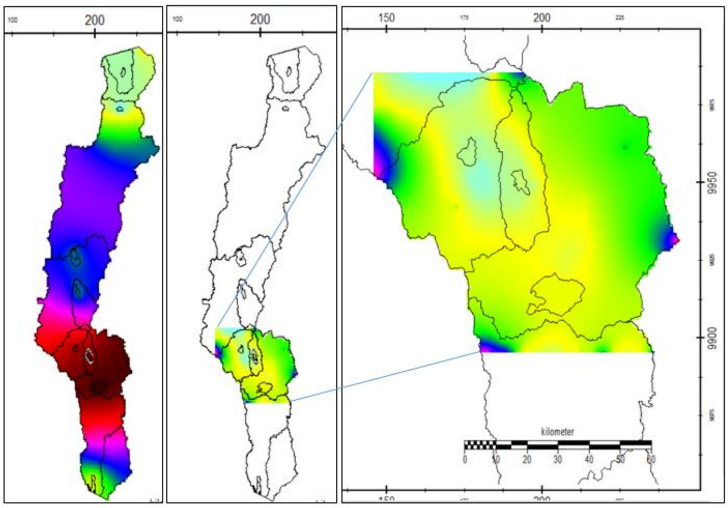


Figure 34: Figure showing the extent of the main model and sub-model

Table 8: Groundwater budget estimates for the sub-model

Flow Components	Inflow (m^3/day)	Outflow (m^3/day)
Storage	312.8427	4.0382
Constant Head Boundary	81410688	28645470
Wells	0.0000	3039.54
River Leakage	16765025	70727512
Recharge	1971.8951	0.0
Lake Seepage	7264150	6120931.5
Total	29273584.0	105496952
In - Out	-54808	
Percentage Discrepancy	-0.05	

Note: Storage values have an asterisk because a transient approach was used to arrive at steady state

5.2. Extent of groundwater flow from Lake Naivasha

5.2.1. North and South flow

Simulation results utilizing iMODPATH show that groundwater outflows from Naivasha is in two directions Figure 36; 37 and 38. Figure 35 shows the equipotential lines which indicate the possible general directions of axial flow from Lake Naivasha. Owing to its situation on the topographic culmination of the floor of the domed Kenya Rift Valley, a potential exist for the leakage to occur in both northerly and southerly directions. The Northbound flow to Lake Elementeita from Lake Naivasha is controlled by the 100m hydraulic gradient between the two lake systems. Isotopic signatures of lake water has also been confirmed in fumaroles which occur both south (Olkaria) and north (Eburru, Menengai)(Becht et al., 2006). Isotopic evidence from the Eburru well EW-1 shows that lake water also passes beneath the Eburru volcanic ridge(W. G. Darling et al., 1996).

It was not possible however, for this study to confirm postulated distribution of 80% southerly flow and 20 % northerly flow as documented by some authors. Actual drilling and isotopic evidence have not provided evidence of lake water further south.

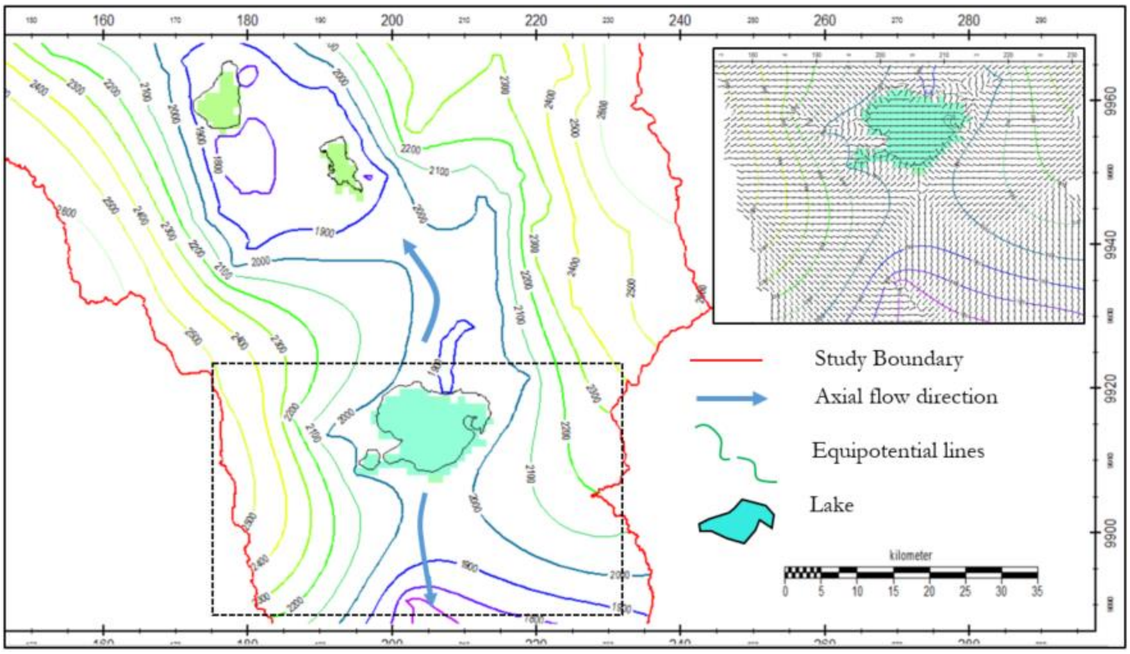


Figure 35: Figure of equipotential lines and inset flow direction arrows intersecting them at right angles

5.2.2. Depth of aquifers and groundwater flow

In the vertical dimension (Z - component), direction of flow was also observed to be in both directions as illustrated in Figure 36 below. This was achieved using pathline simulation with particles flowing from Lake Naivasha. Particles were allowed to flow through all modelled layers (1-6) and their lateral distribution was 1000m by 1000m. Simulation of the particles was done only in the forward direction.

Although many authors estimate that flow to the north is via relatively shallow aquifers, this was not the case in this study. Apparently most of the flow particles originating from Lake Naivasha flow in both directions and are confined in the bottom modelled layer. Probably deeper flow paths would be possible had the model not been confined only to the first 700m. Below this depth, there is the caprock that seals away the high pressure and high temperature geothermal cells which may further complicate flow regimes in the central rift. Hydraulic conductivity is particularly susceptible to heat changes. Reviewed literature indicate that 30% of spring water on the Southern shoreline of Lake Elementeita originated from Naivasha and the model simulation shows that most of the fluxes flowing into lake Elementeita are from local recharge zones within the catchment. See Figure 41.

Yihdego et al., 2016 advocate for the existence of two non-coinciding aquifer systems; a shallower aquifer in direct hydraulic contact with Lake Naivasha and a more deeper aquifer connected to the upper one by leakage terms. With regard to geometric considerations, it would be reasonable to postulate that southerly flow towards Lake Magadi is exclusively through a deep regional aquifer system while northerly flow towards Elementeita and Nakuru is in a shallower system. But northerly flow towards Lake Baringo would be through a deep aquifer as well. These postulations were proven true with the outcome of the Pathline simulations

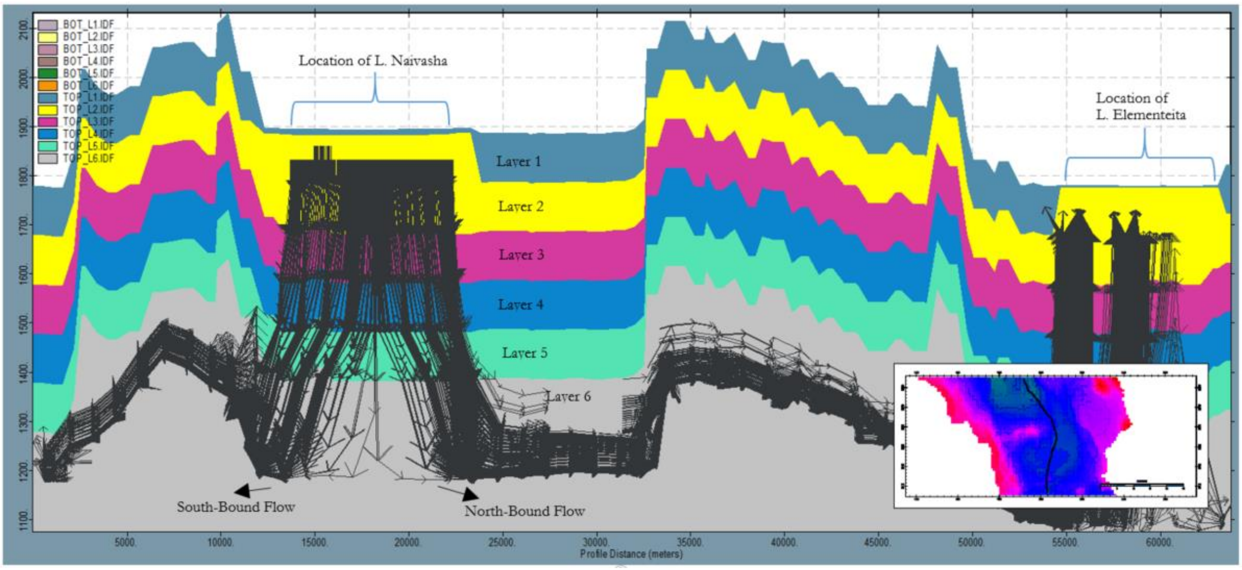


Figure 36: Directions of flow from Lake Naivasha in the vertical cross-sections

5.2.3. Sources and Sinks

Lakes can be can be classified according to their groundwater regime as recharge (source), discharge (sink) or flow through (Anderson & Woessner, 2002). Lake Naivasha is typically a source lake. It does not receive groundwater from any other source. As a closed basin lake, Naivasha owes its freshness to underground outflows estimated at about 50MCM according to many studies. This estimated outflow accounts for 20% of the total recharge from the catchment. Source lakes discharge water into the ground and are often fresh in nature. The arrow directions from Lake Naivasha showed in Figure 36 above are in tandem with generalised flow patterns around a source lake. Figure 37 below shows how water flows in and out of sinks and sources.

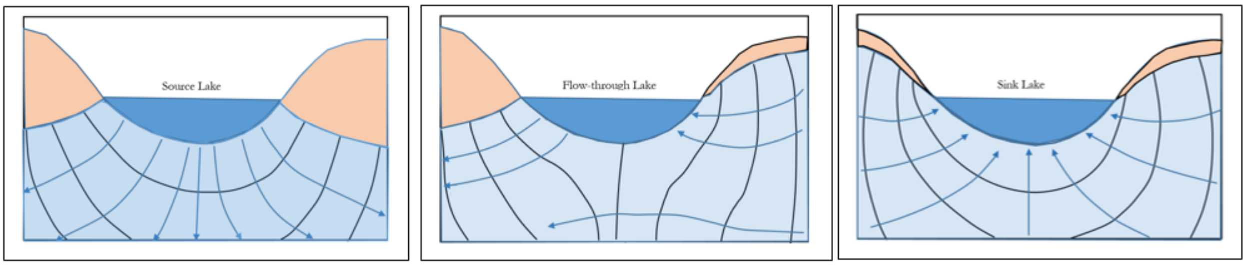


Figure 37: Figure showing a generalised flow pattern around sources and sinks

Simulated pathlines of particles originating from Lake Naivasha have shown that Lake Elementeita is a flow through lake and Lake Bogoria and Baringo are sink lakes. But with regard to regional flows Lake Baringo is not a sink lake since it is the source that feeds Kapedo springs. The simulated flow lines showed that Lake Elementeita allows some water to outflow as groundwater yet it also receives a substantial amount of water from Lake Naivasha. See Figure 38. Results show that Lake Bogoria and Baringo are good sink lakes but Lake Nakuru is a weak sink. See Figure 43

5.2.4. Lake level Trends

Although transient simulation was only used to achieve steady state, it was observed that for every time step or stress period there was a rise or fall in Lake Naivasha, a corresponding rise or fall was also observed in Lake Elementeita. This is also observed in **Error! Reference source not found.** where a noticeable rend exists between the two lake levels over a reasonable period of time. From that figure of historical lake level timeline, a rise in Lake Naivasha level at a given point in recorded time corresponds to a rise in Lake Elementeita at the same time. This proves that the two lakes are hydro-geologically connected since their climatological hypsometrical variables are different. Using this connection, the extent of the north-bound flow can be delineated. This connection between the lakes has been suggested by many researchers (Becht & Harper, 2002; Muno, 2002)based on isotopes

5.3. Particle Tracking for observed Isotope flow

Isotopic investigation has been used in other studies as a better alternative in determining the likely source of Kapedo springs and Lake Elementeita hot springs. The studies concluded that Lake Baringo and Lake Naivasha respectively are the sources of these springs(G. Darling et al., 1990). This has cast more light on subsurface flow in the rift valley as isotopic signatures offer more reliable results. In this study forward particle tracking was executed from both Lake Naivasha and Lake Baringo to establish if the model can simulate isotope results

5.3.1. Particle flow from Lake Naivasha

The extent of modelled flow particles from Lake Naivasha is illustrated in Figure 38 below. A 3D illustration of this flow (Second inset) is shown in Figure 39. This was achieved in the iMOD environment by modelling the forward flow paths based on simulated heads. This results show that flow from Lake Naivasha flows as far North as Lake Baringo. Particles flowing south reach into Lake Magadi located to the south which forms an apparent natural sump for drainage in the southern Kenya Rift.

Although the model showed that south-bound flow reaches Lake Magadi, (see Figure 47 B) the same is not collaborated by isotope chemistry. Isotope studies have not indicated any connection between Magadi hot springs and the highly enriched heavy element samples obtained from Lake Naivasha to link their groundwater recharge from to lake water. The reason for this inconsistency of reality with the model may be due to the catchment extent and Lake Magadi size which was incomplete within the model domain area and therefore the results as modelled for Lake Magadi may not be realistic. Lake Magadi was only used as it is in the model to provide a suitable boundary condition.

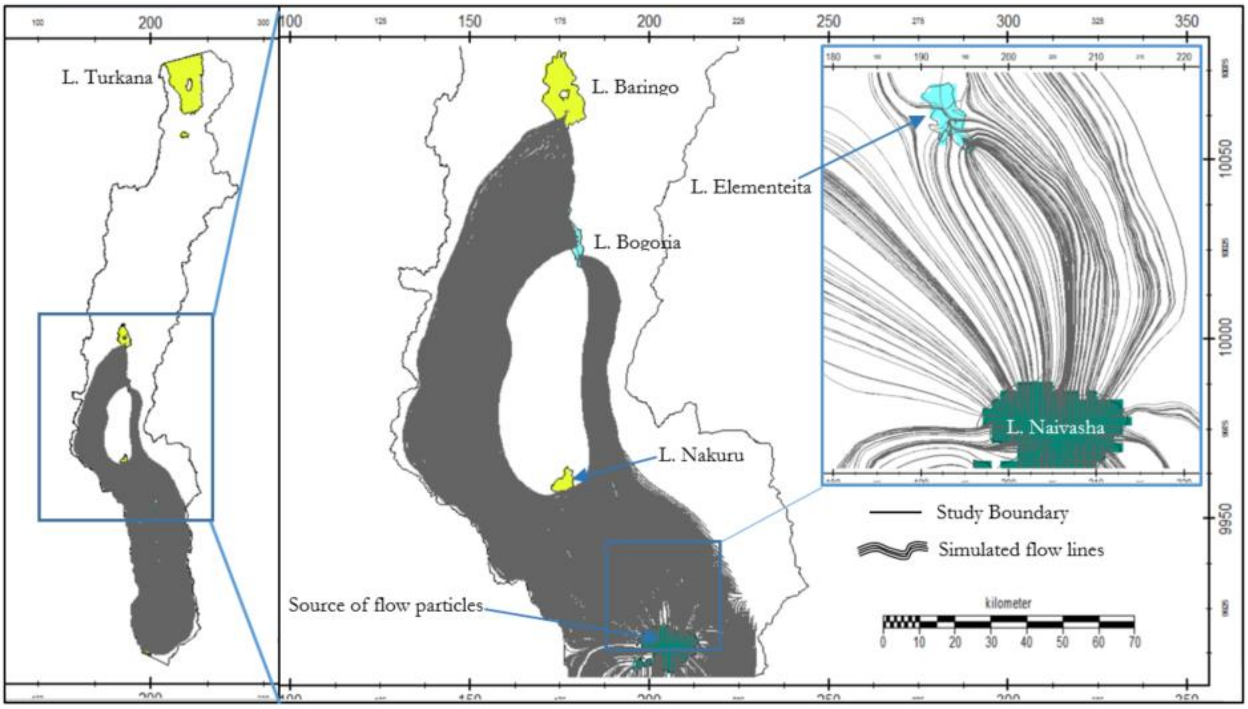


Figure 38: Extent of flow from L. Naivasha showing the modelled source and sinks in the Rift Valley

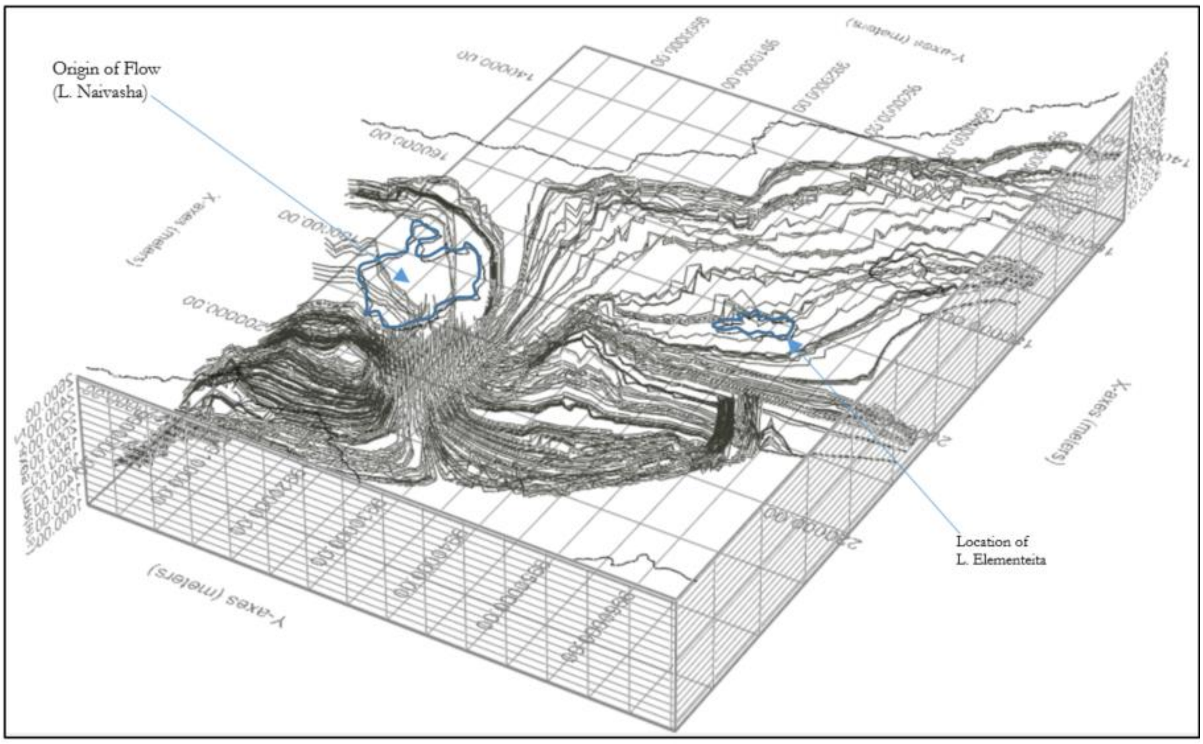


Figure 39: A 3D illustration of groundwater flowlines originating from Lake Naivasha.

5.3.2. Particle flow from Lake Baringo

There is no obvious outlet from Lake Baringo but due to its freshness, the waters are assumed to seep through lake sediments into the faulted volcanic bedrock. The structure of flow within the basement is not known. But as opposed to Lake Naivasha, however, any output from Lake Baringo would have to be directed exclusively to the north on hydrogeological grounds. As suspected, isotope studies concluded that some water from Lake Baringo drain to the north through an underground series of fissures and re-appearing at Kapedo springs, 80 km away. Lake water contributes about 30% composition at Kapedo springs (~50^{0}C) according to (W. G. Darling et al., 1996)

However, this was not the case with this model. The simulation of particle flow from Lake Baringo failed even with the three-fold increase of starting point particles. Unlike the Lake Naivasha case where particles flow out of the lake into groundwater aquifers, Lake Baringo particles only move vertically upwards from locations they are placed. This apparent inability of the model to simulate reality may be attributed to failure to provide the model with accurate information about fault networks that convey water in the area. Since one fault may be a groundwater conduit and another a groundwater barrier, assigning accurate resistance values for respective faults is imperative. Updating fault information in the area therefore becomes a critical action point in improving the model.

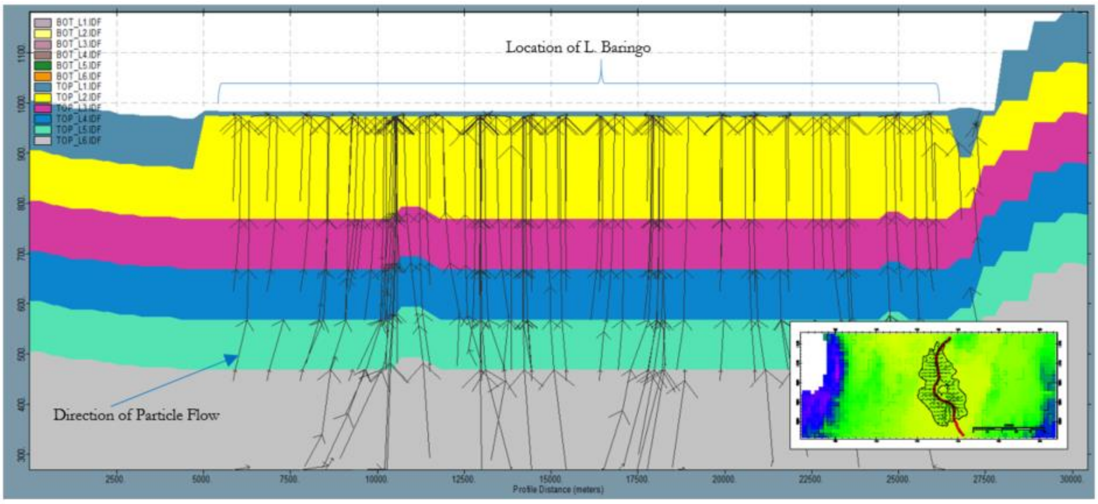


Figure 40: Particles placed in Lake Baringo do not flow away as the case in L. Naivasha

5.4. Local and regional flux directions

Although each lake in the Rift Valley was assessed separately to simulate local fluxes attributable to local recharge, a final integrated matrix of local and regional fluxes was derived and is illustrated in Figure 48. The details and results of local fluxes around respective study lakes are discussed below

5.4.1. Lake Naivasha flow patterns

Inflow into Lake Naivasha is strictly from precipitation and recharge zones within its catchment. This flow towards the lake is from the Mau escarpment and the Kinangop plateau representing the lateral flow. Discharge from this lake to groundwater is characterized by near local (to Lake Elementeita) and regional fluxes flowing as far north as lake Baringo and as far south as Lake Magadi. Figure Figure 41 shows modelled fluxes around Lake Naivasha. It is observed from the simulated flow lines that local fluxes out of the Naivasha sub-catchment are in tandem with the north and south flow of particles from Lake Naivasha as postulated by many authors.

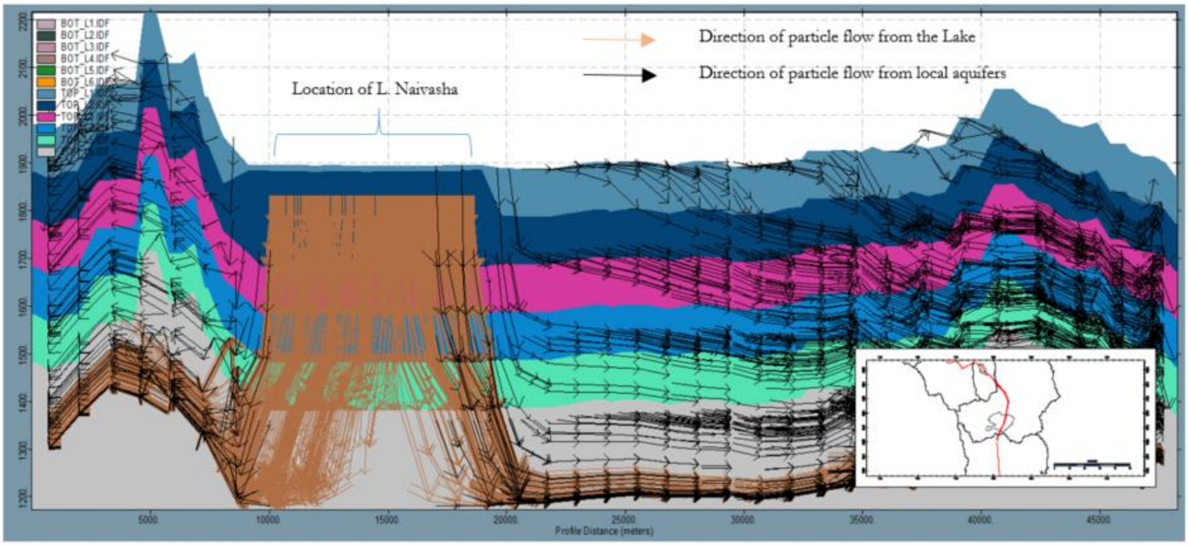


Figure 41: Simulated flux directions around Lake Naivasha

5.4.2. Lake Elementeita flow patterns

Lake Elementeita by proximity is the nearest (about 30km) and is more than 100 m below lake Naivasha is the most logical place to intercept the northerly outflow of Lake Naivasha. The subsurface linkage between Naivasha and Elementeita basins has been established by geochemistry and is consistent with flow simulation derived through modelling in this study. As expected, simulated flow lines terminate at the southern edge of the lake where *Maji Moto* hot springs are located. Also, as a flow-through reservoir, the lake receives regional groundwater from Naivasha in the south and discharges into aquifers in the north that are likely connected to Lake Bogoria by faults. But on a local scale, groundwater fluxes from the edges of the catchment flow radially towards the lake in the center. The inset of Figure 42 shows the used cross-section that coincides with flow paths from Lake Naivasha. Evidently, local fluxes from Lake Elementeita do not exit in this direction. Modelled exit is oriented to the north.

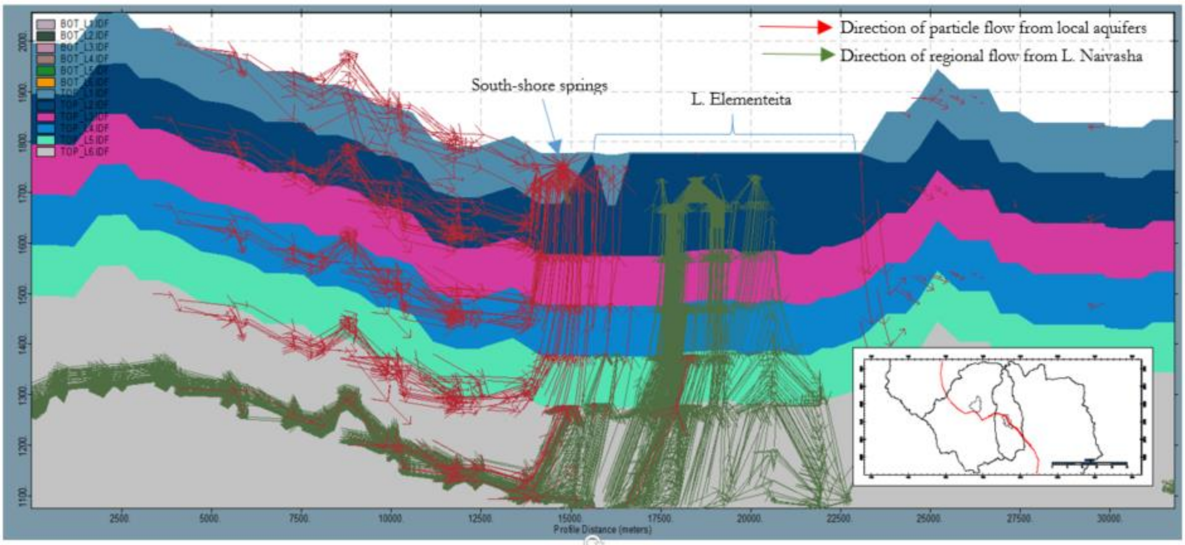


Figure 42: Simulated flux directions around Lake Elementeita

5.4.3. Lake Nakuru flow patterns

Although the origin of the groundwater flow into Lake Nakuru is not yet known, the elevation along the North Western shore of Lake Elementeita is sloping away from the lake indicating some flow from Elementeita towards Nakuru. But interestingly, isotope samples taken in 2004 from the area South of lake Nakuru did not indicate presence of lake water, therefore discounting the possibility of a shallow connection between the two lakes. But as a large closed lake basin, a large amount of flow is lateral flowing in from the flanks of the rift valley.

A cross-section along pathlines from Lake Naivasha which intersects a small portion of Lake Nakuru was taken to show relationship between regional and local flows in the catchment. The simulated flow pattern of both fluxes is shown in Figure 43 below. From the flow lines derived, it is easy to notice that Lake Nakuru is a weak sink of regional groundwater. This indicates that most of the recharge comes in the lake comes from local recharge zones.

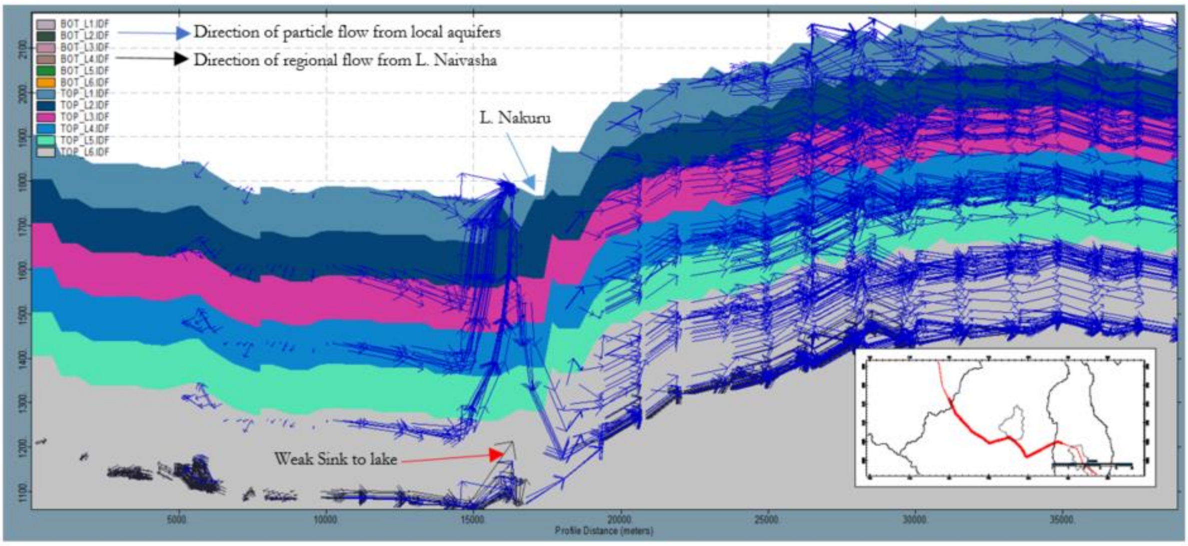


Figure 43: Simulated flux directions around Lake Nakuru

5.4.4. Lake Bogoria flow patterns

Groundwater inflow into saline Lake Bogoria is characterised by geysers and hot springs along the bank of the lake and within the lake. The alkaline hot springs that are present at Loburu, Chemurkeu, and a southern group (Ng'wasis, Koibobei, Losaramat). Lake Bogoria has no surface outlet so the water becomes saline mainly through evaporation, which is high in this semi-arid environment.

Simulated pathlines show that regional groundwater arrives in the lake at a location near the southern shore and also in other parts of the lake. Using the inset cross-section of Figure 44 below, the local and regional fluxed were simulated as shown. This flux directions show Lake Bogoria as a typical sink.

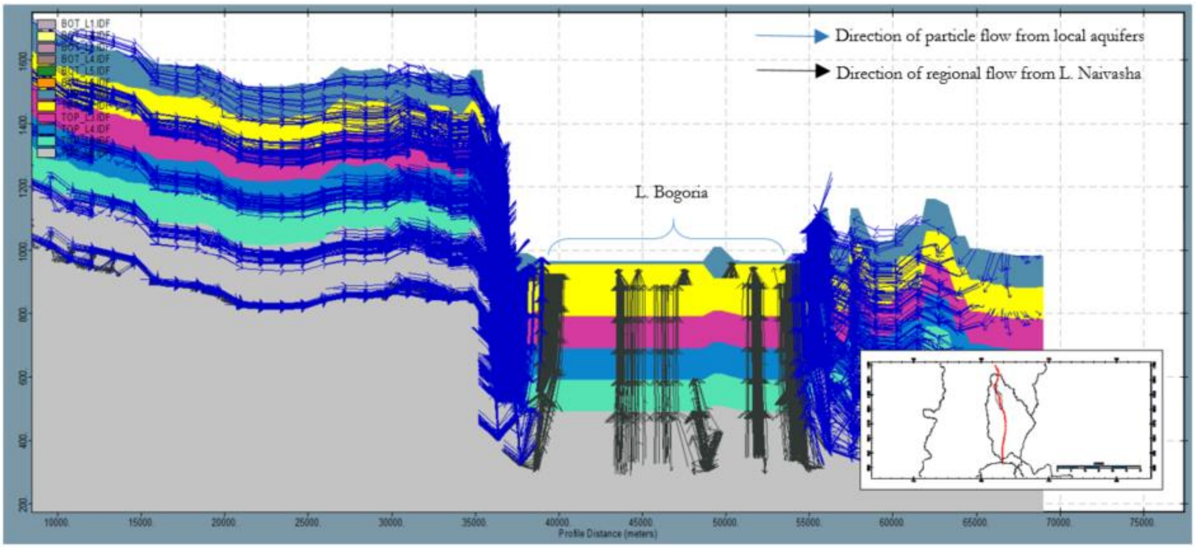


Figure 44: Simulated flux directions around Lake Bogoria

5.4.5. Lake Baringo flow patterns

Results of simulated flow from Lake Baringo has already been discussed in section 5.2.2. Forward particle flow from Lake Baringo failed even with the three-fold increase of starting point particles and possible reasons for the failure have been given. In this section however, local and regional flow arriving at the lake have been simulated as shown in Figure 45. You will note from the figure that regional flow from Lake Naivasha arrives at locations in the south of the lake. Using the cross-section shown in the inset, it is evident that the lake has been modelled as a typical sink. Inflow from the north is related to fumaroles and hot springs related to Korosi Volcano. Ol Kokwe Island also has natural hot springs.

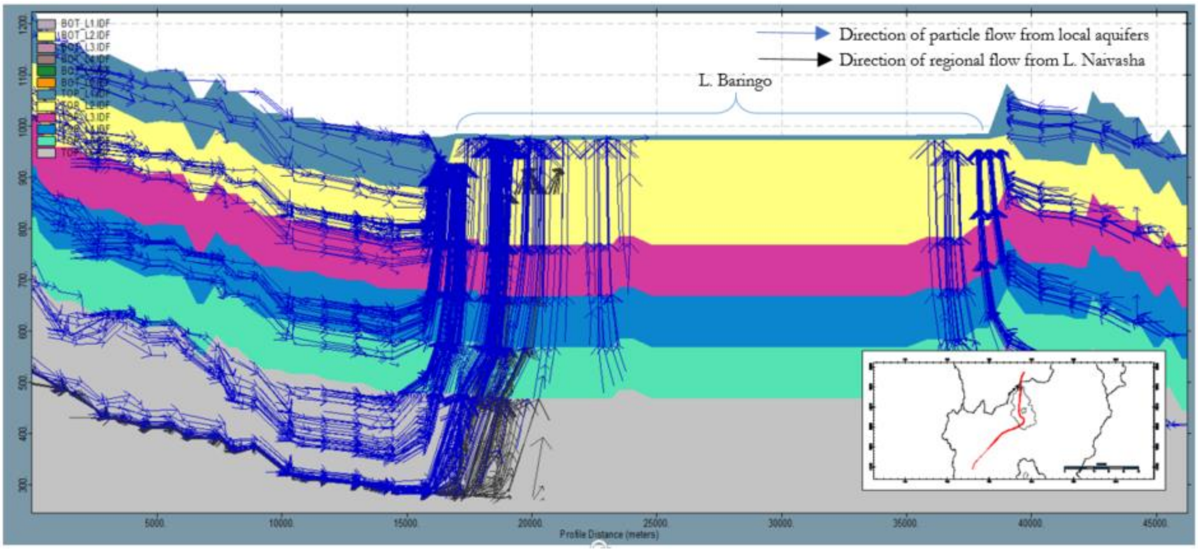


Figure 45: Simulated flux directions around Lake Baringo

5.4.6. Lake Logipi flow patterns

Available literature about Lake Logipi is very limited. This might be due to the little interest in the lake water because of its alkaline nature, which discourages its use for anthropogenic purpose. The area also has a low population density. This saline lake lies north of the Suguta valley and is separated from Lake Turkana by the Barrier volcanic complex. The size of the lake varies rapidly with seasonal changes. A few hot springs discharge into the lake on the northern shoreline and also at Cathedral Rocks near its southern limit. This springs help to maintain lake water at times of extreme dry spells.

Simulated flow lines around Lake Logipi depict it as a textbook case of a true sink lake as showed in Figure 46. Its location at the lowest point of the rift floor means water leaves mainly by evaporation. The simulation also shows the possible location of the northern shoreline springs where fluxes from the north terminate. Flow from the south is characterised by very gentle gradients through the flood plain.

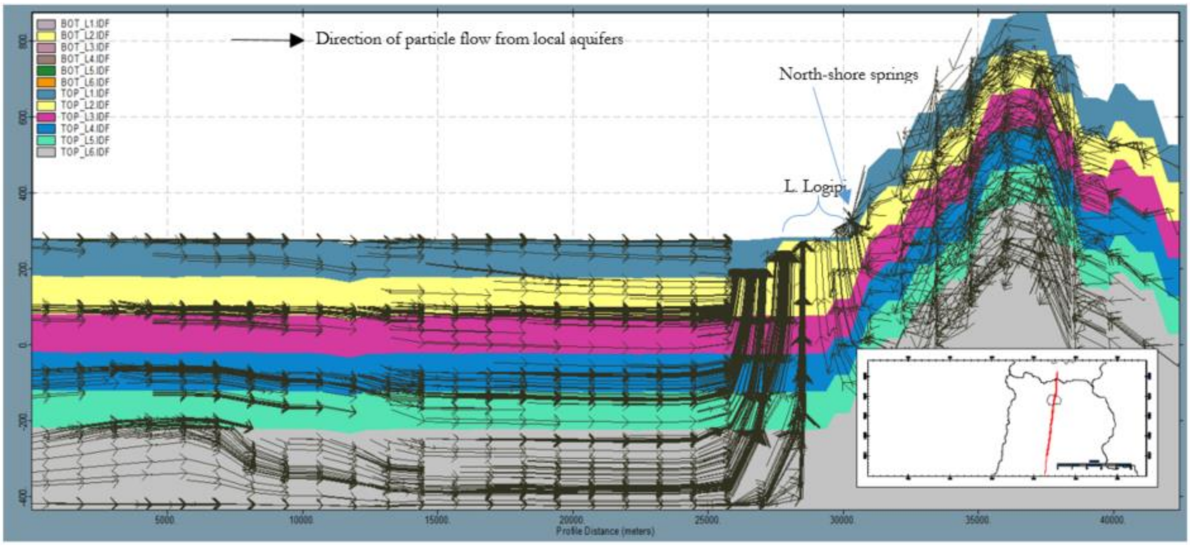


Figure 46: Simulated flux directions around Lake Logipi

5.4.7. Lake Magadi and Turkana flow patterns

As already mentioned, simulated flow paths into Lake Magadi and Lake Turkana may not be accurate as only portions of their lake size and catchment extent were used in the model. The two lakes were only used to provide a suitable boundary condition- constant head boundaries. Their catchment extent and lake sizes were incomplete within the model domain area and therefore water balance results as modelled may not be realistic. Their complete extent would simulate conditions beyond the scope of this research.

However simulated fluxes around these two lakes may not necessarily be totally wrong. For instance boreholes in the Kedong valley sank up to about 300m turned out to be dry meaning there are no shallow aquifers from local recharge zones. The model has realistically illustrated this since there appears to be no flow of groundwater in the first 3-4 layers of the model representing 300-400m below the ground. See Figure 47 B. Only deep seated groundwater flows to the south. Lake Magadi is suspected to be recharged by the Ewaso Ngiro River which loses water through infiltration. The springs along the Western side of the lake have the isotopic signature of rainwater. It is therefore unlikely that the discharge from Lake Naivasha constitutes a large portion of the Lake Magadi inflow.

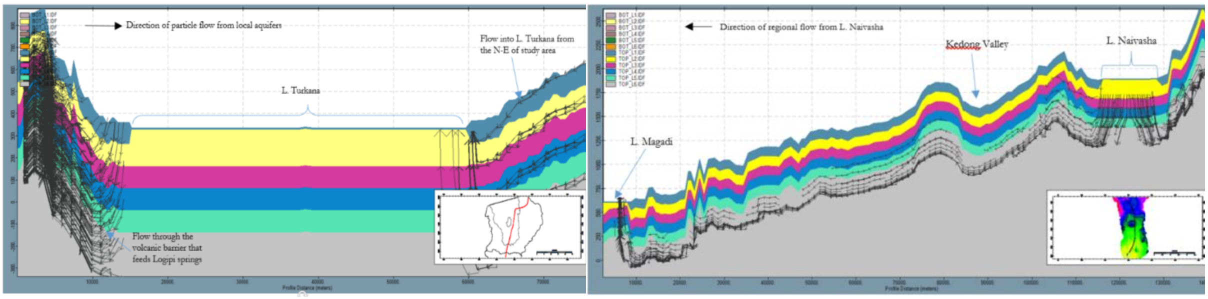


Fig A.

Fig B.

Figure 47: Simulated flux directions around Lakes Turkana and Magadi

5.4.8. Generalized regional flow pattern

Although each lake in the Rift Valley was assessed separately to simulate local fluxes attributable to local recharge, a final integrated matrix of local and regional fluxes was derived. All the cross-sections that were used in analyzing flow across individual lakes were summed up into one and flow generalized as is illustrated in Figure 48. The figure shows the relationship of local fluxes around respective lakes with regional flows in the same view. The bottom confining layer of the model (BOT_L6) is also shown to give an idea as to the depth extent of the model.

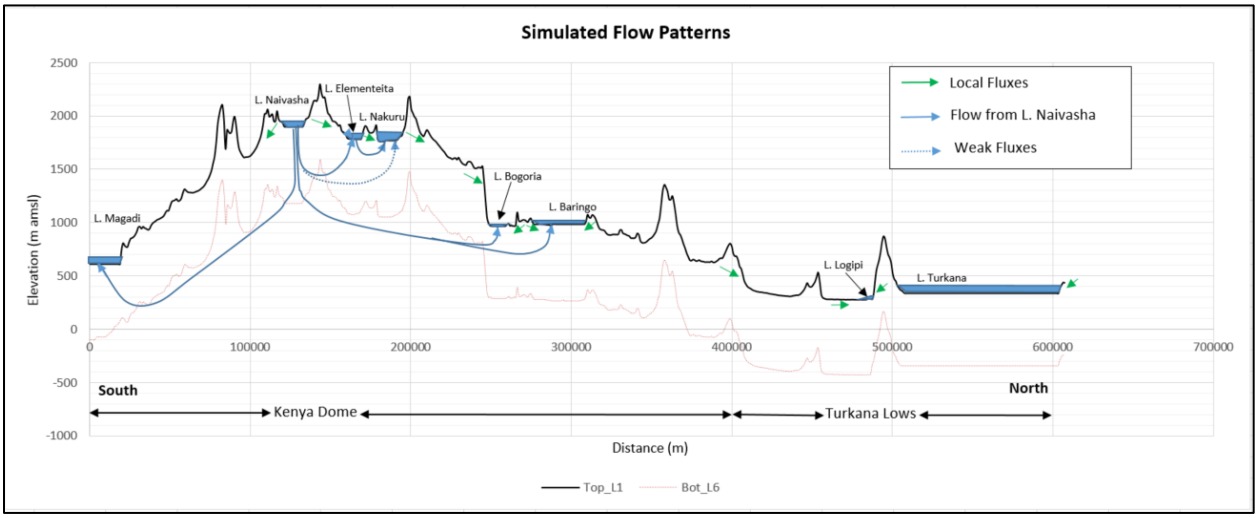


Figure 48: Simulated groundwater flow matrix for the entire model

From the analysis of flux directions in space, the modelling of groundwater flow has revealed two flow patterns: lateral flow pattern and axial flow pattern. Lateral flow into the lake basins originates from the escarpments towards the rift floor. Axial flow starts from the rift ridge at Lake Naivasha thereafter the bulk of the flow from the lake was to the south through the Olkaria & Suswa volcanic complexes and North and North West towards the lakes Elementeita and Nakuru. The Northward flow from Lake Naivasha flows towards and through the Eburru hills and Elementeita Lake basin as was discussed by (Clerke et al., 1990). The extent of this northward flow from Lake Naivasha is not beyond Lake Baringo.

6. CONCLUTIONS AND RECOMMENDATIONS

6.1. Conclusions

The conceptualization of this regional model was based on previous studies and current science. It is therefore reasonable as evidenced by results which are reliable as demonstrated by the comparison between the observed and simulated measurements. The mathematical representation of boundary conditions was also reasonable for the objectives of the study. The model was calibrated with 1km X 1km coarse grids which is fairly good spacing for a regional groundwater models. However, for detailed modeling around the lakes, further refinement to the grid spacing could give better accuracy to the model solutions. Model calibration would have possibly been improved by further breaking down the spatial discretization of some parameters such as recharge, hydraulic conductivity zones and more reliable rainfall estimates. But without more field data the suggested discretization is unjustified

iMOD as a chosen environment for the computer code proved to be a powerful tool in simulating flow lines within the model domain. The iMOD model was best suited for simulation of groundwater flow fluxes and also to provide a general sense of interaction between the lakes. As such, the model may be useful for a region-wide water resource management strategy implementation by integrating the model results with other anthropogenic utilization of groundwater to increase the level of sustainable production and good stewardship of groundwater resources in the rift valley. However, limitations of the model – like any other, should also be taken into account. Water managers should be aware of the model's limitations chief amongst which is that the model is susceptible on the accuracy and variety of input datasets

The research hypothesis of discontinuous flow is not proven since the study results have revealed linkage among the lakes through groundwater. It has been observed that regional groundwater flow is from the Rift Valley flanks toward Lake Naivasha in the rift floor, then diverted southward into Lake Magadi and northwards to Lakes Elementeita and Nakuru guided by good hydraulic gradients and existing faults which form barriers or conduits. The morphological setting of the Rift valley lakes, geology and structural setting in the study area likely controls the flowpaths but not in simple ways. The existence of highly fractured and porous volcanic rocks, alignment features such as volcanoes and faults create highly permeable environments for groundwater flow through the aquifers. But information about resistance to groundwater flow through the major faults is largely unknown and is partly responsible for the failure to simulate flow from Lake Baringo.

Moreover, several serious input data constraints have limited the ability of the model to perform better in order to enhance our current understanding of the groundwater resources and the potential impacts of economic activities including geothermal power generation, irrigation, domestic use and tourism. For instance, lake bathymetry data for some of the lakes did not exist and had to be sketched. The observed discrepancies between net inflows to the lake volume changes indicate possible measurement errors in some model forcings. Runoff calculation as a steady state input was a challenge to estimate since the generation of runoff responds differently to every sub-catchment size, land cover, hypsometry, rainfall amount and intensity. Other uncertainties in the model input parameters include; recharge estimations, anisotropy, horizontal hydraulic conductivity and storage coefficients for respective sub-catchments. Values for these parameters were chosen within the general ranges of published literature values and therefore the model is dependent in part by the accuracy of those estimates

6.2. Recommendations

Although this study has contributed to the understanding of groundwater flow in the Rift Valley, it also provides a basis for further studies. There is need for instance to further characterise the hydrostratigraphic units beyond what is provided in existing literature. The development of the 3D solid model in iMOD failed due to insufficient borehole logs to spatially characterize lithology. Similarly, there is a very strong need for setting up a groundwater monitoring network within the study area. Groundwater monitoring sites need to be carefully located to define accurately water table configurations, groundwater recharge zones and direction of seepage. It is necessary to sink groundwater observation wells and install necessary scientific equipment needed to provide accurate and continuous data on piezometric heads, lake levels and river stage. The network should comprise wells specifically dedicated for monitoring and should not include production wells. Good groundwater management requires a thorough understanding of the interaction among the lakes and causes of lake level dynamics to be prepared not only for extreme events but also for managing long-term water abstraction regimes. To achieve this, more information based research on the groundwater resources in support of sustainable management to meet rising populations, industry needs and potential climate change related threats would be required.

Since accurate hydrometeorological data and analysis is crucial to provide a technical basis for decisions on the quantity of water available and economic development activities in the study area, there is need to improve collection of this data. There is an urgent need to set up more meteorological stations in the area to provide more reliable data to be used in future modelling attempts. Satellite products should be used where insitu measurements are missing. Moreover, lakes can be extremely sensitive to changes in climate on a variety of temporal and spatial scales. Therefore, in order to quantify the linkages between the surface water and groundwater regimes, accurate meteorological data can help to establish whether or not the lakes are in equilibrium with the inflow and outflow terms or if the lake level fluctuations are due to climate variability. Increasing the number of river gauging stations will also be enhance reliability of observed runoff estimates which were a challenge in this study.

This study recommends iMOD as the MODFLOW modelling environment of the future due to its many advantages and particularly the ability to use one model with an expandable data set covering all possible future areas of interest. iMOD's consistency between regional and sub-domain models ensures that the era of building series of individual models is left behind. This means that further refinement of the model will be possible as and when additional data becomes available. Therefore this particular model can be used to predict and cater for projected effects of additional stresses in the Rift Valley system in future through updating input datasets, even in piecemeal.

This study also recommends that transient modelling would be ideal in future simulations since the use of time as a fourth dimension is imperative especially because temporally variable fluxes are more reliable than steady state.

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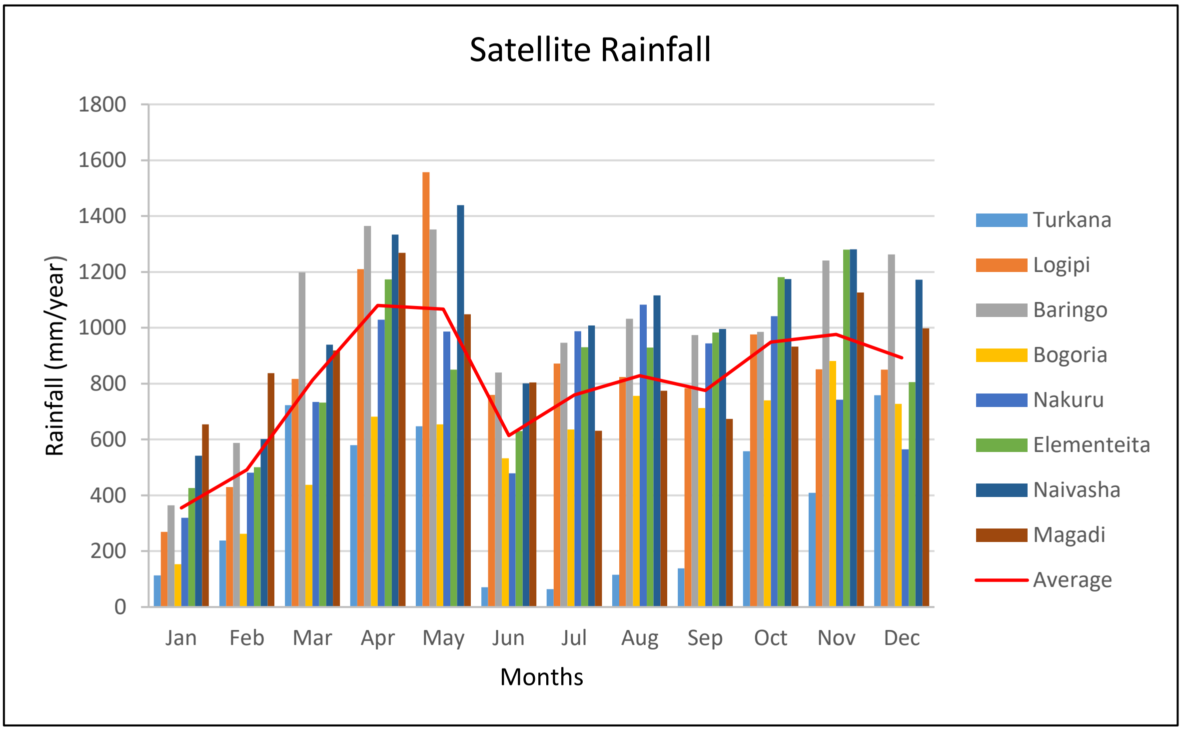
APPENDICES

Appendix 1: Lake Package input data used as driving forces in the modelling and validation exercise.

	Lake	**Precipitation (mm/Year)**		**Runoff (mm/Day)**		**Evaporation (PET)**		**Withdrawal**
		My Values	Olaka (2010)	My Values	Olaka (2010)	My Values	Olaka (2010)	My Values
1	**Turkana**	373.76	1400	0.780867	-	2314	2500	0
2	**Logipi/Suguta**	1199.025	1000	0.010807	-	2165	2309	0
3	**Baringo**	1294.655	1000	0.175488	-	2450	2309	0
4	**Bogoria**	622.325	1000	0.121012	-	2254	2309	0
5	**Nakuru**	809.935	1200	0.089961	-	1356	1400	0
6	**Elementeita**	935.13	1200	0.208249	-	1527	1400	0
7	**Naivasha**	1373.495	1500	0.394521	-	1169	1250	0
8	**Magadi**	1269.115	1000	0.164918	-	1532	1750	0

Appendix 2: Graph of long-term satellite rainfall averaged between 2010 and 2014 in the study area.



Appendix 3: Lake Package parameterization details.

Lake ID		**Lake Stage**			**Area**		**Bathymetry**	
Name	No.	Min Stage (m)	Initial Stage (m)	Max Stage (m)	Lake Area (Km^2)	Catchment Area (Km^2)	Mean Depth (m)	Max Depth (m)
Turkana	8	370	375	380	1160.38	3141.95	35	114
Logipi/Suguta	7	270	275	280	24.98	13076.47	3	5
Baringo	6	970	975	980	149.28	6229.94	2.5	8
Bogoria	5	955	960	965	40.11	1166.74	5.6	10.2
Nakuru	4	1754	1759	1764	32.54	1657.15	2.3	2.8
Elementeita	3	1771	1776	1781	22.21	564.07	0.9	1.2
Naivasha	2	1881	1886	1891	151.22	3252.42	4.9	11.5
Magadi	1	595	600	605	84.22	3955.10	2	4

Appendix 4: Data for calculating simple water balances for respective lake basins

	Lake	**Surface area (Km^2)**		**Precipitation (mm/Year)**			**Evaporation (PET) (mm/Year)**		**Groundwater Exchange MCM/y**
		Basin (A_B)	Lake (A_L)	Basin (P_B)	Ratio Factor	Lake (P_L)	Basin (E_B)	Lake (E_L)	(Qg)
1	Turkana	3141.95	1160.38	373.76	0.5	186.88	Actual ET	2314	
2	Logipi/Suguta	13076.47	24.98	1199.025	0.5	599.5125	Actual ET	2165	
3	Baringo	6229.94	149.28	1294.655	0.5	647.3275	Actual ET	2450	
4	Bogoria	1166.74	40.11	622.325	0.5	311.1625	Actual ET	2254	
5	Nakuru	1657.15	32.54	809.935	0.5	404.9675	Actual ET	1356	24 (Muno 2002)
6	Elementeita	564.07	22.21	935.13	0.5	467.565	Actual ET	1527	15.7 (Muno 2002)
7	Naivasha	3252.42	151.22	1373.495	0.5	686.7475	Actual ET	1169	50.0 (Becht 2006)
8	Magadi	3955.1	84.22	1369.115	0.5	684.5575	Actual ET	1532	69 (Muno 2002)

Appendix 5: Seasonal statistics of satellite precipitation per sub-catchment

Lake	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
Turkana	113.0323	238.149	722.9355	579.1333	647.5806	70.56667	63.58064	115.3871	138.7	558.0968	408.8	758.2581	367.8517
Logipi	269.0011	429.0098	817.1291	1209.367	1556.548	759.2	872.2322	824.1935	783.5333	976.0022	851.6666	850.0968	849.8316
Baringo	363.7441	587.2364	1198.613	1365.1	1351.677	839.5	946.8806	1032.597	973.3333	984.9505	1241	1262.194	1012.235
Bogoria	153.3	261.7032	438	681.3333	654.6452	532.9	635.8065	755.9032	712.9667	739.7334	880.8667	727.6452	597.9003
Nakuru	319.0022	480.7931	734.7097	1029.3	986.6774	479.3667	987.8549	1083.226	944.1333	1041.388	742.1667	565.1613	782.8149
Elementeita	426.2258	500.2118	732.3549	1172.867	850.0968	630.2333	930.1613	928.9839	983.0667	1181.423	1279.69	804.8839	868.3498
Naivasha	541.6129	601.6207	939.5807	1333.467	1438.806	800.5667	1007.871	1115.723	995.1117	1174.358	1281.058	1172.356	1033.511
Magadi	654.5667	836.9827	918.3871	1267.767	1047.903	804.2167	631.0968	774.7419	674.0333	932.5946	1126.536	998.4516	888.9398
Average	355.0606	491.9634	812.7137	1079.792	1066.742	614.5688	759.4355	828.8443	775.6098	948.5683	976.4729	892.3808	

Appendix 6: Tabulation of all boreholes with details of aquifer thicknesses

UTMX	UTMY	ELEVATION	ID	OWNER	LOCALITY	TDEPTH	COND	WRL	SCREEN_I	SCREEN_II	YIELD
156991	10016691	2780	9742	NJOROGE, MAJ. GEN. H. W.	LENGENET SETTLEMENTS	123.0	400	0.0	3@110.6		0.0
159665	9983730	1870	9743	CHELAGAT, BRIG. R. Y.	KAMBI YA MOTO	229.0	400	174.0	1.5@94.5	3.1@184.4	0.0
219177	9923667	2120	9344	NORTH KARATI COMMUNITY	N.KARATI	160.0	91	100.0	6@105	6@135	4.5
177719	9969015	1856	9364	CATHOLIC DIOCESE NKR	PASTORAL CENTRE NKR	126.0	91	102.0	18@105		0.0
170919	9987495	1980	9359	GICHOBO COMMUNITY	GICHOBO	193.0	91	97.0	12@160	3@187	2.7
215058	9920014	1930	9357	NAIVASHA T. C.	NAIVASHA	140.0	91	76.0	6@88	9@115	10.3
215840	9916474	1885	9352	NAIVASHA M. SEC. SCH.	NAIVASHA	100.0	91	78.0	12@79		4.0
215174	9912491	1926	9351	HANDAMAN, D. H.	NAIVASHA	100.0	91	42.0	6@66	3@75	6.0
219844	9926765	2180	9347	NEW KARATI FARMERS	N.KARATI	190.0	91	130.0	6@139	6@154	4.5
204362	9925208	1950	9345	MIRERA MIGAA COMMUNITY	MIGAA	130.0	91	71.0	15@75		7.2
215058	9920678	1880	9339	NAIVASHA PARISH	PARISH CAMP NVSHA.	90.0	91	44.0	8@54	4@74	8.0
181392	10003076	1756	9154	OYUGI, HEZEKIAH	CHEMELIL	70.0	48	18.6	6@64	12@28	6.0
179166	10022597	1960	9441	GITAU,G.M.	MAILI SABA	116.0	59	69.0	24@92		7.6

189191	10005533	2012	10714	EDGEWOOD COMMUNITY	EDGEWOOD	60.0	91	14.4	5@43	3@52	7.7
213949	9912158	1920	10708	KIO GITAU	KENVASH	60.0	91	20.7	30@27		9.0
196464	10091648	1245	10707	KIANGAZI/CESARE	BELLINGERI	65.0	91	44.6	18@42		9.0
225644	9911502	2460	10706	KINUNGI COMMUNITY	KINUNGI	200.0	91	96.2	6@120	9@174	6.0
159672	9956725	2641	10704	EGERTON CO-OP.	NJORO	190.0	91	69.7	9@111	9@138	9.8
207241	9970349	2560	10703	OL'KALOU CATH. MIS.	OL'KALOU	130.0	91	30.8	12@81	15@99	0.0
167844	10105137	915	3868	D.W.D	NGINYANG	122.0	120	9.3	6@36		9.8
212384	9922557	1900	4161	VIAK LTD	NAIVASHA	52.0	120	16.0	5.4@46		36.0
208707	9924436	1905	4178	VIAK LTD		52.0	120	16.0	6@45		36.0
162675	10024072	1160	10824	AYWEYO WOMEN GROUP	NYANDO	35.0	48	4.0	3@32		0.0
219957	9923557	2180	11094	GOOD F.KARATI COMM.	KARATI-NAIVASHA	200.0	91	121.0	6@144	6@191	3.6
180951	9967466	1880	10813	CATHOLIC D.OF NKR.	CDN-PLOT-LANET	130.0	91	69.2	15@100		5.1
186188	10037811	1900	10812	CHOMU COMMUNITY	CHOMU	175.0	91	121.0	12@138		6.8
181841	9968905	1890	10809	CDN KIAMUNYEKI COMM.	KIAMUNYEKI	120.0	91	37.3	12@40	6@111	7.0
180505	9966249	1910	10764	MUHAMED HUSSEIN M.N.	LANET/KIAMBOGO	150.0	27	136.0	20@130		5.4
214275	9926319	1929	4155	NIMONO J.N.	NAIVASHA	183.0	120	27.0	22@58		32.7
210599	9928088	1920	4177	VIAK LTD	NAIVASHA	52.0	120	16.0	6@45		5.4
173381	10051648	1000	6365	D.W.D	NGAMBO	60.0	0	20.3	18@42		1.5
185418	9937480	1960	13910	GINGALILI (1968)LTD.	GINGALILI FARM	144.0	97	83.6	18@84	12@126	4.3
223577	9851210	1799	11038	ALOUKIK PROPERTIES	BIASHARA STREET	254.0	808	123.0	53@177		14.4
223020	9850877	1654	10954	AFRAHA WATER	KAREN	140.0	480	0.0	6@74	6@68	0.0
232899	9886728	1565	7626	KARIUKI, EZEKIEL	NDEIYA	248.0	46	139.0	18@141		0.5
231019	9871018	2200	6060	NGUGI P.M	ZAMBEZI	187.0	48	91.0	6@175	12@159	0.0
235019	9881198	2330	11103	MWICHARO HARISON	BIBIRION	267.0	88	192.0	60@178		7.5
232893	9894913	2090	4152	A.I.C.KIJABE	KIJABE	145.0	0	11.0	36@76	20@125	1.8
195238	9908716	1900	11033	KONGONI GAME VALLEY	SOUTH LAKE RD.	52.0	808	20.0	9@41		28.0
236643	9815715	2225	6007	GIKANGA NGANGA	ONDIRI	112.0	0	38.0	36@69		36.7
200625	9861697	1500	11149	KITONGA SILA B.	SENGANI-TALA	80.0	106	6.7	6@26	18@58	0.8