GROUND AND SURFACE WATER FLOW MODELING IN THE LAKE NAIVASHA BASIN

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ABSTRACT

Lake Naivasha and surrounding aquifer in the Kenyan Rift Valley plays an important role in economy and development of the area because of supplying freshwater which is being extensively used for irrigation, tourism and domestic purposes. Although many studies have been done to investigate the Lake Naivasha and its surrounding aquifer interaction, still the groundwater system in the full extent of the Lake Naivasha Basin is not well known. Previous studies show that the Lake Naivasha outflow is around 50 MCM/year which it flows to north to the Lake Elementaita and to the south to the Hell's Gate. The objective of this research is to model groundwater flow in the full extent of the Lake Naivasha and Lake Elementaita basins and include the ground and surface water interaction.

The steady state groundwater flow modelling in the Lake Naivasha Basin was carried out by using MODFLOW through ModelMuse software (version 3.8.1) and the lake-aquifer interaction was investigated by using Lake Package (LAK7). This model has 1000 meters depth with 10 layers and the grid cell sizes are 1km * 1km. The boundary conditions in layer 10 are different with other layers and limited to no flow in the east and north; and general head boundary in the west and south. The average annual actual evapotranspiration has been estimated based on simple water balance method and then spatially distributed to the study area based on surface elevations through ArcMap 10.3 software. Recharge has been calculated by subtracting raster maps of average annual actual evapotranspiration from precipitation. The average annual recharge rate for the Lake Naivasha and Lake Elementaita Basins is estimated 0.089 and 0.046 m/year, respectively.

The steady state model calibration for 25 hydraulic conductivity zones has been done manually which the calibration target were piezometric water levels observed from 31 boreholes. Based on the simulated hydraulic heads and water balances, groundwater flow directions are presented. The results of this study show that groundwater fluxes are laterally from the west and east escarpments to the valley floor and axially from the Lake Naivasha northerly to the Lake Elementaita and also Lake Nakuru Basin and southerly to the Hell's Gate. Net outflow from the Lake Naivasha into groundwater is calculated 57.5 Mm^3/year and the net inflow from the groundwater to the Lake Elementaita is estimated 14.21 Mm^3/year.

Keywords: Surface-groundwater interaction, Lake Naivasha, Lake Elementaita, water balance

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1. INTRODUCTION

One of the vital resources for the human is water. The water cycle, which also known as the hydrologic cycle, is one of the most important systems in the world. The main components of this system are: precipitation, infiltration, evapotranspiration, groundwater flow and surface runoff (Zhang, 2014). Groundwater studies are crucial for understanding the vast number of lake systems due to effects of groundwater on lake's water budget (Becht & Nyaoro, 2006).

Groundwater resources play a significant role in economic development and population growth in the past half century (Mekki, Jacob, Marlet, & Ghazouani, 2013). However, this development has the cost of intensifying pressure on these water resources (Foster, S., Loucks (2006); Jago-on et al. (2009)). For instance, high rates of groundwater abstraction have led to the reduction of aquifer levels (Ebraheem, Garamoon, Riad, Wycisk, & Seif El Nasr, 2003).

Lake Naivasha which is located in Kenya's Rift Valley creates the unique scene for a wide range of natural and human processes. Providing domestic water, protecting innumerable animal species, allowing trawling and tourism are just some examples of the many services which are provided by Lake Naivasha. Moreover, according to World Wildlife Fund's (WWF) report, exporting the agriculture originating from this area has a remarkable share in Kenya's GDP and around 50000 people are employed directly and indirectly within the area(WWF, 2012).

Increase in water withdrawals from Lake Naivasha can influence on water table in the surrounding aquifers. Since the Lake Naivasha is the only lake in Kenyan Rift valley which has fresh water, growing the demand of water for different purposes is threatening the long-term sustainable development(Yihdego, Reta, & Becht, 2016). Quantitative estimation of the available water resources is absolutely necessary to design an informative action plan which lead to the sustainable management of the water resources in the Lake Naivasha Basin. In order to quantify the water resources, water balance studies have been extensively used. In this research, the long-term groundwater and lake water balance will be estimated through groundwater flow modelling.

1.1. Problem, objectives and research questions

1.1.1. Problem definition

Understanding the groundwater system in the Kenyan Rift Valley is one of the most challenging topics and complicated jobs in hydrogeology. The difficulty for the Rift Valley lays in the fact that the geology and volcanic structure are very complex(Armstrong, 2002). Moreover, change of some parameters in both time or space (such as precipitation, evapotranspiration, aquifer geometry and specific capacity) can lead the groundwater modelling to a labouring task(Yihdego, 2005).

Although there are a lot of lakes in the Kenyan Rift Valley (which is also known as Gregory Rift) only lake Naivasha has been studied comprehensively due to its important role in supplying fresh water for agriculture, horticulture and ecology. Furthermore, the relationship between these lakes are unknown and has not been studied yet while it is necessary to have better understanding of regional groundwater flow system.

Based on previous studies, Lake Naivasha groundwater outflow is around 50 MCM/year however, no one knows for sure where this water goes. Groundwater modellers who have been working on Lake Naivasha area suggested that Lake Naivasha outflow goes to the Lake Elementaita to the North and towards Hell's Gate to the south. Their results show that the southern outflow was disappeared in the south boundary and no study has been done to see where this outflow goes. This study aims to focus on groundwater modelling in the Lake Naivasha Basin with consideration of the Lake Elementaita.

1.1.2. Research objective

The objective is to model groundwater flow in the full extent of the Lake Naivasha and Lake Elementaita surface water basin and include groundwater and surface water interaction.

1.1.3. Specific Objective

To develop and calibrate a steady-state groundwater flow model for the larger Naivasha Basin.
To determine the flow direction.
To determine the amount of groundwater inflow/outflow from/to Lake Naivasha and Lake Elementaita.

1.1.4. Research Question

What are the boundary conditions of the model?
What will happen for the southern outflow from the Lake Naivasha?

1.2. Literature Review

Lake Naivasha is located in the Kenyan Rift Valley has fresh water and no surface outlet but a significant groundwater outflow(Becht & Nyaoro, 2006).
A lot of works have been done in order to have a better understanding of groundwater resources in Lake Naivasha. The first studies have been started as early as the 1880's.
(McCann, 1974) mentioned in his report that "in the Naivasha catchment groundwater generally flows towards the lake from the Mau and Aberdare escarpments, although it is diverted locally by the presence of faults that either from barriers or conduits."
(Trottman 1997) implemented a groundwater model to figure out the interaction between Lake Naivasha and neighbouring aquifer and also investigate the groundwater storage changes corresponding to lake level fluctuations. Although, he oversimplified the model by many assumptions and generalizations.
(Baher 1997) Attempted to promote the concept of interaction between Lake Naivasha and the surrounding aquifers. He built a cross sectional model and optimized different aquifer parameters such as storage coefficient and transmissivity.
(Hermandez 1999) developed a groundwater model and calibrated it to determine the amount of water from Malewa River and Lake Naivasha to the field. Although, the weakness of his work is the scarcity of observations.
Many numerical models have been created to study the long-term water balance of Naivasha Basin(Yihdego, 2005). In numerical models, flow components such as: precipitation, infiltration, evapotranspiration, groundwater flow and surface runoff- must be considered(Anderson, Woessner, & Hunt, 2015). Lake level fluctuations are affected by changing these flow components.

(Ase, Sernbo, & Syren, 1986) focused on the surface hydrology of Lake Naivasha and he estimated monthly water balance based on mass balance equation. He also measured groundwater outflow around 50 m^3/month.

(Owor, 2000) worked on the long-term interaction between the lake and groundwater in order to estimate water budget for the lake and calculate water abstraction from surface and groundwater resources. Although, his model has some defects; for example he has not used any physical measurements (such as borelogs) to define the model's layers. Furthermore, he only used 45 observations to simulate a model for a period of 50 years (1932-1980).

(Reta, 2011) built a steady state model through GMS software and the calibration parameter was hydraulic conductivities of zones. He also used PEST to optimize the calibration method. However, the (Reta, 2011) model too have some structural errors. In layer definition, bottoms of aquifers located in higher position than the top elevation and it has resulted in to flawed MODFLOW consequences. Moreover, it sounds the model is not converged very well because of large amount of errors (around 60%) in groundwater balance closure.

(Yihdego & Becht, 2013) also created a steady state model through GMS software to study the interaction between lake and the aquifer. They calibrated the model by changing the hydraulic conductivity values for each zone and the calibration has been optimized through PEST. Although, their model encountered with the same lack of data of the detailed hydrostratigraphic data of the subsurface. Their model also could not be validated and has not been tested for other stresses than those for which it has been calibrated.

The characteristics of recent models which are the most remarkable ones are given in table 1. This table included summary of groundwater models by (Owor, 2000), (Yihdego, 2005), (Reta, 2011) and (H. J. Hogeboom, 2013).

Table 1. Summary of recent models in Lake Naivasha

	Owor(2000)	**Yihdego(2005) Yihdego & Becht(2013)**	**Reta(2011)**	**Hogeboom(2013)**
Type of model	Groundwater_steady state and transient	Groundwater_steady state and transient	Groundwater_steady state and transient	Groundwater_steady state
Computer code/Software	MODFLOW/PMWIN	MODFLOW/GMS	MODFLOW/GMS	MODFLOW/Model Muse
Spatial scale	500m grid	500m grid	500m grid	500m grid (Lake cell size is set to 250m)
Lake representation	Lake Package	'High K' method	Lake TINs	Lake Package
Layer definition	50m unconfined 10m confined	3 layers with different thickness	60m unconfined 100m confined	100m confined
Calibration method	Frist manual, then automatic(PEST)	Automatic(PEST)	Automatic(PEST)	Automatic(UCODE)
Calibration parameter	Hydraulic conductivity	Hydraulic conductivity and recharge	Hydraulic conductivity	Hydraulic conductivity
Validation	Sensitivity analysis only	Sensitivity analysis only	Sensitivity analysis only	-

One of the most important parameters in groundwater modelling is recharge. Nalugya (2003) tried to figure out the spatial and temporal distribution of recharge in Lake Naivasha area. He concluded that recharge in the study area is very low and it is affected by evapotranspiration, precipitation and soil
properties. Results of her works show that the highest recharge is 43.75 mm/year (around Kedong) and the lowest is 0.69 mm/year (around Ndabibi).
(Becht & Harper, 2002) used the long-term meteorological data of precipitation, evapotranspiration and river inflows for the period (1983-1998) and estimated the abstraction rate to be $60*10^6$ m^3/year.
(Mohammedjemal, 2006) explored the feasibility of artificial recharge north of Lake Naivasha. In order to study the infiltration capacity of the aquifer in the study area, he has done injection and hydraulic conductivity test.
Achieving a better conceptual view of geological process is fundamental to understand hydro-geological behaviours(Yihdego, 2005). (Nabide, 2002) created a 3D conceptual hydrogeological model for the Lake Naivasha area which is based on the combination of geology, hydrochemistry and boundary conditions data. His model is applicable to reduce the range of various assumptions made in previous models.

2. DISCRIPTION OF THE STUDY AREA

2.1. Location

Lake Naivasha is situated 80 km northwest of Nairobi and is located at the pinnacle of the central Kenya's Rift Valley with an average altitude of 1887masl, and dominates the central part of the basin which is carrying the same name of the lake (R. H. J. Hogeboom, van Oel, Krol, & Booij, 2015). There are some other major lakes in the Kenyan rift valley such as Lakes Turkana, Baringo, Bogoria, Nakuru, Elementaita and Magadi (H. J. Hogeboom, 2013); However, lake Naivasha is the most important one in this area due to having freshwater among many saline lakes. Moreover, its water is not only being used for municipal and domestic purposes but also is being exploited for irrigation, tourism and fishing (Yihdego & Becht, 2013).

Lake Naivasha Basin has an area of approximately 3376 km^2 and it is between longitudes 36^{o}09' E and 36^{o}24' E and latitudes 00^{o}30' S and 00^{o}55' S which is shown in figure 1 and figure 2. Lake Naivasha Basin includes Lake Naivasha, Ndabibi Plains to the west of the Lake and Ilkek Plains to the north (Owor, 2000). In North of Lake Naivasha, the first lake is Lake Elementaita which has an approximate elevation of 1776masl. Lake Elementaita is more than 100 m below Lake Naivasha and it absorbs most of the northerly groundwater outflow of Lake Naivasha(Yihdego, 2005).

The Rift is placed on the boundary of the division of African tectonic plate to two new plates. In the west of Rift valley, the Mau escarpment is located and it is formed the western wall of the Rift valley. The surface of Mau escarpment is very rough and engraved with a lot of faults and scarps that are common in this area (Reta, 2011); and the maximum elevation of Mau escarpment is 3080masl. In the east of Rift valley, Kinangop Plateau exists and it is prolonged to the south of Aberdare's mountains with an approximate altitude of 2400masl (H. J. Hogeboom, 2013).

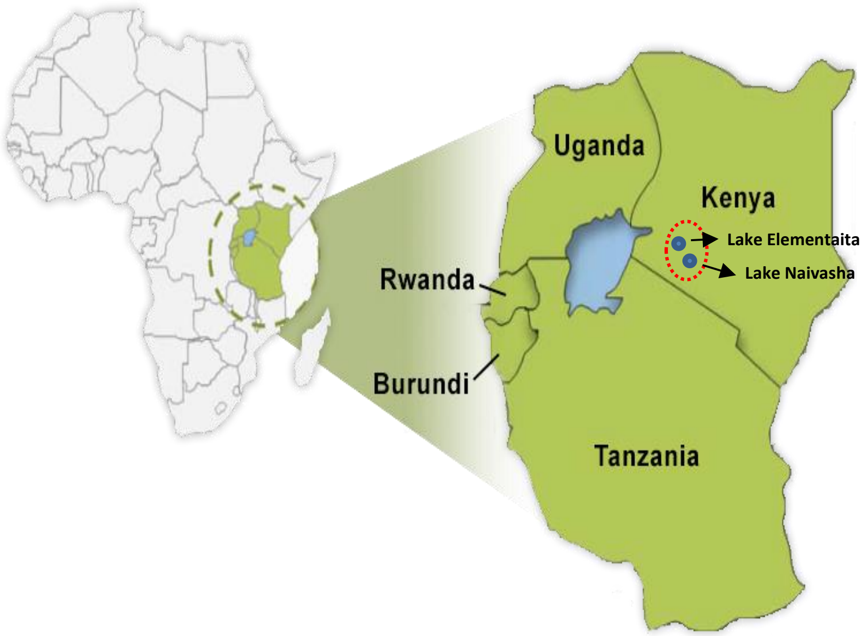

Figure 1. Location map of Lake Naivasha and Lake Elementaita in Kenya.

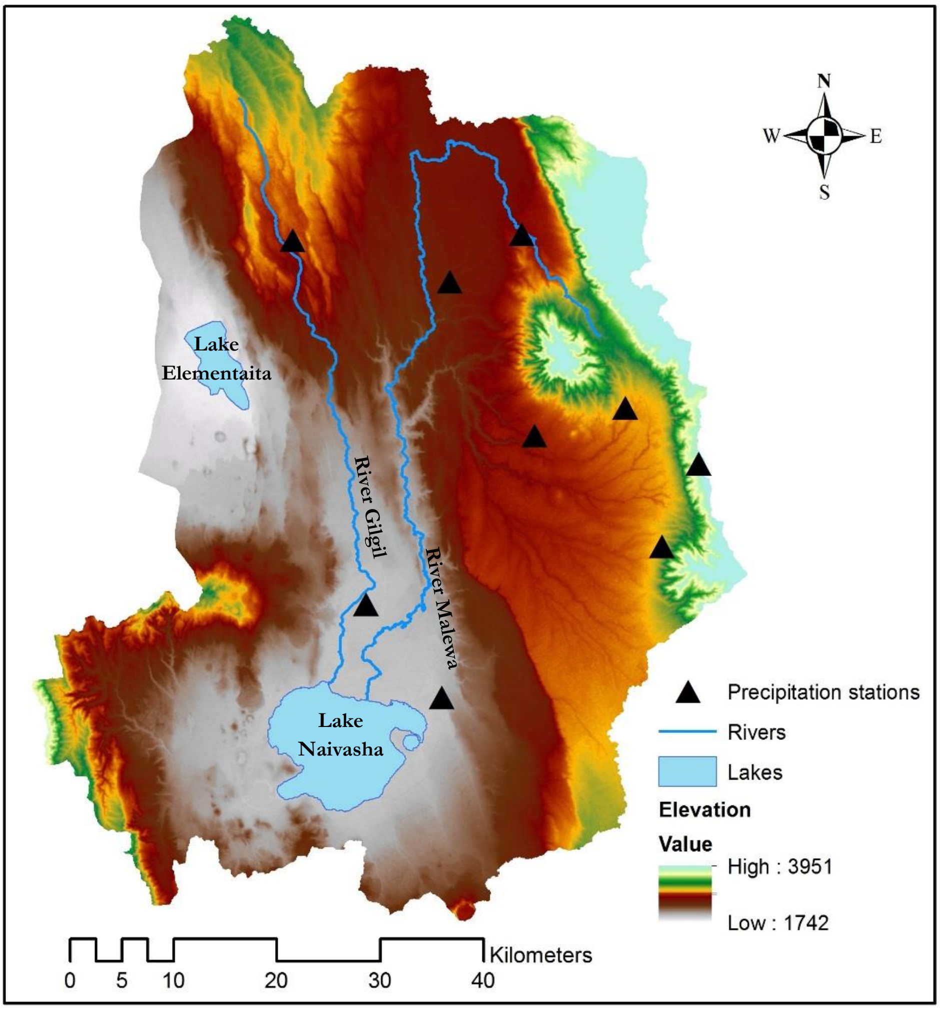

Figure 2. Lake Naivasha and Elementaita Basins showing elevation, the main rivers and the location of rainfall stations.

2.2. Geology and Hydrogeology

A good understanding of the geology and likely flow system is required to develop a conceptual model that will be translated in a numerical model using MODFLOW. Volcanic rocks have been formed by extensive volcanism and they consists mainly of ignimbrite, tuff, rhyolite, trachyte and basalts. During the geological evolution of the rift, these volcanic rocks have been extensively resulting in different transmissivity and hydraulic conductivity (Yihdego & Becht, 2013).

Aquifers in the igneous rock are confined or semi-confined and most likely with very low storage coefficient, whereas storage coefficient in the tuffs and sediments are much higher. The water level depth is in a range of 1m around Lake Naivasha to approximately 250m on the flanks of the rift or on volcanoes. The lake areas have often unconfined aquifer and the permeability values of various layers are comparatively high(Clarke, 1990).

Hydrogeology of Lake Naivasha Basin is very complex and it is affected by geology, topography and some climatic factors (Nabide, 2002). An undisputed aquifer map is lacking and hydrogeological data is very scarce so unfortunately not much details of the subsurface composition is revealed (H. J. Hogeboom, 2013).

Very generally the flanks of the rift, thus the higher parts of the basin are composed of solidified volcanic ashes and ingenious volcanic rocks, whereas the bottom of the rift is composed of a very complex setting of relatively young pyroclastic rock at the volcanic centres and sedimentary rocks composed of a mixture of volcanic ashes and erosion products of the higher parts of the basin, that are deposited in a riverine, deltaic or lacustrine environment.

2.3. Climate and hydrology

The Lake Naivasha and Lake Elementaita Basins are located within the semi-arid belt of Kenya which have the average precipitation of around 700 mm/year. The rainfall in Mau and Aberdare escarpments, where the average is around 1250 to 1500 mm/year, is much higher than near Lake Naivasha with an average rainfall of 650mm annually (H. J. Hogeboom, 2013).

The annual potential evapotranspiration has been estimated approximately 1500-1900mm/year by (McCann, 1974). With Comparison between monthly averaged data of rainfall and evapotranspiration, McCann (1974) estimated that evapotranspiration is 2 to 8 times higher than rainfall for every month (except April) during wetter years. The average monthly temperature is altering between 7-30^{o}C and the mean annual average temperature is 17^{o}C (De Jong, 2011). Figure 3 shows the hydrological cycle of the Lake Naivasha. For more information on climate and hydrology in the Lake Naivasha area, see (Meins, 2013b) and (Meins, 2013c).

The Lake Naivasha Basin is draining by one transitory and two everlasting rivers which all discharges to Lake Naivasha (Reta, 2011). The transitory Karati River drains around 149 km^2 of the eastern part of the catchment and is only permanent in its upper areas. The Malewa and Gilgil Rivers drain 1600 km^2 and 527 km^2, respectively. Discharge from Malewa and Gilgil Rivers is around 523360 m^3/day and 69120 m^3/day, respectively (Becht, Odada, & Higgins, 2005).

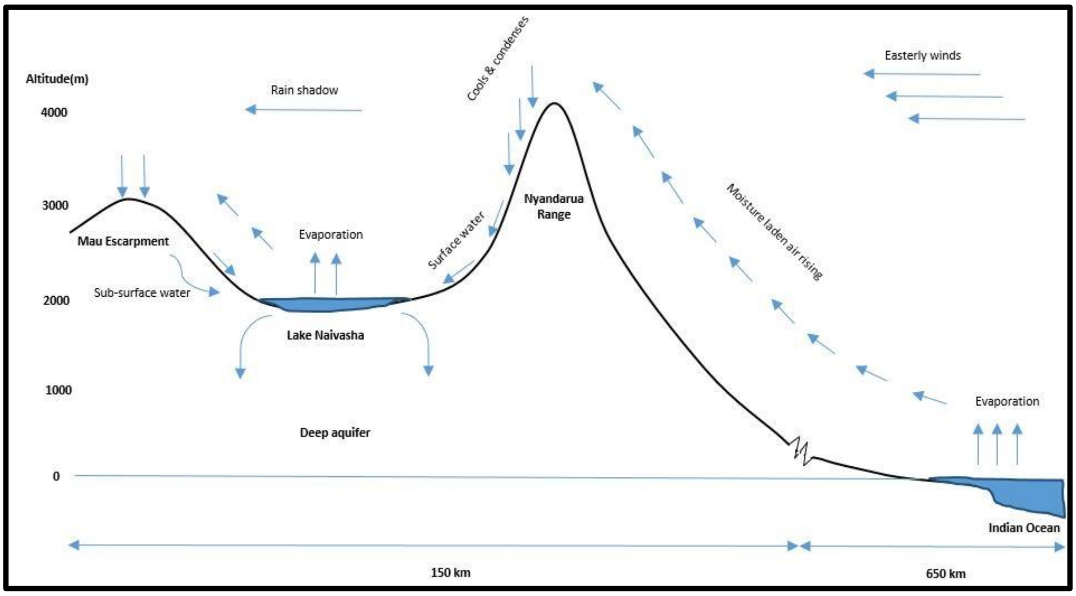

Figure 3. Hydrological cycle of the Lake Naivasha. Edited from Meins (2013a)

2.4. Lake morphology and general setting

Lake Naivasha is shallow and the average depth of the main lake is approximately 4-6 meters, whereas the bottom of the satellite lake enclosed by Crescent Island reaches some 18 meter.

Over the past millennium, Lake Naivasha experienced serious temporal changeability of water levels. In some periods, it had much higher water levels than at present, but it also has gone lower in some years. For more information on water level variations in Lake Naivasha, see (MOWD, 1982). Lake level fluctuation for Lake Naivasha and Lake Elementaita is shown in figure 14 and figure 15, respectively.

2.5. Geologic setting

Generally, the geology of the study area is composed of volcanic rocks and sedimentary rocks. The geological structures of the basin are very complex and due to complex geology, hydrogeology is also very complex.

The sediments of the lake are made up of alluvial, reworked volcanic and wind deposits. The volcanic units are trachyte and tuff units(Nabide, 2002).

The volcanic rocks and their secondary sediments transported and sedimented by rivers and wind show more desirable hydraulic properties than in the highland volcanic (H. J. Hogeboom, 2013). Although, the effects of deep faulting and broad spatial heterogeneity in the Rift Valley have to be considered. Faulting and fracturing enormously affect groundwater flow patterns. Faults may prefer either conduits or barriers to flow depending on whether they are in tension, compression or shear (Faunt, 1998).

The stratigraphy of volcanic rocks is very complex and due to the scarcity of stratigraphic data, acknowledged aquifer mapping is not present (Nabide, 2002).

2.6. Groundwater system

(Clarke, 1990) presented in his work that the reason of having complex hydrogeology in this area is that while the lake has been located at lower elevations than the rift escarpment, it is at the pinnacle of the Rift floor. Also, he has mentioned that without any doubts groundwater flows out from Lake Naivasha because the water in the lake is fresh, although, there is no outlet from the lake and it is in a high evaporation area. To the north, the flow may happen through Gilgil and under Eburru and to the south also groundwater must flow based on the hydraulic gradient.

(Becht, Mwango, & Muno, 2006) proposed that water is going from Lake Naivasha horizontally to shallower layers and vertically to deep-seated geothermal layers. Another discussion topic on groundwater flow is about the interaction between the lake and the surrounding aquifer. (Becht & Nyaoro, 2006) advocated that when the lake levels ascend, the surrounding aquifer will be recharged by the lake; vice versa, if the lake level dwindles the lake will be drained by the aquifer.

Analysis of piezometric map and isotopic studies demonstrate that the groundwater flows along the rift and from the neighbouring highlands into the rift. Besides, piezometric plots and aquifer properties show that much of groundwater outflow from Lake Naivasha basin is going to the south (Reta, 2011).

Based on literature, the percentage of outflow to the south beyond Hell's gate and to the north in Lake Elementaita is estimated approximately between 30-35% and 65-70%, respectively (H. J. Hogeboom, 2013). Figure 4 shows the head distribution and the general flow direction in the vicinity of the Lake Naivasha.

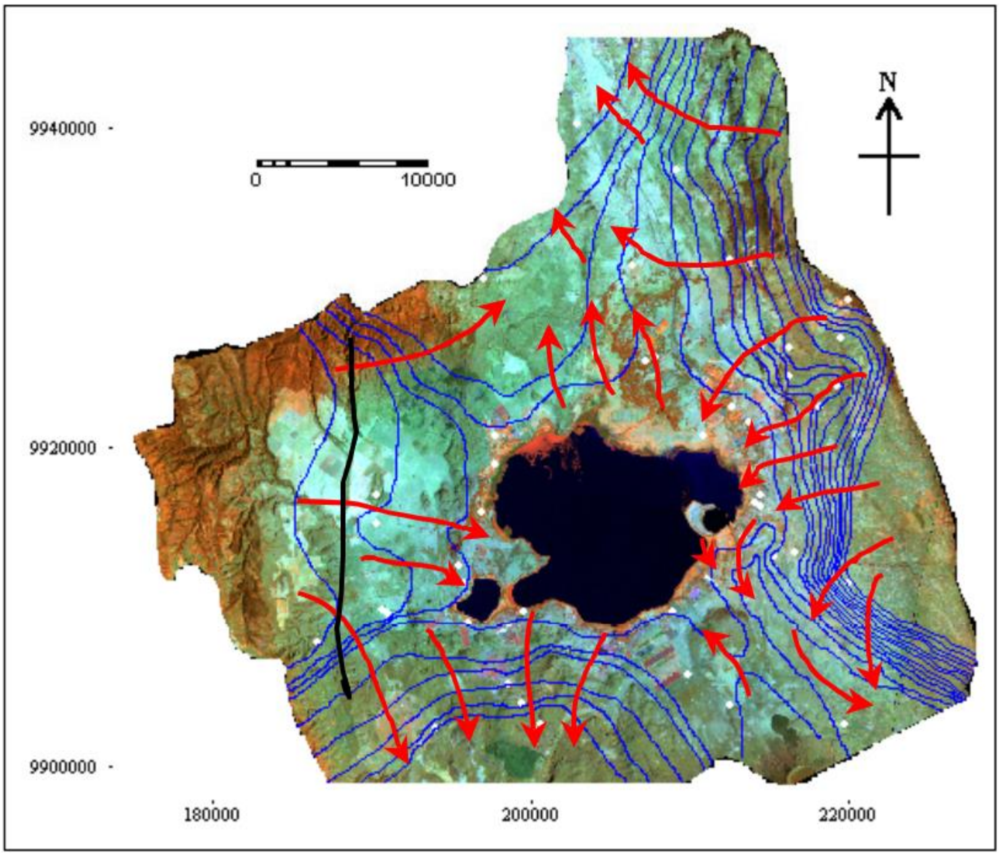

Figure 4. Hydraulic head distribution and flow direction around Lake Naivasha. Adapted from: Owor(2000)

3. METHODOLOGY

This chapter focuses on data collection during and after fieldwork and also analysis of the data for the model. The data which will be discussed are surface elevation, precipitation, evapotranspiration, lake level and recharge. The following flowchart shows the summary of activities which have been done to reach the objectives of this research.

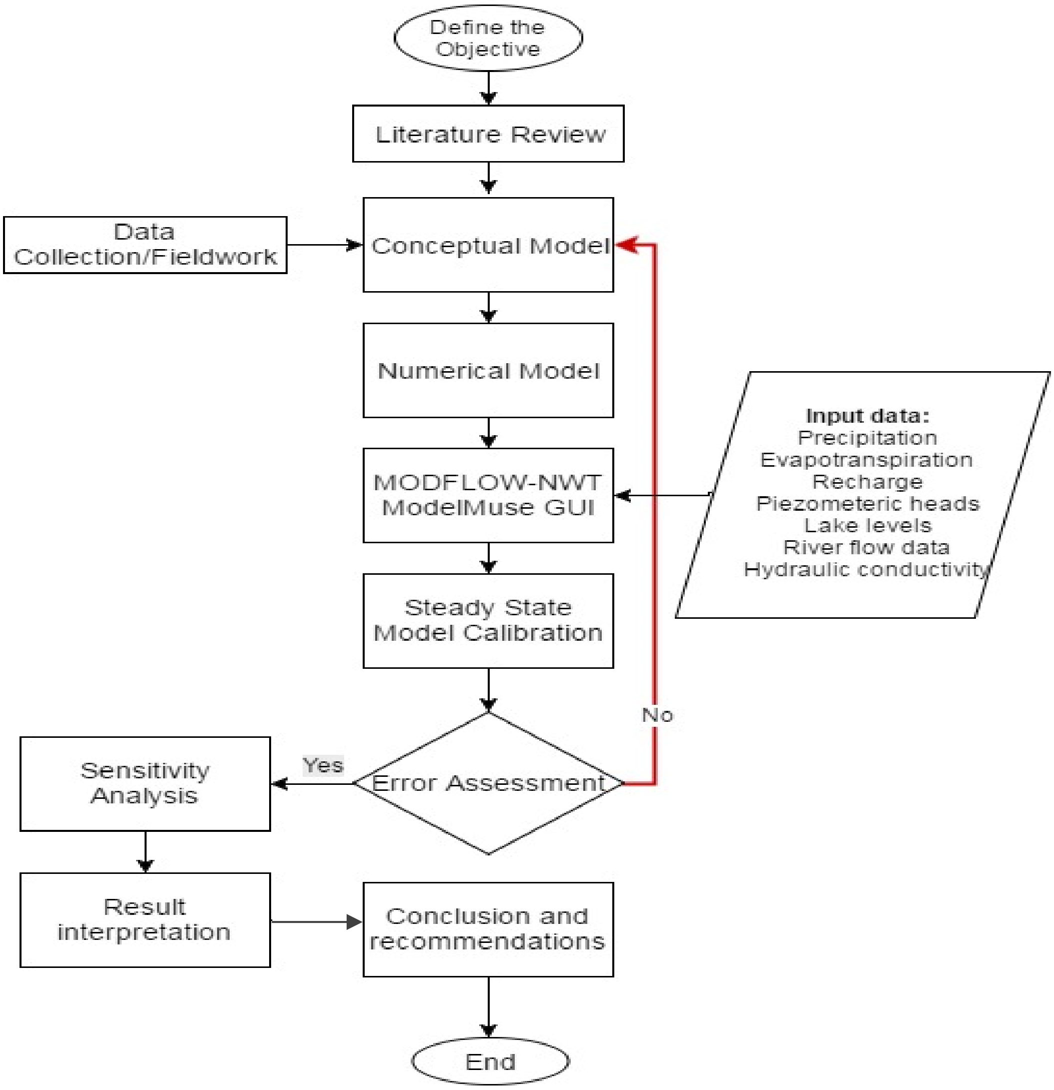

Figure 5. Summarized methodology flowchart

3.1. Pre-fieldwork

In the initial step of this study, literature review has been done to get to know the necessary information for groundwater modelling in this area. Then, exploration of data is done to gather the available data from different references such as papers, MSc thesis and also ITC database.

The data which has been collected before fieldwork are: some groundwater well records, piezometric level data and digital elevation model which is download from USGS server.

3.2. Fieldwork

A 21-day fieldwork was done in Kenya from 6th-27th September 2016. The necessary data was collected from different organizations such as Water Resources Management Authority (WRMA)-Naivasha, Kenya Meteorological Department (KMD)-Nairobi and Ministry of Water Development (MWD).
During fieldwork the following activities have been done:
Collecting the description of geological observation points, collection of recently drilled boreholes and Levelling of wells to define the ground water flow gradient near the Lake Naivasha and Lake Elementaita.

3.3. Post fieldwork

After fieldwork, the data which had been collected from various sources was compared with the data from previous studies. Moreover, the data processing and analysis has been done and the existence of gaps were checked.
Then, the conceptual model was developed and the input data was prepared as raster maps and imported to ModelMuse to create the numerical model. Lastly, the calibration of the numerical model and sensitivity analysis were carried out.

3.3.1. Precipitation

One of the vital parameters in groundwater modelling is rainfall which will be used to calculate the amount of water that flows to the lake as either surface water or groundwater. In this study, the daily precipitation data for the period of 2010-2015 has been downloaded from USGS and then by map calculation in ArcGIS, monthly and annual precipitation have been calculated. Figure 6 shows the average monthly rainfall data from FEWSNET for the period of 2010-2015. The average annual computed rainfall data from USGS has been compared with previous works and the results show that the rainfall values from USGS are higher than other sources. Based on FEWSNET data, the average annual rainfall for Naivasha Basin and Elementaita Basin is approximately 1033mm/year and 868mm/year, respectively.

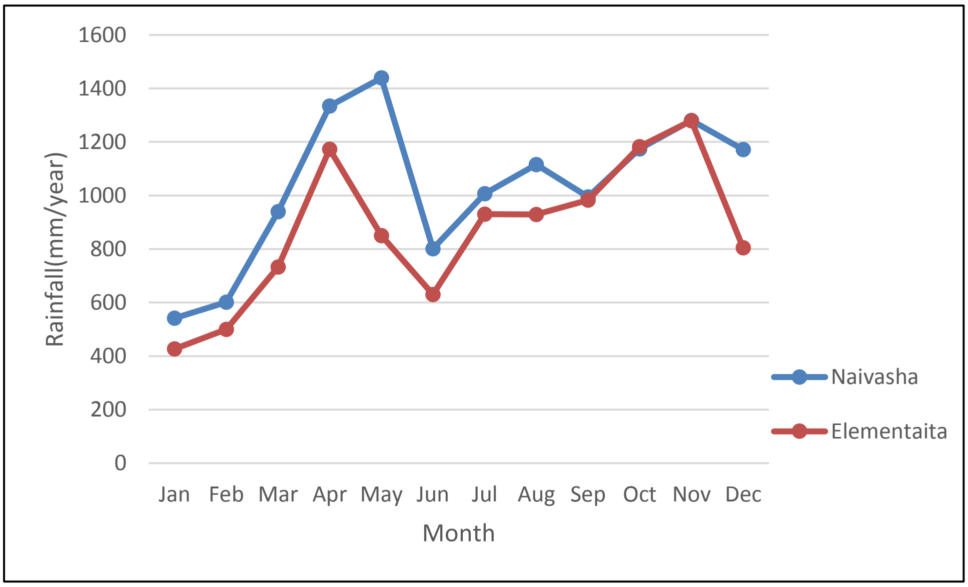

Figure 6. Average annual rainfall data for the period of 2010-2015. Source: FEWSNET. Average for Lake Naivasha Basin is 1033 mm/year and for Lake Elementaita Basin is 868mm/year

(Bhandari, 2005) collected precipitation data from 72 rainfall stations within the Lake Naivasha Basin and he calculated the mean annual rainfall by using SPSS and EXCEL. After analysing data, he claimed that there is a relationship between average annual rainfall and elevation in this study area and the correlation coefficient is equal to 0.5. Based on his work, the average annual rainfall for Lake Naivasha Basin and Lake Elementaita Basin is 1000 and 800 mm/year, respectively.

Despite the fact that I have spent considerable time in processing the FEWSNET (USGS) rainfall estimation, the results were not very satisfactory and I have used the method of Bhandari (2005) to estimate the rainfall rate.

The rainfall data of seven rainfall stations for 2010-2014 was obtained from Kenya Meteorological Department (KMD) and then the average annual precipitation was calculated and interpolated based on DEM file. Lastly, the average annual rainfall for the Lake Naivasha and the Lake Elementaita Basins has been calculated as 935 and 840.mm/year, respectively. The average precipitation on the Lake Naivasha is 686mm/year and Lake Elementaita is 770mm/year. Kriging method has been selected for interpolation similar to (Bhandari, 2005)'s method. Figure 7 shows rainfall distribution on the study area. The summary of previous works and results of this study are given in table 2.

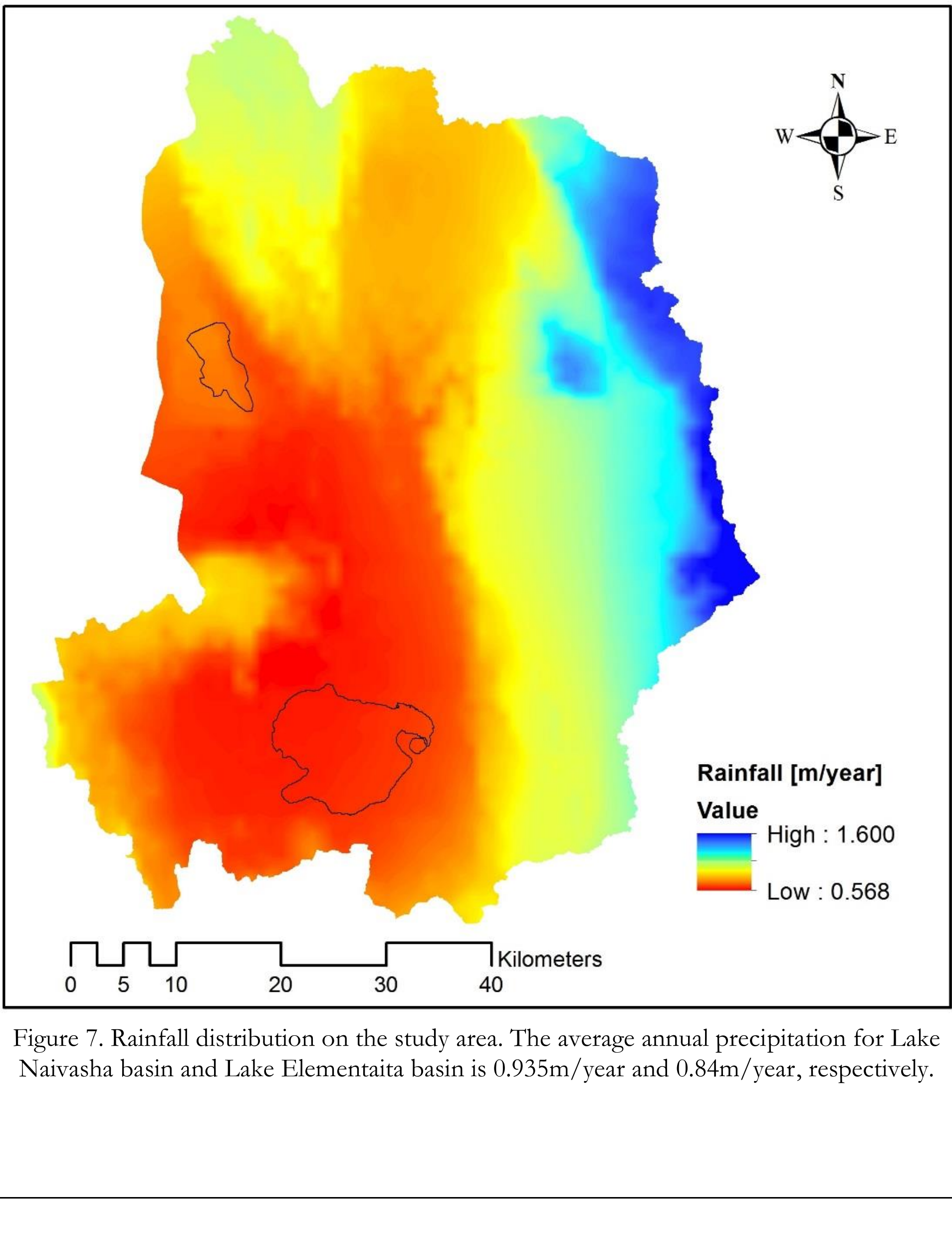

Figure 7. Rainfall distribution on the study area. The average annual precipitation for Lake Naivasha basin and Lake Elementaita basin is 0.935m/year and 0.84m/year, respectively.

Table 2. Summary of previous works for precipitation in the Naivasha and Elementaita basins. (Units: mm/year)

	Bhandary(2005)	Odongo (2016)	FEWSNET data(2010-2015)	**This study**
Lake Naivasha Basin	1000	920	1033	935
Lake Elementaita Basin	800	-	868	840

3.3.2. Evapotranspiration

In the first step, the daily potential evapotranspiration data for the period 2010-2015 from USGS Famine Early Warning Systems Network (FEWSNET) Data Portal has been downloaded. Then, the average monthly and annual evapotranspiration data has been calculated in the ILWIS software.

FEWSNET potential evapotranspiration is a daily global product which is calculated based on climate parameters that acquired from Global Data Assimilation System (GDAS) analysis fields. The GDAS inputs are air temperature, wind speed, relative humidity, radiation (included long wave, short wave, outgoing and incoming) and atmospheric pressure at the surface(Gathecha, 2015).

Based on Penman-Monteith equation, the daily potential evapotranspiration can be calculated as follow:

$$E_p = \frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta+\gamma}E_a \qquad (1)$$

In this equation, E_p potential evapotranspiration (mm/day), Δ is the saturation vapour pressure gradient which is varying with temperature (kPa/^{0}C), λ is the latent heat of vaporization (MJ/kg), R_n is the net radiation to the surface (MJ/m^{2}day) and E_a is the aerodynamic component which depends on the daily wind speed (m/s), average vapour pressure (kPa) and saturation vapour pressure (kPa).

An alternative approach is based on the basin-wide water balance. The average actual evapotranspiration of the basin can also be derived from the basin water balance assuming an average rainfall. Thus, the idea of calculating ET_a based on water balance equation for Lake Naivasha has been proposed.

The water balance equation based on mass conservation law can be written as the following equation below.

$$P + SW_{in} + GW_{in} = E + SW_{out} + GW_{out} + \Delta V \qquad (2)$$

Where P is precipitation, SW_{in} and SW_{out} are surface water inflow and outflow, respectively. E is Evaporation and GW_{in} and GW_{out} are groundwater inflow and outflow, respectively. ΔV is the change of water volume which is stored in the lake during the modelling.

Considering the equilibrium condition for the lake area, equation 2 can be simplified to calculate the interaction between the lake and groundwater system. Equation 3 is the simplified version of equation 2 which is used in this study to determine the average ETa of the basin.

$$A_B\,(P_B\text{-}ET_B) = A_L\,(P_L\text{-}E_L) - Q_g \qquad (3)$$

Where A_B [L^2] and A_L [L^2] represents the area of the basin and the lake area, respectively. P_B [L/T] is precipitation of the basin, P_L [L/T] represents the precipitation on the lake, ET_B [L/T] is actual evapotranspiration from the basin and E_L [L/T] is evaporation from the lake. Q_g [L^3/T] is the net groundwater flow. Components of the simple water balance method are shown in figure 8.

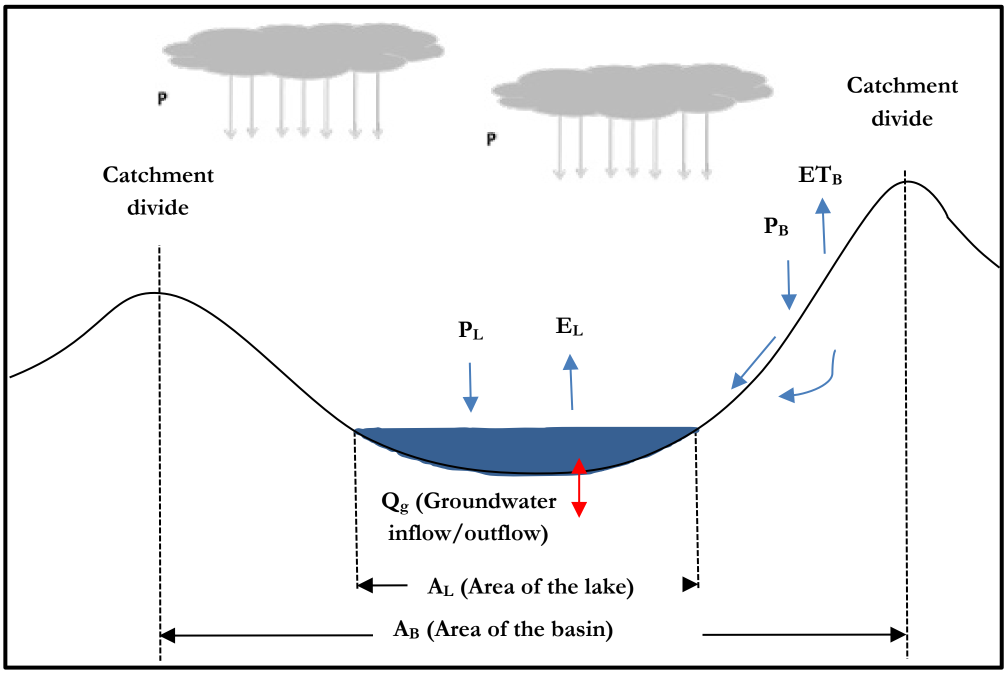

Figure 8. Schematic section of catchment showing components of the simple water balance method.

Considering that all parameters (except ET_B) are known for the Lake Naivasha Basin, average annual evapotranspiration can be calculated. By assuming that there is a linear relationship between evapotranspiration and surface elevation, the calculated ET_B was spatially distributed over the study area based on DEM file. Based on equation 3, the average annual ET has been computed 950mm/year. The data for the simple water balance method is given in table 3.
Regarding the fact that the Lake Elementaita were not studied adequately and the groundwater exchange is unknown, and also because of having a very small area in compare with the Lake Naivasha Basin, ET_B has been calculated based on the Lake Naivasha data and then spatially distributed for whole the study area. The map of spatially distributed average annual evapotranspiration is shown in figure 9.

Table 3. Data for the simple water balance method.

Lake/Basin	**Precipitation (mm/year)**			**Evaporation (mm/year)**		**Area (km²)**		**Groundwater exchange (MCM/year)**
	Basin (P_B)	Lake (P_L)	Ratio	Basin (ET_B)	Lake (ET_L)	Basin (A_B)	Lake (A_L)	Qg
Naivasha	935	686	1.36	Actual ET	1695	3252	140	50

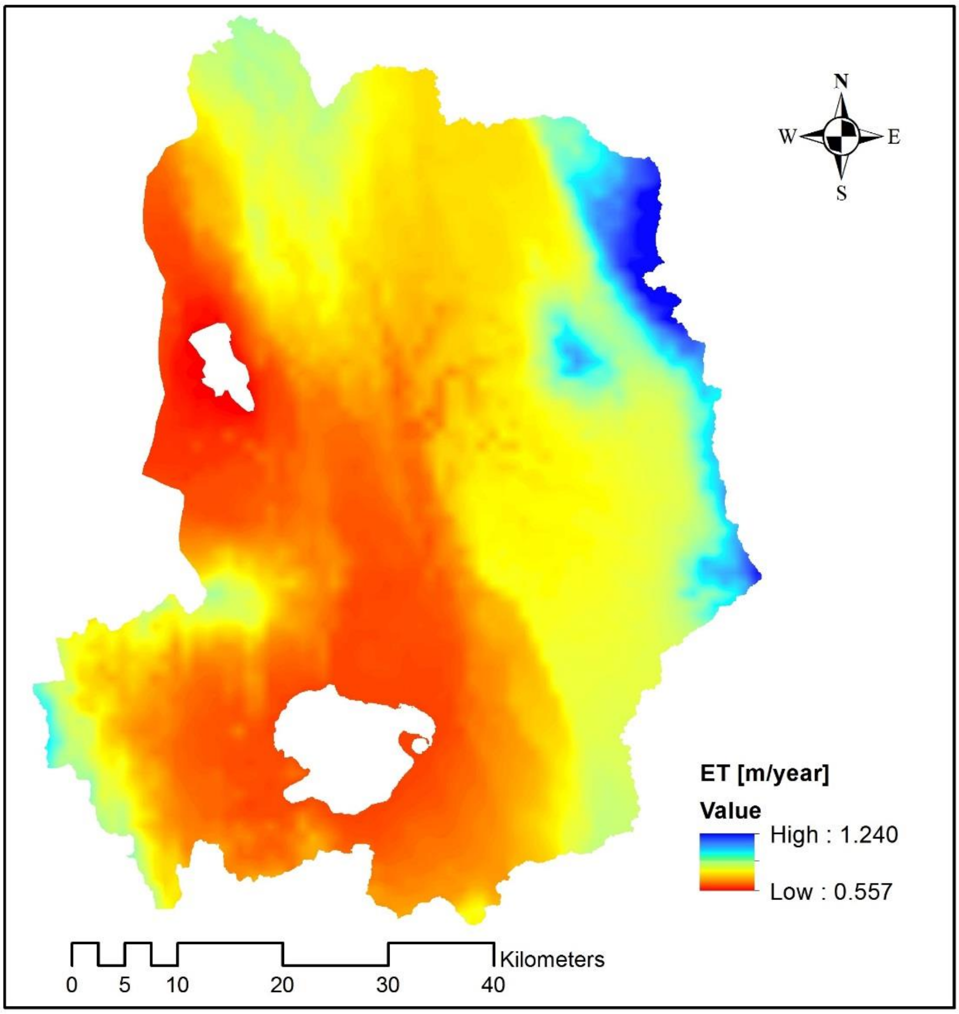

Figure 9. Average annual evapotranspiration distribution on the study area.

The histogram of DEM and ET is shown in figure 10 and 11, respectively. The purpose of histogram comparison is checking the consistency between two or more datasets. Comparing the histogram of DEM and ET shows that their trends follow each other and it strengthens the idea of having similar data structures.

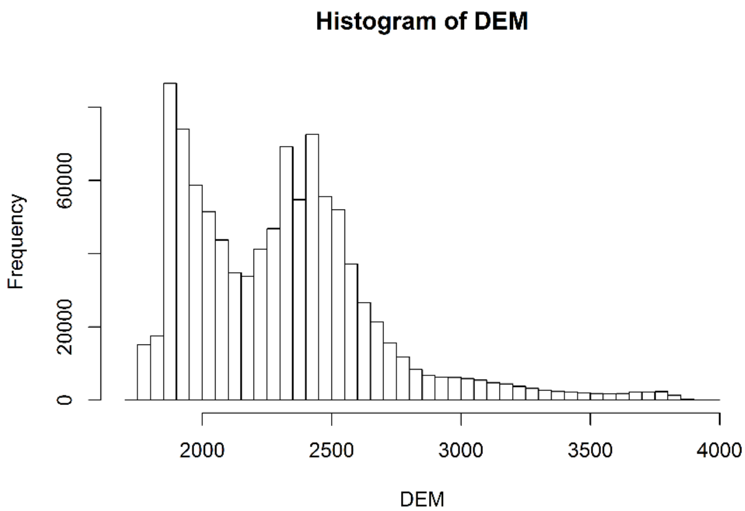

Figure 10. Histogram of DEM file. The unit is in meter.

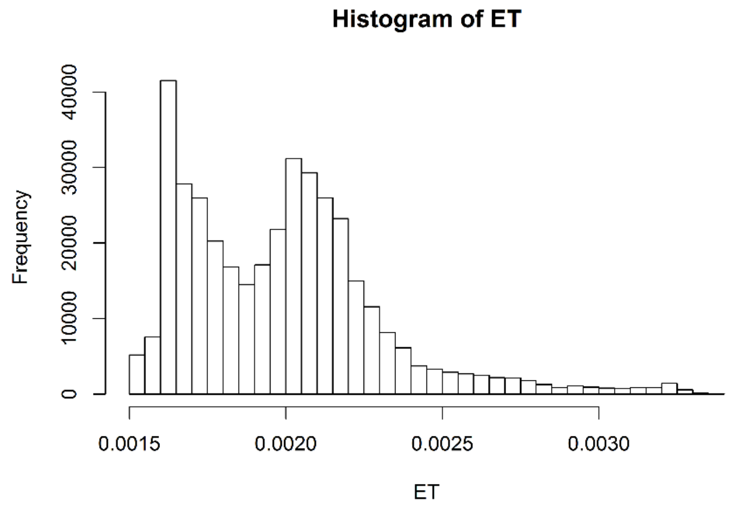

Figure 11. Histogram of the actual evapotranspiration map. ET values are in m/day.

3.3.3. Recharge

Determining recharge to groundwater is a fundamental issue in the water balance calculation of any watershed. There are many sources of recharge such as precipitation recharge, irrigation losses, recharge from rivers, urban recharge and lateral flows from the rift flanks(H. J. Hogeboom, 2013). In order to calculate recharge deliberately, sufficient precise data on geology, hydrology, topography and climate is absolutely necessary(Meijerink, Brouwer, Mannerts, & Valenzuela, 1994). Since the direct measurement of recharge is nearly impossible, difficult and costly(Risser, Gburek, & Folmar, 2005), only very generalized and incomplete method of recharge estimation is used for this study area.

Based on (Nalugya, 2003)'s results from SWAP model, the highest recharge has occurred in 1998, during El Nino period. Table 4 show the results of SWAP model from (Nalugya, 2003)' thesis.

Table 4. Direct recharge estimate. Taken from Nalugya(2003).

Local name	Location		Recharge(mm/day)		Total recharge(mm)		Average recharge(mm/year)	
	UTM_X	UTM_Y	Before El Nino	After El Nino	Before El Nino	After El Nino	Before El Nino	After El Nino
Kedong	209691	9908544	0-0.19	0-7.00	100	350	14.29	43.75
Ndabibi	194490	9914863	0-0.18	0-0.27	0.2	5.5	0.03	0.69
TPF	213403	9924948	0-0.024	0-0.10	18	35	2.57	4.38
Marula	208444	9930840	0-0.28	0-5.50	52	270	7.43	33.75

since this database of recharge is inadequate, more efforts needed to have a better recharge estimation for the whole study area. One of the quickest methods for recharge estimation from precipitation is water balance method(H. J. Hogeboom, 2013). However, recharge from precipitation depends on many factors such as geologic and hydrologic properties of the unsaturated zone, irrigation, spatially distribution of rainfall, the shape of the watershed etc., simplified water balance equation (equation 4) used to determine potential recharge:

$$R = P - ET \tag{4}$$

In this study, the direct runoff is neglected and assumed that precipitation goes to the groundwater system and then based on the groundwater table and riverbed, flow can occur from groundwater system to the river and vice versa.

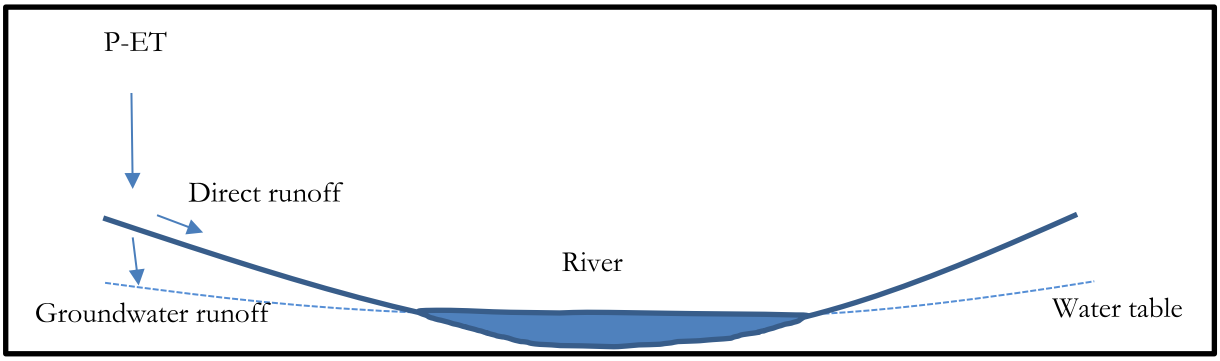

Figure 12. Interaction of streams and groundwater. Gaining streams (receive water from the groundwater system)

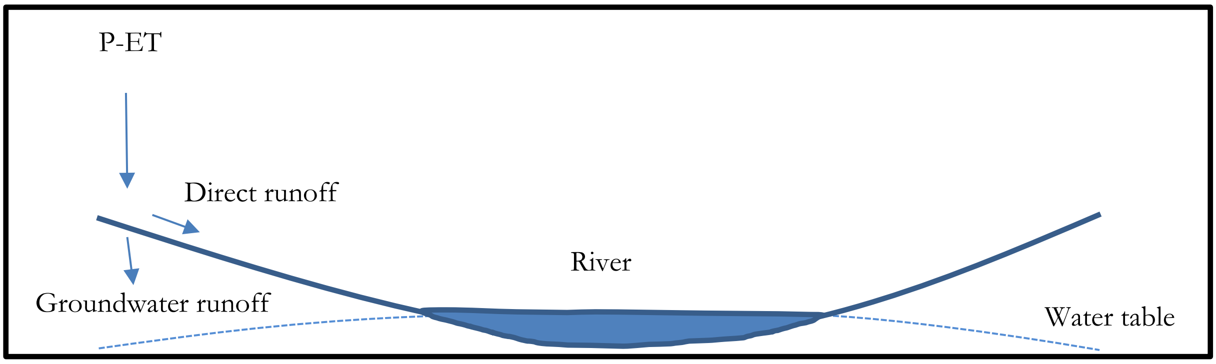

Figure 13. Interaction of streams and groundwater. Losing streams (Lose water to the groundwater system)

Annual groundwater recharge was calculated by subtracting raster map of annual evapotranspiration from raster map of annual precipitation. The recharge raster map which is created by using GIS analysis, shows that most of the soil moisture caused by precipitation is taken by evapotranspiration in most parts of study area. Thus, recharge from precipitation is comparatively low in this study area, except in some high-elevation areas (such as Aberdare Range) where precipitation is higher than evapotranspiration. The final recharge map is shown in figure 19.

3.3.4. Groundwater level

Groundwater level data has been collected from various sources such as ITC' database, WRMA's office and also some measurements in the field. The area around the Lake Elementaita and Nakuru has mainly salty water and if not salty the fluoride content is very high. Therefore, very few boreholes are drilled in this area. The groundwater level for these few boreholes have been measured by sending a probe to the borehole through an airline. However, some boreholes have not any access tubes making the measuring impossible. Some of the groundwater level data has been collected from borehole completion records in WRMA's office and compared with ITC's database. Comparing these data shows that for some boreholes, the water level has not recorded in ITC's database or the values are correspondent. The values which have been recorded in the borehole completion records are where required adopted.

3.3.5. Hydrostratigraphic units

Some previous modellers have assumed that the area has multiple layers (Yihdego, 2005; Reta, 2011). However, due to the lack of aquifer map and existing data scarcity of the area, their models are not well matched with reality. In this study also, there is no conclusive hydrostratigraphy data and it is no surprise that aquifer mapping is absent. Likely, the classical concept of layers/aquifers does not apply to this area.

3.3.6. Hydraulic properties

Previous researchers have measured the hydraulic properties of the shallow and deep aquifers within the Lake Naivasha Basin. The results of their measurements from 205 well logs show that the hydraulic conductivity in south of the Lake Naivasha is in range of 1.5 to 160 m/day (Clarke, 1990).
Hydraulic conductivity values for the lake sediment aquifer have been estimated from 8 to 22 m/day by doing aquifer test in Menera and Panda Flower farms(McCann, 1974).
More information on the whole series of pumping test carried out by ITC students is given in the ITC database.

3.3.7. Lake level

The water level of Lake Naivasha has been observed using three stations (2GD1, 2GD4 and 2GD6) since 1908. Recently, two more stations have been added and the daily lake levels have been recorded. As figures 14 and 15 show, the water levels in Lake Naivasha and Lake Elementaita are changing temporally. Over the past decades, this fluctuation for Lake Naivasha and Lake Elementaita is approximately 6 meters and less than 3 meters, respectively.

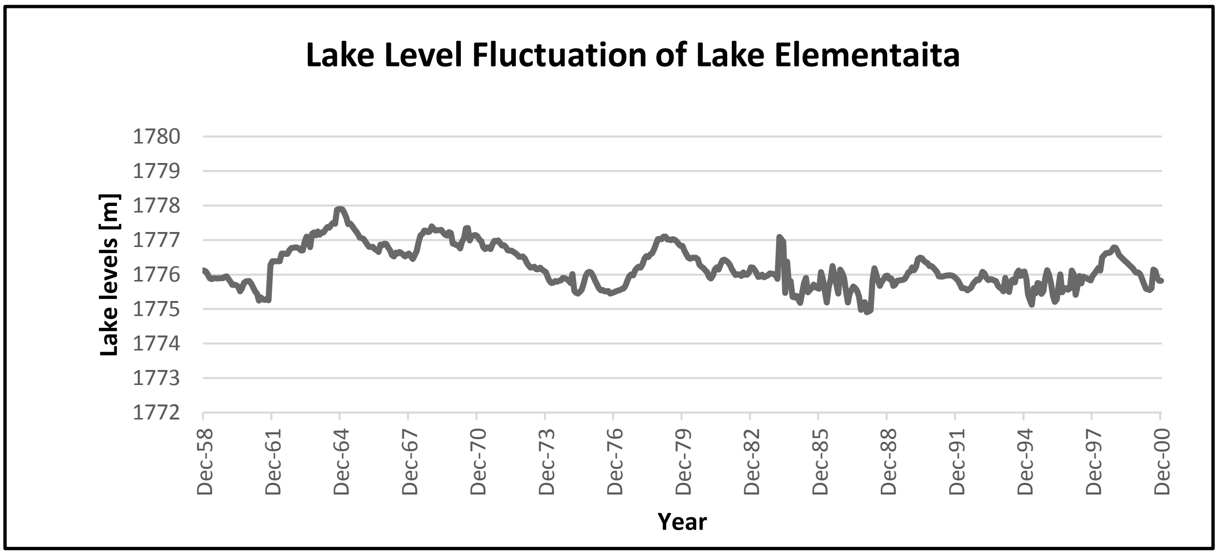

Figure 14. Historical lake level fluctuation of Lake Elementaita for the period 1958-2000.

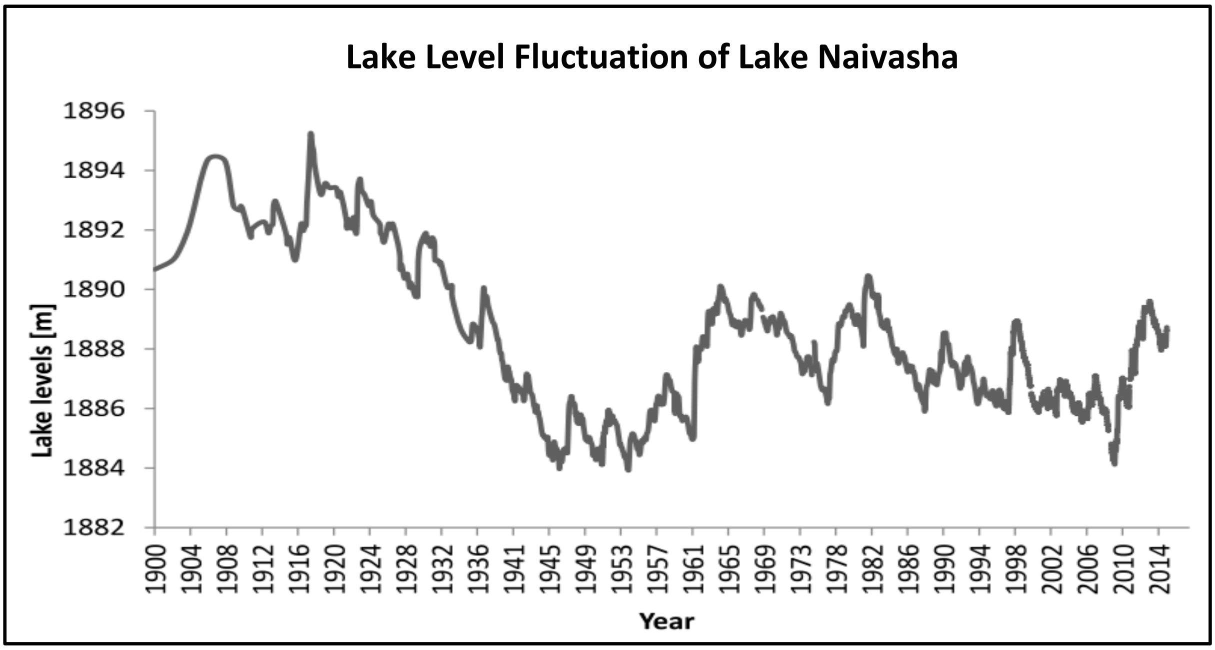

Figure 15. Historical lake level fluctuation of Lake Naivasha for the period 1900-2014. Adapted from: Odongo(2016)

3.3.8. Digital Elevation Model (DEM)

A Digital Elevation Model (DEM) is a digital geographic dataset of elevations of any points in a particular area at a certain spatial resolution. One of the most typical methods for creating elevation map is digitizing contour maps and convert them to a raster file by using interpolation techniques. However, this method has some limitations such as: lack of relief information between adjacent contours and also inaccuracy and imprecision related to the map because of cartographic errors(Muthuwatta, 2004). Considering that new satellite sensors have solved these problems, attempts have been made in this study to find the satellites and sensor systems which produce digital elevation data.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an imaging instrument onboard the NASA's Terra. ASTER can generate high spatial resolution (30 meters) images of the Earth which are taken in 14 spectral bands such as visible, near-infrared, short-wave infrared and thermal infrared. The swath width of ASTER is 60 km and the repeat cycle is 16 days.

In this study, surface elevation data has been downloaded and created from ASTER data which are available in the USGS server. The spatial resolution of the primary DEM file was 30m which has been resampled to 1000m in ArcMap. Then, it was converted to ASCII file and imported to ModelMuse as layer 1 bottom. In order to figure out the interaction of the lake and groundwater, lake bottom bathymetry is absolutely necessary. The bathymetry data of Lake Naivasha and Lake Elementaita has been extracted from Armstrong (2002)'s thesis.

3.4. Software Description

MODFLOW-2005 is a 3D finite-difference groundwater model which has been developed by USGS. This model could be used for steady state and transient flow in disparate aquifer layers; unconfined, confined or an amalgamation of confined and unconfined (A. W. Harbaugh, 2005). MODFLOW is working based on Equation 5 which describes the three dimensional incompressible groundwater flow through porous material.

$$\frac{\partial}{\partial x}(K_x \cdot \partial h/\partial x)+ \frac{\partial}{\partial y}\left(K_y \cdot \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_y \cdot \frac{\partial h}{\partial z}\right) + W = S_s.\frac{\partial}{\partial t} \quad (5)$$

In this formula, K_x, K_y and K_z are showing hydraulic conductivity values in x, y and z direction, which are presume to be parallel to the major axes of hydraulic conductivity (L/T) and h is the potentiometric head (L). Moreover, W is defining as volumetric flux per unit volume which is showing sink and/or sources of water. When W<0.0, water flows out from the system and when W>0.0, water flows into the system (T^{-1}). Ss is representing specific storage of the porous materials (L^{-1}); and t is standing for time (T).
MODFLOW-NWT, a Newton formulation of MODFLOW-2005, was developed to solve the problems involving the drying and rewetting nonlinearities of the unconfined groundwater flow equation(Niswonger, R. G., Panday, S., & Ibaraki, 2011).

3.5. Conceptual model

In the second step of groundwater modelling, development of conceptual model is essential. Conceptual model mainly includes determination of hydrostratigraphic units, system boundaries and groundwater balance.

3.5.1. Hydrostratigraphic units

Geologic units which have similar hydrogeological properties, will be considered as one hydrostratigraphic unit. As mentioned in paragraph 2.4.5 on the hydrostratigraphic data, the hydrogeology of study area is very complex and there is no aquifer map and the only data which are available exhibit an extremely heterogeneous geologic composition.
(Thompson & Dodson, 1963) assume that volcanic materials have been covered by water bearing sedimentary which the maximum thickness of the layer is not more than 32 meters. This claim seems that is taken based on experience and background knowledge of the writers, not based on the real measurements.
(Tsiboah, 2002) tried to measure the geophysical characteristics in some part of northern plains of Lake Naivasha and he figured out that the sedimentary aquifer is located in between 20-80 meters below the surface level. Although, one of the limitations of the electromagnetic experiment is that it could not disclose if the sedimentary layer is situated by either clay or salty water.
(Hernández, 1999) reported the interpretation of two well logs without referencing to the source or name of interpreter of this data. The detailed information of driller logs at Three Ostrich Farm and La Belle Inn are given in table 5 and 6.

Table 5. Well interpretation at Three Ostrich Farm(Hernández, 1999)

0-4	Fine to medium sand
4-6	Clay and silt
6-8	Coarse volcanic material and sand
8-10	Coarse sand and silt
10-12	Fine to medium sand
12-18	Coarse and medium size sand
18-28	Fine to medium sand
28-36	Coarse volcanic material and sand
36-38	Coarse and medium size sand
38-40	Coarse volcanic material, no sand
40-42	Siltstone and carbonaceous material

42-46	Coarse and medium size sand
46-60	Fine to medium sand
60-65	Clay and silt

Table 6. Well interpretation at La Belle Inn(Hernández, 1999)

0-2	Brown silty clay and sand
2-4	Silt with clay
4-12	Coarse, medium and fine size sand and clay
12-16	Fine to medium size sand and clay
16-18	No sample
18-20	Medium to coarse grained material, pumice
20-22	Hard basalt layer, crushed
22-26	Coarse and medium size sand
26-28	Medium to coarse sized sediments
28-30	Pumice layer
30-40	Fine to medium sized sand
40-46	Silt and weathered basalt
46-48	Fresh basalt

In this study, 10 layers with confined conditions have been assumed and the total depth is 1000 meters and the thickness of some layers have been taken from the average of available borelogs. For the rest of layers thickness has been selected based on assumptions. In order to differentiate the hydrogeologic parameters in the study area, several zones have been defined. Hydraulic conductivity zones are created based on soil map which are available from previous works. This soil map has been digitized based on the exploratory soil map of Kenya (1980) on the scale of 1:1,000,000. Regarding the fact that there is no available soil data for different layers, hydraulic conductivity zones have been assumed uniform for all layers. Figure 16 shows the soil map of the study area.

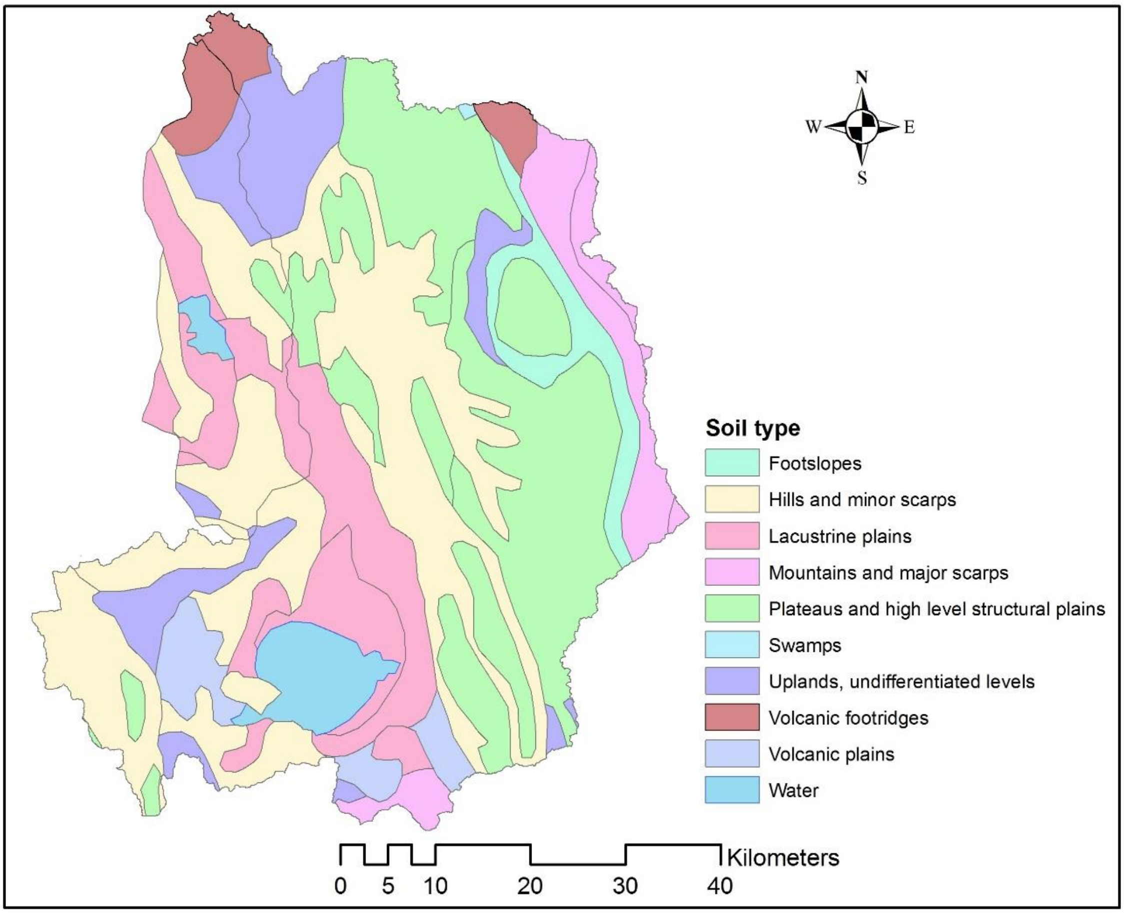

Figure 16. Soil map of Naivasha and Elementaita Basins. Edited from Muthuwatta(2004).

3.5.2. Boundary conditions

In the western part of the study area, the Mau water drainage divide is considered to be no-flow boundary. Based on the available geological map of the study area, there is no proof that groundwater divide is different from surface water divide. So, it has been assumed that this choice is quite certain.

In the eastern part of the study area, the Aberdare mountains are located and formed a section of the eastern edge of the Great Rift Valley. To the west of Aberdare Range, the Kinangop Plateau is situated. In this study, it is assumed that the watershed boundary is coincide with the groundwater boundary. So, Eastern boundary is assumed no flow.

To the west of Lake Elementaita, considering that groundwater flows out to the Lake Nakuru Basin, General Head Boundary is applied.

To the north, based on the watershed boundary and also parallel flows from east to west, the boundary condition is considered as a no-flow.

To the south, analysis of stable isotope compound of fumaroles shows that water could leave the Naivasha Basin(Darling, Allen, & Armannsson, 1990). Although, based on previous models, water is going from the Lake Naivasha to the south and then it is disappeared and no study has been done to investigate the destination of groundwater flow to the south. Therefore, the south boundary condition is defined by general head boundary.

The bottom of the valley floor which is located under aquifers is assumed as no-flow boundary.
The internal boundaries have been defined by Lake Naivasha and Lake Elementaita and also Gilgil and Malewa rivers which drain the study area.

3.5.2.1. No-flow and General Head Boundary (GHB)

In summary, all the model layers have been defined as either no-flow boundary or general head boundary (GHB). From layer one to layer 9, all the external boundaries assigned as no-flow except the western boundary which is defined as GHB. However, in layer 10, the south part of the study area and western boundary have been considered as general head boundary. The reason I considered general head boundary in layer 10 for the south boundary is that water is flowing from the Lake Naivasha to the Hell's Gate and then it is disappeared. The most probably, water is flowing in very deep layers from the study area to the south. Figures 17 and 18 show the boundary conditions for layer 1 and layer 10, respectively.

3.5.3. Water balance

Since the water balance of groundwater system in this study area is not well-known, the lake balance of Lake Naivasha has been used in order to define the groundwater budget terms.
Recharge also is poorly understood and researchers calculated different values. For more information on recharge see paragraph 3.3.3.
The summary of previous works and their inputs and results are given in table 7. It should be mentioned that all of these works were limited to Lake Naivasha and surrounding aquifers.

Table 7. Summary of previous studies and their inputs data

<table>
<tr><th colspan="3">Hydrologic budget (Mm^3/year)</th><th rowspan="2">Precipitation</th><th rowspan="2">River discharge</th><th rowspan="2">Evapo-transpiration</th><th colspan="2">Groundwater seepage</th><th rowspan="2">Total inflow</th><th rowspan="2">Total outflow</th></tr>
<tr><th colspan="3">Modeller</th><th>Inflow</th><th>Outflow</th></tr>
<tr><td colspan="3">(McCann, 1974)</td><td>132</td><td>248</td><td>188</td><td>-</td><td>34[1]</td><td>380</td><td>380</td></tr>
<tr><td colspan="3">(Ase et al., 1986)</td><td>120</td><td>181</td><td>286</td><td>-</td><td>60[1]</td><td>327</td><td>346</td></tr>
<tr><td colspan="3">(Becht & Harper, 2002)</td><td>94</td><td>217</td><td>256</td><td>-</td><td>56[1]</td><td>311</td><td>312</td></tr>
<tr><td colspan="3">(van Oel et al., 2013)</td><td>123</td><td>230</td><td>328</td><td>-</td><td>34[1]</td><td>353</td><td>362</td></tr>
<tr><td rowspan="4">(H. J. Hogeboom, 2013)</td><td rowspan="2">Natural situation</td><td>High[2]</td><td>116</td><td>215</td><td>276</td><td>11.3</td><td>69.5</td><td>342.3</td><td>345.5</td></tr>
<tr><td>Low[3]</td><td>116</td><td>215</td><td>276</td><td>8.3</td><td>63.6</td><td>339.6</td><td>339.6</td></tr>
<tr><td rowspan="2">Abstraction at FBP</td><td>High[2]</td><td>116</td><td>216</td><td>276</td><td>10.8</td><td>71</td><td>342.8</td><td>347</td></tr>
<tr><td>Low[3]</td><td>116</td><td>216</td><td>275</td><td>7.3</td><td>63.5</td><td>339.3</td><td>339.4</td></tr>
</table>

[1] These values are given only as net flux.
[2] High bed leakance
[3] Low bed leakance

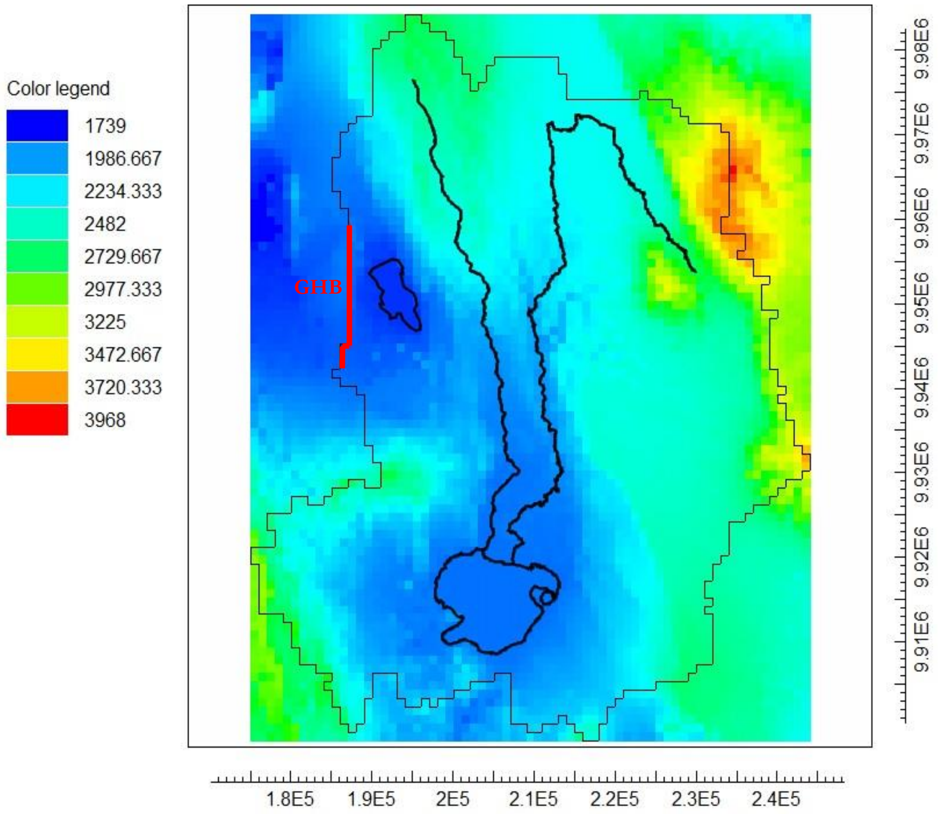

Figure 18. Internal and external boundary conditions in layer 1. The General Head Boundary in west of Lake Elementaita is shown in red color line. Rest of the boundaries are considered no flow. The cell colors show the elevations (m) in layer 1.

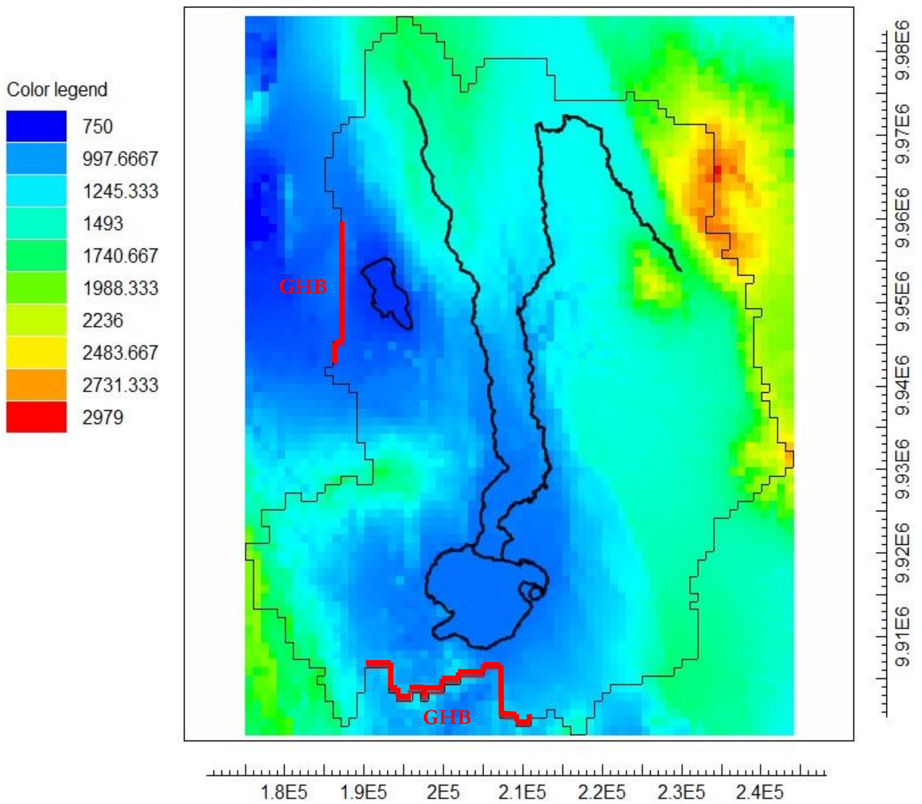

Figure 17. Internal and external boundary conditions in layer 10. The General Head Boundary conditions are shown in red color lines. Rest of the boundaries are considered no flow. The cell colors show the elevations (m) in layer 10.

3.6. Numerical model

3.6.1. General modelling setup

In this step, layers, grids and starting heads must be defined.

3.6.1.1. Layer definition

This study includes 10 layers which the first and second layers are convertible and rest of them are confined. The reason of assuming convertible conditions in these layers is because of using Lake Package. For more information see paragraph 3.6.2.1.

The model top elevation has been defined by DEM and integrated with 1895m and 1780m maximum arbitrary lake level for Lake Naivasha and Lake Elementaita cells, respectively. The bottom of the lakes have been described by the bathymetry data from (Armstrong, 2002).

3.6.1.2. Grids

The DEM grids elevation use the WGS84_UTM_37S coordinate system and the size of cells are 1000 meters by 1000 meters. Since increasing the cell size rises uncertainty and decreasing cell size makes the model slow and time-consuming, this resolution assumed sufficient. The grid smoothing criterion value is selected 1.2 which is the default value of ModelMuse GUI. In summary, the total number of rows, columns and cells in each layer are 86, 69 and 5934, respectively.

3.6.2. Packages in Model Muse

3.6.2.1. Lake Package

One of the purposes of choosing MODFLOW-NWT through ModelMuse GUI in this study is the capability of using the Lake Package so as to simulate the interaction between the lake and groundwater. By specifying the lake nodes in the finite-difference grid model, lake will be defined for the Lake Package in MODFLOW-NWT. Then, based on the total fluxes into and out of the lake and also computed lake water balance, the lake stage will be calculated (Hunt, 2003).

According to Darcy's Law (Equation 6), seepage between the lake and the surrounding aquifers depends on the hydraulic head in the groundwater system (groundwater level), the lake level and the lakebed conductance(Reta, 2011) and (Merritt & Konikow, 2000).

$$q = K\frac{hl-ha}{\Delta l} \qquad (6)$$

In this relationship, q is the specific discharge[L/T], K is the hydraulic conductivity[L/T], h_l is the lake level[L], h_a is the goundwater level[L] and Δl is the distance[L] between the measured points at h_l and h_a.

To measure the rate of volumetric flow [L^3/T], Darcy's Law can be written in the following form:

$$Q = qA = \frac{KA}{\Delta l}\,(hl - ha) = c\,(hl - ha) \qquad (7)$$

Where

A = area of the flow cross-section between two nodes [L^2];

K/Δl = the leakance [T^{-1}];

c = K/Δl is the conductance [L^2/T].

In Lake Package(LAK7), the lake is defined as volume of space within the grid that includes inactive cells. The grid cells of aquifer which surrounded the lake, interchange water with the lake and the rate of exchange relays on proportionated heads and flow resistance in horizontal and vertical directions(H. J. Hogeboom, 2013).

In this study, the top layer has been divided to two layers. The top of upper layer has a thickness of 1 meter above the model top which has been defined by DEM file and the second layer has a thickness of 70 meter below DEM. Although, in the Lake Naivasha and Lake Elementaita area, the top of upper layer has been defined as 1896m and 1780m arbitrary maximum stage, respectively.

The inputs for Lake Package are Precipitation, Evapotranspiration, Runoff and Withdrawal. In this study, assumed there is no withdrawal from the lake. Runoff data from three stations included Malewa, Gilgil and Karati which discharge to the Lake Naivasha for the period 2003-2012 was collected from WRMA's office of the Government of Kenya. The data of precipitation and evapotranspiration on the lake are collected from previous works and compared with up-to-date meteorological data from WRMA which shows the values are correspondent. The values for the mentioned inputs are given in table 8.

Table 8. Inputs for Lake Package. Units are in (m/year)

	Lake Naivasha	**Lake Elementaita**
	m/year	**m/year**
Precipitation	0.686	0.770
Evapotranspiration	1.735	1.620
Runoff	1.452	0.084
Withdrawal	Not considered	Not considered

3.6.2.2. Recharge Package

The recharge values are calculated by water balance method which is explained in section 3.3.3. The precipitation raster map is created based on the precipitation data from rainfall stations in the study area and then distributed based on the surface elevation which is suggested by Bhandari (2005). The Evapotranspiration raster map is developed based on the simple water balance equation which is described in section 3.3.2 and then spatially distributed based on DEM file.

Finally, the raster map of recharge which is created by subtracting evapotranspiration from precipitation, converted to ASCII file and imported to ModelMuse. Recharge Package which is applied on top active layer reads the rate of recharge for each cell and simulate normally occurring recharge to the groundwater. Figure 19 shows the spatially distributed regional recharge rate in the study area.

In summary, recharge to the groundwater in Lake Naivasha and Lake Elementaita Basin is estimated 0.089 and 0.046 m/year, respectively.

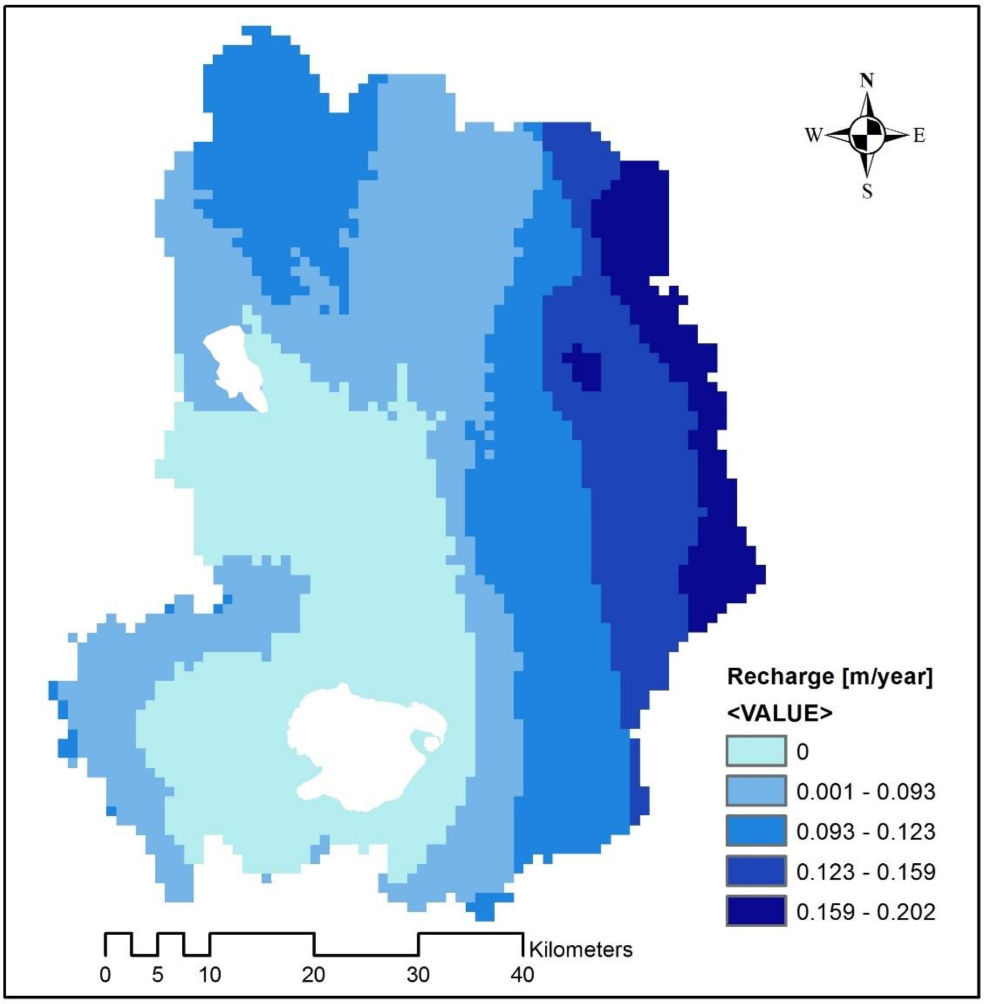

Figure 19. Spatially distributed recharge rate in the study area.

3.6.2.3. River Package

In order to consider the effect of Malewa and Gilgil Rivers in the model, River Package has been used. The shapefiles of rivers in Kenya were collected from WRMA's office and then these two rivers were clipped in ArcGIS and imported as polyline to Model Muse. The Karati River is eliminated because of its impermanent discharge pattern.

Water depths are calculated based on discharge data of Malewa and Gilgil Rivers from stations 2GA01 and 2GB01, respectively. Discharge data for the period 1960-1980 are extracted from (Meins, 2013b)'s thesis and based on the rating curve which is developed by him, river stages are calculated. The final results for stages are 0.42m for the Malewa and 0.56m for the Gilgil.

Regarding the interaction of water between river and aquifer, there are only two sources which mentioned the hydraulic conductivity of Malewa and Gilgil sediments. Based on (Kibona, 2000), conductance value is in the range of 0.1 to 0.38 m/day and (Joliceur, 2000) also estimated this value as 0.25m/day. In this study, riverbed conductance assumed 0.25 which is the same value that (Owor, 2000) has been used in his model.

3.6.2.4. General Head Boundary Package (GHB)

To simulate head dependent flux boundaries the general head boundary package has been implemented. In GHB package, the flow to/from a model cell is proportional to hydraulic conductance and a difference in head which is shown in equation 8.

$$Q = Cb * (Hb - Ha) \tag{8}$$

Where

Q = flow [L^3/T];

Hb = hydraulic heads at the boundary [m];

Ha = hydraulic heads in the aquifer [m];

Cb = the hydraulic conductance [L^2/T].

GHB package needs a head and a conductance as well which must be assigned to the related cells. Generally, water level can influence on the amount of water that comes or leaves the study area. If the water table be in higher elevation than specified head, then the water flows out of the aquifer; and if the water table be in lower elevation than specified head, water flows into the aquifer.

3.6.2.5. Head Observation Package

This package is useful to compare observed heads with simulated heads which are computed by MODFLOW. The data that are needed for this package are: observed head, piezometer ID and also time step. Since this study is focusing on steady state, time step was neglected. After activating this package, all the observation points and their coordinates were imported from ArcGIS to ModelMuse.

Although there are many wells in the Lake Naivasha Basin, most of them are located near the lake. So, attempts have been done to find piezometers which are spatially distributed in whole the study area. Since the concentration of Fluoride in Lake Elementaita Basin is high, there are not many boreholes in the basin.

3.6.3. ZONEBUDGET

Overall groundwater balance can be produced in ModelMuse, although this GUI could not calculate the water balance for a specific zone. In order to get water balance for any zone, (Arlen W. Harbaugh, 1990) developed the ZONEBUDGET by using a FORTRAN code. This code can use MODFLOW results to calculate water budget of different zones. ZONEBUDGET which is available in ModelMuse environment uses cell-by-cell budget data that is saved in a file after a successful MODFLOW model run(Zehairy, 2014). To use ZONEBUDGET, the user must specifying different zone numbers for each single zone and once the model run is completed, the interaction between these zones could be extracted in the output file.

3.7. Model calibration

The aim of calibration is getting a better match between observed and measured values of heads while also producing realistic fluxes. There are two common types of calibration approaches: Inverse and forward. In the inverse procedure, discovering the parameters and hydrologic stresses from known heads are the aims; and in forward approach, parameters such as hydraulic conductivity and hydrologic stresses such as recharge are being identified and then the model simulate the heads. Subsequently, the parameters and hydrologic stresses are being modified until the difference between the simulated heads and observed heads will be in acceptable error range(Hassan, Lubczynski, Niswonger, & Su, 2014). Forward calibration also can be done through trial and error method or automated calibration by using some optimising software such as PEST(Anderson et al., 2015). Automated method has the advantage of being faster, however, manual calibration can force the user to get a better understanding of the system and model behaviour during calibration.

The type of errors that are being used for groundwater levels and lake stages are the mean error(Equation 9), mean absolute error (Equation 10) and root mean square error(Equation 11); and discrepancy values is being used for water balance. The discrepancy value shows the difference between the total inflow and outflow divided by inflow/outflow. The acceptable value of discrepancy for water balance is 0.02 or less(Anderson et al., 2015).

The calibration method in this study is forward method and it is done manually. The steady state model was calibrated based on the long-term average values of hydrologic conditions and the calibration parameter is hydraulic conductivity.

A fundamental component of model calibration is having enough understanding of the range of parameters which are used in the model. Using unrealistic values which are not in the pragmatic range of variation can produce large model errors. Some values maybe known and it is not needed to change them considerably in calibration(Wu & Zeng, 2013). In this model, the primary K values are adopted from previous works and assigned in Upstream-weighting (UPW) package and modified during calibration till the error assessment will be in an acceptable range which is suggested by (Anderson et al., 2015). For more information of error assessment, see paragraph 3.8.

At the beginning of this study, SFR package was supposed to be used although due to the existence of a lot of unknown parameters for calibration such as hydraulic conductivity values of 25 zones, conductance of two lakes and General head boundary conductance, SFR package was replaced with River Package.

3.8. Sensitivity analysis and error assessment

In order to determine the uncertainties in the model, sensitivity analysis is imperative. The reason of existing some uncertainties in the model is uncertain parameters and boundary conditions.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(H_{Obs,i} - H_{Sim,i}) \tag{9}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|H_{Obs,i} - H_{Sim,i}\right| \tag{10}$$

$$RMSE = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(H_{Obs,i} - H_{Sim,i})^2\right]} \tag{11}$$

Where n is the number of observations and H_{Obs} and H_{Sim} are the observed and simulated heads, respectively. Root Mean Square Error (RMSE) presents the average of the squared difference of observed and simulated head. Mean Absolute Error (MAE) shows the average of the absolute and non-squared value of the difference of observed and simulated heads.

In this research, the error assessment was done based on criteria which are suggested by Anderson et al. (2015). MAE, RMSE and Maximum absolute value of model residuals should be less than 2%, 2% and 10% of the total change of observed heads, respectively. In addition, the coefficient of determination (R^2) between observed and simulated heads should be more than 0.9.

4. RESULTS AND DISCUSSION

4.1. Calibration

The calibrated hydraulic conductivity values for each zone are shown in figure 20. As the result shows, hydraulic conductivity is very low in the escarpments and it increases in the direction of the valley floor. Also, the hydraulic properties of valley floor sediments seems correspondent with well sorted sand and gravel or fractured rocks(Nabide, 2002). The model has 26 hydraulic conductivity zones and the results of steady state calibration demonstrate that horizontal hydraulic conductivity values are in range of 0.1 to 15m/day for the lacustrine sediments and 0.005 to 0.1m/day for the volcanic units.

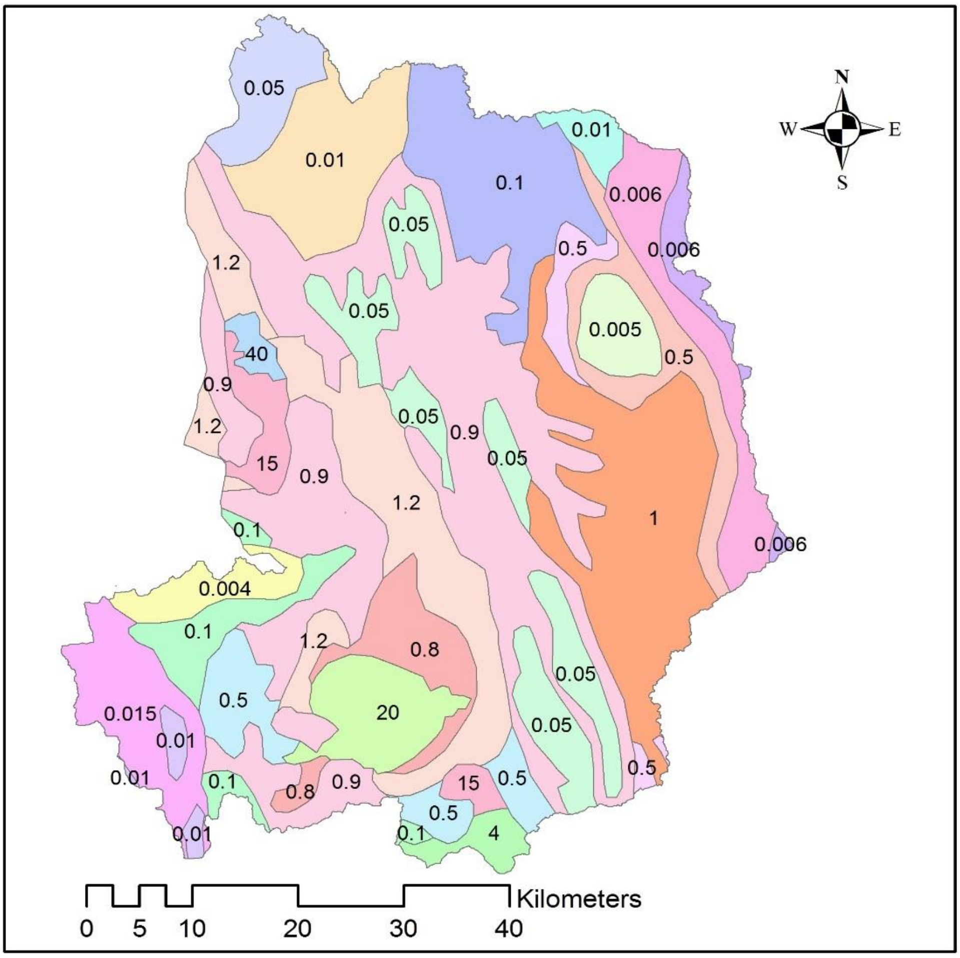

Figure 20. Hydraulic conductivity values (after calibration). Units are in m/day.

The scatter plot of residuals of the observed heads versus computed heads are shown in figure 21. This plot is based on 31 piezometers which are reported in table 9. The coefficient of determination (R^2) is calculated 0.98.

According to the table 9, the values of observed heads are changing between 1782.5 to 2390.25m; and the total change of observed head is 607.75m. The maximum absolute value of model residual, RMSE and MAE also reported 47.42m, 8.64m and 15.85m, respectively. Based on suggested values for error assessment by Anderson et al. (2015) (see paragraph 3.8), calculated MAE and the maximum absolute value of model residuals are less than 2% and 10%, respectively. However, the ratio of RMSE to the total change of heads is 2.5% which is a little higher than the suggested value of 2%. Table 10 shows the calculated error assessment and suggested values by Anderson et al. (2015).

Table 9. The coordinates, observed and simulated heads of the observation points with calculated error assessment. H_{Obs} is Observed head and H_{Sim} is simulated head. Units are in meter.

Borehole Number	Coordinate		H_{Obs}	H_{Sim}	$H_{Obs} - H_{Sim}$	$\mid H_{Obs} - H_{Sim} \mid$	$(H_{Obs} - H_{Sim})^2$
	UTM_X	UTM_Y					
HO_1	218451.7	9916464.4	1901.40	1903.7456	-2.3456	2.3456	5.5018
HO_2	222356	9914326	1961.35	1972.2682	-10.9182	10.9182	119.2071
HO_3	225256	9967848	2224.75	2272.1670	-47.4170	47.417	2248.3719
HO_4	220315	9914934	1932.47	1939.4327	-6.9627	6.9627	48.4792
HO_5	215700	9913972	1889.44	1887.7299	1.7101	1.7101	2.9244
HO_6	219593	9930550.5	1921.55	1919.3309	2.2191	2.2191	4.9244
HO_7	200531.4	9972828.6	2390.25	2422.6299	-32.3799	32.3799	1048.4579
HO_8	214657.5	9926497.1	1883.50	1881.4778	2.0222	2.0222	4.0893
HO_9	231408.1	9911466.2	2017.20	2023.9174	-6.7174	6.7174	45.1235
HO_10	219131	9921644	1907.00	1906.2356	0.7644	0.7644	0.5843
HO_11	194067	9962640	1808.20	1807.1274	1.0726	1.0726	1.1505
HO_12	230715	9909828	2014.65	2020.1713	-5.5213	5.5213	30.4848
HO_13	208760	9929543	1876.85	1877.7119	-0.8619	0.8619	0.7429
HO_14	208644	9925668	1881.35	1881.3972	-0.0472	0.0472	0.0022
HO_15	207903	9928640	1878.15	1878.1245	0.0255	0.0255	0.0007
HO_16	210095	9931464	1878.00	1877.3157	0.6843	0.6843	0.4683
HO_17	206848	9930541	1875.00	1876.5453	-1.5453	1.5453	2.3880
HO_18	207224	9954423	2001.30	2005.4762	-4.1762	4.1762	17.4406
HO_19	212849	9929490	1880.42	1880.3917	0.0283	0.0283	0.0008
HO_20	206342	9934406	1874.30	1873.6595	0.6405	0.6405	0.4102
HO_21	208723	9973750	2205.34	2242.5017	-37.1617	37.1617	1380.9919
HO_22	209513	9926154	1880.50	1880.3331	0.1669	0.1669	0.0279
HO_23	208146	9928434	1878.40	1878.5640	-0.1640	0.164	0.0269
HO_24	208783	9929252	1878.10	1878.0461	0.0539	0.0539	0.0029
HO_25	207926	9930268	1876.50	1876.9089	-0.4089	0.4089	0.1672
HO_26	228233.2	9939337.2	2168.20	2131.6228	36.5772	36.5772	1337.8916
HO_27	189626	9958570.5	1782.50	1783.0201	-0.5201	0.5201	0.2705
HO_28	221729.9	9957589.5	2201.60	2172.9443	28.6557	28.6557	821.1491
HO_29	194564.1	9954722.5	1787.50	1787.3320	0.1680	0.168	0.0282
HO_30	188250	9906750	1912.00	1932.9413	-20.9413	20.9413	438.5380
HO_31	178250	9919750	2315.25	2335.0969	-19.8469	15.0969	227.9164
Max					36.5772	47.417	2248.3719
Min					-47.417	0.0255	0.0007
Median					-0.164	1.7101	2.9244

Table 10. Calculated error assessment and comparison with suggested values by Anderson et al. (2015). RMSE and MAE should be less than 2% of the total head changes. Units are in meter.

	ME	MAE	RMSE
The steady state model calibration results	-3.8192	8.6443	15.8499
Suggested value of MAE and RMSE (2% of total head changes)		12.15	12.15

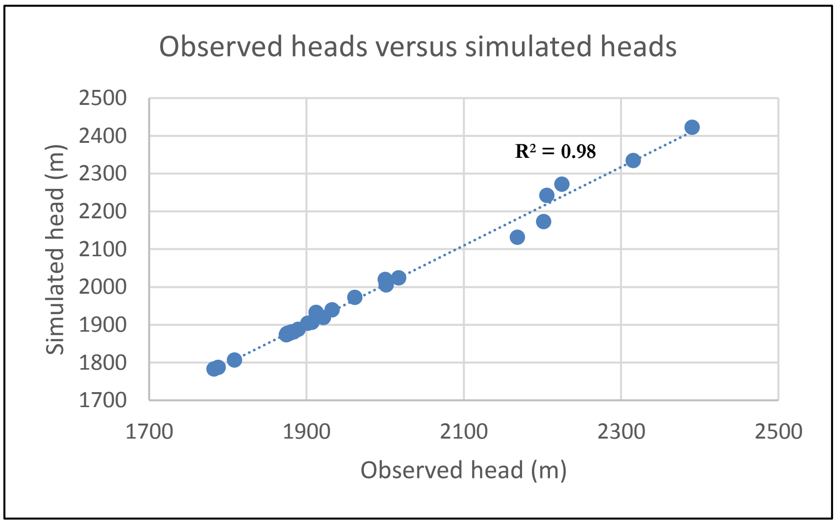

Figure 21. Scatter plot of observed and simulated head (m).

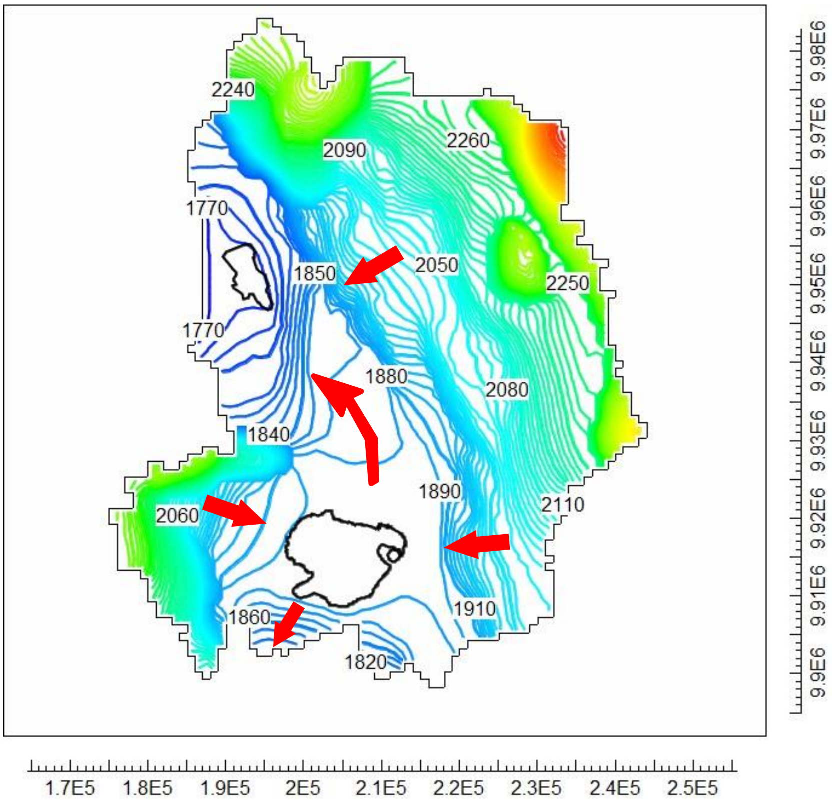

Figure 22. Groundwater contour map in [masl] for the layer 1. The red arrows show the flow directions.

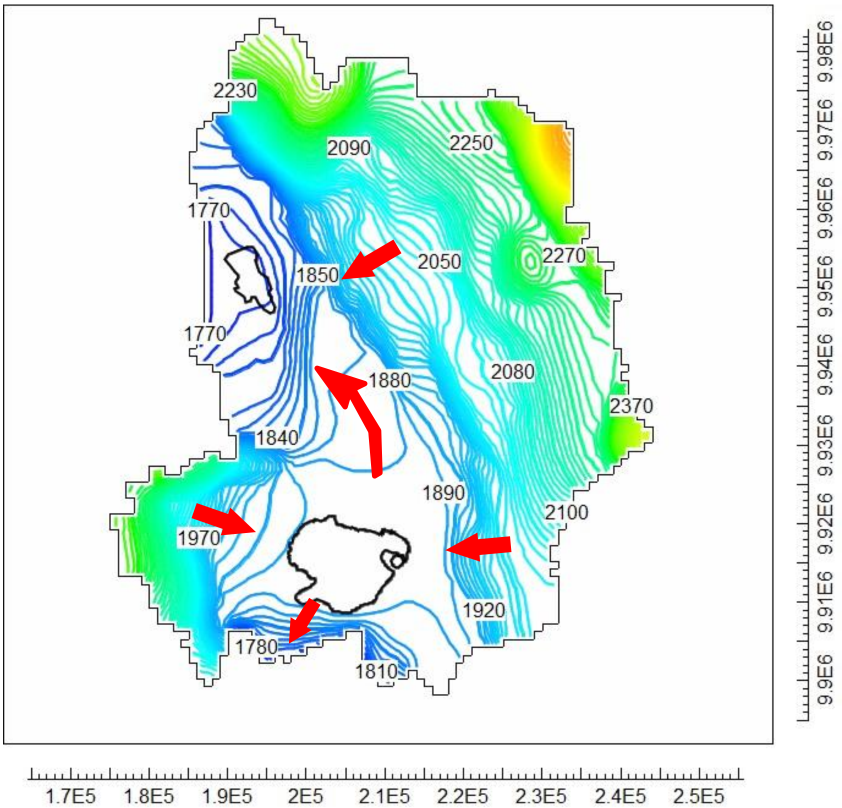

Figure 23. Groundwater contour map in [masl] for the layer 10. The red arrows show the flow directions.

4.2. Sensitivity analysis

Since the uncertainties in the aquifer parameters and boundary conditions can influence on the model, sensitivity analysis is done to measure the uncertainty in the calibrated model. The main reason for doing sensitivity analysis is figuring out the effect of different model parameters and hydrological stresses on the groundwater system and finding the most sensitive parameters which special consideration in the future studies is needed(Reta, 2011).

(Anderson et al., 2015) suggested that sensitivity analysis should be done by changing the calibrated values of the model in a systematically method. In this study, similar approach has been performed by changing the hydraulic parameters of the calibrated model and discover the alteration on simulated heads. For this steady state model, the parameters which has been used to apply sensitivity analysis are: Groundwater recharge, hydraulic conductivity, general head boundary conductance. The value of these parameters were increased and decreased by a magnitude of ±20%, ±40% and ±60% of the calibrated model values. Sensitivity analysis is based on root mean square error (RMSE) as an evaluation criteria.

Figures 24, 25 and 26 show the result of sensitivity analysis for recharge, hydraulic conductivity and general head boundary conductance, respectively.

The model responds highly to increase and decrease of recharge. Moreover, sensitivity of the model to decreasing hydraulic conductivity is higher than increasing. Regarding the general head boundary conductance, the graph shows that the model is more sensitive to the conductance in the south boundary rather than the west boundary.

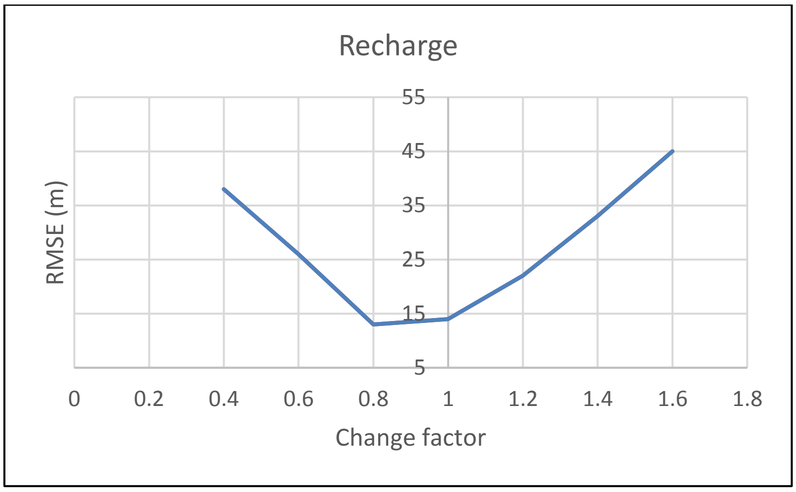

Figure 24. Effect of changing recharge values on the hydraulic heads.

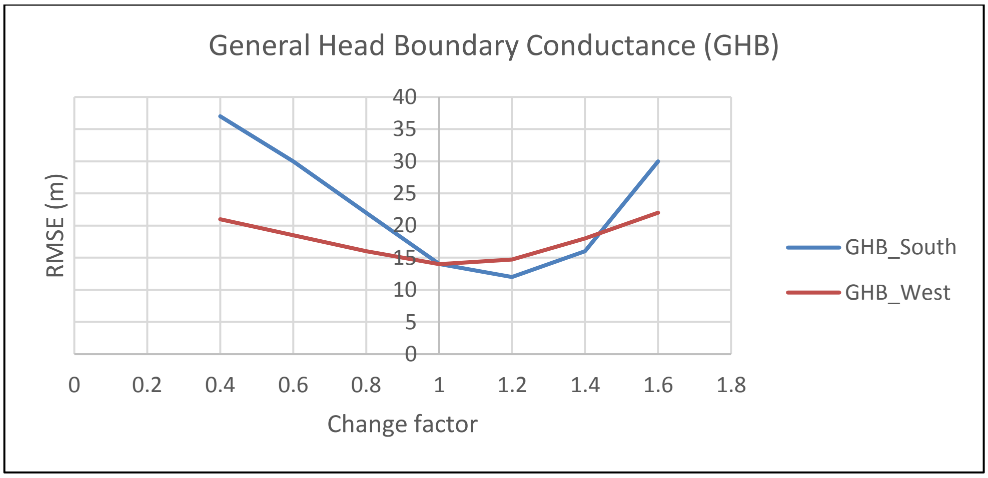

Figure 25. Effect of changing general head boundary conductance values (South and west boundaries) on the hydraulic heads.

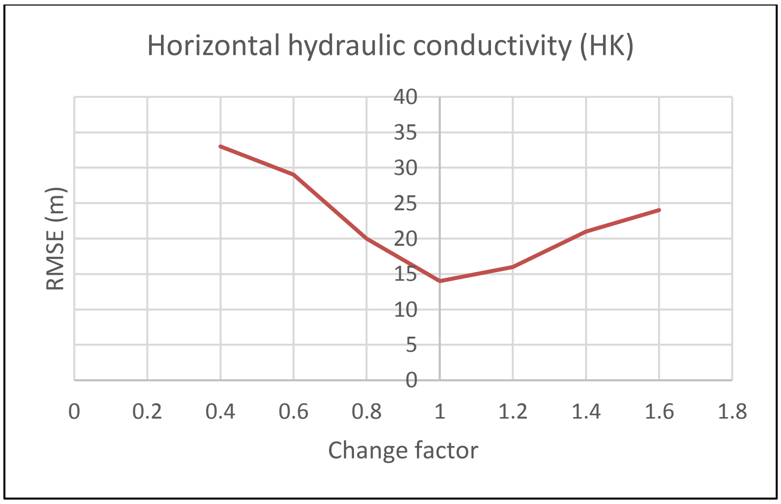

Figure 26. Effect of changing hydraulic conductivity values on the hydraulic heads.

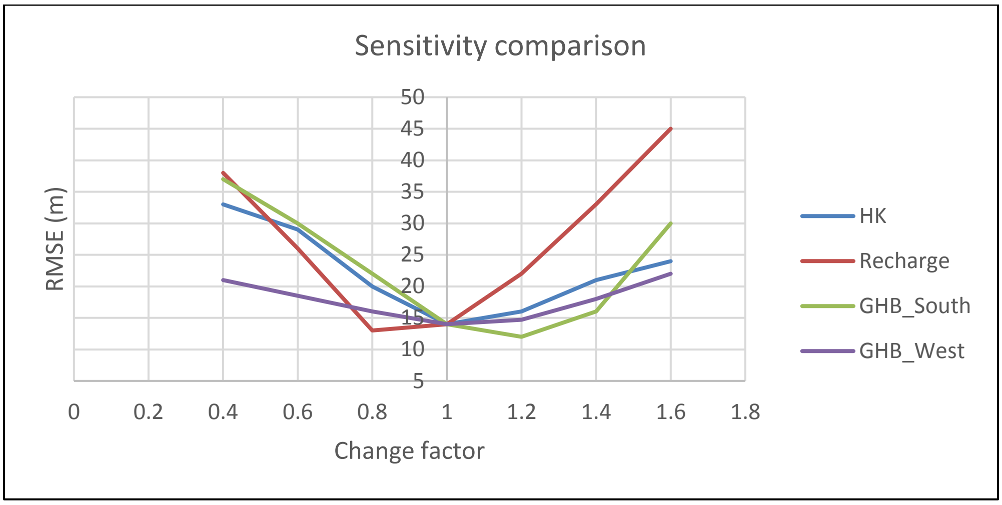

Figure 27. Sensitivity comparison among recharge, hydraulic conductivity values and general head boundary conductance in south and west of the study area.

4.3. Water balance

After model calibration, the groundwater contour map has been created based on simulated heads which are retrieved from MODFLOW. By comparing the contour map of this model with previous works, it is found similar to the historic studies for the Lake Naivasha area. Figure 22 and figure 23 show the groundwater contour map in layer 1 and layer 10, respectively.

The results of lake balance which are extracted from the MODFLOW listing files are given in tables 13 and 14. Based on the groundwater balance results, the total groundwater outflow from the study area is 185.8 Mm^3/year which is controlled by assigning general head boundary conductance of 0.13 and 0.08 for the south and west boundaries, respectively. Recharge for the entire study area has been estimated 172.7 Mm^3/year which is the main input component with 70% contribution of total inflow to the study area.

Considering the literature review, the acceptable range of the Lake Naivasha outflow(net) into groundwater is 55±40 Mm^3/year. In this study, lake seepage(net) has been calculated as 57.5 Mm^3/year which is in the mentioned range. Moreover, it is found that approximately 35% of Lake Naivasha groundwater outflow goes to the north and 65% to the south which is correspondent with the range of 25-35% to the north and 65-75% to the south, from previous studies outcomes.

Lake Elementaita water balance exhibits that total supply to the lake is around 35.02 Mm^3/year of which 16.17 Mm^3/year is provided by direct rainfall to the lake. The evaporation from the lake is 32.35 Mm^3/year and the groundwater outflow is estimated 2.88 Mm^3/year.

Discrepancy value is the difference between the total inflow and the total outflow divided either by the total inflow or outflow and it is being used to show the water balance closure. Anderson et al. (2015)suggested that generally the discrepancy values of 0.2% or less are accepted.

With hydraulic conductivity values which are shown in figure 20, the model converged and resulted in a groundwater budget error of 0.06% (see Table 12). The lake water balance results for the Lake Elementaita and Lake Naivasha shows that the discrepancy between inflow and outflow is 0.59% and 0.17%, respectively (see Table 13 and 14). Since the discrepancy value for the Lake Elementaita is higher than the acceptable range, the inputs and outputs of the Lake Elementaita must be reviewed. Considering that runoff to the Lake Elementaita was unknown and it was made by assuming 9% of precipitation, special attention should be subjected for runoff calculation in the Lake Elementaita Basin.

Table 11. Observed and simulated lake levels (m), lake areas (km²) and lake volumes (Mm³)

	Lake level (m)		**Lake area (km²)**		**Lake volume (Mm³)**
	Observed	Simulated	Observed	Simulated	
Lake Naivasha	1887	1886.92	139	118	460
Lake Elementaita	1776	1776.12	21	21.5	10.9

Table 12. Groundwater balance for the entire model.

Flow component	**Inflow**		**Outflow**	
	m³/day	Mm³/year	m³/day	Mm³/year
recharge	473150.72	172.71	-	-
lake seepage	169534.02	61.88	-	-
Net lake seepage	(118602.74)	(43.29)	-	-
river interaction	30136.98	11	113287.73	41.35
Head dep bounds (South)	-	-	304739.7	111.23
Head dep bounds (West)	-	-	204301.4	74.57
lake seepage	-	-	50931.51	18.59
Total	672821.9	245.58	673260.3	245.74
Discrepancy	0.06%			

Table 13. Lake Elementaita water balance.

Flow component	**Inflow**		**Outflow**	
	m³/day	Mm³/year	m³/day	Mm³/year
Precipitation	44301.37	16.17	-	-
Evaporation	-	-	88630.14	32.35
Streamflow	4821.92	1.76	-	-
Groundwater inflow (lake seepage in)	46820.01	17.09	-	-
Groundwater outflow (lake seepage out)	-	-	7886.12	2.88
Total	95943.29	35.02	96516.14	35.23
Discrepancy	0.59%			

Table 14. Lake Naivasha water balance

Flow component	**Inflow**		**Outflow**	
	m³/day	Mm³/year	m³/day	Mm³/year
Precipitation	252054.80	92	-	-
Evaporation	-	-	638376.20	233
River discharge	545205.50	199	-	-
Groundwater inflow (lake seepage in)	4109.59	1.5	-	-
Groundwater outflow (lake seepage out)	-	-	161647.80	59
Total	801369.9	292.5	800024	292
Discrepancy	0.17%			

4.4. Lake Naivasha flow pattern

Considering the equipotential lines which are shown in figures 22 and 23 the groundwater outflow from Lake Naivasha is axially in two directions. This flow occurs northerly to the Lake Elementaita and Nakuru Basin and southerly to the Hell's Gate and possibly to the Lake Baringo Basin through a very deep groundwater flow system with long flow path.

Flow pattern shows that groundwater discharge to the Lake Naivasha is from Mau escarpment and the Kinangop plateau towards the valley with comparatively sharp gradient.

4.5. Lake Elementaita flow pattern

The closest lake to the Lake Naivasha is Lake Elementaita which the distance between these two lakes are around 30km. The vertical distance between Lake Naivasha and Lake Elementaita is more than 100m and it seems logical that some amounts of groundwater outflow from Lake Naivasha goes to this lake. Although it is not clear that how much of groundwater inflow to the Lake Elementaita is from Lake Naivasha outflow. The groundwater inflow to the Lake Elementaita also includes the groundwater fluxes from the rim of the catchment to the centre of the basin where the Lake is located.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The aim of this study to create and calibrate a steady state groundwater model is brought to a meaningful conclusion. This model has been developed using MODFLOW-NWT through ModelMuse GUI and the calibration has been done manually by applying trial-and-error procedure. The simulated lake levels for both lakes are reasonably well-matched and the aquifer heads are quite calibrated with a squared correlation coefficient (R^2) equal to 0.98. The existence of considerable difference between simulated head and observed head for some observation points are mainly because of effects of faults and abstractions which are not considered in this study.

The interaction between lakes and the surficial aquifer were calculated by Lake Package (LAK7). The input fluxes to the Lake Naivasha include precipitation, groundwater inflow (lake seepage in) and surface inflow with the long term average of 7.67 $*10^6$ m^3/month, 1.25 $*10^5$ m^3/month and 16.58 $*10^6$ m^3/month, respectively. The output fluxes from the Lake Naivasha include evaporation and groundwater outflow (lake seepage out) with the long term average of 19.42 $*10^6$ m^3/month and 4.92 $*10^6$ m^3/month, respectively. Since the lake water abstraction effects on the lake water balance and due to the lack of abstraction consideration in this study, the lake water balance can be different with conditions that abstraction from the lake is also included.

For the Lake Elementaita, the long term average incoming fluxes are precipitation 1.35 $*10^6$ m^3/month, groundwater inflow (lake seepage in) 1.42 $*10^6$ m^3/month and streamflow 1.5 $*10^5$ m^3/month, respectively. The long term average outgoing fluxes are involved evaporation 2.70 $*10^6$ m^3/month and groundwater outflow (lake seepage out) 2.4 $*10^5$ m^3/month.

The groundwater balance shows the long term average fluxes into and out of the surrounded aquifer. The inflows to the groundwater system include recharge 14.39 $*10^6$ m^3/month, river leakage-in 9.2 $*10^5$ m^3/month and lake seepage in (groundwater outflow from the lake) 5.16 $*10^6$ m^3/month. The outflows from the groundwater system include river leakage-out 3.45 $*10^6$ m^3/month, lake seepage out (groundwater inflow to the lake) 1.55 $*10^6$ m^3/month.

The amount of water goes to the head dependent boundary in the south is 9.27 $*10^6$ m^3/month and the amount of water which goes to the head dependent boundary in the west of the Lake Elementaita is 6.21 $*10^6$ m^3/month. Since the surface elevation between Lake Elementaita and Lake Nakuru is almost unchangeable, it sounds that water flows to Lake Nakuru Basin through deep layers.

By doing sensitivity analysis for three parameters such as recharge, hydraulic conductivity and general head boundary conductance, it is found that the model is very sensitive to increasing and decreasing the recharge values. For hydraulic conductivity, the model is more sensitive to decreasing rather than increasing. Regarding the general head boundary conductance, model is very sensitive to changing conductance of the south boundary.

Although this model seems to be able to describe a part of reality in this area, it is not reliable because of a) lack of the detailed hydrostratigraphic data of the subsurface and b) the existence of many uncertainties and assumptions for the model simplification. The geothermal effects which can be significant in depth of more than 700 meter, abstractions and groundwater evapotranspiration are not considered. The hydraulic conductivity zones are assumed same for all the 10 layers.

5.2. Recommendations

Since this model is based on many assumption and lack of data, further studies are absolutely necessary to decrease the uncertainties and improve the model reliability.

This study suffers from the lack of hydrostratigraphic data which is needed for groundwater modelling. Improving the geologic and hydrogeologic knowledge and developing the stratigraphic and hydrostratigraphic models can lead to having a better conceptual model.

In this research, the actual evapotranspiration was spatially distributed based on DEM file and recharge was calculated by subtracting raster maps of actual evapotranspiration from precipitation. For further studies, it is recommended to create the ET map based on land cover as well and compare the results with this study to reach a better recharge estimation.

In order to have a better understanding of Lake Naivasha outflow to the south and to the north, other lakes also in the Kenyan Rift Valley (especially Lake Nakuru and Lake Magadi) should be considered.

Using SFR Package is being recommended for improving the interaction studies between groundwater and surface water.

Since some parameters are responding to the time variations and considering that temporally variable flows could be more reliable than fluxes in the steady state condition, transient studies are also strongly recommended.

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APPENDICES

APPENDIX 1. Average monthly satellite rainfall data for the Lake Naivasha and Lake Elementaita Basins

Lake	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Naivasha	541.6129	602.0325	939.2651	1333.858	1439.012	801.632
Elementaita	426.753	499.865	732.852	1172.563	850.432	630.734
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Naivasha	1006.956	1115.74	994.854	1174.423	1280.956	1172.356
Elementaita	930.423	928.835	983.421	1182.056	1279.65	804.564

APPENDIX 2. Boreholes location in the study area.

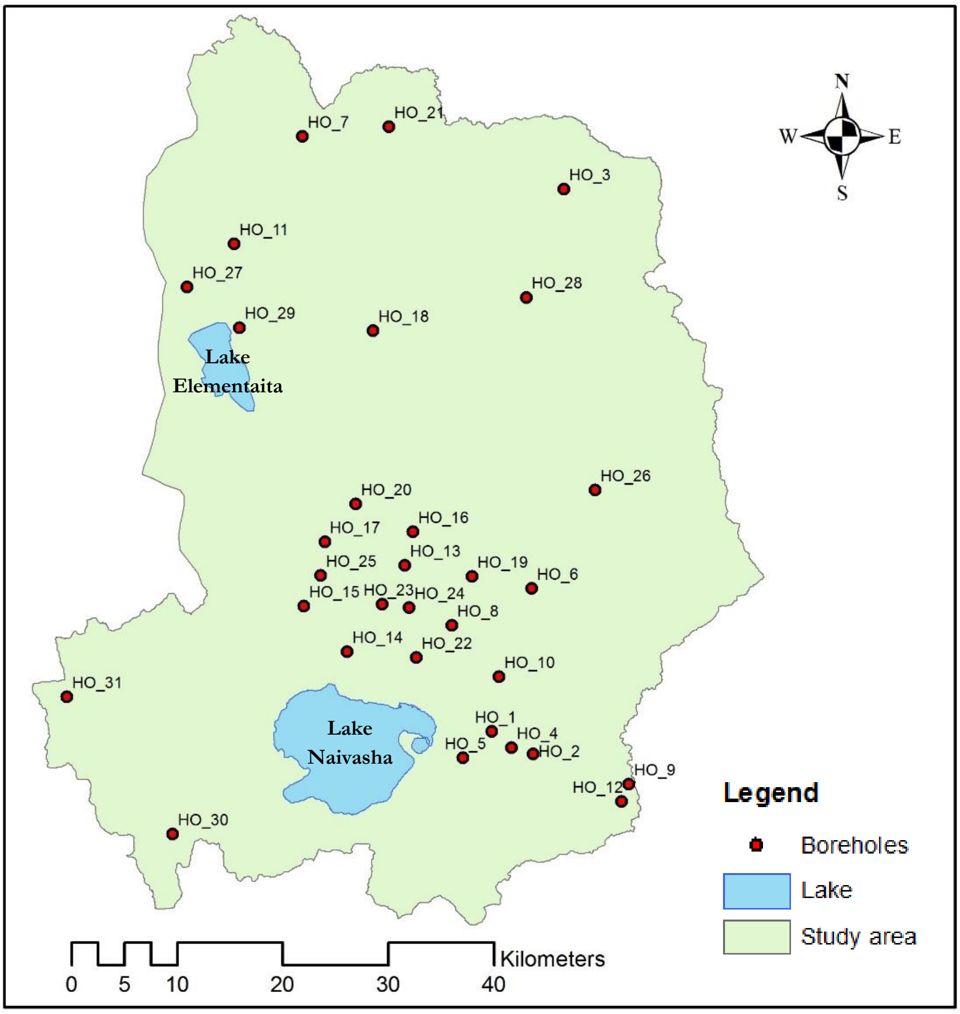

Figure 28. Location of boreholes in the study area.

APPENDIX 3. some photos of fieldwork.