Surface water - Groundwater Interaction. Lake Naivasha, Kenya.

Behar Hussein Abdulahi

April, 1999

Surface water – Groundwater Interaction

Near Lake Naivasha, Kenya.

By

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Thesis submitted to the International Institute for Aerospace Survey and Earth Sciences in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Survey (Hydrogeology).

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To my mother Kimya Abdi and my father Haji Hussein Abdulahi.
To my Sisters - Feriha, Muluka, Eled and Nebat, and
my Brothers - Ferhad, Abdulfetah and Ferid.

&

To my wife and daughter - Ferida Abas and Sebrin Behar.

In the name of GOD, Most Gracious, Most Merciful.

ACKNOWLEDGEMENT

I am greatly indebted to the Ethiopian government for giving me the opportunity to continue my studies at the International Institute for Aerospace Survey and Earth Sciences (ITC). Many thanks are due to the Netherlands government for funding my scholarship. I would like to express my sincere thanks to Harari People National Regional State (HPNRS) Office and HPNRS Bureau of Planning and Economic Development (BOPED), for allowing me to come to ITC despite the then manpower shortage. Special thanks goes to Abdulahi Idris (Head, BOPED), Muhyedin Ahmed (Department Head, BOPED) and Elias Abdosh (Head, HPNRS Population Office) for supporting me in the necessary facilities before coming to ITC.

My sincere heartfelt thanks go to my supervisor Drs. Robert Becht, for his extremely important advice and kind guidance throughout the study period. It was his creative new ideas and enthusiasm which allowed me to carry out the study. I am privileged to thank Dr.Maciek Lubczynski for his advice on groundwater modeling. My thanks go also to Drs. D.Kovacs for his fatherly advice and encouragement.

I would like to express my special thanks to my Class mates Mr. Anthony Duah (Ghana), Ahmad M. Salah (Egypt), Antonio L. Querido (Cape Verde), Ashfaque Ahmed (Bangladesh), Fathi A. Hamouda (Egypt), Jorge Salazar (Bolivia), Julian Gressando (Indonesia), Mekonnen G.Michael (Ethiopia), Robert R. Hernandez (Cuba), Samuel G. Mmbui (Kenya) and Mrs Zhen Xu Tang (China), whom we have worked and complained together, and encouraged each other for the past two years.

No words can fulfill my gratefulness to my wife Ferida Abas who was always the source of my strength. I greatly appreciate for the patience she bore for being alone for such a long time and raising our newly born daughter, Sebrin. All my friends at home in general and Abinet G/Medhin in particular are highly acknowledged for their support in my every day life activity. Their moral, material and spiritual support for my family and me have contributed a great deal to my success.

Last but not least I offer my deepest gratitude to my families who thought me the principles of life.

Behar Hussein Abdulahi
Enschede, The Netherlands
April, 1999

ABSTRACT

With growing economic development, the demand for groundwater increases. There is thus the necessity to study the change in groundwater storage and the interaction between groundwater and surface water, on a longer term. This study addresses both issues. By comparing the groundwater tables observed in wells with the lake level data, the direction of flow is established. Generally speaking, the lake was losing water to the aquifer at a rate of about 55 million-cubic meters per annum, over a period of 1958 to date. To quantify the change in groundwater storage of the aquifer in response to fluctuating Lake Levels, modelling is carried out using PMWIN. This model has a capability of optimizing different aquifer parameters like transmisivity and storage coefficient, which are used to quantify the storage change. The change in groundwater storage was insignificant, accounting for 0.1% of the lake storage change.

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C	-	Conductance
E	-	Evaporation
GHB	-	General Head boundary
GIS	-	Geographic Information System
ILWIS	-	The Integrated Land and Water Information System.
K.C.C	-	Kenya Creamery Corporation
KSS	-	Kenya Soil Survey
KWS	-	Kenyan Wildlife Services
LNROA	-	Lake Naivasha Riparian Owners
Ma	-	Million years
MAE	-	Mean Absolute error
mcm	-	Million Cubic meter
ME	-	mean error
Naivasha D.O	-	Naivasha Division Off
ND	-	no data
P1...P	-	6 - Parameter 1 ... Parameter 6
PEST	-	Parameter Estimation
PMWIN	-	Processing Modflow for Window
RMS	-	Root Mean square error
S	-	Storativity/Storage Coefficient
T	-	Transmisivity
USGS	-	United state geological Survey
W2.... W19	-	well 2 ... well 19
WRAP	-	Water Resources Assessment Project

CHAPTER 1

INTRODUCTION

1.1 Background

Lake Naivasha is the only freshwater resource among many saline Lakes in the Kenyan Rift Valley. Two perennial and one ephermal rivers drain into it but it has no surface outlet. The Lake water is very heavily used for agricultural irrigation, domestic, municipal, the wildlife water supply and geothermal projects. However, recent drop in the Lake water level poses a treat to its sustainability. Proper management of the Lake therefore becomes critically important. The major step in the Lake management is the awareness of the quantity of the resource in four dimensions. Changes in Lake level and volume can be observed, but very little is known about changes in groundwater levels, and their contribution to the Lake. This thesis, therefore, discusses the results from fourteen years of data on temporal water level variations in the shallow wells around the Lake Naivasha, aquifer pumping tests and hydrogeologic simulation of the aquifer parameters with the aim of looking the interaction between the Lake and the surrounding aquifer and quantifying the storage change around the Lake.

1.2 Objective

The main objectives of the study are

1) To study the hydraulic interaction between Lake Naivasha and the surrounding aquifer;
2) To use groundwater modeling techniques to investigate the groundwater storage behavior of the aquifer in relation to the Lake level;
3) To quantify the contribution of groundwater as a potential water resource.

1.3 Previous Studies

Exploration of the Naivasha area began as early as the 1880's by European explorers. Thompson, of the Royal Geographical Society of England, during a visit at that time, noted the freshness of the Lake water, and attributed it to the Lake being either of recent origin, or having an underground channel (LNROA, 1993). Gregory (1922) suggested that the Lake's freshness was due to an undiscovered underground outlet. Nilsson (1938) proposed the Lake's freshness was a result of water both entering and leaving the Lake via underground seepage.

In 1936, Sikes made the first statistical attempt to estimate monthly and annual water budget for the Lake, and magnitude of the proposed underground seepage. It is uncertain which methods he used, but he estimated water was seeping out of the Lake at a rate of 43×10^6 m^3/yr (Darling et. al., 1990). McCann (1974) estimated that about 34×10^6 m^3/yr of water recharges the shallow groundwater aquifers from Lake Naivasha.

Gaudet and Melack (1981), on the basis of rain, river and Lake water chemistry concluded that there is a subsurface water outflow from Lake Naivasha. Ase et. al (1986) worked on the surface hydrology of Lake Naivasha and used precipitation, river inflow, Lake level change and the evapotranspiration mass balance equation to calculate possible subsurface outflow from the Lake.

Darling et. al (1990) was able to indirectly determine (using stable isotope analysis and a water-mixing model) the directions of subsurface outflow from the Lake. They concluded that there is considerable outflow to the south (50-90% of Lake Outflow) and significantly less outflow to the north. (Their research suggests that the northerly outflow is confined to the area between Eburru and Gilgil, while the southerly outflow is between Olkaria and Longonot.) This is in agreement with the work of Allen et al. (1989) who previously came to the same conclusion that most of the Lake outflow ends up between Olkaria and Longonot.

Ojiambo (1992,1996) discussed the hydrogeologic conditions around the Lake and indicates that the main subsurface outflow is from around the intersection of Oloidien Bay and the main Lake with outflow fluxes ranging from 18 x 10^6 to 50 x 10^6 m^3/yr.

1.4 Methodology

1.4.1 Data

Groundwater time series data extending from Sep 1957 to Feb 1970 on a daily basis were available for 12 wells around the Lake. The data were collected from the Ministry of water Development Kenya as hard copy formats. In the field, 2 auger hole transect at two sites, 8 auger hole in KWS Annex, 5 auger hole in Manera Farm, 2 auger holes along Malewa River and slug test in KWS Annex were made. The water level of one shallow well and two boreholes situated along Malewa River were measured.

1.4.2 Method

After the necessary analysis on all of time series well data, four wells with relatively complete data sets were chosen on the basis of their distance from the Lake and their location for further analysis. Out of these four wells, two wells were used in cross-sectional modeling.
The analysis of time series well data was done using statistical package called SPSS 8 and Excel. Processing Modflow for windows (PMWIN) and PEST were used for cross-sectional modeling and estimation of parameters, respectively. ILWIS 2.2 was the GIS package used. Figure 1.1 shows the steps undertaken in this assessment.

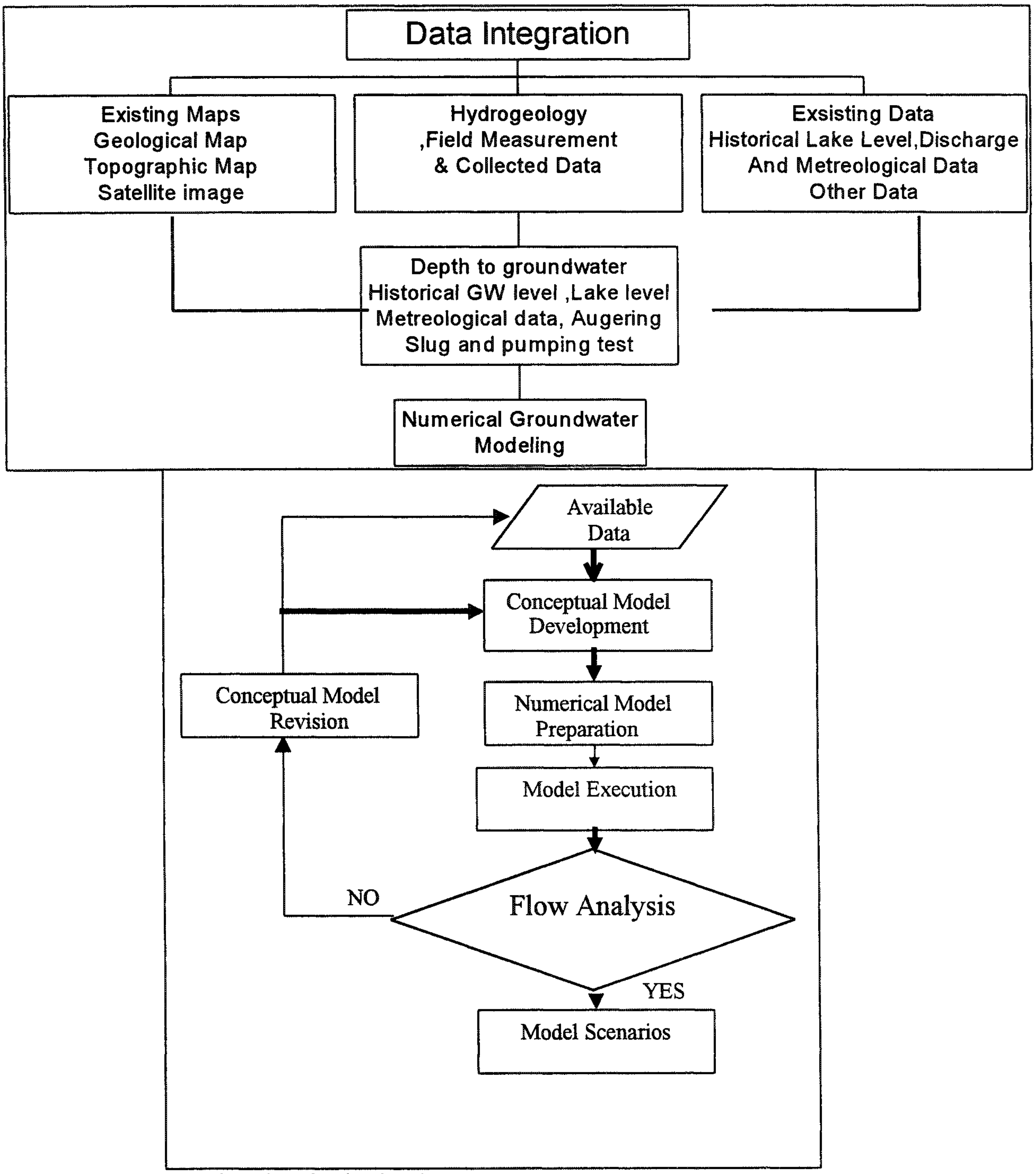


Figure 1-1 Steps undertaken in the Study.

1.5 General Overview of the Study Area

1.5.1 Location

The study area is located approximately 100 km from Nairobi in the Naivasha Division of the Nakuru District (Figure 1) within the UTM zone 37 having the coordinates:

X_{max} 221000 X_{min} 190000
Y_{max} 9934000 Y_{min} 9907000

1.5.2 Topography

The basin can be divided into three physiographic regions: the rift, the escarpment and the highland. The middle part of the basin is the rift floor bounded by Mau Escarpment to the west, the Kinangop Plateau to the east. The topographic difference between the rift and the plateau is around 500 meters whereas between the rift and the top of Mau escarpment is 800 meters.

1.5.3 Drainage

There are many rivers, most of which originate in the northern part of the catchment. The main rivers are Malewa, Gilgil and Karati. The first two rivers drain from the northern part of the catchment and are perennial in nature, while the Karati River, which runs from the northeastern part of the study area, is Ephermal.

The drainage density is high in the Northern part the catchment and low in the rift. Streams lying in the western part of the study area disappear in the rift, before reaching the Lake.

1.5.4 Soil and Landuse

Soil

Several soil surveys have been carried out in the area, with different level of detail. According to Siderius (1980) the distribution of soils in the area is complex, having been influenced by the extensive variation in relief, climate and volcanic activity and underlying rocks. The soils are derived mainly from weathered volcanic and basement rock system. Generally soils of the study area can be grouped into two: soils developed on the Lacustrine plain and those developed on the volcanic plain.

Soils developed on the Lacustrine plain are moderately well drained to well drained, very deep, very dark grayish brown to pale brown, silty clay to clay loam.

Soils developed on the volcanic plain are well drained, moderately deep to very deep, dark brown to pale brown, with non-calcareous to moderately calcareous topsoil, and moderately to strongly calcareous deep soil.

Landuse

Five major landuse units can be identified in the area: a. agriculture (horticulture and flower growing) b. settlements, c. game scantuaries, d. rangeland (dairy) and e. natural vegetation.
Horticulture and flower growing is concentrated around the Lake. Vegetable and dairy farming is practiced on large estates mainly in the northeast shores of the Lake. Game scantuaries are mainly present in the west of the study area however wildlife occupies most of the barren shrub, grass lands. Settlement is mainly concentrated in Naivasha town but scattered homes and villages are present on estates within the study area. The natural vegetation surrounding the Lake is mainly papyrus swamp vegetation. Natural vegetation outside of the Lake surroundings are shrub, acacia and cactus trees.

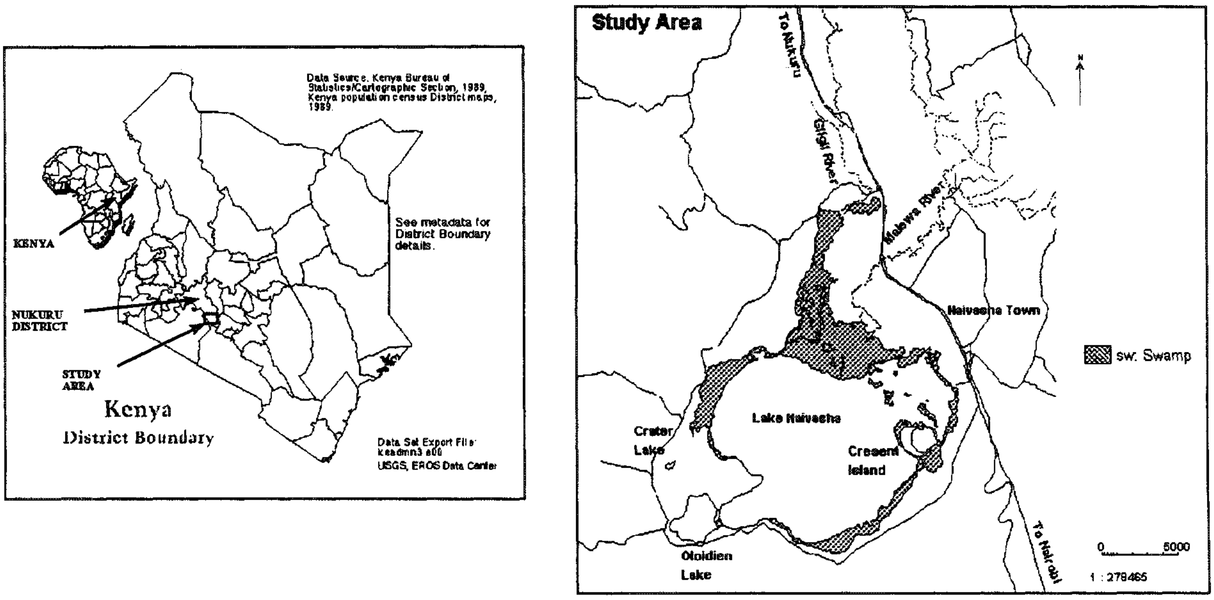


Figure 1-2 Location Maps of the study area.

1.5.5 Climate

The climate is humid to sub-humid in the highlands and semi-arid in the rift valley. The mean monthly maximum temperature range between 24.6°C to 28.3°C, and mean monthly minimum temperature between 6.8°C and 8.0°C. The average monthly temperature ranges between 15.9°C and 17.8°C.
The average annual rainfall ranges from about 1300mm in Kinangop plateau (South Kinangop Njambini) to about 600mm (Naivasha K.C.C. Ltd.) in the rift floor. The rainy seasons are typically from April to May (sometimes June) and October to November. The April-May rainy season is the main rainy period, known as the 'long rains', while the 'short rains' occur during October-November.

CHAPTER 2

Geology, Geomorphology and Aquifer Characteristics

2.1 Geology

Previous systematic geological survey of the project area is covered in Report Number 55, (Naivasha area), of the Geological Survey of Kenya, (Thompson and Dodson, 1963).
Rocks and structures within the study area have all been generated during the past 4 Ma, i.e. are associated with the Full graben and Inner Trough stages of the development of the Rift Valley as outlined in Table 2.1.
Table 2.1 shows the four major episodes of both volcanic activity(V1-V4) and faulting (D1-D4), in the study area, based on work summarized by Baker et al. (1988).

EPISODE		**ACTIVITY**	**AGE RANGE**
V4		Late quaternary to recent salic volcanoes	0.4-0 Ma
	F4	Extensive minor faulting of rift floor	0.8-0.4 Ma
V3		Quaternary flood lavas of rift floor	1.65-0.9 Ma
	F3	Renewed faulting of rift margins	1.7 Ma
V2		Early quaternary flood trachytes	2.0-1.8 Ma
	F2	Formation of step faults (narrowing of graben	3-2 Ma
V1		Pliocene ash flows	3.7-3.4 Ma
	F1	Major faulting of eastern rift margin	4-3 Ma

Table 2-1 Major Volcanic and Deformation Episodes. (From Clarke et. al., 1990)

The following outline stratigraphic column lists the Formations equated with the earlier three volcanic episodes (V1-V3) and also the six Volcanic Groups recognized within the youngest volcanic episode (V4).

Volcanic Episode	Unit Represented
V4	MAJOR CENTERS OR COMPLEXES Longonot Volcanic Group Eburru Volcanic Group Olkaria Volcanic Group MINOR CENTERS Elmenteita Volcanic Group Ndabibi Volcanic Group Akira Volcanic Group
V3	Mt Margaret Formation (Mt) Gilgil Trachyte Formation (Trg) Kijabe Hill Formation (Kb)
V2	Limuru Trachyte Formation (Tr) Karati and Ol Mogobo Basalt Formation (Trb)
V1	Kinangop Tuff Formation (Tk) Mau Tuff Formation (Tkm)

Table 2-2 Outline volcanic stratigraphy of the area around the Lake Naivasha. (From Clarke et. al., 1990)

NB The geological Map also depicts two further units:

a = Fluvio – colluvial deposits, by reworking of the volcanics.
ls = Lacustrine sediments – deposited during the previous Lake highstands in the Naivasha – Elmenteita – Nakuru Basin.
NB: Both these units are interdigitated with or overlie rocks of V4 age.

2.2 Geomorphology

The study region may be divided into three main geomorphologic units: the Mau Escarpment to the west, the Kinangop Plateau to the east, and between these two highlands, the Rift Valley plains (the Naivasha basin). See Figure 2.1

Mau Escarpment (Western margin)

The Mau Escarpment forms the western margin of the Rift Valley in the study region. Its height reaches over 3000 m.a.s.l. and it has a N to NNW orientation. The escarpment is composed largely of soft, porous volcanic ashes and tuffs, with rare outcrops of agglomerates and lavas (Thompson et al, 1963). Down faulted platforms with fault scarps up to 300 m separate the escarpment from the Rift Valley (Min. of Energy, 1990). Faults and scarps are difficult to trace either due to their being eroded, or covered with new material (McCann, 1974).Unlike the Kinangop Plateau, the Mau Escarpment is not flat-topped, but rugged and deeply incised.
The main river draining the escarpment is the Marmonet. It fails to reach Lake Naivasha, instead recharging the alluvium of the Ndabibi Plain. There is no drainage from the escarpment reaching the Lake via surface watercourses.

The Kinangop Plateau (eastern margin)

The western most part of the Kinangop Plateau occurs within the study area where it attains a maximum elevation of about 2740 m. Its western margin is defined by the north-north-west-trending South Kinangop fault scarp, which ranges in height from 100 m to 240 m. Along much of its length, this scarp has very steep or vertical rock faces above less steep talus slopes, but in the extreme south the scarps has been buried by younger pyroclastic rocks. The crest of the scarp is between 500 and 600m high relative to the rift floor, but is separated from the floor by a series of down faulted platforms.
North of Naivasha Town, the combined width of these platforms is between 2.5 and 5km. Between Naivasha Town and Kijabe Hill however, the total width of these platforms is 9km, and their surfaces, like that of the Kinangop Plateau, are gently sloping in a northerly direction. Fault scarps define the western edge of each platform, and many consist, at least in part

The Naivasha Basin

The Naivasha basin incorporates Lake Naivasha , the Ndabibi plains which lie to the west of the Lake , and the Ilkek plains which lie immediately to the north.
Lake Naivasha dominates the Naivasha basin and during a 1998 survey its level stood at an elevation of 1888.3 m. The results of this survey revealed that the Lake is smoothed floored and has a mean depth of 4.4 m. The deepest parts of the Lake occur within Oloiden Bay and that part of the Lake surrounded by Crescent Island. Crescent Island is the highest part of volcanic cone/crater feature approximately 1.5 km in diameter. Oloiden Bay lies immediately west-south-west of the main Lake and is connected to the latter via a narrow channel little more than 300 m wide. Vegetation (mainly Papyrus and salvina) occurs around much of the shore of the main Lake and extends across the channel leading to Oloiden Bay.

The Ndabibi plains extend up to 9km west of Lake Naivasha and separate the Eburu and Olkaria Volcanic Complexes. Gullies on the southern flanks of Western Eburru terminate on reaching the north-west corner of the plains and alluvial fans extend from the mouths of these gullies for up to 1.5 Km onto the plains. The plains are about 1980 m in elevation along their western edge and slope very gently eastwards the Lake.
The Ilkek plains extend up to 23 Km north of the Lake Naivasha and they range in width from a maximum of 13 km in the south, near Naivasha Town, to a minimum of 4km in the extreme north near Gilgil Town. The plains slope gently southwards from a maximum elevation of just below 2000 m in the North. Waterloo Ridge defines most of the western margin, and fault scarps along the lowest of the rift platforms below the Kinangop Plateau define the eastern margin. Ridges formed of volcanic rock occur at and east of the Ilkek settlement, and several have prominent fault scarps along their western sides.

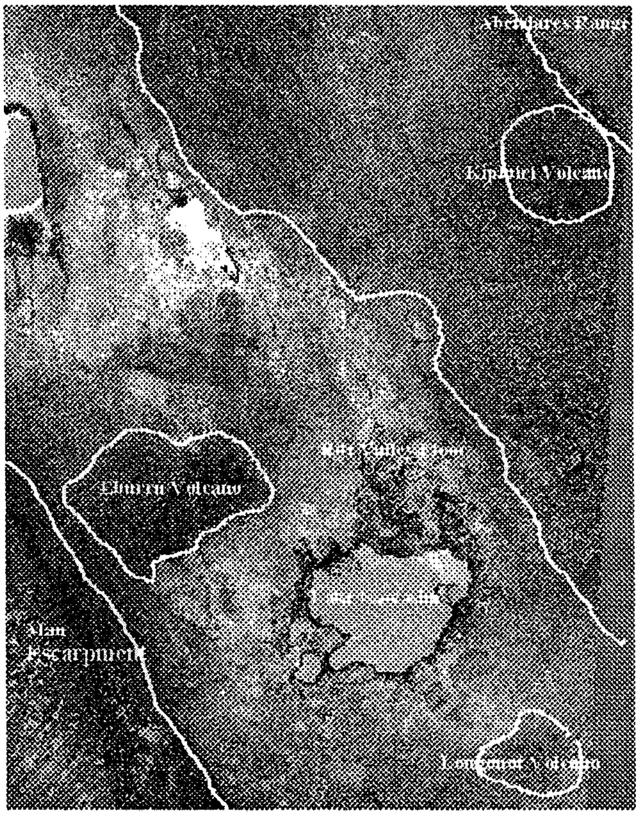
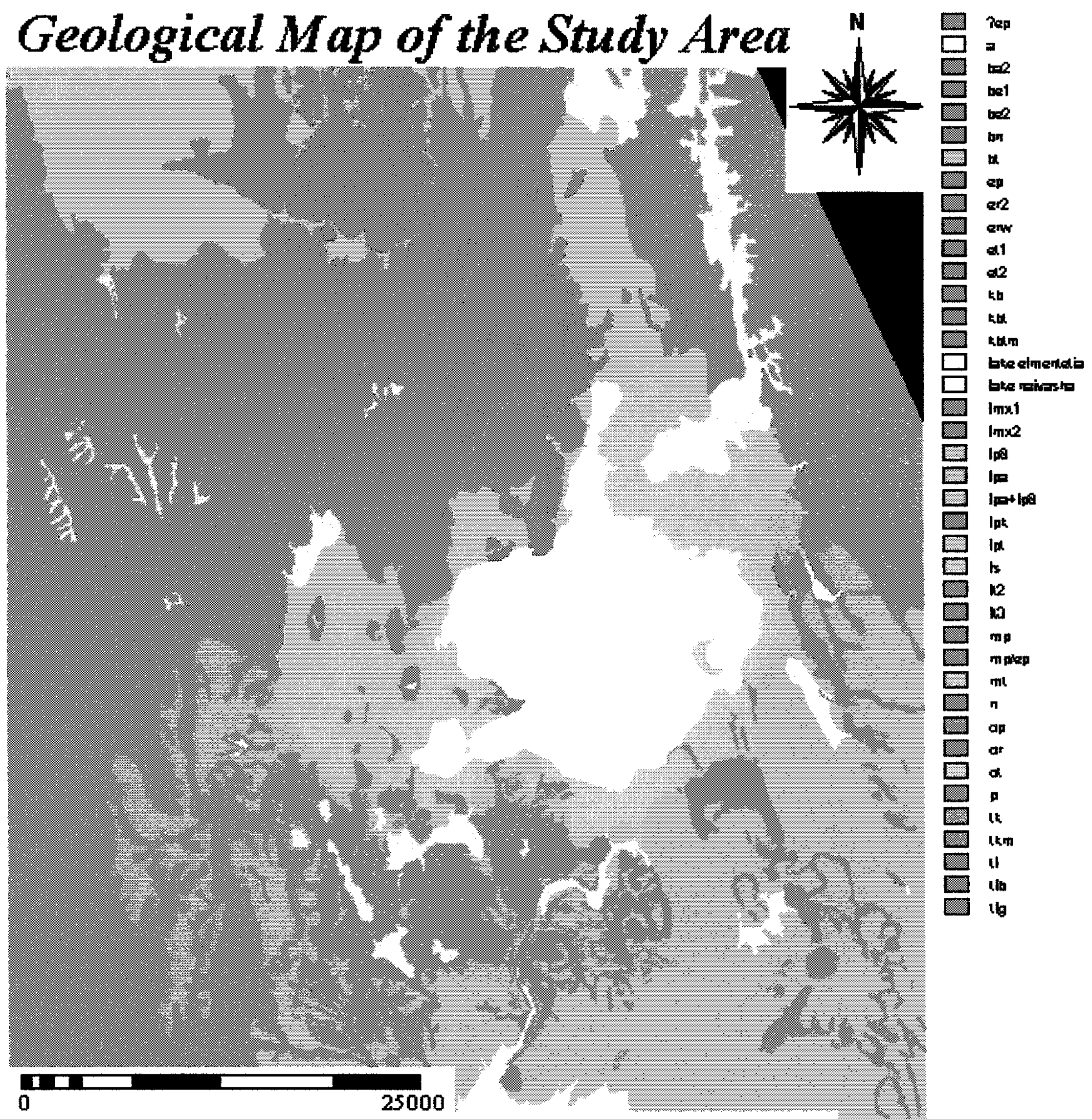


Figure 2-1Main geomorphological units in the study area.



Legend near the Lake

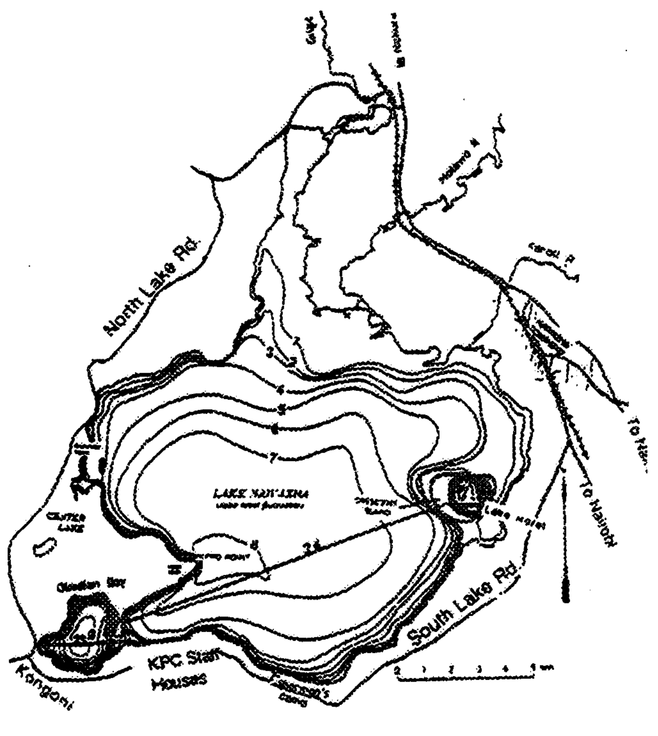
a	Alluvial deposits
er2	Eburru Pumice
ls	Lacustrine Sediments
mp/ep	Maiella pumice and Eburru pumice
lpa + lp8	Akiria pumice and Longonot ash
th	Kinangop tuff

Figure 2-2 Geological Map of the study Area.

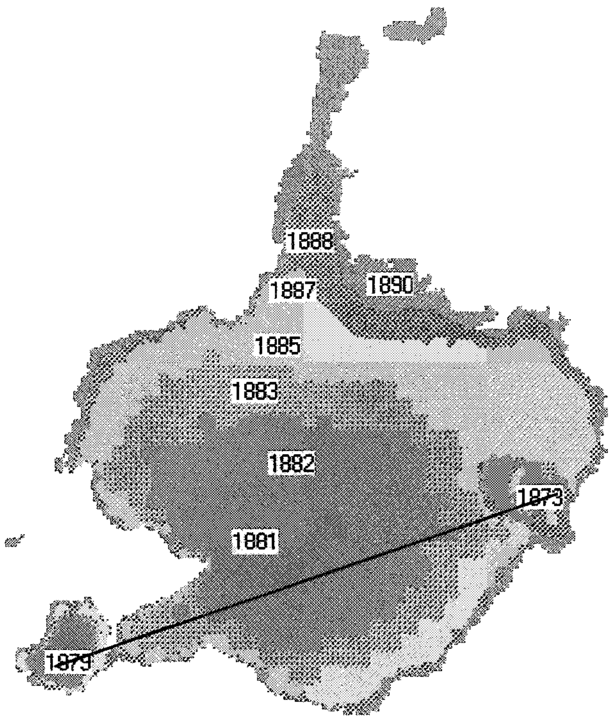
Bottom Morphology of the Lake

Lake Naivasha is a freshwater Lake located at the apex of N-S Rift Valley floor dome with an average elevation of 1888.1 m.a.s.l.. The total surface area of the Lake is about 145 km^2. The Lake is shallow with an average depth of 4.4 meters and estimated volume of 700e+06 m^3. The deepest part of the main Lake is 7 meters which is located near Hippo Point (Figure 2.3a,b). A WSW-ENE bathymetric profile of the Lake bottom (Figure 2.3c and d) shows the flatness of the central and main part of the Lake and the crater like morphology of the two deepest parts of the Lake, the Oloidien bay to the WSW and Cresent Lake to the ENE. Ase et. al (1986) state that the flatness may be due to the fact that the basin has filled up with large quantities of sediments that has resulted in the development of even bottom topography. The two deepest parts of the Lake have typical crater shaped morphology indicating volcanic origin of formation. The bathymetric profile of the Lake bottom shown in Figure 2.3c and Figure 2.3d which are surveyed in 1983 by Ase et. al(1986) and in 1998 by WRAP surveyors respectively shows almost the same morphology. Besides comparison of the bathymetric map of the Lake taken in 1983 by Ase et. al(1986) show similarities to the one draw by the public Works Department (PWD) in 1927 and reproduced by Thompson and Dodson (1963) except for the depth contours of Oloidien bay. Whereas the 1983 maps show the maximum depth of Oloidien bay as 11.5 meters, the PWD map gives a maximum depth of 4.3 meters despite the fact that the Lake level in 1927 was nearly 3 meters higher than in 1983. Ase, Sernbo and Syren, (1986) contend that this large difference may be due to lack of sufficient depth data taken in 1972. This may be a plausible explanation but one may also ask why there is agreement in depth contours in other parts of the Lake except in the Oloidien bay.

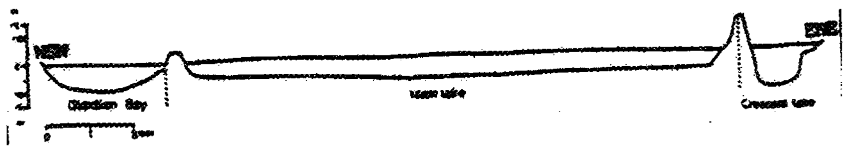
a)



b)



c)



d)

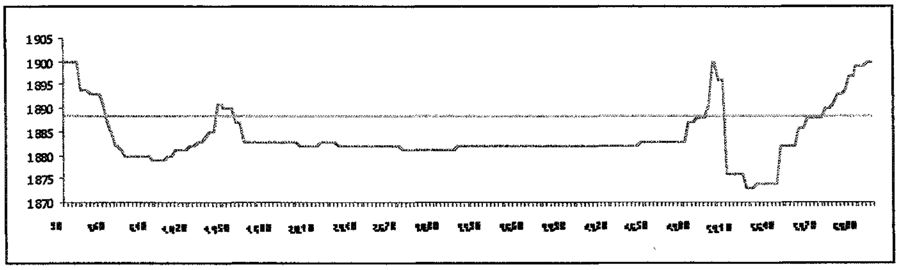


Figure 2-3 a) Bathymetric map of Lake Naivasha based on October 1983 levels (modified from Ase et. al, 1986).b) Bathymetric map of Lake Naivasha based on November 1998 levels (WRAP). c) Bathymetric profile of Lake Naivasha from Oloidien Bay to Crescent Lake, based on soundings 29, 26 and 22 shown in Figure 2.3a (modified from Ase et. al, 1986) d) Bathymetric profile of Lake Naivasha from Oloidien Bay to Crescent Lake, based on soundings survey of WRAP (1998).

2.3 Aquifers and their Properties

There is no information about individual aquifer properties in the study area. Carefully monitored aquifer testing with observation wells has not been undertaken in this area. This is because no well-planned aquifer testing and assessment program or large public groundwater supply-pumping project has been carried out so far. Most of the wells, from which hydrogeological data are available, are privately owned, and they are not very close to each other. The standard field aquifer testing required by the Ministry of Water Development is done by drillers after well completion and involves single well pumping with no observation wells.

2.3.1Reported

Transmisivity and Hydraulic Conductivity

An analysis of the type of shallow aquifer that yields water in the study area was done using well data kept by Ojiambo (1992,1996). According to his analysis, transmisivity value in the area ranges from 3 - 12,000 m^2/day. The corresponding hydraulic conductivity calculated from transmisivity values range from 14 to 750 m/day (Table 2.3).

Pumping test carried out by a private company called VIAK (1975) gives a transmisivity values ranging from 200-500 m^2/day for the Lake Naivasha area.

Geohydrological investigation performed by Wiberg, I. (1976) at the Karati river shows a transmisivity value of 259 m^2/day. Table 2.4 shows the detail.

The above ranges of transmisivity values were used as initial value in parameter estimation in chapter 6.

Storage Coefficient

Ojiambo (1996) gives a storage coefficient of 0.0044 which is calculated using Cooper and Jacob (1946) metric system. Whereas Wiberg, I. (1976) gives 0.0015 as storage coefficient for Naivasha aquifer (Table 2.4). In cross-sectional modelling (Chapter 6) this parameter were also tried to optimize using PEST package.

ID	X	Y	Aquifer Thickness(m)	hydraulic conductivity	Transmisivity
C2660	196950	9911950	9.53	450	4450
C4397	204900	9908300	21.5	490	12000
C4420	204800	9908250	15.19	240	5900
C3924	205100	9908100	28.33	37	1058
C2071	202800	9909500	9	67	605
C579	201100	9910200	20.85	14	292
C630D	197700	9906200	26.3	0.1	3

Table 2-3 Well data, shallow wells, adapted from Ojiambo (1996).

Hydraulic characteristic	Symbol	Value
Transmisivity	T	3×10^{-3} m^2/s (259 m^2/day)
Storage Coefficient	S	1.5×10^{-3}
Leakage Coefficient	P/m	3×10^{-8} (s^{-1})
Safe Yield		25 l/s

Table 2-4 Well data, shallow wells, adapted from Wiberg, I. (1976).

2.3.2 Field investigation

Transmisivity

Single bore pumping tests were also carried out in 5 wells in the study area during this study by Ramirez(1999) . According to the analysis the transmisivity range from 48 - 5860 m2/day. The result of the analysis is shown in Table 2.5.

Location	X	Y	Transmissivity (m/day)
La Belle Inn	214151	9920906	>1000
KCC	209037	9925717	48-132
Manerra Farm	211434	9921380	670-816
Ostritch Farm	213712	9925550	1020-5860
Marula Farm	207698	9925728	168-220

Table 2-5 well data adapted from Ramirez (1999).

Hydraulic Conductivity

Slug Test

Slug tests were performed to determine the hydraulic conductivity of the formation in the immediate vicinity of a monitoring well. This test was used because it involves little time, a few labour, and no piezometer. Moreover, it is useful in areas where wells partially penetrate the aquifer. In this test, a known volume of water is quickly added to the monitoring well, and the rate at which the water level falls is measured. Two slug tests, 700 meters apart, were made in the vicinity of KWS Annex.

Data Analysis

In many cases piezometers, or auger holes, are installed that do not fully penetrate an aquifer. A very convenient method exists to use these piezometers to determine the hydraulic conductivity of the formation in which the screen is installed. This is the Hvorslev method.

Besides Hvorslev method other methods like Bower Rice is included in the software AQUITEST, a package used to analyze different aquifer properties. The software was used to estimate hydraulic conductivity of the aquifer.

The Hvorslev method was chosen for the interpretation as the Bouwer & Rice method require additional information, like radial distance away from the well over which head is dissipated, that could not be easily obtained. However, it is mentioned in Fetter (1992) that comparison of the two methods at sites could produce significantly similar results.

The field data are plotted with log H/Ho on the y-axis and time on the x-axis. The value of To is taken as the time which corresponds to H/Ho=0.37 and K is determined from the equation below. If the length of intake is greater than eight times the screen radius, the following formula applies for solution of K:

$$K = \frac{r^2 \ln(L/R)}{2LT}$$

where ,
K is hydraulic conductivity [L/T; m/day;m/sec]
r is the radius of the well casing [L;m]
R is the radius of the well screen [L;m]
L is the length of the well screen [L;m]
T is the time taken for the water level to rise or fall to 37 percent of the initial change. [T;day;sec]
The result of the analysis is shown in Table 2.6 and the soil descriptions of the auger holes are attached in Appendix 1. As it can be seen in the soil description the material surrounding the Lake, consists of Clay and sandy loam. The arithmetic mean hydraulic conductivity for this material from the two tests as shown in the Table 2.6 is 0.03289 m/day. The result shown below is optimized in the cross-sectional modeling of KWS Annex in chapter 6.

Location	ID	X	Y	Hydraulic conductivity(m/day)
KWS Annex	well 5	214151	9918303	0.014947
KWS Annex	well 7	214340	9918801	0.083722
		Arithmetic mean		0.03289

Table 2-6 hydraulic conductivity results from slug tests.

Slug test well 5
Slug/bail test analysis, HVORSLEV's method
Hydraulic conductivity [m/s]: $1.73*10^{-7}$

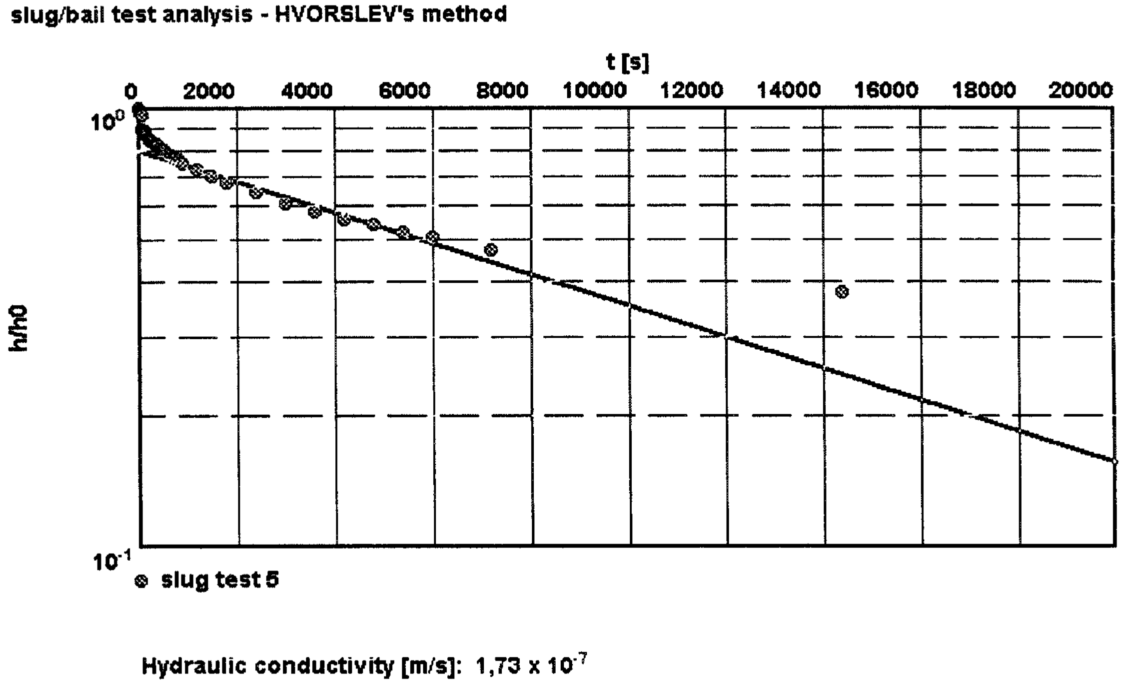


Figure 2-4 Slug test Interpretation result for well 5. (KWS Annex).

Slug test well 7
Slug/bail test analysis, HVORSLEV's method
Hydraulic conductivity [m/s]: $9.69*10^{-7}$

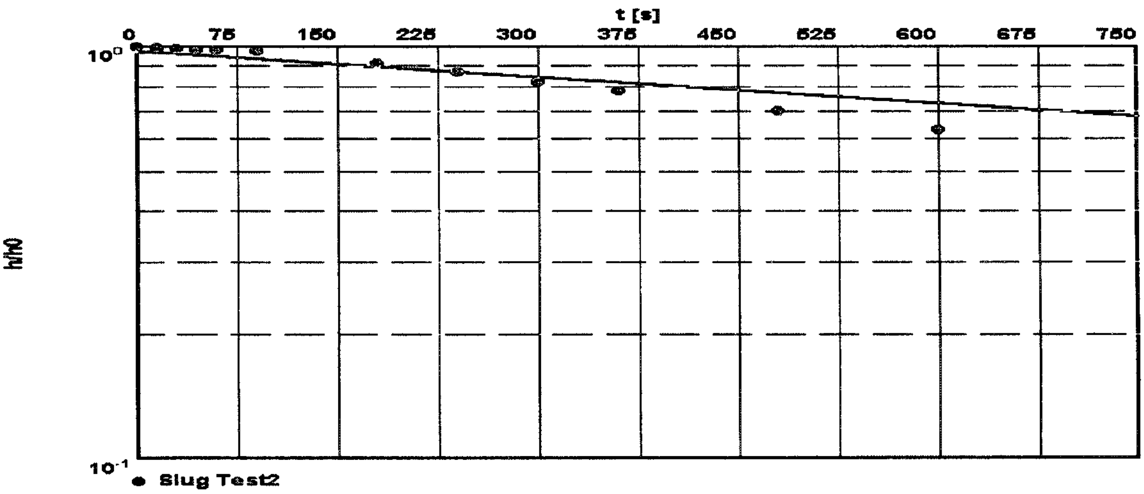


Figure 2-5 Slug test Interpretation result for well 7 (KWS Annex).

Summary of Aquifer properties

As it can be seen in Table 2.7 that the transmisivity value for Naivasha area ranges from 1 to 12,000 m^2/day and the hydraulic conductivity from 0.001 to 750 m/day. Using these values as initial condition it is tried to optimized the aquifer parameter in chapter 6.

	Wiberg, I. 1976	Ojiambo 1992,96	Ramirez 1999	VIAK 1975
Transmisivity (m^2/day)	259	3 –12000	48 - 5860	200-500
Hydraulic Conductivity (m/day)		14 – 750		
Storativity	0.0015	0.0044		

Table 2-7 Summary of Aquifer Properties.

CHAPTER 3

Surface Water Hydrology

3.1 Analysis of Precipitation

Analysis of rainfall in the Naivasha catchment area is very important, because rainfall is the major factor which causes the variations in Lake Level. The spatial and temporal variation in precipitation have been analyzed based on long term mean monthly precipitation records from 43 stations. The mean monthly Precipitation data are listed in Appendix 2.

3.1.1 Spatial variability

Based on the long-term mean annual precipitation data from 43 stations an isohyetal map was compiled (Figure 3.1). The map shows that there is a marked variation in the amount of precipitation between the rift and the highland due to the large difference in altitude; mean annual precipitation of the rifts is in the order of 600 to 800mm. From most parts of the plateau, the annual precipitation about 1300mm.

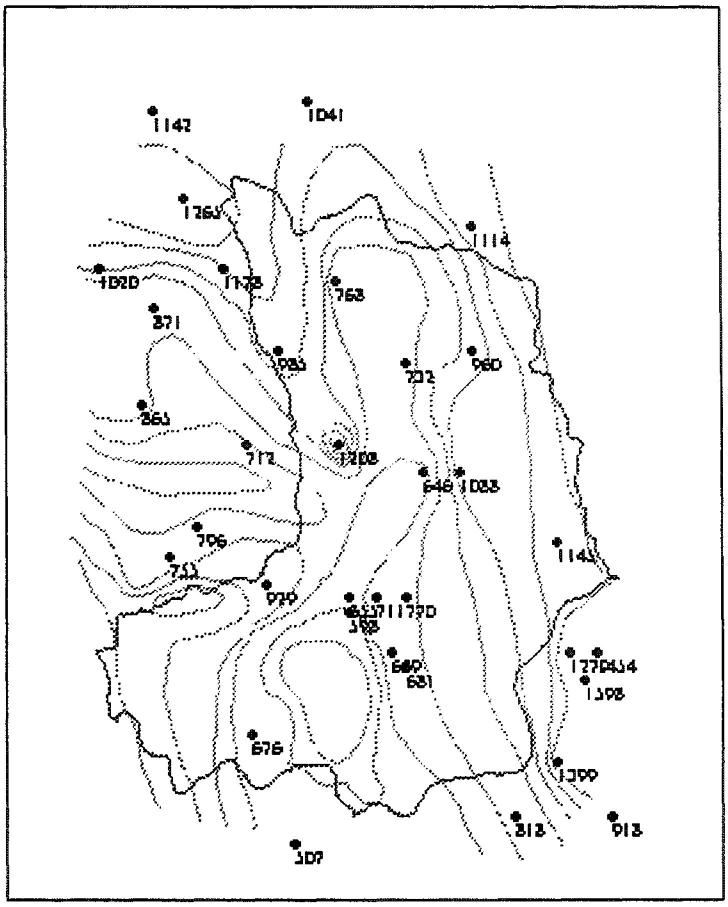


Figure 3-1 Isoheytal map of mean annual rainfall (mm).

3.1.2 Temporal Variation

The general pattern of rainfall can be seen from the graph of long term average for 5 stations in Figure 3.2. It can be seen from the figure that the rainfall patterns for all the stations follow the typical trend of two rainy seasons.

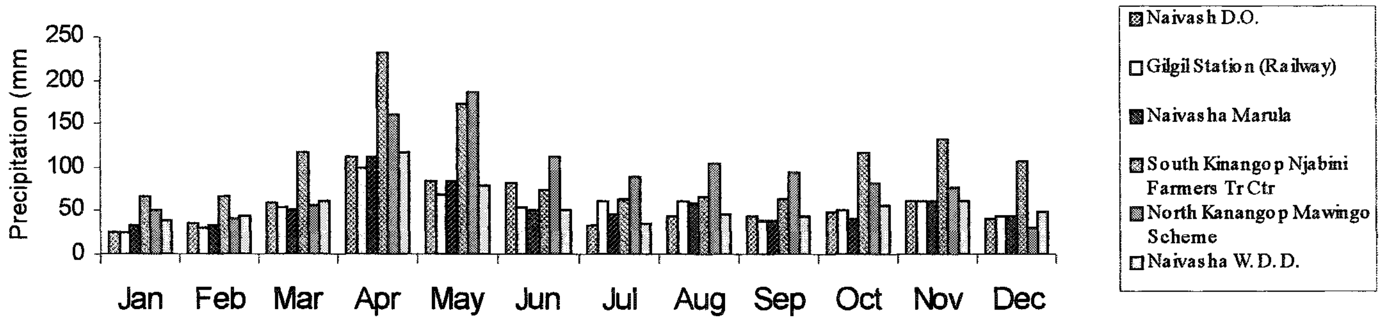


Figure 3-2 Long-term mean monthly precipitation at selected stations.

3.1.3 Estimation of Areal depth of Precipitation

The areal depth of Precipitation was estimated using isoheytal and Theissen polygon methods.

a) For Naivasha Basin

On the basis of the isoheytal map shown in Figure 3.1 and data presented in Table 3.1, the basin wide annual precipitation is estimated to be 856 mm.

Isoheytal range (mm)	Area %	Area (km^2)	Average Precipitation (mm)	Area x Avg. P	
500-600	8	275	550	151250	
600-700	12	379	650	246350	
700-800	20	648	750	486000	
800-900	20	646	850	549100	**856 mm**
900-1000	17	557	950	529150	
1000-1100	14	447	1050	469350	
1100-1200	10	335	1150	385250	
Sum	100	3289		2816450	

Table 3-1 Inter-isoheytal areas and average annual precipitation.

The Theissen polygons shown in Figure 3.3 are based on the mean annual rainfall for 43 stations. The method gives 875 as a long-term mean annual precipitation. The step to calculate the areal precipitation using both methods is attached in Appendix 3. The difference between this method and the isoheytal procedure is 2% of their average, therefore the Theissen polygon method is used in this study for estimation of mean annual precipitation over the Lake.

Isohytal Method	Theisen Method	Difference from their average
856 mm	**875 mm**	**2%**

Figure 3-3 Theisen polygons of the studied basin (station/annual rainfall, in mm).

b) Over the Lake

Using Theisen polygon the areal precipitation for the Lake region was calculated on yearly basis. The detail procedure is attached on Appendix 3. The yearly areal precipitation of the Lake region is shown in Table 3.2. These yearly values after computing the long-term average, latter used for water balance calculation using surface area of the Lake for different years. The surface area of the Lake is adapted from Lake level-surface area relationship made by Mmbui (1999).

Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)
1958	772	110	1969	557	92	1980	693	108
1959	633	90	1970	729	118	1981	848	132
1960	697	94	1971	645	105	1982	815	126
1961	959	125	1972	634	102	1983	632	98
1962	719	115	1973	590	91	1984	462	69
1963	881	145	1974	758	113	1985	491	72
1964	745	127	1975	555	83	1986	685	98
1965	561	94	1976	494	72	1987	690	95
1966	699	113	1977	913	133	1988	768	104
1967	696	113	1978	919	145	1989	814	109
1968	794	135	1979	723	117	1990	778	109
Long term yearly avg. Precipitation in volume						108 mcm/yr		

Table 3-2 yearly areal precipitation of the Lake region (mm and mcm/yr).

3.2 Stream Flow

The main rivers draining into Lake Naivasha are Malewa, Gilgil and Karati. Processed discharge data has been obtained for the these river stations from Mmbui (1999). Contribution of all the three rivers is added and aggregated in yearly basis and shown in Table 3.3.

Date	Yearly	Date	Yearly	Date	Yearly
1958	3.26E+08	1969	8.31E+07	1980	1.41E+08
1959	1.55E+08	1970	2.63E+08	1981	3.30E+08
1960	1.34E+08	1971	2.73E+08	1982	1.85E+08
1961	4.46E+08	1972	1.37E+08	1983	2.57E+08
1962	3.73E+08	1973	1.05E+08	1984	7.34E+07
1963	3.69E+08	1974	2.14E+08	1985	2.33E+08
1964	3.73E+08	1975	2.42E+08	1986	1.64E+08
1965	1.15E+08	1976	1.07E+08	1987	1.06E+08
1966	2.13E+08	1977	3.13E+08	1988	2.31E+08
1967	2.43E+08	1978	3.24E+08	1989	1.92E+08
1968	3.77E+08	1979	2.22E+08	1990	2.19E+08
Long term Yearly Average			2.29E+08 cm		
Long term Yearly Average			229 mcm/yr		

Table 3-3 yearly discharge to the Lake (cubic meter per year from Malewa, Gilgil and Karati Rivers.

3.3 Groundwater Inflow

The groundwater inflow through the western part of the Lake was estimated in chapter 5. Almost the same result was obtained by Mmbui(1999) in his water balance model. Therefore this value, i.e. 1.8mcm/yr, is taken for water balance estimation.

3.4 Analysis of Evaporation

3.4.1 Lake Evaporation

The estimation of Lake Evaporation is attempted from limited pan data. However, two challenges are encountered. The first challenge is related to the represenativeness of the pan data. Doorenbos and Pruitt (1977) showed that the pan placed around the shore of Aswan reservoir could not adequately represent the evaporation from the reservoir, because of reasons associated with the Oasis effect. However, Ashfaque (1999), based on his field measurements over Lake Naivasha, argues that a pan placed around the shore of the Lake can be used to estimate Lake evaporation. The other challenge is related to assigning appropriate value of pan coefficient. In most literature, since pan coefficients are given to convert pan data to evapotranspiration from a grass surface, these values can not be used here. Brind and Robertson (1958) did some study over Lake Naivasha, and suggest pan coefficient values varying from 0.84 to 1.04. The average value, i.e. 0.94 is then used as a pan coefficient to extrapolate pan data into Lake Evaporation. The resulting long-term average evaporation from the Lake is tabulated in Table 3.4a.

3.4.2 Evapotranpiration From Swamp.

Two experiments were carried out in order to study the combined effect of the absorption of water and evapotranspiration from swamp area by Ase et. al(1986), compared to the evaporation from a free water surface under comparable conditions. The results from these sets of experiments indicated that the combined effect of the absorption and evapotranspiration from living Salvinia equaled 80-90% of evaporation from a free water surface. One set of experiments gave the value of 82%, the other 92%. The average of this figures, i.e. 87%, is used in this study. The calculated long term average evapotranspiration from the swamp area is shown in Table 3.4 b.

a)

Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)
1958	1719	246	1969	1612	267	1980	1886	293
1959	2095	296	1970	1505	244	1981	1923	300
1960	2140	288	1971	1584	257	1982	1831	284
1961	2049	267	1972	1695	272	1983	1912	297
1962	1704	272	1973	1598	246	1984	1794	269
1963	1674	276	1974	1534	229	1985	1437	210
1964	1681	287	1975	1624	242	1986	1575	226
1965	1905	320	1976	1739	254	1987	1572	216
1966	1626	264	1977	1501	219	1988	1346	181
1967	1606	261	1978	1598	252	1989	1304	175
1968	1485	252	1979	2180	351	1990	1359	191

Long term Average Evaporation (in volume) = 258 mcm/yr b)

Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)	Date	Yearly Average (mm)	Yearly Average (mcm)
1958	1574	20	1969	1476	19	1980	1727	22
1959	1919	25	1970	1378	18	1981	1761	23
1960	1960	25	1971	1451	19	1982	1677	22
1961	1877	24	1972	1552	20	1983	1751	23
1962	1560	20	1973	1463	19	1984	1643	21
1963	1533	20	1974	1405	18	1985	1316	17
1964	1540	20	1975	1487	19	1986	1442	19
1965	1744	23	1976	1593	21	1987	1439	19
1966	1489	19	1977	1375	18	1988	1232	16
1967	1470	19	1978	1463	19	1989	1194	16
1968	1360	18	1979	1996	26	1990	1244	16

Long term Average Evaporation (in volume) = 20 mcm/yr
Average swamp Area = 13km^2

Table 3-4 a) yearly evaporation from the Lake (mm and mcm/yr) b) yearly evapotranspiration from the swamp (mm and mcm/yr).

3.5 Groundwater outflow and Abstraction

Gaudet and Melack(1987) estimated 44 mcm/yr and 12 mcm/yr for groundwater outflow and abstraction respectively which sum up 56 mcm/yr. Ojiambo (1996) re-evaluated mean value from different studies and gave a value of 39 mcm/yr for groundwater outflow and 12 for abstraction that sum up 51mcm/yr. Mmbui(1999) used 55mcm/yr for groundwater outflow in his water balance model without abstraction. In this study the same approach as Mmbui's considered, i.e. the calculated outflow value of chapter 5 (55mcm/yr) is taken for both groundwater outflow and abstraction.

3.6.Lake Water Balance and Level Fluctuation

3.6.1 Lake Water Balance

Despite limitations on hydrological data for surface and groundwater components, an attempt has been made in this chapter to estimate the water balance of the Lake.
In a watershed where the surface and groundwater divides coincide and hence with no external inflows or outflows of groundwater across the watershed boundary, the general form of the water balance equation of a Lake takes the form of:

$$\Delta V = P_1 + R + G_i + S_1 - E_1 - G_o \pm A$$

where, ΔV = net change in Lake volume
P_I = direct Precipitation onto the Lake
R_I = river water inflow
G_I = groundwater inflow
S_I = surface runoff from ungauged catchment
E_l=Lake water evaporation + evapotranspiration from swamp
R_0 = Surface water discharge from the Lake through rivers
G_0 = groundwater outflow from the Lake
A = abstraction (agricultural, industrial, etc.)

The main input of the Lake comes from Precipitation (P_1) and river discharge by the Malewa, Gilgil and Karati rivers (R_I). The annual direct Precipitation onto the Lake accounts for 108 million cubic meters per year (mcm). The long term mean annual inflow from the three rivers is 229 mcm/yr, Surface runoff from the remaining ungauged catchment is taken as 0.6 mcm/yr from Gaudet and Melack (1981). The estimated groundwater inflow is 1.8 mcm/yr.

Annual Lake water evaporation (E1) is estimated to be 268 mcm/yr, which is 248mcm/yr from open water evaporation, and 20 mcm/yr from the swamp. Groundwater outflow and abstraction value was taken 55 mcm per year.

Table 3.5 illustrates that the difference in the magnitude between the Lake inflow and outflow components is 6.4 mcm/yr, on a long term basis (1958-1990). Taking an average surface area of the Lake (i.e. 145 km^2), this amounts to an equivalent water depth of 0.04m per year, yielding 1.3 meters for the specified period. However, the Lake level observations indicate that the change in water level observed in 1958 and 1990 is 1 meter, which is less than the calculated value by 0.3m. This difference could be explained by many factors, the most important being uncertainties involved in estimating the hydrological components used in the analysis.

A comparison of the calculated water balance component from the previous research is shown in Table 3.6.

Water Balance (mcm/yr)			
Precipitation	108	Evapotranspiration	278
River Discharge	229	Groundwater Outflow	
Surface Runoff	0.6	and abstraction	55
Groundwater Inflow	1.8		
Total Input	339.4	Total Output	333
Storage change = 6.4 mcm/yr			

Table 3-5 Estimated Long-term mean annual water balance of Lake Naivasha.

	McCann (1974)	Gaudet and Melack (1981)	Ase,Sernbo	& Syren (1986)	Ojiambo (1996) (Average)	Mmbui (1999)	Calculated Value
	a	b	c	d	e	f	g
	1957-1967	1973-1975	1972-1974	1978-1980		1932-1998	1958-1990
INPUT							
Precipitation	132	103(range 7-114)	115(range 84-149)	142(range 127-167)	121	92	108
River Discharge	248	185(range 90-260)	187(range 156-263)	254(range 143-383)	212	211	229
Surface Runoff	ND	0.6(range0.4-0.7)	ND	ND	0.6		0.6
Groundwater Inflow	ND	49(range 41-58)	ND	ND	49	3.3	1.8
TOTAL INPUT	380	338(range 208-433)	302(range 240-412)	396	382.6	306.3	339.4
OUTPUT							
Evapotranspiration	346	313(range 289-324)	308(range 294-332)	301(range 272-339)	294	259	278
Groundwater outflow	34	44(range 17-78)	ND	ND	39	55	55
Irrigation + industrial	ND	12(range 7-15)	ND	ND	12		
TOTAL OUTPUT	380	369(range 313-417)	308(range 294-332)	301(range 272-339)	345	314	333
Storage change	ND	-31	0.4	95	37.6	-7.7	6.4

Table 3-6 Comparison of Lake Naivasha Hydrological balance. Units in million cubic meters per year.[mcm/yr].

3.6.2 Lake Water Level Fluctuation

Since continuous water level measurements of Lake Naivasha began in late 1908 (Figure 3.4) the largest water drop has been 9.5 meters, which occurred between 1917 and 1964. Statistical analysis of the Lake water level fluctuations since 1908 by Vincent, et al (1979) shows a periodicity of around 7 years with an indication of an 11-year return period. Ase et. al(1986) attach some significance to the 11 years periodicity because it coincides with the Lake level highs in 1905, 1917, 1937 and 1948. According to these authors, this return period corresponds the sunspot cycle.

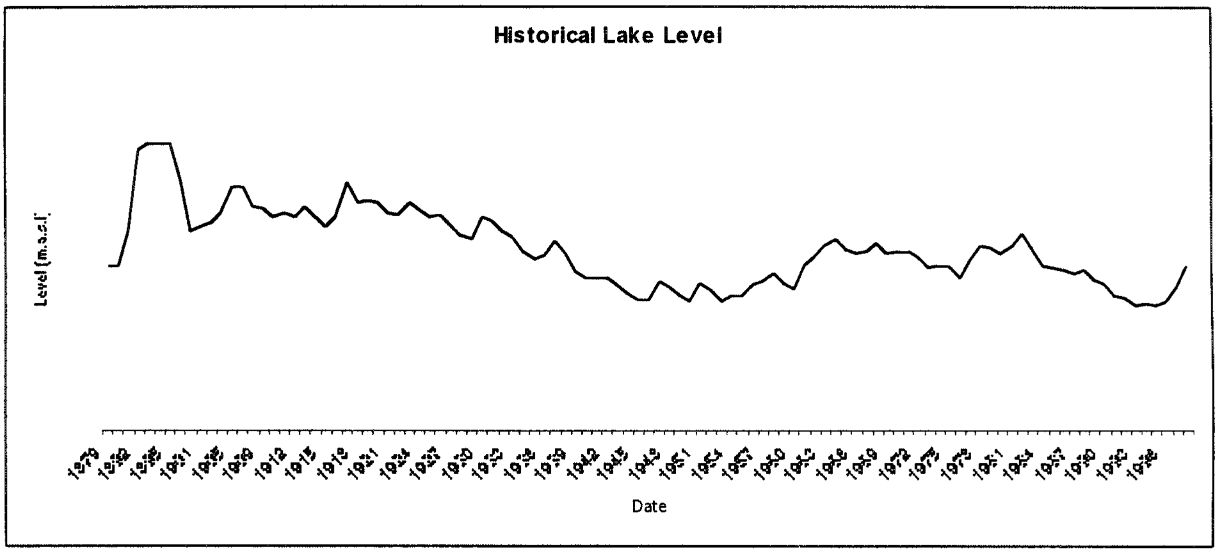


Figure 3-4 Historical Lake level.

3.6.3 Lake Water Level and Rainfall

The monthly variations of the level of Naivasha are depicted from Figure 3.5. One would expect that the Lake level would normally show two peaks, one during the long rains in April-May and another during the short rains in October-November. This is obviously not the case. The Lake level normally drops during the beginning of the year, until the long rains start in April. However, water level monthly continues to rise even during May, June and July and the maximum occurs in August. During the short rains water level normally drops. This can be partly explained by the fact that evaporation is very low in May, June, July and August and increased for the rest of the month.

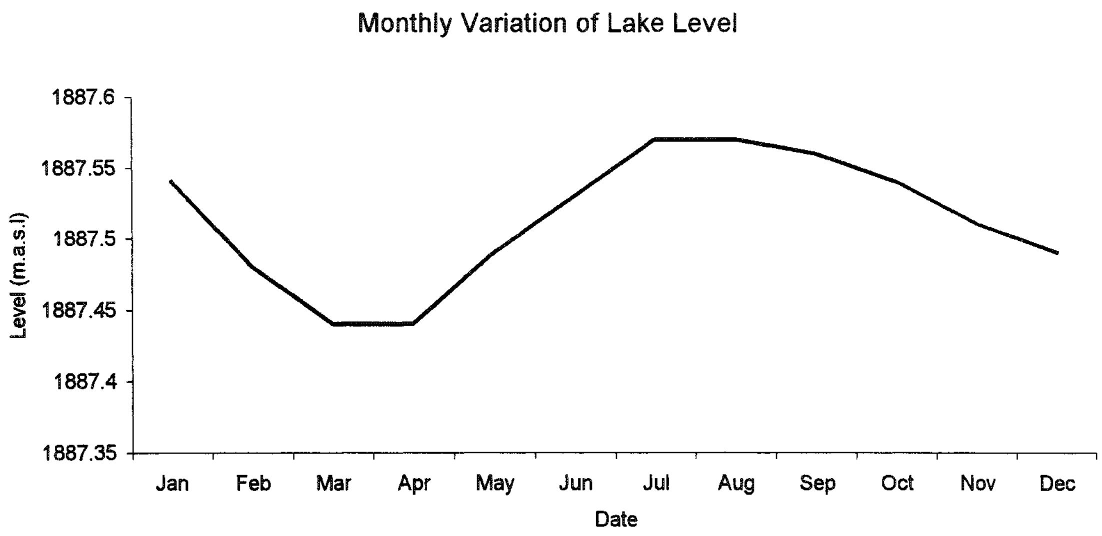


Figure 3-5 Monthly variations of water level in Lake Naivasha.

CHAPTER 4

Groundwater Level Data Analysis

4.1 Availability of Data

The required hydrological data for groundwater level data analyses near the Lake are: rainfall, groundwater level observed in wells, and Lake level.

Rainfall

These data are taken from Naivasha DO Metreological Station. This station was particularly selected in view of its proximity, reliability of its data, and moreover complete Lake level data corresponding to its data were available. This station provides rainfall data on a monthly basis dating back to 1910, its accuracy being confirmed by Podder (1998). The description of this station and its data set is given in Appendix 2.

Lake level

See Section 3.5.2.

Groundwater level Data

Groundwater level measurements data were obtained on a daily basis for 12 wells around the Lake. The well locations are shown in Figure 4.1, and descriptions of the data are given in Table 4.1.

Well	Geographic Location		Altitude	Record Length	Mean annual level
	X	Y	(m.a.s.l)	(years)	
w2	214009	9917763	1890	1958-70	1887.67
w3	213271	9914310	1910	1957-61	1885.93
w8	202435	9909675	1894	1957-70	1887.91
w9	195974	9908951	1893	1957-69	1887.15
w11	196851	9915861	1890	1957-70	1888.13
w12	197660	9918954	1890	1957-70	1887.60
w15	203634	9925042	1891	1957-69	1887.31
w16	207935	9925786	1897	1957-63	1887.90
w17	207165	9925364	1894	1957-65	1885.84
w19	210769	9920726	1889	1957-69	1887.23

Table 4-1Parameters of the wells.

Special statistical package called SPSS 8 for windows were used to organize the data for analysis.

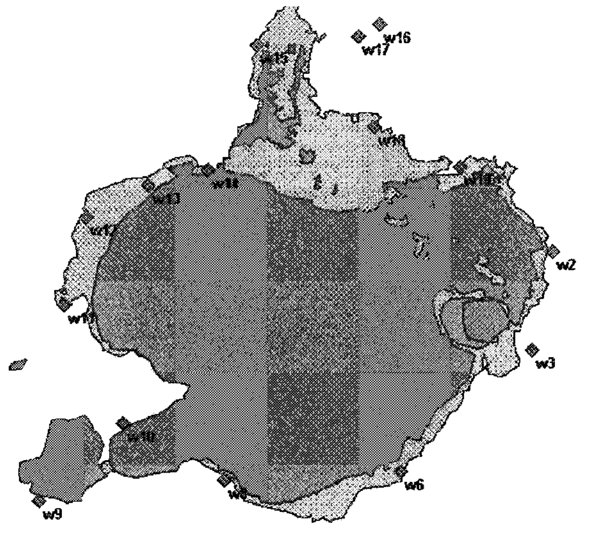


Figure 4-1 Location of Shallow Wells.

4.2 Screening Hydrological Data

4.2.1 Rainfall and Lake level

Rainfall data has been already processed by Podder (1998), and the Lake level by Mmbui (1999).

4.2.2 Groundwater level Data

a) Double-Mass Analysis

A number of methods for detecting inconsistency in time series records are used such as double mass analysis, graphical regression, cumulative deviations from mean value, etc. The most common technique (Dingman S.L. 1994) for detecting and correcting for inconsistent time series data is double-mass curve. In this study, this method is used for detecting and correcting the inconsistent of groundwater level data.
Double-mass-curve analysis is a graphical method of identifying inconsistencies on a time series record by comparing its time trend with those of other reliable records. Successive cumulated annual or seasonal values at one record in question are plotted against those of a near by reliable record, and a double mass-mass-curve is then examined for trend and changes in slope. It also assumes a linear relation between time series data (Dahmen,E.R, 1990). Double mass analysis is used also to find correction factors for errors and fill in gaps.

Since the Lake level is a reliable record to use as base station, the double mass analysis has been carried out by considering the Lake level as a base for the other Wells record. Ten plots have been prepared for analysis of the wells (attached in Appendix 4). *The records of wells appear to be consistent as indicated by the straight-line trace through the points in the plot* absence of change in the slope of the line. It can be concluded that the records have a linear relationship.

b) Missing Record Estimation

There are a number of information transfer techniques, which can be used for filling missing time series record given in the literature. Some of the classical methods are normal ratio method, weighted distance interpolation method, linear regression and time series analysis. The dependability of the estimate can be improved by using data from several surrounding records to estimate data at a single location. Since the records have a linear relationship, simple linear interpolation was used to fill the gaps of the daily record of the wells.

4.3 Correlation between Lake Level and Groundwater level

The degree of correlation between the Lake and the wells may give an indication of how closely they are connected and related to each other. Relationship between the wells and the Lake were established by the computation of correlation coefficients. The variables used in the analysis are monthly average figures. These data are attached in Appendix 5.
The resulting scatter plots are displayed in Appendix 6. Furthermore, the regression parameters are tabulated in Table 4.2 As it can be seen in the table most of the wells have above 90% correlation coefficient(r) except well 9, 12 and 16. It is obvious from this table that the knowledge of one of the well levels can adequately yield the other level.

	R^2	r	Slope	Intercept
Well2	0.96	0.98	0.9446	104.23
Well 3	0.85	0.92	0.8837	219.02
Well 8	0.93	0.96	1.2216	418.56
Well 9	0.70	0.84	0.6297	698.38
Well 11	0.92	0.96	1.1017	191.91
Well 12	0.80	0.89	1.0714	135.28
Well 15	0.94	0.97	1.2196	415.31
Well 16	0.53	0.73	0.8777	231.41
Well 17	0.91	0.96	0.9716	52.499
Well 19	0.86	0.93	0.902	184.26

Table 4-2 Correlation result of Lake and Groundwater Levels.

4.4 Interaction Between Groundwater and Surface water

4.4.1 Past Scenario : 1957 - 1970

Figure 4.2 depicts the water level of all the available wells, and the Lake. To gain a clear insight of the interaction between the wells and the Lake, four closest wells, which lie in diametrically opposite aspects with respect to the Lake, were selected: Wells 2, 8, 11, and 15 (Table 4.4).

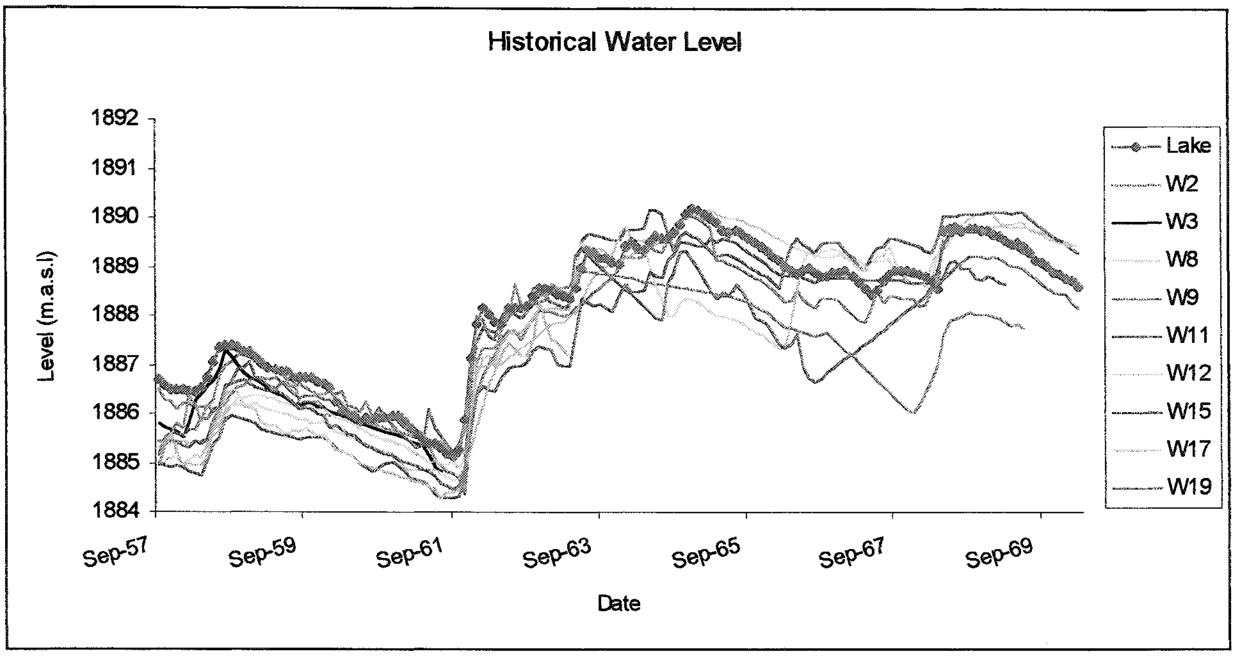


Figure 4-2 Graph showing Long term temporal variability of Lake level and groundwater table as observed in 9 wells.

Wells	Well 2	Well 8	Well 11	Well 15
Location from the Lake	East	South	West	North
Distance from the Lake	750m	350m	1030m	5000m

Table 4-3 Selected Wells for further analysis.

Well 2

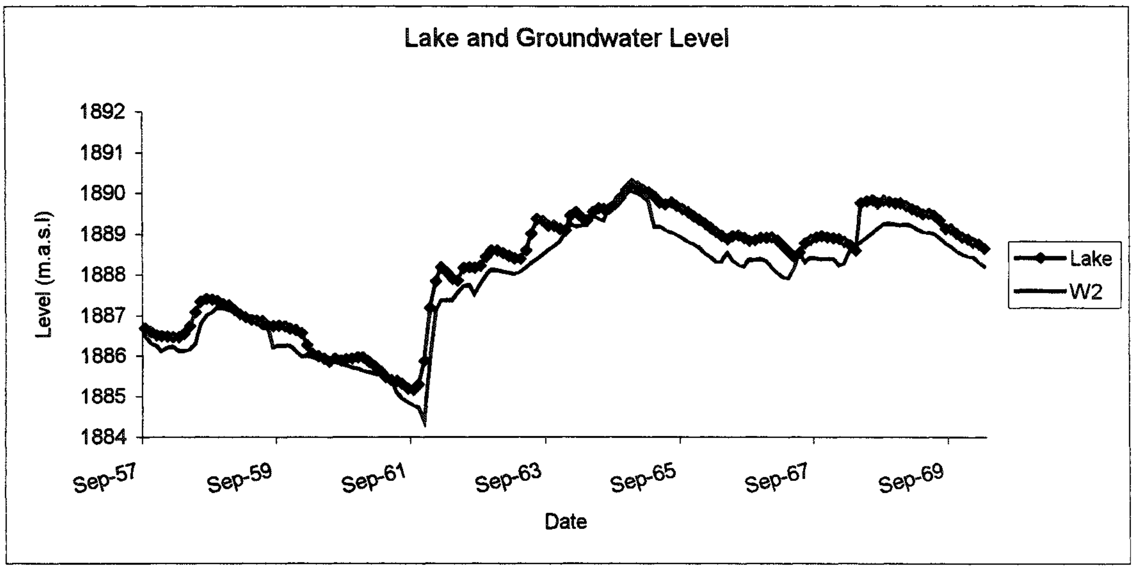


Figure 4-3. Long term temporal variability of Lake level and groundwater table as observed in Well 2.

As one would expect, well 2 which is 750 m from the Lake mimics the Lake fluctuation pattern very closely without any significant time lag. This could be because of the high transmisivity zone between the two. The transmisivity of the material between the Lake and the groundwater was estimated to be 5960 m^2/day (chapter 5). As it can be seen in the graph, the Lake was feeding the well for the complete time period.

Well 8

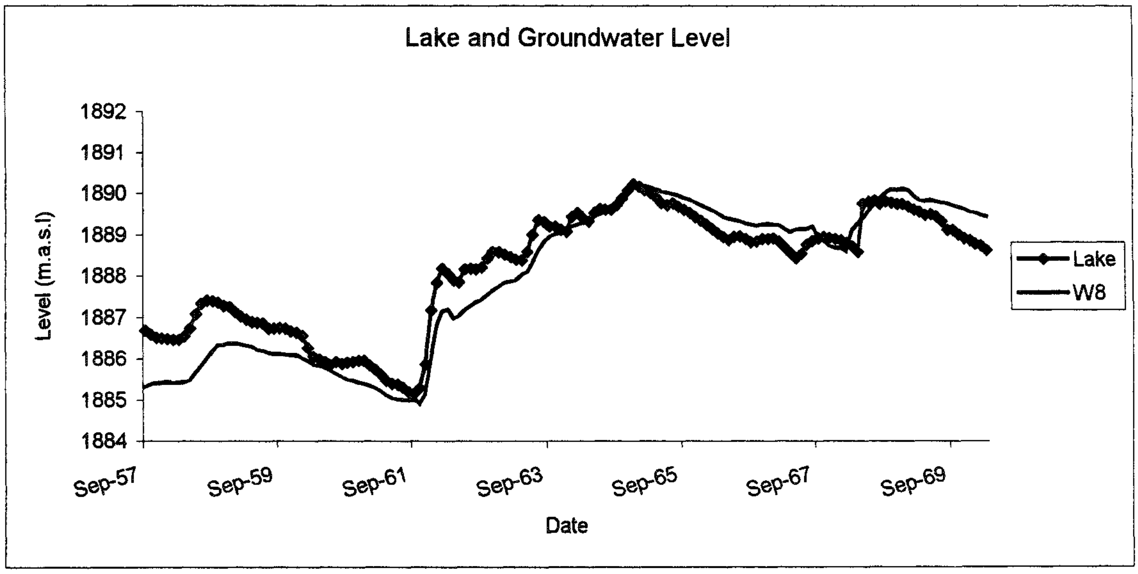


Figure 4-4 Long term temporal variability of Lake level and groundwater table as observed in Well 8.

The same is true for well 8 which is at the southern part 350m away from the Lake, i.e. the well respond with the Lake as the same pattern. The difference start when the Lake level start to drop after it reaches the highest level (February 1965) in this time series. Before February

1965 the Lake was feeding the groundwater after that the reverse happened. Since the response of the well to the Lake level is high and without any significant time lag, the material between the Lake and the well might have high transmissivity value.

Well 11

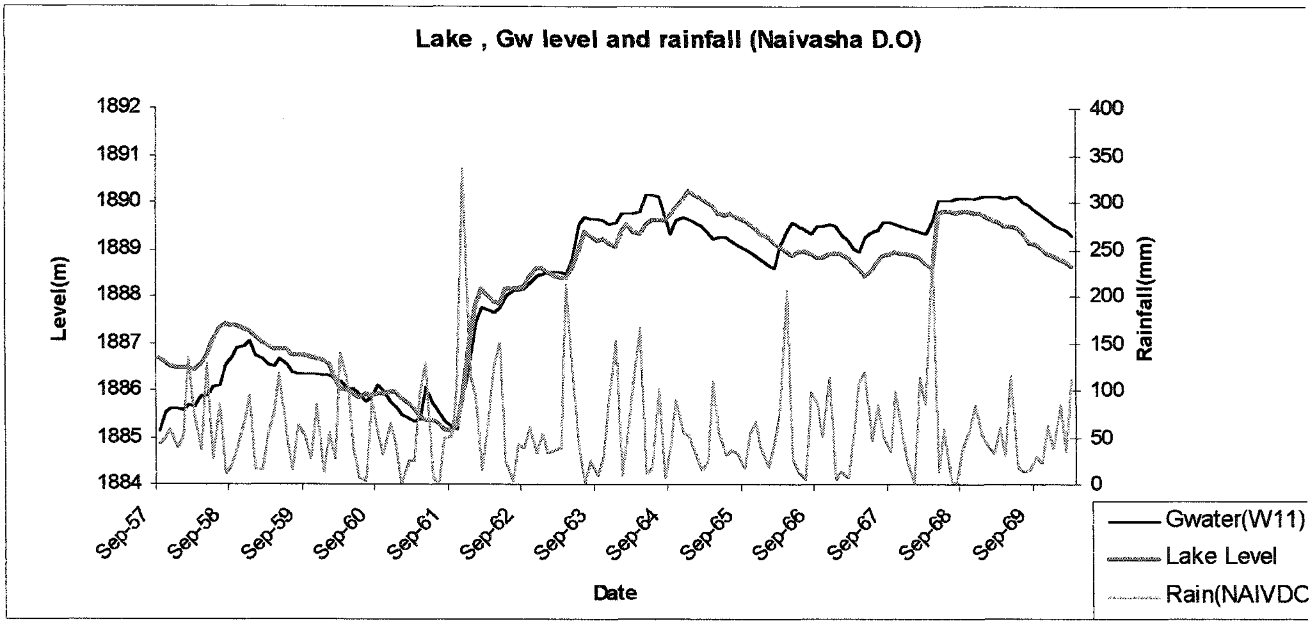


Figure 4-5 A graph showing the long term temporal variability of Lake level, and groundwater table as observed in Well 11, and monthly rainfall recorded in Naivasha D.O. Station.

The above graph clearly shows the well, which is 1030m away from western part of the Lake also, mimics the Lake level. There must be some other driving force causing the rise in groundwater level in April 1961, April 1963 and Feb 1966 and change the direction of water flow. The rise could be due to the heavy rain falling at these times. To show these, the Groundwater level is plotted against the rainfall at Naivasha D.O. Station.(Figure 4.5). At the beginning the Lake was feeding the well till February 1960 then the level of both the Lake and the well coincide. Around April 61 the well rise above the Lake due to the heavy rainfall and then started to feed the Lake till October 1961. The same situation happened from April 63 - August 64 and from February 66 - March 70 as shown in Figure 4.5 i.e. the well feed the Lake. Once again both the levels coincide till April 63 and start to rise due to the heavy rainfall. The well starts to drop faster while the Lake increases around July 1964. This fast drop could be due to low Precipitation as shown in the graph.

Well 15

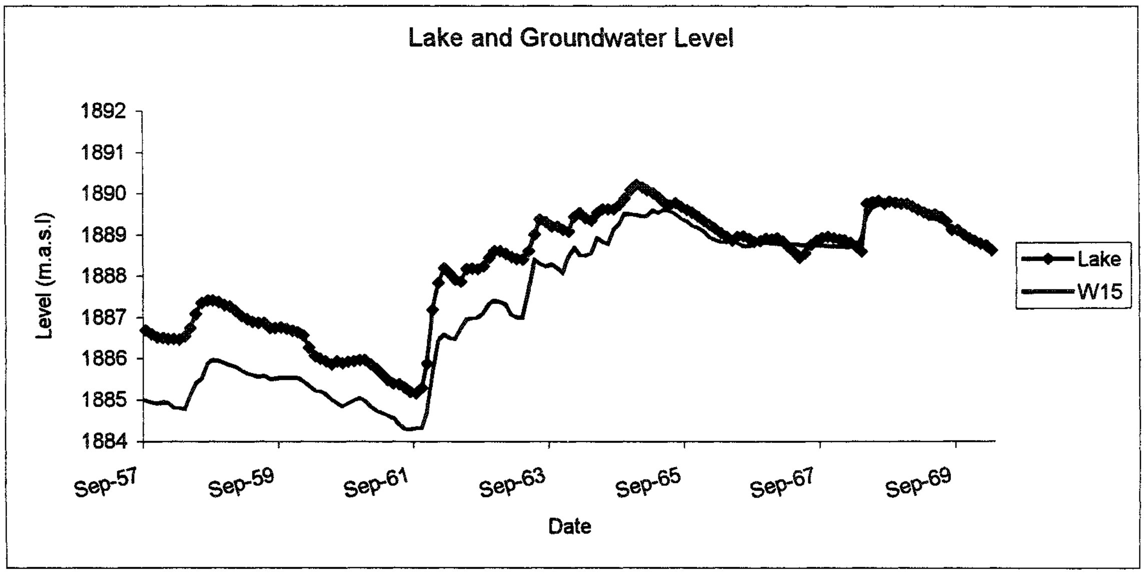


Figure 4-6 Long term temporal variability of Lake level and groundwater table as observed in Well 15.

Figure 4.6 illustrates that, well 15, which is near the inlet of Malewa River and 5Km east of the Lake also mimics the Lake fluctuation pattern very closely without any significant time lag. The reason for this could be attributed to the probably high transmisivity zone between the Lake and the well, or to the recharge of the well by the Malewa river. For the period between 1957 and 1969, the Lake or the river was always feeding the well.

Concluding Remark

From the analysis shown in the preceding section, it becomes clear that the groundwater levels for all wells around the Lake mimics the Lake level. The reason could be mainly explained by the high transmissivity of the Lacustrine deposit surrounding the Lake and a direct recharge from the Lake.

Monthly Water level Analysis

The Groundwater level data were aggregated to get long term mean monthly water level so as to determine the nature of seasonal water level fluctuations and annual change in groundwater storage. The measurements are shown in Appendix 7. The January measurements were taken as the reference points and subsequent measurements were deducted from these to show whether the water level dropped (-ve sign) or rose (+ sign) the graph is drawn for all mentioned wells in Figure 4.7.

Almost all the wells had a drop in water levels. The exceptions were well 3 and 9 which showed water level rising for almost all months and well 11, 12, 15 and 16 during May- July periods. The net water level change range from 0 meters for well 11 to 0.09 meters for well 16. The peak rainfall months in the study area are April-May (long rains) and October-November (short rains). The water level rise in almost all wells shows the time lag between recharge and the peak of the long rains. McCann (1974) found similar time lags ranging from one week to several months of groundwater level response to peak rainfall in the Rift Valley wells. The slow response after the long rains may be due to soil moisture deficiency after long dry periods.

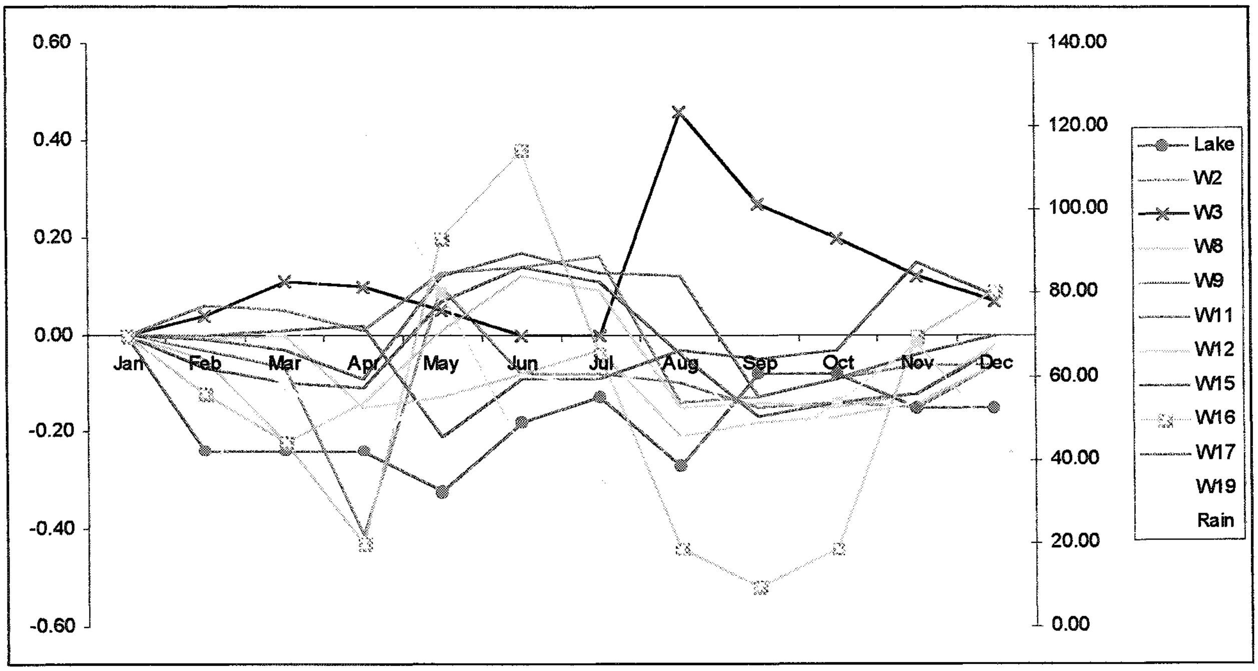


Figure 4-7 Temporal Water Level Variation of Lake Naivasha and surrounding wells.

4.4.2 Present Scenario: October 1998

Two transect were constructed based on data collected during fieldwork, in Manera Farm and the other in KWS Annex. The location of the transects are shown in Figure 4.8 and the description in Appendix 8.

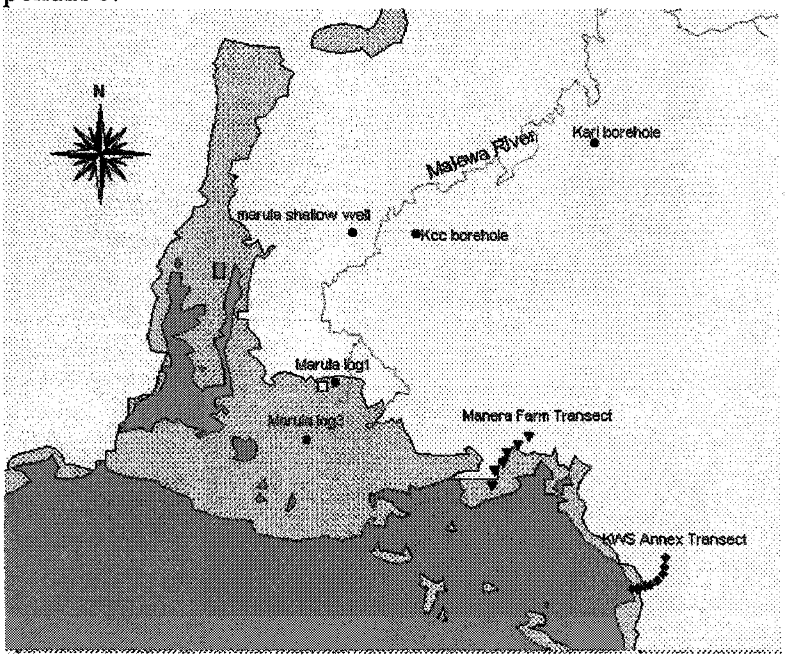


Figure 4-8 Location of the two transect and the site for auger holes and boreholes along Malewa river.

On the transect three curves were drawn for surface, water level and auger depth elevations. As it can be seen on both Figure 4.9 and Figure 4.10 that water levels on both locations are below the Lake level. The Manera Farm transect shows a hydraulic gradient of 0.002 whereas the gradient for KWS Annex transect shows 0.001. For KWS Annex transect an attempt was made to calculate the groundwater flux using Darcy equation after the optimization of the hydraulic conductivity of the cross-sectional model in chapter 5. It can be seen in both Figures 4.9 and 4.10 that the Lake was losing water to the aquifer.

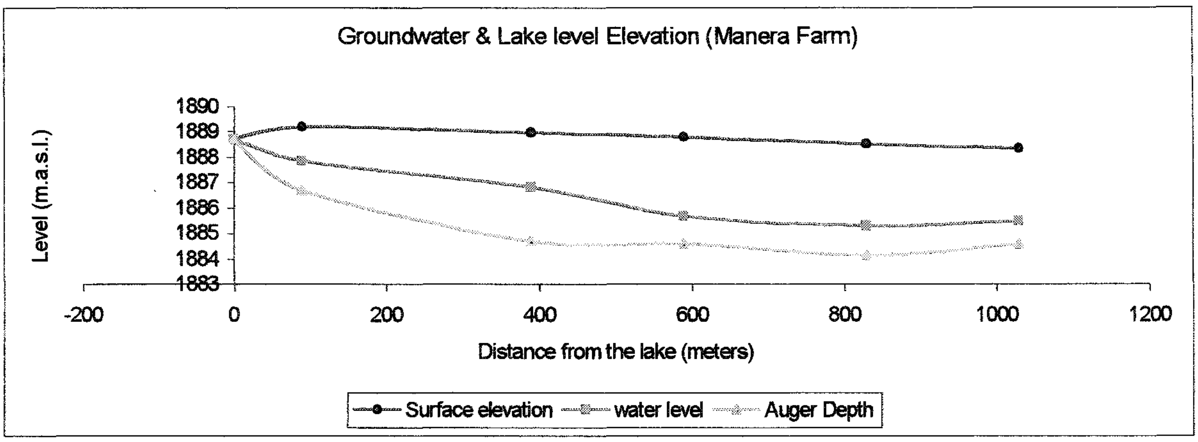


Figure 4-9 Groundwater and Lake level elevation transect in Manera Farm.

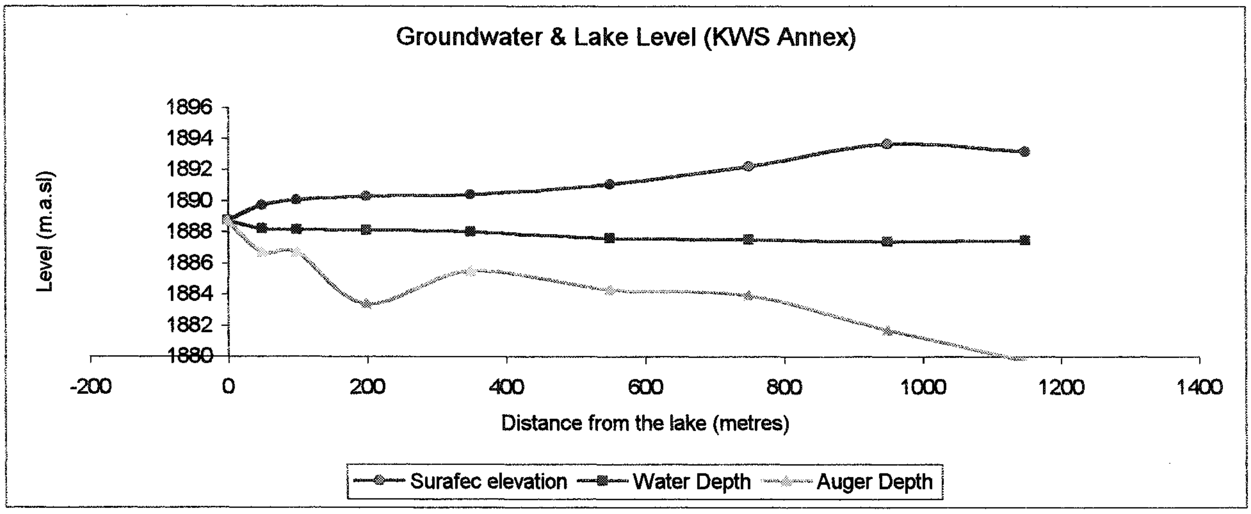


Figure 4-10 Groundwater and Lake level elevation transect in KWS Annex.

Two auger holes were also constructed and the levels of three existing boreholes were measured along Malewa River during fieldwork in order to see the interaction between the river and the groundwater. The location of the auger holes and boreholes are shown in Figure 4.8 and the description in Table 4.4.

As it can be seen in Figures 4.11a to 4.11e, there is seepage of water from the river to groundwater. The relative difference in level between the groundwater table and top water level in the river is, on an average, 10m. An attempt was made to calculate the amount of seepage using Darcy's equation. For a unity hydraulic gradient, river width of 10 meters, river length of 5000m, and hydraulic conductivity of 0.1 m/day, the seepage is calculated to be 5,000 m^3/day under natural condition (i.e. without any abstraction by anthropogenic factors).

Name	ID	X	Y	Depth wrt the river(meters)
K.C.C Borehole	KCC	209037	9925717	10.4
Kari borehole	Kari	212850	9927633	13.5
Marula Farm Shallow well	Marulash	207698	9925728	11.4
Marula farm - Log 3	Marulal3	206685	9921319	8.2
Marula farm - Log 1	Marulal1	207307	9922555	4.2

Table 4.4 Description of Auger holes along Malewa River.

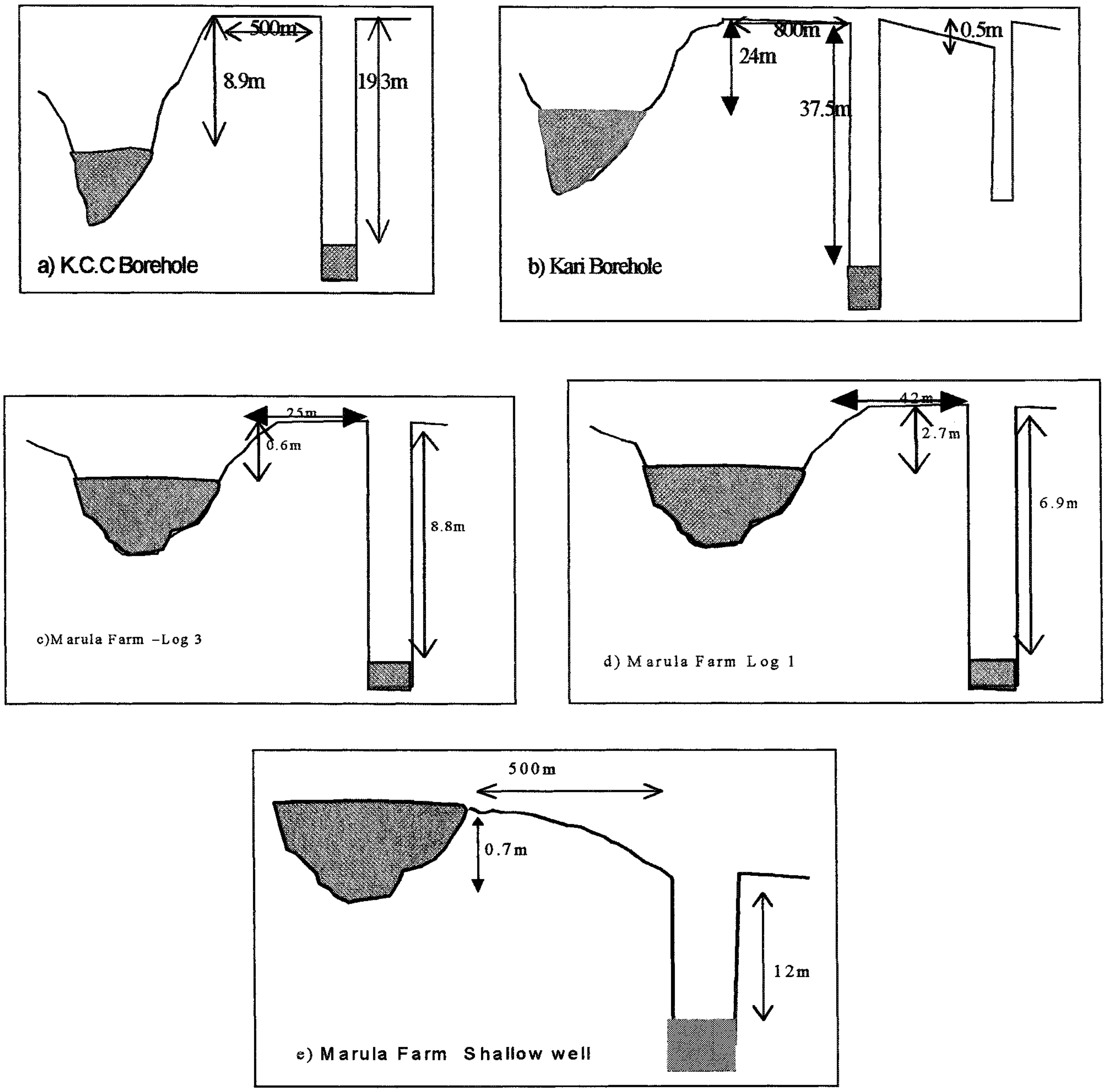


Figure 4.11 Groundwater– and surface water Interaction along Malewa River.

CHAPTER 5

Groundwater Model

A model is any device that represents an approximation of a field situation. A mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model. For time-dependent problems, an equation describing the initial distribution of heads in the system also is needed. Mathematical models can be solved analytically or numerically. When assumptions used to derive an analytical solution are judged to be too simplistic and inappropriate for the problem under consideration, a numerical model may be selected.

A good modeling methodology will increase confidence in modeling results. Models provide a framework for synthesizing field information and for testing ideas about how the system works. Although groundwater models are time-consuming to design and therefore expensive in terms of labor time, it is also true that use of groundwater model is the best way to make an informed analysis or prediction about the consequences of a proposed action.

Transient simulations are needed to analyze time-dependent problems. A transient simulation typically begins with steady-state initial conditions and ends before or when a new steady state is reached. In this research both transient and steady state simulation is done.

5.1 Developing A Conceptual Model

Developing a modeling concept is the initial and the most important part of every modeling effort. It requires a thorough understanding of hydrogeology, hydrology and dynamics of groundwater flow in and around the area of interest. The final result is a computerized database, and simplified maps and cross-sections that will be used in model design.

Figure 5.1 is hydrologic map of the study area showing water table contours and general direction of groundwater flow. The regional conceptual model developed for the study area is shown in Figure 5.2. This conceptual model is consistent with the main features of the natural flow system. There is regional groundwater inflow to the Lake from the highlands on either side as well as from the north, whereas in the south, there is groundwater outflow. Depending on the Lake level relative to the groundwater levels in the aquifer immediately surrounding it, there may be local flow either into or out of the Lake. This is a constantly changing situation and illustrated in chapter 4. In the present study this interaction of the Lake and groundwater is modelled in three locations around the Lake. Figure 5.1 also shows two locations of the cross-sectional models and Figure 4.8 shows the other model (KWS Annex). Figure 5.3 is conceptual cross-section model.

The aquifer for all models is composed of Lake sediments not exceeding a thickness of 30 m. These Lake sediments are derived mainly from erosion of the surrounding volcanic rocks, and consist of volcanic sands and pebble beds, and gravels composed of pumice. Underlying the aquifer is a thick sequence of volcanic rocks, which in the model is considered an impermeable base. There is not much recharge by precipitation in well 2 and KWS Annex (only 1.4e-04 mm/day as initial value for this model) cross-sectional models as the low rainfall rates coupled with high evaporation rates do not permit much infiltrating rain water to reach the water table for whole stress period. Where as for well 11 recharge from precipitation is considered. Besides all of the models receive lateral recharge. In both cases the recharge will be estimated and calibrated.

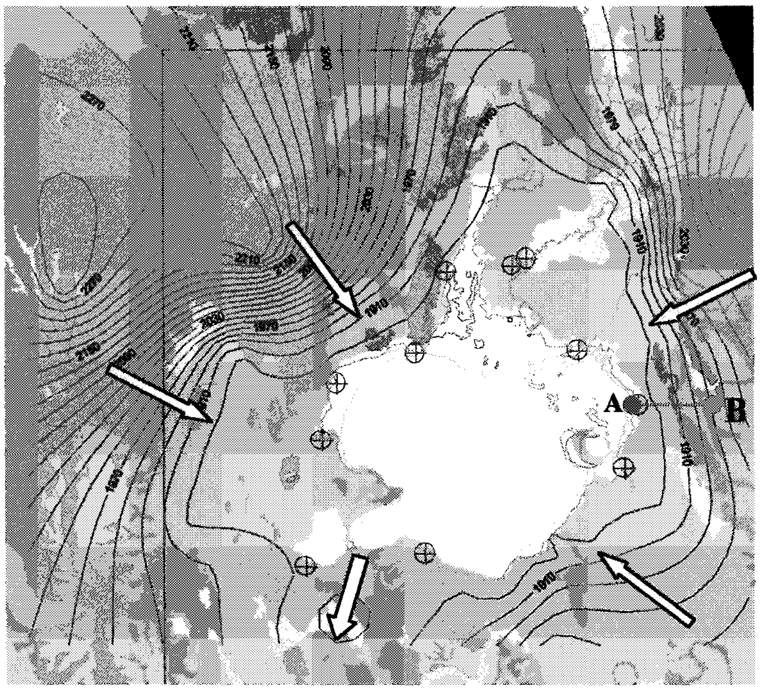


Figure 5-1 Map showing water table contour lines. Arrows indicate general direction of groundwater flow.

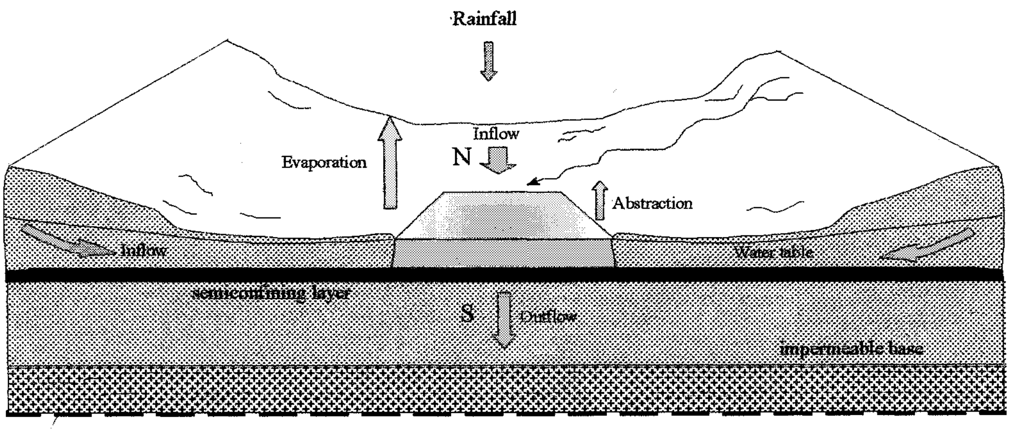


Figure 5-2 Regional conceptual model depicting the interaction between hydrological state variables.

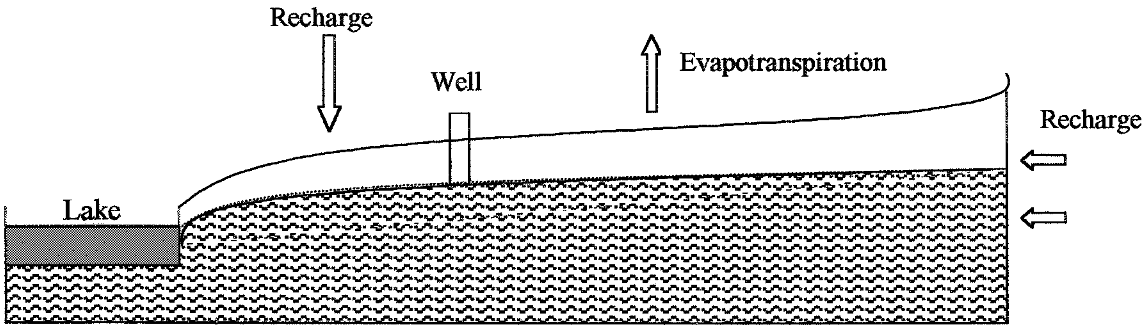


Figure 5-3 Cross-sectional conceptual model showing the hydrological components.

5.2 Governing Equation (Computer Program)

Processing Modflow for windows (PMWIN), a modular three-dimensional finite difference groundwater flow model, developed by USGS (McDonald and Harbaugh, 1988) is used for modeling.
The new parameter Estimation program PEST (Doherty et. al,1994) is also used in data interpretation and in model calibration. The PESTLM which is one of three variants of the non-linear parameter optimizer and works for a variety of problem types especially for groundwater is used.

5.3 Model Design (Cross section)

In a numerical model, a discretized domain consisting of an array of nodes and associated finite difference blocks replaces the continuous problem domain. The nodal grid forms the framework of the numerical model.
When grid size and time step size tend to zero, all approximate solutions of the forward problem must tend to the true solutions of the problem which is unique; Lapidus and Pinder (1982)in Anderson (1992), hence, a smaller grid size of 30m x 30m is used for the model with 100 cells in x direction and 1 cell in the y-direction for a total of 100 cells. Out of this amount, the first cell of the row is modeled as a time variant hydraulic head and at the other end as general head boundary (to incorporate lateral recharge). A layer type 0 which is strictly confined is used for a layer type. Figure 5.4 show the grid setup of the aquifer, which is the same for all cross-sectional models.

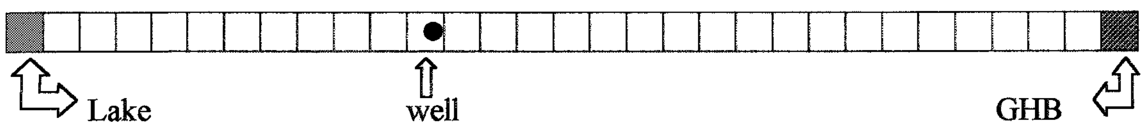


Figure 5-4 Model Layout.

5.4 Boundary Condition

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. Correct selection of boundary conditions is a critical step in model design. In steady state simulations, the boundaries largely determine the flow pattern. The boundaries must be selected so that the simulated effect is realistic. Setting boundary conditions is the step in model design that is subject to serious error.
Physical boundaries of groundwater flow systems are formed by the physical presence of an impermeable body of rock or a large body of surface water. Other boundaries form as a result of hydrologic conditions. These invisible boundaries are hydraulic boundaries that include groundwater divide and streamlines.

Hydrogeologic boundaries are presented by the following three types of mathematical conditions.
Type 1. Specified head boundaries (Dirichlet conditions) for which head is given.
Type 2. Specified flow boundaries (Neumann conditions) for which the derivative of head (flux) across the boundary is given. A no-flow boundary condition is set by specifying flux to be zero.
Type 3. Head dependent flow boundaries (Cauchy conditions) for which flux across the boundary is calculated given a boundary head value. This type of boundary condition is sometimes called mixed-boundary condition because it relates boundary heads to boundary flows.

The boundary conditions used for all cross-sectional models in the study area are as follows. These are based in accordance with the presence of water bodies and hydrological condition of the area. Figure 5.4 shows the boundary array of the model area.

Left boundary : Specified head boundary. For the Lake, time variant specified head package is used in this transient simulation which allows constant head cells to take on different head values for each time steps during a simulation time period.
Right boundary: Head dependent flow boundary. For each time period the head at this boundary is calculated assuming a steady state at the beginning of each stress period. The steps to calculate the head at the boundary are shown in Appendix 9 and the result of the calculation is shown in Table 5.1. Besides, this boundary is located 3 km away from the Lake assuming the stresses of the system will not reach the boundary during simulation and not affecting the observation point near the Lake.

Top and Bottom boundary: No flow boundary. No lateral flow.

	For well 2			For well 11		
period	Date	Lake level	GHB	Date	Lake level	GHB
1	01-Sep-1957	1886.68	1885.89	01-Apr-1958	1886.53	1884.70
2	01-Apr-1958	1886.53	1884.86	01-Aug-1958	1887.4	1884.90
3	01-Aug-1958	1887.40	1885.73	01-Oct-1961	1885.27	1884.95
4	01-Oct-1961	1885.27	1883.04	01-Jan-1962	1887.82	1886.77
5	01-Feb-1962	1888.17	1884.83	01-Apr-1963	1888.38	1888.61
6	01-Dec-1964	1890.22	1889.48	01-Jul-1963	1889.36	1890.29
7	01-May-1967	1888.43	1887.29	01-Dec-1964	1890.22	1888.50
8	01-Apr-1968	1888.59	1888.96	01-May-1966	1888.86	1890.99
9	01-May-1968	1889.75	1885.92	01-Apr-1968	1888.59	1891.56
10				01-May-1968	1889.75	1890.59

	For KWS Annex	
Date	Lake level	GHB
Oct-1998	1885.6	1864.37

Table 5-1 Boundary parameters for well 2, 11 and KWS Annex.

5.5 Discretizing Time

As already mentioned above selection of the time step and construction of the grid are critical steps in model design because the values of the space and time descritization strongly influence the numerical results. Ideally, it is desirable to use small nodal spacing and small time steps so that the numerical representation better approximates the partial differential equation. (Anderson, M.P., 1992). However, for the modeled case two approach is taken, the same time step for all stress period is given for well 2 since the time period is divided according to the Lake level change and different time step according to the time length is given for well 11and is shown in Table 5.2.

In MODFLOW, the simulation time is divided into stress periods, which are, in turn, divided into time steps. The use of stress period is in order to change parameters associated with Time-Variant Specified-Head Boundary (the Lake), and General-Head Boundary and, as well as pumping rates in the Well package (which is used for this study to simulate evapotranspiration from phreatophytes near the Lake).

	Well2		well 11	
Period	Length	Time step	Length	Time step
1	242	20	120	8
2	123	20	1140	76
3	1156	20	90	6
4	120	20	450	30
5	1036	20	90	6
6	811	20	510	34
7	334	20	510	34
8	31	20	690	46
9	669	20	30	2
10			630	42

Table 5-2 Time parameter for well 2 and 11.

5.6 Initial condition

Initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation and thus are boundary condition in time. It is standard practice to select as the initial condition a steady-state head solution generated by a calibrated model. The reason for using this type of head distribution is explained by Franke (1987) in Anderson (1992) as follows:

> Use of model-generated head values ensures that the initial head data and the model hydrologic inputs and parameters are consistent. If the field-measured head values were used as initial conditions, the model response in the early time steps model head values to offset the lack of correspondence between model hydrologic inputs and parameters and the initial head values.

The level of Lake and groundwater on Sep. 1957 for well 2 and April 1958 for well 11 are taken and the corresponding GHB head is calculated. Using the Lake level and the GHB level (both assigned as a constant head boundary) the model run in steady state to get the distribution of head using aquifer parameters of chapter 2. This head distribution is used as initial condition for the transient simulation. Where as for KWS Annex Cross-sectional model, the October 1998 field measured values were used.

5.7 Model Calibration

Calibration is running the model backward to obtain historical data. Before the model can perform its task, it must be calibrated. This means that a check must be made to see whether the model can correctly generate the past behavior, as it is known from historical records. The calibration procedure started by selecting a period for which historical records are available. As earlier discussed in Chapter 4, the historical water levels were determined and the period is selected. The relevant geological information and historical data are fed into the computer. These values are compared, as they are known from historical records. The comparison usually reveals the discrepancy between the two.
Calibration is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field measured values within a certain range of error. Finding this set of values amounts to solving what is known as the inverse problem, the objective is to determine values of the parameters and hydrologic stresses from information about heads.
Model calibration can be performed to steady or transient data sets. The calibration of the model of the study area is performed under both steady state and time variant conditions. The steady-state condition is performed for one cross sectional model, KWS Annex , since there is no temporal head data for these point observations. Where as time variant calibration is performed for well2 and 11, which are found at east and west of the Lake respectively.
There are basically two ways of finding model parameters to achieve calibration, i.e., of solving the inverse problem: These are

1. Manual trial and error adjustment of parameters and
2. Automated parameter estimation.

Solving the inverse problem by manual trial-and error adjustment of parameter doesn't give information on the degree of uncertainty in the final parameter selection, nor does it guarantee the statistically best solution. An automated statistically based solution of the inverse problem quantifies the uncertainty in parameter estimates and gives the statistically most appropriate solution for the given input parameters. Therefore, for this study Automated parameter estimation method is selected for the aforementioned reason.

Automated Calibration

Automated inverse modeling is performed using specially developed codes to solve the inverse problem. One of the highly regarded codes for parameter estimation developed for MODFLOW is PEST. PEST searches a parameter set for which the sum of squared deviations between the model-calculated and measurement values at the observation borehole is reduced to minimum.
Prior running PEST Control data, Parameter list and Boreholes and observations have been supplied. The necessary control data used for this PEST operation is attached in Appendix 10. The initial estimated value of the parameters and /or excitations are supplied in the parameter list in Table 5.3a and 3b. The location of the wells and the Lake are specified in Boreholes and observation menu, which is in Table 5.3c.

a)

Parameter	Discription	PARVAL1	PARLBND	PARUBND	PARTRANS	PARCHGLIM	PARGP	PARTIED	SCALE	OFFSET
P1	Transmisivity	500	1	10000	Log-transformed	factor	1	0	1	0
P2	Storativity	0.1	3.60E-04	0.4	none	relative	1	0	1	0
P3	Conductance	500	1	10000	none	relative	1	0	1	0
P4	Evapotranspiration	-1	-10	0	none	relative	1	0	1	0

b)

Parameter	Discription	PARVAL1	PARLBND	PARUBND	PARTRANS	PARCHGLIM	PARGP	PARTIED	SCALE	OFFSET
P1	Transmisivity	1000	1	10000	Log-transfd	factor	1	0	1	0
P2	Storativity	0.1	1.00E-08	0.4	none	relative	1	0	1	0
P3	Conductance	1	1	10000	none	relative	1	0	1	0
P4	Recharge	1.00E-02	1.00E-04	2	none	relative	1	0	1	0
P5	Evapotranspiration	-1.00E-02	-2	-1.00E-04	none	relative	1	0	1	0
P6	Recharge	1.00E-02	1.00E-04	2	none	relative	1	0	1	0

c)

Borehole Name	Easting	Northing	Layer
Lake	15	20	1
well2	750	20	1
well 11	1030	20	1

Table 5-3 a)Parameter List for well 2 b) Parameter List for well 11 c) Location with respect to Lake.

After feeding all the information, the optimization process started.

5.7.1 Well 2

Various calibrations were undertaken optimizing the four parameters simultaneously. After completing the parameter estimation process, PEST gives the outcomes to the run record file. The detail of the output file is shown in Table 5.5, 5.6 and 5.7 and the optimization result is shown below. The considered parameters are the transmisivity and the storage coefficient of the aquifer, the conductance of the General head boundary and evapotranspiration.

OPTIMISATION RESULTS

Parameter	Unit	Estimated value	95% percent confidence limits lower limit	upper limit
Transmisivity	m^2/day	5960.12	5909.66	6011.02
Storativity	-	8.462209E-04	-4.062540E-03	5.754982E-03
Conductance	m^2/day	1.00000	6967.41	6969.41
Evapotranspiration	m^3/day	-1.13573	-1.22084	-1.05063

Table 5-4 The optimization result of well 2.

Analysis and Discussion of Results

From the above presented optimization results extracted from the Run Record of PEST, the following conclusion can be made.

Parameters: - PEST gives estimated value to each of the parameters and their corresponding lower and upper limits within the 95% confidence limits as listed in Table 5.4. Figure 5.5 shows how far or close is the estimated value of each of the parameters from their confidence limits.

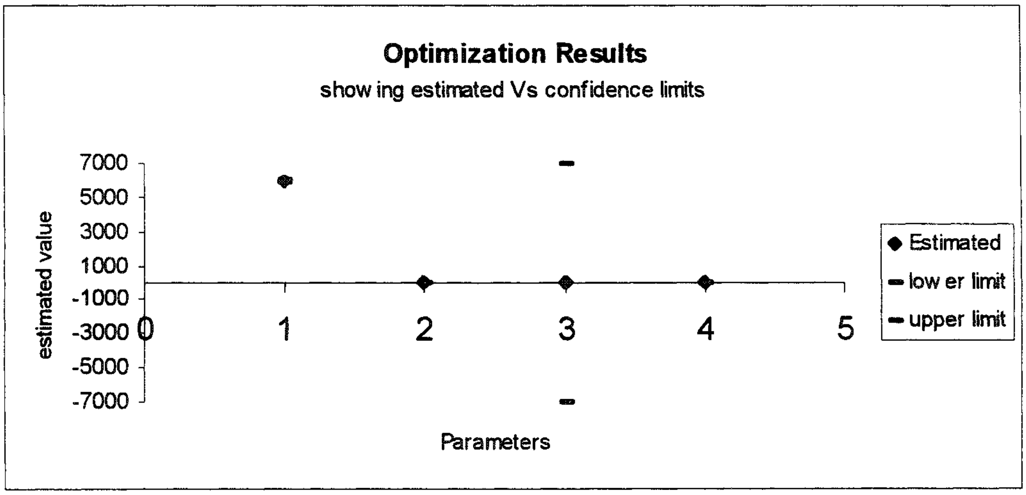


Figure 5-5 Optimization Results showing estimated Vs confidence limits.

Based on the result shown in the above graph and Table 5.4,all the parameters except the conductance show small range of confidence interval. It imply that parameter 3 has large margin of uncertainty while the rest of the parameters are certain.

Observations

PEST list down the observations measured and calculated value and the residual in pestrec file. Figure 5.6 shows the goodness of fit between the measured and calculated heads.

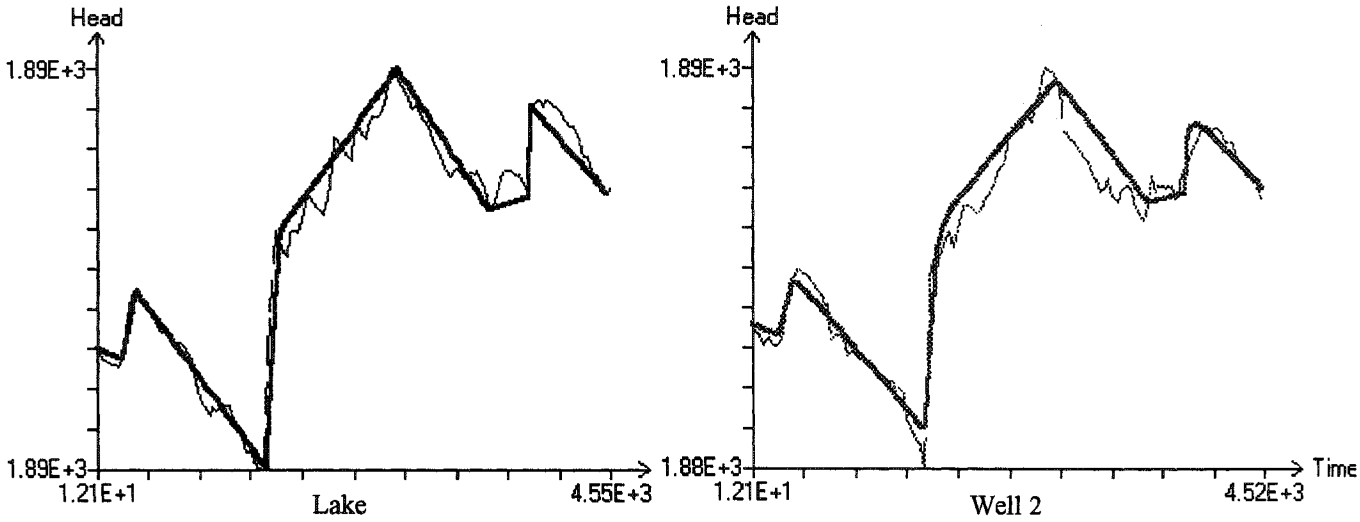


Figure 5-6 Observed vs. Calculated heads (Lake and well 2).

As it can be seen in the above figure the observed and the calculated head show reasonably good fit both for the Lake and the well. Using small range of stress period even can eliminate the small deviation of the calculated head from the observed value.

From the list of the residual calculated, the minimum residual computed is 0 and the maximum is 1.31m. These residual differences from the calculated result could be due to errors that could have been introduced during the processing of the water level data or due to selection of stress periods. Figure 5.7 shows the position of each residual from the x intercept.

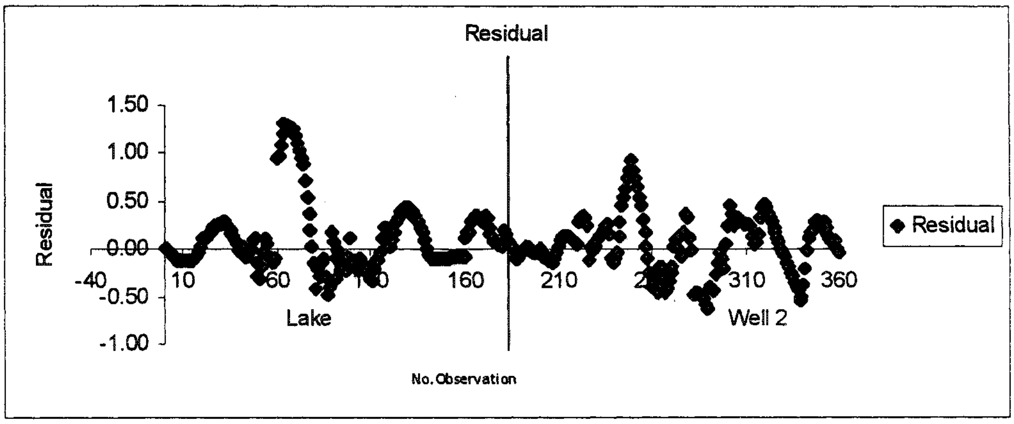


Figure 5-7 Residual (Lake and well 2).

Objective Function

The resulting objective function among 360 observations from the final calibration of the model is 42.53. The calculated ME (mean error), MAE (mean absolute error) and RMS (root mean squared error), values for this PEST run are 0.08m, 0.24m and 0.34m, respectively. The calculated result is attached in Appendix 11.

Covariance Matrix

parameter	p1	p2	p3	p4
p1	3.55E-06	-1.44E-06	-1.062	1.05E-05
p2	-1.44E-06	6.27E-06	-1.074	-8.31E-05
p3	-1.062	-1.074	1.26E+07	12.84
p4	1.05E-05	-8.31E-05	12.84	1.89E-03

Table 5-5 Covariance Matrix of well 2.

As can be seen in the above table, almost all the parameters except parameter 3 have very small (almost zero) variance which indicates the certainty and reliability of the parameter estimation. Parameter 3 (conductance) has also large covariance with parameter 4 as these two parameters are highly correlated.

Correlation Coefficient Matrix

parameter	p1	p2	p3	p4
p1	1	-0.3045	-0.1585	0.1289
p2	-0.3045	1	-0.1206	-0.7642
p3	-0.1585	-0.1206	1	8.32E-02
p4	0.1289	-0.7642	8.32E-02	1

Table 5-6 Correlation Coefficient Matrix of well 2.

Based on the result shown in the above table, parameter 2 is highly correlated with parameter 4 but parameter 2 is not determined with a high degree of uncertainty as evidence by its small confidence interval and very small variance. They may be highly correlated due to the lack of measurement value near the general head boundary to uniquely determine the parameters.

Normalized eigenvectors of covariance matrix

parameter	p1	p2	p3	p4
p1	0.5621	-0.827	6.24E-03	-8.40E-08
p2	0.8264	0.5614	-4.38E-02	-8.50E-08
p3	8.42E-08	-5.21E-08	-1.02E-06	1
p4	3.27E-02	2.98E-02	0.999	1.02E-06
Eigenvalues	**1.89E-06**	**4.08E-06**	**1.88E-03**	**1.26E+07**

Table 5-7 Normalized eigen vectors of covariance matrix of well 2.

As shown in the above table parameter 4 have the highest eigenvalue. As shown in the above table the eigen vector of highest eigen value is dominated greatly by parameter 3. Hence, the parameter estimation process poorly discerns this parameter, as the width of their confidence interval demonstrates.

Sensitivity Analysis

The purpose of sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stress and boundary conditions. Sensitivity analysis is typically performed by changing one parameter value at a time. In this way for all the optimized parameters, sensitivity analysis is performed as follows.

During the sensitivity analysis, the calibrated values of the four parameters, i.e. transmisivity, storage coefficient, conductance and evaporation are systematically changed. Change in percent and the corresponding objective function of the result is shown in Figure 5.8 and Table 5.8.

Sensitivity on Transmisivity										
T = 5960		S=8.4e-4			C=1		E=-1.14		Phi=42.53	
Factor	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
phi	2094	495	206.7	114.5	76.79	59.17	50.35	45.82	43.55	42.53
Factor	x1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	
phi	42.23	42.33	42.69	43.18	43.75	44.36	44.99	45.61	46.22	
Sensitivity on Storativity										
T = 5960		S=8.4e-4			C=1		E=-1.14		Phi=42.53	
Factor	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
phi	42.47	42.48	42.48	42.49	42.49	42.5	42.51	42.52	42.52	42.53
Factor	x1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	
phi	42.54	42.54	42.55	42.56	42.57	42.57	42.58	42.58	42.59	
Sensitivity on Conductance										
T = 5960		S=8.4e-4			C=1		E=-1.14		Phi=42.53	
Factor	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
phi	42.36	42.37	42.39	42.41	42.43	42.45	42.47	42.49	42.51	42.53
Factor	x1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	
phi	42.55	42.57	42.59	42.60	42.63	42.65	42.67	42.69	42.71	
Sensitivity on Evaporation										
T = 5960		S=8.4e-4			C=1		E=-1.14		Phi=42.53	
Factor	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
phi	60.17	55.97	52.31	49.22	46.70	44.74	43.34	42.51	42.24	42.53
Factor	x1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	
phi	43.38	44.8	46.78	49.33	52.43	56.1	60.33	65.13	70.48	

Table 5-8 Sensitivity Analysis of well 2.

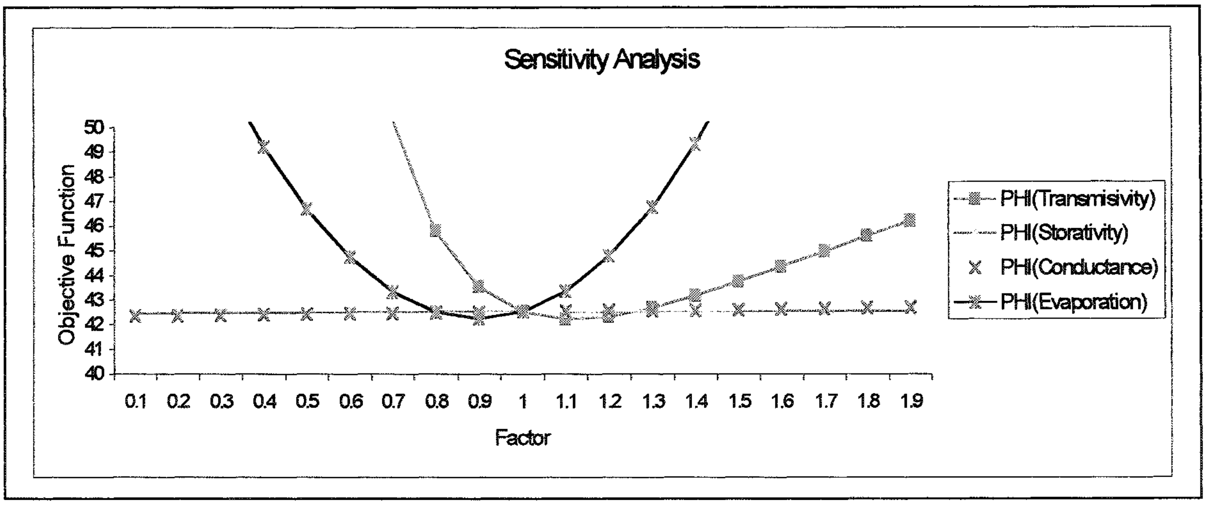


Figure 5-8 Graph showing Sensitivity Analysis on optimized parameters of well 2.

As it can be seen from the above graph decreasing transmisivity increase the objective function more rapidly than the Evaporation component. Whereas increasing the evaporation increase the objective function more rapidly than transmisivity. In case of storage coefficient, increasing or decreasing the parameter in order of 100% doesn't affect the objective function at all but changing the storage coefficient into unconfined behavior i.e. in the order of 0.1-0.2, is highly sensitive to the system. Moreover, for conductance 100% increase is insensitive for the observations since as already explained above the conductance parameter is used for GHB that it has no effect on the observation.

Concluding Remark

The above optimization result indicate that most of the parameters estimated values are within close range of their confidence interval except parameter 3. The covariance matrix shows very small variance except for parameter 3 and also small covariance with their parameter pairs except with parameter 3. The largest eigenvalues is 1.26E+07, which is dominated mostly by conductance (parameter 3). However, the objective function is 42.53,the root mean squared error (RMS), the mean absolute error and the mean error are 0.34,0.24 and 0.08m respectively which shows that the consistency and goodness of fit between the model output and the observations.

5.7.2 well 11

Slightly different approach is followed when optimizing the parameters of this well. On the first run the storage coefficient (S=0.1) is feed as a known component and the other like recharge from Marmonet River and Eburu mountain, evapotranspiration from vegetation around this well, transmisivity and conductance are optimized simultaneously. The two recharge parameters are for stress period 6 and 10 respectively whereas evapotranspiration is for stress period 7. The result is shown in Table 5.9. On the second attempt optimization of all the parameters were tried like well 2, the result of this run is shown in Table 5.10.

OPTIMISATION RESULTS

Parameter	Unit	Estimated value	95% percent confidence limits lower limit	upper limit	
Transmisivity	m^2/day	3317.02	3145.11	3498.34	p1
Conductance	m^2/day	141.36	140.711	142.009	p3
Recharge	m/day	7.11E-04	5.52E-04	8.70E-04	p5
Evapotranspiration	m/day	-9.86E-04	-1.13E-03	-8.44E-04	p6
Recharge	m/day	8.67E-04	7.05E-04	1.03E-03	p7

Table 5-9 The calibrated parameters of the model for well 11 first attempt.

OPTIMISATION RESULTS

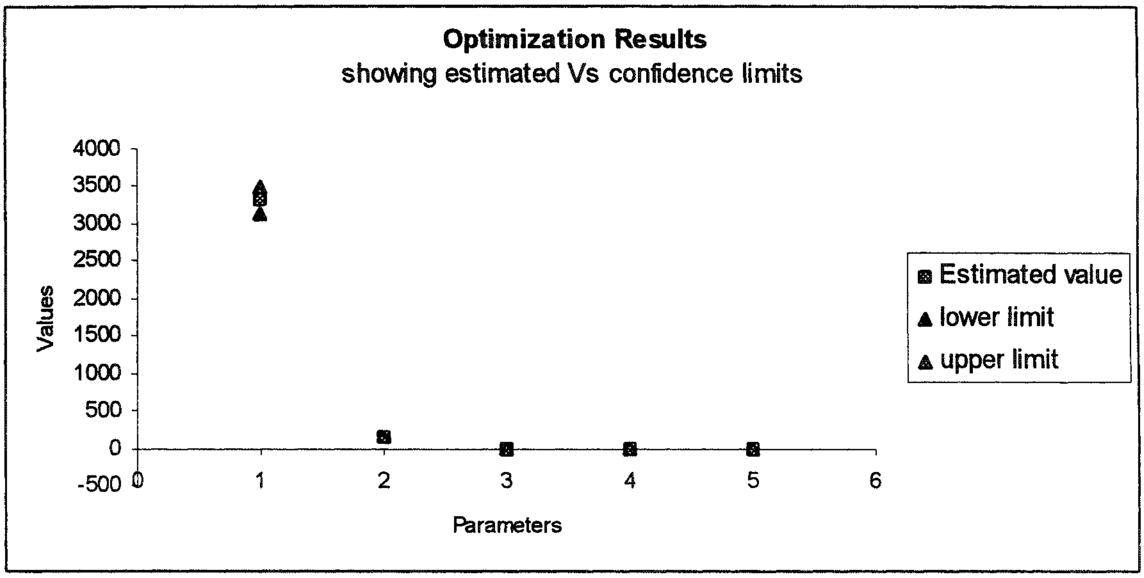
Parameter	Unit	Estimated value	95% percent confidence limits lower limit	upper limit	
Transmisivity	m^2/day	434.44	299.88	629.39	p1
Storage coefficient	-	0.0118	-0.0210	0.0445	p2
Conductance	m^2/day	22.47	21.80	23.15	p3
Recharge	m/day	0.00010	-0.00326	0.00346	p5
Evaporation	m/day	-0.00014	-0.00351	0.00322	p6
Recharge	m/day	0.00011	-0.00329	0.00352	p7

Table 5-10 The calibrated parameters of the model for well 11, second attempt.

Analysis and Discussion of Results

From the above presented optimization results extracted from the Run Record of PEST, the following conclusion can be made.
Parameters: - Figure 5.9a and Figure 5.9b show how far or close is the estimated value of each of the parameters from their confidence limits for the first and second attempt respectively.

a) Case One



b) Case two

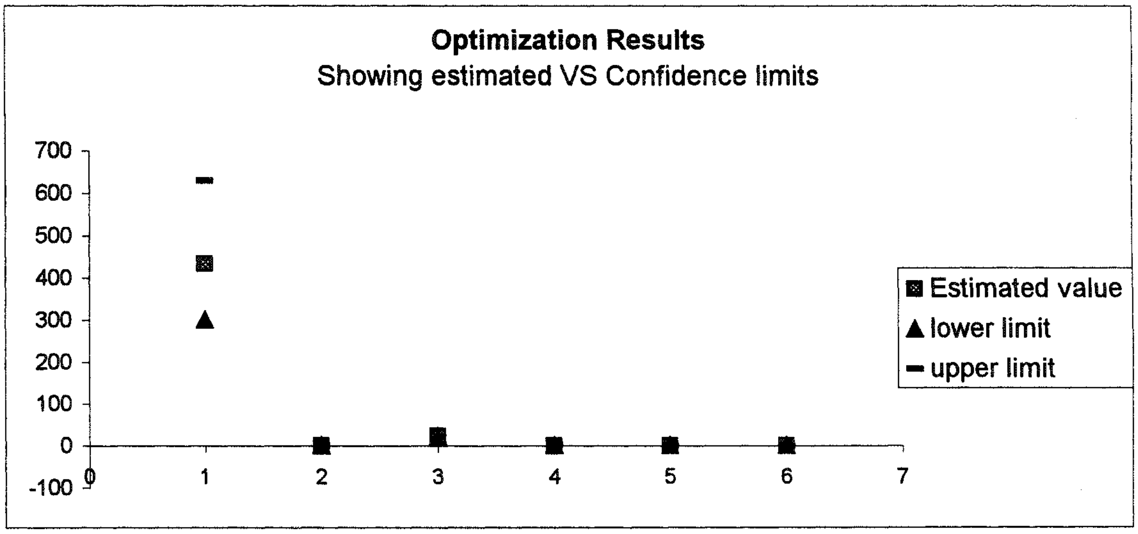


Figure 5-9 Optimization results of well 11 a) Case one b) Case two.

As shown in the above graphs and tables, all the parameters except the transmisivity in Figure 5.9b show small range of confidence interval in both graphs. As it can be seen in Figure 5.9a the transmisivity also shows somehow small range of confidence interval. This implies that the transmissivity has large margin of uncertainty in the second case while the rest of the parameters are certain in both case including transmissivity in the first case.

Observations
Figure 5.10 shows the goodness of fit between the measured and calculated heads. It is almost the same for both cases and therefore only case one graph is displayed.

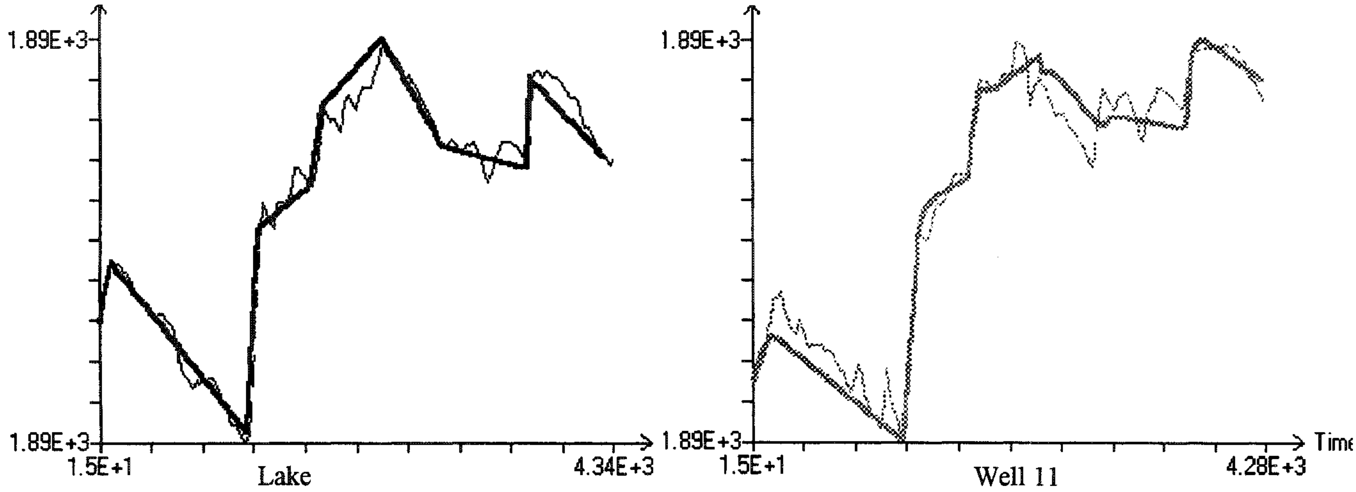


Figure 5-10 Observed Vs Calculated head (Lake and well 11).

As it can be seen in the above figure the observed and the calculated head show good fit for stress period 3,4, 5 and 6 whereas for the rest period the optimum possible fit is shown.

From the list, the minimum residual computed is 0 and the maximum is 0.69m for both cases. These residual differences could be due to errors introduced during the processing of the water level data or due to selection of stress periods. Figure 5.11, which is almost the same for both cases, shows the position of each residual from the x intercept.

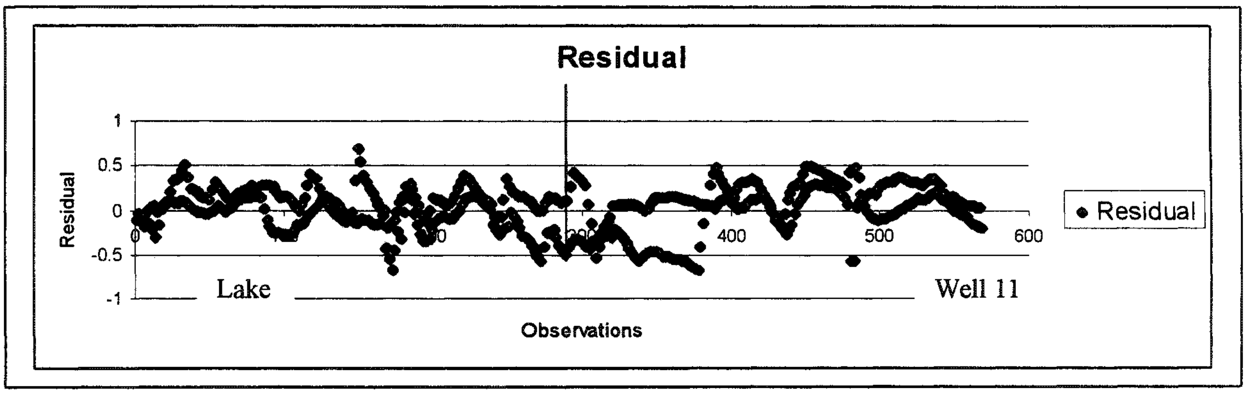


Figure 5-11 Residual (Lake and well 11).

Objective Function

The resulting objective function among 568 observations from the final calibration of the model are 34.3 and 34.19 for case one and two respectively. The calculated ME, MAE and RMS are 0.03, 0.25 and 0.19m for case one and 0.03, 0.25 and 0.24m for case two respectively. The change between these two cases is on their RMS error in which case 2 has 5cm larger RMS error than case one.

Covariance Matrix

Parameter	pl	P3	P4	P5	P6
pl	**1.39E-04**	-3.84E-03	8.76E-07	-8.20E-07	9.13E-07
p3	-3.84E-03	**0.1096**	-2.30E-05	2.17E-05	-2.59E-05
p4	8.76E-07	-2.30E-05	**6.58E-09**	-5.58E-09	5.56E-09
p5	-8.20E-07	2.17E-05	-5.58E-09	**5.30E-09**	-5.29E-09
p6	9.13E-07	-2.59E-05	5.56E-09	-5.29E-09	**6.86E-09**

Case 1

Parameter	pl	p2	p3	p4	p5	p6
pl	**6.75E-03**	1.36E-03	-1.16E-02	1.40E-04	-1.40E-04	1.42E-04
p2	1.36E-03	**2.79E-04**	-1.60E-03	2.86E-05	-2.87E-05	2.90E-05
p3	-1.16E-02	-1.60E-03	**0.1186**	-1.87E-04	1.86E-04	-1.92E-04
p4	1.40E-04	2.86E-05	-1.87E-04	**2.94E-06**	-2.95E-06	2.98E-06
p5	-1.40E-04	-2.87E-05	1.86E-04	-2.95E-06	**2.95E-06**	-2.98E-06
p6	1.42E-04	2.90E-05	-1.92E-04	2.98E-06	-2.98E-06	**3.02E-06**

Case 2

Table 5-11 Covariance Matrix of well 11 a)case one and b) Case two.

As can be seen in the above two tables, almost all the parameters except parameter 3, in both cases, have very small (almost zero) variance which indicates the certainty and reliability of the parameter estimation. The covariance between the Parameters in both cases is negligible.

Correlation Coefficient Matrix

Parameter	pl	p2	p3	p4	p5
pl	1	-0.9838	0.915	-0.9555	0.9349
p3	-0.9838	1	-0.8577	0.9008	-0.9461
p4	0.915	-0.8577	1	-0.9438	0.8272
p5	-0.9555	0.9008	-0.9438	1	-0.8779
p6	0.9349	-0.9461	0.8272	-0.8779	1

Case 1

Parameters	pl	p2	p3	p4	p5	p6
pl	1	0.9897	-0.4103	0.9948	-0.9946	0.9949
p2	0.9897	1	-0.2776	0.9989	-0.9991	0.9989
p3	-0.4103	-0.2776	1	-0.3162	0.314	-0.3205
p4	0.9948	0.9989	-0.3162	1	-0.9999	0.9996
p5	-0.9946	-0.9991	0.314	-0.9999	1	-0.9997
p6	0.9949	0.9989	-0.3205	0.9996	-0.9997	1

Case 2

Table 5-12 Correlation Coefficient Matrix of well 11 a) case one and b) Case two.

Based on the result shown in the above table, all the parameters in case 1 are highly correlated implying the non-uniqueness output of the optimization. In case 2 also, most parameters are highly correlated except parameter 3 and parameter 2.

Normalized eigenvectors of covariance matrix

Parameter	p1	p2	p3	p4	p5
p1	1.01E-02	-1.09E-02	-1.38E-02	-0.9992	3.50E-02
p3	2.36E-04	-3.83E-04	-1.28E-04	-3.50E-02	-0.9994
p4	0.1775	0.7384	0.6504	-1.52E-02	2.10E-04
p5	0.9701	-2.02E-02	-0.2414	1.33E-02	-1.98E-04
P6	0.1652	-0.674	0.72	-8.96E-04	2.36E-04
Eigenvalues	1.72E-10	6.64E-10	7.89E-10	4.47E-06	0.1097

Case 1

Parameters	p1	p2	p3	p4	p5	p6
p1	1.01E-02	1.06E-02	1.39E-02	-0.2115	-0.9718	0.1023
p2	1.68E-02	-4.56E-02	9.86E-02	0.9716	-0.2089	1.45E-02
p3	2.36E-04	3.81E-04	1.35E-04	-7.37E-03	-0.1031	-0.9946
p4	0.1773	-0.7216	-0.6683	2.63E-02	-2.12E-02	1.67E-03
p5	0.9701	1.54E-02	0.2387	-3.57E-02	2.12E-02	-1.67E-03
p6	0.1646	0.6905	-0.6974	9.57E-02	-2.14E-02	1.72E-03
Eigenvalues	1.72E-10	6.62E-10	7.80E-10	1.98E-07	5.82E-03	0.1198

Case 2

Table 5-13 Normalized eigenvectors of covariance matrix of well 11.

As shown in the above two tables, the eigenvector of highest eigenvalue is dominated greatly by parameter 2 and lightly by parameter 1 having values of 0.9994, 0.0350 in the first case and parameter 3 and lightly by parameter 1 having values of 0.9946, 0.1023 in the second. Hence, these parameters are highly correlated and poorly discerned by the parameter estimation process.

Concluding Remark

Even though most of the estimated parameters have a close range of confidence interval, low variance and covariance, they are highly correlated. Besides, the eigenvector of the highest eigen value is dominated by three parameters in both cases. Hence, *this shows that the optimized result is non-unique*.

Therefore, gathering new information on aquifer parameters and checking the boundary condition is the critical point in order to get unique result. Since we don't have sufficient information about the parameters, it is recommended that further study should be conducted to investigate some parameters, which are necessary for optimization of this model.

5.7.3 KWS Annex

Slug test was carried out to get the value of the hydraulic conductivity of the model. This value after multiplying by the aquifer thickness was used as initial value for transmisivity. The initial value for recharge is taken from the study carried out by Wiberg, I. (1976) which is 50 mm/yr. (1.4E-04 m/day). Various calibrations were undertaken to optimize the three parameters simultaneously. But in all cases, error condition prevents to continue the PEST execution because the third parameter, i.e. conductance, has no effect on observation. Therefore, by deactivating the conductance value the two parameters were tried to optimize. After completing the parameter estimation process, PEST gives the outcomes to the run record file. The detail of the output file is shown below.

OPTIMISATION RESULTS

Parameter	Estimated value	95% percent confidence limits lower limit	upper limit
Transmisivity	412.645	301.725	564.341
Recharge	1.40E-04	9.88E-05	1.81E-04
Conductance	4.45	-	-

Table 5-14 The calibrated parameters of KWS Annex.

Analysis and Discussion of Results

From the above presented optimization results extracted from the Run Record of PEST, the following conclusion can be made.

Parameters: - Figure 5.12 shows how far or close are the estimated values from their confidence limits.

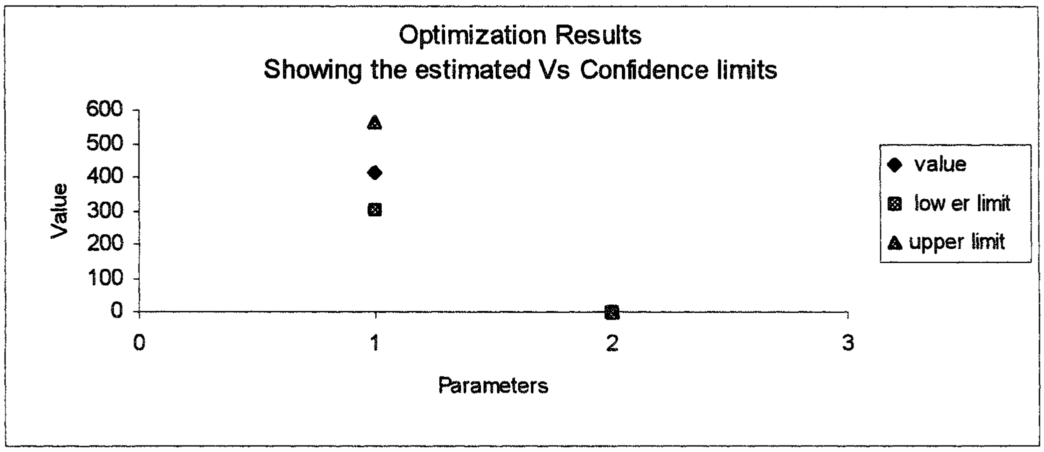


Figure 5-12 Optimization Results showing estimated Vs confidence limits (KWS Annex).

Based on the result shown in the above graph and Table 5.14, the recharge shows small range of confidence interval whereas the transmisivity shows slightly wide range of confidence. It imply that transmisivity has large margin of uncertainty while recharge is certain.

Observations

Figure 5.13 shows the optimized scatter plot which shows the goodness of fit between the measured and calculated heads.

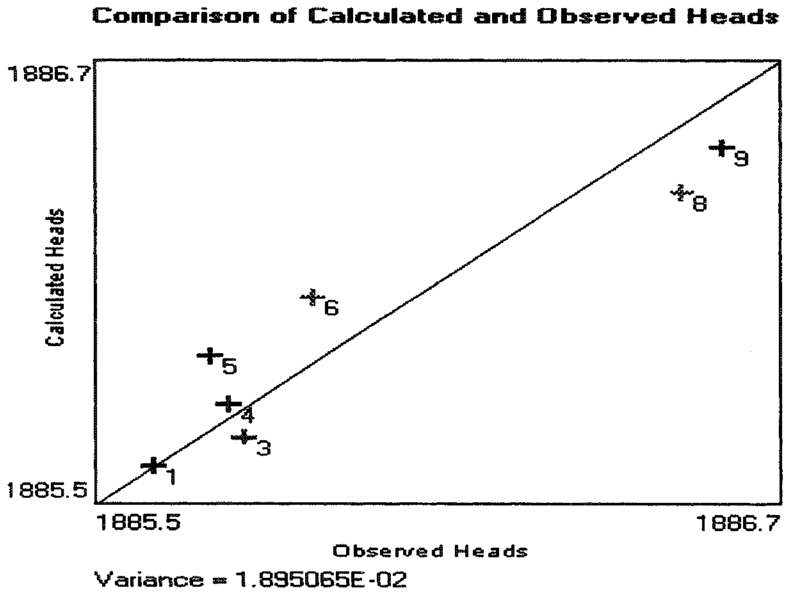


Figure 5-13 Observed VS Calculated heads (KWS Annex).

As it can be seen in the above figure the observed and the calculated head show reasonably good fit.

Objective Function

The resulting objective function among 7 observations from the final calibration of the model is 0.12. The calculated ME, RMS and MAE, values for this PEST run are -0.03m, 0.13m and 0.11m, respectively.

Covariance Matrix

parameter	pl	p2
pl	2.80E-03	8.47E-07
p2	8.47E-07	2.56E-10

Table 5-15 Covariance Matrix of KWS Annex.

As can be seen in the above table, both the parameters have very small (almost zero) variance, which indicates the certainty and reliability of the parameter estimation.

Correlation Coefficient Matrix

parameter	pl	p2
pl	1	1
p2	1	1

Table 5-16 Correlation Coefficient Matrix of KWS Annex.

Based on the result shown in the above table, the parameters are highly correlated, which implies that the optimized parameters are non-unique.

Normalized eigenvectors of covariance matrix

parameter	p1	p2
p1	3.03E-04	-1
p2	-1	-3.03E-04
Eigenvalues	1.69E-15	2.80E-03

Table 5-17 Normalized eigen vectors of covariance matrix of KWS Annex.

As shown in the above table both parameters have low eigenvalue. Hence, these parameters are not poorly discerned by the parameter estimation process.

Concluding Remark

Even though most of the estimated parameters have a close range of confidence interval, low variance and covariance, they are highly correlated. Hence, *this shows that the optimized result is non-unique*.

Therefore, gathering new information on aquifer parameters and checking the boundary condition is the critical point in order to get unique result.

5.8 Estimation of Groundwater Flux

An attempt was made to calculate the groundwater flux in KWS annex, and for wells 2 and 11 using the optimized parameters of well 2. The flux is calculated using the Darcy's groundwater flow equation.

$$Q = KA\frac{dh}{dl} = Kbw\frac{dh}{dx}$$

where
Q= water flux or discharge in [m^3/day]
K= hydraulic conductivity , [m/day]
T = Kb -transmisivity
A= vertical area of the saturated aquifer across the flow direction, [m^2]
$\frac{dh}{dl}$ = I= hydraulic gradient, dimensionless
b= saturated thickness ,[m]
w= aquifer width,[m]

The hydraulic gradient of the KWS Annex as calculated in chapter 5 is 0.001. For well 2 and 11 yearly groundwater gradient is calculated. The optimized transmisivity of the aquifer is 5960 m^2/day, using the above parameters the following result are obtained:

KWS Annex

$$Q = Tw\frac{dh}{dl} = 5960 * 0.001 = 6 \text{ m}^3\text{/day}$$

Therefore, 6 m^3/day was flowing out of the Lake through a unity width.

Well 2 & 11

An attempt was made also to calculate the groundwater flux for well 2 and 11 with the same assumption as the above on yearly basis. The negative sign here indicate that groundwater inflow to the Lake. Table 5.18 show yearly groundwater flux for the two wells.

		Well 2				Well 11			
Date	Lake lev	Well 2	h	i	Q	Well 11	h	i	Q
1958	1886.98	1886.61	0.37	0.0005	2.94	1886.25	0.73	0.0007	4.22
1959	1886.83	1886.6	0.23	0.0003	1.83	1886.48	0.35	0.0003	2.03
1960	1886.01	1885.83	0.18	0.0002	1.43	1885.99	0.02	0.0000	0.12
1961	1885.61	1885.17	0.44	0.0006	3.50	1885.61	0	0.0000	0.00
1962	1888.17	1887.62	0.55	0.0007	4.37	1887.99	0.18	0.0002	1.04
1963	1888.88	1888.37	0.51	0.0007	4.05	1889.17	-0.29	-0.0003	-1.68
1964	1889.66	1889.52	0.14	0.0002	1.11	1889.79	-0.13	-0.0001	-0.75
1965	1889.75	1889.17	0.58	0.0008	4.61	1889.17	0.58	0.0006	3.36
1966	1888.96	1888.35	0.61	0.0008	4.85	1889.29	-0.33	-0.0003	-1.91
1967	1888.77	1888.24	0.53	0.0007	4.21	1889.35	-0.58	-0.0006	-3.36
1968	1889.43	1888.87	0.56	0.0007	4.45	1889.86	-0.43	-0.0004	-2.49
1969	1889.3	1888.86	0.44	0.0006	3.50	1889.94	-0.64	-0.0006	-3.70
1970	1888.93	1887.87	1.06	0.0014	8.42	1889.39	-0.46	-0.0004	-2.66
				Average	3.79			Average	-0.45

Table5.18 Groundwater flux for well 2 and 11.

Groundwater outflow not only occurs in southern and south western part of the Lake as indicated by previous studies (McCann, 1974 ;Ojiambo,1996,1992), but it is also occur in eastern part of the Lake in a magnitude of 3.8 m^3/day as shown in the above table. Whereas in the western part, i.e. well 11, there is seepage in to the Lake in the magnitude of 0.5 m^3/day. These seepage could be from Marmonet river which drains from Mau escarpment and fails to reach Lake Naivasha, instead recharging the alluvium of Ndabibi Plain.

From the discussion raised in the preceding sections, it becomes obvious that groundwater outflow to the lake occurs over most of the lake periphery, while the groundwater inflow from lake is restricted to small part of the lake periphery. However, apart from this qualitative explanation, the exact magnitude of lake perimeter through which groundwater inflow or outflow occurs is not accurately known. If the proportion between the lake perimeters, through which groundwater inflow and outflow occurs, is assumed as 0.28, then the resulting groundwater inflow and outflow fluxes are calculated as 1.8mcm/yr and 55mcm/yr, which fit well with the values obtained by Mmbui (1999).

5.9 Groundwater Storage

In a study of transient groundwater flow, we are directly concerned with gain or loss of water storage. The amount of water released from storage per unit surface area of an aquifer, per unit change in head is referred to as the specific storage coefficient. The specific storage coefficient in unconfined aquifer is equivalent to the specific field or effective porosity, n_e. It may range from 1% to 30%. (Karltheinz Spitz,1996). In a confined aquifer, storage is attributed to compression of both the aquifer and the water, and storage coefficient is comparatively small. In both cases the amount of the water (ΔQ_s) added or released from storage is equal to the product of the volume of rock (V_{rock}) through which the change in water level occurs, the storage coefficient (S_s) and the head difference ($h(t+\Delta t) - h(t)$), which is written

$$\Delta Q_s = V_{rock} S_s [h(t+\Delta t)-h(t)]$$

Although the specific storage coefficient for a confined aquifer is relatively small, the amount of stored or released water becomes significant in field studies where large aquifer systems are investigated. For unconfined aquifer the above equation simplifies to

$$\Delta Q_s = A n_e [h(t+\Delta t)-h(t)]$$

Where A is the area of the investigated aquifer.

In the present study, it was tried to calculate the storage change of the aquifer around the Lake using the optimized parameter of well 2. The assumption here is that, the storage change of the cross-sectional model (well 2) is assumed to be homogeneous for the aquifer 2 km around Lake. i.e. for the Lacustrine deposits. See geology map of the area. The calculated Values are shown in Table 5.19 and the detail procedure to calculate the storage change is attached in Appendix 12. Figure 5.15 shows the groundwater storage change in response to Lake storage change.

Starting Date	Lake level Start	Lake level End	Stress Period	length [day]	storage change of cross-section of well2 (2km)[m^3]	Storage change of the aquifer (2Km) [m^3]	Storage change of the Lake
01-Sep-1957	1886.68	1886.53	1	242	16.11	3.62E+04	1.96E+07
01-Apr-1958	1886.53	1887.40	2	123	-27.33	-6.13E+04	-9.43E+07
01-Aug-1958	1887.40	1885.27	3	1156	84.65	1.90E+05	1.85E+08
01-Oct-1961	1885.27	1888.17	4	120	-65.40	-1.47E+05	-1.95E+08
01-Feb-1962	1888.17	1890.22	5	1036	-169.44	-3.80E+05	-4.64E+08
01-Dec-1964	1890.22	1888.43	6	811	-80.62	-1.81E+05	-2.29E+08
01-May-1967	1888.43	1888.59	7	334	-88.03	-1.98E+05	-2.50E+08
01-Apr-1968	1888.59	1889.75	8	31	-146.47	-3.29E+05	-4.02E+08
01-May-1968	1889.75	1888.63	9	669	-89.69	-2.01E+05	-2.55E+08

Table 5-19 Lake and groundwater Storage change.

The September 1957 level for both the Lake and the aquifer is taken as a reference and according to a draw down at the end of each stress period the above storage change is calculated. In the table a negative sign indicates an increase in storage. At the end of the first stress period (after 242 days), the Lake level decreased by 0.15m i.e.1.96 x 10^7 m^3 and groundwater storage of the aquifer is calculated to have decreased by 3.62 x 10^4 m^3. The loss of the aquifer is 0.2% of the Lake level loss. On the second stress period, the aquifer increased by 9.75 x 10^4 m^3, with the response of 0.72m increase of the Lake level which is 9.43 x10^7 m^3. At the end of the last stress period the Lake level increased by 1.95m, the response of this, increase the groundwater storage by -2.01E+05 m^3, which is 0.1% of the Lake storage increase. The storage change of the rest of stress period is shown in the above table.

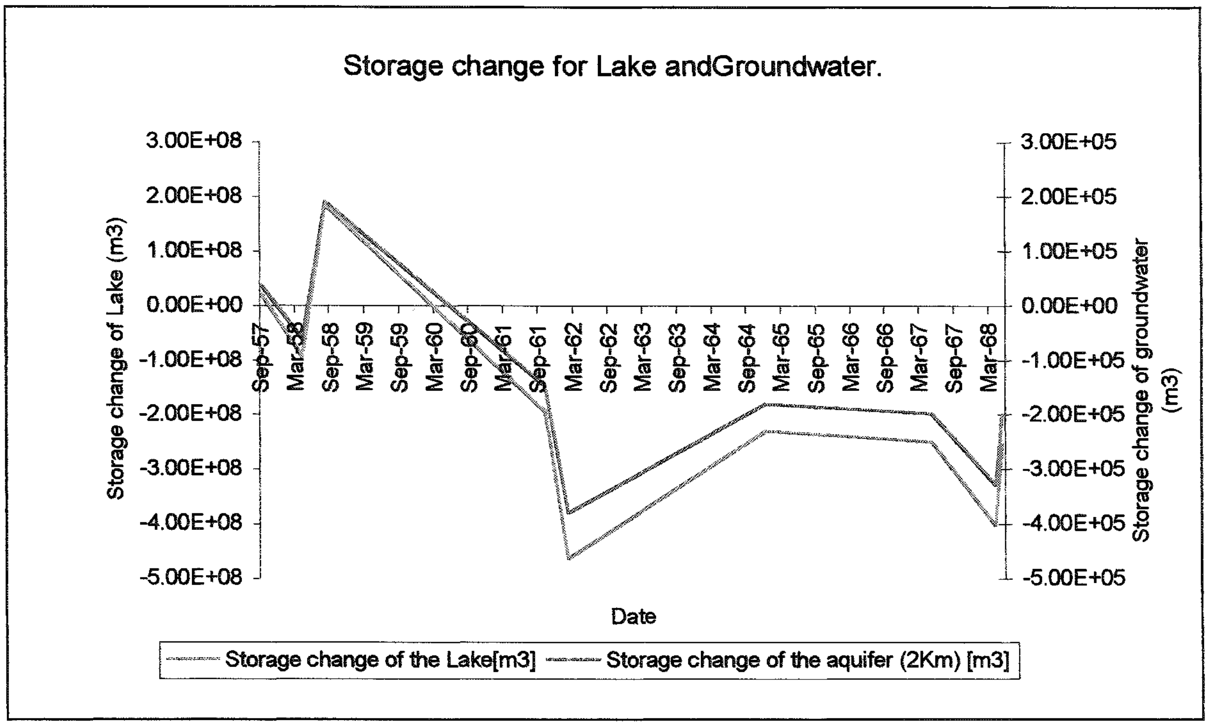


Figure 5-14 Lake and groundwater Storage change.

Starting Date	Lake level	storage change of cross-section of well2 (2km)[m^3]	Storage change of the aquifer (2Km) [m^3]	Storage change of the Lake	% of the Lake
Jan-58	1886.47	12.71	2.85E+04	2.88E+07	0.10
Jan-59	1887.14	-16.45	-3.69E+04	-6.67E+07	0.06
Jan-60	1886.55	22.87	5.13E+04	1.79E+07	0.29
Jan-61	1885.85	56.57	1.27E+05	1.08E+08	0.12
Jan-62	1887.82	-6.96	-1.56E+04	-1.81E+08	0.01
Jan-63	1888.52	-97.15	-2.18E+05	-2.97E+08	0.07
Jan-64	1889.43	-133.29	-2.99E+05	-4.61E+08	0.06
Jan-65	1890.16	-169.44	-3.80E+05	-6.01E+08	0.06
Jan-66	1889.24	-130.21	-2.92E+05	-4.16E+08	0.07
Jan-67	1888.92	-89.63	-2.01E+05	-3.63E+08	0.06
Jan-68	1888.87	-87.22	-1.96E+05	-3.56E+08	0.06
Jan-69	1889.69	-120.72	-2.71E+05	-5.13E+08	0.05
Jan-70	1888.79	-89.69	-2.01E+05	-3.38E+08	0.06
			-1.47E+05	Average	0.08

Table 5-20 yearly storage change

Table 5.20 shows yearly groundwater storage change for a buffer zone of 2km from the Lake. As table shows the groundwater storage change is less than 1 percent from the Lake storage change for the whole period. The overall long-term groundwater storage change is 0.15 mcm which is 0.1% of the Lake storage change. This result is compatible with the value reported by Mmbui(1999) who optimized the water balance parameters.

CHAPTER 6

Summary, Conclusion and Recommendation

As stated in chapter 1, the main objective of this study is to improve the knowledge of the interaction between the Lake Naivasha and the surrounding aquifers. The study employs groundwater modelling techniques to investigate the groundwater storage behavior of the aquifer in relation to the Lake level and to quantify the contribution of groundwater as a potential water resource.

Chapter 2 discusses the geology, geomorphology and aquifer characteristics of the study area. Previous studies about the aquifer properties surrounding the Lake and analysis of slug test is presented.

The surface hydrology of the study area is addressed in chapter 3. The spatial and temporal variability of rainfall and the yearly areal depth of precipitation were analyzed. Attempt was also made to estimate evapotranspiration on a yearly basis. For the water balance of the Lake, the estimated groundwater inflow and outflow components were taken from chapter 5. The rest components of the water budget were taken from previous studies.

In chapter 4, groundwater level data has been analyzed. The data were checked for accuracy, and missing gaps were filled in. The association between the groundwater level and Lake level data were studied. The results of the study reveal that there is a high correlation between the two data. This can be explained by the high transmisivity of the lacustrine deposit surrounding the Lake and the direct recharge from the Lake. Chapter 4 discusses the nature of seasonal groundwater level fluctuation and annual change in storage. The result of the analysis show that the net groundwater level change range from 0 to 0.09 meters, and the water level rise in almost all wells shows the time lag between recharge and the peak of the long rains. Hydraulic gradient of 0.001 and 0.003 have been calculated for transects made in KWS Annex and Manera farm, respectively. The amount of seepage from Malewa River to the groundwater was estimated to be 5,000 m3/day for a river length of 5000m and for an average width of 10m.

Chapter 5 presents different aspects of cross-sectional models around the Lake. In developing the models a number of simplifying assumptions were made. The aquifer was assumed one layer and uniform. This chapter focuses on optimizing the different aquifer parameter of the models.

For a cross-sectional model across the eastern part of the Lake, i.e. well 2, the optimization result gives 5960 m^2/day and 8.5e-4 for transmisivity and Storativity, respectively. Whereas the result of a cross-sectional model taken across well 11(western part of the Lake) and KWS Annex (eastern part of the Lake) gives non-unique result.

Estimation of groundwater flux around the Lake was also conducted by taking the optimized transmisivity value of well 2 as a representative for the different wells around the Lake. Applying this transmisivity value, groundwater flux for KWS Annex was estimated to be 6 m^3/day through a unit cross-section. Besides the yearly groundwater flux was also calculated for wells 2 and 11. The long term yearly groundwater outflow from the Lake to well 2 was estimated to be 3.8 m^3/day whereas groundwater inflow to the Lake from well 11 was estimated as 0.5 m^3/day through a unit cross-section. If the proportion between the lake perimeters, through which groundwater inflow and outflow occurs, is assumed as 0.28, then the resulting groundwater inflow and outflow fluxes are calculated as 1.8mcm/yr and 55mcm/yr.

Finally, it was tried to calculate the storage change of the aquifer around the Lake using the optimized parameters of well 2. The storage change was calculated in two ways, first according to the model's stress periods and secondly using yearly average. The long term yearly average groundwater change was estimated to be 0.15 million cubic meter which is 0.1% of the Lake storage change.

The overall analysis of this study reveals that, over the past 30 years:-

- Generally speaking, the lake has been feeding the aquifer;
- The change in groundwater storage was insignificant, accounting for 0.1% of the lake storage change.

To improve the accuracy of the result of the study, the following improvements should be made:

- Further data on aquifer parameters should be collected in the field;
- Model boundary conditions should be refined;
- The perimeters of the lake through which inflow to the Lake and outflow from the lake occur must be accurately known.

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APPENDICES

Appendix 1. Soil Description of Auger holes in KWS Annex.

Well no 1

Soil depth (meters)	Color	Soil Description
0 to 0.2	Light brown	Silty clay loam
0.2 - 0.6	Light grayish brown	Silty clay
0.6 - 1.0	Light grayish brown	fine gravely sandy loam
1.0 - 1.2	brown	fine gravely sandy loam
1.2 - 1.6	dark brown	clay loam
1.6 - 1.8	Dark brown	clay to clay loam
1.8 - 2.0	greenish gray	clay

Well no 2

Soil depth (meters)	Color	Soil Description
0 to 0.4	Light brown	Silty clay loam
0.4 - 0.7	yelowish brown	Silty clay
0.7 - 1.0	Grayish brown	fine gravely sandy loam
1.0 - 1.5	brown	fine gravely sandy loam
1.5 - 1.9	dark brown	clay loam
1.9 - 2.5	brown	clay
2.5 - 2.8	Dark brown	clay
2.8 - 3.0	Dark brown	clay

Well no 3

Soil depth (meters)	Color	Soil Description
0 to 0.3	Grayish brown	Silty clay loam
0.3- 0.6	brown	Silty clay
0.6 - 1.2	yellowish brown	fine gravely sandy loam
1.2 - 1.7	Dark brown	fine gravely sandy loam
1.7 - 1.9	dark brown	coarse gravely sandy loam
1.9 - 2.3	yellowish brown	clay
2.3 - 2.7	brown	clay
2.7 - 3.2	greenish brown	clay
3.2 - 4.2	brown	fine gravely sandy loam
4.2 - 5.3	brown	fine gravely sandy loam

Well no 4

Soil depth (meters)	Color	Soil Description
0 to 0.3	brown	Silty clay loam
0.3- 0.5	light brownish gray	Clay
0.5 - 0.8	light brownish gray	sandy Clay loam
0.8 - 1.2	light brownish gray	fine gravely sandy loam
1.2 - 1.7	dark brown	fine gravely sandy clay loam
1.7 - 2.1	brown	clay
2.1 - 2.7	redish brown	clay
2.7 - 3.2	greenish brown	fine gravely clay

Well no 5

Soil depth (meters)	**Color**	**Soil Description**
0 to 0.5	light grayish brown	Silty clay loam
0.5- 0.7	grayish brown	Silty clay loam
0.7 - 0.9	light brownish	clay
0.9 - 1.0	brown	clay
1.0 - 1.5	dark brown	clay
1.5 - 2.1	brown	clay
2.1 - 2.7	redish brown	clay
2.7 - 3.0	greenish brown	fine gravely clay
3.0 - 3.2	reddish brown	clay
3.2 - 4.4	greenish brown	clay

Well no 6

Soil depth (meters)	Color	Soil Description
0 to 0.2	light grayish brown	Silty clay loam
0.2- 0.7	grayish brown	silty clay
0.7 - 1.1	brown	fine gravely sandy laom
1.1 - 1.7	brown	clay
1.7 - 2	light grayish brown	clay
2.0 - 2.4	yellowish brown	fine gravely sandy laom
2.4 - 2.5	yellowish brown	clay
2.5 - 2.7	yellowish brown	corase sandy clay loam
2.7 - 3.0	light grayish brown	clay
3.0 - 3.5	light greenish brown	corase sandy clay loam
3.5 - 3.7	greenish brown	clay
3.7 - 4.3	greenish brown	sandy loam
4.3 - 4.8	Dark gray	corase sandy clay loam

Well no 7

Soil depth (meters)	**Color**	**Soil Description**
0 to 0.2	light gray	Silty clay loam
0.2- 0.7	brown	silty clay
0.7 - 1.0	grayish brown	silty clay
1.0 - 1.2	dark brown	coarse gravely sandy laom
1.2 - 1.6	brown	fine gravely sandy laom
1.6 - 2.0	brown	clay
2.0 - 2.4	dark brown	clay
2.4 - 3.2	greenish brown	clay
3.2 - 3.6	light red brwon	fine gravely sandy laom
3.6 - 4.3	greenish brown	clay
4.3 - 4.8	greenish brown	coarse gravely sandy laom
4.8 - 5.4	greenish brown	fine gravely sandy laom
5.4 - 5.8	brown	corase sandy clay loam
5.8 - 6.1	brown	clay
6.1 - 7.0	greenish brown	coarse gravely sandy laom

Generalized soil description of the KWS Annex transect.

Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7
Clay	Clay	Clay	Clay	Clay	Clay	Clay
Sandy	Sandy	Sandy	Sandy	Clay	Sandy	Sandy
	Clay	Clay	Clay	Clay	Clay	Clay
		Clay	Sandy	Clay	Sandy	Sandy
			Sandy	Clay	Clay	Clay
			Sandy			Sandy
						Clay
						Sandy

Appendix 2 Mean monthly Precipitation data

STAT_NAME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ELEV	NO_YRS	TOTYR	Max
Naivash D.O.	25	36	58	113	84	82	34	45	43	49	61	40	1900	77	669	113
North Kinangop Forest Station	43	51	87	174	154	107	75	94	103	99	98	59	2630	72	1145	174
Gilgil Kwetu Farm	30	30	61	149	125	88	98	117	75	77	88	47	2347	68	985	149
Bahati Forest Station	26	32	57	163	210	126	134	164	120	104	92	38	2317	59	1265	210
Gilgil Station (Railway)	24	30	52	101	70	53	62	62	39	50	60	42	2006	51	646	101
Ol Kalou Station	20	18	31	99	105	86	106	128	54	47	53	20	2367	50	768	128
Ol Bolossat Forest Station	39	51	71	123	80	53	37	35	37	39	54	58	2012	23	676	123
Naivasha K.C.C Ltd	28	35	48	102	83	51	40	50	31	39	53	38	1951	57	598	102
Technology Farm, Nakuru	23	36	64	136	131	83	97	117	74	58	71	37	1920	66	927	136
Naivasha Vet. Experimental Stn.	33	39	55	117	96	55	43	55	42	62	68	46	1829	54	711	117
Naivasha Marula	32	33	51	113	84	50	47	59	38	40	62	44	2042	50	655	113
Nyandurua Agric Research Station	33	31	48	122	110	100	138	155	78	53	67	58	2377	44	993	155
Ol Bolossat Forest Station	32	30	51	119	122	102	153	171	78	56	77	49	2377	39	1041	171
Elementaita, Soysambu Estate	28	29	50	112	81	57	66	75	59	50	62	44	1849	54	712	112
Gilgil, Kikopey Ranch	22	28	53	167	72	53	55	69	37	47	59	39	2134	59	701	167
Subikia Pyrethrum Nursery	33	38	56	165	175	95	130	153	107	85	91	57	2134	32	1186	175
South Kinangop Njabini Farmers Tr Ctr	65	67	117	232	174	74	64	65	64	119	133	106	2591	38	1279	232
Kijabe Railway Station	55	51	66	198	163	48	26	26	25	34	62	64	2203	34	818	198
South Kinangop Forest Station	70	79	148	278	219	89	68	64	64	130	160	85	2591	35	1454	278
Kinangop Sasumua Dam	79	81	149	310	267	97	66	69	66	140	179	94	2481	40	1598	310
Elementaita Nderit Ranger Post	30	34	53	145	102	66	69	98	61	53	105	48	1798	33	865	145
Nakuru Lanet Police Post	30	37	53	116	102	72	73	92	75	86	93	41	1890	29	871	116
Geta Forest Station	41	45	75	168	169	110	106	117	125	106	91	55	2591	32	1208	169
Dundori Forest Station	29	29	65	165	161	121	122	132	106	105	105	39	2256	30	1178	165
Kamae Forest Station	71	67	113	303	235	70	50	47	57	125	172	93	2591	32	1399	303
Menengai Forest Station	40	37	65	148	130	82	91	111	99	83	97	37	2155	29	1020	148
Thome Farmers No.2	28	51	44	170	112	68	55	86	53	64	118	83	2350	22	929	170
Eastern Rift Sawmill Ltd.	54	60	89	201	137	42	33	29	36	67	110	62	2591	25	918	201
Nakuru Meteorological Station	28	43	67	141	128	76	92	112	39	67	72	38	1872	27	903	141
Olarogwai Farm Naivasha	31	47	57	124	80	51	45	60	98	61	71	45	1981	26	770	124
North Kanangop Mawingo Scheme	52	41	56	162	185	113	90	104	96	81	77	31	2484	9	1088	185
Naivasha W. D. D.	39	44	60	116	79	51	37	45	44	56	62	48	1936	21	681	116
Wanjohi Chief's Office	36	32	47	123	119	94	94	130	91	78	78	40	2469	19	960	130
Malewa Scheme	30	26	50	111	107	77	64	86	63	53	48	16	2317	14	732	111
Bwani Daniel Farm	63	62	149	207	129	95	124	145	98	53	55	27	1951	7	1208	207
Chamate Gate	35	34	63	145	123	104	112	165	85	69	98	83	2835	11	1114	165
Naishi Ranger's Post	48	29	73	219	97	72	75	85	66	75	87	54	1814	5	980	219
Akira Ranch Hell's P. Post	25	21	35	112	45	50	36	26	31	43	37	47	1798	8	507	112
Bahati Catholic Church	21	41	57	145	191	112	115	134	95	105	94	33	2103	9	1142	191
A.D.C. Ol Jorrai Ranch	19	17	49	149	83	71	64	90	45	46	72	37	1905	8	742	149
A.D.C. Ol Jorrai (Main House)	17	28	76	173	86	77	94	59	37	46	48	27	1920	1	767	173
A.D.C. Ol Jorrai (Primary Sch.)	24	22	56	201	110	73	46	55	46	40	89	35	1981	5	796	201
A.D.C. Ol Jorrai (Hill House)	9	21	56	146	86	44	63	70	36	72	79	74	2286	6	755	146

Location of Rainfall station and long term average yearly total Precipitation.

XCOORD	YCOORD	STAT_NAME	ELEV	Record Length (years)	TOTYR Rainfall
214315	9920714	Naivash D.O.	1900,40	77	669
236582	9935474	North Kinangop Forest Station	2630,40	72	1145
199446	9961275	Gilgil Kwetu Farm	2347,00	68	985
186444	9981558	Bahati Forest Station	2316,50	59	1265
218635	9944686	Gilgil Station (Railway)	2005,90	51	646
206870	9970497	Ol Kalou Station	2367,10	50	768
195758	9909639	Ol Bolossat Forest Station	2011,70	23	676
208743	9926243	Naivasha K.C.C Ltd	1950,70	57	598
167877	9966799	Technology Farm, Nakuru	1920,20	66	927
212455	9928088	Naivasha Vet. Experimental Stn.	1828,80	54	711
208742	9928088	Naivasha Marula	2042,20	50	655
205010	9996312	Nyandurua Agric Research Station	2377,40	44	993
203153	9994468	Ol Bolossat Forest Station	2377,40	39	1041
194994	9948365	Elementaita, Soysambu Estate	1848,90	54	712
184596	9948360	Gilgil, Kikopey Ranch	2133,60	59	701
184586	9996311	Subikia Pyrethrum Nursery	2133,60	32	1186
238446	9920727	South Kinangop Njabini Farmers Tr Ctr	2590,80	38	1279
231034	9898599	Kijabe Railway Station	2202,80	34	818
242157	9920729	South Kinangop Forest Station	2590,80	35	1454
240304	9917041	Kinangop Sasumua Dam	2481,10	40	1598
180880	9953892	Elementaita Nderit Ranger Post	1798,30	33	865
182733	9966803	Nakuru Lanet Police Post	1889,80	29	871
207248	9948369	Geta Forest Station	2590,80	32	1208
192016	9972338	Dundori Forest Station	2255,50	30	1178
236598	9905977	Kamae Forest Station	2590,80	32	1399
175304	9972334	Menengal Forest Station	2154,90	29	1020
197602	9929925	Thome Farmers No.2	2350,00	22	929
244026	9898608	Eastern Rift Sawmill Ltd.	2590,80	25	918
173448	9970489	Nakuru Meteorological Station	1871,80	27	903
216168	9928090	Olarogwai Farm Naivasha	1981,20	26	770
223586	9944688	North Kanangop Mawingo Scheme	2484,10	9	1088
216173	9918872	Naivasha W. D. D.	1935,50	21	681
225436	9961282	Wanjohi Chief's Office	2468,90	19	960
216155	9959436	Malewa Scheme	2316,50	14	732
169736	9961266	Bwani Daniel Farm	1950,70	7	1208
225433	9977875	Chamate Gate	2834,60	11	1114
175311	9950201	Naishi Ranger's Post	1813,60	5	980
201338	9894890	Akira Ranch Hell's P. Post	1798,30	8	507
182729	9993360	Bahati Catholic Church	2103,10	9	1142
179028	9942825	A.D.C. Ol Jorrai Ranch	1905,00	8	742
184600	9939139	A.D.C. Ol Jorrai (Main House)	1920,20	1	767
188315	9937297	A.D.C. Ol Jorrai (Primary Sch.)	1981,20	5	796
184603	9933606	A.D.C. Ol Jorrai (Hill House)	2286,00	6	755

Appendix 3. Estimation of Areal depth of Precipitation

Isohytal approach.

Surfaces representing Precipitation values over an area are usually depicted in the form of maps showing contours of equal Precipitation (isohytes). These maps are used to estimate the areal depth of precipitation, *P*, by considering that the isohytes serve as boundaries of *I* sub-regions within the basin, with all points in the sub-region assigned a Precipitation value equal to the average of the values associated with its boundary isohytes:

$$\hat{P}_i = \frac{1}{2}(P_{i-} + P_{i+})$$

Where P_I is the Precipitation at all points in the i[th] sub-regions, and P_{I-} and P_{I+} are the values of the isohytes that bound the i[th] sub-region. The regional average is then estimated as

$$\hat{P} = \frac{1}{A}\sum_{i=1}^{1} a_i \hat{P}_i$$

Where a_I is the area between the two contours within the region.

Steps

1. The isoheytal map was prepared based on the nearest neighbor interpolation method under GIS environment.
2. Raster map of isohyte was produced using contour interpolation.
3. The map was then sliced using slicing operation in an interval of 100.
4. Area for each isoytal interval is calculated.
5. The average precipitation of the isohytal interval is multiplied by corresponding area to get the areal precipitation for each range.
6. Finally, the areal precipitation of each interval is summed and multiplied by reciprocal of the area of the basin to get the areal depth Precipitation of the Basin.

Theison Polygon approaches.

This method for non-uniform distribution of gauges by determining a weighting factor for each gauge. A weighted mean of the precipitation values can then be computed.

1) The Theisen map was prepared based on the nearest neighbor interpolation method under GIS environment.
   a) First table containing Name of the rainfall station, their location and long-term mean annual precipitation of the area was prepared.
   b) Then the table is converted using table to point operation (attribute rainfall value).
   c) Finally the Theisen map is created using the point map based on the nearest neighbor operation.
2) In order to get areal depth of Precipitation table calculation is performed.
   a) Using the histogram of the Theisen map the total area of the basin and the weight of each sub-region is calculated.
   b) The weight of each sub-region is then multiplied by long-term mean annual precipitation value.

c) Finally, using aggregate function the sum of step 2b is calculated to get areal depth of precipitation.

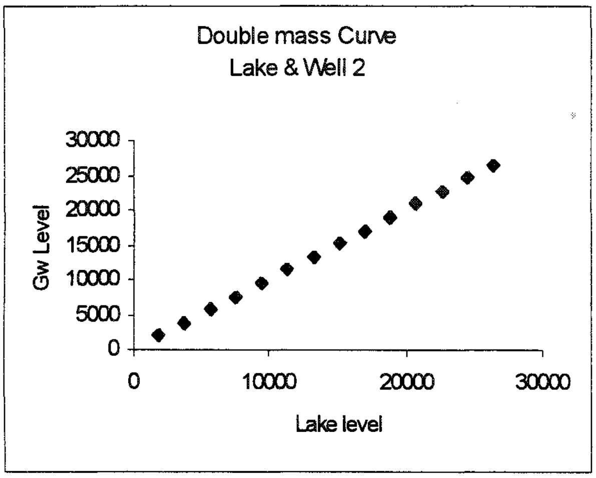
The equation to calculate the areal depth of precipitation is

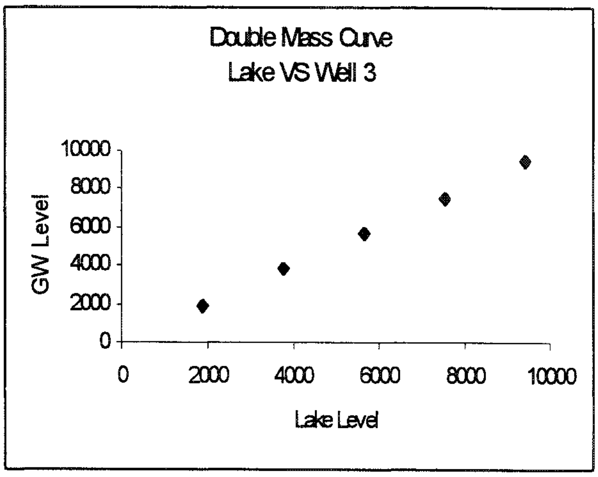
$$\hat{P} = \frac{1}{A}\sum_{g=1}^{G} a_g P_g$$

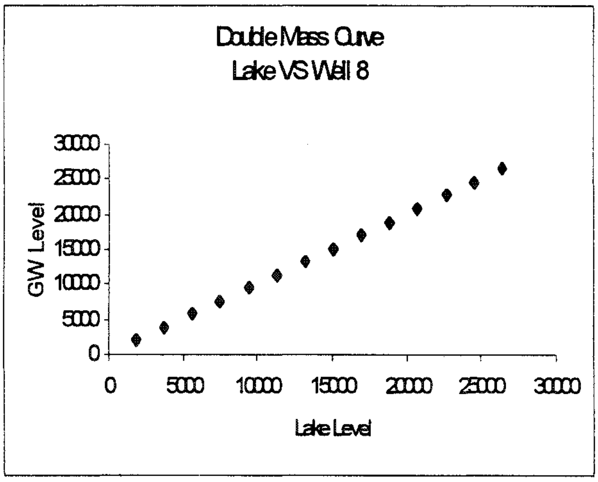
Where,

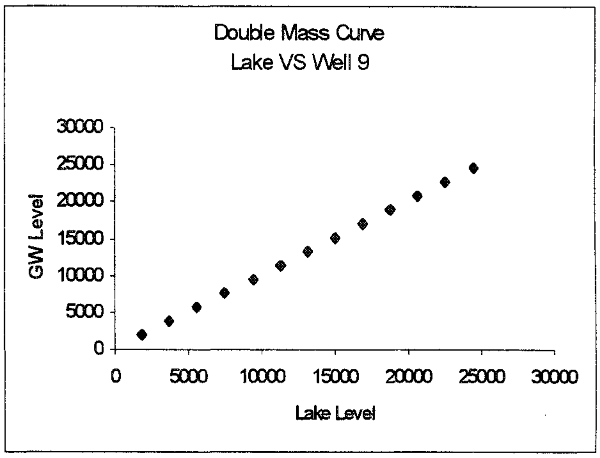
P = Areal depth of precipitation,[mm]
A = total area of the basin, [m^2]
a_g = area of the sub-region, [m^2]
P_g= long-term mean annual precipitation value for each sub-region. , [mm]

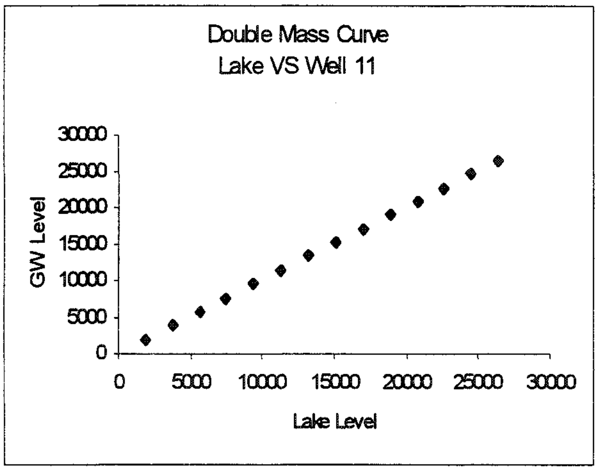
Appendix 4 Figures showing Double Mass Curve for Lake level vs. groundwater level as observed in different wells around the lake.

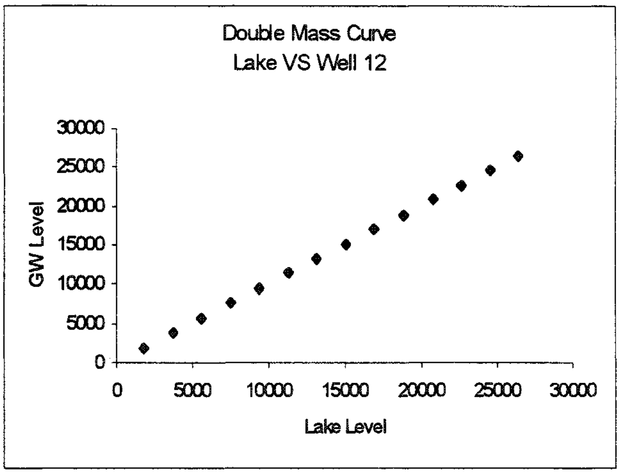


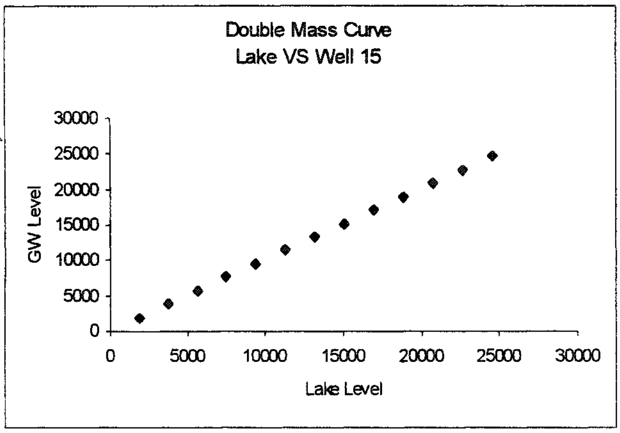


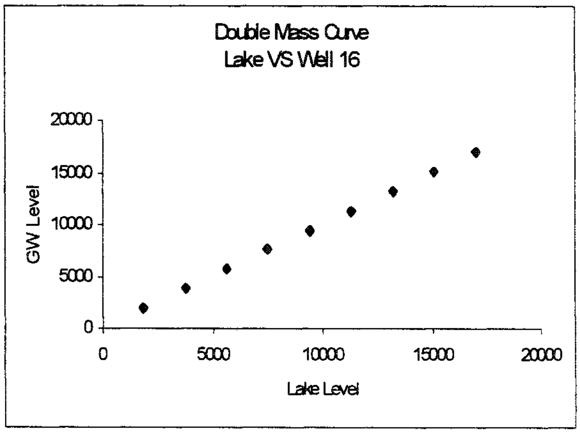


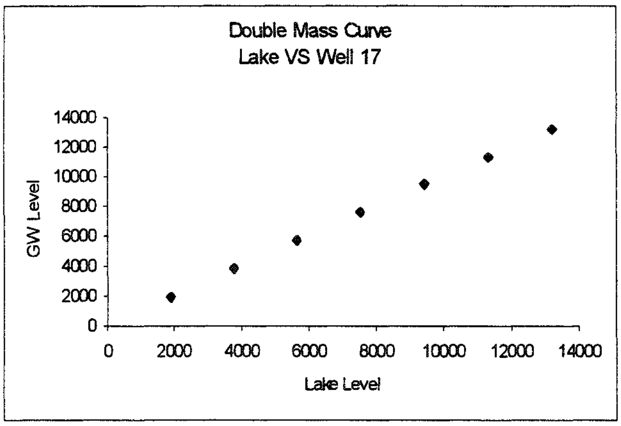


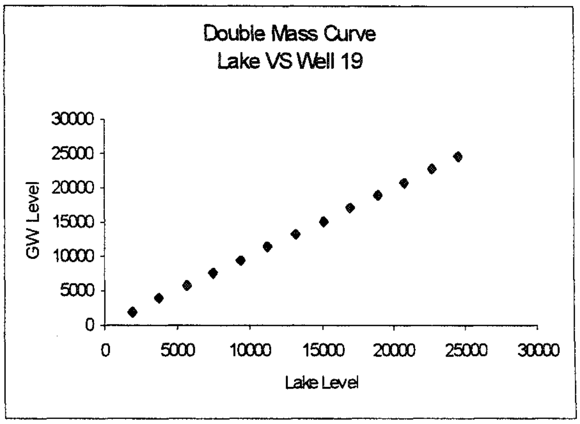





Double Mass Curve
Lake VS Well 15
GW Level
Lake Level
0
5000
10000
15000
20000
25000
30000


Double Mass Curve
Lake VS Well 16
GW Level
Lake Level
0
5000
10000
15000
20000


Double Mass Curve
Lake VS Well 17
GW Level
Lake Level
0
2000
4000
6000
8000
10000
12000
14000


Double Mass Curve
Lake VS Well 19
GW Level
Lake Level
0
5000
10000
15000
20000
25000
30000

Appendix 5 Historical groundwater level measurement.

a) Monthly average

DATE	Lake level	Well2	Well 3	Well 8	Well 9	Well 11	Well 12	Well 15	Well 16	Well 17	Well 19
Sep-57	1886.68	1886.48	1885.78	1885.31	1884.94	1885.15	1884.97	1884.98	1885.64	1885.43	1885.42
Oct-57	1886.59	1886.30	1885.73	1885.37	1885.35	1885.51	1885.03	1884.92	1885.59	1885.37	1885.44
Nov-57	1886.51	1886.23	1885.67	1885.40	1885.60	1885.61	1885.09	1884.91	1885.55	1885.59	1885.43
Dec-57	1886.49	1886.09	1885.63	1885.40	1885.78	1885.60	1885.11	1884.92	1885.57	1885.23	1885.43
Jan-58	1886.47	1886.19	1885.53	1885.43	1885.71	1885.55	1884.97	1884.91	1885.57	1884.96	1885.33
Feb-58	1886.46	1886.21	1885.82	1885.40	1886.37	1885.68	1885.08	1884.80	1885.56	1884.97	1885.32
Mar-58	1886.45	1886.11	1886.29	1885.42	1886.16	1885.66	1885.14	1884.79	1885.55	1884.95	1885.42
Apr-58	1886.53	1886.11	1886.43	1885.42	1885.83	1885.90	1885.10	1884.75	1885.58	1884.95	1885.38
May-58	1886.73	1886.14	1886.57	1885.46	1886.15	1885.90	1885.38	1885.07	1885.63	1885.15	1885.46
Jun-58	1887.07	1886.28	1886.71	1885.65	1886.03	1886.09	1885.55	1885.37	1887.85	1885.76	1885.87
Jul-58	1887.33	1886.77	1886.95	1885.81	1886.07	1886.10	1885.67	1885.50	1887.99	1885.94	1886.08
Aug-58	1887.4	1886.98	1887.30	1886.00	1886.20	1886.54	1886.07	1885.87	1887.92	1886.40	1886.59
Sep-58	1887.39	1887.06	1887.14	1886.18	1886.39	1886.67	1886.18	1885.95	1887.91	1886.49	1886.59
Oct-58	1887.36	1887.18	1886.97	1886.31	1886.52	1886.91	1886.17	1885.93	1887.90	1886.44	1886.67
Nov-58	1887.28	1887.17	1886.81	1886.34	1886.59	1886.93	1886.17	1885.87	1887.85	1886.13	1886.68
Dec-58	1887.25	1887.13	1886.75	1886.36	1886.69	1887.04	1886.18	1885.84	1887.81	1886.12	1886.62
Jan-59	1887.14	1887.09	1886.68	1886.37	1886.75	1886.73	1886.18	1885.79	1887.79	1886.08	1886.54
Feb-59	1887.02	1887.02	1886.62	1886.35	1886.75	1886.66	1886.12	1885.68	1887.74	1885.80	1886.50
Mar-59	1886.95	1886.98	1886.51	1886.31	1886.70	1886.55	1886.09	1885.62	1887.69	1885.74	1886.47
Apr-59	1886.88	1886.90	1886.42	1886.28	1886.72	1886.50	1886.05	1885.59	1887.65	1885.76	1886.44
May-59	1886.86	1886.84	1886.35	1886.21	1886.67	1886.66	1886.01	1885.54	1887.63	1885.65	1886.39
Jun-59	1886.85	1886.68	1886.30	1886.19	1886.62	1886.54	1886.02	1885.56	1887.59	1885.58	1886.34
Jul-59	1886.73	1886.69	1886.20	1886.15	1886.55	1886.40	1885.94	1885.49	1887.51	1885.67	1886.20
Aug-59	1886.73	1886.19	1886.15	1886.11	1886.59	1886.33	1885.88	1885.48	1887.45	1885.65	1886.09
Sep-59	1886.74	1886.24	1886.20	1886.11	1886.54	1886.37	1885.86	1885.52	1887.44	1885.72	1886.11
Oct-59	1886.72	1886.24	1886.20	1886.09	1886.46	1886.36	1885.79	1885.52	1887.38	1885.62	1886.06
Nov-59	1886.66	1886.24	1886.13	1886.08	1886.42	1886.37	1885.81	1885.52	1887.36	1885.55	1885.98
Dec-59	1886.63	1886.11	1886.08	1886.07	1886.42	1886.30	1885.82	1885.51	1887.33	1885.56	1885.95
Jan-60	1886.55	1885.97	1886.04	1886.01	1886.46	1886.30	1885.74	1885.42	1887.28	1885.41	1885.72
Feb-60	1886.25	1886.00	1885.99	1885.94	1886.42	1886.25	1885.65	1885.32	1887.28	1885.28	1885.75
Mar-60	1886.05	1885.95	1885.95	1885.86	1886.45	1886.19	1885.58	1885.22	1886.81	1885.24	1885.66
Apr-60	1885.99	1885.91	1885.90	1885.82	1886.16	1886.03	1885.53	1885.20	1885.28	1885.18	1885.60
May-60	1885.92	1885.90	1885.86	1885.77	1886.11	1886.02	1885.48	1885.12	1886.78	1885.09	1885.57
Jun-60	1885.84	1885.86	1885.81	1885.70	1886.05	1885.92	1885.43	1884.99	1886.98	1884.99	1885.43
Jul-60	1885.92	1885.82	1885.77	1885.63	1886.23	1885.78	1885.38	1884.90	1886.81	1884.94	1885.35
Aug-60	1885.87	1885.78	1885.72	1885.54	1885.97	1885.88	1885.32	1884.83	1886.64	1884.90	1885.29
Sep-60	1885.91	1885.74	1885.67	1885.49	1885.89	1886.10	1885.27	1884.88	1886.47	1884.86	1885.24
Oct-60	1885.92	1885.70	1885.63	1885.47	1885.91	1886.00	1885.22	1884.96	1886.30	1884.82	1885.19
Nov-60	1885.95	1885.67	1885.58	1885.42	1886.01	1885.77	1885.17	1885.02	1886.13	1884.78	1885.13
Dec-60	1885.96	1885.63	1885.54	1885.39	1885.84	1885.64	1885.06	1884.96	1885.96	1884.74	1885.08
Jan-61	1885.85	1885.59	1885.49	1885.34	1885.72	1885.50	1884.90	1884.83	1885.79	1884.70	1885.02
Feb-61	1885.73	1885.55	1885.45	1885.28	1885.63	1885.41	1884.87	1884.71	1885.63	1884.66	1884.97
Mar-61	1885.6	1885.51	1885.40	1885.19	1885.55	1885.32	1884.85	1884.66	1885.46	1884.62	1884.92
Apr-61	1885.47	1885.47	1885.36	1885.10	1885.50	1885.40	1884.85	1884.61	1885.29	1884.58	1884.87
May-61	1885.38	1885.41	1885.13	1885.03	1885.48	1886.07	1884.84	1884.54	1885.13	1884.54	1884.82
Jun-61	1885.37	1885.07	1884.89	1885.01	1885.40	1885.72	1884.84	1884.38	1884.97	1884.43	1884.73
Jul-61	1885.29	1884.92	1884.80	1885.00	1885.43	1885.54	1884.78	1884.30	1884.93	1884.30	1884.56
Aug-61	1885.18	1884.84		1884.97	1885.26	1885.38	1884.75	1884.29	1885.08	1884.40	1884.52

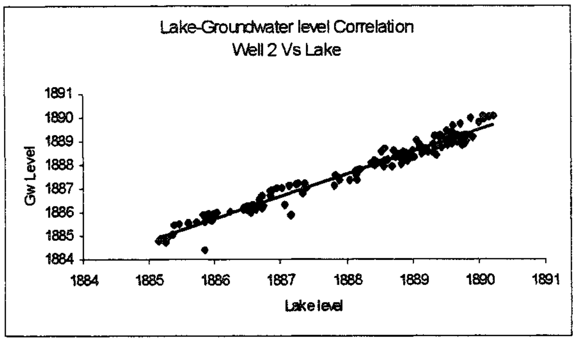
DATE	Lake level	Well2	Well 3	Well 8	Well 9	Well 11	Well 12	Well 15	Well 16	Well 17	Well 19
Sep-61	1885.15	1884.76		1885.01	1885.23	1885.23	1884.67	1884.30	1884.95	1884.40	1884.46
Oct-61	1885.27	1884.71		1884.91	1885.38	1885.16	1884.68	1884.32	1887.35	1884.43	1884.52
Nov-61	1885.86	1884.36		1885.13	1885.66	1885.84	1884.96	1884.70	1891.20	1884.89	1884.89
Dec-61	1887.16	1885.88		1886.01	1885.86	1886.69	1886.07	1885.65	1891.73	1885.32	1886.62
Jan-62	1887.82	1887.08		1886.81	1886.40	1887.46	1886.88	1886.42	1891.20	1885.76	1887.99
Feb-62	1888.17	1887.33		1887.13	1886.78	1887.75	1886.98	1886.55	1891.06	1886.18	1887.92
Mar-62	1888.05	1887.35		1887.18	1887.03	1887.71	1886.98	1886.48	1891.22	1886.60	1887.60
Apr-62	1887.89	1887.35		1886.97	1887.18	1887.66	1887.08	1886.45	1891.41	1886.84	1887.50
May-62	1887.84	1887.52		1887.03	1887.70	1887.77	1887.41	1886.72	1891.48	1887.17	1887.95
Jun-62	1888.15	1887.71		1887.16	1888.01	1888.02	1887.63	1886.93	1891.30	1887.46	1888.20
Jul-62	1888.17	1887.73		1887.26	1888.65	1888.11	1887.69	1886.96	1889.78	1887.33	1888.05
Aug-62	1888.15	1887.50		1887.35	1888.26	1888.12	1887.66	1886.98	1887.90	1887.18	1887.97
Sep-62	1888.21	1887.75		1887.42	1888.20	1888.15	1887.80	1887.07	1887.91	1887.18	1888.09
Oct-62	1888.42	1887.97		1887.52	1888.24	1888.27	1888.02	1887.29	1888.12	1887.51	1888.56
Nov-62	1888.59	1888.11		1887.64	1888.29	1888.43	1888.15	1887.38	1888.20	1888.33	1888.51
Dec-62	1888.59	1888.09		1887.74	1888.33	1888.48	1888.12	1887.34	1887.82	1887.88	1888.40
Jan-63	1888.52	1888.07		1887.82	1888.65	1888.51	1888.16	1887.29	1887.86	1887.51	1888.28
Feb-63	1888.45	1888.04		1887.86	1888.58	1888.51	1888.16	1887.04	1887.89	1887.47	1888.25
Mar-63	1888.4	1888.00		1887.89	1888.56	1888.50	1888.12	1886.98	1887.79	1887.29	1888.15
Apr-63	1888.38	1888.05		1888.02	1888.59	1888.46	1888.14	1886.97	1887.90	1887.17	1888.25
May-63	1888.59	1888.16		1888.09	1888.81	1888.79	1888.81	1887.62	1891.14		1889.22
Jun-63	1889	1888.26		1888.34	1888.93	1889.54	1889.49	1888.38	1891.38		1889.37
Jul-63	1889.36	1888.37		1888.62	1888.91	1889.68	1889.39	1888.27	1890.15		1889.25
Aug-63	1889.31	1888.47		1888.82	1888.89	1889.66	1889.34	1888.21	1889.08		1889.13
Sep-63	1889.19	1888.58		1888.93	1888.87	1889.65	1889.39	1888.26	1889.04		1889.02
Oct-63	1889.2	1888.68		1889.01	1888.85	1889.61	1889.30	1888.17	1888.86		1888.90
Nov-63	1889.12	1888.79		1889.06	1888.82	1889.54	1889.22	1888.06	1888.69		1888.78
Dec-63	1889.07	1889.02		1889.10	1888.80	1889.57	1889.69	1888.45	1889.51		1888.67
Jan-64	1889.43	1889.22		1889.19	1888.78	1889.75	1889.84	1888.67	1889.59		1888.55
Feb-64	1889.52	1889.17		1889.25	1888.76	1889.77	1889.59	1888.50	1889.20		1888.43
Mar-64	1889.39	1889.20		1889.30	1888.74	1889.76	1889.54	1888.48	1889.16		1888.32
Apr-64	1889.33	1889.21		1889.33	1888.71	1889.81	1889.55	1888.53	1889.01		1888.20
May-64	1889.52	1889.44		1889.41	1888.69	1890.17	1889.01	1888.90	1889.30		1888.08
Jun-64	1889.62	1889.36		1889.49	1888.67	1890.15	1888.60	1888.83	1889.35		1887.97
Jul-64	1889.61	1889.31		1889.54	1888.65	1890.10	1888.29	1888.76	1889.29		1887.93
Aug-64	1889.61	1889.61		1889.62	1888.62	1889.71	1887.99	1889.12	1889.59		1888.69
Sep-64	1889.72	1889.73		1889.73	1888.60	1889.35	1888.01	1889.25	1891.38		1888.88
Oct-64	1889.88	1889.93		1889.88	1888.58	1889.62	1888.29	1889.50	1889.82		1889.32
Nov-64	1890.07	1890.07		1890.04	1888.56	1889.70	1888.36	1889.49	1889.91		1889.34
Dec-64	1890.22	1890.03		1890.14	1888.54	1889.63	1888.31	1889.47	1889.85		1889.13
Jan-65	1890.16	1889.99		1890.18	1888.51	1889.58	1888.27	1889.44	1889.77		1888.96
Feb-65	1890.08	1889.90		1890.18	1888.49	1889.48	1888.17	1889.44	1889.57		1888.75
Mar-65	1890.01	1889.78		1890.15	1888.47	1889.36	1888.08	1889.58	1889.44		1888.52
Apr-65	1889.91	1889.15		1890.09	1888.45	1889.23	1887.98	1889.52	1889.31		1888.35
May-65	1889.77	1889.16		1890.04	1888.43	1889.27	1887.99	1889.59	1889.36		1888.48
Jun-65	1889.71	1889.06		1890.01	1888.40	1889.25	1887.96	1889.57			1888.39
Jul-65	1889.76	1889.02		1889.98	1888.38	1889.19	1887.91	1889.49			1888.65
Aug-65	1889.68	1888.95		1889.95	1888.32	1889.09	1887.84	1889.39			1888.49
Sep-65	1889.6	1888.88		1889.90	1888.28	1889.03	1887.76	1889.31			1888.23
Oct-65	1889.53	1888.79		1889.85	1888.19	1888.94	1887.68	1889.21			1887.97
Nov-65	1889.44	1888.74		1889.78	1888.12	1888.87	1887.62	1889.16			1887.92

DATE	Lake level	Well2	Well 3	Well 8	Well 9	Well 11	Well 12	Well 15	Well 16	Well 17	Well 19
Dec-65	1889.34	1888.64		1889.72	1888.06	1888.80	1887.55	1889.07			1887.84
Jan-66	1889.24	1888.51		1889.65	1887.97	1888.68	1887.44	1888.94			1887.62
Feb-66	1889.14	1888.41		1889.59	1887.86	1888.58	1887.34	1888.87			1887.44
Mar-66	1889.04	1888.29		1889.51	1887.76	1889.06	1887.40	1888.83			1887.35
Apr-66	1888.94	1888.32		1889.43	1887.76	1889.43	1887.97	1888.80			1887.41
May-66	1888.86	1888.51		1889.39	1887.73	1889.59	1888.57	1888.91			1887.62
Jun-66	1888.94	1888.33		1889.35	1887.69	1889.48	1889.16	1888.78			1886.95
Jul-66	1888.96	1888.23		1889.32	1887.63	1889.39	1889.29	1888.72			1886.73
Aug-66	1888.9	1888.17		1889.27	1887.59	1889.32	1889.23	1888.71			1886.66
Sep-66	1888.82	1888.37		1889.24	1887.64	1889.49	1889.36	1888.76			1886.75
Oct-66	1888.83	1888.35		1889.22	1887.67	1889.49	1889.34	1888.79			1886.85
Nov-66	1888.9	1888.38		1889.24	1887.56	1889.53	1889.37	1888.78			1886.94
Dec-66	1888.89	1888.31		1889.26	1887.44	1889.49	1889.35	1888.78			1887.04
Jan-67	1888.92	1888.16		1889.24	1887.31	1889.34	1889.23	1888.77			1887.14
Feb-67	1888.83	1888.02		1889.22	1887.19	1889.20	1889.11	1888.77			1887.24
Mar-67	1888.7	1887.92		1889.14	1887.08	1889.04	1889.00	1888.76			1887.33
Apr-67	1888.57	1887.89		1889.05	1886.95	1888.94	1888.94	1888.75			1887.43
May-67	1888.43	1888.14		1889.11	1886.83	1889.24	1889.11	1888.75			1887.53
Jun-67	1888.54	1888.54		1889.14	1886.71	1889.38	1889.24	1888.74			1887.63
Jul-67	1888.75	1888.29		1889.13	1886.59	1889.42	1889.28	1888.74			1887.73
Aug-67	1888.85	1888.40		1889.20	1886.46	1889.59	1889.42	1888.73			1887.83
Sep-67	1888.92	1888.39		1888.95	1886.34	1889.59	1889.14	1888.72			1887.92
Oct-67	1888.94	1888.36		1888.84	1886.22	1889.54	1888.90	1888.72			1888.02
Nov-67	1888.92	1888.38		1888.72	1886.10	1889.50	1888.86	1888.71			1888.12
Dec-67	1888.89	1888.38		1888.67	1886.03	1889.45	1888.83	1888.71			1888.22
Jan-68	1888.87	1888.20		1888.68	1886.21	1889.41	1888.80	1888.70			1888.32
Feb-68	1888.81	1888.25		1888.60	1886.47	1889.37	1888.76	1888.69			1888.42
Mar-68	1888.72	1888.57		1889.11	1886.73	1889.32	1888.76	1888.69			1888.64
Apr-68	1888.59	1888.68		1889.25	1887.04	1889.61	1889.27	1888.93			1888.62
May-68	1889.75	1888.79		1889.40	1887.63	1890.04	1889.67	1889.46			1888.81
Jun-68	1889.80	1888.90		1889.57	1887.90	1890.05	1889.69	1889.66			1889.10
Jul-68	1889.82	1889.01		1889.74	1887.97	1890.06	1889.71	1889.72			1889.12
Aug-68	1889.75	1889.12		1889.87	1888.00	1890.07	1889.73	1889.74			1888.99
Sep-68	1889.81	1889.23		1890.00	1888.07	1890.08	1889.75	1889.78			1888.98
Oct-68	1889.79	1889.24		1890.10	1888.04	1890.08	1889.77	1889.71			1888.76
Nov-68	1889.75	1889.23		1890.08	1888.03	1890.09	1889.79	1889.71			1888.73
Dec-68	1889.75	1889.20		1890.12	1888.06	1890.10	1889.81	1889.77			1888.81
Jan-69	1889.69	1889.23		1890.07	1887.98	1890.11	1889.83	1889.67			1888.77
Feb-69	1889.61	1889.18		1889.93	1887.96	1890.12	1889.85	1889.61			1888.68
Mar-69	1889.56	1889.10		1889.85	1887.89	1890.13	1889.87	1889.52			1888.66
Apr-69	1889.48	1889.03		1889.81	1887.81	1890.08	1889.88	1889.40			
May-69	1889.50	1889.02		1889.84	1887.85	1890.11	1889.90	1889.39			
Jun-69	1889.45	1888.99		1889.81	1887.76	1890.10	1889.90	1889.32			
Jul-69	1889.32	1888.88		1889.79		1889.99	1889.75	1889.25			
Aug-69	1889.12	1888.76		1889.76		1889.92	1889.70	1889.21			
Sep-69	1889.11	1888.67		1889.72		1889.80	1889.67				
Oct-69	1889.01	1888.57		1889.68		1889.72	1889.61				
Nov-69	1888.91	1888.49		1889.63		1889.65	1889.57				
Dec-69	1888.86	1888.45		1889.56		1889.55	1889.50				
Jan-70	1888.79	1888.43		1889.54		1889.47	1889.48				
Feb-70	1888.74	1888.29		1889.48		1889.41	1889.41				
Mar-70	1888.63	1888.18		1889.43		1889.30					

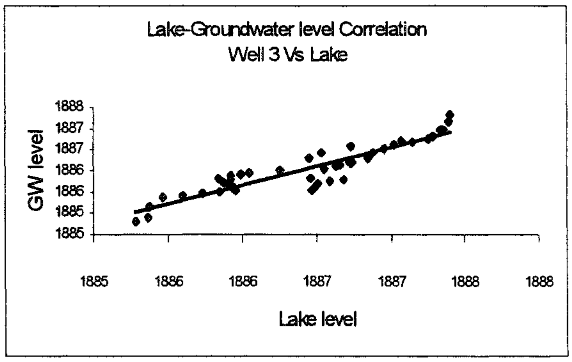
b) Yearly average

Date	Lake	w2	w3	w8	w9	w11	w12	w15	w16	w17	w19
1957	1886.57	1886.28	1885.7	1885.35	1885.26	1885.47	1885.01	1884.98	1885.59	1885.4	1885.43
1958	1886.98	1886.61	1886.6	1885.82	1886.22	1886.25	1885.64	1885.39	1886.93	1885.69	1886
1959	1886.83	1886.6	1886.32	1886.19	1886.6	1886.48	1885.96	1885.57	1887.55	1885.7	1886.25
1960	1886.01	1885.83	1885.79	1885.67	1886.12	1885.99	1885.4	1885.07	1886.56	1885.02	1885.42
1961	1885.61	1885.17	1885.22	1885.17	1885.51	1885.61	1884.92	1884.61	1886.46	1884.61	1884.91
1962	1888.17	1887.62		1887.27	1887.76	1887.99	1887.53	1886.88	1889.78	1887.12	1888.06
1963	1888.88	1888.37		1888.46	1888.77	1889.17	1888.93	1887.81	1889.11	1887.36	1888.77
1964	1889.66	1889.52		1889.58	1888.66	1889.79	1888.78	1888.96	1889.62		1888.57
1965	1889.75	1889.17		1889.99	1888.34	1889.17	1887.9	1889.4	1889.49		1888.38
1966	1888.96	1888.35		1889.37	1887.69	1889.29	1888.65	1888.8			1887.11
1967	1888.77	1888.24		1889.04	1886.65	1889.35	1889.09	1888.74			1887.68
1968	1889.43	1888.87		1889.54	1887.51	1889.86	1889.46	1889.38			1888.77
1969	1889.3	1888.86		1889.79	1887.88	1889.94	1889.75	1889.42			1888.7
1970	1888.93	1887.87		1889.48		1889.39	1889.44				
Avarage	1888.13	1887.67	1885.93	1887.91	1887.15	1888.13	1887.60	1887.31	1887.90	1885.84	1887.23

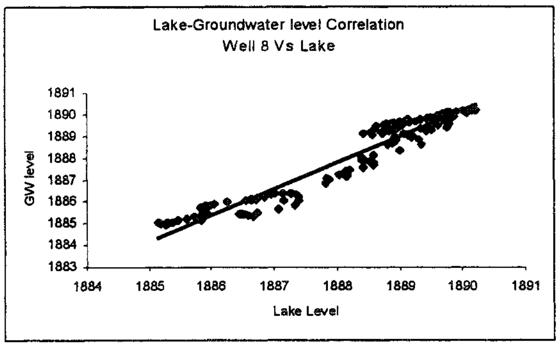
Appendix 6. Scatter Plots Showing Lake Level against Groundwater Level observed in different wells around the lake.



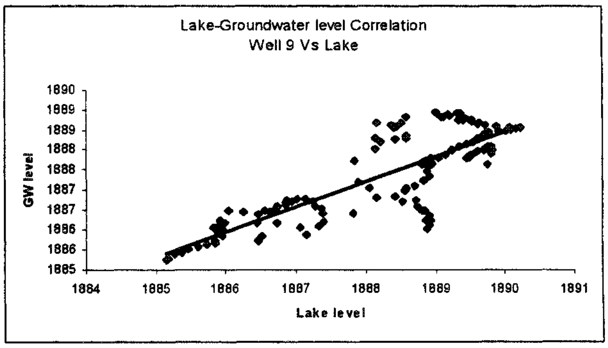
Well 2



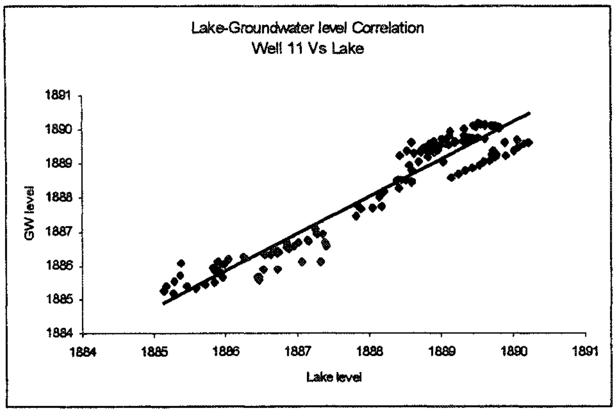
Well 3



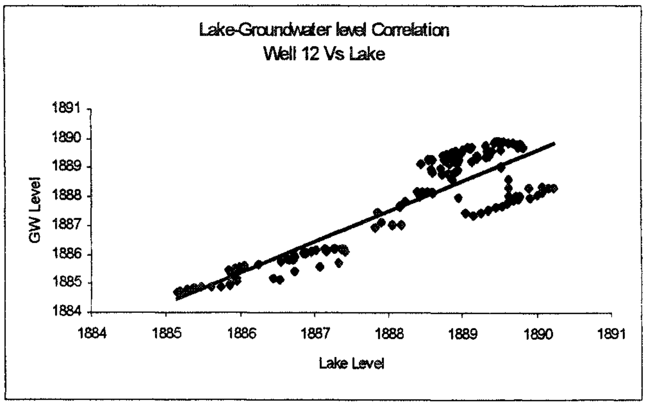
Well 8



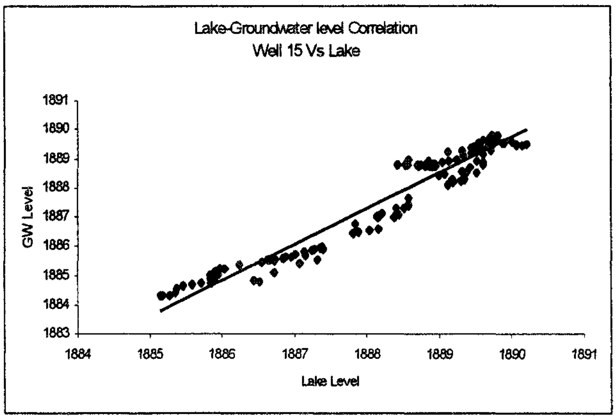
Well 9



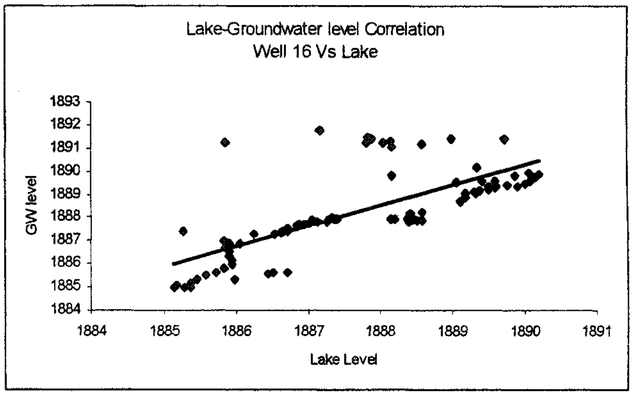
Well 11



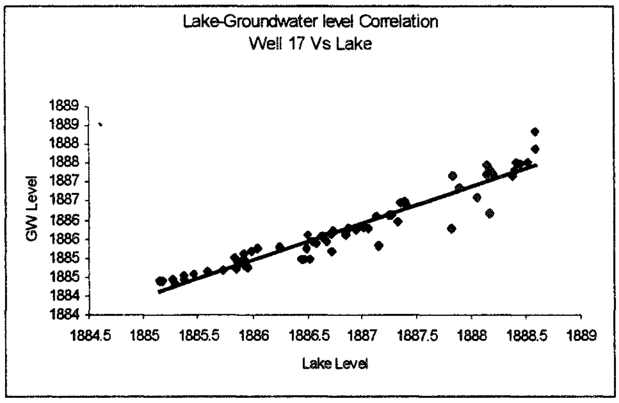
Well 12



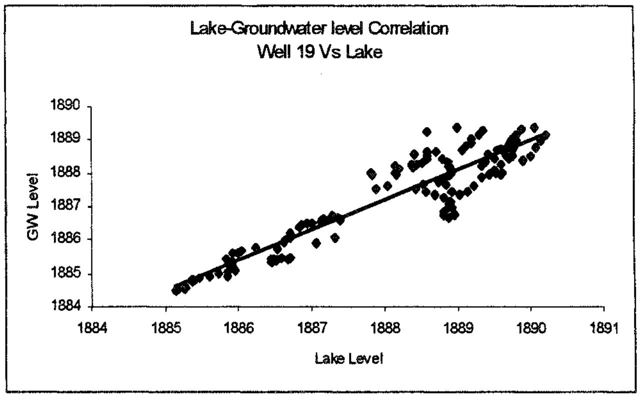
Well 15



Well 16



Well 17



Well 19

Appendix 7 Long term mean monthly Groundwater level Data.

Date	Lake	Rain	W2	W3	W8	W9	W11	W12	W15	W16	W17	W19
Jan	1888.17	36.67	1887.83	1885.93	1888.03	1887.21	1888.18	1887.67	1887.40	1888.11	1885.73	1887.35
Feb	1887.93	38.19	1887.80	1885.97	1888.02	1887.27	1888.17	1887.62	1887.33	1887.99	1885.73	1887.31
Mar	1887.93	57.79	1887.76	1886.04	1888.03	1887.26	1888.15	1887.45	1887.30	1887.89	1885.74	1887.25
Apr	1887.93	117.19	1887.42	1886.03	1887.88	1887.22	1888.09	1887.53	1887.29	1887.68	1885.75	1887.10
May	1887.85	80.08	1887.93	1885.98	1887.90	1887.34	1888.30	1887.68	1887.47	1888.31	1885.52	1887.27
Jun	1887.99	42.63	1887.75	1885.93	1887.95	1887.35	1888.35	1887.79	1887.54	1888.49	1885.64	1887.27
Jul	1888.04	35.26	1887.75	1885.93	1888.00	1887.37	1888.31	1887.76	1887.51	1888.07	1885.64	1887.24
Aug	1887.90	44.39	1887.73	1886.39	1887.82	1887.07	1888.30	1887.52	1887.36	1887.67	1885.70	1887.30
Sep	1888.09	42.43	1887.68	1886.20	1887.85	1887.08	1888.05	1887.53	1887.23	1887.59	1885.68	1887.14
Oct	1888.09	53.93	1887.69	1886.13	1887.86	1887.12	1888.09	1887.52	1887.26	1887.67	1885.70	1887.19
Nov	1888.02	67.88	1887.68	1886.05	1887.89	1887.15	1888.14	1887.55	1887.28	1888.11	1885.88	1887.21
Dec	1888.02	45.81	1887.77	1886.00	1887.97	1887.15	1888.18	1887.65	1887.37	1888.20	1885.81	1887.32

a)

Date	Lake	W2	W3	W8	W9	W11	W12	W15	W16	W17	W19
Jan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb	-0.24	-0.03	0.04	-0.01	0.06	-0.01	-0.05	-0.07	-0.12	0.00	-0.04
Mar	-0.24	-0.07	0.11	0.00	0.05	-0.03	-0.22	-0.10	-0.22	0.01	-0.10
Apr	-0.24	-0.41	0.10	-0.15	0.01	-0.09	-0.14	-0.11	-0.43	0.02	-0.25
May	-0.32	0.10	0.05	-0.13	0.13	0.12	0.01	0.07	0.20	-0.21	-0.08
Jun	-0.18	-0.08	0.00	-0.08	0.14	0.17	0.12	0.14	0.38	-0.09	-0.08
Jul	-0.13	-0.08	0.00	-0.03	0.16	0.13	0.09	0.11	-0.04	-0.09	-0.11
Aug	-0.27	-0.10	0.46	-0.21	-0.14	0.12	-0.15	-0.04	-0.44	-0.03	-0.05
Sep	-0.08	-0.15	0.27	-0.18	-0.13	-0.13	-0.14	-0.17	-0.52	-0.05	-0.21
Oct	-0.08	-0.14	0.20	-0.17	-0.09	-0.09	-0.15	-0.14	-0.44	-0.03	-0.16
Nov	-0.15	-0.15	0.12	-0.14	-0.06	-0.04	-0.12	-0.12	0.00	0.15	-0.14
Dec	-0.15	-0.06	0.07	-0.06	-0.06	0.00	-0.02	-0.03	0.09	0.08	-0.03

b)

Temporal Water Level Variation. a) Long term mean monthly values of measured depth to water in wells and Lake Naivasha levels b)Values are obtained by subtracting measured levels from the initial values(i.e. January)

Appendix 8 Description of KWS Annex and Manera Farm Transect.

Description of Manera Farm Transect.

Name	x	y	Surface elevation	water level	Auger Depth	Distance
Lake	210519	9919689	1888.7	1888.7	1888.7	0
BA	210644	9920323	1889.19	1887.85	1886.68	90
BA2	210713	9920651	1888.96	1886.8	1884.71	390
BA3	210884	9920823	1888.78	1885.66	1884.61	590
BA4	210973	9921029	1888.5	1885.27	1884.13	830
BA5	211194	9921180	1888.32	1885.45	1884.57	1030
Well3	211434	9921380	1890.3	1885.64		1404

Description of KWS Annex Transect.

Name	x	y	Surface elevation	Water Depth	Auger Depth	Distance
Lake	213620	9918120	1888.7	1888.7	1888.7	0
Well 1	213725	9918128	1889.71	1888.16	1886.7	50
Well 2	213751	9918121	1890.02	1888.13	1886.7	100
Well 3	213884	9918174	1890.27	1888.07	1883.4	200
Well 4	214014	9918202	1890.4	1887.98	1885.5	350
Well 5	214151	9918303	1891.04	1887.57	1884.3	550
Well 6	214271	9918436	1892.21	1887.51	1883.9	750
Well 7	214309	9918588	1893.65	1887.38	1881.7	950
Well 8	214340	9918801	1893.15	1887.45	1879.7	1150

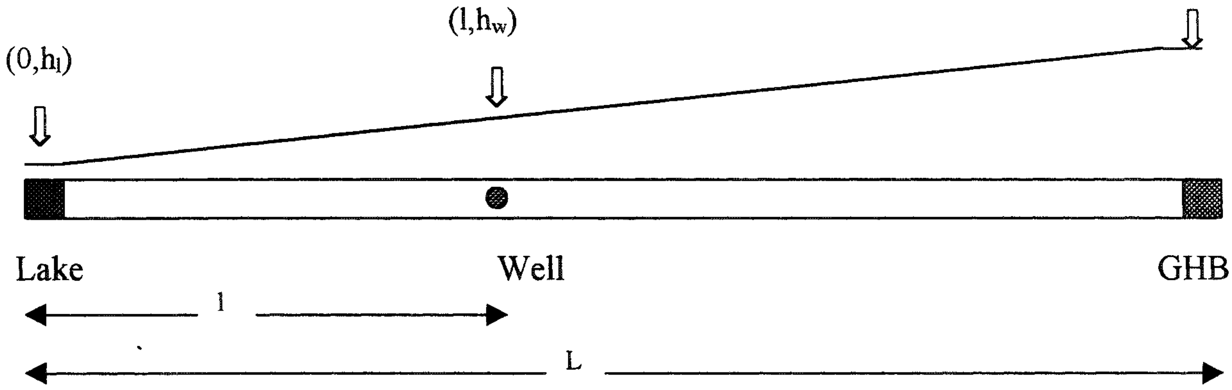
Appendix 9. Calculating the General Head boundary

1) Lake water level and groundwater level as observed in wells were plotted against their corresponding time.
2) Different points were selected according to the trend of the lake water level.
3) For these points (Lake water levels) the corresponding groundwater levels were taken.
4) Using these two points, i.e. the Lake water level and groundwater level, and the distance between them, the general head boundary were calculated using the following equation.

$$\text{h (at GHB)} = \frac{h(well) - h(Lake)}{l} \times L + h(well)$$

where

h(well) = groundwater level as observed in well.[m]
h(Lake) = Lake water level. [m]
L = distance between Lake and the general head boundary. [m]
l = distance between Lake and well. [m]
h(at GHB) = Level at general head boundary. [m]



Appendix 10 Control Data of PEST.

Control Data	Value
RLAMDA1	10
RLAMFAC	2
PHIRATSUF	0.3
PHIREDLAM	0.01
NUMLAM	8
RELPARMAX	10
FACPARMAX	10
FACORIG	0.001
PHIREDSWH	0.1
NOPTMAX	25
PHIREDSTP	0.01
NPHISTP	3
NPHINORED	3
RELPARSTP	0.01
NRELPAR	3

Appendix 11. Table showing Mean , Root mean Square and Mean Absolute error for well 2 and KWS Annex cross-sectional models calculated from output file of PEST.

a) Well 2

Observation	Measured value	Calculated value	Residual	RMS	MAE	Observation	Measured value	Calculated value	Residual	RMS	MAE
1	1886.68	1886.67	0.01	0.00	0.01	48	1886.19	1886.3	-0.11	0.01	0.11
2	1886.48	1886.28	0.20	0.04	0.20	49	1886.93	1886.75	0.18	0.03	0.18
3	1886.65	1886.66	-0.01	0.00	0.01	50	1886.22	1886.34	-0.12	0.01	0.12
4	1886.42	1886.27	0.16	0.02	0.16	51	1887	1886.79	0.21	0.04	0.21
5	1886.62	1886.66	-0.04	0.00	0.04	52	1886.25	1886.39	-0.13	0.02	0.13
6	1886.35	1886.26	0.09	0.01	0.09	53	1887.07	1886.83	0.24	0.06	0.24
7	1886.58	1886.65	-0.07	0.00	0.07	54	1886.28	1886.43	-0.15	0.02	0.15
8	1886.29	1886.25	0.04	0.00	0.04	55	1887.12	1886.88	0.25	0.06	0.25
9	1886.55	1886.64	-0.09	0.01	0.09	56	1886.38	1886.47	-0.09	0.01	0.09
10	1886.26	1886.24	0.02	0.00	0.02	57	1887.18	1886.92	0.26	0.07	0.26
11	1886.52	1886.63	-0.12	0.01	0.12	58	1886.48	1886.52	-0.03	0.00	0.03
12	1886.24	1886.24	0.00	0.00	0.00	59	1887.23	1886.96	0.27	0.07	0.27
13	1886.5	1886.63	-0.12	0.02	0.12	60	1886.58	1886.56	0.02	0.00	0.02
14	1886.18	1886.23	-0.04	0.00	0.04	61	1887.28	1887.01	0.28	0.08	0.28
15	1886.49	1886.62	-0.13	0.02	0.13	62	1886.68	1886.6	0.08	0.01	0.08
16	1886.13	1886.22	-0.09	0.01	0.09	63	1887.33	1887.05	0.28	0.08	0.28
17	1886.49	1886.61	-0.13	0.02	0.13	64	1886.78	1886.65	0.13	0.02	0.13
18	1886.1	1886.21	-0.11	0.01	0.11	65	1887.35	1887.1	0.25	0.06	0.25
19	1886.48	1886.61	-0.13	0.02	0.13	66	1886.82	1886.69	0.13	0.02	0.13
20	1886.14	1886.21	-0.06	0.00	0.06	67	1887.36	1887.14	0.22	0.05	0.22
21	1886.47	1886.6	-0.13	0.02	0.13	68	1886.86	1886.73	0.13	0.02	0.13
22	1886.18	1886.2	-0.02	0.00	0.02	69	1887.38	1887.18	0.19	0.04	0.19
23	1886.47	1886.59	-0.12	0.02	0.12	70	1886.9	1886.78	0.13	0.02	0.13
24	1886.2	1886.19	0.01	0.00	0.01	71	1887.39	1887.23	0.16	0.03	0.16
25	1886.46	1886.58	-0.12	0.01	0.12	72	1886.95	1886.82	0.13	0.02	0.13
26	1886.2	1886.18	0.02	0.00	0.02	73	1887.4	1887.27	0.13	0.02	0.13
27	1886.46	1886.58	-0.12	0.01	0.12	74	1886.98	1886.86	0.12	0.01	0.12
28	1886.19	1886.18	0.02	0.00	0.02	75	1887.4	1887.31	0.08	0.01	0.08
29	1886.45	1886.57	-0.11	0.01	0.11	76	1887	1886.91	0.09	0.01	0.09
30	1886.15	1886.17	-0.02	0.00	0.02	77	1887.39	1887.36	0.04	0.00	0.04
31	1886.45	1886.56	-0.11	0.01	0.11	78	1887.02	1886.95	0.07	0.00	0.07
32	1886.12	1886.16	-0.05	0.00	0.05	79	1887.39	1887.4	-0.01	0.00	0.01
33	1886.48	1886.55	-0.07	0.01	0.07	80	1887.03	1886.99	0.04	0.00	0.04
34	1886.11	1886.15	-0.05	0.00	0.05	81	1887.31	1887.29	0.02	0.00	0.02
35	1886.51	1886.55	-0.03	0.00	0.03	82	1887.17	1886.89	0.29	0.08	0.29
36	1886.11	1886.15	-0.04	0.00	0.04	83	1887.19	1887.18	0.02	0.00	0.02
37	1886.56	1886.54	0.03	0.00	0.03	84	1887.11	1886.78	0.33	0.11	0.33
38	1886.12	1886.14	-0.03	0.00	0.03	85	1886.99	1887.07	-0.08	0.01	0.08
39	1886.64	1886.53	0.11	0.01	0.11	86	1887	1886.66	0.34	0.11	0.34
40	1886.13	1886.13	-0.01	0.00	0.01	87	1886.87	1886.95	-0.08	0.01	0.08
41	1886.68	1886.57	0.11	0.01	0.11	88	1886.88	1886.55	0.32	0.10	0.32
42	1886.13	1886.17	-0.04	0.00	0.04	89	1886.81	1886.84	-0.03	0.00	0.03
43	1886.72	1886.62	0.11	0.01	0.11	90	1886.68	1886.44	0.24	0.06	0.24
44	1886.14	1886.21	-0.07	0.01	0.07	91	1886.73	1886.73	0.00	0.00	0.00
45	1886.79	1886.66	0.13	0.02	0.13	92	1886.2	1886.33	-0.13	0.02	0.13
46	1886.16	1886.26	-0.09	0.01	0.09	93	1886.71	1886.62	0.09	0.01	0.09
47	1886.86	1886.7	0.16	0.02	0.16	94	1886.24	1886.22	0.02	0.00	0.02

Observation	Measured value	Calculated value	Residual			Observation	Measured value	Calculated value	Residual		
95	1886.62	1886.51	0.12	0.01	0.12	145	1888.1	1887.15	0.95	0.89	0.95
96	1886.1	1886.11	-0.01	0.00	0.01	146	1887.28	1886.74	0.54	0.29	0.54
97	1886.25	1886.4	-0.15	0.02	0.15	147	1888.17	1887.3	0.87	0.76	0.87
98	1886	1886	0.00	0.00	0.00	148	1887.33	1886.88	0.45	0.20	0.45
99	1885.99	1886.29	-0.29	0.08	0.29	149	1888.15	1887.44	0.70	0.49	0.70
100	1885.91	1885.89	0.03	0.00	0.03	150	1887.33	1887.03	0.31	0.09	0.31
101	1885.85	1886.17	-0.32	0.10	0.32	151	1888.12	1887.59	0.53	0.28	0.53
102	1885.87	1885.78	0.09	0.01	0.09	152	1887.34	1887.17	0.17	0.03	0.17
103	1885.88	1886.06	-0.18	0.03	0.18	153	1888.1	1887.73	0.36	0.13	0.36
104	1885.79	1885.67	0.12	0.02	0.12	154	1887.34	1887.32	0.03	0.00	0.03
105	1885.92	1885.95	-0.03	0.00	0.03	155	1888.07	1887.88	0.19	0.04	0.19
106	1885.71	1885.56	0.16	0.02	0.16	156	1887.35	1887.46	-0.11	0.01	0.11
107	1885.96	1885.84	0.12	0.01	0.12	157	1888.05	1888.03	0.03	0.00	0.03
108	1885.64	1885.44	0.20	0.04	0.20	158	1887.35	1887.6	-0.25	0.06	0.25
109	1885.78	1885.73	0.05	0.00	0.05	159	1888.02	1888.17	-0.15	0.02	0.15
110	1885.57	1885.33	0.23	0.05	0.23	160	1887.35	1887.75	-0.40	0.16	0.40
111	1885.54	1885.62	-0.08	0.01	0.08	161	1887.84	1888.27	-0.43	0.18	0.43
112	1885.49	1885.22	0.27	0.07	0.27	162	1887.51	1887.86	-0.36	0.13	0.36
113	1885.38	1885.51	-0.13	0.02	0.13	163	1888.16	1888.38	-0.21	0.04	0.21
114	1885.27	1885.11	0.16	0.02	0.16	164	1887.72	1887.96	-0.24	0.06	0.24
115	1885.25	1885.39	-0.14	0.02	0.14	165	1888.17	1888.48	-0.31	0.09	0.31
116	1884.89	1885	-0.11	0.01	0.11	166	1887.6	1888.07	-0.47	0.22	0.47
117	1885.18	1885.28	-0.10	0.01	0.10	167	1888.44	1888.58	-0.14	0.02	0.14
118	1884.75	1884.89	-0.14	0.02	0.14	168	1887.98	1888.17	-0.18	0.03	0.18
119	1886.12	1885.17	0.95	0.90	0.95	169	1888.59	1888.68	-0.09	0.01	0.09
120	1884.66	1884.78	-0.11	0.01	0.11	170	1888.09	1888.27	-0.18	0.03	0.18
121	1886.38	1885.41	0.97	0.93	0.97	171	1888.48	1888.79	-0.30	0.09	0.30
122	1884.97	1885	-0.03	0.00	0.03	172	1888.05	1888.37	-0.32	0.10	0.32
123	1886.64	1885.56	1.08	1.17	1.08	173	1888.39	1888.89	-0.49	0.24	0.49
124	1885.27	1885.15	0.12	0.02	0.12	174	1888.01	1888.48	-0.46	0.21	0.46
125	1886.9	1885.7	1.20	1.43	1.20	175	1888.6	1888.99	-0.40	0.16	0.40
126	1885.58	1885.29	0.28	0.08	0.28	176	1888.16	1888.58	-0.42	0.17	0.42
127	1887.16	1885.85	1.31	1.72	1.31	177	1889.27	1889.09	0.17	0.03	0.17
128	1885.88	1885.44	0.44	0.20	0.44	178	1888.34	1888.68	-0.34	0.11	0.34
129	1887.29	1885.99	1.30	1.68	1.30	179	1889.25	1889.19	0.06	0.00	0.06
130	1886.12	1885.58	0.54	0.29	0.54	180	1888.52	1888.78	-0.26	0.07	0.26
131	1887.42	1886.14	1.28	1.65	1.28	181	1889.18	1889.3	-0.11	0.01	0.11
132	1886.36	1885.73	0.63	0.40	0.63	182	1888.7	1888.88	-0.18	0.03	0.18
133	1887.56	1886.29	1.27	1.62	1.27	183	1889.07	1889.4	-0.33	0.11	0.33
134	1886.6	1885.87	0.73	0.53	0.73	184	1889	1888.99	0.02	0.00	0.02
135	1887.69	1886.43	1.26	1.58	1.26	185	1889.49	1889.5	-0.01	0.00	0.01
136	1886.84	1886.02	0.83	0.68	0.83	186	1889.19	1889.09	0.10	0.01	0.10
137	1887.82	1886.58	1.25	1.55	1.25	187	1889.37	1889.61	-0.24	0.06	0.24
138	1887.08	1886.16	0.92	0.85	0.92	188	1889.2	1889.19	0.01	0.00	0.01
139	1887.89	1886.72	1.17	1.37	1.17	189	1889.53	1889.71	-0.18	0.03	0.18
140	1887.13	1886.3	0.83	0.68	0.83	190	1889.43	1889.29	0.14	0.02	0.14
141	1887.96	1886.87	1.10	1.20	1.10	191	1889.61	1889.81	-0.20	0.04	0.20
142	1887.18	1886.45	0.73	0.54	0.73	192	1889.32	1889.39	-0.08	0.01	0.08
143	1888.03	1887.01	1.02	1.04	1.02	193	1889.67	1889.91	-0.24	0.06	0.24
144	1887.23	1886.59	0.64	0.41	0.64	194	1889.68	1889.5	0.18	0.03	0.18

195	1889.93	1890.02	-0.08	0.01	0.08	246	1888.43	1888.05	0.38	0.14	0.38
196	1889.97	1889.6	0.37	0.14	0.37	247	1888.75	1888.46	0.29	0.08	0.29
197	1890.22	1890.12	0.10	0.01	0.10	248	1888.29	1888.06	0.23	0.05	0.23
198	1890.03	1889.7	0.33	0.11	0.33	249	1888.81	1888.47	0.34	0.11	0.34
199	1890.1	1890.22	-0.12	0.01	0.12	250	1888.35	1888.07	0.28	0.08	0.28
200	1889.92	1889.8	0.12	0.01	0.12	251	1888.86	1888.48	0.38	0.14	0.38
201	1890	1890.13	-0.13	0.02	0.13	252	1888.4	1888.08	0.32	0.10	0.32
202	1889.73	1889.73	-0.01	0.00	0.01	253	1888.9	1888.49	0.41	0.17	0.41
203	1889.85	1890.04	-0.19	0.04	0.19	254	1888.39	1888.09	0.31	0.09	0.31
204	1889.15	1889.64	-0.49	0.24	0.49	255	1888.92	1888.49	0.43	0.18	0.43
205	1889.72	1889.95	-0.23	0.05	0.23	256	1888.38	1888.09	0.29	0.08	0.29
206	1889.08	1889.56	-0.47	0.22	0.47	257	1888.94	1888.5	0.43	0.19	0.43
207	1889.75	1889.86	-0.11	0.01	0.11	258	1888.37	1888.1	0.27	0.07	0.27
208	1889.01	1889.47	-0.46	0.21	0.46	259	1888.93	1888.51	0.42	0.18	0.42
209	1889.64	1889.77	-0.13	0.02	0.13	260	1888.37	1888.11	0.26	0.07	0.26
210	1888.92	1889.38	-0.46	0.21	0.46	261	1888.92	1888.52	0.40	0.16	0.40
211	1889.54	1889.68	-0.14	0.02	0.14	262	1888.38	1888.12	0.26	0.07	0.26
212	1888.8	1889.29	-0.48	0.23	0.48	263	1888.91	1888.53	0.38	0.15	0.38
213	1889.42	1889.59	-0.17	0.03	0.17	264	1888.38	1888.13	0.25	0.06	0.25
214	1888.72	1889.2	-0.48	0.23	0.48	265	1888.89	1888.53	0.36	0.13	0.36
215	1889.29	1889.5	-0.22	0.05	0.22	266	1888.38	1888.13	0.25	0.06	0.25
216	1888.57	1889.11	-0.54	0.29	0.54	267	1888.88	1888.54	0.34	0.11	0.34
217	1889.15	1889.41	-0.27	0.07	0.27	268	1888.28	1888.14	0.14	0.02	0.14
218	1888.42	1889.02	-0.60	0.36	0.60	269	1888.86	1888.55	0.31	0.10	0.31
219	1889.02	1889.33	-0.31	0.10	0.31	270	1888.21	1888.15	0.06	0.00	0.06
220	1888.3	1888.93	-0.63	0.40	0.63	271	1888.83	1888.56	0.27	0.07	0.27
221	1888.89	1889.23	-0.34	0.12	0.34	272	1888.23	1888.16	0.08	0.01	0.08
222	1888.43	1888.84	-0.41	0.17	0.41	273	1888.79	1888.57	0.22	0.05	0.22
223	1888.94	1889.15	-0.21	0.04	0.21	274	1888.32	1888.16	0.16	0.03	0.16
224	1888.34	1888.75	-0.41	0.17	0.41	275	1888.74	1888.57	0.17	0.03	0.17
225	1888.94	1889.06	-0.12	0.01	0.12	276	1888.5	1888.17	0.33	0.11	0.33
226	1888.21	1888.66	-0.45	0.20	0.45	277	1888.67	1888.58	0.09	0.01	0.09
227	1888.85	1888.97	-0.12	0.01	0.12	278	1888.61	1888.18	0.43	0.18	0.43
228	1888.3	1888.57	-0.27	0.07	0.27	279	1888.6	1888.59	0.01	0.00	0.01
229	1888.83	1888.88	-0.05	0.00	0.05	280	1888.67	1888.19	0.48	0.23	0.48
230	1888.35	1888.48	-0.14	0.02	0.14	281	1888.6	1888.65	-0.05	0.00	0.05
231	1888.9	1888.79	0.11	0.01	0.11	282	1888.67	1888.24	0.43	0.19	0.43
232	1888.36	1888.4	-0.04	0.00	0.04	283	1888.59	1888.71	-0.11	0.01	0.11
233	1888.91	1888.7	0.21	0.05	0.21	284	1888.68	1888.3	0.38	0.14	0.38
234	1888.2	1888.31	-0.10	0.01	0.10	285	1888.65	1888.76	-0.11	0.01	0.11
235	1888.82	1888.61	0.21	0.05	0.21	286	1888.69	1888.36	0.33	0.11	0.33
236	1888.01	1888.22	-0.20	0.04	0.20	287	1888.71	1888.82	-0.11	0.01	0.11
237	1888.65	1888.52	0.13	0.02	0.13	288	1888.69	1888.42	0.28	0.08	0.28
238	1887.91	1888.13	-0.22	0.05	0.22	289	1888.77	1888.88	-0.11	0.01	0.11
239	1888.46	1888.43	0.03	0.00	0.03	290	1888.7	1888.47	0.22	0.05	0.22
240	1888.08	1888.04	0.04	0.00	0.04	291	1888.83	1888.94	-0.10	0.01	0.10
241	1888.47	1888.44	0.03	0.00	0.03	292	1888.7	1888.53	0.17	0.03	0.17
242	1888.27	1888.04	0.23	0.05	0.23	293	1888.89	1889	-0.10	0.01	0.10
243	1888.53	1888.45	0.08	0.01	0.08	294	1888.71	1888.59	0.12	0.01	0.12
244	1888.49	1888.05	0.45	0.20	0.45	295	1888.95	1889.05	-0.10	0.01	0.10
245	1888.63	1888.45	0.18	0.03	0.18	296	1888.71	1888.65	0.07	0.00	0.07

297	1889.01	1889.11	-0.10	0.01	0.10
298	1888.72	1888.71	0.01	0.00	0.01
299	1889.07	1889.17	-0.10	0.01	0.10
300	1888.73	1888.76	-0.04	0.00	0.04
301	1889.13	1889.23	-0.10	0.01	0.10
302	1888.73	1888.82	-0.09	0.01	0.09
303	1889.19	1889.29	-0.09	0.01	0.09
304	1888.74	1888.88	-0.14	0.02	0.14
305	1889.25	1889.34	-0.09	0.01	0.09
306	1888.74	1888.94	-0.19	0.04	0.19
307	1889.31	1889.4	-0.09	0.01	0.09
308	1888.75	1888.99	-0.25	0.06	0.25
309	1889.37	1889.46	-0.09	0.01	0.09
310	1888.75	1889.05	-0.30	0.09	0.30
311	1889.43	1889.52	-0.09	0.01	0.09
312	1888.76	1889.11	-0.35	0.12	0.35
313	1889.49	1889.58	-0.08	0.01	0.08
314	1888.77	1889.17	-0.40	0.16	0.40
315	1889.55	1889.63	-0.08	0.01	0.08
316	1888.77	1889.23	-0.46	0.21	0.46
317	1889.61	1889.69	-0.08	0.01	0.08
318	1888.78	1889.28	-0.51	0.26	0.51
319	1889.67	1889.75	-0.08	0.01	0.08
320	1888.78	1889.34	-0.56	0.31	0.56
321	1889.8	1889.69	0.11	0.01	0.11
322	1888.9	1889.28	-0.38	0.14	0.38
323	1889.81	1889.64	0.17	0.03	0.17
324	1889.03	1889.23	-0.20	0.04	0.20
325	1889.77	1889.58	0.19	0.03	0.19
326	1889.15	1889.17	-0.02	0.00	0.02
327	1889.8	1889.53	0.28	0.08	0.28
328	1889.23	1889.12	0.12	0.01	0.12
329	1889.77	1889.47	0.30	0.09	0.30
330	1889.23	1889.06	0.17	0.03	0.17
331	1889.75	1889.41	0.34	0.11	0.34
332	1889.21	1889.01	0.21	0.04	0.21
333	1889.71	1889.36	0.35	0.12	0.35
334	1889.22	1888.95	0.27	0.07	0.27
335	1889.62	1889.3	0.32	0.10	0.32
336	1889.19	1888.89	0.29	0.09	0.29
337	1889.56	1889.25	0.32	0.10	0.32
338	1889.1	1888.84	0.27	0.07	0.27
339	1889.48	1889.19	0.29	0.09	0.29
340	1889.03	1888.78	0.25	0.06	0.25
341	1889.49	1889.13	0.36	0.13	0.36
342	1889.01	1888.73	0.29	0.08	0.29
343	1889.41	1889.08	0.33	0.11	0.33
344	1888.96	1888.67	0.29	0.08	0.29
345	1889.23	1889.02	0.21	0.04	0.21
346	1888.83	1888.62	0.21	0.05	0.21
347	1889.12	1888.97	0.15	0.02	0.15
348	1888.71	1888.56	0.15	0.02	0.15
349	1889.04	1888.91	0.13	0.02	0.13
350	1888.6	1888.5	0.10	0.01	0.10
351	1888.93	1888.85	0.08	0.01	0.08
352	1888.51	1888.45	0.06	0.00	0.06
353	1888.87	1888.8	0.07	0.00	0.07
354	1888.45	1888.39	0.06	0.00	0.06
355	1888.79	1888.74	0.05	0.00	0.05
356	1888.43	1888.34	0.09	0.01	0.09
357	1888.73	1888.69	0.04	0.00	0.04
358	1888.28	1888.28	0.00	0.00	0.00
359	1888.65	1888.63	0.02	0.00	0.02
360	1888.18	1888.22	-0.04	0.00	0.04
			28.88	42.53	86.55
			0.08	**0.34**	**0.24**
			ME	RMS	MAE
n	=	360			
	minimum residual				0.00
	Maximum residual				1.31

b) KWS Annex

Observation	Measured value	Calculated value	Residual ME	RMS	MAE
1	1885.6	1885.6	0	0	0
2	1885.76	1885.68	7.50E-02	0.005625	0.075
3	1885.73	1885.78	-5.10E-02	0.002601	0.051
4	1885.7	1885.92	-0.22	0.0484	0.22
5	1885.88	1886.09	-0.213	0.045369	0.213
6	1886.53	1886.4	0.132	0.017424	0.132
7	1886.6	1886.53	6.90E-02	0.004761	0.069
			-0.208	0.12418	0.76
			-0.02971	**0.133192**	**0.108571**
			ME	**RMS**	**MAE**

Appendix 12. Steps taken to computing the Groundwater Storage

1. Calculating storage change for cross-sectional model (well 2).
   - All the necessary information and the optimized parameters are feed to the computer (of cross-sectional model well 2) and the model run.
   - Using the result extractor dialog box of PMWIN the draw down at the end of each stress period is read.
   - Then the draw down matrix in each stress period is multiplied by optimized Storativity value of 8.14 e-04 and the cell area, i.e. 900 m^2, to get storage change for each cell for the cross-sectional model.
   - The storage change matrix is then saved as an ASCII file and imported to excel to add each cell to get the overall storage change. Here it is assumed that the influence of the lake level for groundwater storage is only 2 km away from the lake this assumption is supported by Trottman (1998). Therefore, the first 67 cells were added to get the overall storage change. In the same way for each stress period the storage change is calculated

2. Calculating the storage change for the whole area.

   - The same procedure is followed but this time the final storage change is calculated first by dividing the overall storage change of step 1 by cell area of step 1 and then multiplying the result by aquifer buffer zone of 30m around the lake.
   - The area of the buffer zone is calculated in ILWIS. The lake polygon is masked from the geological map of the area. This map is then used as a source to calculate the distance around the lake.
   - After the distance calculation, the raster map is then reclassified using slicing operation into an interval of 30 m from the source till 2km away from the lake..
   - Then the area of the buffer zones is obtained from the histogram of the raster map.

Appendix 13 File names for different processed Data's.

SPSS Files

File name = **allfinal**

Columnwise
- Date
- Lake level - lakemmbu
- Rainfall_ monthly
- Naivasha D.O, Naivasha WDD, Naivasha Kongoni Farm
- Groundwater Level_ mean monthly aggregated from daily record from SPSS file **Gwlevel** - (From w2-w12_m)
- Original Groundwater Level_ mean monthly aggregated (daily record) from SPSS file Gwlevel - (From well2-well19)
- Mean monthly discharge data_ aggregated from SPSS file **dis** (daily record for different station starting 1960).

File name = **yrrain**
- yearly total rainfall for different stations.

File name = **Gwlevel**
- daily record of GW level observation wells around the lake (original, screened, and linearly interpolated data, columnwise)

File name = **mon_rain**
- mean monthly rainfall for 10 station.

Excel Files

File name = **Allfinal_corrected**

Sheet 1
- Lake level, monthly total pan data, Pan yearly total, Calculated Lake evaporation using Pan coefficient 0.85, Calculated Swamp evaporation using coefficeint 0.87 (ie 0.87 x lake evaporation), yearly total Rainfall (theison polygon).

Hydrograp_all (Sheet 2)
- monthly average lake level, monthly average groundwater level (well 2 - well 19).
- hydrographs of the lake and groundwater levels as observed in different wells.

monthlyavg (Sheet 3)
- Long-term monthy average lake level , monthly average rain fall and groundwater levels.

well hydro (Sheet 4)

→ well hydrogrphs

***allfinal** (Sheet 5)*
→ Lake level, rainfall Naivasha DO, rainfall Naivsha WDD, Rainfall Kongoni Farm, groundwater levels well 2 - well 19, discharge malewa.

double mass (Sheet 6)
→ double mass curve analysis.

Yearly Gwlev (Sheet 7)
→ Yearly average groundwater level data.

File name = ***disc***

water balance (Sheet 1)
→ water balance component

disc (Sheet 2)
→ aggregated discharge from malewa, gilgil and Karati.

File name = ***storage well 2***

draw down (Sheet 1)
→ draw down data at the end of each stress period.

Volume (Sheet 2)
→ calculated storage change at the end of each stress period.

File name = ***Yearly storage well 2***

storage
→ calculated yearly storage change.

File name = ***GW Flux well 2***

flux well2
→ flux calculation for well 2 and 11.

File name = ***model_datas***

Selected Levels (Sheet 1)
→ Selected Levels for the time variant boundary for cross-sectional model well 2 and 11.

GHB (Sheet 2)
→ calculated levels for general head boundary for well 2 and 11.

File name = ***Theis rain for Lake Region***

detail (*Sheet 1)*
→ yearly Rainfall data for different station.

yearl_all (*Sheet 2)*
→ yearly calculated rainfall.

yearly (*Sheet 3)*
→ Calculated rainfall total near the lake using theison polygon method.