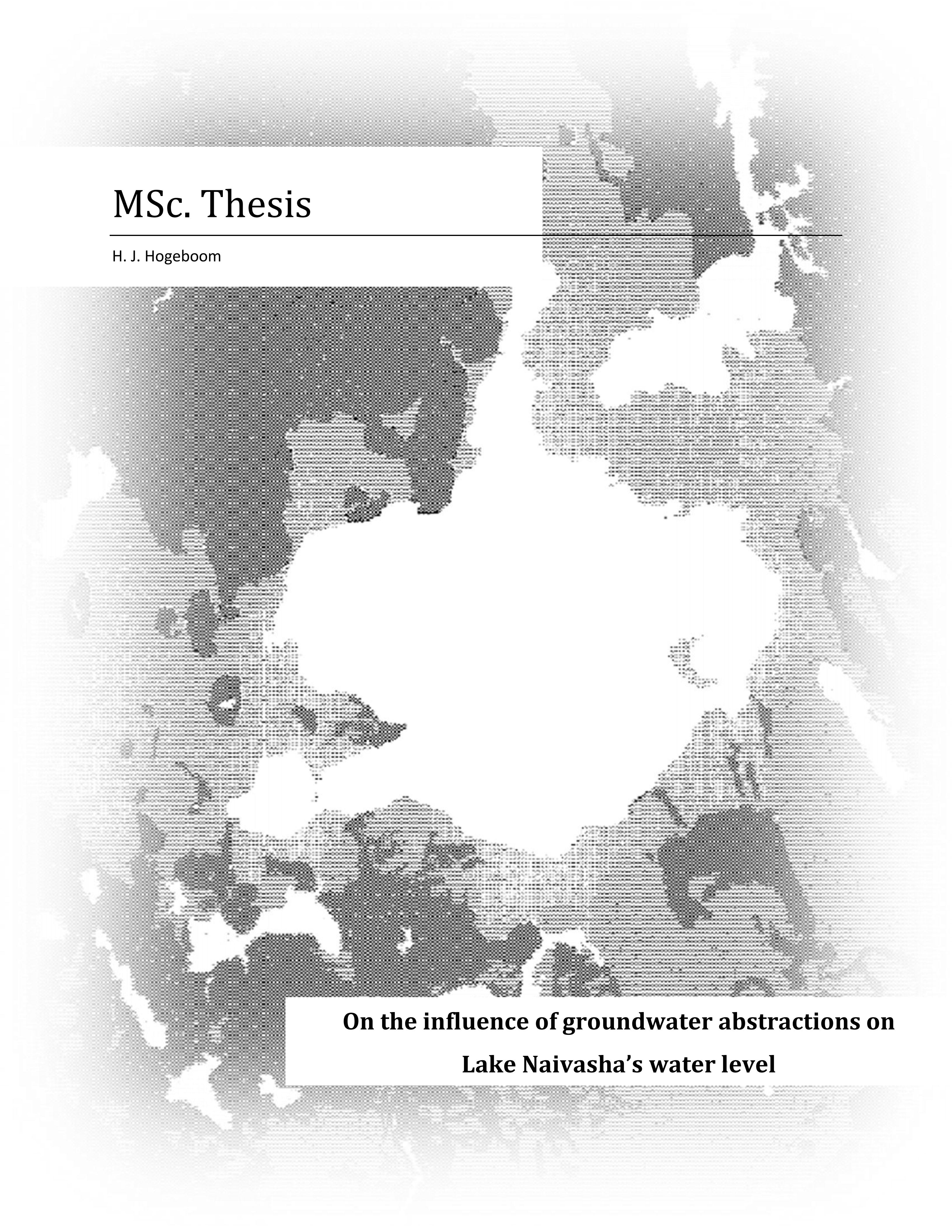

MSc. Thesis

H. J. Hogeboom

On the influence of groundwater abstractions on Lake Naivasha's water level

MSc. Thesis

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Abstract

Lake Naivasha in Kenya's Rift Valley forms the scene for a wide variety of natural and human activities, amongst which its thriving horticulture industry. Starting around the 1980s, the lake provided water for irrigation of the flowers, but the last decade or so uptake is complemented by significant groundwater abstractions. Despite substantial research efforts, the understanding of the groundwater system is still frugal; hydrogeological build-up and parameterization, lake-aquifer interaction, the overall groundwater balance and the effect of groundwater abstractions on lake levels are largely unknown.

The objective of this research is *to determine the influence of groundwater abstractions on Lake Naivasha's water level, by modeling groundwater flow around the lake*. The Flower Business Park (FBP), located some 7 km northwest of the lake, serves as a test case. FBP takes an estimated 10% share in total groundwater abstractions in the lake area, with an average rate (at FBP) of 3.5 Mm^3/yr.

A steady state MODFLOW finite-difference model is developed to simulate exchange of water between the lake and its surrounding aquifer under natural conditions and under abstractions at FBP. The underlying conceptual model is data and literature driven and consists of one 100 m thick confined aquifer with no-flow boundaries along the western and eastern escarpments and two constant head outlets to the north and south across the valley floor. Recharge is estimated via a simple water balance method, whereby potential evapotranspiration is subtracted from precipitation. The rivers Malewa and Gilgil and Lake Naivasha are included in the schematization. A return flow of 1 Mm^3/yr associated with abstractions at FBP is assumed to become runoff into the lake.

Deliberating the uncertainty within the conceptualization of the system, which is attributed to the scarcity of conclusive data, it was hypothesized the model allowed for multiple non-unique parameter sets to emerge from calibration. The hypothesis was tested by developing two parameterizations for the conceptualization, which provide a means to assess similarities of system behavior. The lakebed leakance parameter, which to a large extent governs lake-groundwater interaction, is selected to be fixed at two values: a high value of 0.215 d^{-1} representing a rather leaky lakebed and a low value of 0.01 d^{-1} representing a rather sealed lakebed.

Calibration involved automated and manual adjustment of 26 hydraulic conductivity zones. In both parameterizations, the model simulated heads for 60 boreholes with observations taken prior to 1980 within 5 – 7 m. Calibrated hydraulic conductivity values assumed physically feasible values equivalent to well sorted sand and gravel or highly fractured rocks around the lake to unfractured rocks in the eastern and western mountains. Upon abstracting groundwater at FBP, simulated groundwater depths coincide with the observed depth of 50 – 60 m, thus providing a partial validation.

Flow patterns under natural conditions exhibit similar behavior in both parameterizations, i.e. laterally from the escarpments to the valley floor with relatively steep gradients and axially from Lake Naivasha to the north and south with a smaller drop. Of approximately 160 Mm^3/yr annual outflow from the groundwater system, 21-33% flows out north versus 67-79% south. Outflow from the lake occurs to the north and south, while inflow takes place from the east and west, with a net outflow into groundwater

of around 55.0 Mm^3/yr. Inflow from groundwater to the lake is 6.2 times lake outflow in the low lakebed leakance case, compared to 7.4 in the high bed leakance case.

Flow patterns under abstractions at FBP are similar to those under natural conditions in most parts of the study area, except around FBP where a cone of depression is generated by the abstractions. This cone of depression does not extent to the lake in either parameterization. Nonetheless, less water is flowing from groundwater into the lake upon pumping at FBP. This reduced inflow is ascribed to the interruption of recharge from Kinangop to the lake by FBP abstraction, viz. water pumped at FBP originates (for the largest part) from the higher Kinangop area to the west, rather than from the lake.

Flow paths and water balance differences under abstractions at FBP combined show that the effect of FBP abstractions on Lake Naivasha's water level is a stage reduction. In the high bed leakance case the new equilibrium lake level is 0.7 cm lower than in the natural situation and in the low bed leakance case 7.5 cm. A preliminary estimate of the effect of all abstractions combined was obtained through a linear extrapolation of these lowerings. The resulting lake level reduction range is 7 – 75 cm, which is in the same order of magnitude postulated in previous studies. For a more reliable estimate of the aggregated effect of abstractions on lake levels, it is recommended for further study to explicate other abstraction points in the model as well.

Acknowledgements

This thesis concludes my journey of obtaining an MSc degree in Civil Engineering and Management. My interests in international and integrated water management and poverty alleviation, besides getting challenged technically on a new subject (as groundwater was to me) all joined together in this research. The goals I had envisioned at the onset of this study, though, to some extent had to be refined: it turned out I could not solve Naivasha's water issues within a MSc project's scope and I am not fluent in Swahili. Nevertheless, I am content with what I have achieved. This research, however, could not have come about without the help of a number of people.

A great help along the way has been my daily supervisor at ITC, Pieter van Oel. Even if I brought up an issue at 17:00h, you were available for comments. Especially in my moments of indignation regarding the quite chaotic database, you encouraged me to make tough choices about the model and put things into perspective again. Of course in your typical, humorously derisive way. Then I would like to thank Maarten Krol and Martijn Booij, my UT supervisors. You provided me with ever constructive feedback. I reckon you team up nicely to guard both the conceptual research level and good modeling practice. Last but not least, I would like to thank all other 'Naivashians': Anne, Robert, Vincent, Dawit, Francis, Job, Jane, Mark and Frank. Thanks for the good company.

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1 Introduction

Lake Naivasha in Kenya's Rift Valley forms the scene for a wide variety of natural and human processes. It provides domestic water, supports numerous animal species, allows fishery and enables tourism amongst others. The area's ecological functions are recognized by its designation as a Ramsar site (Ramsar Commission, 1996). Especially the thriving horticulture industry attracts attention, both from a national development point of view and from an economic perspective, where Naivasha provides a viable economic model to be followed by other African nations. Agriculture exports originating from this area claim a significant share in Kenya's GDP and employ around 30 000 people (Deltares, 2011; WWF, 2011).

Starting from the early 1980s, significant abstractions drawn from the lake by the horticulture industries commenced. These lake abstractions steadily increased over the following 25 years. The last decade or so water drawn from surrounding aquifers complemented lake abstractions, thereby increasing total uptake considerably. This is for instance the case at the Flower Business Park (FBP), a large farm complex located some 7 km northwest of Lake Naivasha (Figure 1). The increased demand for lake water and groundwater for irrigation and other activities is reflected by lake level and groundwater level decline and water quality deterioration, indicating overexploitation of the resources (Becht et al., 2005) and inciting governance issues such as monitoring and enforcement of regulation of the numerous, often ill-registered abstraction points (WRMA, 2010).

Water management authorities strive for a safe and wise development of Lake Naivasha's water resources (WRMA, 2010), as they are also required to do under the Ramsar designation. However, significant uncertainty remains concerning how much water can be safely drawn from Lake Naivasha's water system. Despite substantial research efforts, uncertainty remains in the understanding of the water system. The groundwater system in specific is poorly understood in terms of hydrogeological build-up and parameterization (Clarke et al., 1990), lake-aquifer interaction (Deltares, 2011), the overall groundwater balance and the effect of groundwater abstractions on lake levels (Van Oel et al., 2012).

In order to assess sustainability of abstraction schemes, clarification on Lake Naivasha's groundwater system is imperative. This study aims to contribute to the understanding of the groundwater system by exploring the effect groundwater abstractions have on lake levels. This goal is achieved by modeling groundwater flow around Lake Naivasha, while using abstraction rates at FBP as case study to determine sensitivity to substantial water use.

1.1 Scientific context

Lake Naivasha has been a topic of interest to researchers for a long time, starting with the British colonists. This section starts with a description of the study area to acquaint the reader with Lake Naivasha Basin. Since this thesis builds on the work of many researchers, an overview of the most relevant studies is provided next.

1.1.1 Study area

Lake Naivasha is a freshwater lake with its endorheic catchment carrying the same name (Figure 1). It is located in the Central Rift Valley, some 80 km northwest of the capital, Nairobi. The lake is located at the culmination of the Rift's valley floor at an average altitude of 1887 $masl$ and a mean surface area of 145 km^2 (De Jong, 2011a; Muthuwatta, 2001; Oppong-Boateng, 2001). It is one of a series of major lakes in the Rift Valley, of which Lakes Turkana, Baringo, Bogoria, Nakuru, Elmenteita, Naivasha and Magadi are located in Kenya in a north to south direction. Lake Naivasha Basin comprises 3376 km^2.

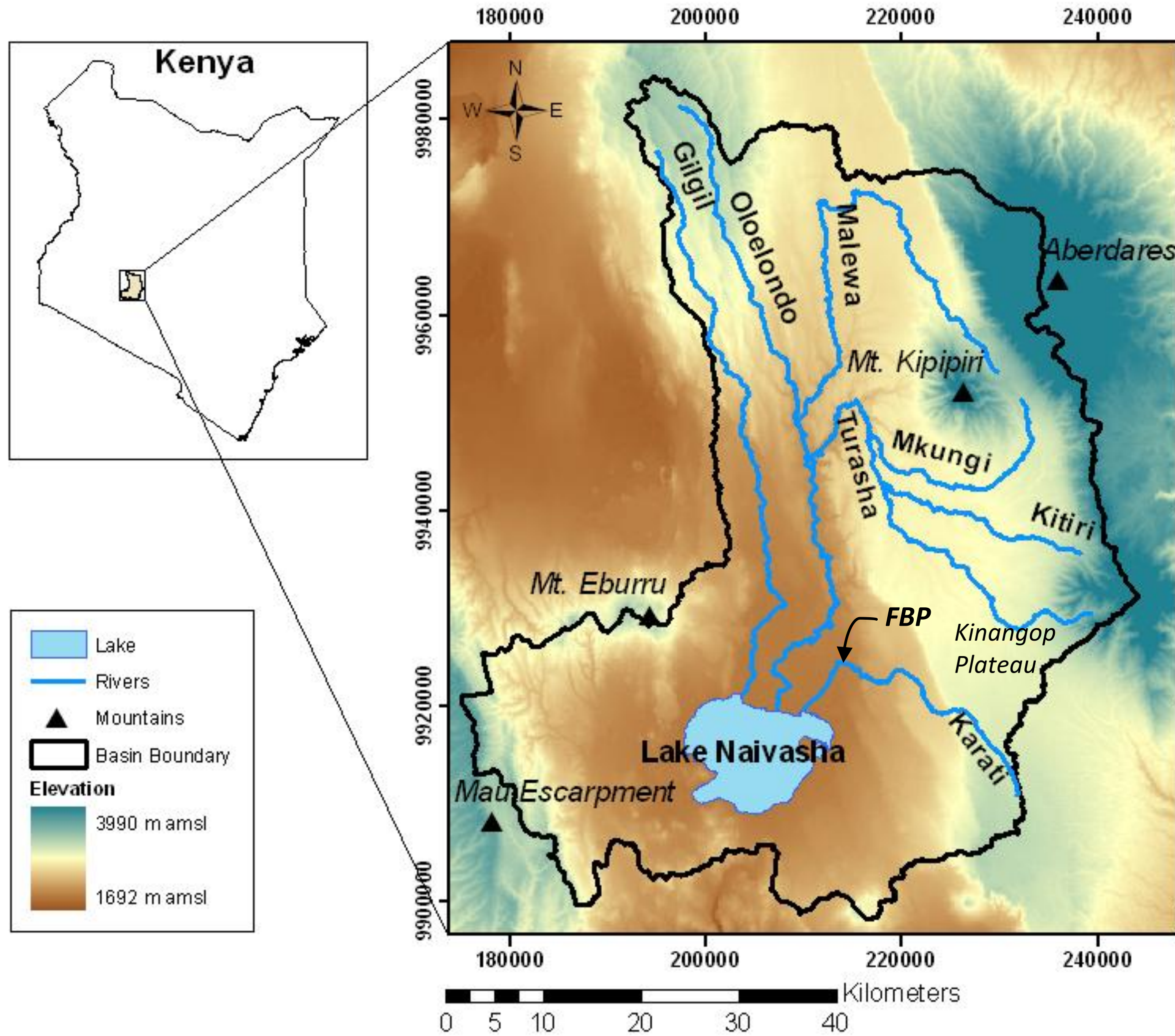

Figure 1: Study area, located between longitudes 36°00'E and 36°30'E, and latitudes 0°30'S and 1°00'S. Coordinates in UTM Arc1960 [*m*]. Elevations in meter above sea level [*masl*]. Adapted from: Meins (2013a).

The Rift is an up-warping of the earth's crust where the African tectonic plate divides into two new plates. The up-warping has thinned the crust and enables rift faulting and volcanic activity to take place. The bulk of material extruded by volcanoes and the attendant rifting occurred in late Pliocene times, and continues till today (Baker and Wohlenberg, 1971; Odada and Olago, 2002). To the west, the Mau escarpment rises up to a maximum of 3080 $masl$, forming the western wall of the Rift Valley. To the east, the Kinangop Plateau appears, extending to the southern mountains of the Aberdare range. It is a broad flat plain at approximately 2400 $masl$. The valley floor is characterized by numerous volcanic cones, craters and gorges. An intensive faulting zone with near vertical attitude can be found in the center of the valley (step-faulting), which parallels the escarpments (Richardson and Richardson, 1972). The valley floor consists of extensively faulted tuffs, welded tuffs and ignimbrites (Thompson and Dodson, 1963), assembling a complex stratigraphy of volcanic and fluvio-lacustrine deposits. The rocks underlying the floor form a complex and fractured mosaic as a consequence of the tectonic activity (Bergner and Trauth, 2004; Stuttard et al., 1999). This study focuses on the part of the valley floor around Lake Naivasha, where large horticulture farms have mushroomed during the last few decennia. In particular, the area around the Flower Business Park (FBP) is of interest due to its large scale groundwater abstraction scheme. For more information on stratigraphy and geological build-up, see section A.7 in the Appendix.

Mean monthly temperature extremes range from 7-30°C with a mean annual average of 17°C (De Jong, 2011a). Precipitation averages from 1250-1500 mm annually in the Mau and Aberdare escarpments to 650 mm around Lake Naivasha. The area experiences a bimodal precipitation pattern: the first rainy period is encountered in April-May and the second, smaller period in October-November. Irregularities from this pattern are common (Becht and Harper, 2002; Gaudet and Melack, 1981; McCann, 1974; Muthuwatta, 2001). Annual potential evapotranspiration ranges from 1500-1900 mm/yr, where the lower figure is encountered in higher altitudes and vice versa (Åse et al., 1986; Meins, 2013b). Given these statistics, Naivasha's climate can be designated as humid subtropical in the highlands and semi-arid in the valley according to the Köppen classification (Peel et al., 2007). For more information on precipitation and evapotranspiration, reference is made to Meins (2013b) and Meins (2013c).

The Lake Naivasha basin is drained by one ephemeral and two perennial rivers, all of which discharge into Lake Naivasha. The ephemeral Karati River drains 149 km^2 of the easterly part of the catchment and is only perennial in its upper parts (Everard et al., 2002). The perennial Malewa and Gilgil Rivers drain and discharge 1600 km^2 and 4.9 m^3/s, and 527 km^2 and 0.8 m^3/s, respectively (Becht et al., 2005; Darling et al., 1990; Ojiambo, 1996c). For more stream flow information, see Meins (2013d).

Lake Naivasha's water levels show significant temporal variability. Over the past millennium, the lake has known periods of significantly higher water levels than at present, but it has gone dry as well (Verschuren, 2001; Verschuren et al., 2000). The main lake's depth averages $4-6\ m$ in present times (Becht and Harper, 2002), with deeper sections in sub-lakes Oloidien and Crescent Lake at ca. 18 m, which are located toward the western and eastern rims, respectively. For more information on lake levels, reference is made to MOWD (1982).

1.1.2 Groundwater system of Lake Naivasha area

The water balance of Lake Naivasha has been of interest for over a century, researchers being intrigued by the fact that there is no surface outlet to the lake whilst still remaining fresh (Becht et al., 2006). Reasons suggested include the existence of a subsurface outlet (Beadle (1932); Becht and Nyaoro (2006); Clarke et al. (1990); Darling et al. (1990); Gaudet and Melack (1981); Ojiambo (1996a); Sikes (1936); Thompson and Dodson (1963)), salt stratum formation (Nilsson, 1932), dilution by river water, sorption (especially by papyrus (Åse et al., 1986)) and sedimentation and precipitation reactions (Gaudet and Melack, 1981). Consensus seems to have emerged, though, that there must be a net loss term to the groundwater from the lake. The water balance, directions and magnitudes of flow of groundwater, however, are less well understood. In part this is due to the complex hydrogeology of the area.

Although conditions strongly vary spatially, two general hydrogeological environments can be identified. In the highland areas Mau and Aberdare deep groundwater tables as well as steep groundwater gradients are encountered. These rocks, which also underlie the valley floor, likely have low permeability and storage capacity, but seem capable of feeding the groundwater system from high precipitation encountered at these higher altitudes (Nadibe, 2002). Occasionally steam is encountered in boreholes, indicating geothermal activity (Thompson and Dodson, 1963). Groundwater gained from recharge flows longitudinally from these highland areas to the valley floor, following surface elevation contours (Clarke et al. (1990); McCann (1974); Thompson and Dodson (1963)).

Shallow groundwater tables, low precipitation and low recharge values characterize the second environment, namely the valley floor, where the actual study area is located. The volcanic rocks and their sedimentary derivatives deposited by the lake, rivers or as wind fall suggest more favorable hydraulic properties than in the highland volcanics. However, throughout the Rift Valley, the effects of intense faulting and large spatial heterogeneity remain to be kept in mind when generalizing as above. Faulting has formed numerous small groundwater compartments and may form either barriers or conduits to flow. Stratigraphic data is scarce, hence undisputed aquifer mapping is absent. A synthesis of mainly the findings of McCann (1974), Clarke et al. (1990) and Becht et al. (2006) suggests water is flowing out of Lake Naivasha vertically into deep geothermal layers and horizontally through shallower layers. Deeper aquifers are replenished through faults, while heads in shallower water-bearing strata follow an axially directed gradient toward both the north and the south. This gradient is due to Lake Naivasha's location on the culmination of the valley floor in combination with lower heads encountered to the north in Lake Elmenteita and to the south beyond Hell's Gate (Figure 2). The magnitude of the geothermal inflow is unknown. The flow northward toward Gilgil is estimated at around 5 – 25 Mm^3/yr, while flow southward toward Hell's Gate is estimated between 20 – 50 Mm^3/yr.

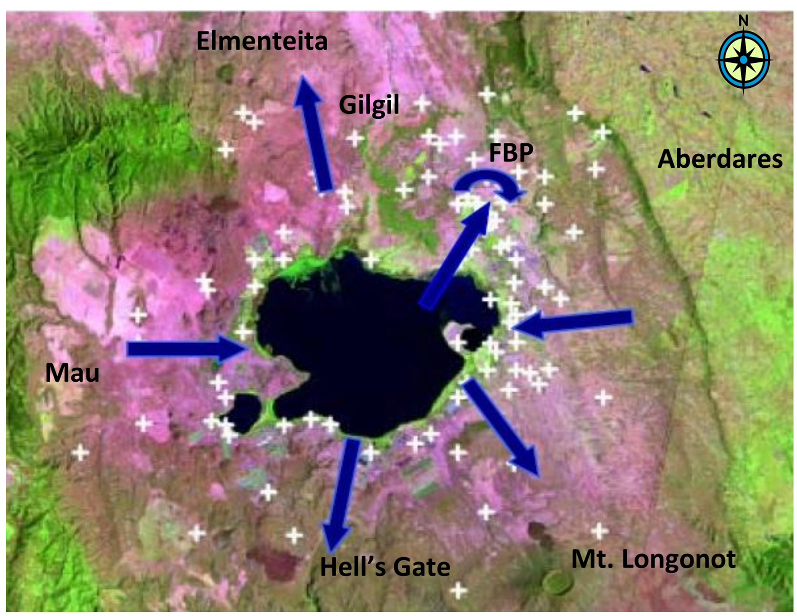

Figure 2: Current groundwater flow directions around Lake Naivasha. White crosses indicate borehole locations. In pre-abstraction times the northwestern flow toward the FBP was opposite this direction. Adapted from: Becht and Nyaoro (2006).

A part of the discussion about groundwater flow depends on how the interaction between the lake and the aquifer surrounding is envisioned. Becht and Nyaoro (2006) suggest that when lake levels rise, the lake will recharge the surrounding aquifers; vice versa, if the lake recedes the aquifers drain into the lake. This interaction leads to inertia in the lake-groundwater system, purporting delayed reactions to external (e.g. meteorological) stresses, so that the aquifer acts as a reservoir absorbing water during high lake levels or wet periods and releasing water during low lake levels or dry periods. A more precise figure describing the 'connectedness' between lake and aquifer does not exist to date (Deltares, 2011).

A complicating factor of influence in the discussion of the groundwater system is the influence of abstractions. A Water Abstraction Survey (De Jong, 2011b) issued by the Water Resource Management Authority (WRMA) in 2010 showed that total basin abstractions amount to about 100 Mm^3/yr. Abstractions around the lake account for two-thirds of the total abstractions. Groundwater abstractions to the north of the lake represent the largest portion to this number, totaling approximately 40 Mm^3/yr. The cone of depression at FBP, for example, that is generated by these abstractions is by some authors (e.g. Becht et al. (2005)) assumed to have reversed the flow from the mountains to the lake, hence altering groundwater flow as well as lake levels (Figure 2).

1.1.3 Groundwater models for Lake Naivasha area

Becht and Harper (2002) have made a first numerical attempt to obtain insight into the magnitude of the outflow from the lake into the groundwater system. More sophisticated pursuits to evaluate the behavior of the Lake's surrounding aquifer system followed, in the form of spatially explicit finite-difference groundwater models. Most notable are the ones by Owor (2000), Yihdego (2005) (published as Yihdego and Becht (2013)) and Legese Reta (2011). Table 1 provides an overview.

The Becht and Harper (2002) cascade spreadsheet model has been updated and improved by Van Oel et al. (2013). Using precipitation and evaporation as stressors to the lake, water is routed from the lake cascade to a groundwater cascade or vice versa, based on their respective heads and one conductance parameter separating the two cascades. The groundwater cascade can be seen as a representation of one lumped, homogenous and spatially undifferentiated aquifer of 100 km^2 and specific yield of 0.2. Although the model functions well to illustrate the different effects of abstractions taken from either surface or groundwater, this approach cannot be used for spatial assessment of groundwater or to reveal the intricacies related to the extensive groundwater use around the lake.

The Owor (2000) model performs similar to the cascade model in terms of simulating lake levels. The model has not been validated nor evaluated for other performance measures such as groundwater level lowering upon abstraction. Most importantly, though, is that if one is to attempt to obtain a spatial representation of the groundwater system, one does need to have to one's avail proper data on hydrologic stresses, hydrogeological parametrization and head recordings. Owor's layer definition has little backup from physical measurements like e.g. borelogs. Furthermore, only 45 observations are used in the steady state model to represent a period of almost 50 years (1932-1980). Besides, it is debatable whether a steady state model is an appropriate assumption given the large fluctuations in lake levels during this period, since this variability implies the lake was not in equilibrium. See Appendix A for more information about available (or unavailable) data sets.

The Yihdego and Becht (2013) model suffers from the same lack of data to support the detailed hydrostratigraphic representation of the subsurface put forward. On top of this, the model has been thoroughly scrutinized by Deltares (2011), who concluded "it contains too many serious and structural errors and omissions to be used in future modeling" (p.23). This model too is not validated, nor tested by subjecting it to stresses other than those for which it has been calibrated.

The Legese Reta (2011) model likewise has little support in actual measured system variables. This model too contains structural errors. The layer definition places bottoms of aquifers higher than the top elevations, leading to erroneous MODFLOW outcomes (this is most likely due to inapt interpolation methods employed). Also, the way the upper aquifer is schematized introduces very large storage potential toward the edges of his model area, which is particularly relevant in transient runs. It seems his model did not converge at all, given the missing output data and a groundwater balance closure error of over 62%. Lastly, the numerical schematization does not correspond its description in his accompanying thesis.

Table 1: Overview of existing model characteristics.

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

1.1.4 Problem statement

The synthesis above teaches that if the effects abstractions have on the water system is to be explored, a spatial assessment of groundwater around Lake Naivasha is imperative. The lumped cascade model by Van Oel et al. (2013) proved insufficient. Conceptual schematizations of spatially distributed modeling exercises (Legese Reta (2011); Owor (2000); Yihdego and Becht (2013)) lack support by (proper quality) data. Such speculative modeling can in the best case prove to be right, but in the worst case give the impression the system is much better understood that it actually is. Water management based on these models may have unintended consequences. To avoid these undesired results, a new (conceptual) groundwater model for the Lake Naivasha area should be build, based on literature and data.

1.2 Research objective

Based on the context described in the previous section, the following objective is formulated for this study:

The objective of this research is to explore the influence of groundwater abstractions on Lake Naivasha's water level, by modeling groundwater flow around the lake.

1.2.1 Scope

The absence of a systematic database on historical and current abstractions drawn from lake, river and groundwater makes it no light task to obtain such a data set within the bounds of this study's time frame. Proper quality data is, however, available from the Flower Business Park (FBP, 2013), see Appendix section A.6. Thus this study singles out the FBP abstraction scheme to serve as a test case.

If one is to make any assertions regarding the temporal behavior of the groundwater system, e.g. in terms of response or recovery times, a transient groundwater model on top of a steady state model is imperative. Previous modelers have attempted to assemble such a time-dependent model (Legese Reta, 2011; Owor, 2000). The only time series of heads available, however, are lake levels, if one is willing to see the lake as a large well. Given the lack of proper quality time series of heads and recharge (see Appendix A) in this study it is judged inappropriate to (re)develop a transient groundwater model.

1.3 Research questions

To guide this study in reaching the objective, the following research questions have been formulated:

1. *How can the exchange of water between Lake Naivasha and the surrounding aquifer system be modeled?*
2. *What do flow patterns and water balances look like under natural conditions?*
3. *What is the effect on flow patterns, water balances and lake levels of groundwater abstractions at the Flower Business Park?*

1.4 Research approach

This section explains how the objective was to be reached and the research questions answered.

1. *How can the exchange of water between Lake Naivasha and the surrounding aquifer system be modeled?*

For answering this research question the basic modeling cycle as proposed by Wang and Anderson (1995) and Hogeboom (2012) was used.

Purpose
Given the scarcity of data on most system variables, the model is fore-mostly used for explorative analysis and learning how the system behaves (spatially) rather than prediction (Brugnach and Pahl-Wostl, 2007).

Conceptual model
The second step in groundwater modeling is the development of a conceptual model of the water system around Lake Naivasha that serves as the parsimonious representation of reality (i.e. reality simplified enough to be modeled manageably yet retaining enough detail to draw meaningful conclusions). Choices are made on what geologic units of similar hydrogeologic properties to summarize into hydrostratigraphic units, including a rough estimation of their hydrogeological parameters (e.g. hydraulic conductivity, thickness, layer definitions). Additionally, a water balance is useful as a means to check water budgets produced by the numerical model after calibration. Ranges for in- and outflow, recharge, and other sink and source terms are given. Once all components are estimated, they are checked for groundwater balance closure. The in- and outflow could be determined from the hydraulic gradient and transmissivity estimates, which require flow patterns. Patterns and directions have been based on available historical heads. Lastly, model or system boundaries have been established.

Numerical model
Numerical groundwater models rely upon generating a solution to the basic equations for groundwater flow (Fetter, 2001; Freeze and Cherry, 1979; Hogeboom, 2012). One of the most widely used software packages is MODFLOW 2005, a finite difference modular groundwater code (Harbaugh, 2006). This code is chosen for its robustness, its performance record and the fact that the code became Open Source. To ease generation of input files for MODFLOW, ModelMuse version 2.19 is used as preprocessor graphical user interface (Winston, 2009). ModelMuse is a state of the art open source interface, developed by USGS, that stores spatial input data separate from the grid. This allows for alterations to grid size, layering and position without reconfiguring data sets. The number of layers, grid design, implementation of boundary conditions and the way Lake Naivasha and the rivers are represented had to be defined, all based on the conceptual model developed previously.

Calibration and sensitivity analysis
The uncertainty in the scarce data qualifies many model parameters for estimation during calibration. For instance, one of the most important parameters that drive lake-groundwater interaction is the conductance of the lakebed sediments. Nothing is known or measured about this parameter and it can thus take a wide range of physically feasible values. Likewise, hydraulic conductivity, riverbed conductance and recharge contain large uncertainty bands. A lot, if not most, of the uncertainty however,

is attributed to the conceptual model itself. Perceived boundaries and system layering determine to a great extent the behavior of the internal model parameters.

Thus reasoning, sensitivities of parameters (and subsequently of results) will only be relative to the schematization. Given the uncertainty in the conceptual model, laying out a thorough quantitative sensitivity analysis is judged of limited use. To accommodate still for the sensitivity of model results, it is tried to compare two calibration sets. Each set is appointed a lakebed leakance value, which largely governs lake-aquifer interaction and lacks even prudent estimation.

The hypothesis is that the large number of degrees of freedom within the conceptualization of the system will allow for two non-unique parameter sets to emerge from calibration. The different model outputs resulting from these two parameterizations can then provide a means to assess similarities in system processes. Note that this sensitivity analysis is valid only for the a priori chosen conceptual model.

The method of testing the hypothesis stated above is as follows. The value of lakebed sediment leakance is set to two fixed values: a high value of 0.215 d^{-1} representing a rather leaky lake; and a low value of 0.01 d^{-1} representing a rather sealed lake. These bed leakances correspond to a lake bed of 1 m thick with a vertical hydraulic conductivity of 0.215 m/d and 0.01 m/d, respectively. The upper value coincides with the calibrated outcome of the Owor (2000) model and represents lakebed sediments to be composed of sandy/silty materials. The lower value is the arbitrarily chosen equivalent of clayey material. Given these lakebed leakance values, the model is calibrated by adapting hydraulic conductivity. Automated calibration is performed in ModelMate version 1.0.1. Like ModelMuse, ModelMate is developed by the USGS. ModelMate is an Open Source postprocessor graphical user interface (Banta, 2011) that generates input files for UCODE_2005 (Poeter et al., 2005). UCODE is an executable that performs automated parameter estimation and sensitivity analysis for (amongst others) MODFLOW models. It uses the powerful Gauss-Newton inverse modeling algorithm to adjust the value of user selected input parameters in an iterative procedure. The objective function is to minimize the squares of observed and simulated heads. Manual adjustments of automated calibration output had to ensure physically sound output. Furthermore, lake and groundwater balances should have been checked for closure. Results include a plot showing observed versus simulated heads for each observations.

Validation
The calibrated steady state models could only be validated to a limited extent. In calibration, water balance closure and the physical feasibility of parameter values have been checked, but this did not necessarily guarantee proper model performance under different conditions. The physically measured groundwater levels that accompany the FBP abstraction rate, however, provide a means of verification: if the same rate is abstracted in the model, the resulting drawdown should be comparable to the measured drawdown. Further, more qualitative validation, is sought in identifying processes that take place under both parameterizations. In every attempt, however, the judgment of whether the fit between model and reality is good enough is a subjective one and any verification effort should be considered only a partial one (Anderson and Woessner, 1992; Małloszewski and Zuber, 1992). This is acceptable, though, given the explorative nature of this study.

2. *What do flow patterns and water balances look like under natural conditions?*

Even without the complications introduced by large scale abstraction schemes, the groundwater balance is poorly understood. These abstractions began roughly around 1980. The period prior to this year can be regarded as the natural situation of the system. Now that the numerical model is functioning appropriately, it can be used to obtain insights into the groundwater balance and lake-aquifer interaction. MODFLOW output includes an overall, lumped system budget. This budget fails to distinguish between different in or outflow zones. This differentiation can be made using ZONEBUDGET version 3.01, a post-processing utility to MODFLOW available in ModelMuse (Harbaugh, 1990). Output includes a water balance overview of in- and output terms in the natural situation, as well as a contour map.

3. *What is the effect on flow patterns, water balances and lake levels of groundwater abstractions at the Flower Business Park?*

The newly developed groundwater model should be able to provide additional or improved insights into the effect groundwater abstractions have had on lake levels. The model is run with a sink term at FBP, which is the case of interest to this study, to account for groundwater abstractions. This is done for both calibrated parameter sets. Note that abstractions at FBP account for only about 10% of all estimated groundwater abstractions in 2010 (De Jong, 2011c).

Next, the difference between simulated lake levels and observed lake levels is to be assessed. Since the lake, rivers and recharge qualify as sources for abstracted water, it is interesting to obtain insight in the origin of the water. This will be done using MODPATH version 3, a particle tracking post-processing utility for MODFLOW available in ModelMuse (Pollock, 1994). Note that, given the fact that the model is steady state, conclusion refer to equilibrium situations, where abstractions continue ‘perpetually’. Output includes groundwater contours and source plots showing the origin of water particles pumped.

1.5 Outline

This thesis is built up as follows. In Chapter 2 the modeling cycle as described in section 1.4 (Research Approach) is gone through. Conceptual model choices are elucidated and numerical whereabouts of the MODFLOW model are elaborated on. The Chapter concludes with the account of the calibration procedure. In Chapter 3 the results of the model for both parameterizations are presented. A comparison is made between the two outputs. In Chapter 4 the research approach, modeling method and results are discussed, to conclude this thesis in Chapter 5 with the answering of the research questions and further recommendations.

2 Modeling method

This chapter describes the modeling cycle described in section 1.4. The conceptual and numerical modeling methods are expounded in the first two sections (2.1 and 2.2), followed by an account of the calibration procedure in section 2.3.

2.1 Conceptual model

The conceptual model comprises a definition of the hydrostratigraphic units, system boundaries and the definition of a preliminary groundwater balance.

2.1.1 Hydrostratigraphic units

As elaborated on in paragraph 1.1.2 on the groundwater system of Lake Naivasha area, hydrogeology of the area is very complex. Undisputed aquifer mapping is lacking and the few data sources that exist (see section A.7) show a highly heterogeneous subsurface composition. The multiple layers assumed by previous modelers (Legese Reta, 2011; Owor, 2000; Yihdego, 2005; Yihdego and Becht, 2013) are therefore considered unsubstantiated by data and to overcomplicate the model. Reference is made to section 1.1.3 for a discussion on these models. As a consequence, a one layer system is postulated under confined conditions and with a thickness of 100 m throughout the study area. This layer is composed of an aggregation of undifferentiated sedimentary and volcanic deposits. The thickness is determined on the average conception of the available borelogs. The choice for confined conditions emerges from notes found on borehole completion records (see section A.2). Hydrogeologic parameters are spatially differentiated by defining zones within the layer. The 26 zones as defined by Legese Reta (2011), who based delineation on the surface geological map, are adopted for this purpose (see paragraph 2.2.1).

This rather simple schematization is used as the first attempt to spatially distribute groundwater flow based on available data and literature. The modeled cross section is shown in Figure 3.

2.1.2 System Boundaries

To the west the Mau[1] surface water drainage divide is taken as a physical no flow boundary. The Geological Map (Figure 22) does not provide evidence for a groundwater divide different from the surface water (and thus recharge) divide, which makes this choice relatively certain.

To the east, the Kinangop fault which separates the plain from the valley floor is assumed to be connected to Mount Longonot in the southeast, also forming a physical no flow boundary. The Kinangop fault can be seen on the original, non-digital geological map (Government of Kenya Ministry of Energy Geothermal Section, 1988). Steep gradients encountered across this fault provide the rationale for the no flow assumption in the northern parts. ITC231[2], which lies east of the fault, has a recorded groundwater level of 2264 $masl$, while just west of the fault ITC153 has a groundwater level of 2142 $masl$ and ITC228 of 2162 $masl$. This means heads drop more than 100 m over less than 1 km distance.

[1] For geographical references, see Figure 1 and Figure 2.
[2] Borehole ID's available in ITC database take the format: ITC-number. For georeferences, see Table 14.

In previous modeling excercises (Legese Reta, 2011; Owor, 2000) outflow could occur between Kinangop and Longonot volcano as well. This outflow, however, is based on an erroneous head value supposedly observed at ITC136. This well goes under multiple or different ID's, coordinates and altitudes in different databases (see section A.2). Given the ambiguous whereabouts of this borehole, it is removed from the database. In doing so, there remains no valid reason to assume outflow between Kinangop and Longonot; the interpolated head map (Figure 16) does not show a gradient directed southeastward.

To the northeast, the Eburru surface water divide is followed to provide a physical no flow boundary. The few boreholes drilled at Eburru have yielded steam or shallow heads, indicating no outflow underneath Eburru. It is assumed that the volcanic complex extends to greater depths, as is indicated by the Geological Map (Government of Kenya Ministry of Energy Geothermal Section, 1988).

The base of the valley floor underlying the aquifer is taken as a physical no-flow boundary. The hard bedrock encountered at depth in some borelogs (section A.7) is assumed to have very low hydraulic conductivities that can be neglected in this modeling exercise.

The Karati, Gilgil and Malewa rivers drain the study area. The latter two take the lion's share in total surface water runoff. Besides, their discharge series are more thoroughly scrutinized by Meins (2013a) than for Karate series. Therefore, the Malewa and Gilgil are taken up as internal boundary conditions in the model. Lake Naivasha forms the last internal boundary condition.

To the north, an approximately 12 km wide outlet is assumed along the narrowest section of the valley floor, as determined from the DEM, at the latitude of Gilgel town. Here, water is assumed to leave the Naivasha study area to reemerge in Lake Elmenteita up north. Water with Lake Naivasha's signature has been detected in springs and seeps south of Lake Elmenteita (Becht et al., 2006; Darling et al., 1990). The artificial boundary head along this sections is estimated at 1850 $masl$, based on wells R23 with a recorded groundwater level of 1844 $masl$ and R27 with 1857 $masl$ located just north of this boundary.

To the south, an approximately 18 km wide outflow area is assumed from Hells Gate to Longonot volcano. Here, water is assumed to leave the Naivasha study area to reemerge further south. Darling et al. (1996) confirmed the suggestion of considerable southerly outflow through this section in their analysis of stable isotope composition of fumaroles in the southerly area. The artificial constant head along this boundary is estimated at 1800 $masl$, based on wells R213 with a recorded head of 1822 $masl$ and R31 of 1795 $masl$ located just north and south of this boundary, respectively.

Given these boundaries, the modeled area encompasses approximately 1400 km^2 (see Figure 3).

2.1.3 Water balance

The water balance of the groundwater system is poorly understood. The more prominent lake balance therefore serves as a partial basis to determine groundwater budget terms. Table 2 provides an overview of researchers and their findings concerning the lake water balance. Outflow from the lake is taken as input to the groundwater in Table 3 (lake seepage).

Recharge is largely unknown (for available data, reference is made to section A.1 in the Appendix), so caution is warranted.

The same holds for river in- or outflow, although DIC (2003) claimed there is flow of water from the Malewa river to groundwater. This is indicated by the water quality samples from wells close to the river which contain much lower fluoride levels (because of dilution) as compared to boreholes closer to Naivasha Town, while most likely sharing the same aquifer. Hence, a net contribution of the rivers to the groundwater seems credible.

As for outflow terms, some rechearchers have tried to estimate outflow to the north and south (see also paragraph 1.1.2 on the groundwater system of Naivasha).

The overview in Table 3 does not account for the effects of faults, which may route water to deep geothermal layers, nor evapotranspiration of groundwater in shallower regions. Although both terms are likely to have their share in the water balance, it is judged that the associated uncertainty does not justify the added complexity. After all, the overview shows that the water balance has a closure error of approximately 40 Mm^3/yr. Either the inflow or the outflow is thus wrongly estimated. The modeling exercise should be able to provide more insights into the (steady state) groundwater budget.

Table 2: Lake balance in pre-abstraction era. Based on Van Oel et al. (2013)

	McCann (1974)	Gaudet and Melack (1981)	Åse et al. (1986)		Becht and Harper (2002)	Van Oel et al. (2013)	Range
Hydrologic budget item[1]	Various years	1973-1975	1972-1974	1978-1980	1932-1981	1965-1979	
Total inflow	**380**	**337**	**279**	**375**	**311**	**353**	**340±70**
Precipitation	132	103	106	135	94	123	116±20
River discharge	248	234	148	215	217	230	215±50
Total outflow	**380**	**368**	**351**	**341**	**312**	**362**	**352±80**
Evapotranspiration incl. swamp	188	312	284	288	256	328	276±90
Groundwater seepage	34	56	67	53	56	34	50±20
Assumptions[2]							
Precipitation	639[3]	683	575	709	648	695	658±70
Evapotranspiration	1791[4]	1989	1542	1504	1788	1788	1734±250

[1]Units: Mm^3/yr
[2]Units: mm/yr
[3]Based on rain stations s9036322 and s9036179 (Naivasha DO) for the period 1957-1998 (Meins, 2013c).
[4]Based on pan evaporations at Naivasha DO for the period 1959-1990 (Meins, 2013b).

Table 3: Groundwater balance in pre-abstraction era.

Hydrogeologic budget item[1]	McCann (1974)	Gaudet and Melack (1981)	Åse (1987; 1986)	Clarke et al. (1990)	(Ojiambo (1996a); Ojiambo (1996b); Ojiambo (1996c))	Various sources/ estimate	Range
Total inflow							**135±100**
Recharge	-	-	-	-	450	0-130[2]	80±50
Lake seepage (net)	34	67	53	-	-	30-70	55±50
River (net)	-	-	-	-	-	unknown	unknown
Total outflow							**95±75**
Constant head boundary North	39	37-51	0	5-25	-	0-60	35±25
Constant head boundary South	-	18-76	46-56	27-270	18-50	18-270	60±50
Discrepancy							**-40±175**

[1]Units: Mm^3/yr
[2]Recharge calculated based on estimates of 0-520 mm/yr.

2.2 Numerical model

The conceptual model described in the previous section is translated into a numerical MODFLOW model. MODFLOW is divided into a series of packages, each of which performs a specific task. Input for each package must be stored in a separate input file. ModelMuse facilitates the process of translating the data assigned to objects in the ModelMuse interface to these input files that MODFLOW can read. The packages needed to obtain a numerical translation of the above conceptual model are described in this section.

2.2.1 Required and Flow Packages

The required packages include the Basic (BAS), Discretization (DIS) and Output Control (OC) Packages, while the flow package chosen for this study is the Layer Property Flow (LPF) Package. The layer type is set to confined (LAYCODE=0).

Layer Definition

Although the model comprises only one layer, for Lake Package (LAK) purposes two layers have to be defined in MODFLOW: one containing the lake cells (top) and one underneath the lake cells, since per definition lake cells extent to the bottom of the system. In passing, this is what went wrong in Legese Reta's (2011) model. The layer definition is thus as follows.

The top of the first layer is described by the DEM, integrated with a 1896 m arbitrary maximum stage for all lake cells. The bottom of the first layer is set at DEM-1 m throughout the study area, except for the lake cells which are assigned the bathymetry. The DEM and bathymetry map are taken from Legese Reta (2011), who integrated both files and fitted them to a number of GPS-surveyed wells he took during his field work. The upper cells beside the lake have no function but accommodate solver convergence. The bottom of the second layer, i.e. the layer of interest, is set at DEM-100 m or bathy-100 m throughout the entire area. The lake thus drains from the 'top' layer into the 'second' layer underlying the lake. See Figure 3 illustrating the above.

Grid

In order to obtain an adequate resolution around the area of interest (i.e. FBP), cell size is set to 100 m squared. The lake cell size is set to 250 m squared. Given the uncertainty increase toward model edges, a lower resolution of 500 m square suffices. A grid smoothing criterion of 1.3 is applied transitioning high resolution cells to lower resolution cells. The resulting grid contains 178 rows and 180 columns, see Figure 3.

Starting heads

For initial heads, the groundwater tables of the pre-abstraction era have been used. A historical contour map has been drawn based on the available piëzometer recordings prior to 1980 (see section A.2 and Figure 16 in the Appendix) and the long-term average lake level of 1887 m. The observations have been interpolated using a nearest neighbor technique. From this map, starting heads have been extracted to each grid cell. Due to data scarcity toward the edges of the modeled area, no reliable interpolated groundwater tables could be drawn here. Hence, for these border areas starting heads were assumed to be 100 m below the DEM. Resulting starting heads are displayed in the colored background of Figure 3.

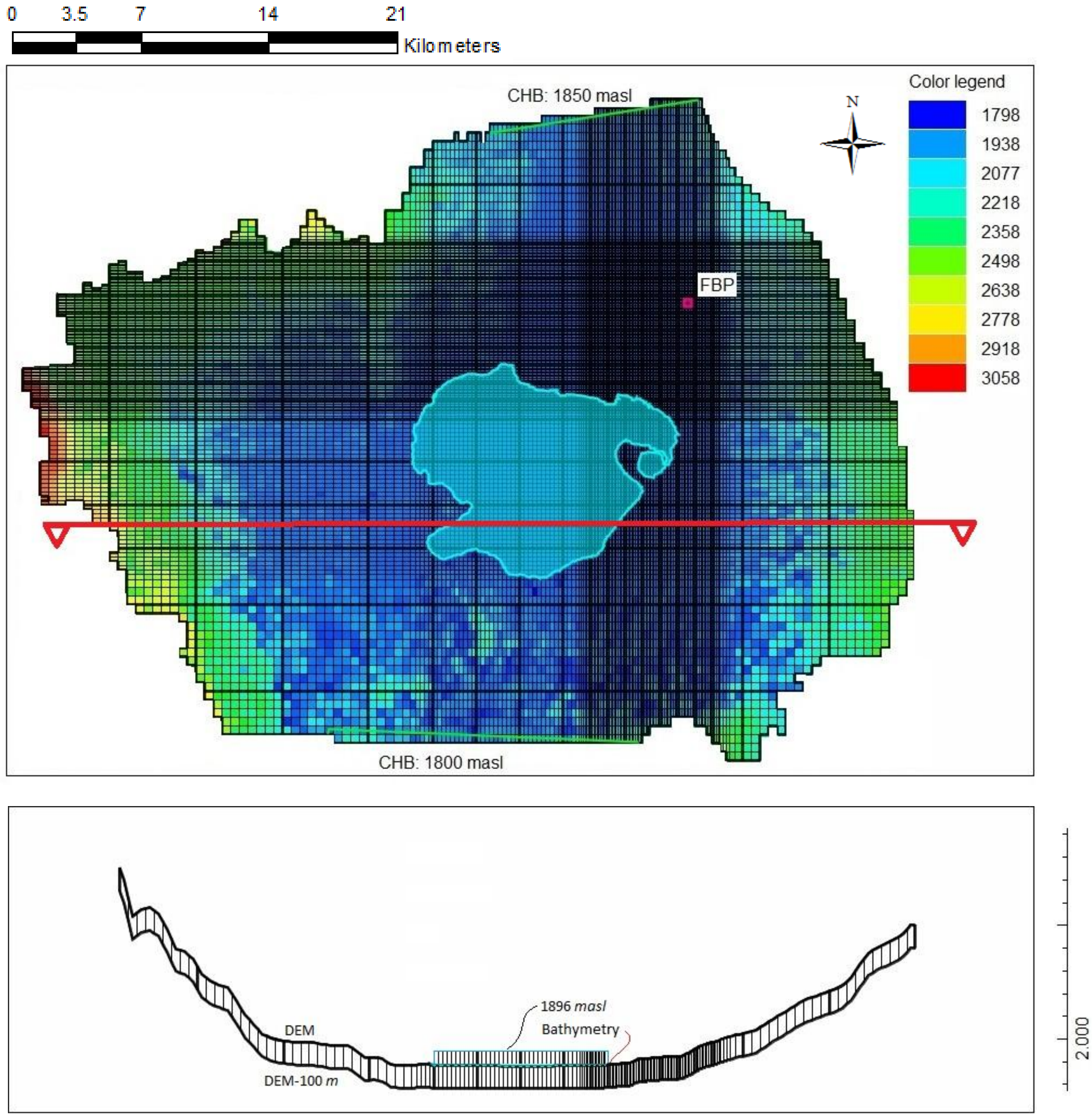

Figure 3: The modeled area. Constant head boundaries (CHB) form boundary conditions along northern and southern transects. All other borders are no-flow boundaries. Colors indicate surface elevation. Grid cell size increases from 100 *m* squared at FBP to 500 *m* squared toward fringes. The cross-section is taken along the red line. Coordinates are in UTM Arc1960 [*m*].

Hydraulic Conductivity

Based on a digitized version of the simplified surface geological map (Government of Kenya Ministry of Energy Geothermal Section, 1988), Legese Reta (2011) defined 26 zones of hydraulic conductivity (Figure 17 in Appendix A). This zonation is also chosen for this study, albeit minor changes are made to accommodate the different model boundaries. The calibrated horizontal hydraulic conductivity values by Legese Reta are taken as starting values for this model. In general, zones around the lake are assigned a higher conductivity than toward the edges of the model. Horizontal conductivity is assumed isotropic. As a rule of thumb (Freeze and Cherry, 1979), vertical conductivity is taken as 10% of the horizontal conductivity value, except for the aquifer polygon underlying the lake (polygon ID 6 in Figure 17), for the following reason.

Total exchange of water between lake and aquifer cells is determined by the aggregated conductance (c_{total}) of both lakebed material and aquifer, through:

$$\frac{1}{c_{total}} = \frac{1}{c_{lakebed}} + \frac{1}{c_{aquifer}} \quad \text{or} \quad c = \frac{A}{\frac{\Delta l}{K_b} + \frac{\Delta z}{K_{z;\,aquifer}}} \qquad [m^2/d]$$

where A is the cell area $[m^2]$, Δl lakebed thickness $[m]$, Δz aquifer thickness (=50 m), K_b vertical hydraulic conductivity of lakebed sediments $[m/d]$ and $K_{z;\,aquifer}$ vertical hydraulic conductivity of the aquifer $[m/d]$ (USGS, 2000). $K_b/\Delta l$ is referred to as bed leakance $[d^{-1}]$. If during calibration horizontal conductivity is adapted, automatically vertical conductivity of the aquifer is adapted too through the 10% formula. This in turn leads to an adaptation of total conductance through the aquifer conductance term. Although this split between lakebed and aquifer assigned conductance is physically sound, it introduces yet another degree of freedom to the already poorly defined model. After all, both bed leakance and aquifer conductance are unknown. To reduce the number of degrees of freedom, vertical hydraulic conductivity of the aquifer is fixed to a value of 50 m/d. The result of setting this rather high value compared to the bed leakance values (0.01 and 0.215 d^{-1}) is that total conductance is, for the largest part, dictated by bed leakance. Note that in doing so bed leakance has in fact become an aggregate term in itself, representing resistance in both lakebed and aquifer materials.

2.2.2 Specified Head Package (CHD)

The Specified Head Package is used to set lateral Dirichlet boundary conditions as established in the conceptual model (see paragraph 2.1.2). Along a 12 km northern transect, heads are fixed to 1850 $masl$. To the south, along a 18 km line heads are fixed to 1800 $masl$. The boundary positions are displayed in Figure 3.

MODFLOW automatically assumes no-flow boundaries if active cells are bordered by inactive cells, so no packages need to be employed to accommodate these boundary conditions.

2.2.3 Recharge Package (RCH)

Recharge is estimated using the simple water balance method proposed by Simmers et al. (1997), as explained in section A.1. In short, five polygons are delineated based on surface altitude. For each polygon monthly average potential evapotranspiration is subtracted from precipitation. The recharge areas and values thus obtained are imported from a shapefile into ModelMuse and are shown in Figure 4.

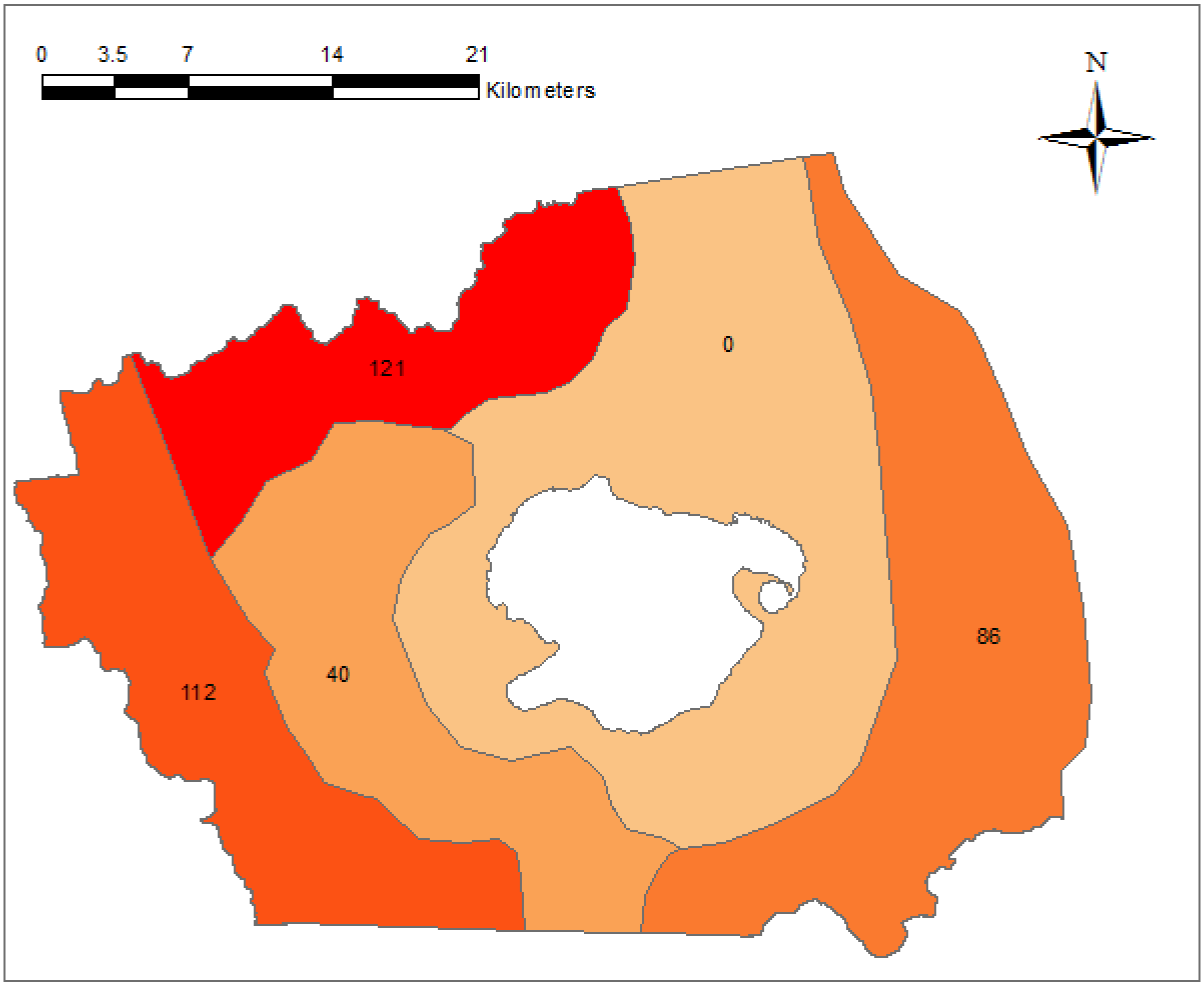

Figure 4: Recharge zones and values [mm/yr]. Atmospheric recharge to the lake is dealt with in the Lake Package.

2.2.4 Lake package (LAK)

The Lake Package was developed to represent lake-aquifer interaction in MODFLOW (USGS, 2000). It represents the lake as volume of space within the grid which consists of inactive cells extending downward from the upper surface of the grid. Aquifer grid cells bordering this space exchange water with the lake at a rate determined by their relative heads and by resistance to flow in both horizontal and vertical direction.

All cells within the periphery of the lake polygon (and which contain the bathymetry map by Legese Reta (2011)) are designated as lake cells. The lake area corresponds to an approximate lake stage of 1887 m and is shown in e.g. Figure 4.

The initial stage of the lake is set to 1887.0 $masl$, which is the average lake level during the period 1939-1980 using data by MOWD (1982). The maximum stage coincides with the 1896 $masl$ arbitrary datum set before in the layer definition (see paragraph 2.2.1). The minimum stage is set to 1874 $masl$, which is derived from the bathymetry map.

The water balance assigned to the Lake Package is based on Table 2 and the area of the lake at 1887 $masl$ levels (i.e. 116 km^2). Runoff includes Malewa and Gilgil fluxes, but also Karati River and overland discharge into the lake.

Table 4: Input water balance to Lake Package. Units in [Mm^3/yr].

Inflow	**331**	**Outflow**	**276**
Precipitation	116	Evapotranspiration	276
River discharge	215	*Deduced groundwater outflow*	*(55)*

In case the model is run with the Well Package included (see paragraph 2.2.6), an input term of 1 Mm^3/yr is added to represent irrigation return flow.

As set out in the section 1.4 Research Approach, two lakebed leakance values are adopted, which have to be assigned to the Lake Package. These values are 0.215 d^{-1} (leaky lake) and 0.01 d^{-1} (sealed lake).

2.2.5 River Package (RIV)

The River Package is used to include the Malewa and Gilgil Rivers into the model. River reaches within the model domain are imported as polylines from their shapefiles (Meins, 2013d). The Karati River is excluded due to its succinct and ephemeral discharge scheme. River bottom elevations are set at ground level, i.e. the top of the grid cell as given by the DEM.

The water depths of the Malewa and Gilgil are set by taking the mean flows at stations 2GA01 and 2GB01, respectively, for the period 1960-1980 from Meins (2013c). These discharges are then converted to stages using the rating curves developed by the same author. This procedure results in a stage of 0.55 m for the Gilgil and 0.41 m for the Malewa.

Riverbed conductance is set to 0.3 m/d based on fieldwork of Joliceur (2000) and Kibona (2000) (see section A.5 in the Appendix).

2.2.6 Well package (WEL)

The model is applied to assess the effect abstractions at FBP have on lake levels. The rate of abstractions is set to 3.5 Mm^3/yr (i.e. 4.9 mm/d application rate for the irrigated area), which is the gross average abstraction rate over the period 2008-2012 (FBP (2013), see also section A.6). Not all of this water drawn from groundwater is consumed by FBP flowers; following measurements by Mpusia (2006) the net consumption is 3.5 mm/d. The difference between gross and net abstractions is accounted for by adding the amount (which equals 1 Mm^3/yr) to lake inflow.

Not one but multiple pumps combined generate the above abstraction rate. In order to better represent this situation, a 400 m by 400 m area is designated as abstraction zone in the model. This prevents overestimation of drawdown, as might be the case if all abstractions were assigned to only one cell.

The Well Package is used only when the model is applied to represent the abstractions at FBP. Under natural conditions, the Well Package is rendered inactive.

2.2.7 Observations Package(OBS)

The data analysis of recorded piëzometer values prior to 1980 (section A.2) yielded 84 observations. Of these, 8 are located outside the model domain. The 76 remaining values are entered into the Observation Package. Another 16 points are added to these 76 values. Eight points refer to observations taken after 1980, but are included since they significantly improve the spatial distribution of observations over the modeled area. The other eight are artificial, non-existing observations which have been added in the fringe, i.e. mountain, polygons to force the model to attain physically realistic heads. Without these, some polygons have only one observation assigned to them: in calibration the model optimizes for these single observations while storing up or depleting water in the rest of the polygon cells. All observations are listed in Table 14.

2.2.8 Strongly Implicit Procedure Package (SIP)

The Strongly Implicit Procedure is a solver commonly used in MODLFOW to determine the equilibrium situation. The maximum number of iterations is set to 5000 and the head change criterion to 0.01 m. When the maximum absolute value of head change from all nodes during an iteration is less than or equal to this value, iteration stops.

2.3 Calibration

Like previous studies, this modeling exercise includes hydraulic conductivity as calibration parameter (see paragraph 1.1.3). The zoning of hydraulic conductivity, as laid out in Figure 17, is basically the same in all spatially explicit groundwater modeling exercises (Legese Reta, 2011; Owor, 2000; Yihdego and Becht, 2013). The calibrated values for each of these zones as obtained by Legese Reta (2011) serve as initial input for automated parameter estimation in UCODE_2005 through ModelMate. For a lack of better estimates, confidence intervals are set at 0 and 700 m/d for the lower and upper boundary, respectively. The sum of squared residuals for simulated minus observed heads was minimized for the 76 heads written to the OBS Package (paragraph 2.2.7). Unfortunately, the objective function cannot be set to include (lake) water balance closure. Also, physical feasibility of calibration outcome is not guaranteed by the automated estimation process. Hence if necessary, output from UCODE has been manually re-adjusted for both additional criteria.

Preliminary results showed that, although higher than the aforementioned studies, the still rather low ratio of observations to calibration zones leads to non-convergency issues. This is especially the case for observation-scarce mountain polygons. In an attempt to reduce the number of calibration parameters, hydraulic conductivity zones located above approximately 2000 $masl$, are optimized for their enclosed observations with UCODE and subsequently set to non-adjustable in further calibration rounds. This led to the fixation of 11 zones (see Figure 17). Furthermore, comparison of subsequent UCODE iterations indicated that zones 6, 11 and 14 were highly correlated. Since these three zones displayed similar behavior, they were unified. This leaves 13 zones adjustable in following calibration rounds. Note that since not every zone contains observations, the calibrated hydraulic conductivities for the fixed zones are somewhat arbitrary. It is therefore recommended to use this model with caution when considering these (mountain) polygons.

The 13 remaining zones were resubmitted to automated calibration in UCODE and subsequently to zone-by-zone manual trial and error calibration to accommodate lake balance closure and feasibility. Observations located in the nonadjustable polygons (16 observations in total) are excluded from the residual calculation in order to focus on the effects in the area of interest. This left 60 observations for analysis.

Two error metrics are adopted to analyze of calibration residuals. First, the Root Mean Square error (RMS), which gives the average of the squared difference of observed and simulated heads:

$$RMS = [\frac{1}{n}\sum_{i=1}^{n}(obs_i - sim_i)^2]^{0.5} \qquad (m)$$

where n is the number of observations and obs and sim the observed and simulated head values, respectively.

Second, the Mean Absolute error (MAE). This error expression, which yields the average of the absolute, non-squared value of the difference of observed and simulated heads, is a more intuitive metric to assess model performance:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|obs_i - sim_i| \qquad (m)$$

The RMS is integrated in UCODE; MAE is calculated after calibration for final residuals.

3 Results

The two MODFLOW parameterizations, one for each of the a priori set bed leakance values, can now be used to explore system intricacies. Output of the calibration is given in section 3.1. The assessment of the flow pattern and water budgets under natural conditions is described in section 3.2. The chapter concludes with the model results in case of abstractions at the Flower Business Park in section 3.3.

3.1 Calibration

The resulting hydraulic conductivity values for the high and low bed leakance parameterizations are shown in Figure 5 and Figure 6, respectively. In general, conductivity is low in the escarpments and increases towards the valley floor. For both bed leakance parameterizations, valley floor sediments show hydraulic characteristics equivalent to well sorted sand and gravel or highly fractured rocks (Fetter, 2001), albeit the low leakance case is on the lower end of this spectrum. The most sensitive polygon in both calibrations was polygon 7, which is intermediate the lake area polygon and the outflow boundary to the south. A 10% alteration of hydraulic conductivity in this polygon may already lead to non-convergence.

With the presented hydraulic conductivity values, however, MODFLOW did converge for both parameter sets with a groundwater budget closure error of 0.0% (see also Table 7). The lake water balance closed with a discrepancy between in and outflow of -0.02% in the low bed leakance case and -4.64% in the high bed leakance case (see Table 8).

Figure 7 shows a plot of the residuals of the observed heads versus their simulated equivalents. These plots are based on 52 of the 60 observations located in adjustable polygons for individual observations (indicated by red asterisks). The remaining 8 residuals[3] were by far the most deviant in both calibration sets, with values well over 20 m. Since individual observations may over-represent the few polygons which have multiple observations ascribed to them, zone averaged observations and their simulated equivalents are plotted too (as indicated by blue diamonds). Only those (adjusted) hydraulic conductivity zones which have either multiple observations within their periphery or are located adjacent to FBP have been taken up into this figure (8 in total).

Given that apart from the peculiarity of topping both residual listings no reason was found to remove the 8 aforementioned deviant observations from the dataset altogether, they are included in the calculation of RMS and MAE in Table 5.

Table 5: Error metrics for calibrated sets.

Error metric	HIGH bed leakance		LOW bed leakance	
	Value 60 observations	Value 52 observations	Value 60 observations	Value 52 observations
RMS [m]	16.13	6.81	16.28	7.43
MAE [m]	9.22	5.32	9.61	5.82

[3] This concerns observations of well IDs R10, R13, R15, R29, R31, ITC100, ITC104 and ITC130.

Note that, although an average miss by the model of $5 - 7\,m$ seems significant, lake levels have fluctuated more than $6\,m$ over the period under consideration, i.e. 1940 – 1980. Observations are snapshots within this period. Furthermore, adjacent head recordings sometimes differed significantly. Given that in calibration the extent of spatial adjustment is determined by the area of a polygon, the algorithm cannot suit one observation within a given zone without leaving a residual to the other.

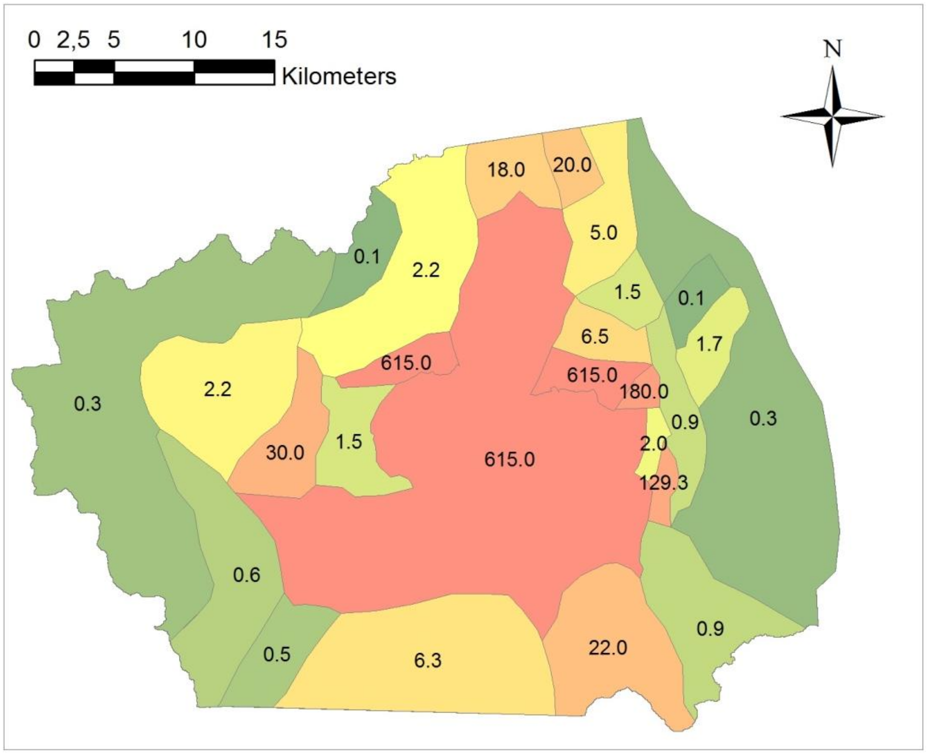

Figure 5: Calibration output in case of HIGH bed leakance. Hydraulic conductivity values [m/d] per zone.

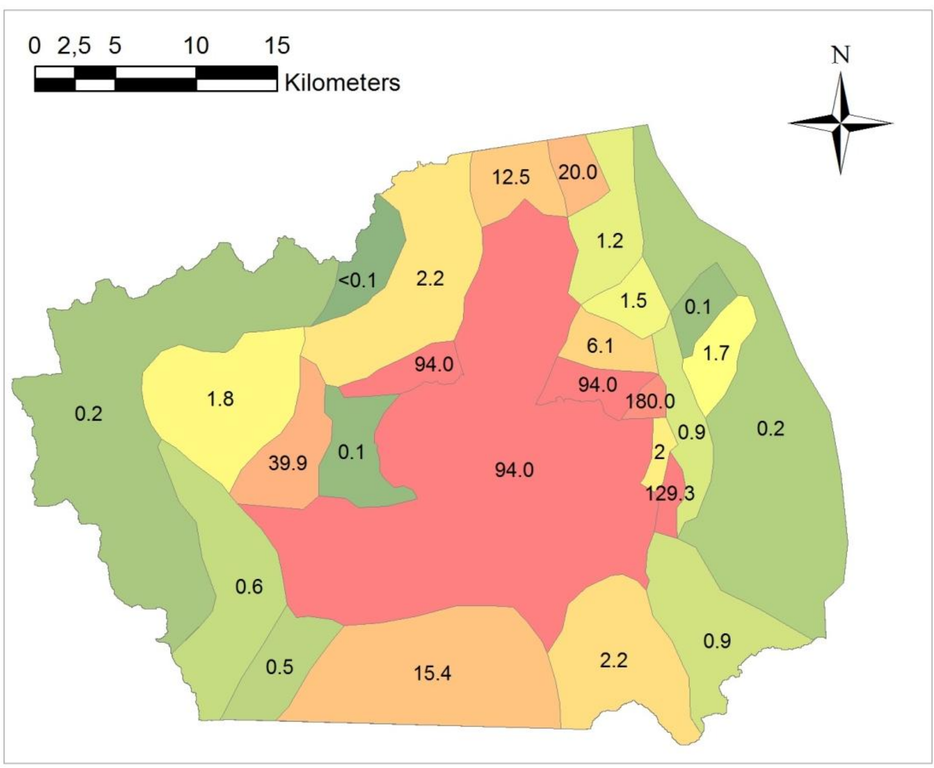

Figure 6: Calibration output in case of LOW bed leakance. Hydraulic conductivity values [m/d] per zone.

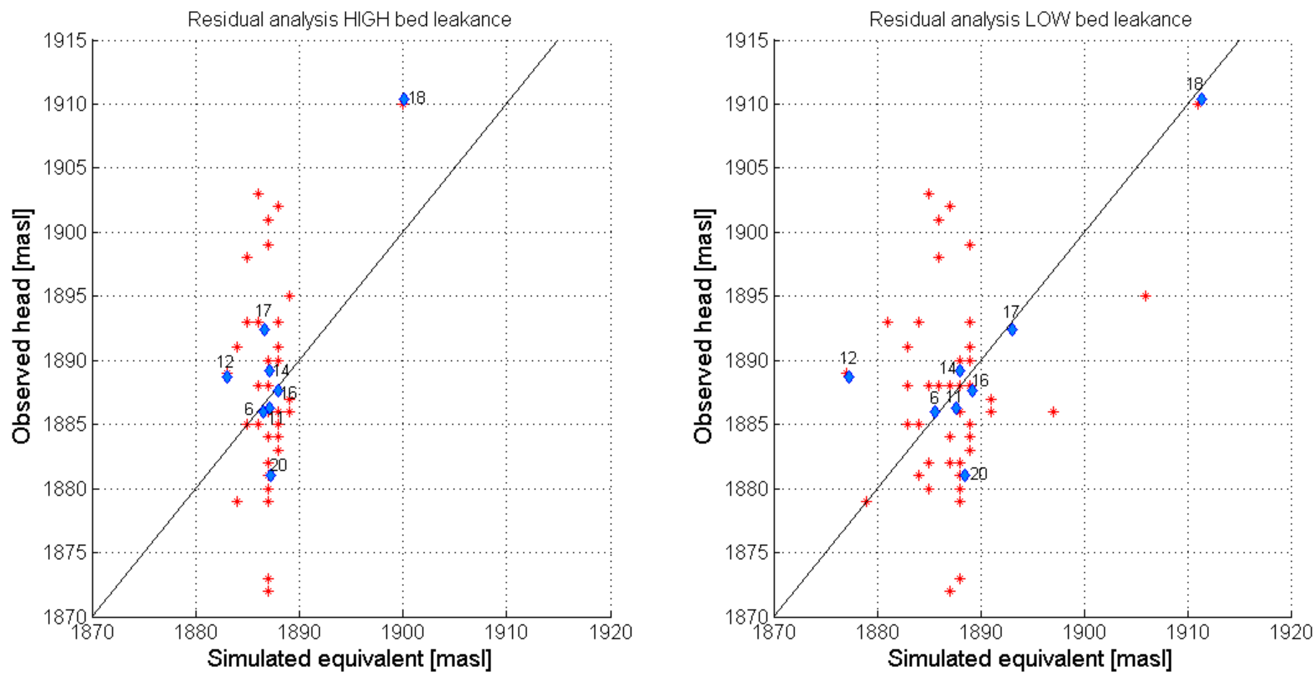

Figure 7: Residual plot for high and low bed leakance calibration sets. Individual observations are indicated by red asterisks. Observations averaged per hydraulic conductivity zone are indicated by blue diamonds. Numerical labels for diamonds refer to zone ID.

3.2 Flow pattern and water balance under natural conditions

The calibrated steady state groundwater model is run for both bed leakance values described in section 1.4. The simulated heads for each grid cell are extracted from MODFLOW to obtain the historical groundwater contour maps presented in Figure 8 and Figure 9. The equilibrium water balance for the groundwater system is retrieved from the MODFLOW listing files and presented in Table 7. The lake water budget generated by the Lake Package is shown in Table 8. For comparison purposes, the value range per budget item from Table 2 and Table 3 are added.

Flow patterns exhibit similar behavior in both parameterizations, i.e. laterally from the escarpments to the valley floor with relatively steep gradients and axially from Lake Naivasha to the north and south with smaller drop. Outflow from the lake occurs to the north and south, while inflow takes place in the east and west. The high bed leakance model shows smaller gradients towards the north than its low bed leakance equivalent.

Considering the groundwater budget, outflow from the groundwater system is on the high end of the estimated spectrum (162.4 and 156.6 Mm^3/yr for the high and low bed leakance case, respectively). The percentages of northerly and southerly outflow are 33% and 67% for the high leakance model, respectively, and 21% and 79% for the low leakance case.

Considering the lake water balance, the net amount of lake outflow into groundwater takes the same order of magnitude (58.2 and 55.0 Mm^3/yr) as postulated in literature (55±50 Mm^3/yr). This being said, the ratio between lake outflow to and inflow from groundwater does differs between the high and low leakance model. The former shows 6.2 times as much lake outflow to groundwater (69.5/11.3) as inflow compared to 7.4 in the latter case (63.6/8.6).

All in- and outflow terms of the lake as well as the groundwater budget yield values that are enveloped by the ranges found in literature in both leakance models.

Groundwater levels at FBP are above the lake stage in both instances. The groundwater levels are 1893 and 1897 $masl$ for the high and low leakance case, respectively. Corresponding depths to groundwater at FBP, with a surface elevation of approximately 1910 $masl$, are 17 and 13 m.

Groundwater levels under natural conditions at FBP have not been recorded. Two nearby wells with assigned historic measurements include ITC031 and ITC090. They are located 2 km to the west and 1.5 km to the south of FBP, respectively. From Table 6 it can be deduced that the simulated heads at FBP in the natural situation compare well to the observed heads surrounding it.

Table 6: Natural heads at FBP and surrounding wells. Observed heads indicated by (O). Simulated heads indicated by (S). Subscripts h and l refer to high and low bed leakance simulations. Units in [$masl$].

	Elevation	**Head**
FBP	1910	1893 (Sh), 1897 (Sl)
ITC031	1905	1890 (O)
ITC090	1902	1887 (O)

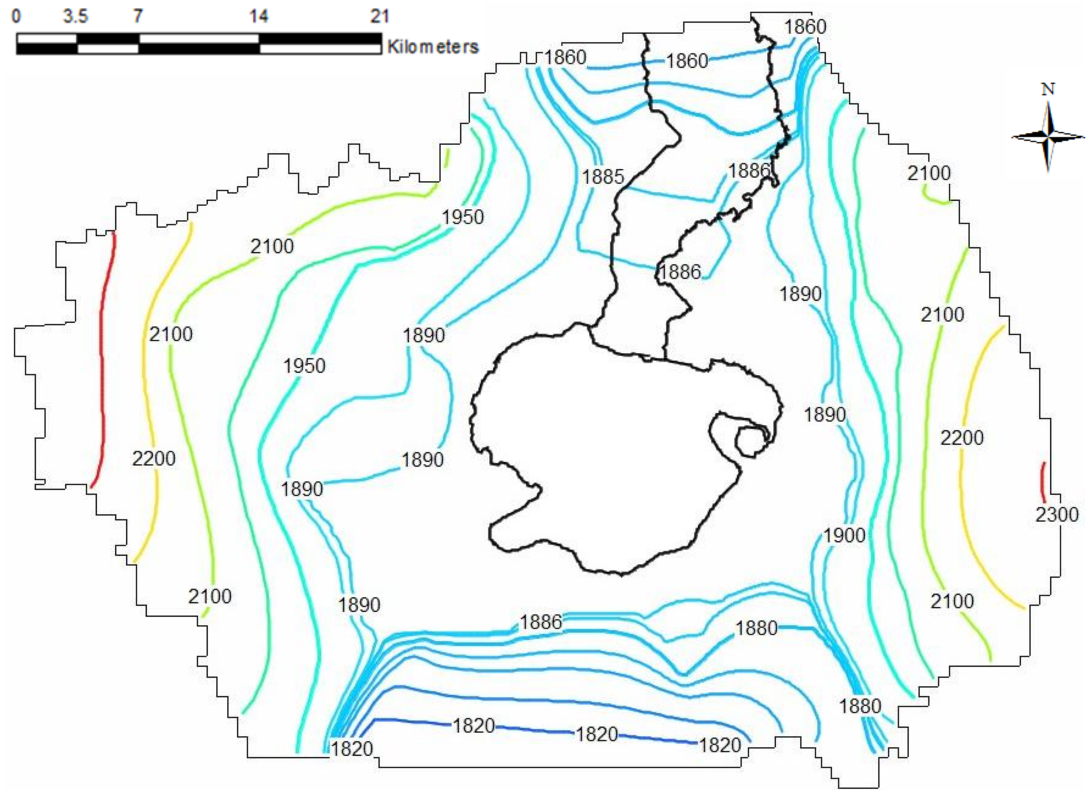

Figure 8: Groundwater contours in [*masl*] for the natural situation in HIGH bed leakance model.

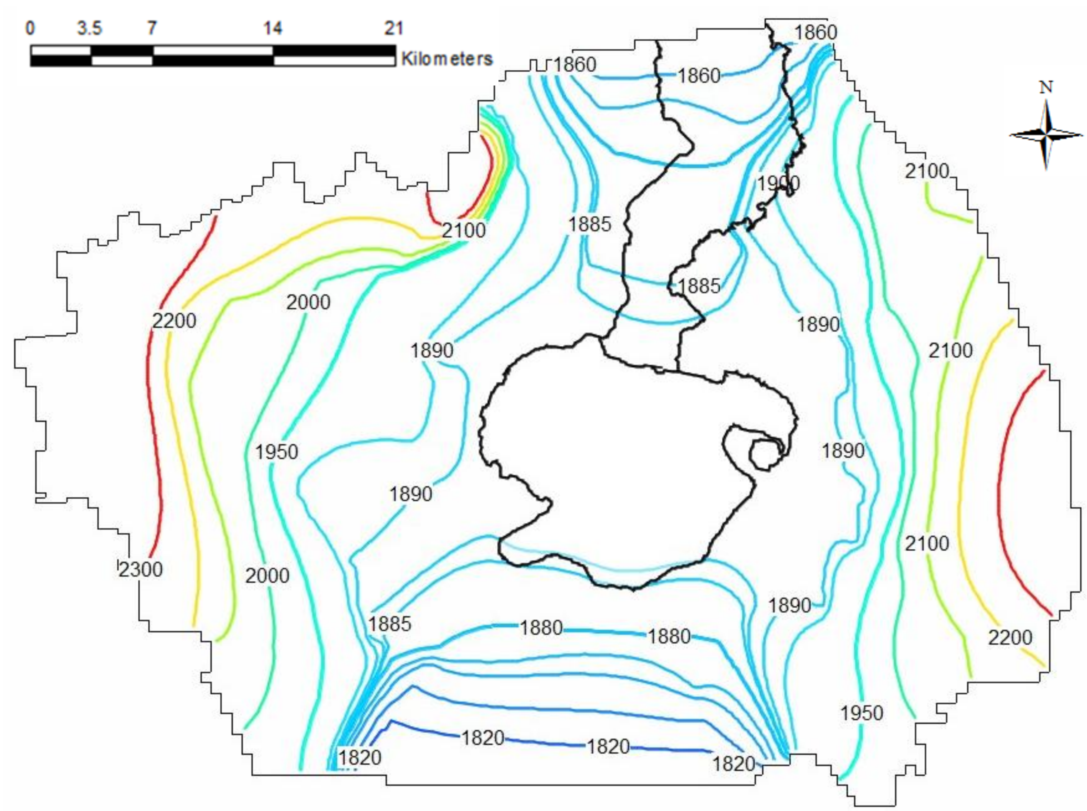

Figure 9: Groundwater contours [*masl*] for the natural situation in LOW bed leakance model.

Table 7: Groundwater balance in natural situation as simulated by the model. Italic and bracketed net lake seepage is added for comparison to literature range.

Hydrogeologic budget item	Range from literature	HIGH bed leakance model		LOW bed leakance model	
	Mm^3/yr	m^3/d	Mm^3/yr	m^3/d	Mm^3/yr
Total inflow	**135±100**	**445013**	**162.4**	**428957**	**156.6**
Recharge	80±50	232888	85.0	232888	85.0
Lake seepage (net)	55±50	*(159520)*	*(58.2)*	*(150721)*	*(55.0)*
Lake seepage	-	190448	69.5	174261	63.6
River	unknown	21677	7.9	21809	8.0
Total outflow	**95±75**	**445025**	**162.4**	**429024**	**156.6**
Lake seepage	-	30928	11.3	23540	8.6
Constant head boundary North	35±25	134700	49.2	84765	30.9
Constant head boundary South	60±50	279390	102.0	320720	117.1
Discrepancy	*-40±175*	*-0.02%*	*0.0*	*-0.00%*	*0.0*

Table 8: Lake water balance in natural situation as simulated by the model.

Hydrologic budget item	Range from literature	HIGH bed leakance model		LOW bed leakance model	
	Mm^3/yr	m^3/d	Mm^3/yr	m^3/d	Mm^3/yr
Total inflow	**340±70**	**937777**	**342.3**	**930389**	**339.6**
Precipitation	116±20	317808	116.0	317808	116.0
River discharge	215±50	589041	215.0	589041	215.0
Groundwater seepage	-	30928	11.3	23540	8.6
Total outflow	**352±80**	**946612**	**345.5**	**930425**	**339.6**
Evapotranspiration incl. swamp	276±60	756164	276.0	756164	276.0
Groundwater seepage	50±20	190448	69.5	174261	63.6
Discrepancy	-	*-4.64%*	*-3.2*	*-0.02%*	*-0.0*
Characteristics					
Lake stage [m]	-	1887.01		1887.03	
Lake area [km^2]	-	115.65		115.55	
Lake volume [Mm^3]	-	462.30		459.74	

3.3 Flow pattern and water balance under abstractions at FBP

To assess the effect of groundwater abstractions on lake levels, the model is applied including abstractions at FBP. The simulated heads serving as basis for the groundwater contour maps under abstractions are shown in Figure 10 and Figure 11. The equilibrium water balance for the groundwater system is presented in Table 9 and the lake water budget in Table 10.

Flow patterns are similar to the natural situation in most parts of the study area, except around FBP. The cone of depression generated by the abstractions here is clearly seen. The high leakance scenario shows a slightly larger spatial extent than its low counterpart, which in turn is modestly distorted westward.

Considering the groundwater budget, the amounts flowing out of the groundwater model to the north and south do not differ much in the abstraction scenario in both instances. Percentages of northerly and southerly outflow are therefore similar too with respect to the natural situation either.

Considering the lake budget, differences do occur. In the high leakance case, more lake water flows into the groundwater upon pumping than in the natural situation (from 69.5 to 71.0 Mm^3/yr); in the low leakance case this effect is absent. Moreover, less water is flowing from groundwater into the lake upon pumping at FBP (from 11.3 to 10.8 and from 8.6 to 7.3 Mm^3/yr in the high and low bed leakance model, respectively). The ratio between lake outflow to and inflow from groundwater differs more than in the natural situation, with ratios of 6.6 in the high (71.0/10.8) and 8.7 in the low leakance scenario (63.5/7.3).

These differences in budget items result in a lake stage reduction. In the high bed leakance model the new equilibrium lake levels are 0.7 cm lower and in the low leakance model 7.5 cm.

Groundwater levels at FBP are below the lake stage in both instances. The groundwater levels are 1864 and 1868 $masl$ for the high and low leakance case, respectively. Corresponding depths to groundwater at FBP, with a surface elevation of approximately 1910 $masl$, are 56 and 52 m. The drawdown relative to the natural situation is 29 m both parameterizations.

In order to assess the place of origin of the water pumped at FBP and each source's relative contribution, MODPATH and ZONEBUDGET are employed. Path plots for both parameterizations are shown in Figure 12 and Figure 13. Water pumped in the high bed leakance case originates for 96% from higher Kinangop area to the west and for 4% from Malewa River; the low leakance equivalent draws all water from Kinangop. Travel times from the place of origin to FBP range from 6 months for the closest to several decades for the farthest recharge location in both parameterizations.

3.4 Validation

As set out in the research approach, the physically measured groundwater levels that accompany abstractions at FBP provide a means of model validation. The groundwater levels of 1864 and 1868 $masl$ for the high and low leakance case, respectively, correspond to depths of 56 and 52 m. These values compares well with the measured levels as listed in Figure 18 (where groundwater depths reach between 50 – 60 m) and increases confidence in the model. It should be noted, though, that this steady state schematization yields equilibrium heads under 'perpetual' withdrawals. In reality such equilibrium has not set in yet.

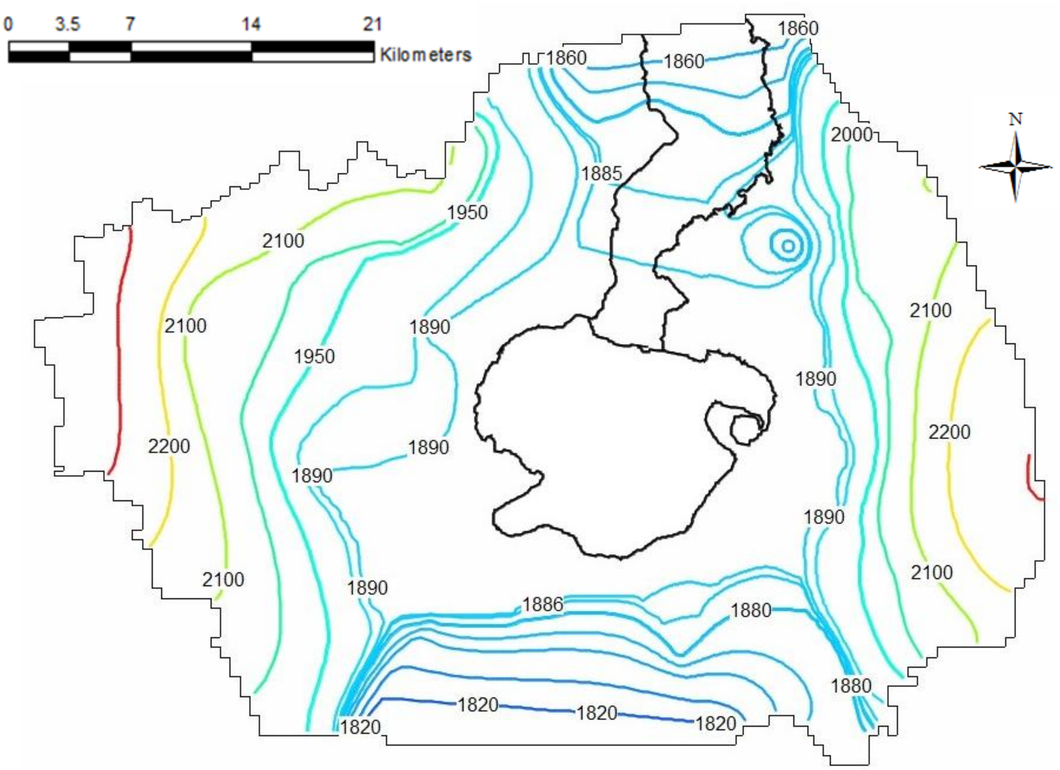

Figure 10: Groundwater contours [*masl*] if abstraction takes place at FBP in HIGH bed leakance model. Note the cone of depression at FBP.

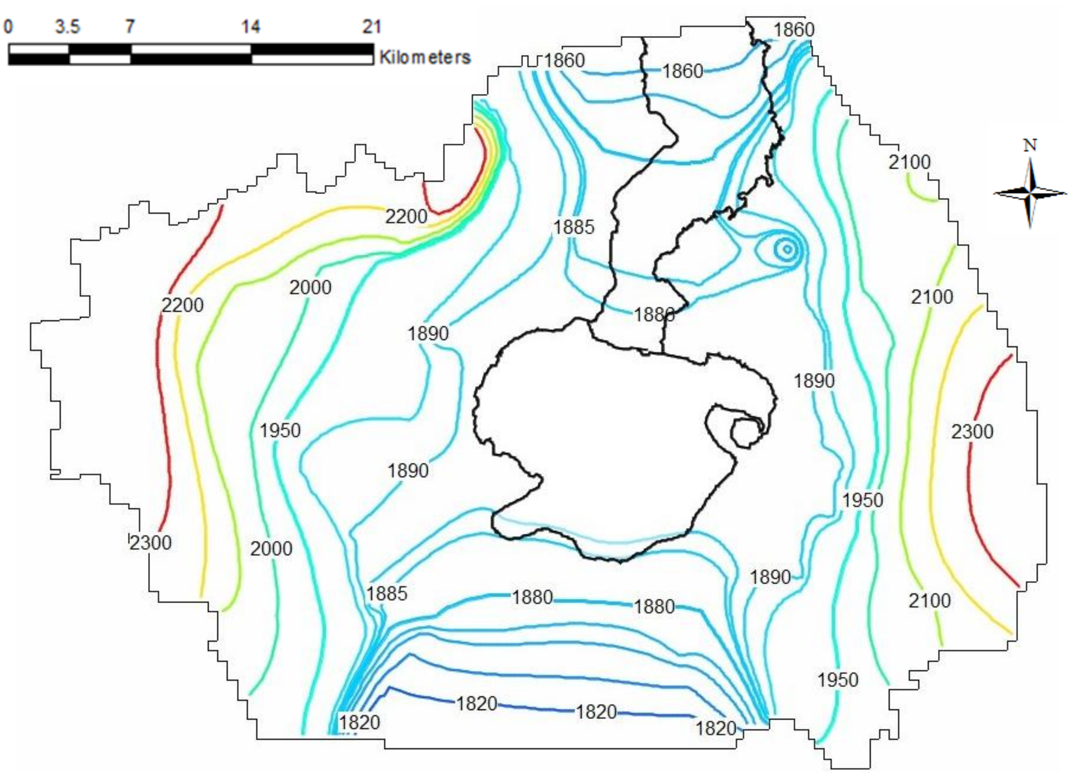

Figure 11: Groundwater contours [*masl*] if abstraction takes place at FBP in LOW bed leakance model.

Table 9: Groundwater balance under abstractions at FBP as simulated by the model. Italic and bracketed net lake seepage is added for comparison to literature range.

Hydrogeologic budget item	HIGH bed leakance model		LOW bed leakance model	
	m^3/d	Mm^3/yr	m^3/d	Mm^3/yr
Total inflow	**449040**	**163.9**	**428753**	**156.5**
Recharge	232888	85.0	232888	85.0
Lake seepage (net)	*(164820)*	*(60.2)*	*(154098)*	*(56.2)*
Lake seepage	194464	71.0	174002	63.5
River	21688	7.9	21863	8.0
Total outflow	**452765**	**165.3**	**433803**	**158.3**
Lake seepage	29644	10.8	19904	7.3
Constant head boundary North	134150	49.0	83820	30.6
Constant head boundary South	279370	102.0	320480	117.0
Wells	9600	3.5	9600	3.5
Discrepancy	*-0.83%*	*-1.4*	*-1.17%*	*-1.8*

Table 10: Lake water balance under abstractions at FBP as simulated by the model.

Hydrologic budget item	HIGH bed leakance model		LOW bed leakance model	
	m^3/d	Mm^3/yr	m^3/d	Mm^3/yr
Total inflow	**939233**	**342.8**	**929493**	**339.3**
Precipitation	317808	116.0	317808	116.0
River discharge	591781	216.0	591781	216.0
Groundwater seepage	29644	10.8	19904	7.3
Total outflow	**950628**	**347.0**	**930166**	**339.4**
Evapotranspiration incl. swamp	756164	276	756164	275.0
Groundwater seepage	194464	71.0	174002	63.5
Discrepancy	*-5.86%*	*-4.2*	*-0.39%*	*-0.2*
Characteristics				
Lake stage $[m]$	1887.00		1886.95	
Lake area $[km^2]$	115.51		115.29	
Lake volume $[Mm^3]$	458.90		453.64	

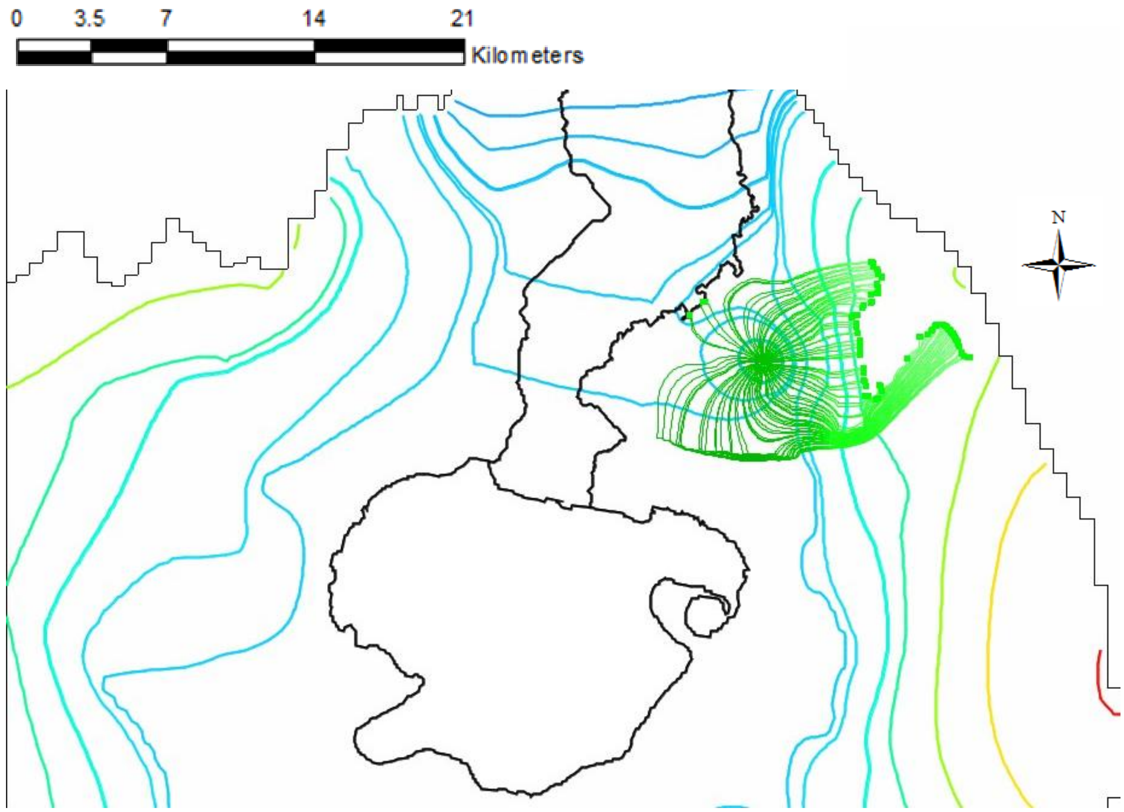

Figure 12: Water particles pumped at FBP traced back to their point of origin in the HIGH bed leakance model.

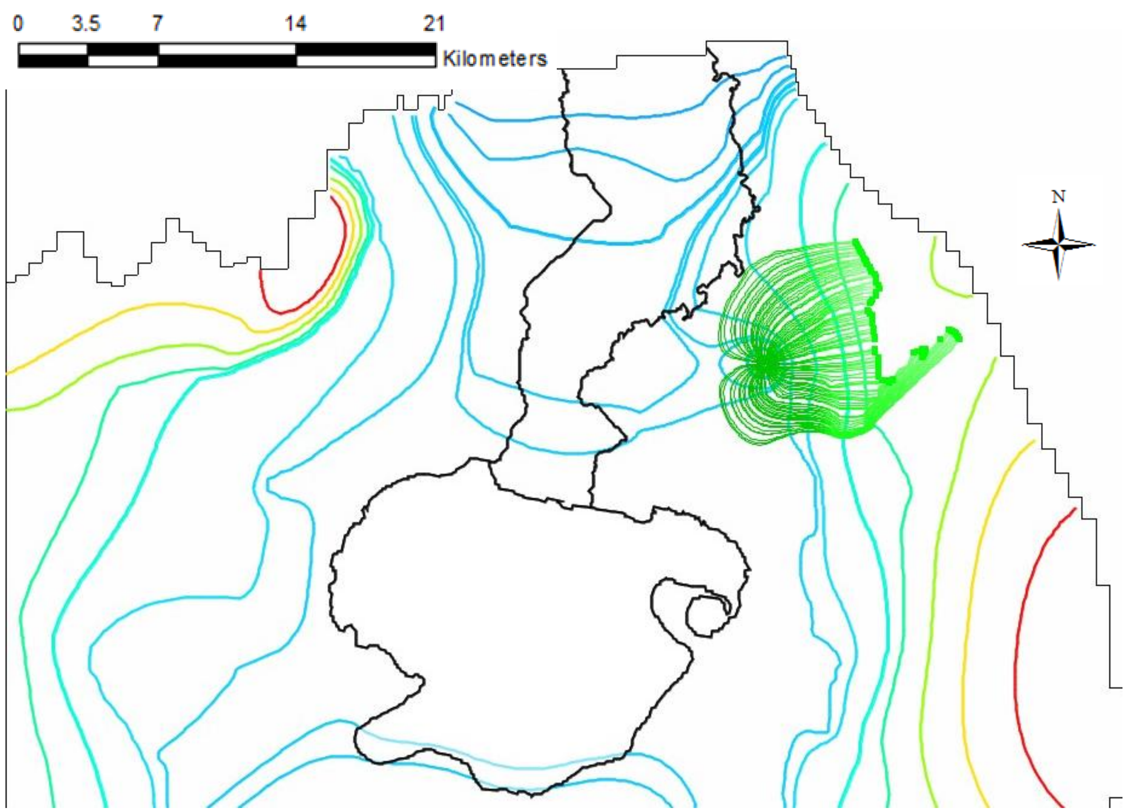

Figure 13: Water particles pumped at FBP traced back to their point of origin in the LOW bed leakance model.

4 Discussion

In the course of this research, assumptions have been made about the groundwater system of the study area and its behavior. As far as possible, these assumptions have been based on available data and literature. During the modeling cycle certain issues came about that are addressed in the first section of this chapter (4.1). Next, the results of the groundwater model are discussed in section 4.2. The chapter concludes with a consideration of the research approach adopted in this study 4.3.

4.1 Data and modeling method

Analysis of the data showed relevant data is scarce or, if available, of mediocre quality. Wells are known to have penetrated multiple water-bearing layers, thereby aggregating pressures. Geographic coordinates can be off by several hundreds of meters on the surface and tens of meters in elevation. Time series, revealing seasonal or annual variations, are generally absent altogether. Fragmented database management introduces additional, unknown uncertainties. Recharge is poorly understood. Underlying meteorological stresses are only sparsely known or are based on significant interpolation endeavors (Meins, 2013a). Besides, the build-up of the subsurface is known to be complex and heterogeneous (Clarke et al., 1990; Thompson and Dodson, 1963).

This lack of appropriate data has often led to speculations on (parts of) system behavior (Legese Reta, 2011; Owor, 2000; Yihdego and Becht, 2013). Such speculative modeling can in the best case prove to be right, but in the worst case give the impression the system is much better understood that in actually is. Water management based on these models may have unintended consequences. To counterbalance this trend, the development of the conceptual model is led by literature and data as much as possible; limited data availability supports only a coarse conceptual model.

One of the drawbacks of having limited data that emerged during conceptual modeling, is that individual, error-prone data points can significantly influence the perception of the system. For instance, one of the major decisions that had to be made when developing the conceptual model was whether or not outflow could occur underneath the Eburru volcanic complex. The geological map (Government of Kenya Ministry of Energy Geothermal Section, 1988) does not indicate such a possibility, but given the younger geological age of the complex than early lake sediments such outflow is conceivable (Thompson and Dodson, 1963). The validity of the assumed boundary condition thus has a weak basis.

Another engaging example is the question whether or not to include well ITC136 into the database (see paragraph 2.1.2). Inclusion led to a southeastern outflow zone between Longonot and Kinangop; exclusion contradicted such a conception.

Substantial inflow into the groundwater system stems from recharge. The water balance method employed to estimate recharge compared monthly precipitation and potential evaporation data. This method itself is known to be only approximate and likely to underestimate recharge. On the other hand, recharge may be overestimated. Rainfall and evaporation stations on which recharge values per polygon have been estimated were not all located within the appointed polygon. Consequently, the rainfall station used in estimating recharge in for instance the Kinangop polygon is located at the highest point of the polygon, where precipitation may be relatively high. Hence, an overestimation of recharge is a possibility. Both under- and overestimation processes make quantification of this uncertainty speculative at best.

As regards to abstractions at FBP, the 4.9 mm/d applied is a gross measure. Mpusia (2006) showed net consumption is 3.5 mm/d. The difference between gross and net abstractions is assumed to become surface runoff and to end up in Lake Naivasha through the Karati River. Since the Karati is not included in the model as a river due to its ostensibly insignificant contribution, the residual is accounted for by adding it to the lake. This amount, which equals 1 Mm^3/yr, may however, in whole or in part return to the groundwater or evaporate from the greenhouses. In this case the model overestimates lake inflow.

Considering calibration, the uncertainty attributed to many (if not all) model parameters qualifies other parameters besides hydraulic conductivity for calibration too. Few data exists on river bed leakance, stressors to the lake are variable and, as mentioned above, recharge is ambiguous. The fact that this study tried to generate two non-unique calibration sets for the same schematization, while only altering bed leakance, underscores this issue. However, even within the current calibration sets, the extents of the 26 predefined hydraulic conductivity zones are debatable as to their necessity or appropriateness. In retrospect, the subterfuge of reducing the number of zones by fixating certain polygons might have been anticipated: the ratio observations over calibration parameters is rather low. Still, a further simplification of the model by reducing the number of zones would likely fail to turn out the desired spatial resolution.

In the present schematization, the flipside of the more detailed zoning of the aquifer came to light in automated calibration through UCODE. The low number of observations in combination with the large number of degrees of freedom allowed UCODE a vast range of possible, physically valid outputs. After all, plausible values for hydraulic conductivity envelop many orders of magnitude. The effect of starting values could thus be detected, especially in the observation-scarce mountainous polygons. Caution is prompted when considering these fringe areas.

Regarding the difference between the low and high calibration outputs, many interplays between hydraulic conductivity values of different zones are at work. Of importance seems the location of the lake on the culmination of the valley floor, which, in a rather leaky lake tends to drain the lake more easily than under sealed conditions. At the same time, lateral recharge from the eastern and western mountains more easily enters the lake when it is leaky as well. The amounts of lake inflow and outflow support this idea: more water flows (laterally) into the lake (11.3 versus 8.6 Mm^3/yr) and more water flows (longitudinally) out of the lake (69.5 versus 63.3 Mm^3/yr) in the high bed leakance case than in its low equivalent. Although net lake outflow to groundwater is approximately the same in both parameterization at 55 Mm^3/yr, the larger outflow component in the leaky lake increases the amount of water routed through the lake to the northern and southern outlets, rather than directly from the mountains to the outlets. To prevent this excess outflow of water from overestimating heads along the north – south flow path, hydraulic conductivity of this part of the aquifer (polygon 6, see Figure 17) has to increase with respect to the low bed leakance case (615 and 94 m/d , respectively). In turn, to prevent the whole groundwater system from draining in the high bed leakance case, the lowered hydraulic conductivity of fringe polygon 7 (6.33 m/d) with respect to its low equivalent (15.36 m/d)

functions as a stop, keeping the water in the system. The small gradients encountered in this north – south transect allow both parameterizations without significantly increasing error metrics (Table 5).

Polygon 6 is one of the most important polygons for the present study (see Figure 17) in governing flow around the lake. Despite both low and high leakance case calibrations yielded physically feasible values, the horizontal hydraulic conductivity of the lake area polygon is in the high range of plausible values in the high leakance parameterization. The polygon assumes a value of 615 m/d, which is equivalent to well sorted sand and gravel or highly fractured rocks (Fetter, 2001). Borelogs, although few and of ambiguous quality, did not reveal this kind of material at such an extent as the 100 m presumed in the conceptual model. A suggestion why this value is found is that the aggregated aquifer incorporates the effects of non-modeled hydraulically active faults and fractures, which ease flow in especially a north-south direction. Both the geological features and this orientation are known to prevail in the area (Government of Kenya Ministry of Energy Geothermal Section, 1988).

Another issue with UCODE is that the objective function of minimizing the sum of squared residuals between observed and simulated heads failed to ensure a physically sound closure of the lake water balance. Manual calibration attempts had to be carried out in this matter. While in the low bed leakance calibration run both groundwater and lake budgets closed with minimal error, the high leakance equivalent reserves a more significant closure error of 4.6%.

Also, by aggregating all possibly water-bearing layers into one modeled layer, hydrogeological properties will be aggregated representations too. This impedes point-to-point comparison of for instance calibrated values for hydraulic conductivity and available data.

What has not been described in this report, but does touch on previous model efforts, is the issue of modeling resolution. During calibration, the grid size was set to 500 m^2 at first throughout the modeled area in order to save calculation time. Upon calibration, cell spacing was refined in the areas of interest to 100 m^2. The calibrated parameter sets at 500 m spacing did not converge for their higher resolution equivalents. Especially around the lake (minor) parameter adjustments had to be made. Apparently, the model is sensitive to the resolution of investigation. Existing spatially distributed groundwater models of the are all use 500 m^2 grids (Legese Reta, 2011; Owor, 2000; Yihdego and Becht, 2013).

4.2 Discussion of results

Both parameterizations of the schematization of the area endorse the view held in literature (Becht et al., 2006; Clarke et al., 1990) of groundwater flowing laterally from the escarpments to the valley floor at large gradients and axially along the valley floor to the north and south at a shallower drop. The percentages of flow, ranging from 21-33% to the north and 67-79% to the south, seem a fair representation of reality. However, the expected but unknown outflow term feeding deeper geothermal layers has by definition been included in either one of output terms. The fact that total modeled (i.e. shallow) outflow is on the relatively high end of the range provided by literature, may indicate shallow outflow is somewhat overestimated to the detriment of (not modeled) deeper outflow.

The model demonstrates in both parameterizations that upon abstractions less water flows from the groundwater into the lake. At the same time, only the high leakance case shows a minor increase from lake to groundwater upon abstractions, while the low bed leakance equivalent does not yield such an outflow. Moreover, the high case lake outflow to groundwater is not directed toward FBP. This is contradictory to the view held by amongst others Becht et al. (2006), as displayed in Figure 2. They assumed FBP draws predominantly water with its origin in the lake. Becht et al. supposedly base their view on the assumption that the cone of depression generated by (FBP) pumping reaches to the lake. Although this still may be the case in reality, where all abstractions are contributing to flow patterns instead of just FBP's, this is not the case in this study's model.

From the numerical schematization this flow pattern can be explained by the hydraulic conductivity encountered in the polygon underlying the lake, which is much higher than that of the FBP polygon. Together with the low northern specified head boundaries, the path of least resistance of water particles originating from the lake is towards the north, rather than northwest to FPB, even in case of abstractions at FBP. Alternatively, from physical processes it can be explained by an interruption of longitudinal flow from Kinangop toward the lake, since both parameterizations indicate that the main source of water for FBP is the easterly Kinangop area (Figure 12 and Figure 13). This recharge, which would have fed the lake, is now prematurely abstracted in favor of FBP's horticulture.

Continuing on the water pumped, ZONEBUDGET showed that water pumped in the high bed leakance case originates for 96% from the higher Kinangop area to the west and for 4% from the Malewa River. The low leakance equivalent eventually draws all water from Kinangop. The fraction ascribed to the Malewa is to a great extend governed by the conductance assigned to the river bed sediments. This value is highly uncertain. The fraction of water pumped at FBP may thus very well be higher or lower, depending on this parameter. The fact that the high lakebed leakance case draws from the Malewa and the low case does not can be explained by the higher hydraulic conductivity assigned to the lake area polygon (ID 6) in the former parameterization. Resistance to flow from FBP towards the west is diminished, which is depicted by the distorted cone of depression (see Figure 11).

An explanation for the difference between lake level reductions in both bed leakance parameter sets is sought in the sensitivity of the inflow and outflow balance in the equilibrium situation. It appears that this balance is more delicate in the low bed leakance case, where disturbances to the system such as pumping, lead to a greater lake stage reduction than its high leakance equivalent (7.5 cm versus 0.7 cm). A suggestion why this is so is found in the steeper gradients in the proximity of the lake in the low leakance case than in the high bed leakance case. A minor alteration may significantly impact the new equilibrium stage assuming the lake is sealed, whereas in the leaky lake case the better conducting aquifer underlying the lake may even out disturbances over a larger area, thereby mitigating the effect on the new equilibrium stage. Another part of the explanation is the ineluctable closure error (Table 8) of the lake balance in the high bed leakance parameterization.

This study builds on the water balance model developed by Van Oel et al. (2013). This model showed lake levels are lowered by about 3 m when taking into account all known abstractions around the lake, both from surface and groundwater. If the total amount of abstractions is artificially drawn from groundwater, the lowering of lake levels is estimated at about 1 m. Note that the period under consideration is 1990 – 2010 in this dynamic, i.e. unsteady state, cascade model. In the current groundwater model, the effect of the abstractions on lake levels differs in both parameterizations (0.7

cm and 7.5 cm, for the high and low bed leakance case, respectively), but these reductions are due to pumping at FBP only. Abstractions at FBP account for about 10% of total groundwater abstractions (see section A.6). A quick linear extrapolation yields a lake stage lowering of 7 – 75 cm due to groundwater abstractions. The former seems rather low with respect to the 1 m of the cascade model; the latter compares well. This calculation is merely approximate, given the spatial layout of abstraction points throughout the area and their associated hydraulic links with the lake. Further study is needed to assess the effect of total combined abstractions on lake levels.

4.3 Research approach

This study aimed at developing a data-driven spatially distributed groundwater model to assess the effect of abstractions on lake levels. Little is understood of the groundwater system and undisputed aquifer mapping is absent. Relevant data is scarce and if available of mediocre quality. Time series are absent altogether. Besides, the statistical exercises on the abstraction time series (section A.6) proved useful in their most elementary consideration of groundwater behavior. It seems legit to ponder whether such a circumstantial finite difference modeling exercise is justified by the data and the succinct understanding of the system. Perhaps analytical exercises are as beneficial for local assessment.

On the other hand, even the present schematization may not do justice to the complex hydrogeological build-up of the area and related difficulty to aggregate scarce spatial observations to areal averages. More detail may have to be included in the conceptual model.

Although the need for additional, high quality data is assented to and hydrogeological complexity is appreciated, it is believed that the adopted approach suffices to reach the objective. Despite data-scarcity, this relatively simple conceptual model seems capable of fulfilling the purposes of learning and exploring the effect of abstractions on lake levels. Only incidentally had to be resorted to speculation on system behavior, for instance with the definition of hydraulic conductivity zones. Spatially distributing hydrogeological properties, however, was deemed requisite to obtain differentiated groundwater levels at the lowest resolution needed. Nonetheless, introducing additional (avoidable) degrees of freedom to the model has been prevented. Given that both parameterizations in the schematization seem valid – calibration assumed physically feasible values for hydraulic conductivity; flow patterns and water budgets of lake and groundwater coincide with literature and abstraction scenarios yield similar drawdown at FBP as measured – it is judged a serviceable sequel in understanding Naivasha's water system.

5 Conclusions and recommendations

The objective of this research was to determine the influence of groundwater abstractions on Lake Naivasha's water level, by modeling groundwater flow around the lake. The research questions set out beforehand are answered in section 5.1, followed by recommendations for use of these findings and further research (5.2).

5.1 Conclusions

1. *How can the exchange of water between Lake Naivasha and the surrounding aquifer system be modeled?*

Due to the large uncertainty concerning the conception of the groundwater system around Lake Naivasha and the scarcity of conclusive data, it is believed multiple numerical schematizations can be developed that may plausibly simulate exchange of water between the lake and its surrounding aquifer. To verify this claim and to answer this research question, a MODFLOW groundwater model was developed for two lakebed leakance values: a high value of 0.215 d^{-1} representing a rather leaky lakebed and a low value of 0.01 d^{-1} representing a rather sealed lakebed. This resulted in two non-unique calibration parameter sets, one for each bed leakance value. Lack of requisite time series inhibited transient modeling, so the model is restricted to a steady state analysis.

The conceptual model consists of one 100 m thick confined aquifer with no-flow boundaries assigned to the west and east and a constant head at 1850 $masl$ to the north around Gilgil and 1800 $masl$ underneath Hell's Gate. Recharge was estimated via a simple water balance method. The rivers Malewa and Gilgil were represented by MODFLOW's River Package; Lake Naivasha by the Lake Package.

Calibration involved adjusting 26 hydraulic conductivity zones, both automated through UCODE and manually by trial and error, whilst minimizing the Root Mean Square error and Mean Absolute Error between simulated and observed heads. In both parameterizations RMS and MAE ranged from 5 – 7 m. Groundwater budgets closed in both instances, as did lake balances, although the high bed leakance case has an ineluctable closure error of 4.6%. All budget items are enveloped by literature estimates. Hydraulic conductivity assumed physically feasible values, overall increasing from the mountains towards the lake.

Upon abstracting groundwater at FBP, simulated groundwater depths in both parameterizations coincide with the observed depth of 50 – 60 m. This partial validation supports the claim that the method described above suffices to model the exchange of water between Lake Naivasha and the surrounding aquifer system and thereby achieve the objective set for this research.

2. *What do flow patterns and water balances look like under natural conditions?*

Flow patterns under natural conditions exhibit similar behavior in both parameterizations, i.e. laterally from the escarpments to the valley floor with relatively steep gradients and axially from Lake Naivasha to the north and south with a smaller drop. Outflow from the lake occurs to the north and south, while inflow takes place in the east and west. The high bed leakance model shows smaller gradients toward the north than its low bed leakance equivalent.

Simulated outflow from the groundwater system under natural conditions is on the high end of the spectrum estimated in literature (162.4 and 156.6 Mm^3/yr for the high and low bed leakance case versus 95±75 Mm^3/yr in literature). The percentages of northerly and southerly outflow are 33% and 67% for the high leakance model, respectively, and 21% and 79% for the low leakance case. The fact that total modeled (i.e. shallow) outflow is on the relatively high end of the range provided by literature, may be ascribed to an overestimation of shallow outflow to the detriment of (not modeled) deeper outflow to geothermal aquifers.

Considering the simulated lake water balance under natural condition, net amounts of lake outflow into groundwater take the same order of magnitude as postulated in literature (55±50 Mm^3/yr). This being said, the amounts of and ratio between lake outflow and inflow does differs between the high and low leakance model. The former shows 6.2 times as much lake outflow to groundwater as inflow (69.5/11.3) compared to 7.4 in the latter case (63.6/8.6). In both instances, however, these ratios show that the lake is not merely draining water to groundwater (longitudinally), but also receives significant inflow from (lateral) recharge.

3. *What is the effect on flow patterns, water balances and lake levels of groundwater abstractions at the Flower Business Park?*

Flow patterns affected by FBP abstractions are similar to the natural situation in most parts of the study area, except around FBP, where a cone of depression is generated by the abstractions. The high leakance case shows a slightly larger spatial extent of this cone than its low counterpart.

Considering the groundwater budget under abstraction conditions, the amounts (and hence percentages) flowing out of the groundwater model to the north and south do not differ much in the abstraction case with respect to the natural situation in both parameterizations.

Considering the lake budget under abstraction conditions, differences do occur. In the high leakance case, more lake water flows into the groundwater upon pumping than in the natural situation (from 69.5 to 71.0 Mm^3/yr); in the low leakance case this effect is absent. Moreover and more interestingly, less water is flowing from groundwater into the lake upon pumping at FBP (from 11.3 to 10.8 and from 8.6 to 7.3 Mm^3/yr in the high and low bed leakance model, respectively). The ratio between lake outflow and inflow differs more than in the natural situation, with ratios of 6.6 in the high (71.0/10.8) and 8.7 in the low leakance scenario (63.5/7.3). The reduced inflow from groundwater into the lake is ascribed to the interruption of recharge from Kinangop to the lake by FBP abstractions. This recharge, which would have fed the lake, is now prematurely abstracted in favor of FBP's horticulture. This view is contrary to Becht et al. (2005), but is favored by both parameterizations in the current groundwater model: water pumped at FBP originates for the greatest part from the higher Kinangop area to the west. Hence, the bulk of water drawn at FBP has recharge as its source, rather than the lake.

Flow paths and water balance differences under abstractions at FBP combined show that the effect of FBP abstractions is a reduction of Lake Naivasha's water level. In the high bed leakance model the new equilibrium lake level is 0.7 cm lower than in the natural situation and in the low bed leakance model 7.5

cm. A suggestion why these reduction figures differ is found in the steeper gradients in the proximity of the lake in the low leakance case than in the high bed leakance case. A minor alteration may significantly impact the new equilibrium stage assuming the lake is sealed, whereas in the leaky lake case the better conducting aquifer underlying the lake may even out disturbances over a larger area, thereby mitigating the effect on the new equilibrium stage. Another part of the explanation is the ineluctable closure error of the lake balance in the high bed leakance parameterization.

FBP abstractions account for about 10% of total groundwater abstractions according to the 2010 Water Abstraction Survey (De Jong, 2011c). Since FBP was the only abstractor with reliable abstraction estimates, the aggregated effect of all individual abstractions, both from groundwater and surface water, remains to be evaluated. Nonetheless, linearly extrapolating the current findings about lake level lowering under abstractions at FBP to all groundwater abstractions, yields a preliminary range of 7 – 75 cm.

Note that every estimate regarding the behavior of the groundwater system based on the groundwater model developed in this study carries with it the uncertainty in the conceptual model and its input data, both of which are known to be significant, as is underscored by the possibility to generate two non-unique but valid sets of calibration parameters.

5.2 Recommendations

Given the uncertainty encountered in the conceptual model, its input data and thus its outcome, the following admonitions and recommendations are warranted.

First and foremost this model should not be used for purposes other than exploration and learning of system behavior. The model has not been properly validated, as was inhibited by lack of data. Using model predictions to establish water management policy would be premature.

Even in the current model, exploring the behavior of the groundwater system in the fringes of the modeled area, i.e. Mau and Kinangop, requires caution. The few observations in these regions do not substantiate any conclusions drawn from processes encountered here.

No conclusive choice for either bed leakance case could be made. Before continuing use of this model, an additional validation should be carried out in for instance the form of isotope analysis of water pumped at FBP, establish its origin. Any lake water detected renders this model invalid and should prevent it from being used in the current form.

If recharge is found to be its primary source, however, the model could prove useful in increasing understanding of the effects abstractions have on lake levels. In this case, an important next step would be to explicate other abstraction points as well. For this, all major abstractors, such as farms but also public water supply, should be monitored. Alternatively, irrigated area could be estimated from satellite images and assuming a feasible application rate per hectare.

Furthermore, the current modeling exercise may be extended or updated with a number of data sets. It is suggested the following data should be acquired.

As mentioned above, abstraction data would be the most useful first addition. Obtaining additional heads, at least in the fringe areas, augments the spatial resolution of observation and is requisite for improving the model parameterizations for mountain polygons. Measuring heads just north and south of the outlet transects could substantiate the boundary conditions assumed in this study. Time series of heads should be collected in the direct proximity of the lake for future transient modeling. Historical head recording sites should be revisited and geodetically surveyed to establish confidence in the geographical position and elevation of these boreholes. Another possibility of improving quality of historical data is to scrutinize the hardcopy colonial data at ITC by someone with local expertise, to locate or verify incomplete records. Obtaining additional transmissivity and storage values would be meaningful at FBP in particular. It is suggested an observation well is drilled next to FBP and carry out pumping tests. To establish recharge, evapotranspiration could be measured at more locations with a higher temporal resolution than the current monthly increment. If funds allow, drilling lake and river bed sediments may underscore leakance assumptions.

Once the conceptual model is substantiated with (parts of) this additional data and sufficiently validated, a transient version of the model could be developed. This transient groundwater model could eventually be linked to a surface water model like SWAT or PRMS to allow for integrated surface-groundwater modeling.

References

Abdulahi, B. H. (1999). Surface water - groundwater interaction. Lake Naivasha, Kenya. MSc, ITC.

Anderson, M. P. and W. W. Woessner (1992). Applied Groundwater Modeling: Simulation of Flow and Advective Transport. London, Academic Press, Inc.

Åse, L. E. (1987). "A Note on the Water Budget of Lake Naivasha, Kenya - especially the role of *Salvinia molesta* Mitch and *Cyperus papyrus L.*" *Geografiska Annaler* **69A**.

Åse, L. E., K. Sernbo and P. Syren (1986). Studies of Lake Naivasha, Kenya and its Drainage Area. Forskningsrapport. Stockholm, Naturgeografiska Institutionen, Stockholm University. **63**.

Baker, B. H. and J. Wohlenberg (1971). "Structure and Evolution of the Kenya Rift Valley." *Nature* **229**(5286): 538-542.

Banta, E. R. (2011). ModelMate -A graphical user interface for model analysis. U.S. Geological Survey Techniques and Methods, U.S. Geological Survey Techniques and Methods. **6-E4**.

Beadle, L. C. (1932). "Scientific results of the Cambridge Expedition to the East African Lakes, 1930-1.—4. The waters of some East African Lakes in relation to their fauna and flora." *Journal of the Linnean Society of London, Zoology* **38**(258): 157-211.

Becht, R. (2007). Environmental Effects of the Floricultural Industry on the Lake Naivasha Basin. Enschede, ITC.

Becht, R. and D. M. Harper (2002). "Towards an understanding of human impact upon the hydrology of Lake Naivasha, Kenya." *Hydrobiologia* **488**.

Becht, R., R. Mwango and F. A. Muno (2006). Groundwater links between Kenyan Rift Valley lakes. Enschede, ITC.

Becht, R. and J. R. Nyaoro (2006). The influence of groundwater on lake-water management: the Naivasha Case. Enschede, ITC.

Becht, R., O. Odada and S. Higgins (2005). Lake Naivasha : experience and lessons learned brief. International Lake Environment Committe Foundation (ILEC), Kusatsu, In: Lake basin management initiative : Experience and lessons learned briefs. including the final report: Managing lakes and basins for sustainable use, a report for lake basin managers and stakeholders.

Bergner, A. G. N. and M. H. Trauth (2004). "Comparison of the hydrological and hydrochemical evolution of Lake Naivasha (Kenya) during three highstands between 175 and 60 kyr BP." *Palaeogeography, Palaeoclimatology, Palaeoecology* **215**(1–2): 17-36.

Brugnach, M. and C. Pahl-Wostl (2007). A broadened view on the role for models in natural resource management: Implications for model development. Adaptive and IntegratedWater Management. Coping with Complexity and Uncertainty. C. In Pahl-Wostl, Kabat, P. and J.Möltgen, Springer.

Clarke, M. C. G., D. G. Woodhall, D. Allen and G. Darling (1990). Geological, volcanological and hydrogeological controls on the occurrence of geothermal activity in the area surrounding Lake naivasha, Kenya. Nairobi, Ministry of Energy, Kenya.

Darling, W. G., D. J. Allen and H. Armannsson (1990). "Indirect detection of subsurface outflow from a Rift Valley Lake." *Journal of Hydrology* **113**: 297-305.

Darling, W. G., B. Gizaw and M. K. Arusei (1996). "Lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley: isotopic evidence." *Journal of African Earth Sciences* **22**(4): 423-431.

Davis, J. C. (2002). Statistics and Data Analysis in Geology. Kansas, John Wiley & Sons.

De Jong, T. (2011a). Review on riverwater resource monitoring and allocation planning in the Lake Naivasha Basin, Kenya. BSc, Wageningen University.

De Jong, T. (2011b). Water abstraction survey. Internship report, Internship report. WRMA / SNV / University of Wageningen.

De Jong, T. (2011c). Water Abstraction Survey in Lake Naivasha Basin, Kenya. Internship report. Wageningen, University of Wageningen.

Deltares (2011). Groundwater Model for the Lake Naivasha Area, Kenya. F. Kloosterman and R. Becht. Delft, Deltares.

DIC (2003). Preparatory study on the water and sewerage system of Naivasha Town in Kenya. Nairobi, Development Impact Consulting.

Everard, M., J. A. Vale, D. M. Harper and H. Tarras-Wahlberg (2002). "The physical attributes of the Lake Naivasha catchment rivers." *Hydrobiologia* **488**(1-3): 13-25.

FBP (2013). Groundwater data Flower Business Park. FBP. Naivasha, ITC.

Fetter, C. W. (2001). Applied Hydrogeology. New York, Pearson Education International.

Freeze, R. A. and J. A. Cherry (1979). Groundwater. Englewood Cliffs, N.J., USA, Prentice-Hall, Inc.

Gaudet, J. J. and J. M. Melack (1981). "Major ion chemistry in a tropical African lake basin." *Freshwater Biology* **11**.

Government of Kenya Ministry of Energy Geothermal Section, k. (1988). Geological Map of Longonot Volcano, the Greater Olkaria and Eburru Volcanic Complexes, and Adjacent Areas. Nairobi, Kenya.

Harbaugh, A. W. (1990). A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model. U. S. G. Survey, U.S. Geological Survey. **90-392**.

Harbaugh, A. W. (2006). MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process., U.S. Geological Survey - Techniques and Methods.

Hogeboom, R. (2012). On the influence of groundwater abstractions on lake levels - Literature Study. Enschede, ITC.

Joliceur, J. L. C. (2000). Groundwater contamination potential of agriculture around Lake Naivasha: Comparison of five unsaturated soil zones models. MSc, ITC.

Kibona, S. R. U. (2000). Temporal and spatial varation of groundwater level north of Lake Naivasha, Kenya (Analysed using Modflow). MSc, ITC.

Kruseman, G. P. and N. A. De Ridder (1994). Analysis and evaluation of pumping test data. Wageningen, International Institute for Land Reclamation and Improvement.

Legese Reta, G. (2011). Groundwater and Lake water balance of Lake Naivasha using 3-D transient groundwater model. MSc, ITC.

LNGG (2001). Lake Naivasha water resource management programme. Water Status Report. Lake Naivasha Growers Group. Naivasha.

LNROA (1993). A three phase environmental impact study of recent developments around Lake Naivasha. Lake Naivasha Riparian Owners Association. Nairobi, John Goldson Associates.

Małloszewski, P. and A. Zuber (1992). "On the calibration and validation of mathematical models for the interpretation of tracer experiments in groundwater." *Advances in Water Resources* **15**(1): 47-62.

McCann, D. L. (1974). Hydrogeologic investigation of Rift Valley catchments, United Nations - Kenya Government Geothermal Exploration Project.

Meins, F. M. (2013a). Evaluation of spatial scale alternatives for hydrological modelling of the Lake Naivasha basin, Kenya. MSc., University of Twente.

Meins, F. M. (2013b). Evapotranspiration data Naivasha basin. Enschede, ITC.

Meins, F. M. (2013c). Precipitation data Naivasha basin. Enschede, ITC.

Meins, F. M. (2013d). River runoff Naivasha basin. Enschede, ITC.

Mekonnen, M. M., A. Y. Hoekstra and R. Becht (2012). "Mitigating the Water Footprint of Export Cut Flowers from the Lake Naivasha Basin, Kenya." *Water Resources Management* **26**: 3725–3742.

MOWD (1982). Lake Naivasha water level variations. . Kenya Ministry of Water Development (MOWD) Directorate of Public Works, Nairobi, Kenya.

Mpusia, P. T. O. (2006). Comparison of water consumption between greenhouse and outdoor cultivation. . MSc, ITC.

Musota, R. (2008). Using WEAP and scenarios to assess sustainablility water resources in a basin - Case study for Lake Naivasha catchment, Kenya. MSc, ITC.

Muthuwatta, L. P. (2001). Long term rainfall-runoff-lake level modelling of the Lake Naivasha basin, Kenya. MSc, ITC.

MWI (2012). Lake level data Lake Naivasha, Kenya. M. o. W. a. Irrigation. Nairobi, ITC.

Nadibe, I. K. (2002). Development of 3d conceptual hydrogeological model for lake naivasha area. MSc, ITC.

Nalugya, E. (2003). Estimation of direct recharge on natural vegetations of the Lake Aquifer (A case study of Lake Naivasha basin, Kenya). MSc, ITC.

NG-IA. (2013). Retrieved retrieved July 2013, from http://earth-info.nga.mil/GandG/coordsys/online datum/DatumTable.html#ADINDAN.

Nilsson, E. (1932). Quaternary Glaciations and Pluvial Lakes in Britisch East Africa. PhD, Stockholm Hogskola.

Odada, E. O. and D. O. Olago (2002). The East African great lakes : limnology, palaeolimnology, and biodiversity. Dordrecht, Kluwer Academic Publishers.

Odongo, V. O. (2010). Uncertainty in reflectance factors measured in the field: implications for the use of ground targets in remote sensing. PhD, ITC.

Ojiambo, B. S. (1996a). Characterization of Soutern Lake Naivasha Flow System using δ18O, δD isotopes and 3H/ 3He age dating PhD Diss. Reno, University of Nevada.

Ojiambo, B. S. (1996b). Characterization of subsurface outflow from a closed-basin freshwater tropical lake using major ions and strontium isotopes. PhD Diss. Reno, University of Nevada.

Ojiambo, B. S. (1996c). Hydrogeologic Investigation of Groundwater Flow System South of Lake Naivasha, Kenya. PhD Diss. Reno, University of Nevada.

Oppong-Boateng, R. (2001). Assessment of the use of groundwater for irrigation in the southern part of Lake Naivasha, Kenya. MSc, ITC.

Owor, M. (2000). The long-term interaction of groundwater with Lake Naivasha, Kenya: a numerical simulation of the relationship between groundwater and lake allowing for fluctuating lake levels. MSc, ITC.

Peel, M. C., B. L. Finlayson and T. A. McMahon (2007). "Updated world map of the Köppen-Geiger climate classification." *Hydrology and Earth System Sciences* **11**: 1633-1644.

Poeter, E. P., M. C. Hill and E. R. Banta (2005). UCODE_2005 and six other computer codes for universal sensitivity analysis, calibration, and uncertainty evaluation constructed using the JUPITER API. U.S. Geological Survey Techniques and Methods, U.S. Geological Survey Techniques and Methods. **6-A11**.

Pollock, D. W. (1994). User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model. U. S. G. Survey, U.S. Geological Survey. **94-464**.

Ramírez Hernández, R. (1999). Groundwater flow modelling of Naivasha basin, Kenya. MSc., ITC.

Ramsar Commission (1996). The Convention on Wetlands of International Importance update. Ramsar Convention 1996 edition, United Nations.

Richardson, J. L. and A. E. Richardson (1972). "History of an African Rift Lake and Its Climatic Implications." *Ecological Monographs* **42**(4): 499-534.

Rushton, K. R. (2003). Groundwater Hydrology - Conceptual and Computational Models. West Sussex, J. Wiley & Sons Ltd.

Sikes, H. J. (1936). "Notes on the hydrology of Lake Naivasha." *Journal of the East African and Uganda Natural History Society* **13**: 73-89.

Simmers, I., J. M. H. Hendrickx, G. P. Kruseman and K. R. Rushton (1997). Recharge of Phreatic Aquifers in (Semi-) Arid Areas. Rotterdam, A.A. Balkema.

Stuttard, M., J. B. Hayball, G. Narciso, M. Suppo, L. Isavwa and A. Oroda (1999). Modelling lake level changes: examples from the Eastern Rift Valley, Kenya., In: Harper, D.M. and A. Brown (eds). The sustainable management of tropical catchments. Wiley.

Thompson, A. O. and R. G. Dodson (1963). Geology of the Naivasha Area. Nairobi, Government of Kenya, Ministry of Commerce and Industry Geological Survey of Kenya.

Tsiboah, T. (2002). 2d resistivity and time-domain EM in aquifer mapping: a case study north of lake Naivasha, Kenya. MSc., ITC.

USGS (2000). Documentation of a Computer Program t Simulate Lake-Aquifer Interaction Using the MODFLOW Ground-Water Flow Model and the MOC3D Solute-Transport Model. Water Resources Investigations Report 00-4167. Tallahassee, FL, USGS.

Van Oel, P. R., D. Mulatu, V. Odongo, F. Meins, R. Hogeboom, R. Becht, A. Stein, J. Onyando and A. Veen (2013). "The Effects of Groundwater and Surface Water Use on Total Water Availability and Implications for Water Management: The Case of Lake Naivasha, Kenya." *Water Resources Management*: 1-16.

Van Oel, P. R., V. O. Odongo, D. W. Mulatu, J. W. Ndungu, F. K. Muthoni, J. Ogada, G. Khroda, J. M. Mathooko, R. Becht, N. Kitaka, J. O. Onyando and A. van der Veen (2012). An Earth Observation and Integrated Assessment (EOIA) Approach for the Sustainable Governance of a Socio-Ecological System: The Case of the Lake Naivasha Basin, Kenya. Water Management Issues in Africa. Port Louis, Mauritius.

Verschuren, D. (2001). "Reconstructing fluctuations of a shallow East African lake during the past 1800 yrs from sediment stratigraphy in a submerged crater basin." *Journal of Paleolimnology* **25**: 297–311.

Verschuren, D., K. R. Laird and B. F. Cumming (2000). "Rainfall and drought in equatorial east Africa during the past 1,100 years." *Nature* **403**(6768): 410-414.

VIAK (1976). Naivasha Water Supply Project - Ground Water Investigation. I. Wiberg. Nairobi, Ministry of Water Development.

Wang, H. F. and M. P. Anderson (1995). Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods. London, Academic Press.

Winston, R. B. (2009). ModelMuse - A graphical user interface for MODFLOW-2005 and PHAST. U. S. G. S. T. a. Methods, U.S. Geological Survey Techniques and Methods.

WRMA (2010). Water Allocation Plan - Naivasha Basin. W. R. M. Authority, Water Resources Management Authority - Republic of Kenya.

WRMA (2013). Groundwater Monitoring dataset Marula, Kinyanjui, Sopa Lodge, Rubiri and Ushirika 2012. D. Wambua.

WWF (2011). Shared Risk and Opportunity in Water Resources: Seeking a Sustainable Future for Lake Naivasha., World Wildlife Fund. **2**.

Yihdego, Y. (2005). A three-dimensional groundwater model of the aquifers around Lake Naivasha area, Kenya. MSc, ITC.

Yihdego, Y. and R. Becht (2013). "Simulation of lake–aquifer interaction at Lake Naivasha, Kenya using a three-dimensional flow model with the high conductivity technique and a DEM with bathymetry." *Journal of Hydrology* **503**(0): 111-122.

Appendices

Appendix A: Data analysis and overview

Both conceptual and numerical modeling require proper quality data regarding numerous system variables. Although ITC keeps a database with all Naivasha related research data, the database fails to present a systematic overview of the inventory. Considerable time has been taken to scavenge through this fragmented database, in addition to obtaining new or unrecorded data from ITC documents, WRMA and FBP. This appendix provides an overview of hydrogeologic and abstraction data known to this author, a scrutinizing of data quality and, if applicable, further (statistical) analysis. For hydrologic data reference is made to the work of previous MSc student Frank Meins (2013c), whose data is used without further analysis. Please note that the data and literature references mentioned here are by no means exhaustive or conclusive.

Table 11:Inventory of data. Specifications in bold have been taken up in the following paragraphs of this chapter.

Theme	Specification		Source	Reference
Geography	Digital Elevation Model (DEM), 50m cell size, calibrated with GPS surveyed wells.		Literature	Owor (2000)
	Bathymetry map Lake Naivasha, incorporated in DEM.		Literature	Owor (2000)
Land use and vegetation	Land use and vegetation, shapefile from satellite images.		Literature	Odongo (2010)
Hydrology	Precipitation, daily and monthly time step 1957-2010 for multiple stations.		Literature+Data	Meins (2013a) Meins (2013c)
	Evapotranspiration, long-term monthly averages (ET_0) for 5 stations (potential ET).		Literature+Data	Meins (2013a) Meins (2013b)
	River runoff, monthly time step 1960-2010 of Malewa, Gilgil and Karati Rivers.		Literature+Data	Meins (2013a) Meins (2013d)
	Lake levels, daily and monthly time step 1943-2012 taken at multiple stations.		Data	MWI (2012)
Hydrogeology	Geological map plus cross-sections (rough) image; digitized into generalized shapefile.		Literature	Government of Kenya Ministry of Energy Geothermal Section (1988) Thompson and Dodson (1963) Owor (2000)
	Stratigraphy. Collected borelogs.		Fragmented	VIAK (1976) Ramírez Hernández (1999) Tsiboah (2002) AMHA (2011), unpublished MSc available in Naivasha room only.
	System boundaries (faults from Geological Map, see above)		Fragmented	-
	Aquifer geometry		Fragmented	-
	Recharge		Fragmented	-
	Heads	Watertabs ITC database	Data+Analysis	Accompanying .xlsx files.
		NKU borehole inventory	Data+Analysis	Accompanying .xlsx files.
		Hardcopy data Naivasha room	Data+Analysis	Naivasha room at UT only
		Bonn University	Data+Analysis	Accompanying .xlsx files.

		FBP	Data+Analysis	FBP (2013)
		WRMA	Data+Analysis	Accompanying .xlsx files.
	Flow patterns		Literature	Becht and Nyaoro (2006)
	Transmissivity		Fragmented	Legese Reta (2011) FBP (2013)
	Storage coefficients		Fragmented	-
	Leakage parameters		None	Kibona (2000)
	Lake – aquifer interaction		None	-
Abstractions	Groundwater abstractions	WAS1997	Data	Naivasha room at UT
		WAS2010	Literature+Data	De Jong (2011c)
		FBP	Data	FBP (2013)
Groundwater models Lake Naivasha	Numerical models	Owor, Reta, Yihdego, Oel et al.	Literature	(Deltares (2011); Legese Reta (2011); Owor (2000); Van Oel et al. (2013); Yihdego (2005); Yihdego and Becht (2013))

From the above Inventory it follows that not all variables can be substantiated by data. If this is the case, i.e. when no data is available, one has to resort to parameter values or claims of system behavior from literature. The difficulty is that most literature references consist of unpublished, not peer-reviewed work done by ITC students. Their claims or results usually are not backed by a systematic quality assessment or sometimes a justification is absent altogether. Even if the reference had been reviewed, it is implausible that underlying data sources had been assessed as well, due to either the scattered nature of the existing database, re-referencing to unpublished work or to the fact that the underlying data may have been available once but was lost in time (e.g. (McCann, 1974)). A retrospective quality assessment thus proved difficult for many sources, if not impossible. This addendum submits available data series to a quality assessment.

A.1 Recharge

Recharge to groundwater is one of the most difficult parameters to estimate (Rushton, 2003). Recharge has many sources such as precipitation recharge, river recharge, irrigation losses, inter-aquifer flows and urban recharge, all of which show high spatial and temporal variability (Simmers et al., 1997).

Few measurements that have been recorded were found. Ojiambo (1996a; 1996b; 1996c) did several experiments, yielding a recharge for the 'study area' of 0.52 m, which seems way to high given the precipitation-evapotranspiration balance. In Nalugya (2003) the following overviews were found:

Table 6.2: The recharge received (1990-1998), after the El Nino

Location	Recharge ($mmday^{-1}$)	Total recharge (1990-1998) (mm)	Average recharge ($mmyear^{-1}$)
Kedong	0 – 7.00	350	43.75
Ndabibi	0 – 0.27	5.5	0.69
Three Point	0 – 0.10	35	4.38
Marula	0 – 5.50	270	33.75

Table 6.3: Direct recharge estimates from a 1-D mixing model.

Type of recharge	Stable isotope	$mmday^{-1}$	$mmyear^{-1}$	Average recharge ($mmyear^{-1}$)
Mixed recharge; Lake, rain,	18-Oxygen	$1x10^{-5} – 7x10^{-5}$	3.65 – 25.55	14.6
	Deuterium	3x10-5 – 7x10-5	10.95 – 32.85	21.9

Figure 14: Results of field work experiments by MSc student Nalugya (2003). Figure taken from his thesis.

Given this small database, attempts have been made in this study to obtain a better estimate for recharge. Focus will be on recharge by precipitation, the evaluation of which will be done using the quick and inexpensive water balance method. Although precipitation recharge is affected by factors such as geologic and hydrologic characteristics of the vadose zone, antecedent moisture, vegetation, precipitation distribution within and between years, local topography, watershed shape etcetera, a simplified water balance to estimate potential recharge is given by:

$$R = P - ET_p$$

Reliability of this method depends on the precision with which precipitation and recharge have been determined; small errors can cause large errors in recharge estimates. Actual recharge will be lower than potential recharge. Averaging over longer periods will also yield lower recharge estimates, so estimates provided by this method will likely be too low (Simmers et al., 1997). With prudent appreciation for these limitations, it is judged the most suitable practice for the Naivasha case.

An overview of the rain stations and evapotranspiration series used is given in Figure 15 and Table 12. The area delineation is based on DEM contours. For an evaluation of the underlying data, see Meins (2013a).

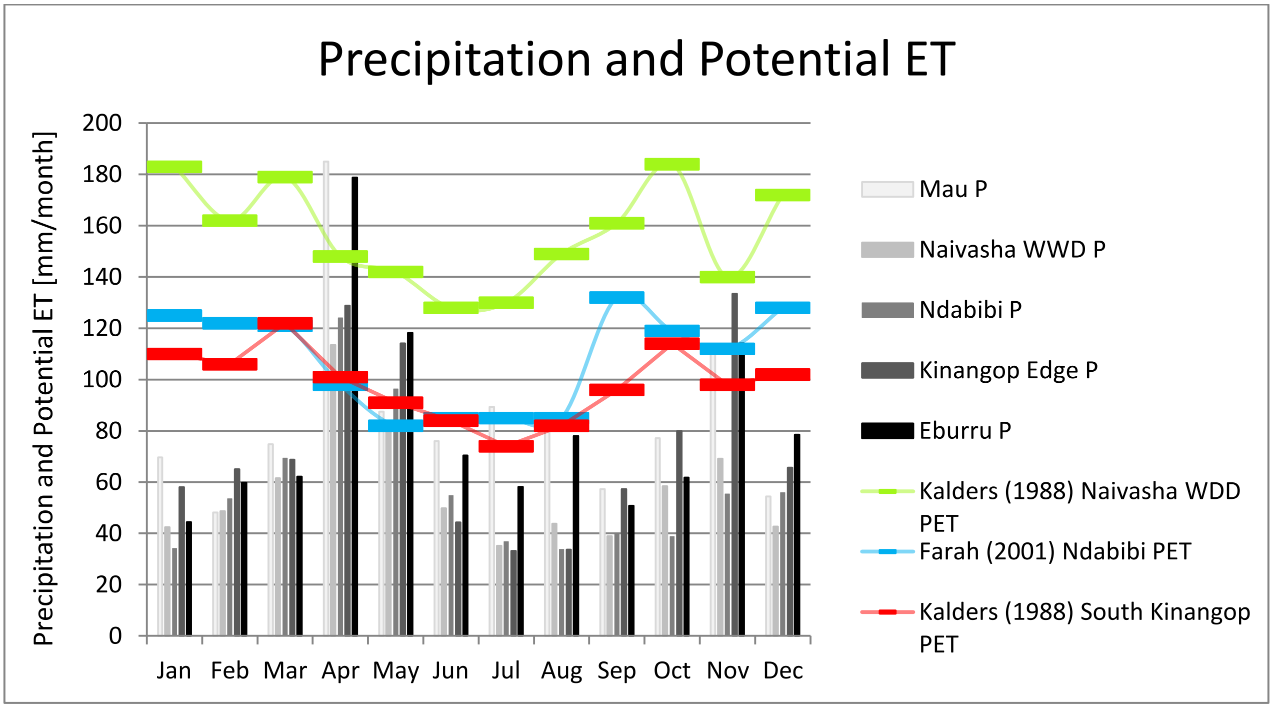

Figure 15: Precipitation and potential evapotranspiration per recharge area.

Table 12: Locations and characteristics of rainfall stations used to estimate recharge per area.

Area	X	Y	Elevation	Rain station	Recharge [mm/yr]	Area [m2]	R [MCM/yr]	
Naivasha WDD	216173	9918908	1996	s9036281	0	408953511	0,0	
Ndabibi	195795	9909602	1882	s9036062	40	206859765	8,4	
Kinangop Edge	227310	9918914	2531	s9036186	86	298623570	25,8	
Eburru	197565	9929962	2350	s9036253	121	156087653	18,9	
Mau	169710	9935480	2531	s9036337	112	217320989	24,4	
							77,5	**Total**

A.2 Piëzometer recordings

Piëzometer recordings had to be retrieved from numerous, sometimes quite chaotic sources. The main sources used are listed here, accompanied by a description of their content and an assessment of their quality. All recordings that stood the test are added to a new database which can be found in the ITC Naivasha dropbox folder under Groundwater. Please note from the assessment given below that the selection of a head reading into this new database is by no means infallible. More is to be gained if someone with local knowledge is willing to spend the time on it.

GroundwaterData and Watertabs database

The most complete piëzometer database available at the beginning of this study is found in ['GroundwaterData.xls'] and its accompanying shapefile ['Groundwaterwells.shp'] and will be referred to as GD. These documents are composed of borehole completion record (see paragraph on Hardcopy data below), and heads recorded by MSc students during their field work (Legese Reta (2011): 32 recordings), but it relies most heavily on the ['Watertabs_2004.xls'] spreadsheet (referred to as WT). GD contains 530 groundwater level readings for 278 borehole UTM-coordinates, starting from 1939.

WT contains transcripts of what seem to be borehole completion records, Msc student recordings and head readings taken during the 1997 Water Resources Abstraction Survey (WRAS). MSc-students generally re-measured existing wells, leveled them with GPS and updated the elevation of the wells. Non-leveled well elevations have to be taken from the DEM. Included in WT is data by most students involved in groundwater modeling: Ramírez Hernández (1999): 3, Abdulahi (1999): 16, Nadibe (2002): 11, Kibona (2000): 31 and Yihdego (2005): 30. All wells in GD and WT had been given an ITC coding, which overwrites the old borehole name, e.g. C-numbers or owner-given names. C-numbers are official borehole IDs under which they are registered by the Ministry of Water Development of Kenya.

GD's UTM-coordinates have been exported from the shapefile and taken as localities of boreholes. GD is taken as the base to be extended with other data sources during this study.

Quality

Location: The accuracy of the location coordinates depends on the original source and the modifications made to them. Most GW coordinates seem to originate from WT. WT's source is partly measurements by students using GPS devices. Their spatial accuracy is in the order of meters. Other sources are unknown, so may contain errors. Most likely they stem from digitized hardcopy borehole completion record. See paragraph 'Hardcopy data in Naivasha room' below for their quality assessment.

For wells without a clear original source, sometimes the owner or farm name is known, providing a means for verification of the UTM coordinates. This is quite an undertaking to do for every well. For time's sake, quality assessment is limited to a manual sample check of certain borehole coordinates. This short analysis indicates GW coordinates may be a few hundred meters off in both spatial directions. Given the high borehole density especially around the NE of the lake this may mean identical boreholes are listed multiple times under slightly different coordinates.

Confusion arises over what datum has been taken for determining positions of boreholes and what transformations have taken place. This is the case for all sources of borehole localities under investigation. Especially colonial bcr's cannot have been geodetically measured in the commonly used WGS84 standard, but probably their geographical coordinates in longitude and latitude are treated as such upon their projection into Cartesian/plane UTM denotation. Also students generally did not mention what datum and/or transformations they applied. Since in general and without resetting the equipment GPS devices are by default set to WGS84, it is assumed that all UTM coordinates mentioned are based on the WGS84 standard.

With some exceptions, WT coordinates were off 95m on the abscissa and 302m on the ordinate axis compared to GW. This is due to translating WGS84 datums into Arc 1960 datums, which is the local projection standard for Kenya (NG-IA, 2013).

If local refinements are to be made in a follow-up study in order to assess groundwater at a higher spatial resolution, more attention to the locality of boreholes is recommended.

Altitude: A similar argumentation goes for borehole altitudes. Wells measured by students have been geodetically surveyed to affirm their altitude with an accuracy in the order of centimeters, but the datum used is of interest. For all other boreholes altitudes are taken from either the altitude listen on the borehole completion record or the DEM. The former margin of error is unknown; the latter will be in the order of meters (up to 20 m). This may prove to be a rather large source of error, especially in the more accentuated areas.

Head reading: As mentioned in the chapter on Hydrogeology, boreholes penetrate multiple layers. The measured head will thus be an aggregated pressure, not representing a specific aquifer. This may mean, for instance, that one shallow borehole record gives only the head of the layer it penetrates, whereas a nearby deeper wells yield a very different reading because of the added pressure of the deeper layers it penetrates. Although for the wells for which a borehole completion record exists some specifics might be retrieved about layering and depth of borehole, no further effort is made to obtain this information. The measurements may be well off, as can be seen for instance in BOX 1

Box 1

	ITC135	**ITC136**
UTM coordinates inventory:	197705E9913027N	197705E9913027N
Altitude [$masl$]:	2132.4	2132.4
Date:	22/03/1957	15/09/1958
Groundwater depth:	21.0	260.3

Other remarks: Recordings, be it dimensional or head, are subject to unquantifiable human measurement errors. Another source of erring is in the unanswerable question whether or not a well had recovered fully upon measuring if the measuring concerns a pumped well. Also, the unsystematic naming of boreholes proved confusing[4].

Some boreholes have been referred to under multiple ITC ID's. If wells were located within 10m of each other, they were taken to be the same borehole. The result showed that no less than 56 ITC ID's referred to only 23 unique wells. Sometimes, the case was that there were multiple valid measurements taken at

[4] Take for an illustration of confusing naming the following: Three Point Farm is the name of a farm located west of Lake Naivasha a great many years ago. The farmer moved to an area north-west of the lake, renaming the farm Three Ostrich Farm. However, the old name was still used by many to refer to this new farm. Sometimes the new farm was referred to as Three Point Ostrich Farm. The farm was taken over by Panda Flower some 15 years ago, which in turn became part of the wider known Flower Business Park. Under all these names recordings are found in documentation. On top of this, Three Point Farm owned a drilling installation which was contracted by other farmers to drill their wells. The name of the well owners however, was sometimes written as Three Point Farm, even though it did not refer to the farm but the drilling agency.

different times in one well; in most cases, however, the double references showed very different and irreconcilable recordings (see BOX X). In these difficult cases the earliest recording was kept as true and the later ones discarded.

Other irregularities were found upon comparing recordings from (Nadibe)from 2001 and (Yihdego) from 2004. In many cases they listed identical head readings, which is dubious if true. It is kept this way, though.

On the other hand, the 1997 WRAS as recorded by water bailiff Opiyo, occasionally shows very *dis*similar values for the same well from Kibona (2000), while measurements were taken only one week apart. In these cases, the most unlikely value from the series has been removed.

Another peculiarity was found for some 1999 recordings. For some unique wells, it listed multiple recordings at the same date, but which again were very dissimilar. One value was attributed to . Abdulahi (1999), while others did not have a name of investigator to it. These latter values have been removed. The above three inconsistencies led to the removal of 16 records.

Again concerning Abdulahi (1999), there are groundwater levels listed for e.g. ITC156-ITC161 for every first of June from 1957 till 1970. This is peculiar, since these dates overlap with the erroneous colonial record (see paragraph 'Hardcopy data in Naivasha room' below). Since no conclusions will be derived from these readings in isolation, they will be kept in the database to serve for rough contour mapping.

Lastly, 51 ITC ID's with recorded XYZ coordinates do not have observations assigned to them. This is peculiar, since why would one create the ID in the first place if no data is available. These BH's are removed if later on in the analysis no observation could be assigned to them, which was the case for 36 of them. All this shows once the more the feeble ground of the whole database.

NKU borehole inventory

The Naivasha – Nakuru borehole inventory, found in ['NKU_BHS.xls'] , contains a listing of 732 C-numbers in Nakuru and Naivasha basins. It seems to be composed by digitally transcribing of hardcopy borehole completion records, but by whom could not be retrieved. Coordinates are given in UTM denotation, although original hardcopy borehole completion records have a longitude – latitude denotation in degrees, implying some modifications have taken place.

Quality

Location: The database displays strange coordinate denotations, with many obvious errors. Conversion from degrees to UTM coordinates using a different map datum may be one of the reasons. However, a systematic split within the dataset to separate conversions per map used could not be retrieved. All ordinate values which were too long due to a 9 too much in them (e.g. **9**9924050 instead of 9924050) have been modified. Both abscissa and ordinate coordinates that clearly fell outside of the study area were discarded of as well. This exercise deleted 489 boreholes for this study. These points may prove useful in the future if correct coordinates can be retrieved from preferably hardcopy records. The remainder has been tested to the extent that a small sample of boreholes with a degree denotation from hardcopy records has been converted to UTM using WGS84 as map datum. The difference was in de order of 10^2 M, which, for the purposes of this modeling exercise was judged fair enough. However, a second cross-checking with WT showed very strange inconsistencies. For some ITC ID's in WT the former

C-number is known. Using this number, WT coordinates of the well under investigation could be compared to its equivalent in NKU database. It turned out that all coordinate values were off by a few to aa few hundred meters, but 23 C-number boreholes deviated from WT by multiple kilometers. These 23 points have been removed from both datasets. Since not all ITC ID's have a (known) C-number, this test could not be done for every C-number in NKU inventory. The only resolution to solving the exact whereabouts of each well is by having an investigator with local knowledge go through all hardcopy completion records and pinpointing them on the map. This exercise is recommended for further research.

Altitude: No altitudes are recorded in the database.

Head reading: As mentioned above, the remainder of the database could only in part be compared to WT coordinates. Since in order to have made the database conversions from feet to meters were necessary and because water struck levels are easily exchanged for water rest levels, the decision was made that only those C-numbers listed in NKU inventory would be taken up for this study if the stated information could be checked for verification from original hardcopy well completion records or other external sources. Hence doing, of the remaining 242 boreholes located within the approximate study area, 158 could be verified by hardcopy data or other sources; 84 could not.

Other remarks: The NKU inventory provides coordinates and water level measurements, but not the date of measurement, well depth and confined – unconfined conditions etc. It is tried for the 158 hardcopy-backed boreholes to complete the missing information. For 36 C-number boreholes all information needed (coordinates, groundwater reading and date of reading) could be retrieved; these 36 wells were added to the overall inventory of this study. Nine of these 36 were already in the overview under different names, so 27 new points added from this exercise.

Of the incomplete remainder, 75 wells are listed inThompson and Dodson (1963). Although no exact date is given here either, it is explicitly stated they were taken before 1956. These wells are not added to the used inventory, but may be useful for drawing historical contours. The remnant of (158-36-75=) 47 boreholes could not be supplemented with more information from the hardcopy backup and are thus left out.

Last, the C-numbers are not continuous nor up to date (higher, more recent numbers lack), implying the inventory is not complete.

WRMA Monitoring Data

WRMA (2013) sent a number of documents containing groundwater level readings at five boreholes in the Naivasha area, taken in 2012. Four of these five wells were new to the database; one had been taken up earlier for previous head recordings.

Quality

How these numbers came to be could not be assessed. The number format indicates an accuracy in the order of centimeters. The layout of the Excel source files is conspicuous, but the readings for the known well seem in accord with previous measurements. This data source added 43 head readings to the database. Of particular interest is the series taken at Marula farm, located just North of the lake, since this large farm is reluctant in sharing its groundwater data.

Hardcopy data in Naivasha room

In the Naivasha room at ITC some hardcopy data is available for analysis. These maps contain a lot of rather unorganized data, which is rearranged by this author to obtain three main pieces of work, which are listed below, and some unidentifiable copies of field work notes.

Quality

Borehole Completion Records: These records were taken by the driller of the well when they were assigned a C-number, to be registered with the authorities. Earliest accounts date back to 1939. Position and elevation determination techniques at the time were not very accurate, but it is difficult to quantify. Accounting of data on the survey forms has generally been done systematically by the colonists. Some wells however, lack coordinates or groundwater level recordings, the latter of which may be due to the fact that the hole was dry, or it was simply forgotten to file. For a few records that did not mention its coordinates, pinpointing the location on a map from farm or owner name provided approximate coordinates after all. Like in the NKU borehole inventory, higher (i.e. more recent) C-numbers are not to the avail of the Naivasha room. The quality of this source is virtually impossible to assess. Still, measurements from these reports are included. All data available has been compared with the digital GW inventory. A number of 71 boreholes or measurements not available digitally but only hardcopy has been digitalized and added to the inventory.

Data edited by Abdulahi (1999): A possibly very valuable hardcopy document contains daily head measurements in 12 wells around the Lake, taken in the period 1957 – 1970 by British colonists has been disregarded for further use for the following reasons. Previous effort have been put into the analysis of this hand-written, colonial record by several researchers, amongst whom Behar Abdulahi. Strange discontinuities as well as outliers are encountered in the time series. Most likely these are at least in part due to datum shifts (with certainty it can be said a 2 ft increment was added in 1962). The visual use of the double-mass analysis employed by Abdulahi is judged inapt to overcome all difficulties with the series. Furthermore, from his thesis it remains unclear what corrections he actually applied to the data based on his analysis results. The fact that the series are linearly related does not 'prove' their reliability. After spending considerable time analyzing them no arguable and conclusive explanation could be found by this author to justify their further use. This is a pity indeed, since it would by far be the longest historical time series of groundwater data available to date.

Water Resources Abstraction Survey 1997: Water bailiff Opiyo conducted an abstraction survey in 1997-1998 for 117 boreholes in the Naivasha area. It does not seem the results have been thoroughly analyzed, although a digital transcript was found on the Naivasha drive. This document was not complete, however, so efforts have been put into the completion of the missing dates and head readings. In total, 64 of the 117 boreholes yielded complete information for the purposes of this study. In the aforementioned WT, the alias of seven WRAS boreholes (identified as BH-numbers) could be retrieved: the figures corresponded well. The remaining 57 recordings most likely are taken into the GD database, but since GD only gives ITC ID's, one on one comparison is troublesome.

Measurements University of Bonn, Germany

Researchers of University of Bonn recorded groundwater measurements in six wells along three transects (two wells form one transect of few hundred meters) approximately perpendicular to but very nearby the lake. Between April and September 2011 they took a measurement every 4-5 days at each of the wells. Given their locality adjacent to the lake, measurements do not deviate much from lake levels .

Quality

Recordings were taken with Nikon AP-7 and Leica 500 GPS leveling equipment, which, if properly employed should yield high accuracy in the order of centimeters. A few relatively small outliers are detected, though. All observations are taken up into the database.

Flower Business Park measurements

Industrial farmers at the Flower Business Park are large-scale consumers of groundwater. Starting in January 2006, monthly water levels and amounts pumped are known until May 2012 (FBP, 2013).

Quality

It is unknown what method has been employed in coming to these measurements. It is implied from their format that the accuracy is in the order of tens of centimeters. At FBP, there are at least nine wells from which water is withdrawn. It is unknown which well exactly the head readings are from. For nine months no recordings were made, gapping the series, mainly in 2008. Apart from this gap, this data series forms the best continuous time series for one specific borehole. Since the effects of FBP abstractions are the focus of this research, these series are highly valuable. A further analysis of this source is given in my MSc thesis.

Summary

In Table 13 a statistical overview is given of the final database resulting from the above mentioned sources. In conclusion it can be said that a large number of boreholes provide only about two head recordings per well aggregated over the entire stratigraphy over an 80 year period. Potentiometric surfaces per aquifer cannot be deduced nor can much be said about the spatial extend of the heads recorded. Seasonal and longer term variations in groundwater levels go largely undetected too.

Table 13: Summary of borehole inventory and observations.

	Number of boreholes	Number of observations	Observations per borehole
Pre 1980	84	201	2,4
After 1980	196	491	2,5
Total	**280**	**692**	**2,4**

	Boreholes with multiple observations	Observations	Observations per borehole	Maximum number of observations
Pre 1980	19	136	7,2	14
After 1980	71	366	5,2	73
Total	**90**	**502**	**6,2**	**87**

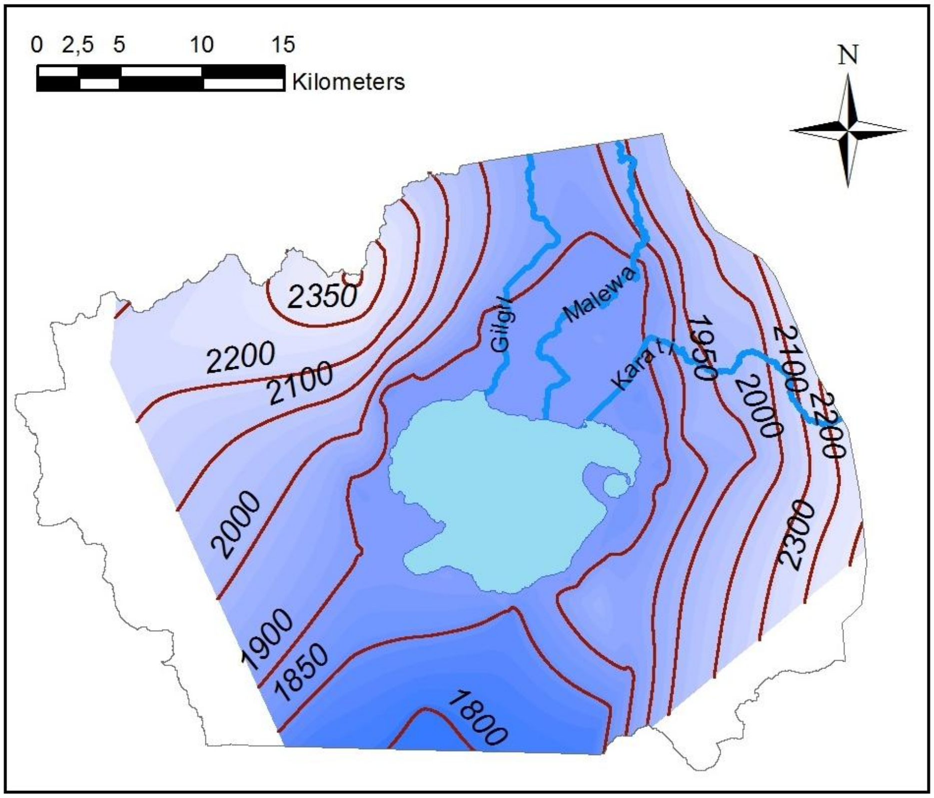

Figure 16: Historical (pre-1980) contour map of the study area. The map becomes more unreliable towards the mountains/edges of the model, where no data is available.

Table 14: Observations prior to 1980. Six artificial and eight post 1980 points are added for modeling purposes. Observations towards the edges which have a lower weight in calibration are given the remark 'Fixed polygon observation'.

Name	Observation	X	Y	Remark
ALTPOINT1	2155	188250	9906750	Artificial observation, Fixed polygon observation
ALTPOINT2	2214	222250	9905750	Artificial observation, Fixed polygon observation
ALTPOINT3	2265	223750	9912250	Artificial observation, Fixed polygon observation
ALTPOINT5	2361	181250	9924750	Artificial observation, Fixed polygon observation
ALTPOINT6	2398	224750	9908250	Artificial observation, Fixed polygon observation
ALTPOINT7	2522	178250	9919750	Artificial observation, Fixed polygon observation
ITC029POST	1887,9	204034	9928849	After 1980 observation, Fixed polygon observation
ITC040POST	1886,7	201591	9926461	After 1980 observation, Fixed polygon observation
ITC053	2334,3	197600	9929926	Fixed polygon observation
ITC057	2037,7	216171	9926241	Fixed polygon observation
ITC058	2013,7	218032	9922558	Fixed polygon observation
ITC059	1995,6	216171	9924404	Fixed polygon observation
ITC060	1982	216175	9918873	Fixed polygon observation
ITC069	1878,4	201326	9920701	Fixed polygon observation
ITC073	1906	199465	9922547	Fixed polygon observation
ITC107	1892	212412	9903826	Fixed polygon observation

ITC160	1889	196851	9915861	Fixed polygon observation
ITC161	1890,6	197660	9918954	Fixed polygon observation
ITC196POST	1991,2	209054	9904649	After 1980 observation, Fixed polygon observation
ITC212POST	1943,3	191487	9908739	After 1980 observation, Fixed polygon observation
ITC227POST	1885,8	189794	9911609	After 1980 observation, Fixed polygon observation
ITC230POST	2070,4	219411	9926765	After 1980 observation, Fixed polygon observation
ITC234POST	1884,1	187845	9909103	After 1980 observation, Fixed polygon observation
ITC240POST	1892,6	214204	9907097	After 1980 observation, Fixed polygon observation
R09	2052,2	219905	9924502	Fixed polygon observation
R12	2016,2	195810	9919079	Fixed polygon observation
R14	2122,9	217934	9930239	Fixed polygon observation
R21	1822,3	210522	9900728	Fixed polygon observation
R25	1988,1	219789	9917329	Fixed polygon observation
R32	2265	180799	9922838	Fixed polygon observation
R33	1882,1	195605	9915502	Fixed polygon observation
R49	1880,5	196205	9914652	Fixed polygon observation
ITC011	1895,1	213101	9928951	
ITC012	1910,4	214504	9926572	
ITC014	1890,8	210378	9929246	
ITC016	1885,9	212958	9923304	
ITC021	1885,1	211822	9923166	
ITC022	1884,1	212334	9922728	
ITC023	1883,3	212267	9923041	
ITC027	1893,4	207680	9925645	
ITC031	1890,7	211769	9924324	
ITC032	1885,8	211300	9924682	
ITC033	1888,2	202866	9922388	
ITC034	1884,1	202342	9920746	
ITC041	1888,2	203634	9925042	
ITC042	1885,1	207165	9925364	
ITC043	1888,1	210769	9920726	
ITC045	1893	209462	9928455	
ITC046	1883,5	214220	9919875	
ITC049	1885,1	208741	9926237	
ITC050	1878,5	214314	9918872	
ITC052	1880	214316	9917024	
ITC055	1881,1	214375	9916225	
ITC056	1881,1	213900	9916550	
ITC064	1882,4	197608	9917014	
ITC065	1881,5	212466	9918870	
ITC067	1888,1	203174	9922549	
ITC068	1884,1	205035	9920703	
ITC072	1888,4	197605	9920698	

ITC074	1887,6	213600	9921500	
ITC075	1901,3	210602	9924401	
ITC076	1893,1	212463	9922555	
ITC078	1903,1	203173	9924397	
ITC079	1890,3	212463	9922555	
ITC080	1873,4	212469	9913339	
ITC081	1902,4	195762	9911480	
ITC084	1899,4	214313	9920708	
ITC085	1886,2	212995	9923310	
ITC087	1885,7	211625	9927400	
ITC088	1884,4	213350	9921550	
ITC089	1892,8	203600	9925900	
ITC090	1887,1	213100	9923300	
ITC100	1859,1	201332	9911484	
ITC104	1837,9	205043	9907802	
ITC129	1872,2	212468	9915175	
ITC130	1909,5	214317	9915176	
ITC133	1880,1	208751	9909641	
ITC134	1882,4	210610	9911490	
ITC156	1889,5	214009	9917763	
ITC157	1888,2	213271	9914310	
ITC158	1882	202435	9909675	
ITC159	1881,2	195974	9908951	
ITC183POST	1888,7	208314	9931186	After 1980 observation
R10	1860,1	212987	9920854	
R11	1887,9	213631	9920750	
R13	1972,2	210517	9908108	
R15	1868,5	197510	9921000	
R17	1897,9	210505	9928388	
R20	1887,8	204825	9908066	
R29	1905,7	201238	9909938	
R31	1794,7	199805	9901402	
R41POST	1878,9	207165	9930594	After 1980 observation

A.3 Transmissivity

Like for head recordings, transmissivity or hydraulic conductivity values are fragmented too. A less elaborate quality assessment of available recordings has been carried out. The large range of transmissivity values found in literature and ITC databases emphasize the spatial heterogeneity of materials encountered. A more precise figure for each measured conductivity will not likely narrow this range. In general it can be said that most values are simply postulated as such in excel files accompanying student theses or attached in thesis appendices. These values have most likely been collected during field work, but a proper description that may serve as a basis for quality analysis is generally lacking. In some cases farmers were asked to put their pumps at the investigator's disposal to carry out a pumping test. If allowed, these tests were carried out at night in between irrigation periods. The well may not have had a full recovery, nor was the time for pumping and monitoring recovery as long as one would want to. Different techniques to calculate transmissivities from the retrieved data therefore led to sometimes very different output values. An illustration is provided by Ramírez Hernández (1999), who came to a transmissivity value of 7100 m^2/d at Three Ostrich Farm (FBP) using the Hantush and Jacob method, but in Aquitest software package a value of 1020 m^2/d rolled out.

An overview developed by Legese Reta (2011) has been taken as a basis to add addition values found in literature and the ITC database. Other (non-student) sources include:

VIAK (1976) is an engineering firm that carried out geohydrological investigation at boreholes ITC013, ITC016 and ITC085 with different pumping tests (step drawdown of Gustafsson, recovery test of Theis, pump test of Jacob, Hantush, Jacob and Thiem, see Kruseman and De Ridder (1994) for test specifications). The analysis showed that the different strata act as a leaky aquifer system with a transmissivity of 200-500 m^2/d, depending on the method.

Clarke et al. (1990) carried out geohydrological investigations under auspices of the geothermal plant south of Lake Naivasha. The source data is unknown, but the document suggests underlying borehole evaluations have been carried out to come to their conclusions. Hydraulic conductivity values are derived from transmissivities by assuming aquifer thicknesses of 5-25 m. No coordinates of exact borehole locations are given, however.

Table 15: Overview of available pumping test results. Updated from base collection by Legese Reta (2011).

Well ID	Source	X	Y	Transmissivity [m2/d]	Hydraulic Conductivity [m/d]
well5	Abdulahi (1999)	214151	9918303	-	0,015
well7	Abdulahi (1999)	214340	9918801	-	0,084
NE Naivasha	Clark et al. (1990)	-	-	307	12
SE Naivasha	Clark et al. (1990)	-	-	502	20
SW Naivasha	Clark et al. (1990)	-	-	297	63
NW Naivasha	Clark et al. (1990)	-	-	1601	148
BH C	Kibona (2000)	213459	9924929	1150 (462)	
TB4	Legese Reta (2010)	213178	9915081	-	24
PT1	Legese Reta (2010)	210645	9911550	10640	480
PT2	Legese Reta (2010)	210645	9911550	10640	480
Delamer BHO	Legese Reta (2010)	213083	9924646	131	4,4
Kreative BH1	Legese Reta (2010)	215408	9924546	72,8	1,2
Kenya nut BH1	Legese Reta (2010)	209340	9924782	557	15,5
Kenya nut BH2	Legese Reta (2010)	208643	9924724	1360	22,7
Riftvalley WSB BH1	Legese Reta (2010)	212870	9927912	9,47	0,2
Riftvalley WSB BH2	Legese Reta (2010)	212870	9927912	78,6	1,9
Riftvalley WSB BH3	Legese Reta (2010)	212870	9927912	14,1	0,3
Malewa Bay Investment	Legese Reta (2010)	202214	9925931	959	40,0
Sunshine Rehab Center	Legese Reta (2010)	212613	9921327	267	7,4

Upendo village	Legese Reta (2010)	218185	9915645	12,8	0,4
C2657	McCann (1974)	193901	9913327	307	-
C1482	McCann (1974)	214316	9917024	1330	-
C1063	McCann (1974)	197600	9929926	38,9	-
C2071	Ojiambo (1992)	202800	9909500	155	-
C2534	Ojiambo (1992)	209050	9910000	166	-
C2557	Ojiambo (1992)	195300	9912500	696	-
C2638	Ojiambo (1992)	210050	9911100	166	-
C2660	Ojiambo (1992)	196950	9911950	166	-
C2701	Ojiambo (1992)	195760	9909300	261	-
C2997	Ojiambo (1992)	209900	9899950	21	-
C3924	Ojiambo (1992)	205100	9908100	377	-
C4397	Ojiambo (1992)	204900	9908300	1055	-
C4420	Ojiambo (1992)	204800	9908250	671	-
C4500	Ojiambo (1992)	198300	9914500	309	-
C4501	Ojiambo (1992)	196100	9913900	267	-
C4989	Ojiambo (1992)	208800	9909260	1382	-
C575	Ojiambo (1992)	203050	9905900	6019	-
C579	Ojiambo (1992)	201332	9911484	292	-
C630	Ojiambo (1992)	197700	9906200	127	-
C630D	Ojiambo (1992)	197700	9906200	3	-
UBH	Ojiambo (1992)	203950	9909450	10660	-
BH	Ramirez Hernandez (1999)	207698	9925728	220	-
Manera	Ramirez Hernandez (1999)	211434	9921380	670	-
Three Ostrich Farm	Ramirez Hernandez (1999)	213712	9925550	1020	-
KCC	Ramirez Hernandez (1999)	209037	9925717	75	-
La Belle In	Ramirez Hernandez (1999)	214151	9920906	1000	-
BH 1	VIAK (1975)	212921	9923339	233,28	-
BH 3	VIAK (1975)	212995	9923310	224,64	-
BH 4	VIAK (1975)	212936	9923318	198,72	-

Based on a digitized version of the simplified surface geological map (Government of Kenya Ministry of Energy Geothermal Section, 1988), Legese Reta (2011) defined 26 zones of hydraulic conductivity Figure 17. This zonation is taken over in this study, albeit minor changes are made to accommodate for the different model boundaries. The numbers displayed represent zone ID’s, which will correspond to the parameter number in calibration.

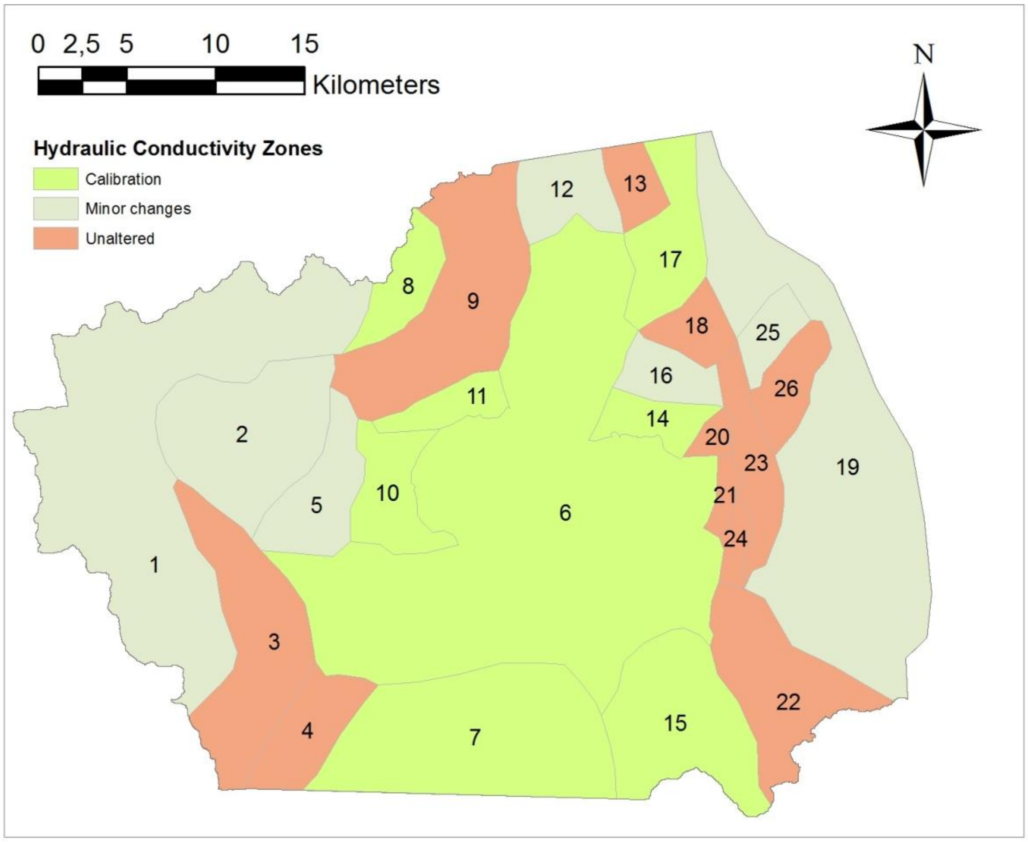

Figure 17: Hydraulic conductivity zones with ID numbers.

A.4 Storage coefficients

Since this modeling study does not include a transient run, storage parameters are not required as input parameters. Nonetheless, storage parameters encountered during data analysis have been provided in Table 16. From the previous section on Transmissivities it could be learned that few tests have been carried out to determine hydraulic conductivities. Given the fact that for estimating storage coefficients an observation well needs to be in place beside a pumped well, the reader will understand storage measurements are even more scarce. A note to the overview below is that it could not be retrieved what parameter exactly is measured. Especially the distinction between specific storage (S_s) and storativity (S_s*thickness) is often left aside.

Table 16: Overview of storage coefficients. Updated from base collection of Legese Reta (2011).

Well ID	Source	X	Y	Storativity
Delamer BHO	Legese Reta (2010)	213083	9924646	0,0000115
Malewa Bay Investment	Legese Reta (2010)	202214	9925931	0,000122
Kreative BH1	Legese Reta (2010)	215408	9924546	0,0021
Upendo village	Legese Reta (2010)	218185	9915645	0,0242
Kenya nut BH2	Legese Reta (2010)	208643	9924724	0,0253
BH C	Kibona (MSc 2000)	213459	9924929	0,00146-0,00395
Near Malewa	VIAK (1976)	-	-	0,00031-0,0011

A.5 Leakage parameters

Only two recordings of measurements related to the exchange of water between river and aquifer have been discovered. Kibona (2000) determined hydraulic conductivity of Malewa and Gilgil sediments during field work to be in the order of 0.1 to 0.38 m/d. Owor (2000) quotes similar values of fieldwork by Joliceur (2000) of 0.25 m/d. Note that no thickness of these bed sediments is recorded.

Lake-aquifer leakage parameters have not been found in literature. Owor (2000) used lakebed leakance (=conductance expressed per unit area, i.e. divided by area) as a calibration parameter, which he estimated at 0.215 d^{-1}.

A.6 Abstractions

Starting from the early 1980s, significant agricultural abstractions, drawn from the Lake, commenced. These lake abstractions steadily increased over the following 25 years. The last decade or so water drawn from surrounding aquifers complemented lake abstractions, thereby increasing total uptake considerably (Becht and Nyaoro, 2006). Besides lake and groundwater uptake, abstractions can take place from Malewa and Gilgil Rivers. Purposes include not only irrigation, but also domestic water supply, animals, industry or storage. Comprehensive and structural recording of abstractions in space and time is absent. Partial attempts have been made to measure water consumption in the basin in whole and around the lake in particular.

A number of literature references are given here, but these are estimates not backed by actual data. These sources include LNROA (1993), Mpusia (2006), Musota (2008), LNGG (2001), Becht (2007), Mekonnen et al. (2012) and DIC (2003). What follows is an assessment of the two most interesting and useful records in terms of data availability and quality (Water Abstraction Survey of 2010 (De Jong, 2011c) and FBP recordings (FBP, 2013)). Note that in 1997 a more limited water abstraction survey was carried out too. This survey has not been analyzed. The main benefits of this survey are the groundwater levels that have been collected: these are included in the head overview given in section A.2.

Lake Naivasha Riparian Owners Association (LNROA, 1993)

In 1993, the Lake Naivasha Riparian Owners Associations (LNROA) resolved to commission an independent environmental impact study of the lake. The first phase document contains an assessment of current information on the lake. It mentions for the year 1988 an irrigated area of 3200 ha. Water applied is taken from the lake at a rate of 35 Mm^3/yr and at 37 Mm^3/yr from rivers, over the entire catchment. Groundwater abstractions are unknown. If groundwater abstractions are set at nil, the equivalent irrigation depth would be just over 6 mm/d.

This source illustrates the wide range estimates take. Both the area under irrigation and amounts abstracted are at the high end of the spectrum, especially for this early year. Data sources for their findings could not be retrieved. These numbers would provide abstractions for the early exploitation years, but they are out of sync with later estimates (see below).

ITC Students

Mpusia (2006) measured actual evapotranspiration from flowers inside greenhouses to be 3.5 mm/d and 5.4 mm/d for outdoor irrigation. This seems to be the most accurate application rate (see also (Van Oel et al., 2013) for a discussion on application rates).

Musota (2008) writes about a pipeline from the Malewa sub-basin to Gilgil and Nakuru Town. The pipeline became operational in 1992 and pumps 20.000 m^3/day (i.e. 7.3 Mm^3/yr). This is an abstraction to Naivasha Basin.

Lake Naivasha Growers Group Water Status Report (LNGG, 2001)

LN Water Status Report by LNGG (2001) estimated the area under irrigation in 1996-1997 was 6835 ha. Satellite analysis resulted in 7353 ha for the same period, making 7000 ha a reasonable estimate. With an annual abstraction of 70,5 Mm^3 this corresponds to an irrigation depth of 2.8 mm/d. At least 95% of the abstraction took place within the lake area. No source is mentioned, although surface water is the most likely origin. Their estimate on the 2001 situation is 9200 ha under irrigation using between 78 – 116 Mm^3/yr, which corresponds to an irrigation depth for this period of 2.4 – 3.5 mm/d. These are rather low figure, given the fact that return flow is not accounted for.

Becht (2007)

Becht mentions the irrigated area around Lake Naivasha exhibits dynamic, rotating growing schemes that are sometimes rain-fed, sometimes irrigated. An expert on the surroundings, a WRMA hydrologist in Naivasha, was asked in 2006 to distinguish irrigated areas, specify their crop, type of irrigation and water source, amongst others. He came up with the 4467 ha of irrigated area of which 39% received its water from groundwater, 55% from the lake and 6% from the rivers. If abstractions without return flow are calculated, the total amount would be 60 Mm^3/yr at a generalized gross irrigation depth of 3.7 mm/d. Based. The net abstraction calculated by Becht using estimates for irrigation depths in GIS, is 40 Mm^3/yr.

Furthermore, he states the area under irrigation has not significantly changed since 2000, that virtually all irrigation takes place north of lake and that northern abstractions are mainly groundwater Mekonnen et al. (2012)

Mekonnen et al. (2012)

A Water Footprint (WF) study has been carried out for the commercial farms around the lake. The resulting blue WF (surface water) amounts to 18.4 Mm^3/yr over the 1996-2005 period, whilst using the irrigated area of 2006 (4327 ha). This corresponds to an irrigation depth of a mere 1.2 mm/d, which has to be an underestimation. No distinction between ground and surface water is made.

Water is used for drinking water supply is estimated as 1.2 Mm^3/yr, assuming a population of 650.000, 50 $l/cap/d$ and 90% return flow, i.e. 10% is actually consumed.

DIC (2003)

Development Impact Consulting (DIC), a consultancy firm, estimated public water supply. Their aim was to provide information on 2003 and future water demand trends for planning the water supply system. Supply is distributed by Naivasha Municipal Council and the water undertaker is National Water Conservation and Pipeline Corporation (NWCPC). Main boreholes are (without georeference): Police Line, Booster Pump, Waterworks and Slaughter House, added with private wells, inter alia at the hospital and the prison. The NWCPC does not keep records of either abstractions nor groundwater levels (personal communication Wiebe Berkhout, Vitens representative dd. 06-08-2013).

DIC notes that in 1975 the public water demand was 900 m^3/d which was abstracted from surface water. Since then groundwater became the principle source. In 2003 the estimated abstractions from boreholes was 1200 m^3/d. The real domestic water abstractions for that year (2003), however, are estimated at 7800 m^3/d. The difference is due to illegal connections, vandalized pipes and donkeys or tankers drawing water.

Water Abstraction Survey 2010

The WAS contains the most comprehensive abstraction record available. It was issued by WRMA in 2010 and processed and analyzed by De Jong (2011c). The WAS included over a thousand abstraction points,394 of which are located around the lake. Of these 394 points within the study area, 335 were groundwater abstraction points (wells, boreholes etc.). It has to be noted that only 14% of all abstraction points near the lake have a valid permit. If no meters were available at a particular farm (50% of cases), the area under irrigation was multiplied by 60 $m^3/d/ha$, viz. an irrigation depth of 6 mm/d.

Results showed that total basin abstractions amount to just over 100 Mm^3/yr. Per source, 37% is drawn from the aquifer around the lake, 27% from the rivers and 27% from the lake (9% other). Per purpose, 87% is used for irrigation, 5% for domestic and 8% for commercial use. Groundwater abstractions to the North of the lake represent the largest portion of this figure, totaling 39 Mm^3/yr.

Quality

The method of calculating irrigated areas with an irrigation depth is prone to errors, since the height of the irrigation depth is a subject of debate. Different researchers have used different figures (see summary below), such as the much lower application rates used by LNGG (2001) or Mekonnen et al. (2012). The fact that many abstractors have no meters and the majority does not even have a valid permit allows for the possibility of the farmers not being conclusive about their actual withdrawals to the investigators. Moreover, it shows it is unlikely that all abstraction points have been included in the survey. Furthermore, the survey is a snapshot in time, not providing actual time series of abstractions. For this modeling exercise one would prefer to know temporal developments. The labor-intensive quest for the implementation into the model of the spatial distribution of all abstraction points surveyed is considered not worth the effort in this study. All in all, the figures mentioned should not be taken to represent actual abstractions, but as proper estimates.

Flower Business Park measurements

Industrial farmers at the Flower Business Park are large-scale consumers of groundwater. Starting March 2008, monthly amounts pumped and area under irrigation have been measured and are known until April 2012 (FBP, 2013). This data series is one of its kind. It is the longest abstraction time series available. No other series shows better measurements for a large commercial farm and the effect it has on groundwater levels. A plot of the most interesting data is given in Figure 18. Taking the amount of water applied per hectare per month, the resulting irrigation depth over the entire data set is 5.0 mm/d.

Table 17: Abstraction statistics FBP data.

Year	Annual abstraction $[Mm^3/yr]$
2008	3.5
2009	3.7
2010	3.2
2011	3.4
average	*3.5*

Quality

It is unknown what method has been employed in coming to these measurements. It is implied from their format that the accuracy is in the order of tens of cubic meters. The time series is continuous and does not contain gaps for abstractions, although groundwater measurements have been skipped at times (see Figure 18). Abstractions do not equal consumption, since return flow is not accounted for.

Statistical analysis

Due to the lack of proper quality time series, this study does not include a transient version of the groundwater model. This FBP source, however, is subjected to a statistical analysis to see if temporal system intricacies can be disclosed.

A general reflection teaches that withdrawals are approximately constant over this four year period, with a minor downward trend. The same holds for acreage under irrigation, albeit with a minor upward trend. Abstractions are more variable that acreage under irrigation and groundwater levels.

A moving average smoothing algorithm was applied to lake and groundwater levels to obtain an idea about their respective variations. Results showed lake level fluctuations were 7, 6 and 4 m in 2009, 2010 and 2011, respectively (see Figure 20a). Groundwater variations followed a similar decrease in magnitude of fluctuations with 2, 1.5 and 1 m for those years (see red bold line in Figure 19a).

The groundwater level and abstraction series were tested for periodically repeating patterns by analyzing their autocorrelation (see Davis (2002) for more information on statistical tools for time series). Autocorrelations are tested for significance at a 95% confidence interval. Assuming the time series are independent and identically distributed random variables, the variance of the correlation r at a given lag k (denoted as r_k) is

$$var(r_k) = \frac{1}{N}$$

and r_k is normally distributed. The 95% confidence limits can therefore be plotted at:

$$\frac{-1}{N} \pm \frac{2}{\sqrt{N}}$$

where N is the number of observations (i.e. 40 (months)). These bands are often further approximated to:

$$\pm \frac{2}{\sqrt{N}}$$

These are the dashed horizontal lines above and below the x-axis in Figure 19b.

To account for the so called large lag standard errors of r_k, confidence intervals are also calculated for the variance that is adjusted for this large lag using:

$$var(r_k) = \frac{1}{N}(1 + 2\sum_{i=1}^{k} r_i^2)$$

These are the widening dashed purple lines in the same figure.

Using these confidence intervals, abstractions did not show significant repeating patterns. This may be interpreted as the absence of a detectable growing season at FBP.

Groundwater levels, however, were significantly autocorrelated (r=0.45) at a lag of just over a year, see Figure 19. This may be interpreted as an annually repeating pattern in groundwater levels. Upon a closer look at this cycle, low groundwater levels (=greater depths to groundwater) are encountered around January, whereas higher levels a found around July. It is interesting to find that the reported bimodal raining season cannot be detected in the groundwater levels. Reasons might be that the minor rainy period does not significantly contributes to recharge or that the source feeding the FBP area does not show this bimodal pattern after all.

Since this study aims to understand the effect abstractions have on lake levels, a comparison to the latter may prove worthwhile. Hence average lake levels during the 2009-2012 period were tested for autocorrelation too. The result is they did not show any seasonality either. Since a longer time series yields a more reliable autocorrelation, lake levels from 1990-2012 were used instead. Interestingly enough, this time series did not show any statistically significant intra-annual patterns either.

Next, interdependencies of the time series in assessed using cross-correlation. Again, significance is tested at the 95% confidence levels. This time, a two-sided t-test is performed to set the confidence intervals (the dashed red lines in Figure 20 and Figure 21).

Results show lake levels and groundwater levels are not significantly correlated at any lag Figure 20. This may be interpreted as a less well-established connection between the lake and the aquifer around FBP.

Abstractions and groundwater levels did show significant correlation at lag 12 (r_k=0.48), i.e. high (low) abstractions are followed by deep (shallow) groundwater tables one year later Figure 21. Although statistically significant, this conclusion seems to have little physical grounds to be useful. The fact that at other, smaller lags no correlation was found may indicate a relatively large reservoir where the water is drawn from: it seems the abstractions, although considerable in size, do not impact groundwater levels to the extent that these groundwater levels are dictated by the abstraction regime. Rather, adequate recharge to the well area dampens out completely the effect of abstractions. What is more, since abstractions and groundwater levels seem to be uncorrelated, the smoothed, attenuated groundwater series as displayed in Figure 19a may be considered as the natural groundwater level fluctuation in this area.

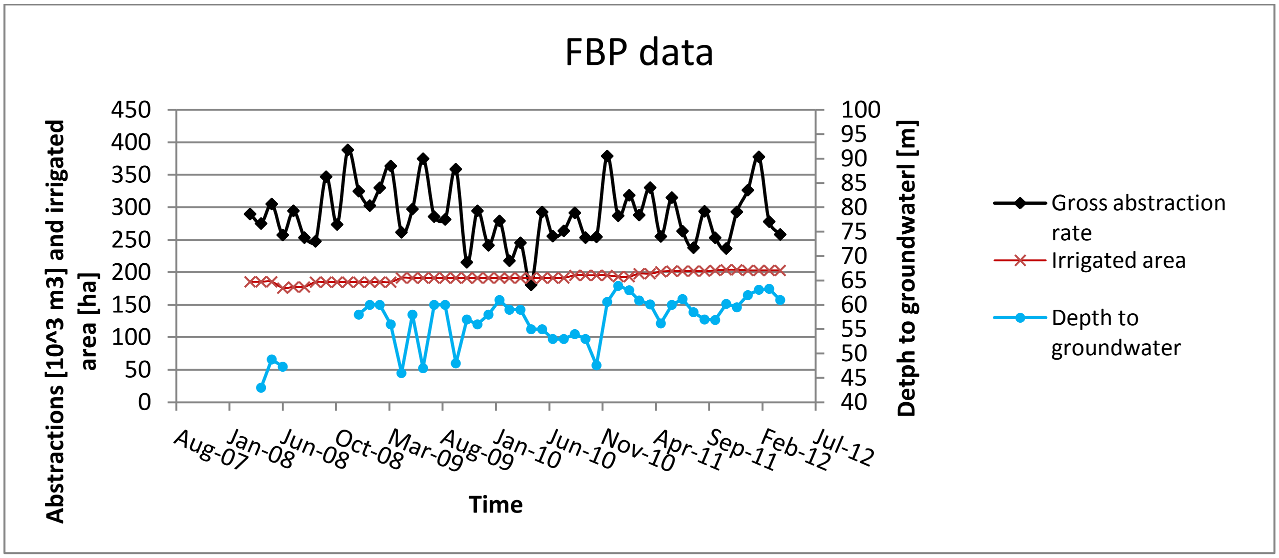

Figure 18: Abstraction rate, irrigated area and depth to groundwater from March 2008 to April 2012 at FBP.

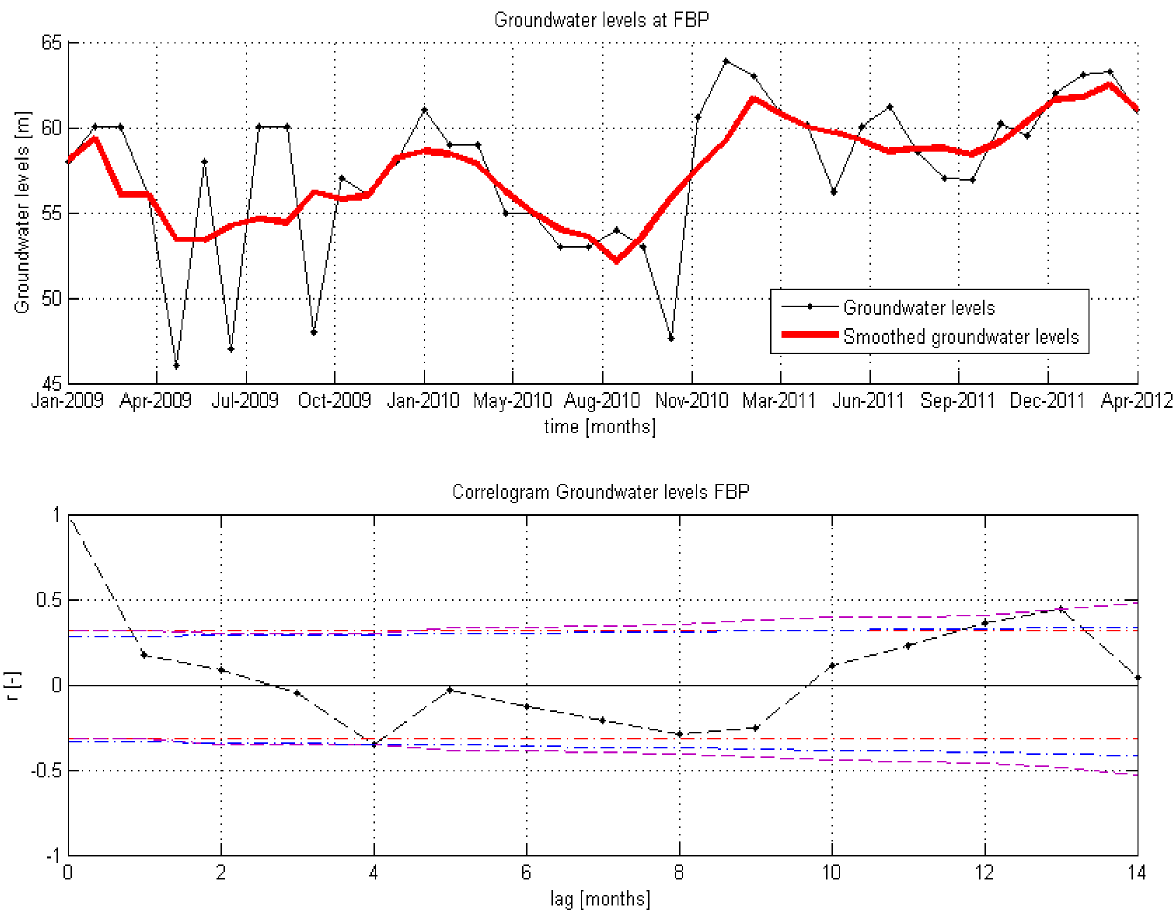

Figure 19: Auto-correlogram of groundwater levels at FBP.

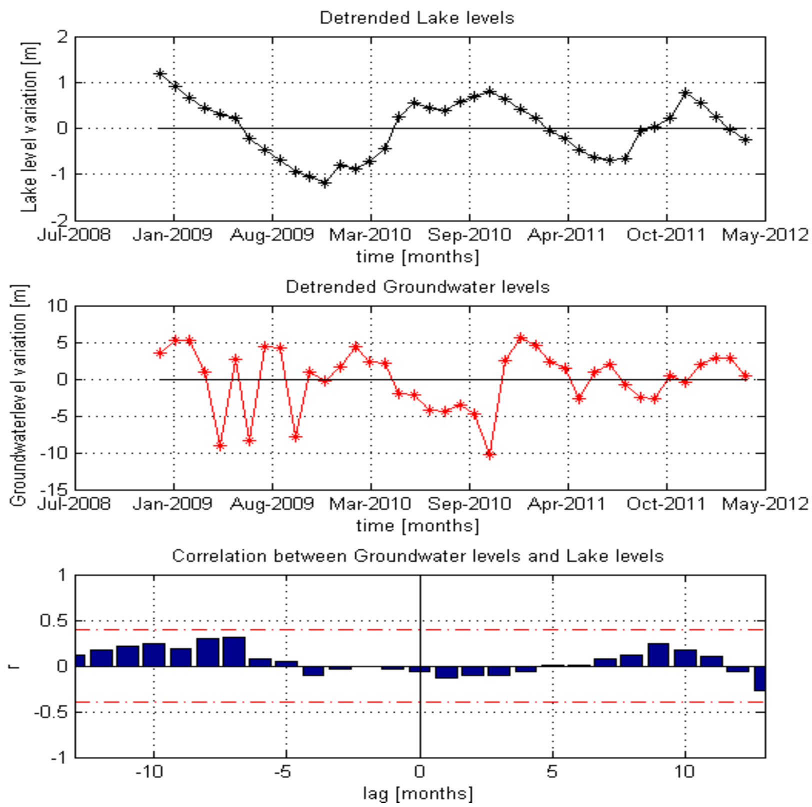

Figure 20: Cross-correlogram of lake and groundwater levels.

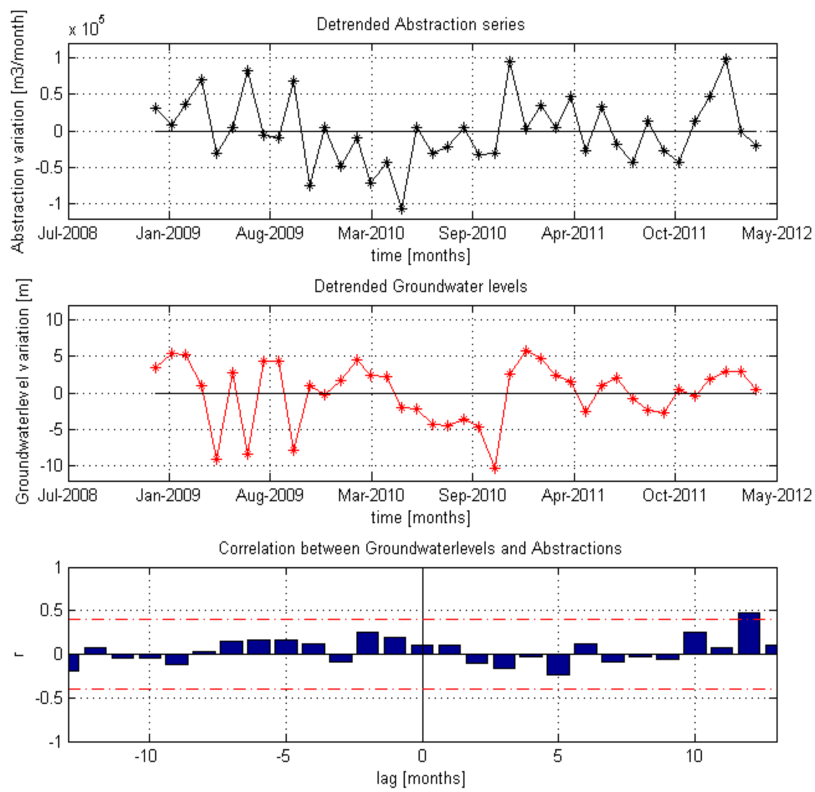

Figure 21: Cross-correlogram of abstractions and groudnwater levels at FBP.

A.7 Geology and stratigraphy

Geology in the area is complex, hence hydrogeology will be complex too. Beside general geology, the fact that the lake and its surroundings are lower than the Rift escarpments but concurrently at the culmination of the Rift floor make the hydrogeology a difficult subject (Clarke et al., 1990). Hydrogeological conditions strongly vary spatially. Variation is among other factors due to topography and climate. An attempt is made to provide an overview of the most relevant literature and data.

Thompson and Dodson (1963) claim a volcanic deposit base is overlain by the water-bearing sedimentary deposits that do not exceed a thickness of 31 m. This conclusion seems to be drawn on expert judgment rather than actual measurements.

VIAK (1976) carried out an analysis to determine the suitability for groundwater exploitation for Naivasha Town's domestic water supply. Two aquifers are distinguished north of Naivasha Town, labeled Manera and Malewa aquifer. The former consists of coarse sand, gravel and pebbles at 30-40 m below ground level and is based on drilling logs of C3472 (which has no dated groundwater record, so it has not been taken up into this study's database; C3472 is located some 3 km northwest of ITC016). The latter is quite different, with lava interbedded in the sediment stratification according to this firm. They make these claims based on logs of C3417 (which has no groundwater observations assigned either; C3417 is located at the Malewa River, roughly 2 km northwest of C3472 or 5 km of ITC016. A quite different account of the same measuring campaign can be found in DIC (2003): their strata are sand and sandstone layers separated by impermeable layers of sandy silt and clay.

Government of Kenya Ministry of Energy Geothermal Section (1988) produced a geological map, including cross-sections of a roughly east-west transect. Since the cross-sections extent to several hundreds ofmeters of depth, its use is limited. See also Hogeboom (2012).

Ramírez Hernández (1999) published two interpretations of driller logs in his thesis. He does not give a reference to the source or who performed the interpretation. The lithology at Three Point Farm (R07) appears to be drawn from the same source as where Tsiboah (2002) retrieved his schematization. Both stratification schemes can be found in Table 18.

Tsiboah (2002) carried out geophysical measurements north of the lake and found the sedimentary aquifer extent from 20-80 m below ground level, tipping off away from the lake. The electromagnetic experiments could not reveal whether the sedimentary layer was underlain by either salty water or clay. He did find intercalated clay lenses in the sedimentary deposits. See Figure 24 for some of his interpreted logs.

Nadibe (2002) supposes an upper, clay-intercalated lacustrine layer of 120 m thick, which spatially extent some 60m from the lake before tipping off. In the west the aquifer diminishes spatially already after 20m. Altough his sources and referencing are lacking, it seems he has taken his own interpretations of Tsiboah's (2002) findings to come to this build-up (Figure 23).

Yihdego and Becht (2013)used Nadibe (2002) findings and claims to have added 'newly drilled boreholes and geological observation points' as well as 'synthetic wells and supplementary cross sections' (p. 46). The source of this new data could not be retrieved from his files and thus not be verified either.

Probably the best quality source of recent times is the description of the layers found in the unpublished MSc thesis of Amha in 2011. This document is available in the ITC database and contains a description of the stratigraphy of a 45 m deep hand dug well at the Flower Business Park, see Table 19.

Lastly, the hardcopy well completion records available in the ITC room (see section A.2) sometimes provide a description of the material encountered during drilling. Due to time constraints and lack of interpretation skills for borelogs no further effort was made in trying to synthesize a stratigraphic model based on these colonial drilling records.

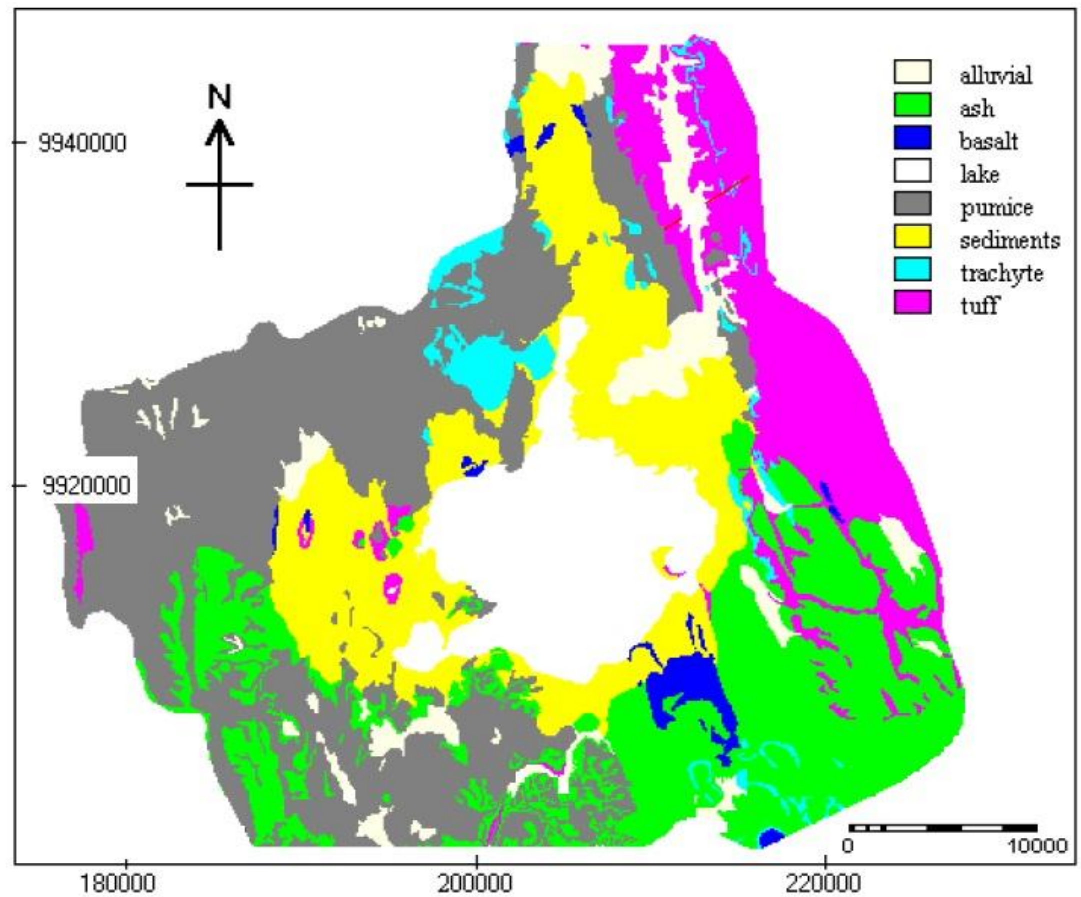

Figure 22: Generalized geological map of the study area. Adapted from Owor (2000).

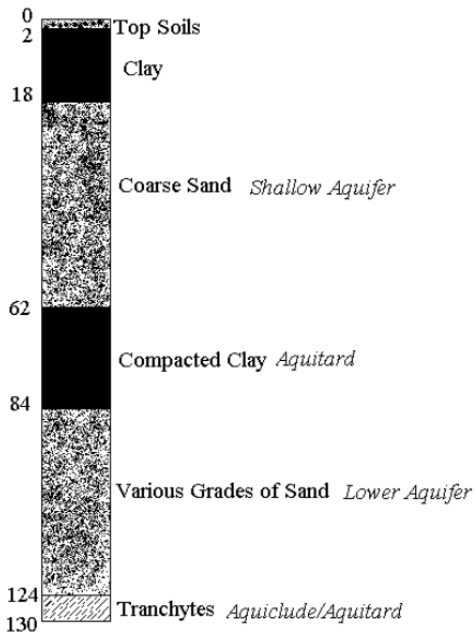

Figure 23: Interpreted drillers' log of bh C11527 (=ITC001) by Nadibe (2002). This borehole is just 1 km north of ITC016.

Table 18: Log interpretation by Ramírez Hernández (1999).

0	Fine and medium sand
4	Clay and silt
6	Coarse volcanic material and sand
8	Coarse sand and silt
10	Fine and medium sand
12	Medium and coarse sand
18	Fine and medium sand
28	Coarse volcanic material and sand
36	Medium and coarse sand
38	Coarse volcanic material
40	Siltstone
42	Mix coarse and medium sand
46	Fine and medium sand
60-65	Clay and silt

Three Ostrich Farm (R07)

0	Silty clay and sand
2	Silt and clay
4	Fine, medium and coarse sand and clay
12	Fine and medium sand and clay
16	No record
18	Medium and coarse pumice
20	Hard crushed basalt
22	Mix medium and coarse sand
26	Medium and coarse sand and clay
28	Pumice layer
30	Fine and medium sand and clay
40	Silt and weathered basalt
46-48	Fresh basalt

La Belle Inn

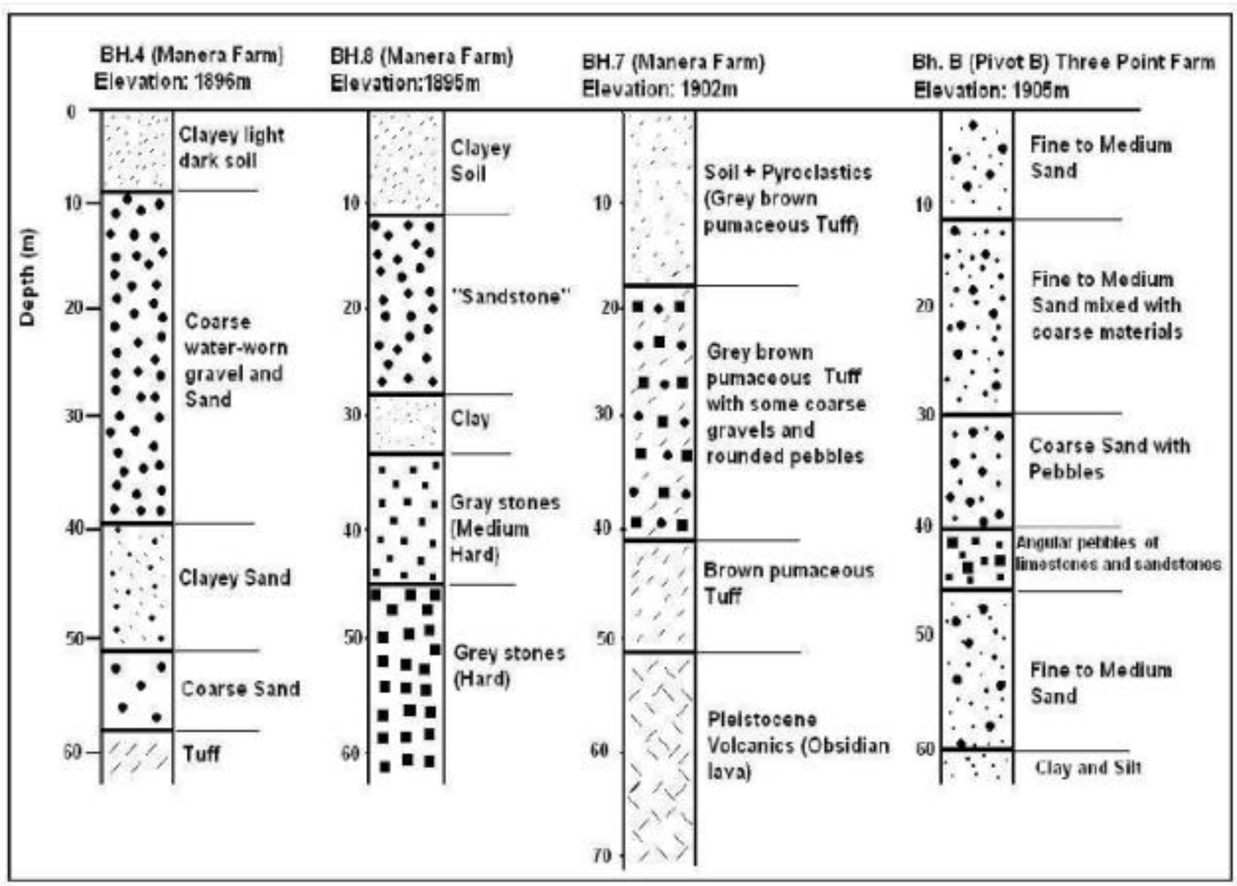

Figure 24: Lithological logs northwest to Lake Naivasha (Manera and Three Point Farms) according to Tsiboah (2002). Original source unknown.

Table 19: Hand dug well at Panda Flower farm at FBP lithological descripition. Taken from unpublished work by MSc Amha at ITC.

Depth [m]	Lithologic description
1 – 5	dark red clay, but grey when dry
5	very fine (volcanic) sands
6	sands with rounded pumice
7	fine unconsolidated pumice sand + somewhat consolidated fine tuff layer
8	very fine layered pumice sand silt formations
9	coarse brown/ red stratified dark minerals and pumice sand
10	dust silt layer
11	similar to the 10m sample but slightly coarser
12	thin layer of ash plus some lighter materials (diatomite)
13	layered volcanic ash/clay/diatomite plus fine sands
14 – 15	grey colored ash
16 – 18	ash but with some layering
19 – 20	a mixture of coarse unconsolidated sand, pebbles of hard volcanic + clay
21	well layered ash dust plus diatomite
22	diatomite and ash
23	slightly consolidated dust with some clay
24	volcanic ash plus lighter materials
25	very fine red/brown sand, very well sorted, unconsolidated (cavity formation)
26	red/brown colored coarse sand
27	similar to the 26m sample but coarser
28 – 29	volcanic ash/dust with minor traces of structures
30 – 32	similar sample to 30-32m, but slightly coarser
33	very fine sand hard sands, which are consolidated
34	gradually coarsening mixture of dust/ash + very fine red/brown sand
35	ultra fine red/brown sands very vague sedimentary structure
36	the typical red brown coarse unconsolidated layer deposits, no pebbles
37 – 40	identical brown colored unconsolidated deposits of silt and clay
40 – 45	brown to black colored coarse sand, with little gravels and silt clay materials