Alternate Solution to Lake Beseka Water Level Rise Containment

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Certification

The undersigned certify that he has read the thesis entitled**: Alternate solution to Lake Beseka water Level rise containment** and hereby recommend for acceptance by the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science.

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Dr. Mebruk Mohammed (Advisor)

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Date

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Abstract

Environmental change that has taken place over the last few decades is an essential task to understand the impacts that natural processes and anthropogenic factors have on hydrological settings and ecosystems. Environmental concern regarding the expansion of Lake Beseka has become a major issue. The expansion of Lake Beseka has caused an irreversible damage to the nearby Awash River which is a resource for the surrounding irrigation schemes and downstream water supply. This paper tried to predict the maximum possible Lake level so that it is contained in its territory to control the contamination of Awash River. A numerical groundwater model, TAGSAC, has been used for predicting this maximum possible Lake level rise. For the identification, a steady state groundwater model was first created and calibrated for the inventoried wells. The model is conceptualized by considering a constant head boundary condition for the Awash River in locations where the river is perennial. The calibration of the model was made by changing the recharge and hydrogeologic parameters of the basins. The goodness of fit indicators (GoFIs) showed that the measured and simulated heads of the model have a better match. The maximum Lake level rise was determined by raising the lake water level where the flow was reversed away from the Lake by assuming the Lake is contained in its territory. As the result of this study indicates the maximum Lake level where the flow completely reversed is 12m.

Key Words: Lake Beseka, Environmental change, Maximum Lake level rise, Groundwater modeling, Containment of Lake Beseka, TAGSAC

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List of Acronyms

DEM: Digital Elevation Model

ENGDA: Ethiopian National Groundwater Database

FDM: Finite Difference Method

FEM: Finite Element Method

GoFI: Goodness of Fit Indicators

IFD: Integrated finite difference

MAE: Mean Absolute Error

ME: Mean Error

MER: Main Ethiopian Rift

MoWR: Ministry of Water Resources

NMSA: National Metrological Service Agency

OWWDSE: Oromia Water Works Design and Supervision Enterprise

REV: Representative Elementary Volume

RMSE: Root Mean Squared Error

WWDSE: Water Works Design and Supervision Enterprise

1. Introduction

Freshwater resources provide essential services to society. Arguably, the most important of these services is fresh drinking water for municipalities around the world. However, lakes and other freshwater resources also provide other important services, including power generation, water for irrigation and industries and sites for recreational activity. Declining or low water quality impacts the value of lakes – economically, environmentally, and socially. For example, if pollution enters a lake, it can reduce the water quality enough such that it is unsafe to drink as well as harm organisms that live in the water, reducing the ecological value of the lake. These changes can alter perceived value of the water body. Water quality is also an important concern for human use of lakes and other freshwaters as well as the ecological value of water bodies. Water quality is used in determining the state of aquatic environments and is an interesting point of study in determining both human impacts and natural processes in the environment.

Environmental degradation has caused the reduction of water level in lakes, rivers and streams. However, the water level of Beseka Lake has been rising for more than three decades. The surface area of the lake has been expanding from 3km^2 to 46.6km^2 between 1973 to 2008 with corresponding to rise in lake water level (Goerner et al. 2008).The expansion of Lake Beseka has still continued and severely affecting the life of the surrounding community and also becoming the contaminant to Awash River due to the saline and polluted nature of the Lake. To minimize the expansion rate of the Lake, Awash Basin Authority had installed six surface pumps of 1.7 m3/sec capacity and had been pumping water from the lake and released to Awash River (WWDSE 2011). However, discharging the saline lake water to Awash River is causing irreversible damage to the river which is the source to the irrigation schemes and downstream water supply.

Although many researchers have conducted different studies to minimize the expansion of Lake Beseka, there was no significant mitigation measure that could control the water quality of Awash Basin. However, this research aimed to control the release of Lake Beseka to Awash River which is polluted by the highly saline lake.

1.1. Statement of the Problem

One of the major current problems within Lake Beseka is the rise in Lake water level and expansion of the lake into the adjacent development areas, settlements and other infrastructures which have caused serious problems to the community in the area as well as associated development activities.

The rise of Lake Beseka water level has been a concern from more than 30 years ago when the rapid increase of the lake level threatened the nearby development activities. Previous records indicate that in the early 1960s, the lake surface area was only 3km^2. While during the years 1976 and 1998, the lake area has increased to 27.5km^2 and to 40km^2 respectively. At present, after the expansions and introduction of new irrigation systems the total area of the lake has reached about 48km^2.

Though lake Beseka is habitat of a variety of birds, crocodiles, waders and other aquatic lives and serves as additional attraction to the adjacent Awash national park, and it is also the source of fish for the nearby Metehara town and the community of the large irrigation farms around it, the negative consequences of the lake expansion (destruction of the infrastructure and its reconstruction, and possible pollution of the Awash River), is consuming a considerable budget which could, otherwise could be channeled into the economic sector. The major impacts- of the lake level rise, both real and potential include:

- Destruction of infrastructure: the only railway line connecting the country to Djibouti and the main highway have been repeatedly raised, until they were abandoned recently. The road between Metehara town and Addis Ketema has been run over by the overflow of Beseka.
- Loss of agricultural land (Abadir farm) and grazing land and a few tourism facilities. About 300 ha of sugar plantation has been invaded by the lake water and two resorts have been engulfed.

- Greater potential threats include the contamination of the Awash river and groundwater downstream
- Incursion of the lake water into the town of Metehara and flooding of the Main road on the low lying area immediately east of the town.

The expansion of this highly saline and polluted Lake Beseka and its' sever water quality problems have been becoming treat to the nearby Awash River and downstream irrigation projects. To identify the differential vulnerability of the nearby areas to future inundation hazards as a result of the Lake expansion, it is necessary that timely actions to be taken. Different actions have been considered to solve the problems. One of those measures is by discharging/releasing the polluted lake water to the nearby Awash River. This action brings irreversible damage to the river which is the most widely utilized water resource over the country. Its impact includes the contamination of the Awash River and groundwater downstream. Contamination of the river with the saline lake water creates extended damage on downstream water supply and irrigation projects which are entirely contingent on Awash River.

1.2. Objectives of the Study

The objectives of the research may be viewed as having:

- General objective
- Specific objectives

1.2.1. General Objective of the Study

The general objective of the research is to predict the maximum possible lake water level rise which can reverse the ground water recharge.

1.2.2. Specific Objective of the Study

The specific objectives include:

- To determine the groundwater table map
- To identify the flow direction

- To redraw the hydrogeology map

- To draw the groundwater accessibility map

1.3. Structure of the Study

The study is organized in six chapters. Chapter one deals with the general introduction, statement of the problem and objective of the study. Chapter two gives a literature review on groundwater modeling, groundwater dynamics, surface water-groundwater interaction, expansion of Lake Beseka,cause of Lake Beseka Lake level rise and environmental impacts of the Lake level rise. Chapter three gives an overview on methodology of the study which includes location of the study area, data collection, processing and analysis, groundwater modeling, determination of maximum Lake level rise and model conceptualization. In Chapter four the result and discussion part of the work follows. It includesmodel calibration, discritization of the study area, Hydrogeology map, flow direction and groundwater table map, maximum possible Lake level rise, maximum expansion of Lake Beseka and groundwater accessibility of the study area. Chapter five is about conclusion and recommendation. And finally in Chapter six lists of the References are included.

2. Literature Review

2.1. Groundwater

2.1.1. Groundwater Modeling

A model is any device that represents an approximation of a field situation. A mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model (boundary conditions). Mathematical models can be solved analytically or numerically. Either type of solution may involve a computer. When assumptions used to derive an analytical solution are judged to be too simplistic and inappropriate for the problem under consideration, a numerical model may be selected. A numerical model may also be easier to apply than an analytical model if the analytical problem involves complex superposition of solutions, e.g., with image well theory. Generally speaking, the fewer the simplifying assumptions used to formulate a model, the more complex is the model (Anderson, 1992).

There are two conceptual views of groundwater systems—the aquifer viewpoint and the flow system viewpoint.

The aquifer viewpoint is based on the concept of confined and unconfined aquifers. In this viewpoint, groundwater flow is assumed to be strictly horizontal through aquifers and strictly vertical through confining beds. It is used to simulate two-dimensional horizontal flow in confined and unconfined aquifers whereas, in the flow system view point equipotential lines pass through all geologic units, both aquifers and confining beds.

Groundwater models are an attempt to reperesent the essensial features of the actual groundwater system by means of a mathematical counterpart. Groundwater models can be classified in several ways: steady state or transient; confined, unconfined or a combination of confined and unconfined; one dimensional, two dimensional, quasi three dimensional or three dimensional.

Five numerical methods are used in groundwater modeling: finite differences, finite elements, integrated finite differences, the boundary integral equation method, and analytic elements. The boundary integral equation method and analytic elements are relatively new techniques and are not yet widely used. Integrated finite difference (IFD) techniques are closely related to the finite element method. Finite differences and finite elements are more commonly used to solve flow problems (Anderson, 1992).

2.1.1.1. Finite Difference Method

Finite difference method is widely used and accepted by many governing bodies. It is the most popular groundwater simulator available. The finite difference method is easy to understand, calculate and fewer input data are needed, the solutions are mass-conservative. However, the finite difference method is not without weakness. Although grids are easy to create, they cannot be efficiently refined around areas of interest, such as wells and model boundaries. And also Finite difference grids are rectangular and the area modeled is not. Special problems like movement of water table and seepage face are difficult to handle. The grid is created using structured, rectilinear (rectangular) grids. It computes a value of the head at the node which also is the average head for the cell that surrounds the node. The node represents the finite difference cell.

2.1.1.2. Finite Element Method

The finite element method can also be used to solve the groundwater flow equation. Finite elements are easier to adjust the size of individual's elements as well as the location of the boundaries with the finite element method. This method is better to handle internal boundaries such as fault zones and water tables. Finite element methods are able to approximate irregular shaped than the finite difference method. It uses triangular mesh to represent the model domain. The use of triangles allows for a more efficient refinement around wells and boundaries. The triangular mesh can more easily adapt to variable stratigraphy such as sloping or pinch outs, and allows for versatile discretization of non-rectangular model domains. And it allows more flexibility in designing a grid. Finite element model define the variation of head within an element by means of interpolation, heads are calculated at the nodes for convenience, but head is defined everywhere by means of basis functions.

Finite element models simulate point sinks and sources more accurately than finite difference model and no correction is needed. No method is perfect; finite difference method is easy to understand than Finite element method but the approximation of boundary conditions can be more accurate in Finite element method than in finite difference method. In general, the method has several advantages:

- Irregular or curved aquifer boundaries, anisotropic and heterogeneous aquifer properties, and sloping soil and rock layers can be easily incorporated into the numerical model,
- The accuracy of solutions to groundwater flow is very good (exact in some cases),
- Simulate point sinks and sources more accurately than finite difference method.

2.1.2. Groundwater flow equation

The first step in the finite element method is deriving an integral formulation for the governing groundwater flow which leads to a system of algebraic equations that can be solved for values of the field variable (hydraulic head, pressure head) at each node in the mesh generated. Several methods can be used to derive the integral formulation for a particular differential equation. The method of weighted residuals is a more general approach that is widely used in groundwater flow modeling. In the method of weighted residuals, an approximate solution to the boundary or initial value problem is defined. When this approximate solution is substituted into the governing differential equation, an error or residual occurs at each point in the problem domain. Then the weighted average of the residuals for each node in the finite element mesh will be forced to equal zero. Galerkin's Method is the subset of the method of weighted residuals that is most commonly used to solve groundwater flow problems (Istok, 1989). In Galerkin's Method the weighting function for a node is identical to the interpolation function used to define the approximate solution. The general three dimensional groundwater flow equation for steady state is summarized from Istok as follows.

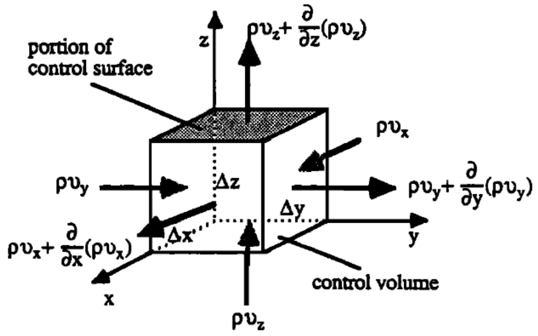

Figure 2.1.Representative control volume(REV)

The law of conservation of mass for steady-state flow requires that the rate at which fluid is entering the control volume is equal to the rate at which fluid is leaving the control volume (net rate of inflow = inflow - outflow = 0) for purposes of analysis, consider the rate at which groundwater enters the control volume per unit surface area to consist of three components $\rho\upsilon_x$, $\rho\upsilon_y$, and $\rho\upsilon_z$, where ρ is the density of water and υ_x, υ_y and υ_z are the apparent velocities of groundwater flow entering the control volume through control surfaces perpendicular to the x, y, and z coordinate axes. Where a differential equation and known boundary conditions are given, an approximate solution may be obtained by applying a numerical method. Then using a Taylor Series approximation, the rate at which groundwater leaves the control volume in the x direction can be written as;

$$\rho\upsilon_x+\frac{\partial}{\partial x}(\rho\upsilon_x)\Delta x+\frac{\partial^2}{2!\,\partial_x^2}(\rho\upsilon_x)\Delta x^2+\frac{\partial^3}{2!\,\partial_x^3}(\rho\upsilon_x)\Delta x^3+\cdots\text{..............................Equation I}$$

If the size of the control volume is small enough, one can neglect higher-order terms (i.e. those involving Δ^2, Δ^3 etc.) and, because it has been chosen a unit control volume (Δx = Δy =1) the rate at which groundwater leaves the control volume is, $\rho\upsilon_x+\partial/\partial x(\rho\upsilon_x)$, and this is the same as Euler's method. The net rate of inflow in the x direction is then (net rate of inflow in x direction = rate of inflow in x direction - rate of outflow in x direction) i.e., $\rho\upsilon_x$- $[\rho\upsilon_x+\partial/\partial x(\rho\upsilon_x)]$ =$-\partial/\partial x(\rho\upsilon_x)$ and in the same fashion the net rate of inflow in the y and z directions are $-\partial/\partial y(\rho\upsilon_y)$ and$-\partial/\partial z(\rho\upsilon_z)$, respectively. Because the net rate of inflow for the entire control volume must equal zero if the law of conservation of mass is to be satisfied, then it can be written as;

$$-\frac{\partial}{\partial \mathbf{x}}(\boldsymbol{\rho}\upsilon_{\mathbf{x}})-\frac{\partial}{\partial \mathbf{y}}(\boldsymbol{\rho}\upsilon_{\mathbf{y}})-\frac{\partial}{\partial \mathbf{z}}(\boldsymbol{\rho}\upsilon_{\mathbf{z}})=\mathbf{0}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation I}$$

If it is assumed that groundwater density, ρ is constant (i.e., the fluid is incompressible), one can use the product role of calculus to evaluate a typical term in equation II, $-\partial/\partial x(\rho\upsilon_x)=-[\rho(\partial\upsilon_x/\partial x)+\upsilon_x(\partial\rho/\partial x)]$, But $\partial\rho/\partial x$ is zero since the fluid is assumed to be incompressible. Thus $-\partial/\partial x(\rho\upsilon_x) =-\rho(\partial\upsilon_x/\partial x)$ similarly for the y and z direction$-\rho(\partial\upsilon_y/\partial y)$, $-\rho(\partial\upsilon_z/\partial z)$ respectively. Because groundwater density appears outside the derivative it cancels from equation III;

$$-\frac{\partial\upsilon_x}{\partial x}-\frac{\partial\upsilon_y}{\partial y}-\frac{\partial\upsilon_z}{\partial z}=0\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation IV}$$

Now the apparent groundwater velocities in x, y and z direction are given by Darcy's Law

$$\upsilon_x=-k_x\frac{\partial h}{\partial x},\ \upsilon y=-k_y\frac{\partial h}{\partial y}\ \text{ and }\ \upsilon z=-k_z\frac{\partial h}{\partial z}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation IV}$$

Substitute equation Vinto equation VIthe three-dimensional form of the equation for steady-state groundwater flow through saturated porous media is written as;

$$\frac{\partial}{\partial x}(k_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial h}{\partial y})+\ \frac{\partial}{\partial y}(k_y\frac{\partial h}{\partial y})\pm q=0\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation VII}$$

Where Kx, Ky, and Kz are the saturated hydraulic conductivity of the porous media in the x, y, and z coordinate directions, h is hydraulic head and q is the recharge. This general saturated groundwater flow equitation is applicable under either confined or unconfined conditions (Engineers, 1999).

Hydraulic conductivity

Hydraulic conductivity is a characteristic proportionality constant K (L/T) in Darcy’s Law, and as such is defined as the flow volume per unit cross-sectional area of porous medium under the influence of a unit hydraulic gradient. It is empirical constant to be measured in laboratory. Real subsurface materials always have a complex and irregular distribution of hydraulic conductivity. K is often described as distributions using the terms heterogeneity and anisotropy. In a heterogeneous material the value of K varies spatially, and in a homogeneous material K is independent of location. Anisotropy implies that the value of K at a given location depends on direction. Isotropy implies that K is independent of direction at a given location (Fitts, 2002). The hydraulic conductivity of a given medium is a function of the properties of the medium and the properties of the fluid. If hydraulic conductivity is dependent on the direction of groundwater movement the aquifer is anisotropic and the hydraulic conductivity is a second rank tensor.

$$\begin{matrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} = K \\ K_{zx} & K_{zy} & K_{zz} \end{matrix}$$

The path lines that water travels are often very irregular due to the heterogeneous distribution of hydraulic conductivities in the subsurface. In a high-conductivity layer, water tends to flow parallel to the layer boundaries. But in a low-conductivity layer, water tends to take the shortest path through the layer, flowing nearly perpendicular to the layer boundaries (Fitts, 2002).

2.1.3. Building conceptual model

The first step in the modeling protocol is to establish the purpose of the model; the second step is to formulate a conceptual model of the system. A conceptual model is a pictoral representation of the groundwater flow system, frequently in the form of a block diagram or a cross section (Anderson, 1992). The nature of the conceptual model will determine the dimensions of the numerical model and the design of the grid.

The purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily. The data requirements for a groundwater flow model are listed below. These data should be assembled when formulating the conceptual model. It is critical that the conceptual model be a valid representation of the important hydrogeologic conditions.

Data Requirements for a Groundwater Flow Model:

A. Physical framework

1) Geologic map and cross sections showing the areal and vertical extent and boundaries of the system.
2) Topographic map showing surface water bodies and divides.
3) Contour maps showing the elevation of the base of the aquifers and confining beds.

4) Isopach maps showing the thickness of aquifers and confining beds.
5) Maps showing the extent and thickness of stream and lake sediments.

B. Hydrogeology framework

1) Water table and potentiometric maps for all aquifers.
2) Hydrograph of groundwater head and surface water levels and discharge rates.
3) Maps and cross sections showing the hydraulic conductivity and/or transmissivity distribution.
4) Maps and cross sections showing the storage properties of the aquifers and confining beds.
5) Hydraulic conductivity values and their distribution for stream and lake sediments. (Moore, 1979)

2.1.4. Groundwater dynamics

2.1.4.1. Groundwater Recharge

The main source of groundwater recharge in the Lake Beseka region is rainfall. Considering the relatively low annual rainfall the direct recharge from rainfall is expected to be low. But, highland rainfall makes the major contributor to the groundwater system of the rift floor. This is also apparently the case in Beseka area (OWWDSE, 2013). Groundwater flows in to the catchment from outside the boundary mainly from the Western highlands. However, the presence of highly fractured volcanic rocks favors higher recharge through discreet fractures mainly during the time when there is high rainfall intensity. In high rainfall months (July and August) the recharge is expected to be high. In fact surface runoff is quite low in the catchment.

At regional scale, Lake Beseka catchment is located at relatively lower topographic position. This favors the convergence of groundwater into this catchment. The dominant and even in some cases the sole source of recharge to the rift valley aquifers or rift thermal waters comes from groundwater inflow from the mountains bounding the rift. The presence of many faults crossing the lake catchment favors convergence of groundwater to this catchment. Hence, groundwater recharge out of the surface water catchment boundary is very likely (OWWDSE, 2013). Aside from the direct recharge from rainfall, irrigation return flows are expected to play important role in the groundwater recharge. This is also in part attributed to the expansion of the lake. Hydrochemical and isotope studies indicate that the lake gets substantial groundwater inflow from the southern side.

2.1.4.2. Groundwater Discharge

Discharge refers here the emergence of groundwater to the ground surface. When groundwater emerges to the surface it forms springs or seepage zones. Wide seepage zones may also through time form ponds or small lakes. All these features are evident in the area (OWWDSE, 2013). Springs emanate along the shore of the lake following major regional faults and many springs are likely to be submerged below the lake. The water balance of Lake Beseka has been computed in many researches. The result indicates that Lake Beseka is a groundwater dominated lake i.e groundwater is the major component of the lake water balance (OWWDSE, 2013). On the contrary groundwater is also being discharged out of the lake through fractures. The recent appearance of new ponds east of Metehara town displays that groundwater is also being discharged out of the catchment substantially. Probably the occurrence of new ponds and seepage zones out of the lake is attributed to the recent expansion of the lake which leads to the corresponding increase of the hydraulic gradient of the groundwater in the designated outflow zone. The lake tends to be open in the subsurface.

2.2. Surface water – groundwater interactions

Surface-groundwater interaction is the interplay between water on and beneath the land surface, including the flow of surface water into the groundwater system and vice versa. Groundwater and surface water are not isolated components of hydrologic system but a linked component of a hydrologic continuum, which interact in a variety of physiographic and climatic landscapes. Surface water is commonly hydraulically connected to groundwater, but interactions are difficult to observe and measure. Surface water bodies such as lakes, streams and wetlands form an integral part of most groundwater flow systems, and play an important role in the water budgets of the system. Interactions between groundwater and surface water are complex (Elleni, 2009).

In groundwater models, surface-groundwater interactions has been treated as boundary conditions varying from the simple specified head or flux boundaries to head dependent flux boundaries. In the case of the specified head boundary, the head at the surface water is specified as the elevation of the water surface, and the flow across the boundary is computed using Darcy's law, whereas for specified flux boundary, the flow across the boundary is specified and the model calculates head value at the boundary.

Despite their simplicity, both approaches suffer from the drawbacks that hydraulic conductivity at the interface cannot be determined precisely, and they do not take bottom elevation of surface water into consideration. Thus, flow across the boundary interface can be potentially unlimited. The head dependent flux boundary is a value-dependent boundary condition where flow across the surface-groundwater interface is computed based on relative water levels between the aquifer and the surface water, and conductance term at the boundary.

2.3. Water Resources of the Lake Beseka Area

The water resources in the Lake Beseka area include hot spring, cold spring, groundwater, Awash River and Lake Beseka.

2.3.1. Hot spring

There are numbers of hot springs in the Lake Beeka catchments, but the most important ones are Tonne and Chelelektu springs. They are situated at the southern end of the lake. They discharge significant volume of water to the lake. There are also some submerged hot springs inside the lake and hot water seepage throughout the southwest periphery of the Lake (MoWR, 1999). The hot spring is very alkaline water in nature.

2.3.2. Cold Spring

There is a cold spring situated at the northern end of Lake Beseka near to the rail line. It is locally known as Abdula-tebel. The water quality of this spring is different from that of the other water resources in this area. It is very hard water as compared to hot springs and Lake Beseka water. Contrarily to the alkaline nature of the hot springs and Lake Water, the spring is neutral and its PH is about 7. The discharge rate of this spring seems insignificant as compared to the hot springs in the catchment.

2.3.3. Groundwater

Groundwater in the lake area is generally unconfined. Groundwater quality in the Lake Beseka area is generally unfit for drinking purposes. Especially those ground waters situated near the Lake in the eastern direction contain very high concentration of fluoride and other salts. Excess fluoride in drinking water is toxic and it causes bone and teeth fluorosis.

2.3.4. Awash River

Awash River basin has a catchment area of 112,696 km^2 and originates from Central West part of Ethiopia, flowing 1200 km long, and provides a number of benefits to Ethiopia. Relatively, the most utilized river basin and the only river entirely in the country. The Awash River meanders in a southwest to northeast of the Lake Beseka. It is the only big river passing near by the Lake. The shortest distance between the Lake and the river is about 3Km.

The water quality of Awash River is suitable for irrigation and it has been used for irrigation more than any other rivers in the country. However, due to the high turbidity and high bacterial pollution, it is not suitable for drinking and domestic uses without further treatment.

2.4. Expansion of Lake Beseka and water level rise

The Ethiopian rift is characterized by a chain of lakes of various sizes and hydrological and hydrogeological settings. The rift lakes and Feeder Rivers are used for irrigation, soda extraction, commercial fish farming, and recreation, and they support a wide variety of endemic birds and wild animals. The levels of some of these lakes have changed dramatically over the last three decades. Lakes situated in the main Ethiopian rift valley are affected by climate changes, such as rainfall and its seasonality, which might change on a regional or global scale. Their hydrological regime is also strongly influenced by the geologic phenomena characterized by rifting and associated magmatism and sedimentation. However, effects of non-climatic factors induced by human-induced activities might exceed climate-change driven effects on lake level. Lakes that are relatively uninfluenced by human activities (Langano and Abaya) remain stable except for the usual inter-annual variations, strongly influenced by rainfall. Some lakes have shrunk due to excessive abstraction of water; others have expanded due to increases in surface runoff and groundwater flux from percolated irrigation water. Lakes Abiyata and Beseka, both heavily impacted by human activities, show contrasting lake level trends: the level of Abiayata has dropped by about 5 m over three decades because of the extraction of water for soda and an upstream diversion for irrigation. However, Lake Beseka has expanded in area over the last three decades because of increased groundwater inputs from percolated irrigation water.

Lake beseka is located at about 200 Km east of Addis Ababa, in the main Ethiopian Rift, near Metehara town. The lake level and areal extent has been more or less constant with minor fluctuations during the wet and dry seasons until the late sixties and early seventies, and has been increasing since then. Formerly the lake was on the southwest side of the main high way and railway lines, joining the capital to the eastern part of the country and Dijibouti. Currently the lake has engulfed the lines and covers the area on both sides.

Previous records indicate that in the early 1960s, the lake surface area was only 5km2. While during the years 1976 and 1998, the lake area has increased to 27.5km^2 and to 40km^2 respectively. The steady rise of the water level of Lake Beseka, over the past thirty years has required the highway and railway lines to be raised several times. Apart from threatening the existing infrastructures, drastic expansion of the lake has flooded and inundated the adjacent grazing lands and partially inundated Abadir farm, part of Metehara sugar Estate, which is located to the southeast of the lake in the vicinity.

The results of the study conducted in 1997-98 by the MoWR revealed the following changes in lake level and volume:

- ❖ During the years 1964 – 1972(8 years and 5 months), the total change in volume of the lake was about 13.4 MCM, i.e., the volume of the lake increased at a rate of about 1.7 MCM/yr and the lake level rose at a rate of about 0.24 m/yr.
- ❖ During the years 1972 – 1978(6 years and 4 months), the total change in volume of the lake was about 86.6 MCM, i.e., the volume of the lake increased at a rate of about 13.7 MCM/yr and the lake level rose at a rate of about 0.66 m/yr.
- ❖ Between the years 1978 – 1998(20 years and 8 months), the total change in volume of the lake was about 129.6 MCM, i.e., the volume of the lake increased at a rate of about 6.3 MCM/yr and the lake level rose at a rate of about 0.18 m/yr.

The Lake level has raised by 4m during 1976 – 1977 as evidenced from Lake daily stage records. The expansion pattern of Lake Beseka (starting from 1976 - 2006) is summarized below.

year	Lake level rise(m)	year	Lake level rise(m)
1976	0.71	1992	3
1977	1.21	1993	3.18
1978	1.46	1994	3.45
1979	1.48	1995	3.55
1980	1.4	1996	3.89
1981	1.76	1997	3.91
1982	2.03	1998	4.27
1983	2.05	1999	4.36
1984	1.91	2000	4.55
1985	1.9	2001	4.74
1986	2.13	2002	4.93
1987	2.07	2003	5.19
1988	2.09	2004	5.72
1989	2.44	2005	5.78
1990	2.66	2006	5.65
1991	2.776		

Table 2.1.Expansion pattern of Lake Beseka and change in depth at different years (Abdi, 2007)

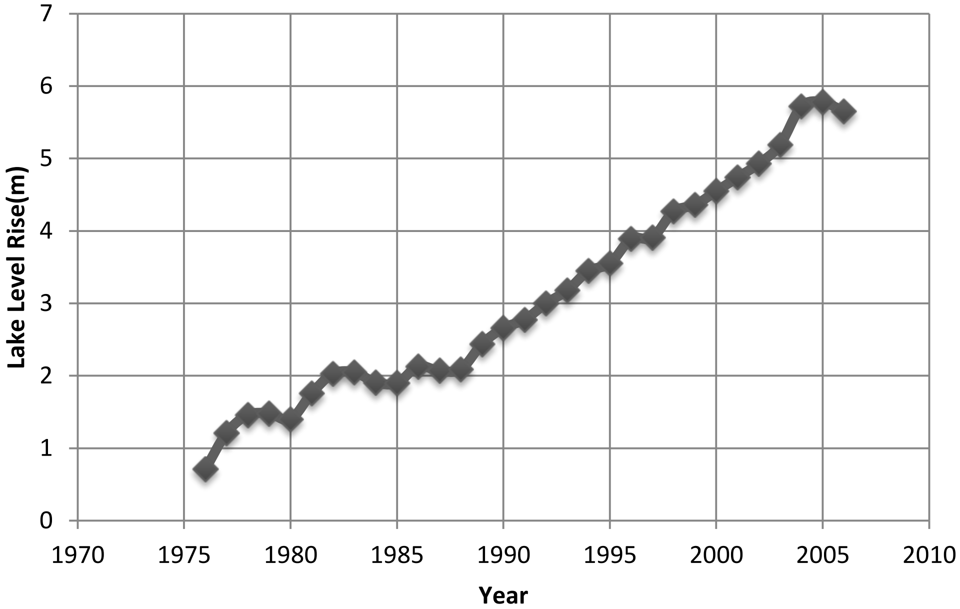

Figure 2.2. Plot of expansion pattern of Lake Beseka

2.5. Causes for the expansion of Lake Beseka

The main cause for the expansion of the Lake surface area and rise in level is the increased groundwater flow from the western part of the watershed. The discharges to the Lake from hot springs constitute as the major source and it is estimated to be 51% of the total inflow to the lake. However, some investigators relate the phenomena to neotectonism (Tessema 1998). The average annual increment of the Lake was 0.2 m and the level of the Lake has risen by four meters from 1976 to 1997 (Goerner et al 2009). The expansion and flooding of the Lake became a reason for the loss of 57 human lives, inundation of about 35 km^2 of grazing land, and displacement of 910 people.

The starting time of Lake Beseka expansion is not exactly known. However, most previous studies tend to agree that the problem has initiated in 1964 when the Methara mechanized farm around the lake was stated to be irrigated for cultivation of cotton and citric fruits and latter shifted to sugarcane development (Ayenew 2007).

The main change in the water balance of Lake Beseka comes from the irrigation fields and construction of koka dam located at 152 km upstream. Prior to the construction of the koka dam, Awash River could sometimes go dry between December and March. However, after the construction of the dam there has been fairly steady flow throughout the year. Hence, regulated flow has become a source of continuous recharge to groundwater ultimately feeding the Lake. Recent estimation of the water balance shows that groundwater contributes 50% (53.8 MCM/yr) input to the lake and 64% of the groundwater input to the lake inflow comes from outside the catchment area i.e. the Awash River transmission loss and irrigation loss accounting 23.5 and 10.5 MCM/yr respectively (Tessema, 1998).

2.6. Environmental impact of the expansion of Lake Beseka

Recently, the river faces a great environmental concern; mainly the saline water of Beseka lake expansion affects the surface and ground water dynamics and soil properties of the region and the condition is specifically dangerous for the sustainability of Matahara Sugar Estate and Matahara town in particular, and the Awash river basin in general. This would be disastrous, as the quality of the river water will be deteriorated such that agricultural development downstream would be at risk (Eleni, 2009).

The expanding Beseka Lake is in less than 3 km from the River Awash, which is the source of drinking water and irrigation for millions of people downstream. If the lake continues to expand at the current rate and other influencing factors remain the same, the lake will cross the natural water divide and invade the town of Addis Ketema and join the River Awash. This would be disastrous, as the quality of the river water will be polluted and agricultural development downstream would be at risk (Eleni, 2009). Hence it was decided to discharge water of Beseka Lake into Awash River and reduced its volume to certain level. The blending proportion is fixed to 2% of the Awash River flow rate, during peak flow, which was studied by the Water Resource Authority as harmless.

The main concern of using the blending technique is environmental issue. Discharging this polluted Lake water to Awash River causes a contamination to the river which is the mainly utilized resource of water. If this technique continues, it will cause an irreversible damage to the nearby river.

To mitigate the problem of Lake Beseka, different measures has been taken by the government. A pumping station having 8 (eight) pumps (3 of them 300 l/s and 5 of them 166 l/s), with a maximum capacity 1.73 m^3/s and minimum of 0.166 m^3/s was constructed and operational from 2007 to 2008. The amount of Lake Water discharged to Awash River is in 2007 – 11.5 MCM and 2008 -13.92 MCM .In 2009 the pump station is flooded by the lake level rise and the pumps were dismantled. The lake level rise was so abrupt and the lake level raised more than 1.5 m and the pipe lines used to discharge by pumping started discharging by gravity. The pumping scheme turned into gravity scheme since 2009 and in 2010 an outlet canal from the lake to Awash River was constructed to discharge the overflow of lake water. The discharge of lake water overflow was not recorded. Here best estimate of overflow by gravity along the pumping scheme and along the outlet canal is made by per personal judgment made during different period's field visits to the lake (OWWDSE, 2013).

- In 2009 - 2010 when the pumping schemes changed to gravity, the discharge was estimated to be about 0.7m^3/s during dry seasons and about 2.0m^3/s during rainy seasons.
- In 2010 the overflow outlet canal was completed and a discharge of about 1.0 m^3/s during dry period and about 3 to 4 m^3/s during rainy season was discharged in 2011 and 2012.

Accordingly the estimated annual discharge of Lake Outflow considered for lake water balance computation is given in table 2.2. This table shows that the flow from the Lake to Awash River is the same after the season where the pumping scheme turned into gravity system

Year	Outflow through the canal, MCM
2009	35.3
2010	35.3
2011	51.8
2012	51.8

Table 2.2. Annual Discharge of Lake Beseka outflow 2009-2012

Moreover, the rapid increase in Lake Beseka level and expansion of the lake in recent years into the wider area has brought a serious concern, due the inundations of large areas around the lake including irrigation farms, residential areas, and infrastructures. The flooding of the lake water into the adjacent productive lands under irrigation (Metahara and Abadir farm) and infrastructures and public utilities like health centers, schools, offices, roads and residential areas has caused negative impacts.

2.7. Previous studies

Many studies have been conducted regarding the problem of Lake Beseka by institutions, individuals as well as national and international organizations since the problem has raised. They have carried out intensive investigation, including different techniques to determine the cause of the Lake level rise and In order to design remedial measures.

Integrated studies on natural studies in particular on natural resources, lake water balance modeling, water quality analysis, environmental isotope studies and groundwater flow modeling resulted in identifying the main cause for the continuous Lake level rise to be the increment of the groundwater discharge flowing to Lake Beseka at the southwest side of the Lake. After determining the main cause of the lake level rise, some remedial measures were proposed. The environmental and socio-economic impact and financial implication of each proposed measure were analyzed, and the necessary remedial measure with least environmental impact and financial implication was recommended and detail designs were made.

Some and most significant previous studies, on the Lake level rise problem, can be listed below.

- Inter – Ministerial Technical Committees (IMTC) study reports: There are two IMTC studies, which were organized for urgent solutions when the Lake level rise threatened to flood the highway, railway and telecommunication lines passing through the Lake in 1978 and 1990.
- Direct studies on the rise of Lake Beseka level: There are two studies; the first is the comprehensive study conducted by Halcrow (1979) at project level as per the recommendation of the first IMTC, and the second, an initial appraisal report by Roofe (1990). The objective of the studies was to identify the main cause of the lake level rise and recommended remedial measures.
- Indirect study reports by NEDECO (1983) who were employed to reappraise and design the irrigation system of Metehara Sugar Estate considered a diversion of surface water to Awash River in order to alleviate the rise of Lake Beseka level.
- MacDonald and partners (1986) employed by Sugar Corporation to design irrigation works for the Abadir farm extension considered the possibility of constructing a drain at the limit of the extension area in order to convey all drainage water to Awash River, possibly by pumping.
- Recently Ministry of Water, Irrigation and Energy (2013) made a study on assessment and evaluation of causes for Beseka Lake level rise and design mitigation measures. Regarding the Lake – groundwater interaction, the report stated to address detailed hydrogeological studies in the future. The hydrogeological evaluation of the study indicates that the groundwater system is very much linked with the lake. Given the limited climatic changes and absence of clearly visible recent fault systems the recent lake level change is likely to be related to anthropogenic factor. This is most likely related to the irrigation activity within and outside the lake catchment. Probably the new irrigation system within the catchment may cause the dramatic lake level changes (OWWDSE, 2013).

Many studies have been carried out over the last two decades which are mainly academic exercises and few resulted in practical interventions. However, the problem attached to lake expansion remains unresolved. In recent years, the expansion has become a real concern at the national level demanding urgent intervention and as a result this study has been initiated. In spite of all the efforts made by various institutions, organizations and individuals, no study have reported in the literature, regarding determining the maximum possible lake water level rise which will indicate the reverse of the groundwater recharge to control the environmental damage of the Lake and the nearby Awash River.

3. Materials and Methods

3.1. Description of the project area

3.1.1. Location

Lake Beseka is situated in Oromia National Regional state of East Shoa Zone, Fantale District at about 200 km from Addis Ababa adjacent to Matahara, the capital town of Fantale district which is one of the areas continuously flooded by Lake Beseka. It is at about 958 meter above sea level, at the foot of mount Fentale. The present lake area is also estimated to about 48.31km^2.

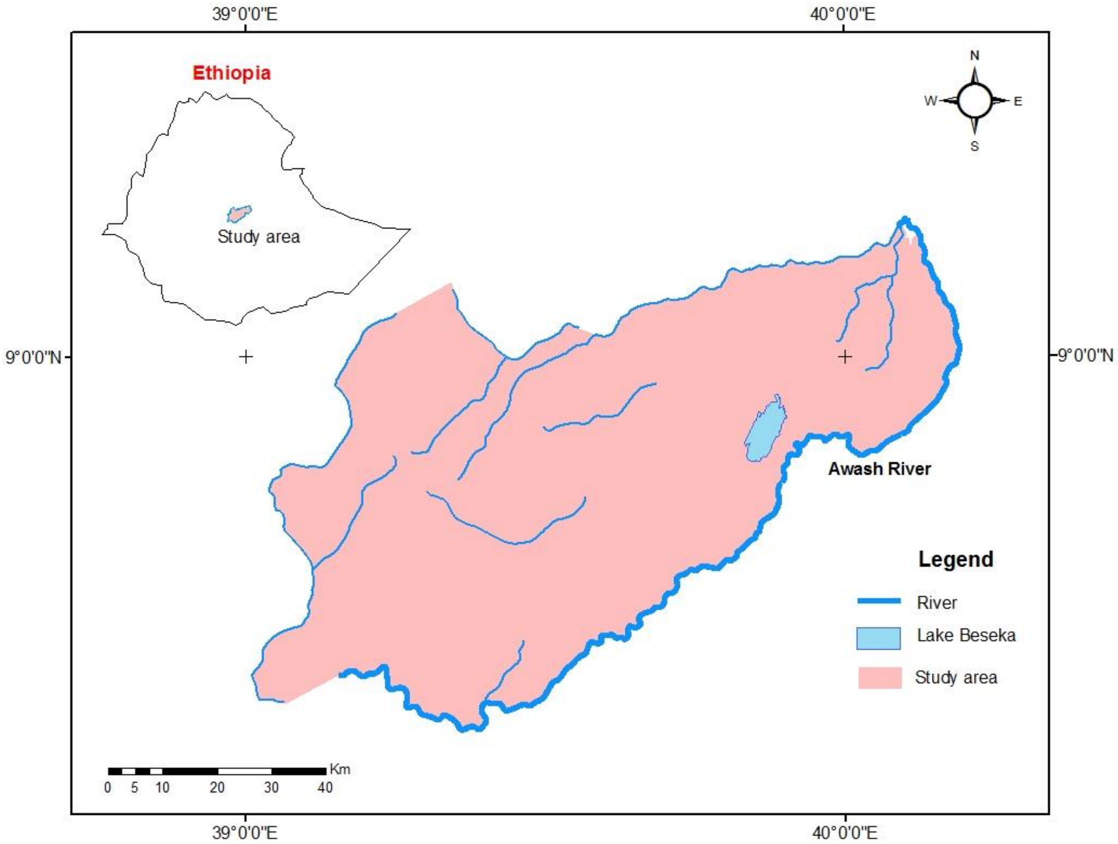

Figure 3.1. Location of the Study area

The Study area is part of the Awash Basin comprising parts of Lake Beseka catchment having an area of 6378km^2. It is geographically bounded by UTM of 501300E - 631100E and 926400N – 1020000N as shown in the figure below. The study area has its longer dimension along the North – East to South – West direction, bounded in the North by mount Fentale and highway from Addis

Ababa to Djibouti, in the South – East by Awash River and in South by Abadir farm (Metehara farm). It runs adjacent to the River Awash. The study area has been selected as a groundwater basin for the study because it is assumed that the Lake will influence or influenced by any activity within this region. It includes all the natural boundaries such as perennial Rivers and faults.

3.1.2. Climate

The study area is characterized by arid and semi-arid climate. : The area is well known by erratic rainfall that with inconsistence in quantity. Average annual rainfall in the study area varies from 500-1200mm with mean annual value of 885mm.

The agro-climatic division of Fentale district is within kola agro-ecology. The rainy season is characterized by uniform rainfall pattern.

Temperature: The mean monthly maximum temperature of the study area varies from 31^{o}C to 36^{o}C; while the mean monthly minimum temperature varies from 13^{o}C to 22^{o}C. The mean monthly temperature of the area estimated according to the data of Metehara station varies from 22^{o}C to 29^{o}C. Monthly variation in temperature is low which characterizes the semi- arid or Kola nature of the climate prevailing in the area (OWWDSE, 2014).

3.2. Data Processing

The data process starts with planning, which focuses on collecting the available groundwater related information, the questions at hand is to determine the maximum possible Lake level rise through modeling. After all the relevant data are ready, groundwater modeling will follow using the data collected. Trial hydrogeological parameters will be entering in the model and the hydraulic head will be checked with the well inventory data by a fitness indicator. If the fitness is not acceptable, the trial hydrogeological parameters will be changed and the process will be revised again. This iteration will continue until the goodness of the fitness indicator is acceptable. But if the fitness is acceptable the process will end and that hydraulic head will be taken as the head which reverse the ground water recharge. The procedure is summarized in the following chart.

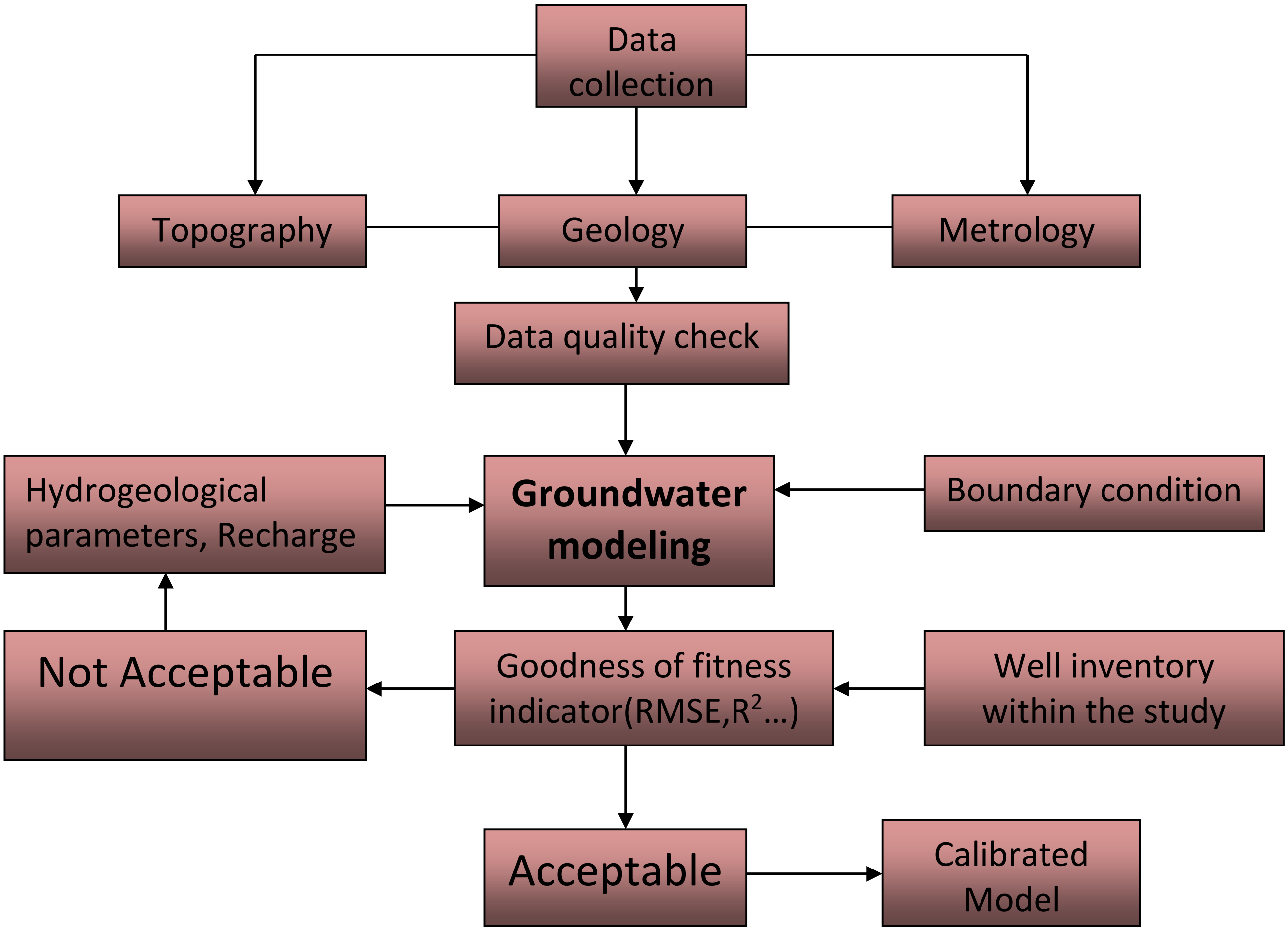

Figure 3.2. Groundwater Modeling Flow Chart

3.3. Determination of maximum Lake water level

Once the model is calibrated for existing well inventory data a process for identifying the maximum lake water level is computed. The maximum Lake level rise is determined by raising the lake water level and the calibrated model is run for this new lake water level thereby the groundwater flow direction is computed. The maximum lake water level is set at the lake water level which brings about a groundwater flow direction away from the lake.

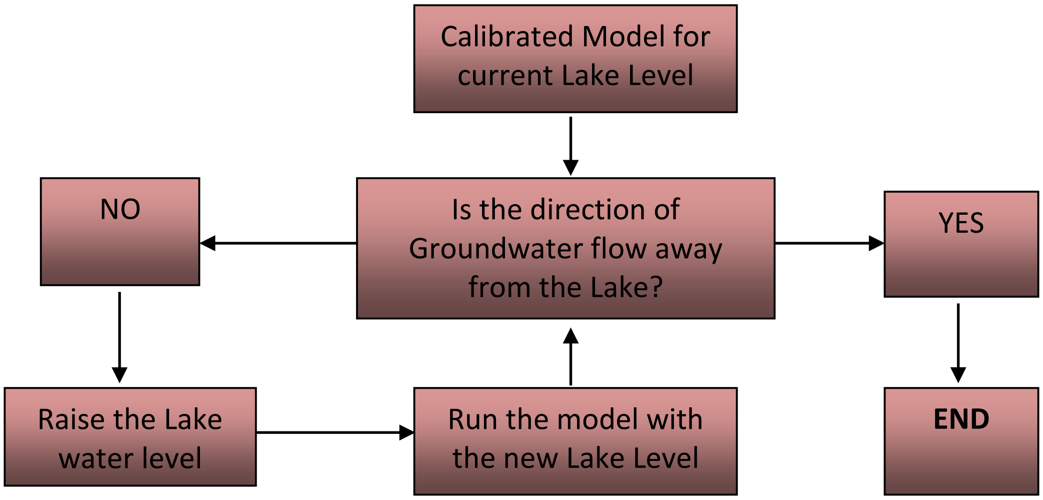

Figure 3.3. Flow Chart for the Determination of Maximum Lake Level Rise

3.4. Data collection and analysis

Based on the research objectives, the study is based primarily on existing geologic, hydro-geologic, Metrologic and topographic data. Field data collection which includes recording of latitude, longitude, elevation and static water level of the boreholes and springs is performed where existing data are not available. Geological map of Ethiopia, annual rainfall data, Digital Elevation Model (DEM), and well/spring location information were collected from different offices. The data collected were processed for quality and consistency and missing data will be filled.

3.4.1. Metreology

Annual meteorological data were obtained from the Ethiopian National Meteorological Service Agency (NMSA). To develop the mean annual rainfall distribution, a Thiessen polygon method of interpolation among the rainfall gauging stations within and nearby the modeling area was adopted.

Thiessen polygon method attempts to allow for non-uniform distribution of gauges by providing a weighting factor for each gauge. The stations are plotted on a base map and are connected by straight lines. Perpendicular bisectors are drawn to the straight lines, joining adjacent stations to form polygons, known as Thiessen polygons. Each polygon area is assumed to be influenced by the rain gauge station inside it, i.e., if P_1, P_2, P_3,....P_n are the rainfalls at the individual stations, and A_1, A_2, A_3, ... An are the areas of the polygons surrounding these stations, (influence areas) respectively, the average depth of rainfall for the entire basin is given by;

$$P_{av} = \frac{\sum P_i A_i}{\sum A_i}$$

Where, P_i mean annual rainfalls recorded at each rain gauge stations, P_{av} Average aerial depth of rainfall of the basin and $\Sigma A_i = A$ Total area of the basin under concern (Ragunath, 2006).

Thirty metrological stations in and very close to the study area were first identified. The monthly rainfall data of these selected stations were checked for data quality and consistency. After using the Thiessen polygon method twenty three meteorological stations are found to contribute to the study area. The result of the Thiessen polygon analysis is as shown in Figure 3.4 and Table 3.1.

Station Name	**Longitude**	**Latitude**	**Annual Rainfall(mm)**	**Area(Km2)**
Mojo	39.1254	8.592	930.346	271
AdisHiywet	39.5889	8.5097	837.086	393
Metehara	39.9129	8.8997	656.259	790
MelkaJilo	39.6106	8.8991	754.901	903
ChefeDonsa	39.1313	8.9797	1166.81	180
MetehBila	39.7061	9.2068	796.629	210
Koka	39.0249	8.4395	845.358	94
Wenji	39.2138	8.4493	851.617	89
Nazret	39.2694	8.5361	866.852	317
Sodere	39.3795	8.4052	827.998	215
Welenchiti	39.4291	8.6543	837.321	626
Abomsa	39.8268	8.4808	1018.76	3
Abadir	39.9008	8.7555	876.639	323
Awash	40.1598	8.9957	639.037	443

Balchi	39.3666	8.911	928.277	385
Arerti	39.4267	8.9298	867.133	336
DebreZeyt	38.9862	8.746	967.667	62
Ejere	39.2589	8.7751	1005.61	514
Godino	39.0231	8.8686	1029.63	35
Koremas	39.2985	9.2277	1086.76	31
Shola Gebeya	39.4072	9.2117	1195.31	12
MelkaSede	40.1446	9.2523	503.457	145

Table 3.1. Annual Precipitation of Metrological Stations in the Study Area

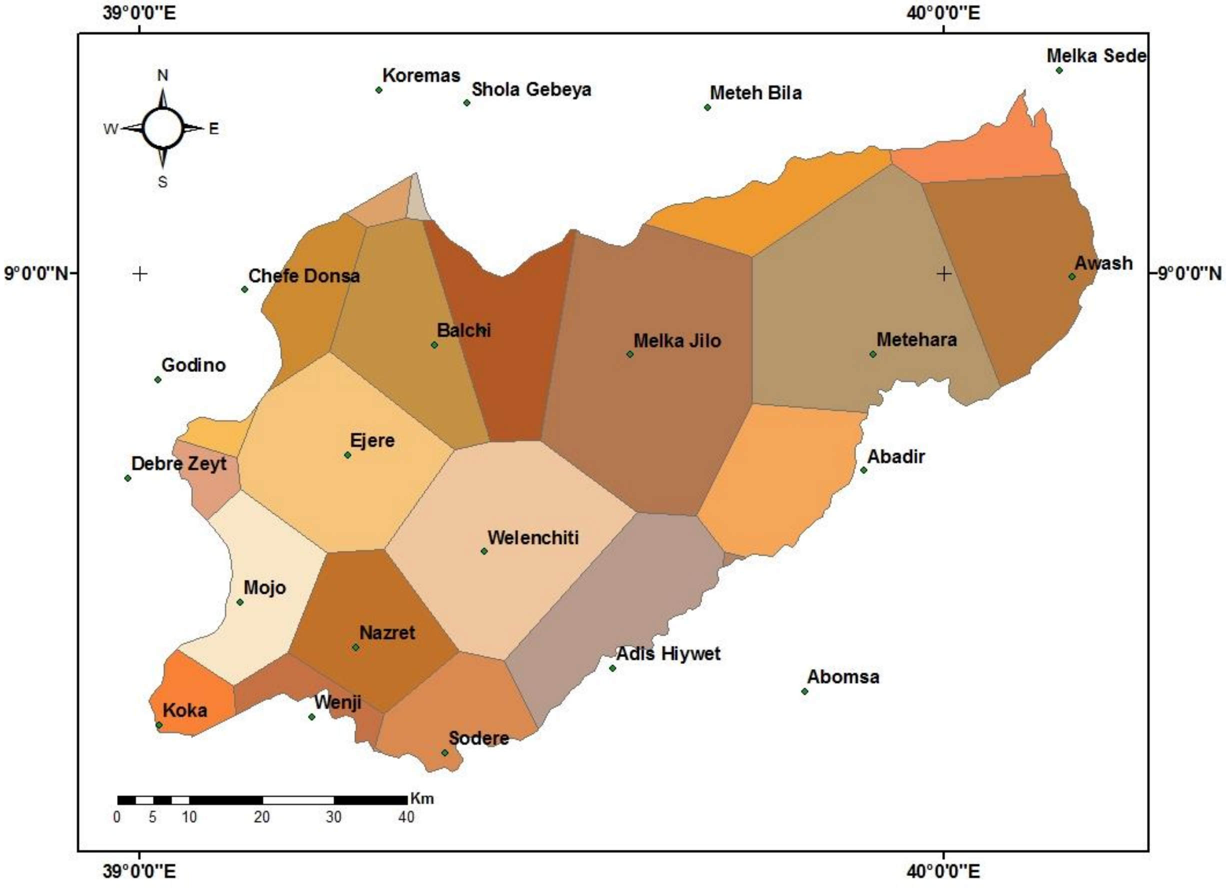

Figure 3.4. ThiessenPolygon of the Study Area

3.4.2. Geology

The lake is situated within an active tectono-magmatic segment of the Main Ethiopian Rift. Volcanic and seismic activity and faulting are phenomena linked to the geologic processes in the axial part of the rift resulting from strain localization after the abandonment of the border faults during the Pleistocene.

Lake Beseka is one of the lakes which are found within the volcanically active rift floor and is located at the northern end of the main Ethiopian rift in the Awash basin. The Main Ethiopian Rift, which belongs to the northern most braches of the East African Rift System, is characterized by active extensional tectonics. It is seismically, tectonically and volcanically active since early Miocene time (WoldeGabriel et al., 1990).

Most of the study area and shores of Lake Beseka are underlain by Pleistocene to sub recent basalt, often coarse grained with phenocryst (Halcrow, 1978). Pleistocene basalts are exposed in most fault scarps and form the southeastern and western edges of Lake Beseka. The fault scarp cutting the Pleistocene basalt at the southwestern shore of the lake is characterized by hot springs. It is assumed that Pleistocene basalts mainly represent lava pouring through fault fissures rather than being the product of volcano eruption (Eleni a., 2009).

A substantial portion of the southwestern part of the lake watershed is covered by undifferentiated lava flow of trachytic to rhyolitic composition with minor ignimbrite intercalations, which are believed to be the product of the Kone volcanic complex. The Fentale volcano complex consists of two caldera volcanoes, the older Tinish Fentale and the younger Fentale volcano.

Geological data were obtained from Water works design and supervision enterprise. It is used to get the geological characterstics of the aquifer. The aquifer characterstics is obtained from the delineated study area in ARCGIS as shown in figure 3.5 and table 3.2 below.

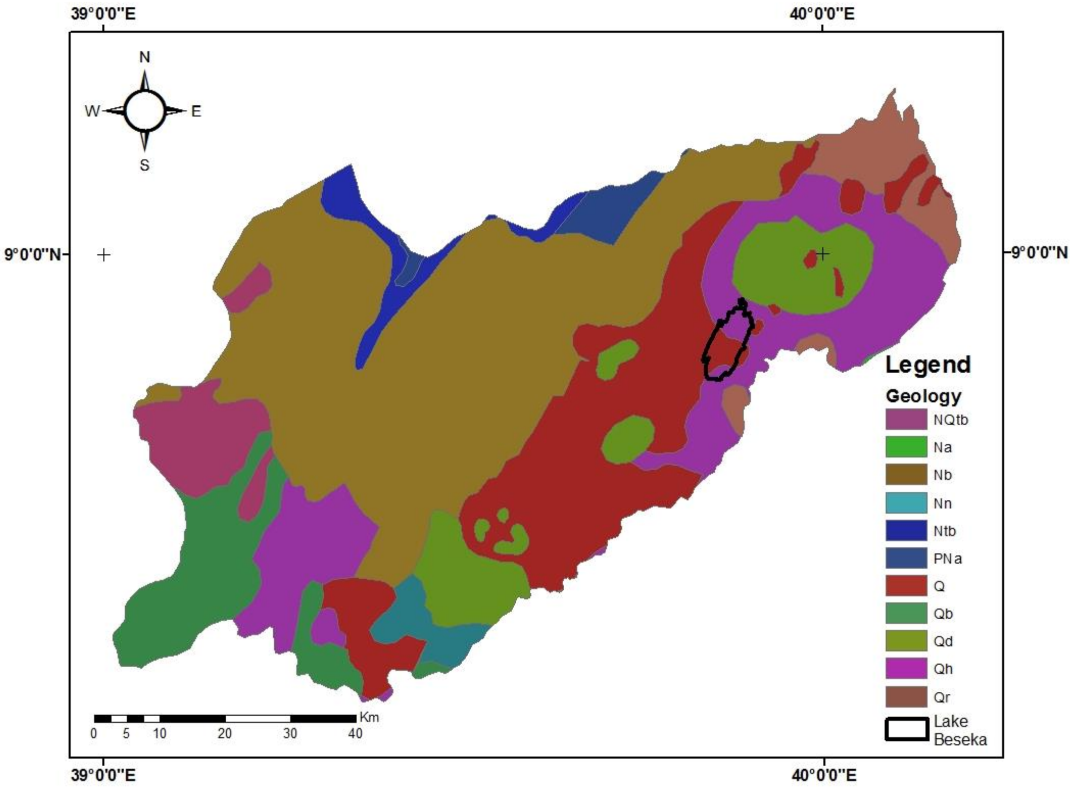

Figure 3.5. Geological Map of the Study Area

Na	Afar series: Alkaline basalt with subordinate alkaline and peralkalinesilicics (rhyolitic dome and flows and ignimibrites)
Nb	Mursi and bofa Basalts: Alkaline basalt
Qd	Dino formation: Ignimbrite, tuff, course pumice, waterlainpyroclastic rocks with rare intercalations of lacutrine sediments
Qr	Rhyolitic volcanic centers, obsidian pitchstone, pumice, ignimbrite, tuff, subordinate trachytiv flows (predominantly peralkaline in composition)
Qh	Undifferentiated alluvial, lacustrine and beach sediments.
Qb	Basalt flows, spatter cones and hyaloclastites. a) Transitional type between alkaline and tholeiitic b) Alkaline olivine basalt
Nn	Nazret series-Ignimbrites, unwelded tuffs ash flows, rhyolite flows, domes and trachyte
NQtb	Bishoftu formation: Alkaline basalt and tarchyte
Ntb	Tarmabermegezez formation: Transitional and alkaline basalt
PNa	TarmaberGussa formation: Alkaline to transitional basalts often forming shield volcanoes with minor trachyte and phonolite flows
Q	aluvial and lacustrine deposits: sand, silt, clay, diatomite, limestone and beach sand

Table 3.2. Description of Geological Annotations of the Study Area

3.4.3. Topography

Digital Elevation Model (DEM), with resolution of 30mX30m is used to obtain topographic map. The minimum and maximum elevation of the study area is attained at 683 m and 2644m above mean sea level (amsl) respectively. The Lake has a minimum and maximum elevation of 930 m and 1071m above mean sea level (amsl) respectively. The current elevation of the Lake is 958m amsl. The topography of the study area is shown in figure 3.6.

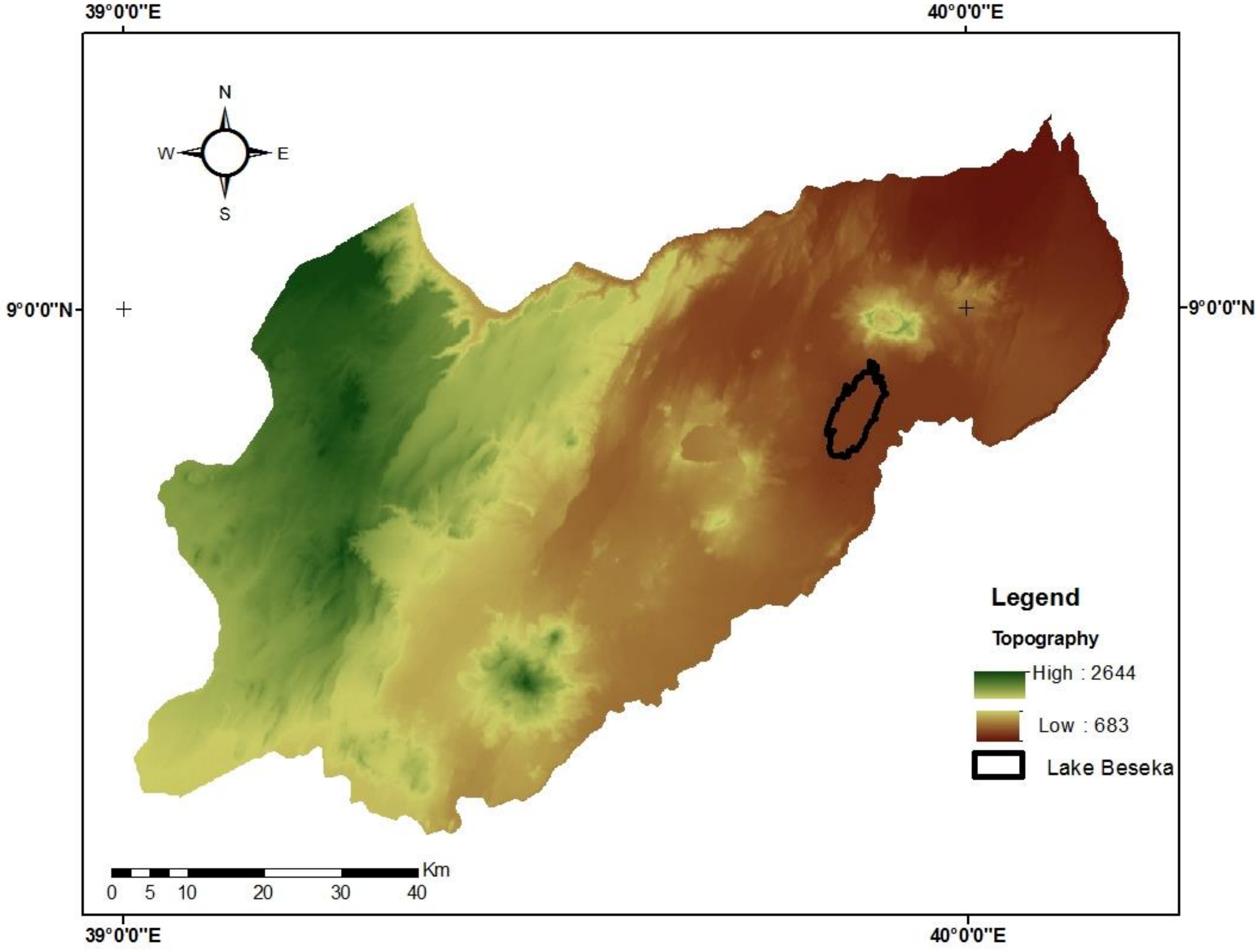

Figure 3.6. Topography of the study area

3.4.4. Well and spring inventory

More than 100 wells were inventoried within the study area. The data were collected from Federal Water works design and supervision Enterprise and Ethiopian National Groundwater Database (ENGDA). Borehole data around the Lake were collected from Federal Water works design and supervision Enterprise which were recorded at 2010. The rest data were found from both sources. From these inventoried data the data quality and consistency checking has resulted in 83 wells/springs for analysis. Among these 9.6% are above 150m surface water depth and 90.4% are below 150m surface water depth. Most of the wells are shallow wells with minimum depth of 0.23 m (which is around the Lake) and few are deep wells with maximum depth of 207.6m. The information from these wells used in the model are: well location (UTM coordinate of each well) and static water level. The selected wells location is shown in Figure 3.7 and the Annex.

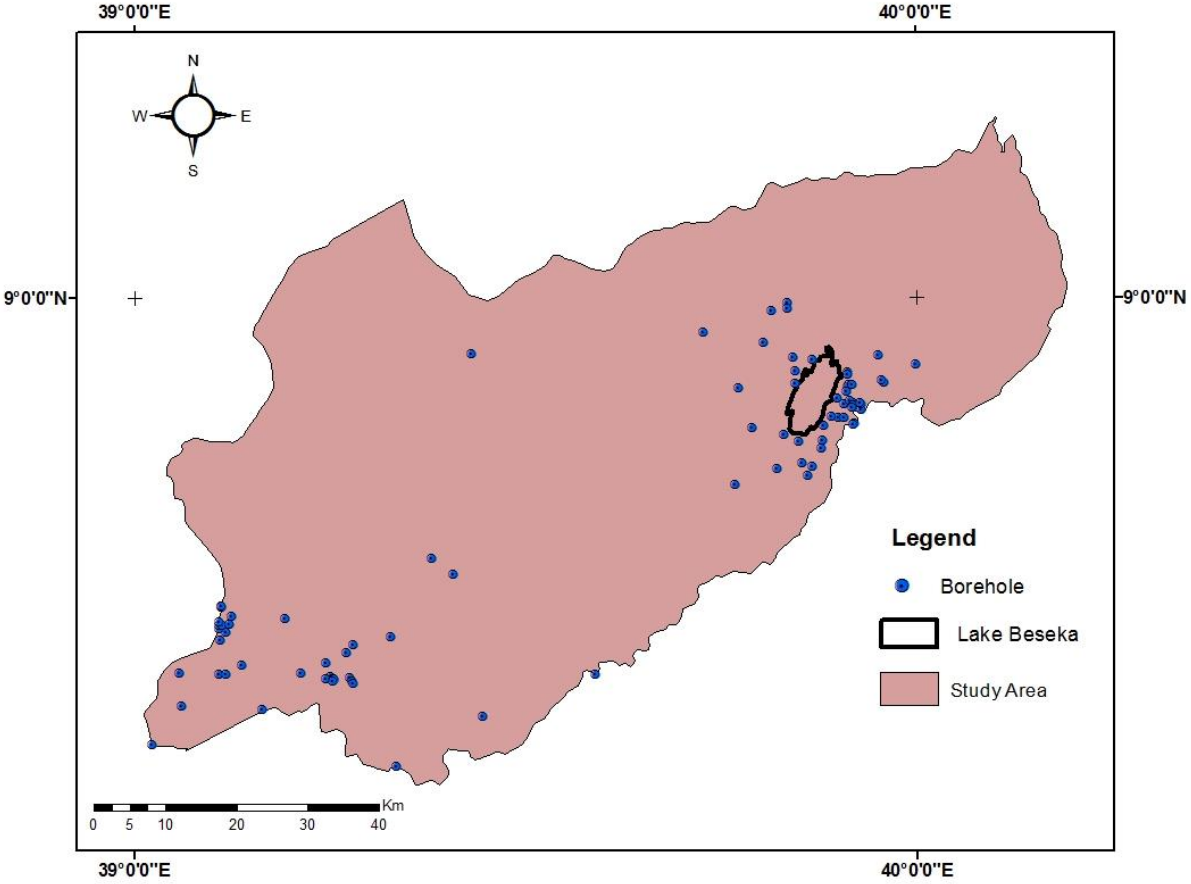

Figure 3.7. Inventoried Well/Spring Location of the Study Area

3.5. Conceptual Model

The purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily. Features often described in conceptual models include Relationship and extent of hydrogeologic units, Aquifer material properties (hydraulic conductivity), Potentiometric surfaces, Boundary locations (depth to bedrock, impermeable layer boundaries, etc.), Boundary conditions (fluxes, heads, natural water bodies) and System stresses (withdrawal wells, infiltration trenches, etc.)

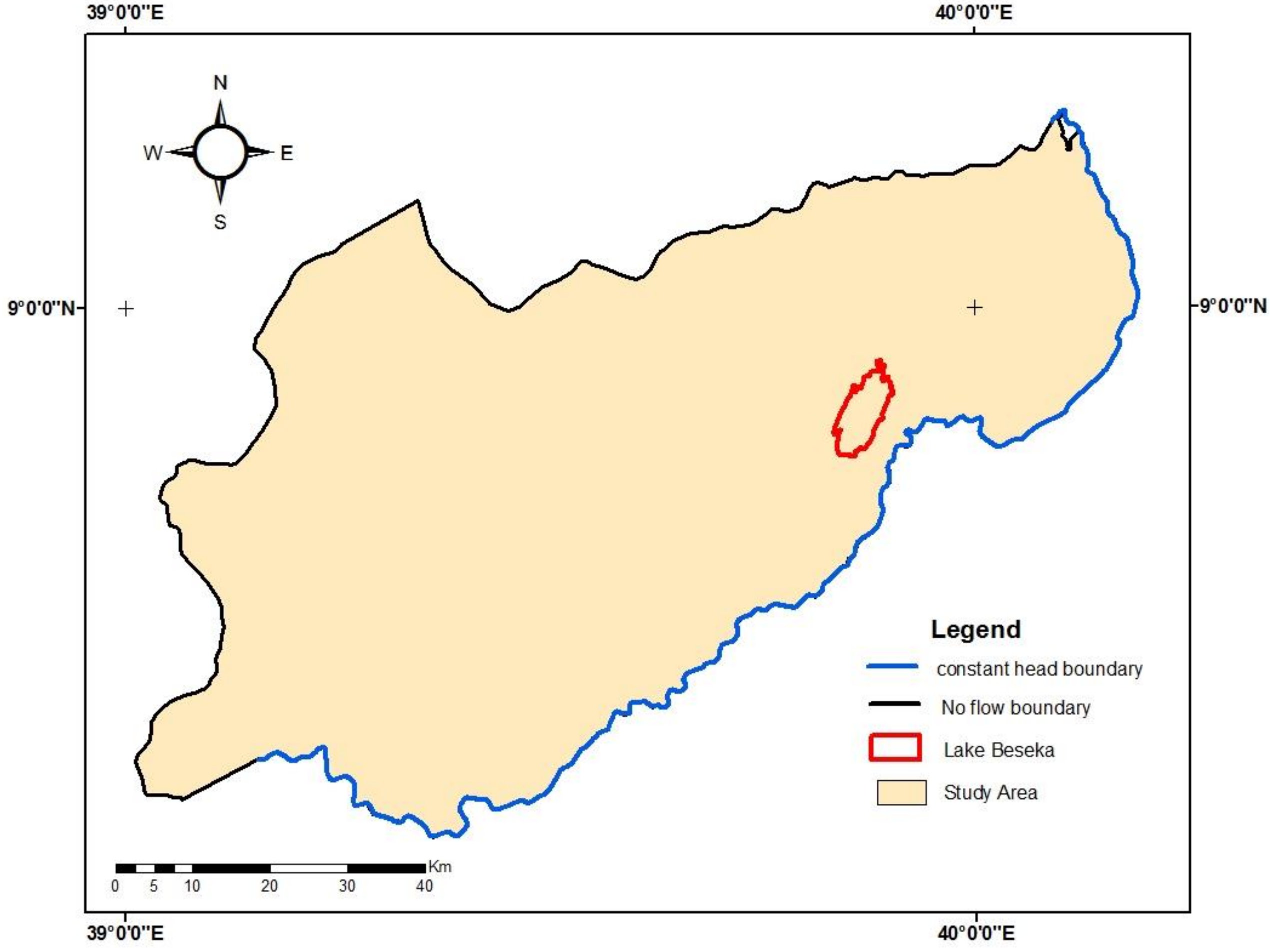

Figure 3.8. Conceptual Model of the Study Area

3.6. Groundwater Modeling

A mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model (boundary conditions). Mathematical models can be solved analytically or numerically.

Numerical models were found to have more advantages over other solution techniques. Unlike analytical methods numerical methods do not need yield approximate solutions to the governing equation through the discretization of space and time. In this study TAGSAC is used for solving the groundwater flow equation. In the TAGSAC approximation procedure, the flow region is first discretized into a network of finite elements, and an interpolating trial function is used to represent the unknown dependent variable (hydraulic head) over the discretized region. An integral approximation of the flow equation is then obtained using the Galerkin weighted residual criterion. Spatial integration is performed piecewise over each element. Upon assemblage of the elements and incorporation of boundary conditions, a system of nodal equations is obtained. For a steady-state simulation, these nodal equations are algebraic equations. TAGSAC has proofed to be applicable in a number of researches done all over the globe (Mohammed and Ayalew, 2016).

For two dimensional flows the most common shapes for finite elements are triangles and trapezoids. And for that of three-dimensional flow triangular and trapezoidal prisms are the most common ones. In this study triangular prism element is selected.

3.6.1. Discretization of the problem domain

Numerical methods yield approximate solutions to the governing equation through the discretization of space and time. The FEM uses concept of piecewise approximation technique to obtain solutions to a wide variety of problems. The domain of the problem that is the extent of the aquifer (model basin) to be simulated is divided into a set of elements or pieces. So the first step in the solution of a groundwater flow by the finite element method is to discretize the problem domain. This is done by replacing the problem domain with a collection of nodes (or nodal points) and elements referred to as the finite element mesh. In the finite element analysis the precision of the solution obtained and the level of computational effort required to obtain a solution will be determined to a great extent by the number of nodes in the mesh. A coarse mesh has a smaller number of nodes and will give a lower precision than a fine mesh. However, the larger the number of nodes in the mesh, the greater will be the required computational effort and cost. The size and shape of the elements in a mesh is determined primarily by the size and shape of the problem domain, the number of different types of aquifer materials, and by the number of nodes in the mesh. The most common shapes for finite elements are triangles and trapezoids for two-dimensional flow, and triangular and trapezoidal prisms for three-dimensional flow (Fitts, 2002). In problems that have a complex geometry (e.g., caused by an irregular depth to bedrock) or geologic structure (e.g., due to the presence of faults) many elements will be required. Even if the problem domain contains curved boundaries or interfaces different types of elements we use single type of elements for simplicity.

3.6.2. Recharge boundary

Recharge is one of the parameters in the model calibration. During calibration a trial fraction of the total rainfall over a surface is used. In humid areas with porous soils, 25% of annual rainfall may recharge the aquifer; in contrast, in desert regions recharge is very small to 1% of rainfall or less. Accordingly since the location of the study is not desert while calibrating, the recharge fraction in the model was varied between 5% and 25%.

3.6.3. Boundary condition

Mathematical models of groundwater flow based on equations are classified as boundary value problems. To obtain a unique solution of such equations additional information about the physical state of the process is required. This information is supplied by boundary and initial conditions. For steady-state problems, only boundary conditions are required.

Boundary conditions indicate how an aquifer interacts with the environment outside the model domain. They include things such as heads at surface waters in contact with the aquifer, the location and discharge rate of a pumping well. For a distinct solution, at least one distinctive boundary condition is specified. There are three types of boundary conditions. But the most basic types of boundary conditions in groundwater flow analysis are two which are constant head boundaries and no-flow boundaries. Constant head boundaries occur along the boundary of water bodies like lakes or reservoirs. No-flow boundaries occur at the interface between the aquifer and materials with markedly lower hydraulic conductivity.

The finite element method can handle all types of boundary conditions, including no-flow boundaries, specified head boundaries, specified flux boundaries, and leakage boundaries.

In the model constant head boundary condition was set for the Awash River in the locations where the river is perennial which is in the South and South-West direction of the study area. The Lake Beseka boundaries that come in contact with the model are treated as constant head boundaries. In the North and North-West direction of the study area is treated as No flow boundary. The top surface of the study area is treated as a recharge boundary where the recharge is taken as a fraction of the annual rainfall over the surface. The upper boundary is fixed on the basis of its effect on the model domain. Figure 3.8 shows the boundary conditions of the study area.

3.7. Materials used

For data processing and consistency checking, the following application software were used.

- ArcGIS 10.1 has been employed for developing input data for modeling. It has been used to develop DEM, Thiessen polygon, geologic classification for the study area, conceptual model.

- MATLAB (R2010b) has been used for modeling and determining the hydraulic head. Numerical groundwater model codes, TAGSAC, has been developed using MATLAB to determine the maximum Lake level rise.

- Surfer 10 has been used to develop an input data for the numerical model, it has also been employed to plot maps and analyze the results that have been computed by the model.

4. Result and Discussion

Surface waters such as Lakes, Rivers, Ponds, reservoirs and seas are vulnerable to unexpected variation on environments due to different factors. Environmental sustainability of these water resources is the major concern all over the world. Protections of existing water resources from environmental degradation must be prioritize to use, manage and preserve the water bodies. The growth of Lake Beseka is a natural disaster for the surrounding ecosystems, as the expansion has created an unstable transitional zone between the wetland and nearby terrestrial ecosystem. Lake Beseka is a very saline Lake which cannot be used as a resource. A groundwater modeling has been adapted for predicting the maximum possible lake Beseka Level rise if it is contained in its territory instead of discharging it to the nearby river, Awash River. Containment of this saline Lake has the advantage of protecting the Awash River from irreversible damage.

4.1. Discretization of the study area

The hydrogeologic parameters are specified for each element in the mesh. By taking into consideration the study area and the computer in use the mesh is generated by 1000 meters element length. The nodes have right-handed Cartesian coordinates (x, y, z), z-axis points in the vertical upward direction (the elevation of the nodes above sea level). The model has generated 15268(7634X2) nodes and 14,849 elements.

When drawing the finite element mesh, each element is assigned with a unique element number. The element numbers begin with one and continue sequentially to the number of elements in the mesh for each model basin independently. Each element is described using six nodes; the nodal coordinates define the size and shape of the element. For this reason the node numbers for each element are listed. The material properties are specified for each element in the mesh. The properties for each material set are then listed once.

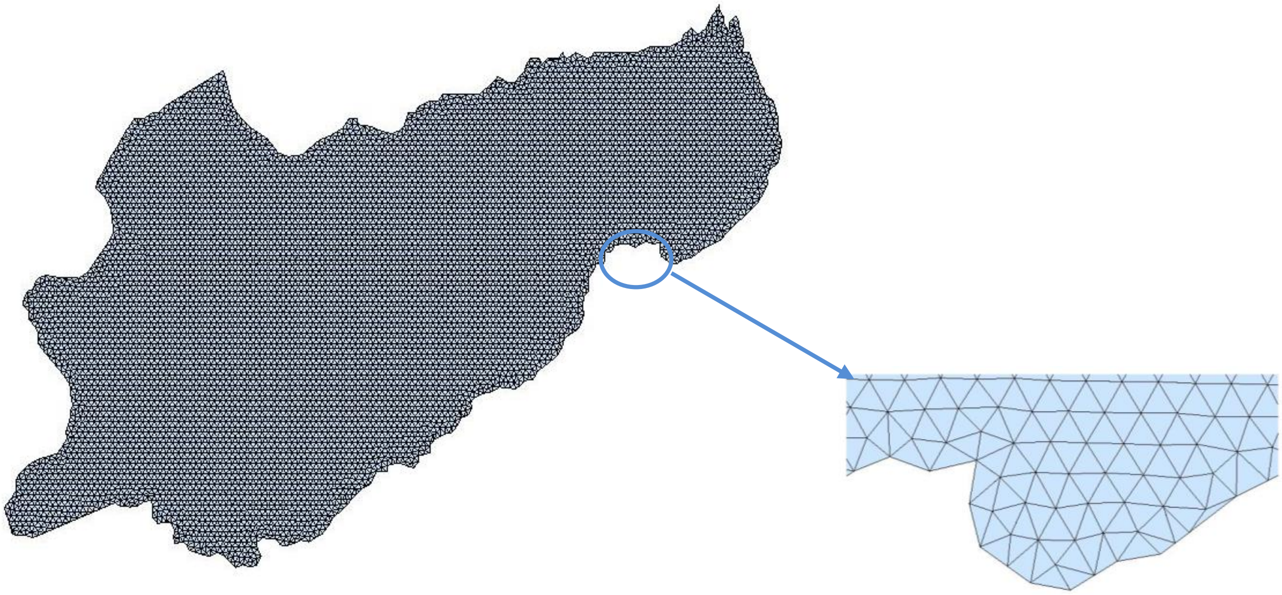

Figure 4.1. Generated Mesh for the Study Area

4.1. Model Calibration

To demonstrate that groundwater models are realistic, field observations of aquifer response are compared to corresponding model simulated values in model calibration, with the general objective of reducing the difference.

Calibration is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error. Calibration is one of the primary processes used to maintain Model accuracy. There are two methods of calibrating a model: manual trial-and error calibration and automated calibration. Sensitive model parameters are adjusted such as material properties and recharge conditions until the model is consistent with the available data and computed values of head closely match measured values at selected points in the aquifer (locations of wells and springs). Although, automated methods are becoming increasingly usable and accepted due to its familiarity and easy of understanding in complex solutions, trial and error is mostly used one. The calibration of a deterministic groundwater model is often accomplished through a trial-and-error adjustment of the model input data to modify model output. In this study the calibration procedure follows a "trial and error" calibration process where the flow model is considered to be calibrated when it can reproduce, to an acceptable degree, the hydraulic heads of the natural system being modeled. This is accomplished by finding a set of values for the boundary conditions and aquifer properties. In other words, calibration methods solve a problem inversely by iteratively adjusting the unknowns until the natural system matches the hydraulic heads.

A scatter plot of measured against simulated heads is a way of showing the calibrated fit. Deviation of points from the straight line should be randomly distributed. A listing of measured and simulated heads together with their differences is a common way of reporting calibration results. The primary calibration target in this study is hydraulic head (water level).

For the best hydraulic conductivity and recharge values, the modeled and the measured values comparison can be seen in figure 4.2. The best fit equation obtained between the simulated (y-axis) and measured head (x-axis) is made for the model. In an ideal calibration, the points will fall on a straight line with a 1V:1H slope that means the computed value equals the measured value. The degree of scatter about this theoretical line is a measure of overall calibration quality. The slope in the best fit equations in figure being closer to one implies the acceptability of the modeling results.

Accordingly, steady-state calibration was made using static water level observations of 83 wells and springs. The average of the differences is then used to quantify the average error in the calibration. The objective of the calibration is to minimize this error (Anderson Mary p., 1992). Three ways of expressing the average difference between simulated and measured heads are commonly used.

1. The *mean error* (ME) is the mean difference between measured heads (hm) and simulated heads (hs).

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)i$$

Where n is the number of calibration values. The ME is simple to calculate but is usually not a wise choice because both negative and positive differences are incorporated in the mean and may cancel out the error.

2. The mean absolute error (MAE) is the mean of the absolute value of the differences in measured and simulated heads.

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |(h_m - h_s)i\,|$$

3. The root mean squared error (RMSE) or the standard deviation is the average of the squared differences in measured and simulated heads.

$$\mathrm{RMSE} = (\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2)^{0.5}$$

The maximum acceptable value of the calibration criterion depends on the magnitude of the change in heads over the problem domain. If the ratio of the RMSE to the total head loss in the system is small, the errors are only a small part of the overall model response. As a general calibration criteria RMSE equal to or less than 10% of the observed head range in the aquifer being simulated is better (Anderson, 1992). The mean error (ME) and the mean absolute error (MAE) are characterized by low values indicating that the model was well calibrated. But due to the accuracy of GPS and the element dimensions in use RMSE slightly greater than 10 are taken as an acceptable error.

On the other hand R^2 value compares estimated and measured head, and ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the between the modeled and measured values or there is no difference between the estimated and measured values. At the other extreme, if the coefficient of determination is 0, the regression equation is not helpful in predicting. In the computed regression plots the intercept was made zero.

Accordingly, the scatter plot with computed calibration errors and R^2 values are presented in figure 4.2 and table 4.1 below.

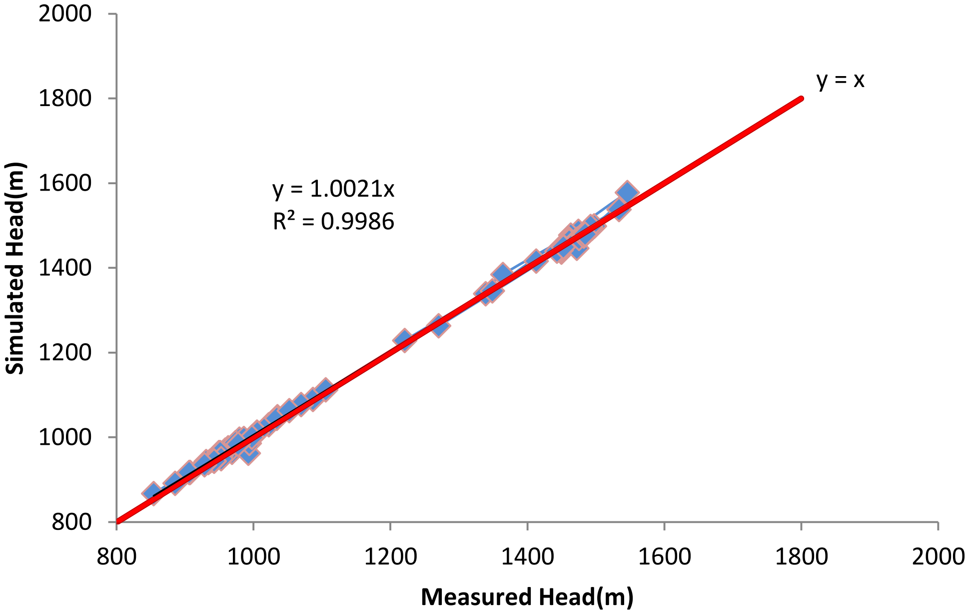

Figure 4.2. Simulated versus measured head comparison

RMSE(m)=	**9.449**
ME(m)=	**-3.284**
MAE(m)=	**7.435**
R-squared=	**0.998**
Intercept=	**1.002**

Table 4.1. Calibration Errors of the Model

The observed head range in the aquifer is 867.55m - 1577.87m. The RMSE is then 1.33% of this observed head range which is much less than the recommended value (10%). Therefore, the above calibration criterions clearly show that the measured and simulated heads of the model have a better match.

4.2. Hydrogeology

Hydrogeology parameters are known to be transmissivity, hydraulic conductivity, storativity and the like. Hydraulic conductivity and transmissivity are the most sensitive parameters in groundwater modeling. Transmissivity is the hydraulic conductivity multiplied by the aquifer thickness.

In the model hydraulic head is computed by varying the hydraulic conductivity for the eleven geologic zones of the area and the surface recharge from the rainfall. After many trial and error works selection of a set of hydraulic parameters for geologic zones and recharge for each model basin, the following parameter values are selected as the best among other combinations.

Geology No	**K_{XX}(m/yr)**	**K_{YY}(m/yr)**	**K_{ZZ}(m/yr)**	**Surface recharge**
1	**0.6912**	**0.432**	**0.06912**	**10%**
2	**0.864**	**0.6912**	**0.0864**	
3	**0.6048**	**0.432**	**0.0432**	
4	**0.432**	**0.6048**	**0.0432**	
5	**0.1728**	**0.3456**	**0.01728**	
6	**0.1728**	**0.2592**	**0.01728**	
7	**0.0864**	**0.864**	**0.00864**	
8	**0.5184**	**0.432**	**0.05184**	
9	**0.5184**	**0.2592**	**0.05184**	
10	**0.864**	**1.2096**	**0.0864**	
11	**1.728**	**0.864**	**0.1728**	

Table 4.2. Hydrogeologic parameter of the study area for classified geologic zones

Hydraulic conductivity is not the same in the horizontal and vertical direction. Horizontal hydraulic conductivity is always greater than vertical hydraulic conductivity. Due to this, the aquifer is highly influenced by the horizontal hydraulic conductivity rather than the vertical hydraulic conductivity. The hydraulic conductivity of the study area is classified as high, medium and low according to the result computed for the project domain. The horizontal hydraulic conductivity shown in Figure 4.3 shows that the Southern and South-Western part of the study area has high horizontal hydraulic conductivity which indicates that groundwater moves faster in this direction to the Lake. Most studies described that these parts (Southern and South-Western) of the groundwater basin are major sources of recharge for the Lake Beseka and take major contribution to the rapid rise in the Lake Level. The result of this study also shows that these areas have a significant role in the Lake level rise. Northern part of the study area and an area around the Lake has a medium and low horizontal hydraulic conductivity respectively.

High vertical hydraulic conductivity is also noticed in the Southern area of the study area and the rest part of the study area has low hydraulic conductivity which indicates that the southern and south-western part of the study area contribute a major role for the rapid rise in Lake Beseka level.

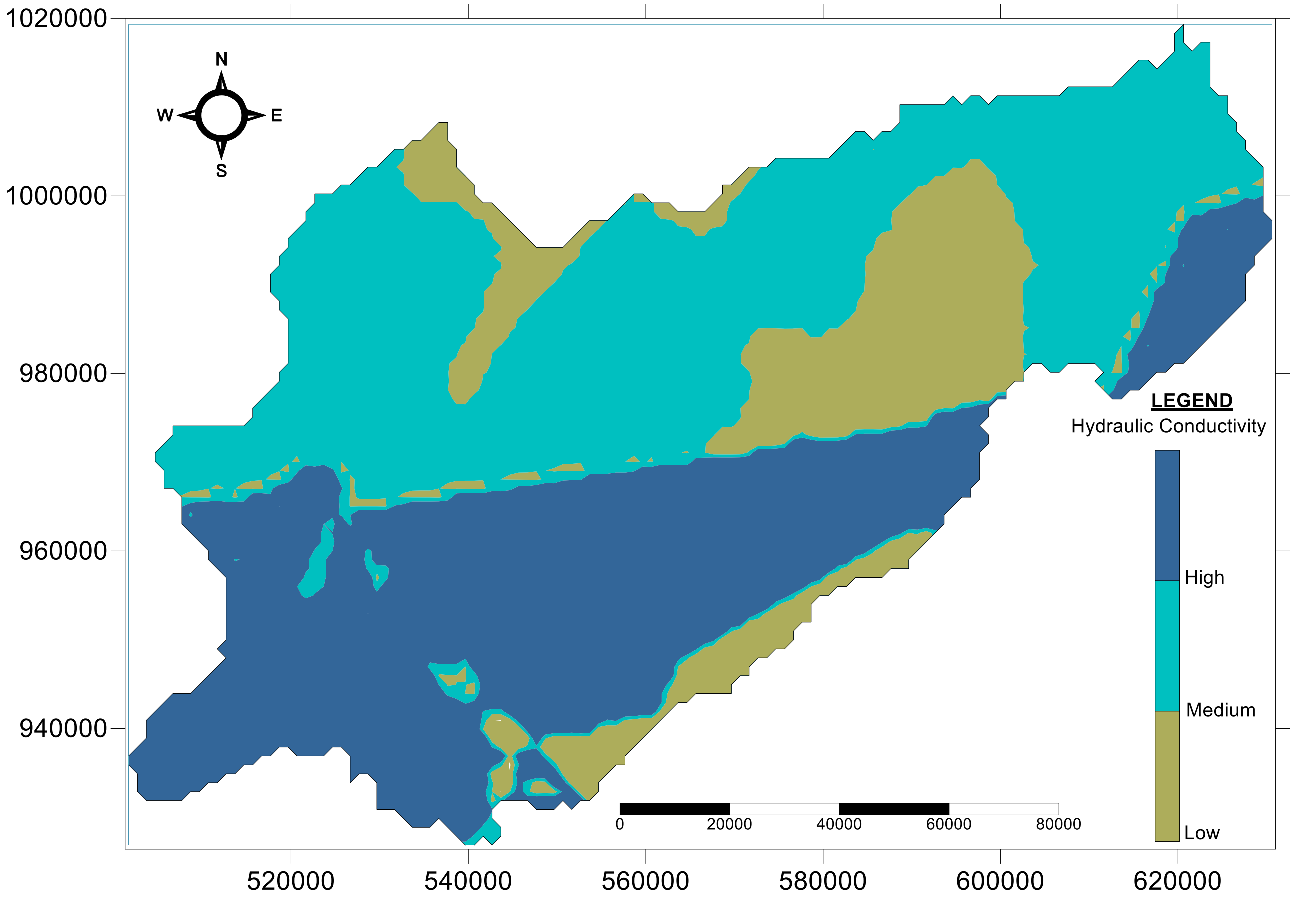

Figure 4.3. Hydrogeology map with horizontal hydraulic conductivity

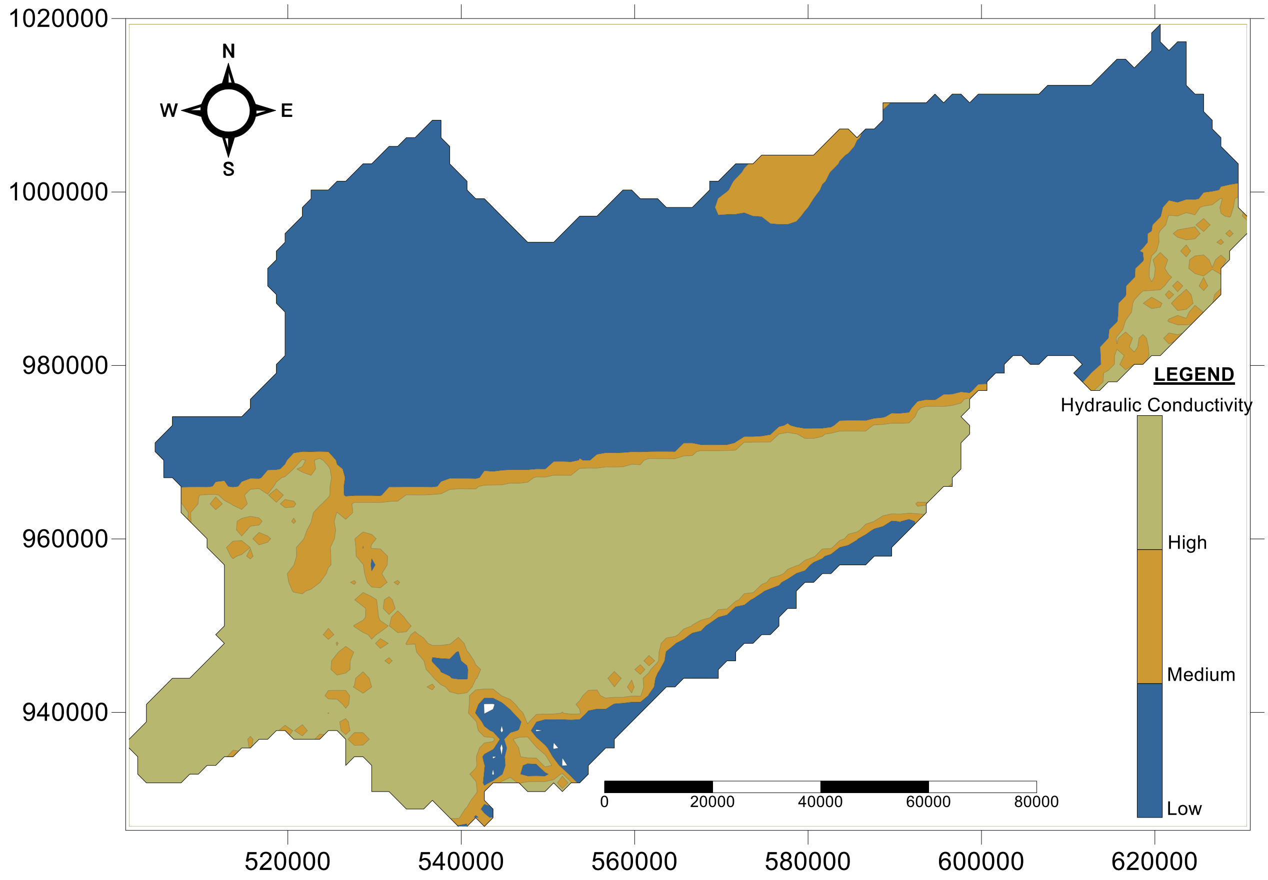

Figure 4.4. Hydrogeology with vertical hydraulic conductivity

4.3. Groundwater Flow Direction

Groundwater flow direction map depicts figure 4.6 the flow magnitude and direction in the study area. Groundwater table map shows the level of water table in the ground. Overlaying these two maps indicates the movement of groundwater from a higher hydraulic gradient to a lower hydraulic gradient. Using the calibrated model for the current lake level, the groundwater table map and groundwater flow direction have been identified. The minimum and maximum groundwater table in the study area is 650m and 1600m respectively. Groundwater table starting from around the Lake to Awash River in the Eastern direction is shallower and groundwater table in the south and south-west direction deeper than the other places in the study area.

The Groundwater flow direction clearly shows that groundwater is moving towards to the lake from the western and southern direction of the study area. It also indicates that the groundwater that is coming from the western and southern direction passes through the Lake Beseka and joins Awash River in the Eastern direction.

Flow direction arrows tell about the magnitude and direction of the groundwater flow. The size of the flow direction arrow shows the magnitude of the groundwater flow. The longer an arrow, the faster and large in magnitude the flow is. Accordingly, the groundwater flow in the south and South-West direction of the study area is relatively large in magnitude and faster compared to the other areas. Flows in the Eastern direction are also large in magnitude and faster when the flow reaches around the Awash River.

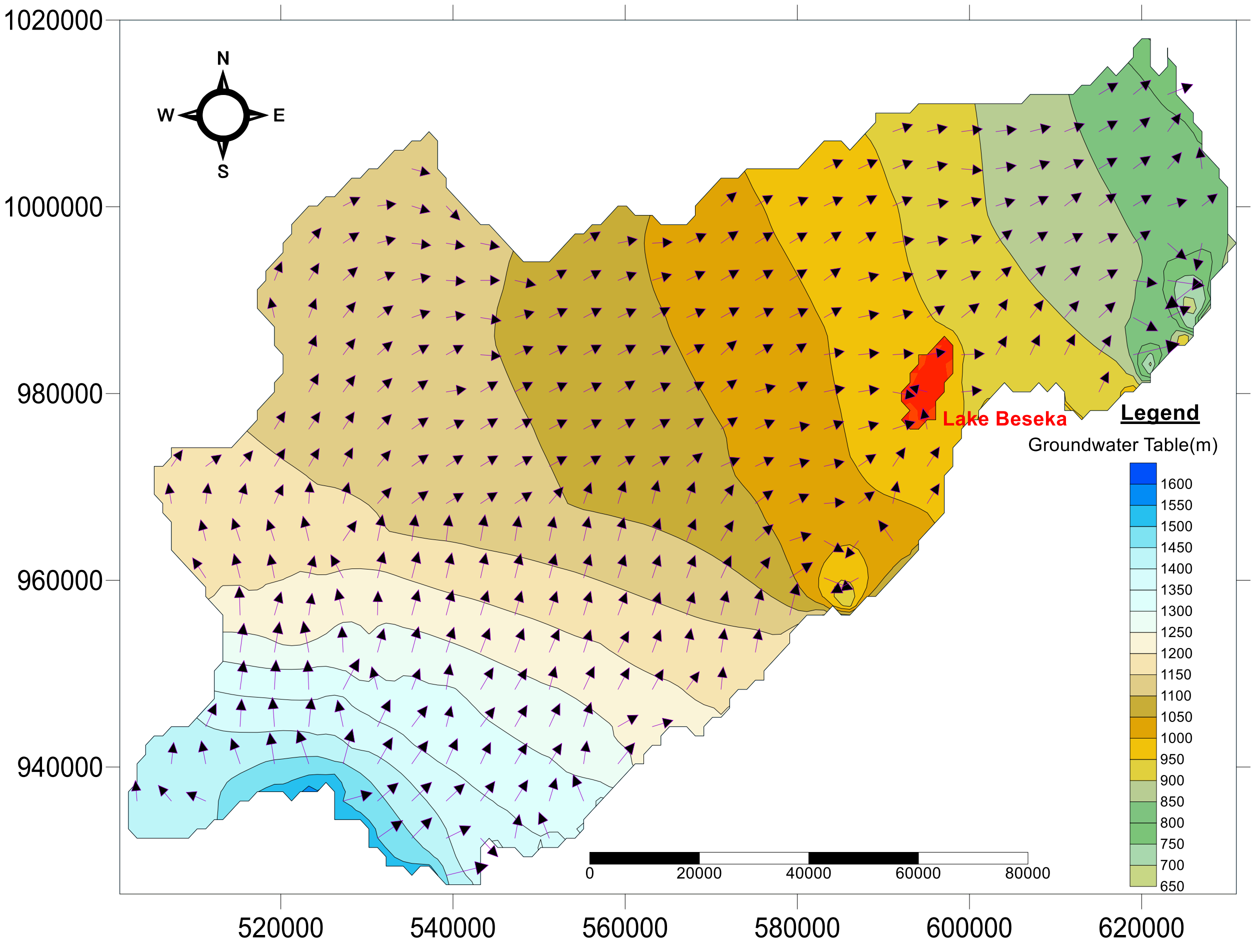

Figure 4.5. Groundwater flow direction map with the current Lake level

4.4. Maximum Lake water level rise

The maximum Lake water level rise of Lake Beseka is determined by raising the lake water level until the groundwater flow direction is reversed to away from the lake assuming that the lake water is contained within its territory. The resulted groundwater flow direction with the current lake elevation is computed in the above figure 6.2. As stated earlier the flow direction indicates that the groundwater moves towards the Lake. The flow direction arrow still shows the groundwater flow in the south and South-West direction of the study area is fast and large in magnitude. The groundwater table for the maximum Lake water level is also the same with that of the groundwater table for the current Lake water level except areas around the Lake. This is due to the raising of the Lake level to determine the maximum Lake level where the flow direction is reversed to away from the Lake.

By slightly raising the lake water level, the flow direction has been computed for different elevations. Groundwater flow direction is computed for lake elevations of +7m, +10m, +11m and +12m from the current lake water level. At Lake Elevations of +7m, +10m and +11m from the current lake water level, the groundwater flow directions slightly change which is the flow of groundwater somewhat started to direct away from the Lake. However, a complete reverse in flow direction of groundwater has been noticed when the Lake elevation was set to +12m from the current Lake water level. Therefore, 12m is the maximum Lake water level rise. The map below shows that a clear movement of groundwater flow away from the Lake Beseka.

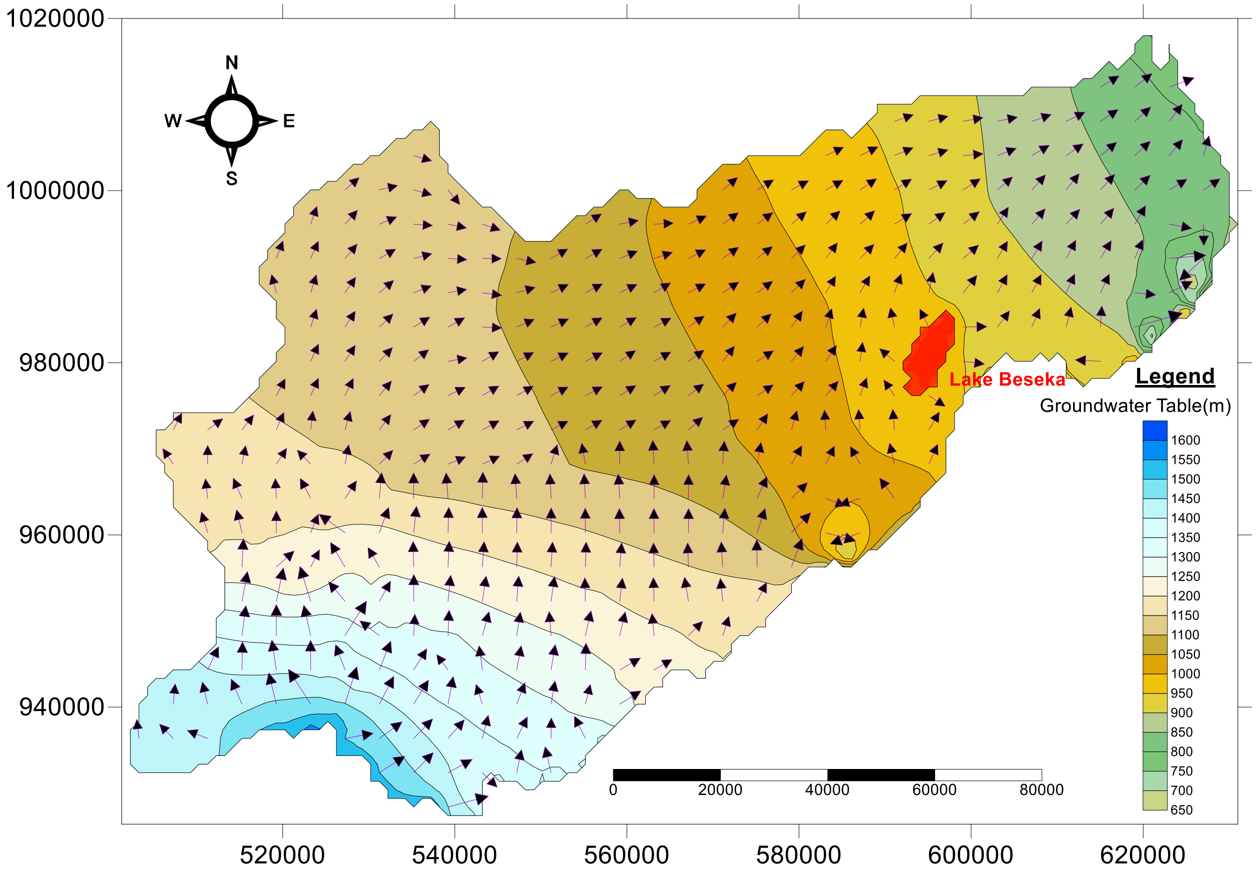

Figure 4.6. Groundwater flow direction map with maximum Lake Level

4.5. Maximum Expansion of Lake Beseka

The maximum expansion of the Lake is an areal expansion in which the Lake is expected to extend until it reaches its capacity. The advantage of determination of this maximum expansion is to take measures before the lake inundates the surrounding compound. It has been determined using the maximum Lake water level rise which is 12m from the current Lake water level rise. The contour of this maximum Lake water elevation determines the maximum areal expansion of the Lake.

The current area of the Lake is 48.31km^2. The maximum expansion will extend to a contour where the maximum Lake water level rise is determined in the East direction and to Awash River in the South and South-East direction. Thus, this areal expansion that can be reached by the Lake is determined to be 224 km^2. This shows that the lake water will inundate any property or infrastructure or irrigation farm that is within this expansion area. It also indicates that the Lake will join the Awash River.

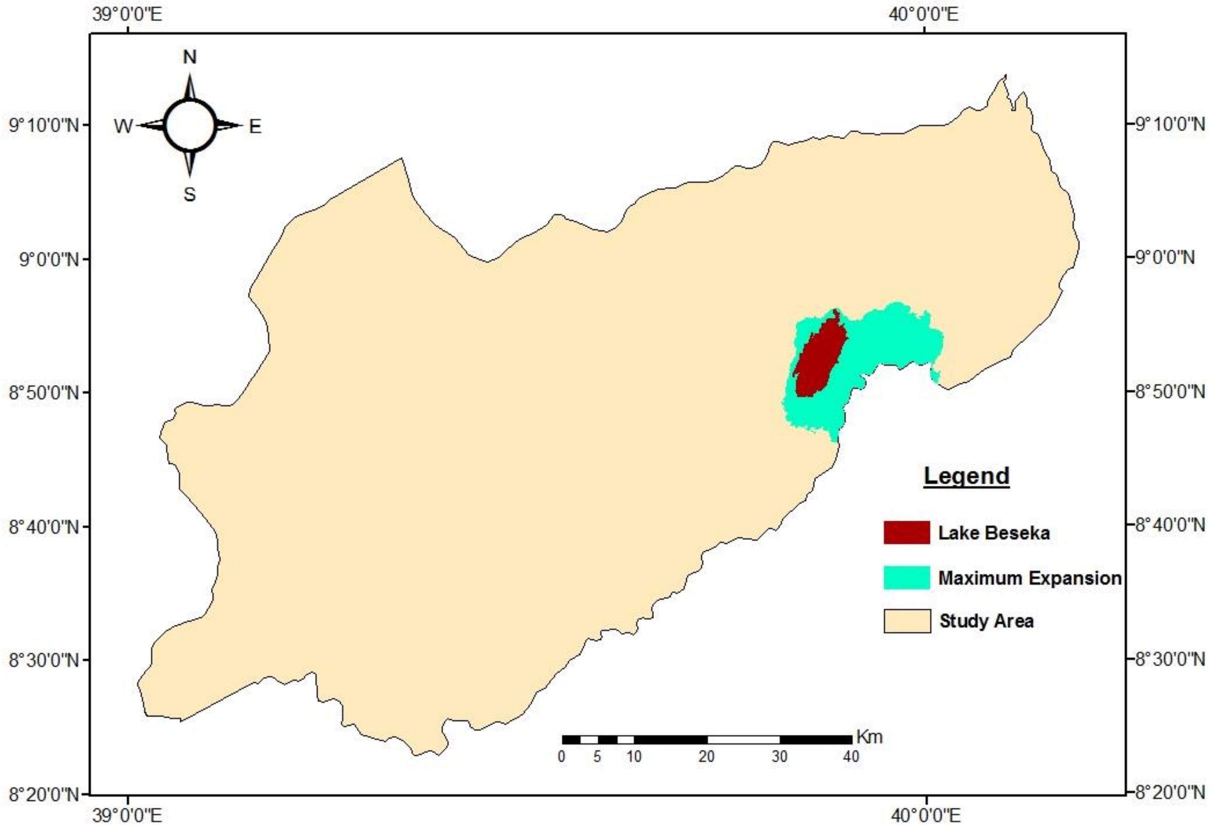

Figure 4.7. Maximum expansion of Lake Beseka

4.6. Groundwater Accessibility

Groundwater accessibility is the depth at which water can be found from the ground at a specified location. Groundwater might be accessible in shallow depth or in a very deep depth depending on the groundwater table and the topographic situation at a location. The near the groundwater to the ground, the accessible the water is in a shallow depth and vice versa.

Groundwater accessibility map has been computed both for the current Lake water level and the maximum Lake water level (12m above the current Lake water level). The groundwater accessibility map with the current Lake water level as shown in figure 4.9 shows that water can be found from 0m – 1300m amsl depth below from the ground. The negative value shows a depth below ground. The area at and around the Lake has a groundwater elevation of 0m which implies that the water is on the surface of the ground. Shallow groundwater is found near to the Lake which can be accessed up to hundred meters of the ground depth. At the North-West direction of the study area water can be accessed in a very deep depth up to 1300m amsl.

Groundwater accessibility map for the maximum Lake level has also been plotted to observe the difference in the groundwater table from the current level. It is noticed that the groundwater table has risen in most part of the study area. The map is shown in figure 4.10.

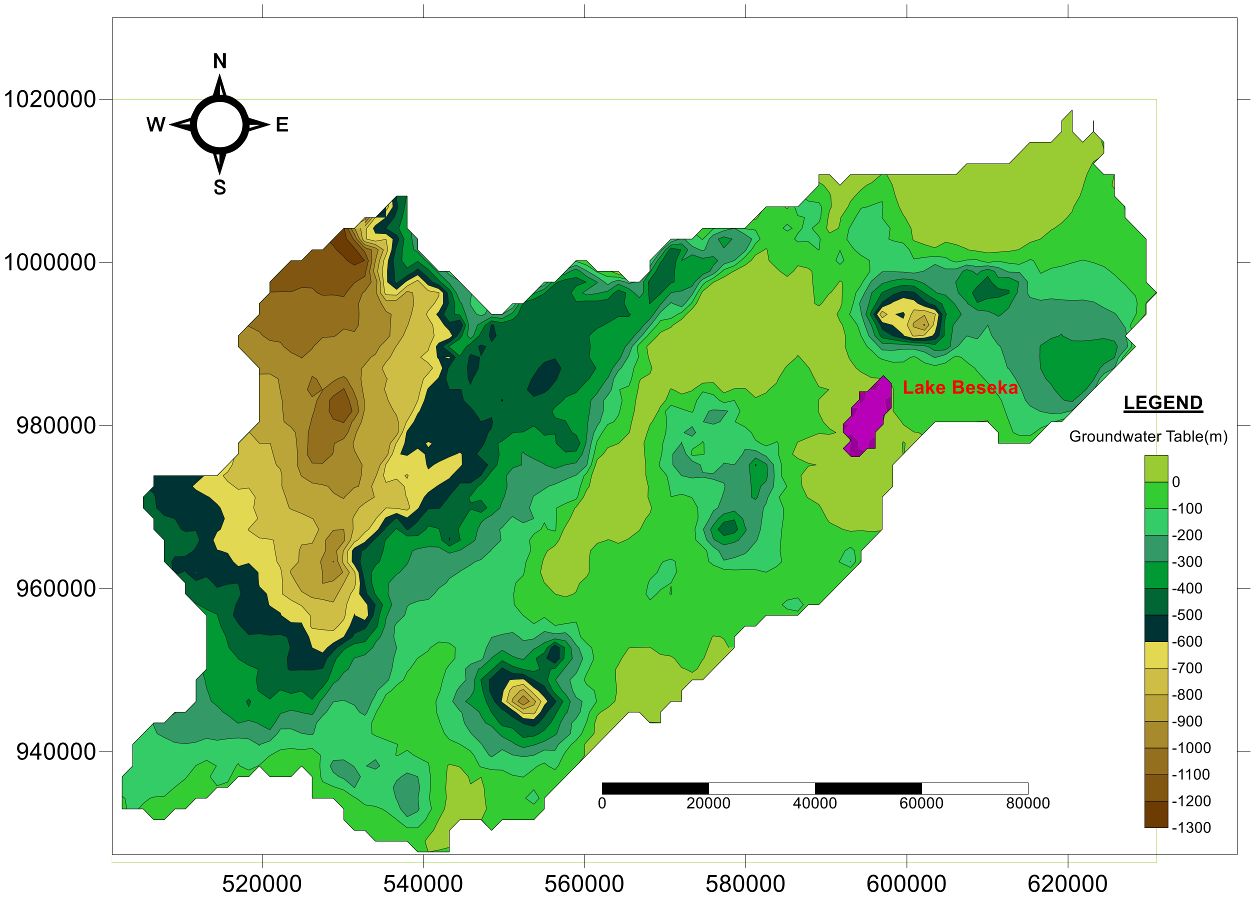

Figure 4.8. Groundwater accessibility map for the current Lake level

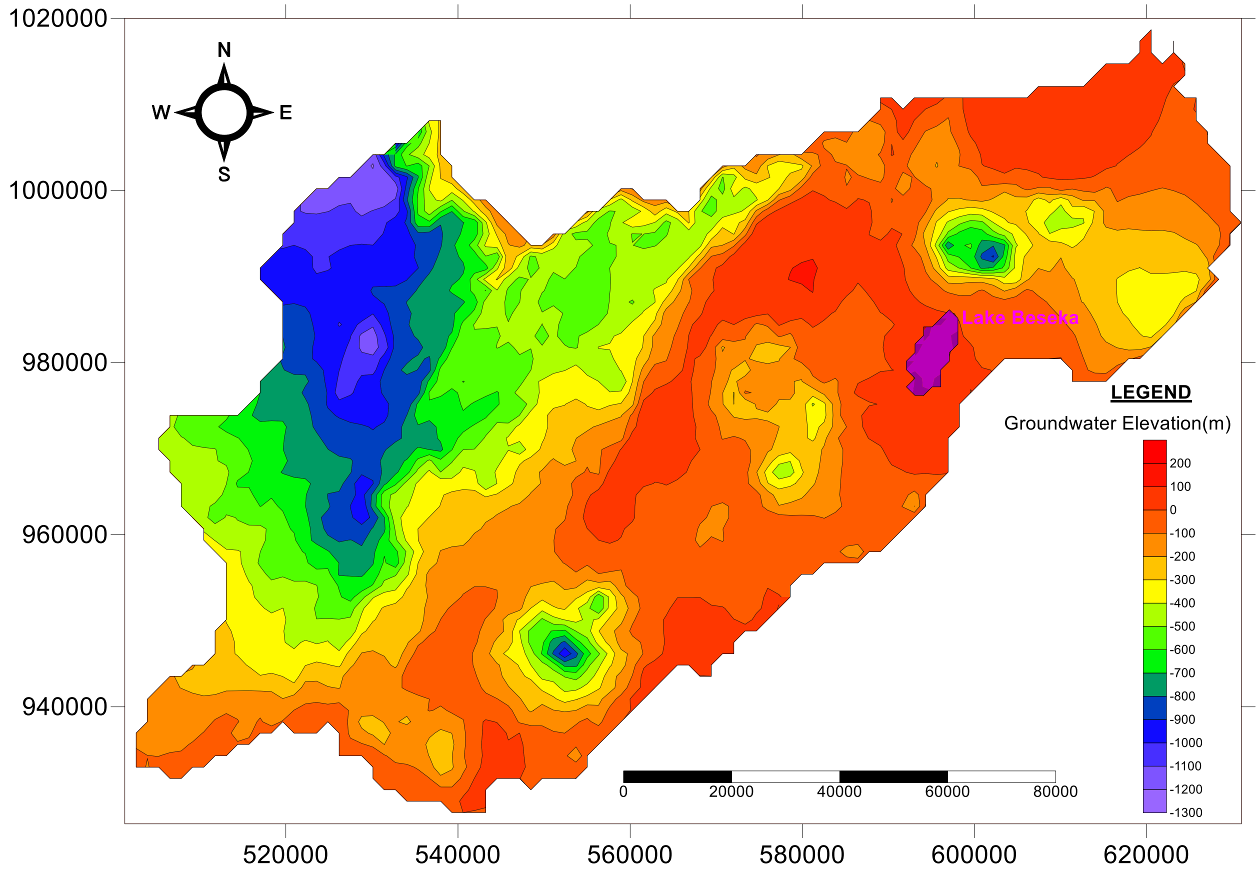

Figure 4.9. Groundwater accessibility map with the maximum Lake level

The groundwater table rise around the Lake that has been noticed for the maximum Lake level is shown in figure 4.11. This figure indicates that the rise in level around the Lake is within 0m - 20m range. Thus due to this, Abadir and Metehara farm will be affected by the rise in level of the Lake.

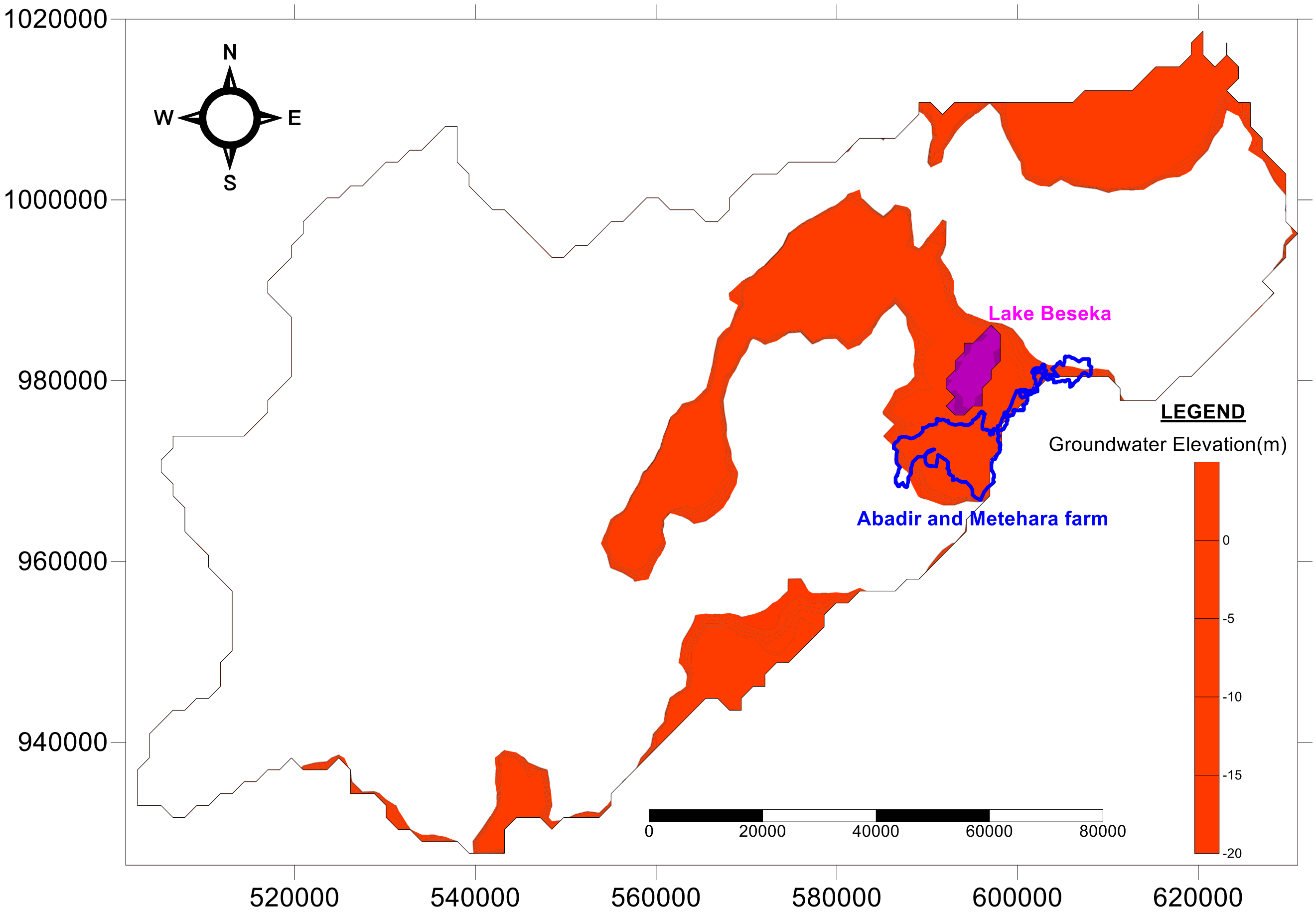

Figure 4.10. Vulnerability of Abadir and Metehara farm to Lake Beseka level rise

The difference between the groundwater table of the current Lake water level and the maximum Lake water level has also been computed. This difference shows the rise in groundwater level from the current Lake water level when it reaches the maximum Lake water level. Negative value of groundwater table difference indicates a rise in groundwater level. The map shown in figure 4.12 shows that there is a rise. It also showsthe range of rise in groundwater level when the Lake water reaches its maximum level in most parts of the study area. The groundwater table in the study area has risen up to 50m. However, this value of rise has been noticed only in some parts of the North – West direction of the study area. Most parts of the study area show a rise of groundwater table up to 15m. This indicates the maximum Lake water level that will be reached by the Lake is within this range.

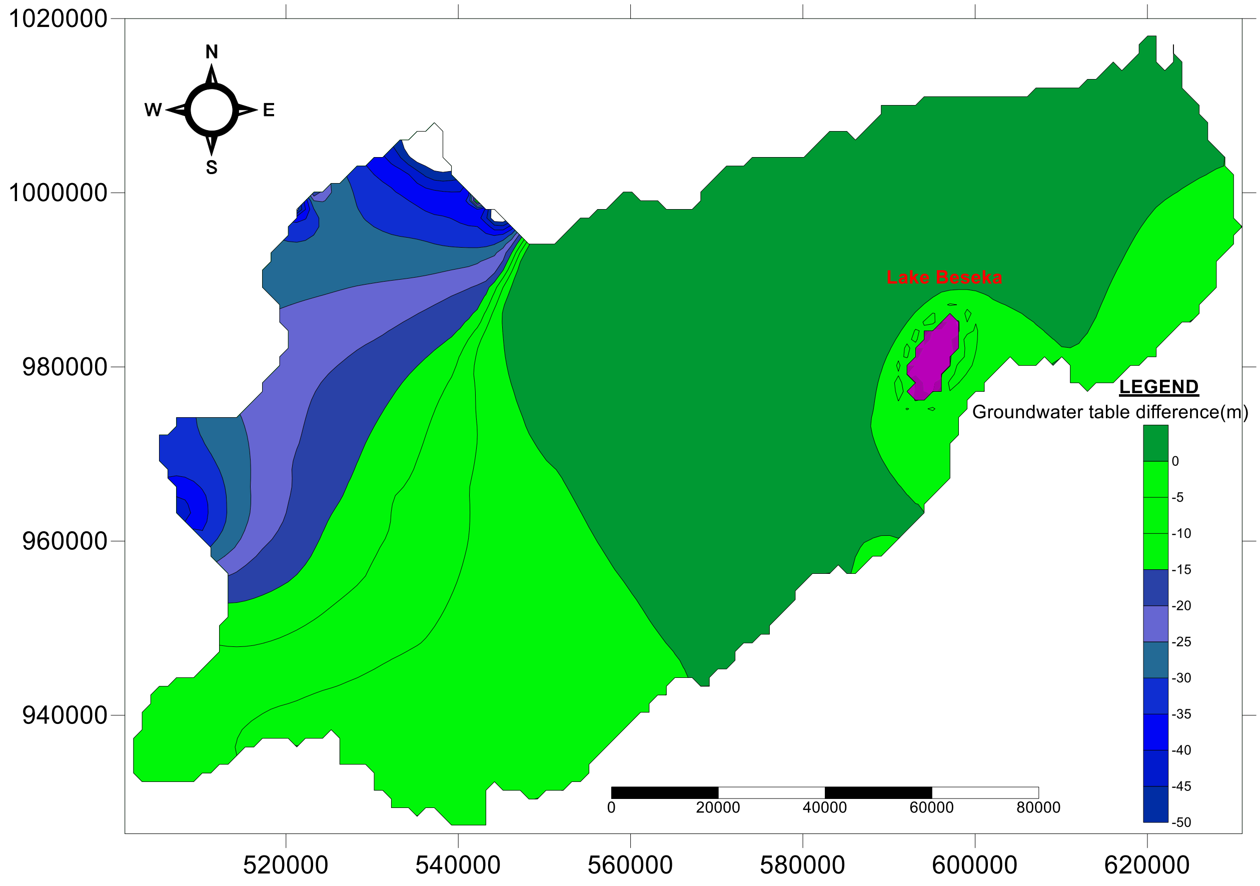

Figure 4.11.Groundwater table Difference between the current and maximum Lake level

5. Conclusion and Recommendation

5.1. Conclusion

The environmental concern of the expansion of Lake Beseka has become a treat to Awash River due to the salinity of the Lake. Protections of existing water resources like Awash River from environmental degradation around the Lake must be prioritize to use and preserve the water bodies. The current trend to control the Lake level rise is discharging/diluting the Lake water to the nearby river, Awash River. However this solution creates an environmental problem to the river. To give a sustainable solution to the problem of Lake Beseka, a groundwater modeling has been developed to predict the maximum possible lake Level rise if it is contained in its territory.

Groundwater flow is determined with the differences in hydraulic gradient. Groundwater flows from areas with higher hydraulic gradient to areas with lower hydraulic gradient. In these unconfined aquifers, the elevation of the water table surface is used to determine distribution of hydraulic head and indicate the direction of groundwater flow. The groundwater flow direction with the current Lake level of the model displays that the major groundwater flows into the lake in the southern and southwestern side while the groundwater outflow is in the eastern side of the groundwater basin.

For the prediction of the maximum possible Lake Beseka Level rise, a groundwater model has been created. The model has a constant head and a no-flow boundary condition in the southern direction (Awash River) and in the Northern direction of the Lake, respectively. The calibration of this model was made by changing the recharge and hydrogeologic parameters of the groundwater basin. For the calibration, 83 wells and springs were inventoried whereby the modeled and measured hydraulic head at these well/spring locations is tested for measure of goodness of fit. Among the goodness of fit indicators obtained for the model, the RMSE was found to be 9.449m. These results are well below the recommended values for calibrated model.

The maximum Lake level rise was determined by raising the level of the current lake elevation until the groundwater flow direction is reversed to away from the Lake. This is determined by assuming that the Lake is contained in its territory. Flow directions for different elevations of the Lake (+7m, +10m, +11m and +12m) were computed. However, a complete reverse in flow direction to away from the Lake was obtained at an elevation of +12m from the current Lake level. Therefore, 12m is the maximum possible Lake Beseka level rise from the current Lake level.

Using the maximum Lake level rise (12m), the maximum possible Lake Beseka expansion was identified. For the determination of this maximum areal expansion, the contour of the maximum lake elevation was used. The expansion extends to this contour and it is estimated to be 224 km^2. This expansion predicts that the Lake joins the Awash River in Southern direction. Thus,the irrigation farms near the Lake Beseka (Metehara and some part of Abadir Farm) are vulnerable to the inundation by the Lake. This will affect the productivity of the farms.

Groundwater is accessible at a shallow depth (up to 100m) near the Lake. The groundwater accessibility difference between the current and the maximum Lake level displays that the level rise around the Lake ranges between 0m to 15m. This result supports the determined maximum Lake level rise which is 12m.

The current outflow from the Lake to Awash River affects the biophysical environment downstream along the course of the Awash River. This study provides the determination of maximum possible Lake Beseka level rise. This result is useful to take remedial measures for the future and for protection of the environment specifically the nearby Awash River from contamination.

5.2. Recommendation

As it has been determined in the course of this study the maximum lake level rise and expansion, the following recommendations are forwarded with regard to remedial measures of the lake.

- The blending of the Lake to the Awash River should be stopped to protect the River from contamination. Thus, the irrigation farms will be productive and the downstream water supply scheme will not be vulnerable to the inundation by the saline Lake.
- Further treatment of the Lake could be used after the containment of the Lake. In previous studies the total dissolved solids (TDS) of the Lake Beseka indicated that it is brackish water which can be treated with a more advanced technology. Though the technology for treatment of saline water is very expensive, Lake Beseka can at least be treated for the use of agriculture or irrigation. Thus, the Lake will be used as an alternative water source for other services.
- Any new development like irrigation farms and any infrastructure within the maximum expansion area should be avoided so that it will not be affected by the Lake level rise.
- This study is conducted based on a groundwater model. However, detail hydrochemical and hydrogeological investigations should be conducted to achieve a better result.
- The research could have a better result if field test is included. Therefore, field test should be incorporated in a further detail research.
- Although a steady state condition is assumed for the groundwater modeling, transient state gives a more reliable outcome. Transient state needs an intensive data but it represents the real situation. Therefore, a model with a transient state condition should be adopted.
- Finer grid sizes better simulates a model than larger ones. Therefore, the groundwater model can give a better result if fine grid sizes than the one that is used in this research's model is considered.

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Appendix: Well/Spring data

ID	utm-E	utm-N	Elevation(m)	Surface Water Level(m)
1	506728	937459	1669	53.27
2	512159	946729	1792	72.52
3	521269	949730	1914	207.6
4	512957	947774	1783	36.7
5	511927	948292	1770	8.3
6	511976	948671	1786	35.34
7	512408	948682	1782	34.14
8	512011	949196	1785	31.77
9	513423	948940	1784	37.2
10	513773	949998	1795	39.52
11	536113	947062	1693	160
12	530429	941358	1595	162.1
13	530748	940960	1593	149.7
14	527667	941523	1626	99.1
15	526928	943518	1656	162.7
16	512282	951356	1762	7.34
17	512355	951516	1777	9.25
18	530792	940526	1618	172.6
19	515109	943100	1772	67.58
20	506464	941989	1697	74.6
21	536900	928900	1538	17.5
22	549000	935900	1429	29
23	544900	955900	1451	177.5
24	518000	936900	1607	25.9
25	502500	932000	1592	29
26	528000	941200	1606	12.8
27	527000	941200	1617	17.7
28	547400	986900	1751	115.8
29	511900	941900	1712	12.2
30	523400	942000	1661	36.6
31	512900	941900	1704	57.9
32	530900	946100	1643	108
33	528100	941100	1612	162.7
34	528200	941200	1612	108
35	529900	944900	1619	108
36	527900	941000	1612	158.9

37	564900	941900	1229	13
38	541900	958100	1493	121.3
39	593035	982691	958	5.44
40	592930	984497	964	0.23
41	595362	986153	974	20.41
42	600252	984352	959	7.02
43	600305	982301	953	1.9
44	591413	975520	959	4
45	593389	974555	955	0.54
46	600517	982590	953	1.91
47	600207	981559	953	1.85
48	599903	979853	954	2.63
49	598914	980723	953	1.44
50	590483	970777	1020	54.74
51	593879	971578	967	16.4
52	600250	984000	960	12
53	584500	968500	1200	176.5
54	580000	990000	980	22.8
55	596921	976889	955	1.7
56	599118	977968	959	6.28
57	598043	978183	965	11.74
58	599916	977954	964	6.4
59	591853	994109	995	42.07
60	591843	993329	1001	46.78
61	589634	992954	985	31.41
62	588477	988474	1005	50.31
63	609923	985407	967	63.29
64	604599	986801	952	6.41
65	596854	974753	973	13.07
66	584990	982082	1120	159.5
67	605405	982881	950	4.8
68	601152	980062	953	3.1
69	600646	980333	953	2.37
70	601116	979750	953	3.64
71	600941	979443	953	4.12
72	605069	983266	952	4.79
73	586845	976572	1050	87.63
74	592664	986463	981	28.2
75	601259	977156	957	3.89
76	601097	976963	964	13.26

77	602298	979030	950	4.57
78	594785	969889	988	29.43
79	595371	971036	976	21.65
80	596616	973698	965	10.95
81	602168	979920	950	2.9
82	602009	979970	951	949.35
83	600989	982516	953	2.25