

ADDIS ABABA UNIVERSTY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES

CHARACTERIZATION OF GROUNDWATER- LAKEWATER INTERACTION IN LAKE HAWASSA BASIN

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING (MAJORHYDRAULIC ENGINEERING)

BY

YENENEH ATNAFU

ADVISOR

MEBRUK MOHAMMED (Dr. Ing.)

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ADDIS ABABA UNIVERSTY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
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Bikila Teklu (Dr.) _	_____	_____
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Tenalem Ayenew (professor)	_____	_____
External Examiner	signature	date
Geremew Sahilu (Dr. Ing.)	_____	_____
Internal Examiner	signature	date
Mebruk Mohammed (Dr. Ing.)	_____	_____
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ABSTRACT

Being at the center of booming economic and social development, Lake Hawassa Basin is one of the most prone to pollution lake waters in Ethiopia. Shallow groundwater table near by the lake suggests there is a direct link through unconfined aquifer between the lake water and groundwater. Thus the lake water could affect or affected by any anthropogenic and/or natural activities done on the nearby groundwater. Lake Hawassa level rising has also pronounce as a problem of part of Hawassa city and surrounding residence is the main issue which need, investigation to alleviate the problem. This research has made its objective in analysis of the lake water and groundwater interaction. Since groundwater recharge area might extend well over the location where the lake water and groundwater interfaces, the study extends its area of analysis to the natural hydrologic (surface water) catching boundary of the lake.

The Hawassa lake basin is part of the central main rift of Ethiopia which is topographically closed catchment cover an area of about 1440 km^2. For understanding of Lake Basin ground water behavior a numerical groundwater flow model was used for steady state and three dimensional flow conditions. The basin have been discretized in to 13500 triangular prism elements of average 500 m edge lengths. The whole study area was divided in six hydrogeological settings. The Lake water and the perennial rivers within the basin are considered as constant head boundaries while the entire basin boundary is treated as a groundwater divide (Hydraulic no flow boundary). To make sure that the model parameters (Hydraulic conductivities in three dimensions) are appropriate to the area, a number of trail values of these parameters are given to the model to predict the 68 inventoried groundwater tables within the basin. The parameters appropriateness is evaluated based on Mean error, Root Mean Squared Error and r^2 statistics, the result obtained were -2.73m, 12.33m and 0.755, respectively. From the data quality used in the model, the model extent and hydrogeological regions used in the model the result obtained was taken as acceptable. The hydraulic conductivity obtained for the whole region is in the range of 2.5×10^{-8} and 1×10^{-6} m/s.

The calibrated finite element numerical flow model (TAGSAC model) of this research was simulated for different lake water levels observed during 1969 and 2013. The model

simulated groundwater flow direction is towards the lowest elevation of the basin (Lake Hawassa). The lake water level variation has significant effect on the groundwater on its western part than locations in the other directions. Larger groundwater abstraction on the western part than the other parts in the basin will bring about the same variation in the lake water level. Thus it can be suggested that lake water level variation affects or affected significantly by any water resources management made on the its western boundaries. From pollution point of view the reverse is true, i.e. any pollution that takes place in the eastern part of the lake will bring about larger pollution at a faster rate to the lake environment. This is because of the higher gradient, there by higher groundwater velocity in this location. Unfortunately this part of the lake (eastern part) is susceptible to pollution due to the vast, economic and social development. The presence of the Hawassa city is a clear threat to the lake water pollution not only from surface water pollution but also from groundwater pollution point of view.

Within the analysis period (1969 – 2013), the region which was not affected by the lake water variation is again located in the eastern part of the lake. This region has shown no change in the groundwater level. No change in groundwater level at a location imply that this location either receives water from some other location or is itself a source. The location being at higher elevation in the lake basin makes it the major recharge source of the basin. The site which includes the highest development (social and industrial) makes the biggest threat to groundwater thereby lake water pollution.

Finally, for any groundwater and/or lake water planning work, the model created in this research should be applied with caution, considering all drawback and limitations related to model input parameters.

Key Words

Groundwater-Lake water interaction; Groundwater model; Hawassa city; Hawassa Lake; Numerical modelling; TAGSAC;

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1. Introduction

For economical and scientific management of groundwater sources with surface water interaction, system modeling is getting priority in advanced scientific interest. Because of modeling is the best way to simplify organize and to synthesize data collected from field and literatures and to get as one part of the components of the assessments of the hydrogeology properties of the system materials, recharge rate and groundwater abstractions.

Groundwater flow equations are derived by mathematically combining a water balance equation with Darcy's law. The derivation is traditionally done by referring to a cube of porous material that is large enough to be representative of the properties of the porous material and yet is small enough so that the change of head within the volume is relatively small. This cube is called a representative elementary volume. The derived equation can be solved analytically when simplified. The simplifications usually involve assumptions of homogeneity and one- or two- dimensional flow. Except for applications to well hydraulics, analytical solutions are not widely used in practical applications (Anderson and Woessner 1992). Numerical solutions are much more versatile and are now easier to use than some of the more complex analytical solutions. Among different ways of solving flow equations numerically, finite differences and finite element methods are widely used.

To identify and understand the behavior of the aquifer system in Lake Hawassa basin, the properties of materials found from borehole log, literature works done – on the hydrogeological behavior of the aquifer including field visit were conducted.

The output of this study will pave different scenarios of study results which describes detail groundwater flow system of the lake basin. It also develops ideas for sustainable utilization and better managements to plan multipurpose projects for the regional capital city Hawassa including areas over the lake basin.

1.1 Purpose and Scope

Three-dimensional models have been used extensively for groundwater modelling in Ethiopia and are generally adequate for predicting aquifer head changes. However, the three dimensional model described in this report was developed

- To identify the major groundwater sources of recharge over the Hawassa Lake basin;
- To investigate the groundwater-Lake water interaction.

The scope of activities associated with developing and applying the three-dimensional model in this study is to:

- Create the three-dimensional conceptual model of the Site
- Develop and calibrate a numerical model based on the three-dimensional conceptualization
- Apply the three-dimensional model to simulate groundwater lake water interaction.

1.2 Modeling approach

The choice between a finite difference and finite element method depend on the problem to be solved and the preference of the user. In general fewer input data are needed to construct a finite difference grid. Finite elements are better to approximate irregularly shaped boundaries than the standard finite differences. It is easier to adjust the size of individual elements, nodes as well as location of boundaries with the finite element method, making it much easier to test the effect of nodal spacing on the solution. Finite elements are also better able to handle internal boundaries such as fault zones, and can simulate boreholes that can be described with a single node than finite differences. From the above discussion it is evident that finite element method is appropriate for the current study and hence adopted in the whole study.

Several conceptual models have been developed for describing fluid flow in fractured porous media. Fundamentally, each method can be distinguished on the basis of the storage and flow capabilities of the porous medium and the fracture. The storage

characteristics are associated with porosity, and the flow characteristics are associated with permeability. Four conceptual models have dominated the research: 1) explicit discrete fracture, 2) dual continuum, 3) discrete fracture network, and 4) single equivalent continuum. In addition, multiple-interacting continua and multi-porosity/multi-permeability conceptual models (Sahimi, 1995) have recently been introduced in the literature. Further distinctions can be drawn on the basis of the spatial and temporal scales of integration, or averaging, of the flow regime. Bear and (Berkowitz 1987) describe four scales of concern in fracture flow: 1) the very near field, where flow occurs in a single fracture and porous medium exchange is possible; 2) the near field, where flow occurs in a fractured porous medium and each fracture is described in detail; 3) the far field, where flow occurs in two overlapping continua with mass exchanged through coupling parameters; and 4) the very far field, where fracture flow occurs, on average, in an equivalent porous medium.

This study focuses on equivalent porous medium approach. The equivalent continuum approach uses equivalent properties of rock mass as the input data for a continuum analysis. This is a common modeling method used in the field of rock mechanics and hydrogeology. However, there are still unresolved questions; how can the equivalent properties be determined and is the equivalent continuum approach suitable for modeling the discontinuous fractured rock mass.

This research has tried to determine the equivalent properties of the rock mass based on fitting the water table measured on boreholes within the study area. The observed water tables in these boreholes include the groundwater level variation. The above data collected are supposed to be fitted with a numerical model designed to accommodate these field borehole location and their respective piezometric head variation.

The numerical model is based on a three-dimensional conceptual model which uses the available information on the site. Therefore this thesis presents a description of a three-dimensional conceptual and numerical model of groundwater flow in the unconfined aquifer system. While calibrating the model with the observed data at the boreholes a trial and error method has been adopted. In this method a trial set of effective hydraulic parameters and recharge are given to the model and the result is evaluated according to its fitness with the measured data.

1.2 Thesis Organization

This thesis is organized as follows. Chapter 2 briefly describes an overview of the Lake Hawassa basin and site-wide data collection efforts that have been conducted on the site that are relevant to the current model development. Section 3.0 describes the theoretical back ground in developing the mathematical thereby the numerical model formulation. In section 4.0 after describing the finite element grid discretization of the site it tries to explain the hydrogeological conceptual model framework used in the modeling. Section 5.0 describes the calibration and the results of the Lake water groundwater interaction, this modeling effort which finally leads to the conclusion on the entire model performance.

2. Literature Review

Hawassa Lake basin has been the subject of particular interest by the local administration (Sidama Zone), region (South Nation Nationalities and Peoples regi0nal state) and national government. Studies of the lake have been undertaken to develop understanding of the hydrological setting, salinity levels and floral and faunal characteristics of the lake. The current study is designed to further knowledge of the subsurface hydrologic system of the lake in particular and the Lake basin in general. This in turn could be used to develop appropriate water management strategies, to maintain the lake water and groundwater levels to nondestructive situation.

Besides; the lake is the major recreation for the people around and tourists and the groundwater near by the lake has been utilized for a number of domestic purposes with the exception of drinking.

2.1 Surface topography

The study area consists of two major areas of focused sub basins, namely Lake Hawassa sub basin and Cheleleka swamp, which includes the lake water body that plays greater role of the study as a whole and the water shade of the catchment. These sub basins have the much importance in the assessment of lake water ground water interaction.

The lake and lake catchment has combinations of topographic situation which are swamps, ridges, depressions, plateau, undulating, rolling and dissecting plains. As shown in Figure 2 the catchment has arrange of attitude 1683 – 2963 meters above mean sea level (m. a.m.s.l.).

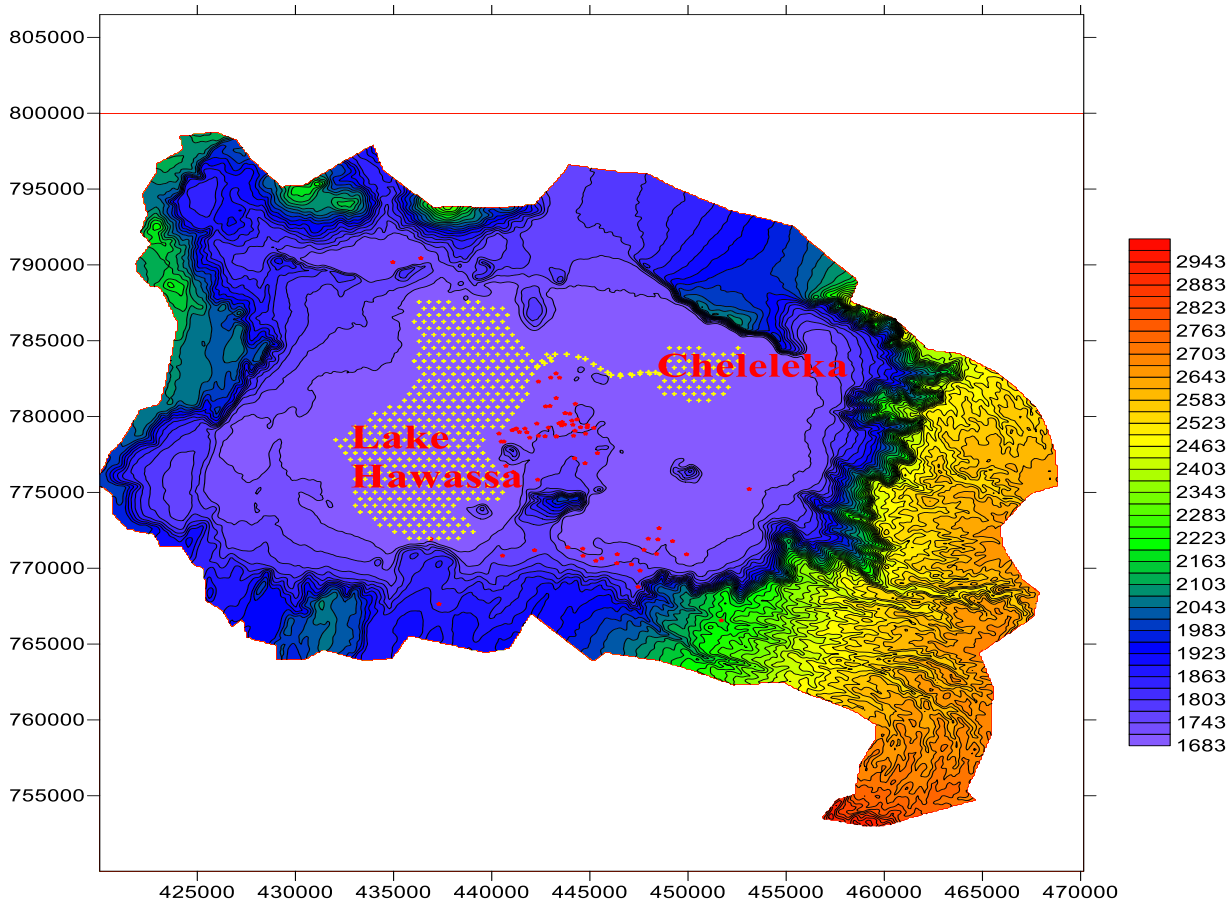


Figure 1 Surface topography of Lake Basin and Boreholes Inventoried (Red Points)

The topographic nature of the lakes in the rift system reveals Hawassa Lake is at the highest elevation. According to the study conducted by GSE (See Figure 3), the elevation lake Hawassa, 1680 m, compared with lake Zeway, (1636m\), Langano, (1585m), Abyata, (1578m), Shalla, (1550m) and Abaya and Chamo (1180m) (not shown in the figure), suggests that there is a possibility for groundwater to flow from Hawassa lake basin to lower laying lake (GSE, 2000).

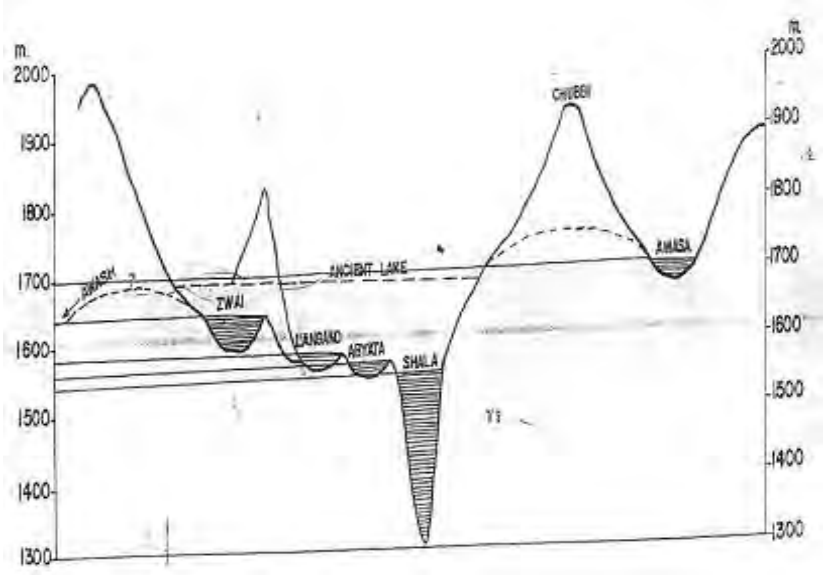


Figure 1 Quaternary lake levels in the rift valley (adapted from GSE, YEAR)

Average surface area of top level of the lake Hawassa is estimated 100 Km^2. In 1972 area of Cheleleka swamp was 12 Km^2 however in 2005 it is about 3 Km^2 almost changed to swampy area. (WWDSE, 2001). According to 1:1000 scale map surface area of the catchment was 1440 Km^2 from which Lake Hawassa covers only 7% of the total catchment. The major surface water resource draining towards the lake, Tikur-wuha River, has drainage area of 625 Km^2

In some Ethiopian rift lakes the increased obstruction of water lead to conflicting options among the different riparian groups concerned with water resources development and conservation (Ayenew T., 2004).

2.2 Hydrometeorology

The climate in the area is characterized as dry sub humid climate condition base on Thorns Waite's system of defining climate or moisture regions. Classified as temperate. The rain fall regime of the lake basin is described by one As per local climate classification with mean annual temperature of about 19.5^0c and attitude rang 1683 – 2963 m a.m.s.l. The area is predominately categorized as Woyna Degas zone and rainy season, that the rainy months are contiguously distributed and the rain pattern is uni-modal type with only one dry season. The rainfall is well distributed throughout rainy

season (rain fall co-efficient are in the range of 1.0 -0. 998 during eight months period and said to be moderate concentration) (Gebreegziabher, 2004).

There are seven rainfall station near by the Hawassa lake catchment of which five but two (Aje and Shashemene stations) are within the catchment. The mean annual Rainfall at these stations is as shown in Table a. The moisture for precipitation originates from southwest equatorial air stream, which moves north wards with inter tropical convergence zone (WWDSE, 2001).

The spatial and temporal variation of rainfall is strongly dominated by inter annual movement or position of the inter tropical convergence zone (ITCZ). ITCZ represents a lower pressure area of convergence between Tropic Easterlies and Equatorial Westerlies along which wave disturbance takes place. The shifting of this low pressure area governs the availability of rain driving wind direction. In Ethiopia, ITCZ occurrence at the central Northside of Ethiopia influence equatorial westerlies from South Atlantic Ocean and southerly wind from the Indian Ocean. This is the period that favor the occurrence rainfall.

In the region there are three known seasons, which are, Kiremet or rainy season (June - September), Bega or dry season (October - January), belg (march-may). The study area (Lake Hawassa basin) receives heavy rain fall in the period of July to September (WWDSE 2001).

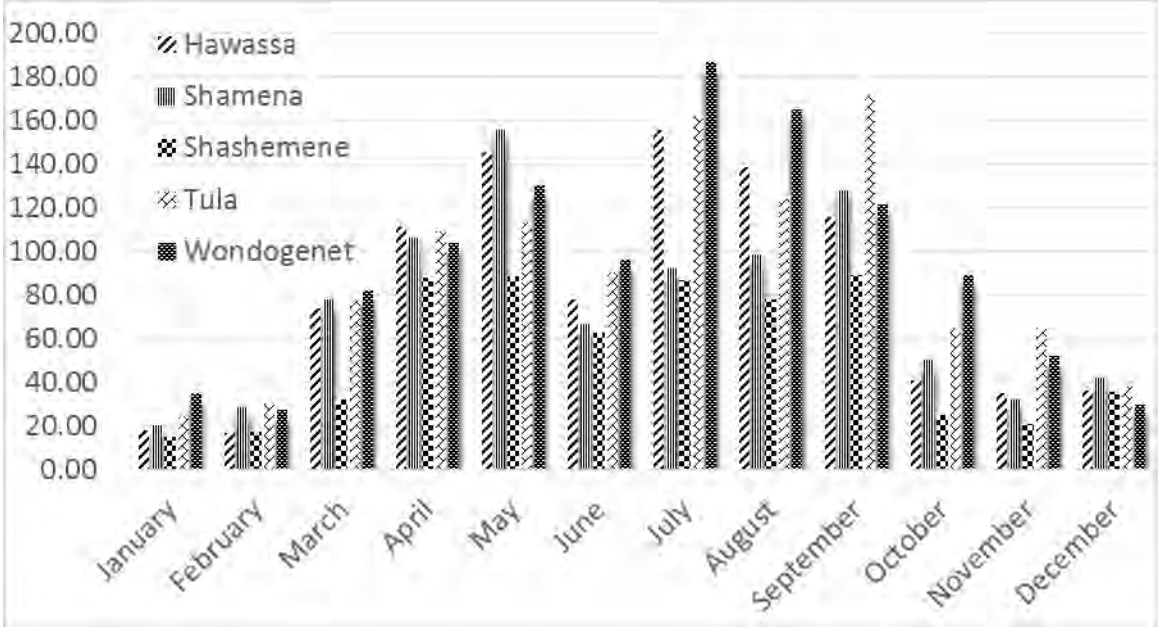


Fig. Average monthly total rainfall observed at the five stations

2.3 Geology and hydrogeology

The study area is the central part of in the Ethiopia main rift valley system. The Ethiopia main rift valley lake has main things in common with regard the geological and hydrological settings; one of the remarkable similarities is the existence of a series of lakes filling volcano technical depression separated by volcanic hills in the floor of the rift (Tenalem A and Robert B., 2007).

The major inputs to lake Hawassa comes mainly from eastern high land rainfall generating perennial and seasonal flows in the form of rivers, springs, and surface run off. Ground recharged by direct rainfall also has a great contribution the lake Hawassa characteristics. Lake Hawassa is highly variable in its geomorphic and morphometric settings (Tenalem A., 2004).

Tadesse D. and Zenaw T., (2003), studied Hydrogeology and engineering geology of Hawassa lake catchment. The study result of hydro geological water quality and isotope techniques show that Hawassa lake water is mainly surface water and contribution of ground water is insignificant that 3.2 Mm^3/year or less than 100 l/s.

Lake Hawassa, being used for various purposes progressively, is contributing an agent role in the lives of thousands of people living the lake basin. The lake basin is becoming very significant area for activist of flower farming for the development of horticultural production, tourism industries and other human activities. it is in fussed around the lake coastal area since there mentioned activities are expected to proceed in alarming way as wells the lake, groundwater, springs and rives is proceeding without the understanding of the complex nature of the lake basin hydrogeology and geologic system, this study tried to create water and catchment ground water system.(Ayenew and Robrt B., 2007) Long period records of lake, hand dug wells, bore(deep) wells, hydro meteorological data springs and river flow data helped (used) in the understanding of the interconnection characteristics of the ground water and lake water linkage.

For this reason, it is possible of the lake catchment with particular reference to the movement and occurrence of groundwater and its relation to subsurface interaction of Lake Hawassa, accordingly to the above reasons establishing the lake basin water sources management plan without the understanding of groundwater interaction behavior to the lake will be resulted in missed water use practice.

2.3.1 Geology

The Hawassa lake basin lies in the Main Ethiopia Rift (MER). The main Ethiopian rift is divided based on structural features in to three geographic area. Represented by the northern (Fentale, Nazeleth) Central (Nazareth – Hawassa) and southern (Hawassa – konso) sectors. The central sector where the Hawassa lake basin belongs is a symmetric rift basin where both sides the rift margins are fully defined except in the region between Guraghe and Sodo regions of the western escarpment and in the Shashemene area of the eastern margin (GSE,203). The closed basin of nested Hawassa – Corbett caldera complex is a giant elliptical depression 30 to 40 km/s wide.

There are a number of rift system faults with north and north east trend along with the length of Lake Hawassa is oriented. These faults are expansion (normal fault) forming step faults. They are mainly dominant to the south and south western of the lake. The volcanic collapse structure (caldera) forms nearly circular around Lake Hawassa basin. This collapse shifts some of the Central MER faults systems showing that the collapse

has taken place subsequent to the rifting. In the Hawassa caldera a line of young fault affect the rift floor. These faults, the Wonji fault shattered the rift floor into several relatively small horst and graben. Lake or swamps occupied the more depressed areas. Recent latchstring and alluvium deposit scoria cones, Rhyolitic lava flows and associated ignimbrite tuffs and volcanic ash form the Hawassa lake basin. (Zenaw T. and Tadesse D., 2003)

According to study of lake pollution by AG consulting (2007) the geology of Lake Hawassa basin is summarized in the following ways:

- Basalt and ignimbrite of the plateau trap series (late Miocene):- The most ancient rocks exposed in the area. The rocks are exposed locally near the base of the eastern caldera wall. These rocks consist of fine grained meteorite overlain by 30 to 50 m thick welded tuff dominated by collapsed pumice clasts and feldspar.
- Old alkaline and per alkaline silicic rock (late Pliocene – early Pleistocene):- This unit includes the rift pyroclastic and old rhyolite lava flows that are widely distributed in the basin. Rock of this group are exposed on the eastern side of the Caldara wall in the area where the cold springs are located. They consists of welded tuff, pumices deposits, surge deposits and the hyalite ridges at wondogenet
- Record Basaltic lava flow, basaltic hyaloclastite and scoria cones (Pleistocene to recent):- This unit is represented by small monogenic cones, which are sprinkled forming the only relied in the floor of caldera. The scoria is found mainly associated with scoracious basalt flows
- Recent acidic volcanic (pleistocene to recent):- These rocks are distributed dominantly around the coribetti caldera north of Lake Hawassa most of them consists of pyroclastic, such as un welded pumice flows, pumice falls ,ashes and rhyolite with associated obsidian flows. The pyroclastic deposets overlying the Pliocene deposits on the eastern and western caldera wall are included in this unit.
- Volcano – lacustrine deposits (pleistocene to recent):- They cover mainly the floor of the caldera towards Lake Hawassa.

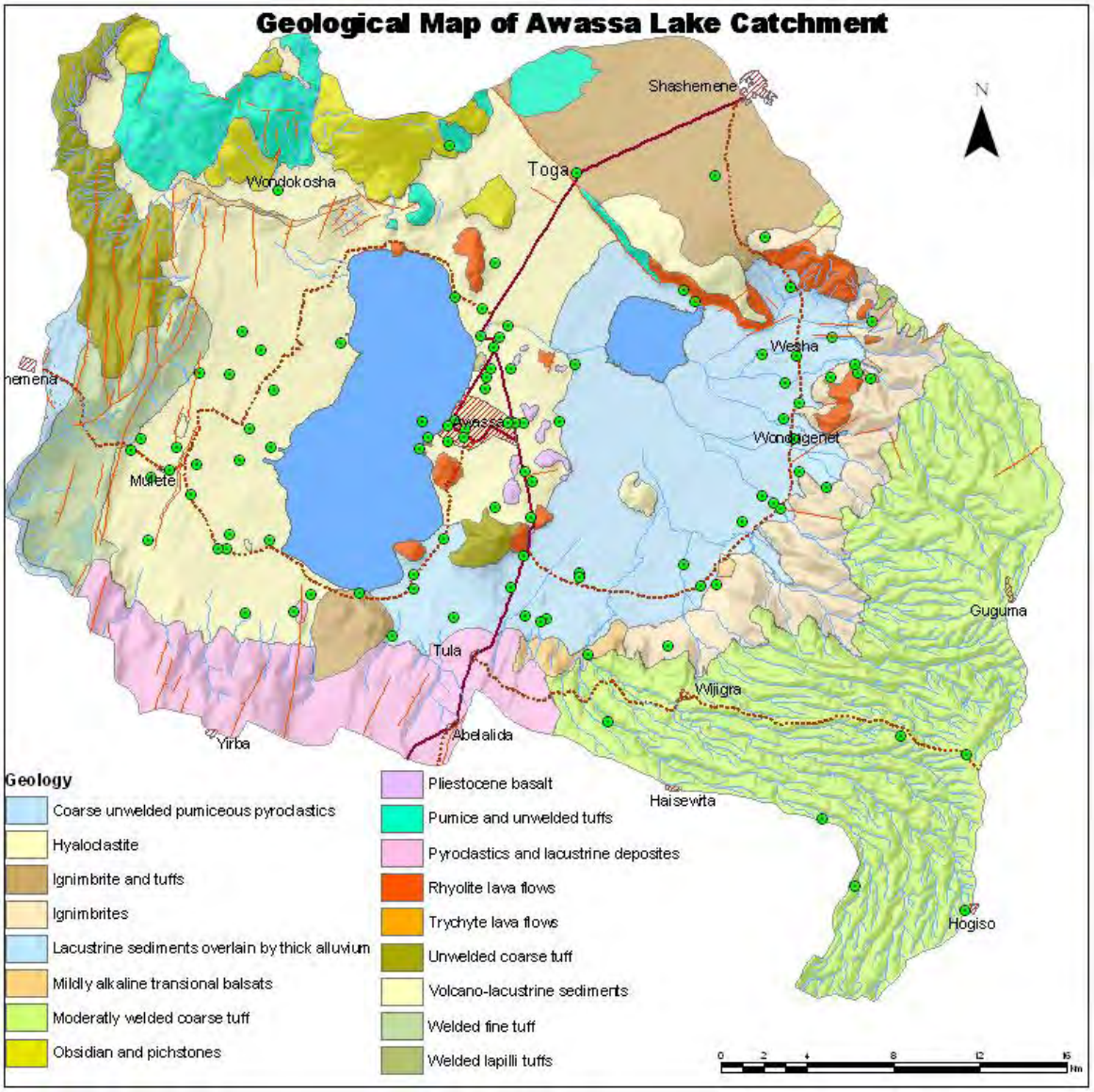


Fig. Geological map of lake basin (Source AG consulting 2007)

2.3.2 Hydrogeology

Fractured and jointed ignimbrites and the overlying volcano – lacustrine are the two major aquifers in the region. The underling, down faulted tertiary ignimbrites, if not buried too deeply, will probably incorporated the most extensive aquifer in the MER. Volcano lacustrine sediments are composed aquifers of sands, tuff, and pumice inter layered with clay aquitard. Ignimbrites are also the major water bearing formation of the geothermal fluid in the region. The lacustrine sediment serves as a cap formation, where

it is not broken young Wonji faults to impend the free movement of geothermal fluid to the surface.

The occurrence of cold water is confided to shallow depth of ignimbrites aquifer and the over laying inter-granular aquifers. The lacustrine sediment has thickness ranging from 40 to 60m. Frequently one more aquifers, separated by clay aquitard, are encountered in boreholes drilled in the lacustrine sediments. (GSE,2003)

Hydrogeology of the lake basin or potential of aquifer zones are categorized based on recharge capability hydraulic parameters like, permeability, hydraulic conductivity, stativity, specific yield of springs, groundwater tables and aquifer thickness and topography of the catchment.

Absolute aquifer classifications can be made with the help quantitative data generated by actual pump tests and geo- physical investigation. In this study hand dug water tables: deep well water tables springs out flow levels, long term rainfall records, lake level records, rivers and calibrated hydraulic properties of aquifers are used in the model for understanding of the behavior of lake water – groundwater interaction of the lake basin. Based on hydraulic, hydrologic and behavior of the lake basin aquifer, the study area can be classify in to 6 (six) potential zones depending on their behavior of permeability discharge recharge spring outlet behavior, topographic behavior of catchment. As shown in figure 4 south east of the Wondogenet escarpment that is the wgigra-guguma highland is the main recharge area with localized shallow groundwater and there are many perennial rivers with good discharge that emanates from wgigra-guguma escarpment and flow in to the area that fed the groundwater of the area specially the chelelekа swamp.

Western part of Wondogenet escarpment; that is, beneath of the mountainous western region is the main discharge area, which is described by the existence of numerous springs flowing to the swap as river. Wondogenet, Wesha and Tulla are suggested as highly recharging areas of the aquifer system of the lake basin. These aquifer areas are found surrounding the eastern and south western part of Chelelka swamp.

Most of the chelelekа swamp with shallow intergranular deposits underlain by confined ignimbritic aquifer; with confined water table exists in artesian ground water condition; that is in the form of ground water flowing above ground surface.

2.4 Hydrology

The area perennial streams which have their headwater in the eastern high land and flow to the west, Hawassa caldera, crossing the Wondogenet escarpments that finally join together to form Tikur-Wuha River which subsequently leads in to Lake Hawassa. According GSE some of perennial ungauged streams which flows from Easter highlands through Cheleleka swamp and joining Tikur-Wuha river, which is the only tributary river to lake Hawassa, are listed below (Table 1) with their discharge rate measured using floating method (AG consulting, 2007)

Table 1 Streams draining towards Lake Hawassa

No	1	2	3	4	5	6
Name of stream	Bela	Weha	Worka	Sole	Shenkoraweha	Comosha
Discharge (m^3/d)	6598	64895	32400	20412	2800	3733
No	7	8	9	10	11	
Name of stream	Gimat woha	wodesa	abosa	kedo	bogete	total
Discharge (m^3/d)	48384	74756	5184	43131	2117	304410

2.5 Tikur-wuha River

Tikur-wuha is the only perennial river, whose destination is the Hawassa Lake. It has been gauged since 1981 Tukur-wuha river drainage area in the lake basin cover about 625 km^2 that contributes the lake surface recharge.

2.6 Lake Hawassa

Lake Hawassa is found in Ethiopia rift system which covers about 100 km^2 of surface area of the study basin. Lake Hawassa is not affected by direct water abstraction currently there is a potential danger of using the lake and Tributary Rivers for irrigation in the near future (WWDSE 2001). The average water level of Lake Hawassa measured since 1969-2008 varies from 1682.586 -1685.209m (See Figure 6), the lowest being observed in 1976 and the maximum is recorded in 1998.

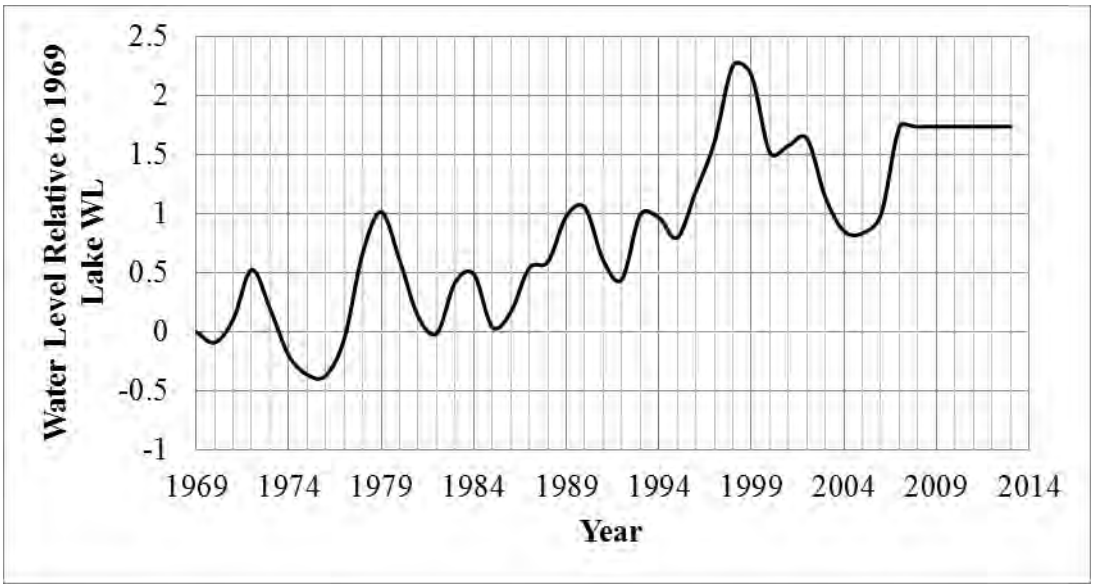


Fig. Recorded Hawassa Lake level 1969 to 2013 (Source:)

According to the bathymetric survey carried out by WWDSE (2001, see Figure 7) showed that deepest point of lake Hawassa measures about 21 m below the average water level. WWDSE (Water work design and supervision Enterprise 2001) in studying lake level rising of lake Hawassa in case of Hydrogeology of the catchment found conclusion that there is a homogeneous water system in the catchment the lake for the reason the, the cold and hot springs, the ground water and rivers water correlate with correlation factors varying from 0.90 to 0.998 indicating that there is one homogeneous water system in the lake catchment. This study showed that the level rise\lake expansion\had affected hundreds of urban households 100^{th} thousands of farmer households 10^{th} of organization and created conducive environment for mosquito breeding.

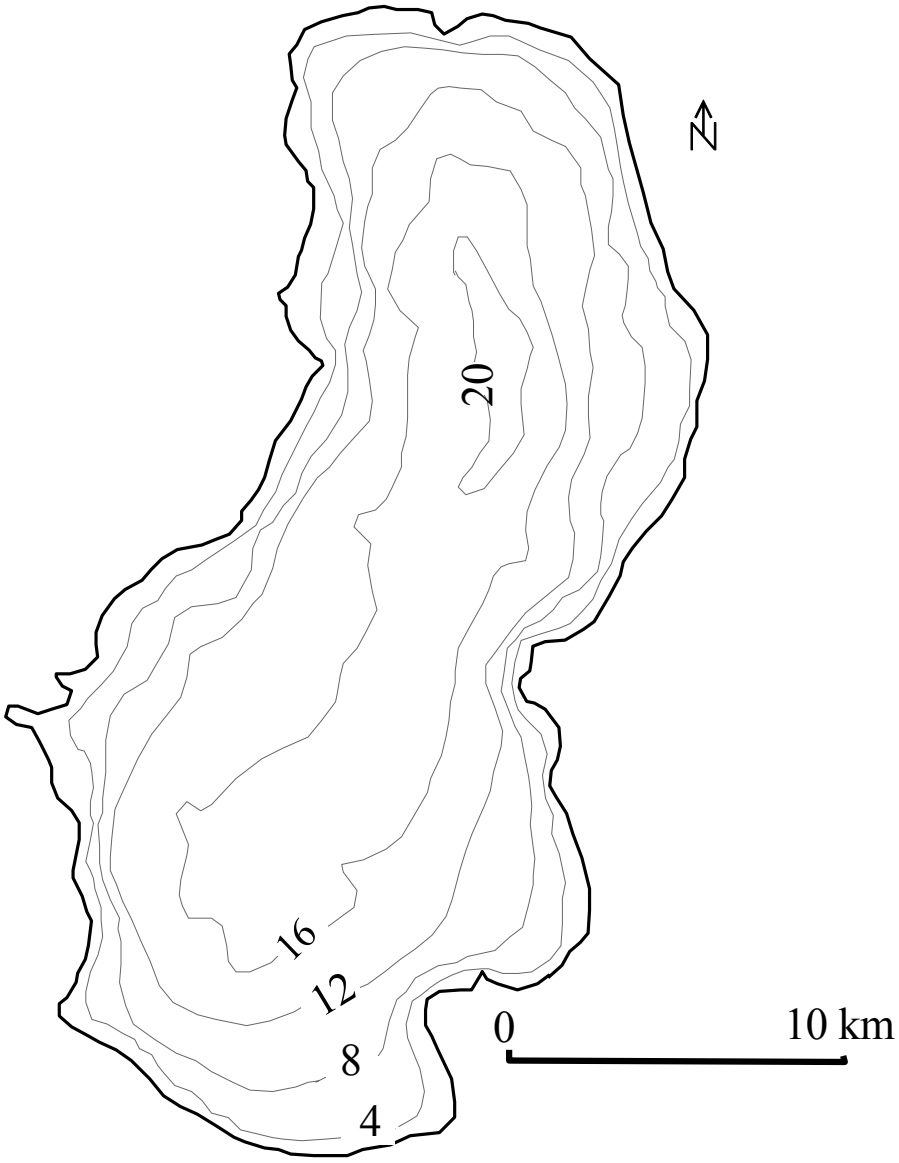


Figure 2 Bathymetry survey of Lake Hawassa (Source: WWDSE, 2001)

2.6 Groundwater

SNNPR Regional State Water Resources Development Bureau has studied "Pollution of lakes and Rivers" by AG-consult consulting hydro geologists and Engineers in 2007. From the contour map of Ground water level it can be inferred that Hawassa town is located at a local recharge area where ground water pollution is likely take place, in which shallow and deep ground water are dominated by local recharge from lake Hawassa, precipitation and runoff.

Even if Lake Hawassa has been of wide interest for many years, the question matter of lake water balance and the causative factors which require careful study of the components of the hydrological cycle in relation to natural and anthropogenic factor that may affect the lakes has never been studied .

Ayenew T. and Robert B. under take comparative study of the hydrology and hydrogeology of selected Ethio-Kenyan Rift lakes (2002) and reports that the results elaborate the intricate nature of the sub surface hydrology of the rift and much greater role of ground water in the water balance of most lakes.

According to Gebregziabher (2004) assessment, since the rift floors is distributes with multi-directional fault systems, thus their relationship with the surface and ground water flow system needs to be studied in detail.

2.7 History of Lake Hawassa

Hawassa, Zeway, Langano and Abyata are lake of tectonic origin with alignment to the main tectonics trend of the rift (Mohr 1967) lake Hawassa was first roughly mapped by traverse by(Darragon 1898). The Main Ethiopia Rift (MER), from Lake Ziway to Lake Hawassa, seems to have been occupied by a single huge lake during late Pleistocene wet climatic period. The lake then dried to a degree more severe than at the present day (Mohr, 1966)

Lake Hawassa and Shalla, situated in Hawassa caldera, were united as a single lake in the last century (Mohr, 1970). However resent terraces are much less well preserved in the lake Hawassa basin than Ziway – Shalla lakes. To the north the areas may lie in the water climate of Hawassa region.

The existence of terraced pumicing lacustrine sediments both sides of the fresh transverse faucets which limits the present lake Hawassa basin to the north suggests that in pluvial times this basin was concerned to that of Zeway – Shalla. There were separated by post pluvial block faulting and tilting (Mohr, 1960). Lake sediment to ancient Hawassa lake level was in countered in borehole located north of the lake shore at 1700 m elevations, which shows a drop of 30 m to the present lake level of the level of hyaloclastite at 1725m is taken, the present day level of Lake Hawassa has dropped by 40m. Recently the

level of Hawassa Lake has been rising. The lake level has been recorded since 1969 and the level has increased by about 3.82 meters over the last 30 years. The level increased by about 2 meters since January 1996 showing that the level is increasing at an unusual rate in recent years (Adapted from Geological survey of Ethiopia (GSE, 2003)).

2.8 Groundwater flow Model formulation

Physical models such as laboratory sand tanks simulate groundwater flow directly. 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). For time dependent problems, an equation describing the initial distribution of heads in the system is also needed (initial conditions). Mathematical models can be solved analytically or numerically. Since it is very difficult to deduce assumptions for our current study area to be solved analytically, the numerical solution technique is chosen.

In this chapter first we try to formulate the governing mathematical model and its inputs, limitation and assumptions and the numerical model is then formulated based on the mathematical theories and assumptions.

Ground water models are an attempted represents the essential feature of the actual ground water system by means of counterpart (Todd and Mays, 2005) which have capacity to test and related model based forecasts.

Ground water models according to Todd are physical based mathematical models derived from Darcy's low and low of conservation of mass. Various establish solution techniques based upon either finite difference or finite element approximations or a combination of both, are available for solving equations of the model. The accuracy of the solution (model prediction) is dependent up on the reliability of the estimated model parameters and the accuracy of the prescribed boundary condition.

The finite difference method requires a rectangular element shaped discretization of the aquifer and the finite element method concuss of triangular discretization is the process of subdividing the continuous hydro geologic units in to discrete segments or cells. Finite element is easy to define boundary of irregularly shaped aquifers and to ensure that node

points coincide with monitoring wells or various types of geographic features. Since finite element models are reported to be somewhat superior to finite difference models for problems that have a moving boundary, such as cross-sectional model a water table that is transient, as well as coupled problems, such as contaminant transport (Wang and Anderson, 1982). The finite –element model also has the advantage of being much more flexible interims of mimicking the geometry of an aquifer system than the finite-difference method and requires fewer nodes (Fetter, 2001).

Groundwater flow models can be transient or steady state and one, two, or three spatial dimension. Steady state flow accurse when at any point in flow field the magnitude and direction of the flow are constant with time (Anderson and Woessner, 1992). Selecting conceptual model for a given problem is one of the most important step in modeling process. The key data require mint in the process of conceptualization include data about hydro-stratographic units, surface water bodies, physical and hydraulic boundaries recharge and discharge zones. (Andeison and Woessner, 1992)

Once the conceptual model is translated into a numerical model in the form of governing equation, with associated boundary and initial condition, a solution can be obtained by transferring into a numerical model and writing a computer program (code) for solving it. This includes design of grid, setting boundary and initial conditions and preliminary selection of values for aquifer parameters. The input parameters include model grid size, layer elevations (thickness), boundary condition, hydraulic conductivity, recharge and additional model for steady state condition. Model calibration consists of changing values of model input (data) parameters in an attempt to which field condition with some acceptable criteria (Anderson and Woessner, 1992)

2.9 Groundwater flow equation

The functional relationship between the lake water level variation and the resulting hydraulic pressure variation in the basin can be set using any of the numerical methods for groundwater flow such as finite difference method or finite element method. The choice between the finite difference and finite element method depends on the problem to be solved and the preference of the user. Finite difference methods are easy to understand

and program. Finite element methods are better able to approximate irregular shaped boundaries than the standard finite difference methods. Finite element methods are also better able to simulate point sources and sinks, seepage faces and moving water tables than the finite difference method (Anderson and Woessener, 1992).

2.9.1 Governing Equations for Saturated Groundwater Flow

The governing equation for water flow in saturated medium can be obtained by combining a special form of Darcy's law (derived from the water phase momentum balance) and the continuity equation written for the water phase. The derivation is traditionally done by referring to a cube of porous material (Fig. 11) that is large enough to be representative of the properties of the porous medium and yet small enough so that the change of head within the volume is relatively small (Anderson and Woessner, 1992).

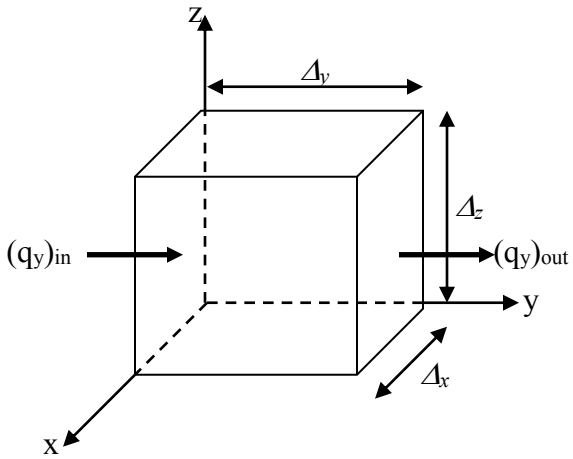


Fig.3 The representative elementary volume used in the derivation

The cube in Fig. 11 is called the representative elementary volume (REV). Its volume is equal to $\Delta_x \times \Delta_y \times \Delta_z$. The flow of water through the REV is expressed in terms of the discharge rate (q), whose magnitude in the three coordinates will be q_x, q_y, and q_z.

The water balance equation (conservation of mass) states that:

$$Outflow - Inflow = Change\ in\ storage$$

Consider flow along the y-axis of the REV. Influx to REV occurs through the face $\Delta_x\Delta_z$ and is equal to $(q_y)_{in}$. Flux out is $(q_y)_{out}$. The volumetric flow rate along the y-axis is:

$[(q_y)_{in} - (q_y)_{out}]\Delta_x\Delta_z$. This can also be written as $\frac{(q_y)_{in} - (q_y)_{out}}{\Delta_y}\Delta_x\Delta_y\Delta_z$ dropping the in and out subscripts, the change in flow rate through the REV along the y-axis is $\frac{\partial q_y}{\partial y}\Delta_x\Delta_y\Delta_z$.

Similar expression can be written for the change in flow rate along the *x*- and *z*- axes. The total change in flow rate is equal to the change in storage and is expressed as:

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)\Delta_x\Delta_y\Delta_z = Change\ in\ storage \tag{2.1}$$

The existence of sink (e.g. a pumping well) or source of water (e.g. injection well or some other source of recharge) within the REV is undeniable. The volumetric inflow rate of such sources is represented by $R^*\Delta_x\Delta_y\Delta_z$. Here the R^* is defined to be intrinsically positive when it is a source of water; therefore it is subtracted from the left hand side of Eq. 2.1. Therefore Eq. 2.1 becomes:

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - R^*\right)\Delta_x\Delta_y\Delta_z = Change\ in\ storage \tag{2.2}$$

The change in storage is represented by specific storage (S_S). It is defined as the volume of water released from storage per unit change in head (h) per unit volume of aquifer (Anderson and Woessner, 1992) i.e. $S_S = -\frac{\Delta V}{\Delta h\Delta_x\Delta_y\Delta_z}$. The sign convention is that the ΔV is intrinsically positive when the Δh is negative, or in other words, water is released from the REV when head decreases. The rate of change in storage in REV will be:

$$\frac{\Delta V}{\Delta t} = -S_S\frac{\Delta h}{\Delta t}\Delta_x\Delta_y\Delta_z \tag{2.3}$$

Combining Eq. 2.2 and Eq. 2.3

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -S_S\frac{\partial h}{\partial t} + R^* \tag{2.4}$$

Darcy law is used to set the relationship between q and h. Darcy law in three dimension is written as; $q_x = -K_x \frac{\partial h}{\partial x}$, $q_y = -K_y \frac{\partial h}{\partial y}$, $q_z = -K_z \frac{\partial h}{\partial z}$ (Anderson and Woessner, 1992). Substituting these expressions in Eq, 2.1.4

The desired groundwater flow equation is

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_S \frac{\partial h}{\partial t}-R^* \qquad (2.5)$$

Where K_x, K_y, and K_z are components of the hydraulic conductivity tensor.

In the above derivation it is assumed that K_x, K_y, and K_z are collinear to the x, y- and z-axes. If the geology is such that it is not possible to align the principal direction of the hydraulic conductivity tensor with the rectilinear coordinate system, a modified form of equation that utilizes the hydraulic conductivity tensor is required. The hydraulic conductivity tensor is written, $K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$.

By using a global coordinate system for the entire problem domain and a local coordinate system for each finite element in the grid, the off diagonal terms in the hydraulic conductivity tensor could have zero value (Anderson and Woessner, 1992).

$$K = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix}$$

2.9.2 Assumptions of Groundwater Flow

This study mainly uses a flow system conceptual viewpoint of groundwater systems. By flow system view point it means the study is not concerned with identifying aquifers and confining beds but is concerned in constructing the three dimensional distribution of heads, hydraulic conductivities, and storage properties everywhere in the system. (Anderson and Woessner, 1992)

Major assumptions of the flow model are as follows:

- Darcy's law is valid and hydraulic head gradients are the only significant driving force for fluid motion.
- Water is the only flowing fluid phase (i.e., the air phase is assumed to be inactive).
- The fluid is considered to be slightly compressible and homogeneous.
- The fractured medium maybe represented by a single continuum porous medium of spatially invariant properties.
- The porosity and saturated hydraulic conductivity are constant with time.
- Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.

2.9.3 Limitations

The major limitations of this study include:

- The model is tailored to isothermal fully saturated fractured porous medium systems.
- In performing a saturated flow analysis, the study handles only single-phase flow of the liquid (i.e., water) and ignores the flow effects from other potential phases (i.e., air or other non-aqueous phases) which, in some instances, can be significant.

3. Methodology

The objective of the study is to work out the interaction of the Hawassa lake water and groundwater of the Hawassa basin. To achieve this objective a numerical groundwater flow modelling is selected. Accordingly this chapter will describe the methodology that defines the input data needs and the procedures adopted in creating the numerical model.

3.1 Location

The focal point of the study area that is Lake Hawassa and its basin is found about 275 Km from Addis Ababa. The lake occupies the lowest elevation of the catchment. The lake basin lays between two regional states of SNNPRS and Oromiya RegionalGovernment. It located between latitude 6^0 48' 45" to 7^0 14' 49" N and longitude 38^0 16' 34"to$38^0$43'26"E

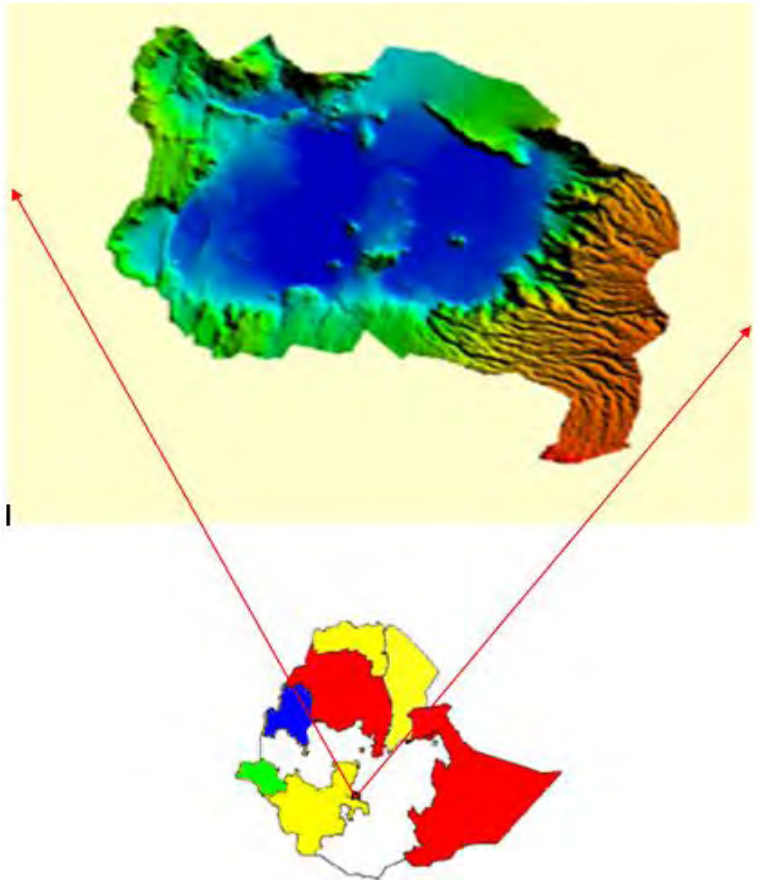


Figure 4 Location map of Lake Hawassa Basin

3.2 Numerical Solution Techniques

Eq. 2.5 can be solved analytically or numerically. Since it is very difficult to deduce assumptions for Lake Hawassa to be solved analytically, the numerical solution technique was chosen. In this study we have chosen a model called TAGSAC (Imai and Yanagizawa, 1990) for solving the groundwater flow problem. The numerical approximations of the groundwater flow equations describing fully three dimensional problems are obtained using the Galerkin finite element technique. 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. For a transient simulation, the nodal equations are first-order in time ordinary differential equations (and possibly nonlinear) that are integrated using a finite difference approximation. For each time step, this gives rise to a system of algebraic nodal equations that are solved using an iterative matrix solution procedure. TAGSAC has proofed to be applicable in a number of researches done all over the globe. (Mohammed et. al., 2009)

Lake water- ground water interaction of Lake Hawassa basin aquifer system is simulated using three dimensional steady state FEM ground water flow model. The steady-state flow of groundwater is described by a form of the Laplace equation, which is a form of potential flow and has analogs in numerous fields. The groundwater flow equation is often derived for a small representative elemental volume (REV), where the properties of the medium are assumed to be effectively constant. A mass balance is done on the water flowing in and out of this small volume, the flux terms in the relationship being expressed in terms of head by using the constitutive equation called Darcy's law. As of the transient simulation discussed above for steady simulation we can derive flow equation of the form:

$$\frac{\partial}{\partial x_i}\left(K_{ij} \frac{\partial h}{\partial x_j} \right) = -q$$

This equation is similar to equation 2.5, with the transient term omitted. Therefore every discussion we have made (mathematical and numerical) is applied to this case with the exception of using the storage terms and time dependent terms.

3.3 Input Data

Data required for the groundwater flow simulation include values of the saturated hydraulic conductivity and specific storage of each aquifer and aquitard material, the geometry and configuration of the flow region, as well as, initial and boundary conditions associated with the flow equation.

Input Data for groundwater Flow Problem

Input data of the flow model include the following

(1) System Geometry

- Horizontal and vertical dimensions including layering and other heterogeneity (L)

(2) Porous Medium Properties (Hydraulic properties of the basin geology)

- Horizontal Saturated hydraulic conductivity component, K_{Hx} (LT^{-1})
- Vertical Saturated hydraulic conductivity component, K_{Hz} (LT^{-1})
- Specific storage coefficient, S_s (L^{-1})
- Effective porosity, Φ

(3) Boundary Conditions

- Specified head nodes
- Specified flow nodes

(4) Well inventory data

3.4 Numerical Groundwater Modelling

3.4.1 Spatial discretization

This study employs a right-handed Cartesian coordinate system (x, y, z) to generate a three dimensional triangular grid for finite element analysis. The grid is oriented such that the z-axis points in the vertical upward direction (the elevation of the nodes above sea level). In the areal extent the grid is confined to be comprised of triangular elements, while in the vertical direction distorted elements are handled. Based on the formulation chosen and accuracy considerations, the level of horizontal and vertical elemental distortion from a triangular shape should be kept to a minimum.

Varying levels of spatial discretization of the solution domain are performed prior to the main model execution. In the aerial view a triangular grid is used to represent three dimensional model domain. The vertical planes (i.e., the x-z and y-z planes) are constrained to be flat surfaces that are perpendicular to each other; therefore, the resulting elements are also triangular in shape and their shape remains invariant in the vertical direction. The overall three dimensional mesh is unstructured.

Each element is represented by a linear (6- nodded) finite element that is triangular in the horizontal direction. The vertical coordinate (z-axis) is in the opposite direction relative to the gravity vector.

The surface of about 1440 km^2 study area was divided into a grid on a two dimensional plane so that, the boreholes and the springs in the water shed are represented. Elevations of the individual nodes are calculated from the digital elevation model (DEM) in 90 m-interval to express the topography of the study area. The ground surface elevation ranges from 1683 to 2963m a.m.s.l.

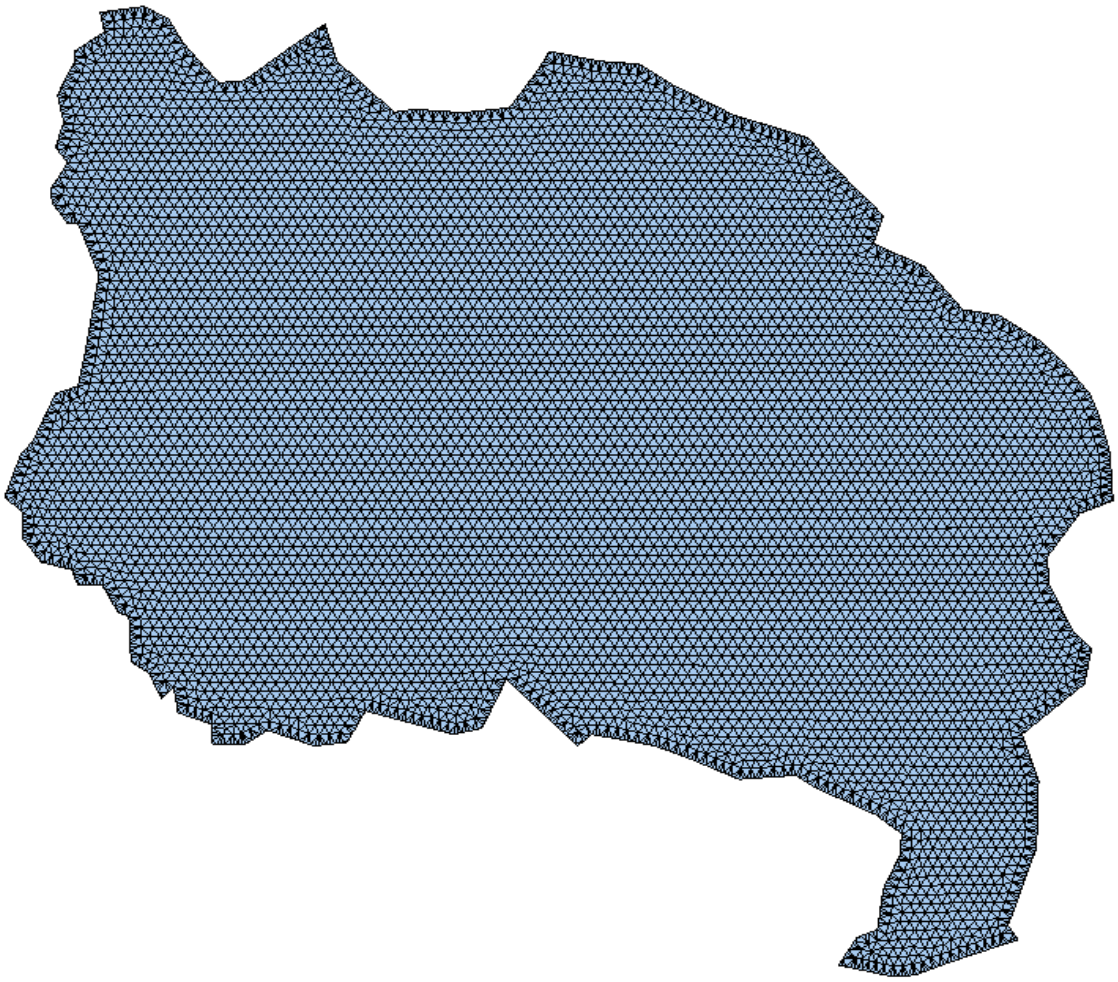


Figure 3 Finite elements discretization for the Lake Hawassa Basin

An aerial depiction of the surface finite-element grid and boundary conditions used in the three-dimensional models of the unconfined aquifer is illustrated in Figure 9. It illustrates the grid chosen for current study area simulations. The mesh is composed of the nearly same dimensioned elements. The average planar size 500 × 500 meters of triangular elements, smaller sized elements occurs towards the boundary of the model area. The entire study area from surface to the bottom of has been divided into a horizontal layer having dimension of 500 meters height. A total of 13500 triangular prism elements are formed from 14320 nodes distributed all over the study area. The mesh is non-uniform, hence needs more refinement near the boundary, because sharp changes are expected there.

3.4.2 Model Conceptualization

This section briefly describes the conceptual model of the Lake Hawassa basin aquifer system. The conceptual model was developed from information on the geologic structure of the aquifer, spatial distributions of hydraulic and transport properties and boundary conditions.

Several conceptual models have been developed for describing fluid flow in fractured porous media. Fundamentally, each method can be distinguished on the basis of the storage and flow capabilities of the porous medium and the fracture. The storage characteristics are associated with porosity, and the flow characteristics are associated with permeability. Four conceptual models have dominated the research: 1) explicit discrete fracture, 2) dual continuum, 3) discrete fracture network, and 4) single equivalent continuum. In addition, multiple-interacting continua and multi-porosity/multi-permeability conceptual models have recently been introduced in the literature. Further distinctions can be drawn on the basis of the spatial and temporal scales of integration, or averaging, of the flow regime. Bear and Berkowitz (1987) describe four scales of concern in fracture flow: 1) the very near field, where flow occurs in a single fracture and porous medium exchange is possible; 2) the near field, where flow occurs in a fractured porous medium and each fracture is described in detail; 3) the far field, where flow occurs in two overlapping continua with mass exchanged through coupling parameters; and 4) the very far field, where fracture flow occurs, on average, in an equivalent porous medium.

This study focuses on equivalent porous medium ideologies, in which fractured material is represented as an equivalent porous medium (EPM) by replacing the primary and secondary porosity and hydraulic conductivity distributions with a continuous porous medium having the so called equivalent or effective hydraulic properties. The parameters are selected so that the flow pattern in the EPM is similar to the flow pattern in the fractured system.

To develop a conceptual model of the physical application a schematic description of the study area, its geometry, and the important features is shown in Figure 4. In the figure different geologic zones of different material properties are clearly depicted with some of the water bodies in the lake basin.

3.4.2.1 Hydraulic Properties

Hydraulic properties important to the three dimensional conceptual model include both horizontal and vertical hydraulic conductivities, specific storage coefficient and porosity. To apply a numerical model, the distribution of these parameters must be specified for each hydrogeological unit. However since the model is based on the principles of equivalent porous medium, Hydraulic properties have been replaced by equivalent or effective values. To achieve this, a conceptual model having six different sections which will have different effective values of hydraulic properties is adopted. The value of these hydraulic parameters is obtained during the calibration process of the steady state saturated ground water flow model designed for the study area.

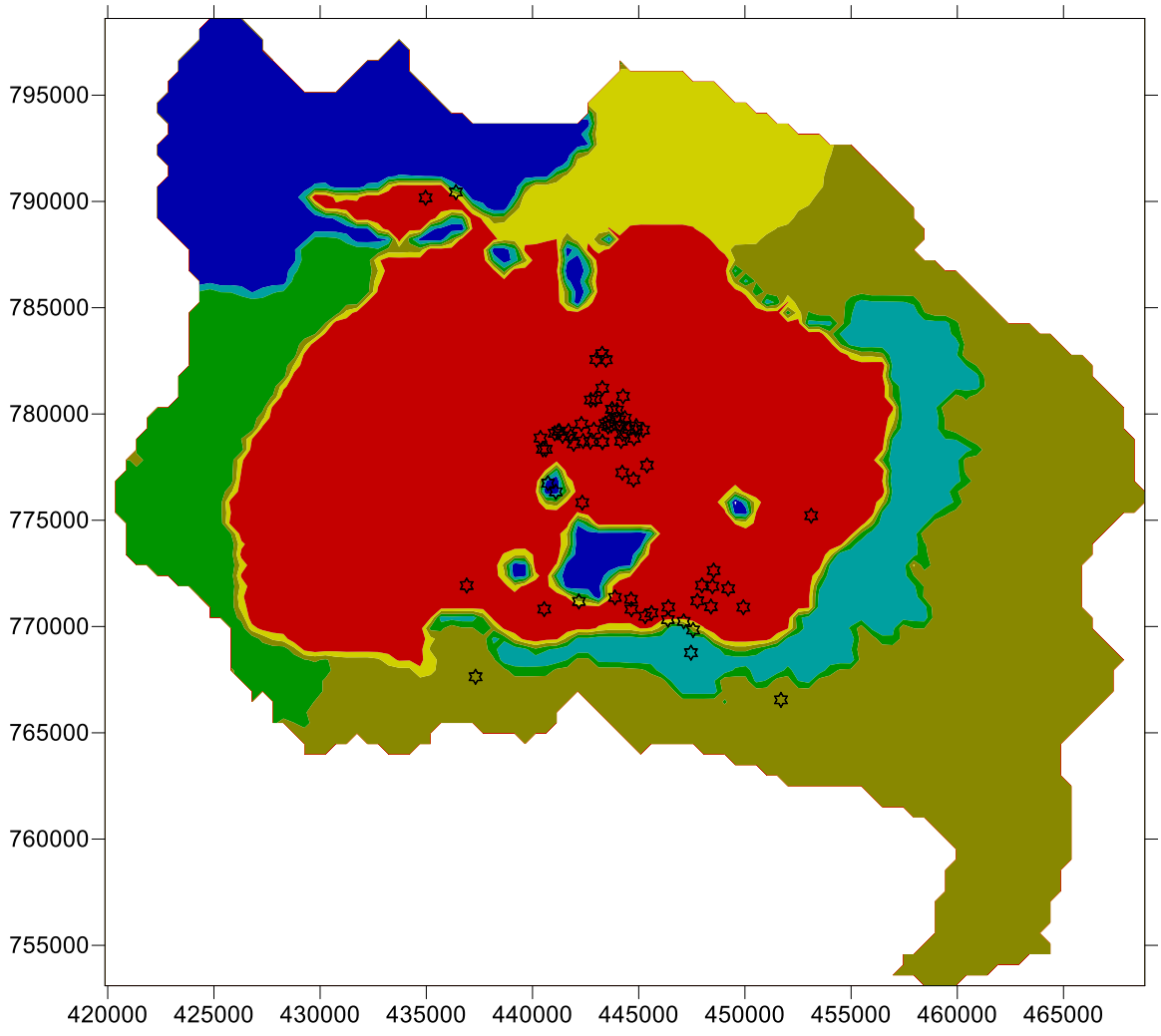


Figure 4 Hydrogeological conceptual model

3.4.2.2 Recharge and Flow System Boundaries

Natural recharge to the unconfined aquifer system occurs from infiltration of runoff from elevated regions along the north and eastern boundary of the site, and precipitation falling across the Lake Hawassa basin. Natural recharge from runoff and precipitation provides a source of groundwater inflow to the area of interest. Area recharge from precipitation falling on the study area is highly variable, both spatially and temporally, and depends on local climate, soil type, and vegetation.

Ground water recharge is defined as the entry in to the saturated zone of water made available at the water table with the saturated zone.(freeze and cherry 1977) quantifying the rate of recharge to aquifers is the most difficult of all measures in the evaluation of ground water resources. Estimation of groundwater recharges requires modeling of the interaction between all the important process in the hydrologic cycle such as precipitation infiltration, surface run off, evapotranspiration, soil moisture, and ground water level variations (Jyrkama and Skyes, 2007)

There are many sources of recharge to groundwater aquifer system. These include recharge from precipitation, rives, irrigation losses, urban water sources and inter aquifer flow (learner et.al 1998) which have defined principal as direct, local and indirect recharges (Tenalem A.,1998).

In many cases, combination of various types of recharge will occur (simmers, 1997). The existence of different combination of groundwater recharge makes the quantification process difficult. (Tenalem A., 1998), which leads to different recharge estimations technique e.g. direct recharge measurement, water balance methods, Darian approach, Trace techniques and empirical methods. Due to so many inconvenient and data limitation or unavailability of well-studied and organized data sources of hydrogeology and geology of the lake basin; getting accurate quantity of ground water recharge was very difficult. In this research recharge is estimated by trial and error. The recharge at a point in the study area is expected to be some fraction (percentage) of the annual rainfall existing at this point. The trial and error estimation involves finding appropriate percentage of the annual rainfall to predict the observed groundwater table throughout the lake basin.

In this study estimated aquifer recharge area of the basis is classified based on Topography, characteristics of the aquifer, rain fall distribution and conceptualized groundwater system. Thus estimating the rainfall distribution all over the basin is vital.

3.4.2.3 Flow system Boundary

This boundaries condition is a mathematical model that determines how and where the groundwater inflows or out flow in to or from the aquifer system. The boundary specifies the dependent variables or derivatives of the dependents variable at boundary problem domain (Anderson and Woessner, 1992). This boundary condition falls in to one of the following categories according to Franke et.al. (1987)

- Specified head or Dirichlet condition
- Specified flux or Neumann condition
- Mixed or Cauchy boundary condition
- Free surface boundary condition and
- Seepage face boundary condition

But from these boundary, Anderson and Woessner (1992) define three type of mathematical conditions used to represent hydrogeological boundaries:

1. Specified head boundaries \Dirichlet conation\
2. Specific flow boundaries \Neumann condition\
3. Head dependent flow boundary \Cauchy or Mixed condition\

If the head is known at the boundary of the flow region the boundary is specified condition is Dirichlet. If the flux across a boundary to the flow region is known the boundary condition is Newman condition. In some cases the boundary condition will be mixed that is, with some portion having known flux (Wang and Anderson, 1982).

3.5 .Borehole investigations

Borehole investigations are one of the most important methods to investigate the hydrogeology of the site. These investigations allow collection of core samples, groundwater sampling and measuring the hydrogeological and rock mass properties to depth. However from this study objective point of view well location its elevation and the water table depths are collected. The well inventory in this research includes collecting the above information on hand dug wells, deep wells and springs. While collecting these well inventory a GPS was used, the accuracy of the GPS in estimating the elevation of these data was seldom accurate than +/- 7 m. These data are used in optimizing the aquifer hydraulic properties and recharge rates.

3.6 . Lake-Water Groundwater Interaction

Head distribution is at first calculated by taking the current lake water level, (2013 water level) prior to other years lake water groundwater relationship simulation. This is because the well data inventoried is related to the 2013 year lake water level. Figure 11 illustrates the procedures of FEM calculations. First arbitrary combinations of vertical (K_V) and horizontal (K_H) hydraulic conductivity were given in the one layer hydro-geological model. Then a dynamic steady state pore pressure distribution was calculated for predicting the 2013 pore pressure distribution. Measured water levels in the wells were compared with the calculated values. K_V and K_H values of having better approximation were selected. After getting the 2013 head distribution and the corresponding vertical and horizontal hydraulic conductivity values, FEM simulation was analyzed for other year's lake water groundwater level simulation.

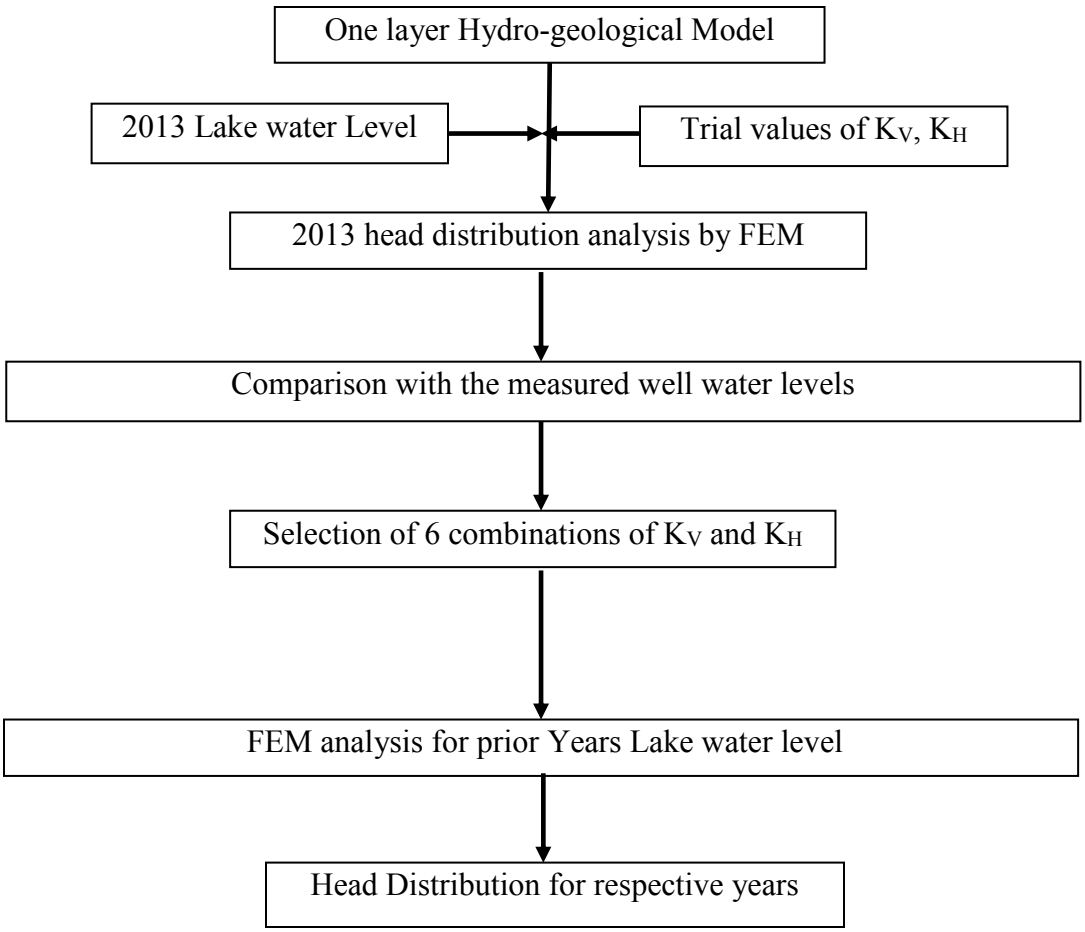


Figure 5 Model calculation flow chart

3.6.1 Model calibration

Model calibration for the modeler is a means of correcting gaps between the measure head values and simulated values of ground water levels and the model relays or the measured head to match the simulated. The target of calibration is to bring the matching of measured simulated head difference or residual value to the permissible gap of 20m. But depends on heads. This should be 1.5 of the maximum and minimum head difference of the measured ground water level (Samson M., 2003). This is tolerable to the difference gradient. Which is working to achieve the objective of understanding groundwater elevation and the flow pattern in the lake basin. In this model calibration, inverse solving method was used. According to Anderson and Woessner (1992), there are two inverse solving techniques.

1. Manual trial and error calibration
2. Automated parameter estimation

Manual trial and error calibration

Trial and error calibration was the first technique to be used and is still the technique preferred by most users (Anderson and Woessner, 1992). It is the process of manual adjustment of input parameters until the model simulated value shows similarities with the measured head and range of error values. Assuming constant recharge and discharge, the model was calibrated under steady state condition. Calibration was conducted with trial and error by varying the hydraulic conductivity of the aquifer system. Trial and error calibration was continued until the result comes in the range of predetermined residual (error) criteria.

The hydro geologic map of the study area was divided in to 6 regions hydraulic conductivity zones depending on the previous studies of the lake catchment, and the best fit results were achieved by trying different hydraulic conductivity vales in these different zones with their respective parameters. The following diagram adapted from Andersen and Woessner, (1992) shows procedure of trial and error calibration process.

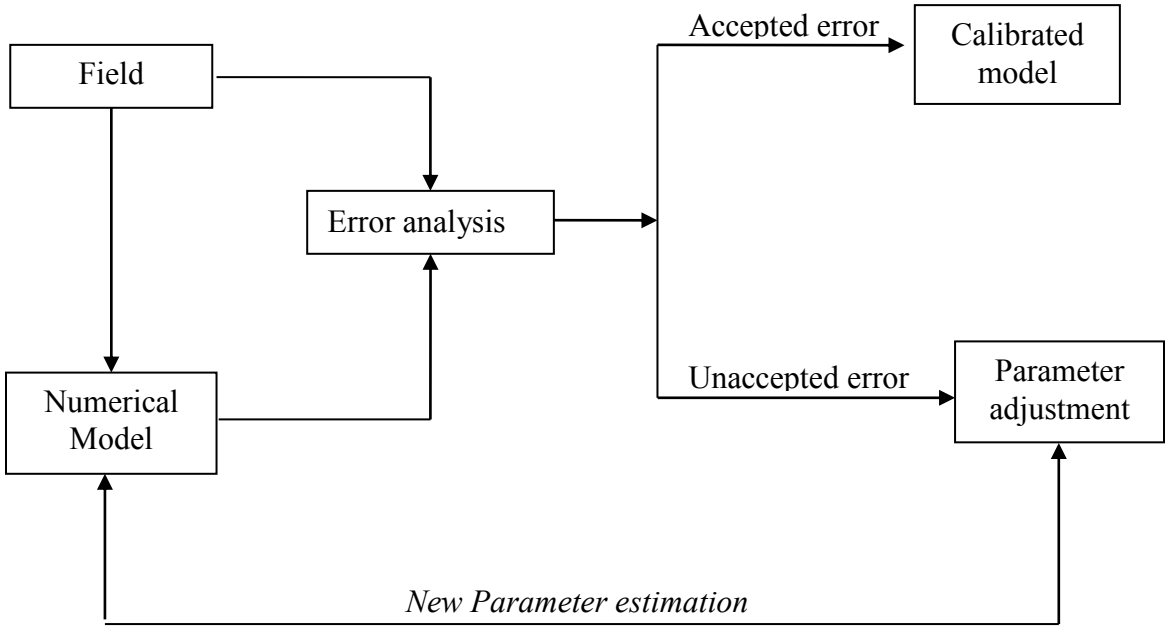


Figure 6 Procedure of trial and error calibration process

3.6.2 Calibration Evaluation

The result of the calibration should be evaluated both qualitatively and quantitatively (Anderson and Woessner 1992). The mean of the observed and simulated head differences was used to quantify the average error in the calibration process. The differences between measured (h_m) and simulated heads (h_s) respectively can be expressed by the mean error (ME) and the root of mean square error (RMSE). The objective of calibration is to minimize these error estimates.

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(h_{mi} - h_{si}\right)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_{mi} - h_{si}\right)^2}$$

RMSE is the best method to measure error. The maximum acceptable value of calibration criterion depends on the magnitude of the change in head over the problem domain (Anderson and Woessner, 1992). The scatter diagram generated by model also shows the matching property of the measured simulated head. The scatter plot is usually examined by the position of points scattered in the graph away from the straight line, that is; random distribution of point in the plot shows the deviation between measured and simulated groundwater heads.

4. Result and Discussion

On the basis of the methodology described in chapter 3 this section details the results obtained and discusses these results pertinent to the groundwater lake water interaction. The results will be described in their order of application in the modeling process.

4.1 Well Inventory

In the study area more than **83** measured water levels (springs, deep wells and shallow wells, see appendix A) have been inventoried. 68 boreholes have been selected in this research. shallow wells depths range (0m-35m) and boreholes (having depth range up to 200 meters deep). Their location in the study area can be seen in Figure 1. (See Appendix A for well inventory made).

Since the study focuses on collecting already existing wells the distribution seems concentrated towards the location of Hawassa city. The results that would be obtained from this research is then more representative of the groundwater lake water interaction that is occupied by the hydrogeology similar to the hydrogeology of Hawassa city.

4.2 Rainfall Distribution

Decadal rainfall for 7 stations has been collected from the National Meteorological Service Agency (NMSA). Based on meteorological station the spatial temporal distribution of the Hawassa lake catchment precipitation recording stations shown in the following table.

Estimation of the areal rainfall over a given catchment is useful for estimating the total recharge that could occur over the entire catchment. Various methods can be implemented to estimate the areal rainfall amount in the intervening catchment but the most famous method is the Thiessen Polygon, where by the influence of each rainfall station is determined and the weighted average rainfall estimated. The Thiessen polygon, generated on the basis of the seven stations described above, in the Lake Hawassa basin

is as shown in Figure 13. The area of the Thiessen polygon bounding each station will receive the same average annual rainfall recorded over the station. The average annual rainfall observed over these stations is shown in Table 2.

Table 2 Rainfall Data Availability for Lake Hawassa Basin

Met. station	**Location (UTM)**		**Mean rainfall**
(Symboling)	Latitude, N	Longitude, E	(mm)
Hawassa (S-1)	795876	157119	986
Shashemene (S-3)	795876	455838	942
Shamena (S-2)	782703	4952.43	818
Tulla (S-4)	769138	441897	1046
Haisawita (S-7)	761827	451307	1018
Wondogenet (S-5)	782831	457593	1117
Aje (S-6)	408693	806499	1034

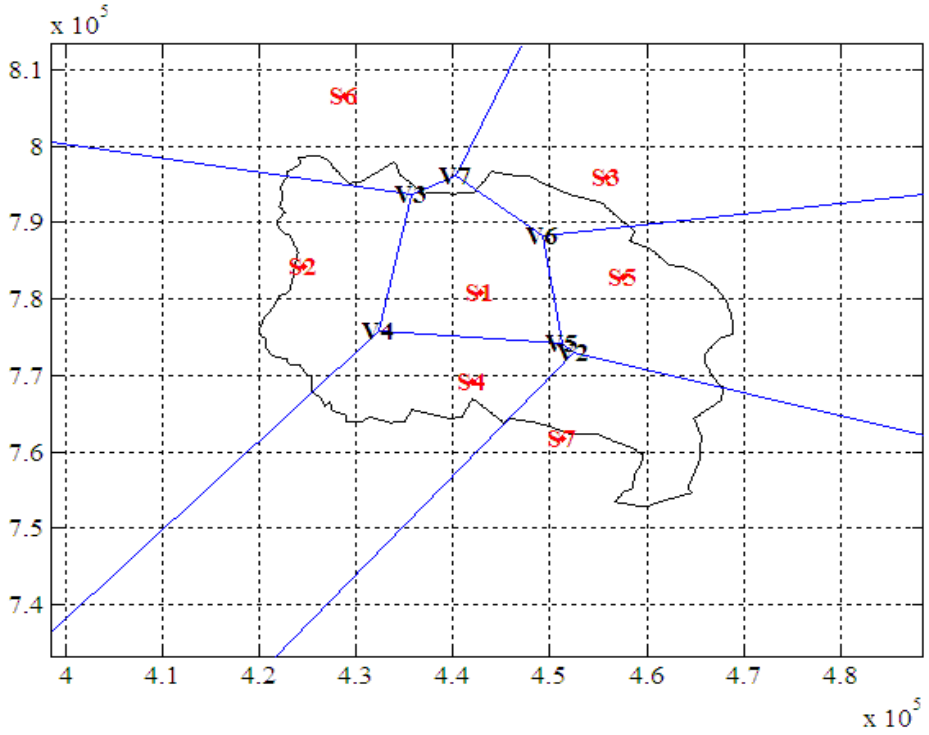


Fig. Rain gauge stations area coverage of Lake Hawassa basin by Thiessen polygon
(See Table 2 for the station symboling)

4.3 Flow system Boundary

The main perennial stream flowing to Cheleleka swamp and Lake Hawassa are significant river boundaries which describes surface water and ground water interaction. Streams from the foot of Wondgenet Guguma escarpments are main contributes of groundwater recharge to Cheleleka during dry period. During wet period when these rivers head exceeds the head of the nearby ground surface, those rivers recharge the nearby aquifer.

To include the natural hydraulic boundaries like rivers and groundwater divides nearby around the catchment, the analyzed domain was extended towards the watershed divide. The wells locations in within the study domain are represented by nodes. The site unconfined aquifer system is also bounded by the Tikur-Wuha River, Lake Hawassa and Lake Cheleleka, shown in the following Figure 12. Both the Rivers and the Lakes represent point of regional discharge for the unconfined aquifer. The amount of groundwater discharging to the river and Lakes is a function of the local hydraulic properties of the aquifer and of the hydraulic gradient between the groundwater elevation alongside or beneath the river/Lakes, and the river/Lakes stage. This hydraulic gradient is variable at any given time, since the river stage is affected by seasonal variations in precipitation and temperatures in other regions of the river drainage system. In this three-dimensional modeling effort, the surface nodes at the river edge and Lakes were simulated as constant-head boundary conditions reflective of the assumed river stage or Lake water level. The nodes below the surface and along the center of the river were simulated as no-flow boundaries. This design leads to a more accurate approximation of the upward movement of groundwater as the groundwater flow is controlled by the hydraulic gradient between the aquifer and the river/Lakes.

Therefore the Lakes and Tikur-Wuha River are constant head boundary nodes (Dirichlet nodes); the head value being equal to the water level at that specific node. In the same manner the mountainous ridges (watershed divides) bounding the model area are

hydraulic boundaries (groundwater divides) in which nodes at the water table are taken to be constant flux nodes (Neumann nodes) with flux equal to zero. The boundary at 500.0 m below the surface was set to be a no flow boundary. The whole drainage surface area, with the exception of the Lakes and Tikur-Wuha River, is taken as recharge/discharge boundary.

The ground surface is set as a free seepage face. Recharge at the top surface boundary takes precipitation, evaporation and run-off into consideration. Recharge rate of 19.63 is given to the model for proper estimation of the water levels measured in the wells.

Side boundaries along the ridges could be assumed as the groundwater divides and hence no flow boundary condition was given. Side boundaries along the rivers are also set as no flow boundary conditions. Bottom boundary assumed at 500 m below the surface was set as a no-flow boundary, so that at such depth bed rock is assumed to exist.

The boundaries described are shown in Figure 14. The dark Brocken lines all over the model area are groundwater divides representing a no flow boundary. The constant head boundaries are the Lake Hawassa and the Cheleleka swamp. The dotted line connecting these two water bodies is the Tikur-Wuha River which is also a constant head boundary.

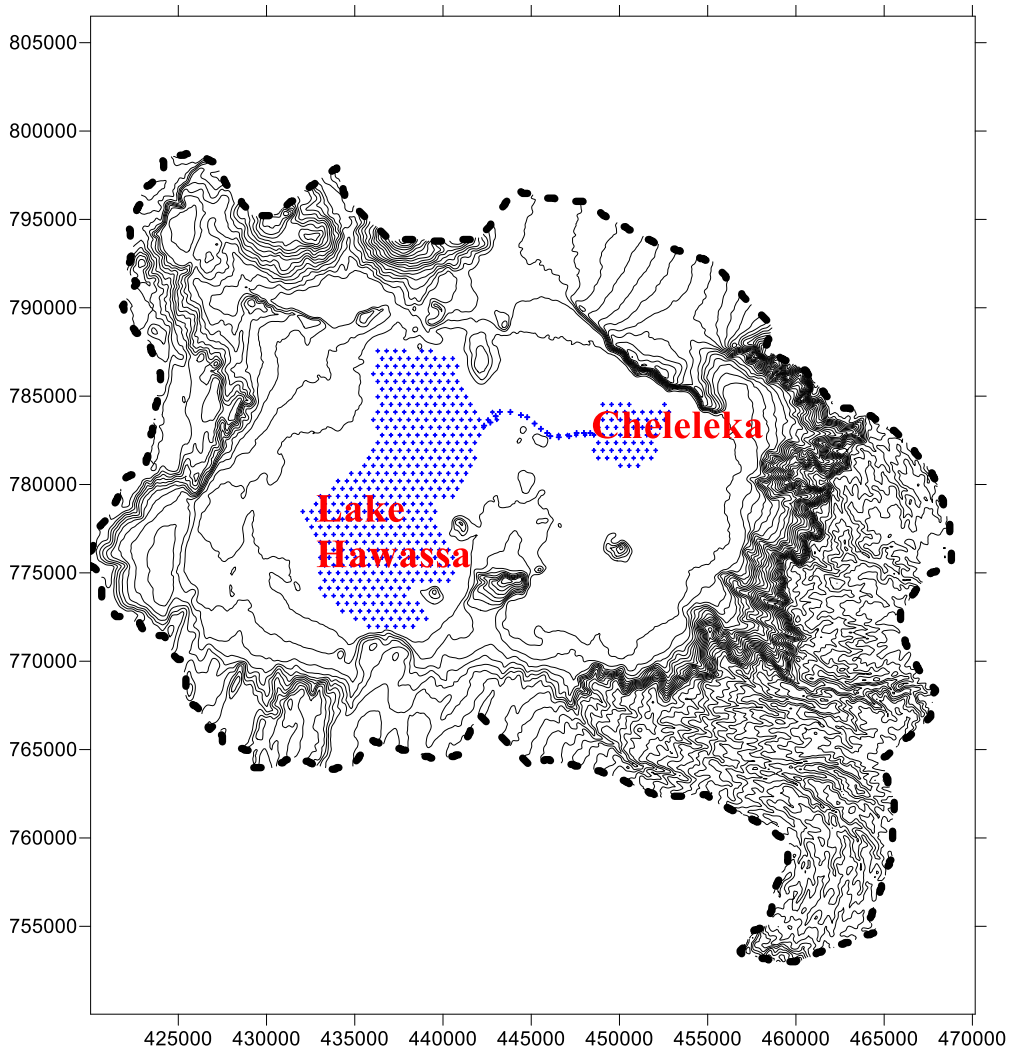


Figure 7 Boundary conditions location used in the model

The boundary conditions discussed above had been used in the steady state simulation of the groundwater flow which is coded to set the initial condition for the transient simulation. In the transient simulation, in addition to the above boundaries, time dependent boundaries are also necessary. These time dependent boundaries are entirely related to Lake Hawassa water level variation shown in Figure 6.

4.4 Model calibration

There are basically two ways of finding model parameters to achieve calibrations. (1) Manual trial and error adjustment of parameters and (2) automated parameter estimation. In this study the manual trial and error adjustment of parameters is used. The model calibration is performed to data observed at wells inventoried (Black dotes in Figure 15). The observed data at these boreholes describes the water level variation in the boreholes from January till end of March of 2013. For the lake level observed in 2013 the developed model is computed by varying the hydraulic conductivity and the recharge. After a number of trial and error selection of a set of hydraulic parameters for zones in Figure 15 and recharge for zones in Figure13, the following parameter values are selected as the best among other combinations.

It is clearly seen that the geologic zones of medium 1 and 2 have resulted in similar hydraulic conductivity values (Table 3) the same is true for medium 4 and 5; thus, are of the same hydrogeological character. Essentially the hydrogeological zones are then four.

Table 3 Calibrated hydrogeological parameters for the zones

Hydrogeologic medium	Kx (m/s)	Ky (m/s)	Kz (m/s)
Medium 1	1×10^{-7}	1×10^{-8}	1×10^{-7}
Medium 2	1×10^{-7}	1×10^{-8}	1×10^{-7}
Medium 3	1×10^{-6}	1×10^{-7}	1×10^{-7}
Medium 4	1×10^{-6}	1×10^{-8}	1×10^{-6}
Medium 5	1×10^{-6}	1×10^{-8}	1×10^{-6}
Medium 6	1×10^{-6}	1×10^{-8}	2.5×10^{-8}
The Medium are as described on Figure 15			

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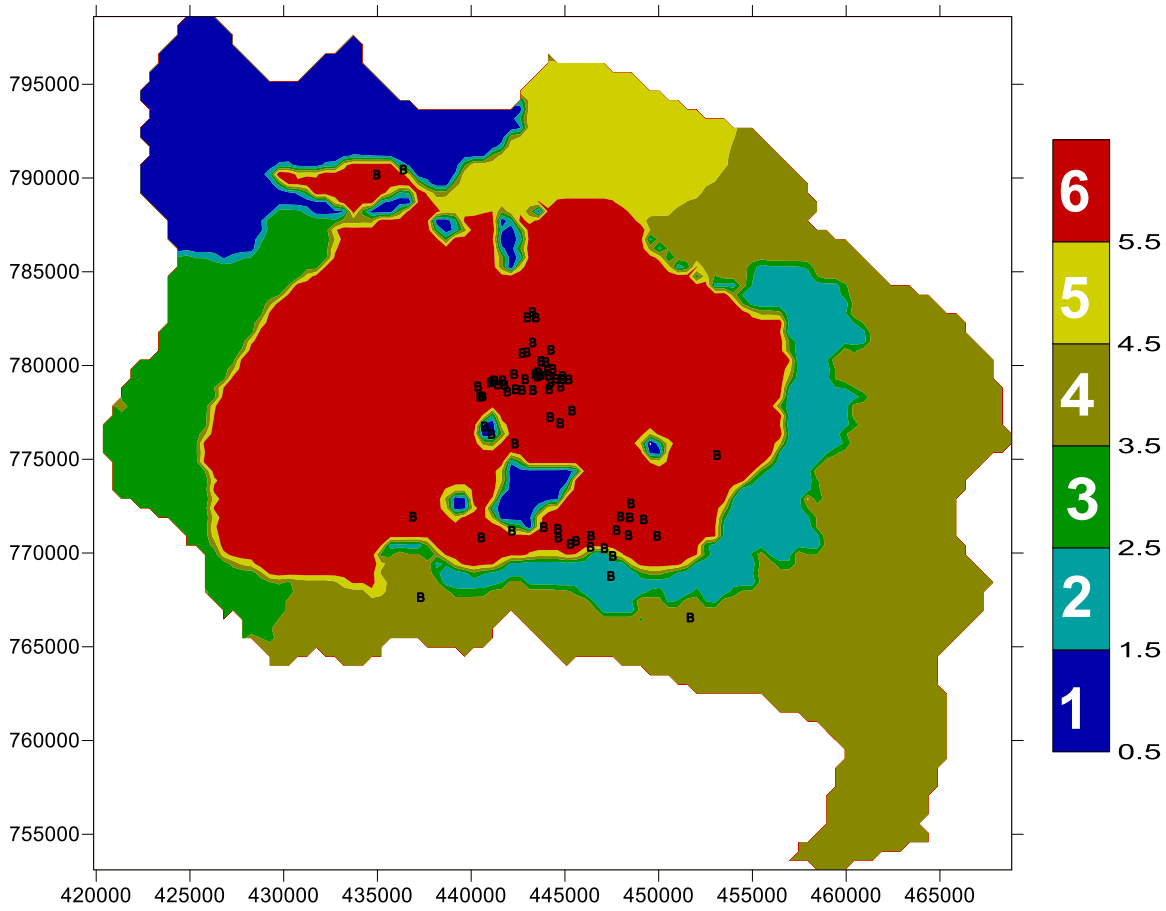


Figure 8 Hydrogeological map and their zonal description

The recharge taken in the model is 19.63 % of the annual rainfall received at the same point.

For the above hydraulic conductivity and recharge values the modeled and the measured values comparison can be seen in Figure 16. In the figure the best fit equation obtained between the modelled and Measured (well inventory data) is made by making the intercept at the origin (0, 0). The average indicators between modeled and calibrated results is shown in the following table.

Table 4 Average indicators obtained

Wells and springs	ME[a] (m)	MAE[b] (m)	RMSE[c] (m)	r^2	F
(*n*=68)	-2.73	7.45	12.33	0.755	1905980

A. Mean Error $ME = 1/n \sum_{i=1}^{n} (h_m - h_s)_i$

B. Mean Absolute Error $MAE = 1/n \sum_{i=1}^{n} \left| (h_m - h_s)_i \right|$

C. Root Mean Squared Error $RMSE = \left[1/n \sum_{i=1}^{n} (h_m - h_s)_i^2 \right]^{0.5}$

Where h_m and h_s are measured and simulated results and n is the number of data.

The coefficient of determination, r^2, compares estimated and actual groundwater level -values, and ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the between the modelled and measured values — 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 the groundwater level-value.

The F statistic is used to determine whether the observed relationship between the modelled and simulated groundwater values occurs by chance. F can be compared with critical values in published F-distribution tables or the **FDIST** function in Excel can be used to calculate the probability of a larger F value occurring by chance. The appropriate F distribution has v_1 and v_2 degrees of freedom (DF). The degrees of freedom is used to find F-critical values in a statistical table. Compare the values you find in the table to the F statistic obtained to determine a confidence level for the model. For n = 68, DF = 68 -1 -1 = 66. Then v_1 = 68 – DF – 1 (= 1) and v_2 = DF (= 66). The **FDIST** function — with the syntax **FDIST** (F, v_1, v_2) — will return the probability of a higher F value occurring by chance. Assuming an Alpha value of 0.05, the critical level of F is 6.18×10^{-149}. Since F = 1905980 is much higher than 6.18×10^{-149}, it is extremely unlikely that an F value this high occurred by chance. (With Alpha = 0.05, the hypothesis that there is no relationship between ***modelled*** and ***measured groundwater level*** is to be rejected when F exceeds the critical level, 6.18×10^{-14}

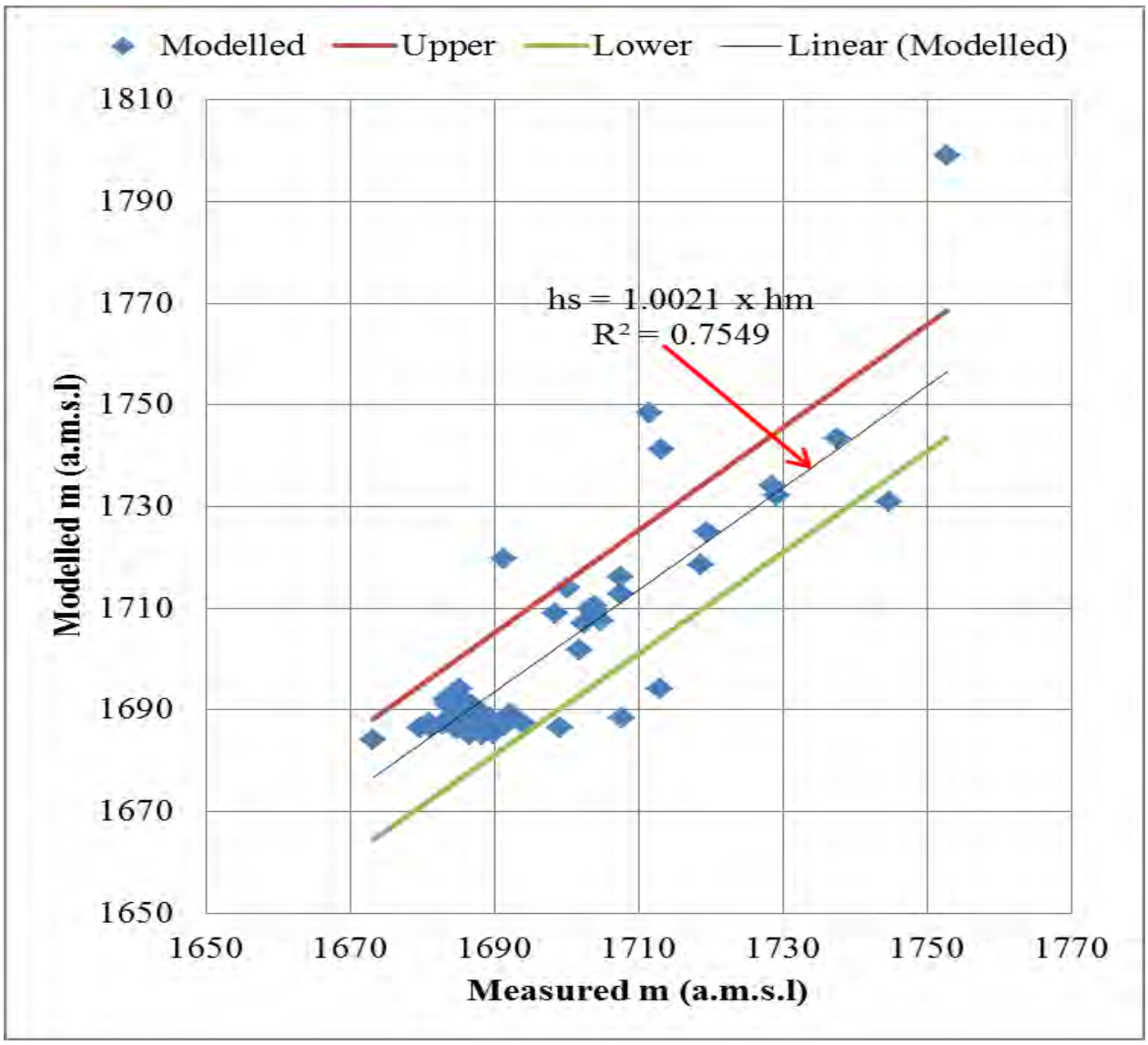


Figure 9 Measured vs. Modelled Groundwater level for inventoried data

For error normally distributed data, RMSE is the best method to measure error. The maximum acceptable value of calibration criterion depends on the magnitude of the change in head over the problem domain (Anderson and Woessner, 1992). Owing to the accuracy of the well inventory data collection method, (A GPS, with +/- 7 m elevation error was used), the topographic map of the basin being created from 90 m by 90 m digital elevation model, the hydrogeological classification with respect to the basin size, the numerical error that would occur due to the inherent approximations and assumptions, the RMSE, ME and MAE are acceptable.

Evaluation of boundary conditions

For the steady-state-simulation, the results approximately reproduce the existing groundwater hydrology. It suggests that the boundaries as defined are appropriate. However, simulated values are generally lower than measured values. This may be due to underestimation of the recharge rate. It might also be possible that the predicted hydraulic parameters are not well approximated.

4.5 Lake Water Groundwater Interaction

After having accepted the hydraulic parameters and recharge over the conceptual model developed, the groundwater lake water interaction was analyzed. This analysis takes the Lake Hawassa water level variation from 1969 till 2013 as input to see how the groundwater table in the basin respond to it. The following figures (Figure 17 – 20) show only the results of the groundwater table map of the basin in 1969, 1976, 1998 and 2013. 1976 and 1998 show the lowest and highest groundwater table observed within the analysis period (1969 – 2013). In these figures the direction of the ground water flow is also depicted (Arrows). The direction of groundwater flow is determined from the hydraulic head gradient computed.

In these figures the blanked white center represents the ground water table having head between 1686 and the corresponding year lake water level. The lake being shown at the center. From these figures the groundwater level is affected more in its western direction than the eastern direction. Thus it can be suggested that lake water level variation affects or affected by any water resources management made on the its western boundaries. From pollution point of view the reverse is true, i.e. any pollution that takes place in the eastern part of the lake will bring about larger pollution at a faster rate to the lake environment. This is because of the higher gradient, there by higher groundwater velocity in this location. Unfortunately this part of the lake (eastern part) is susceptible to pollution due to the vast, economic and social development.

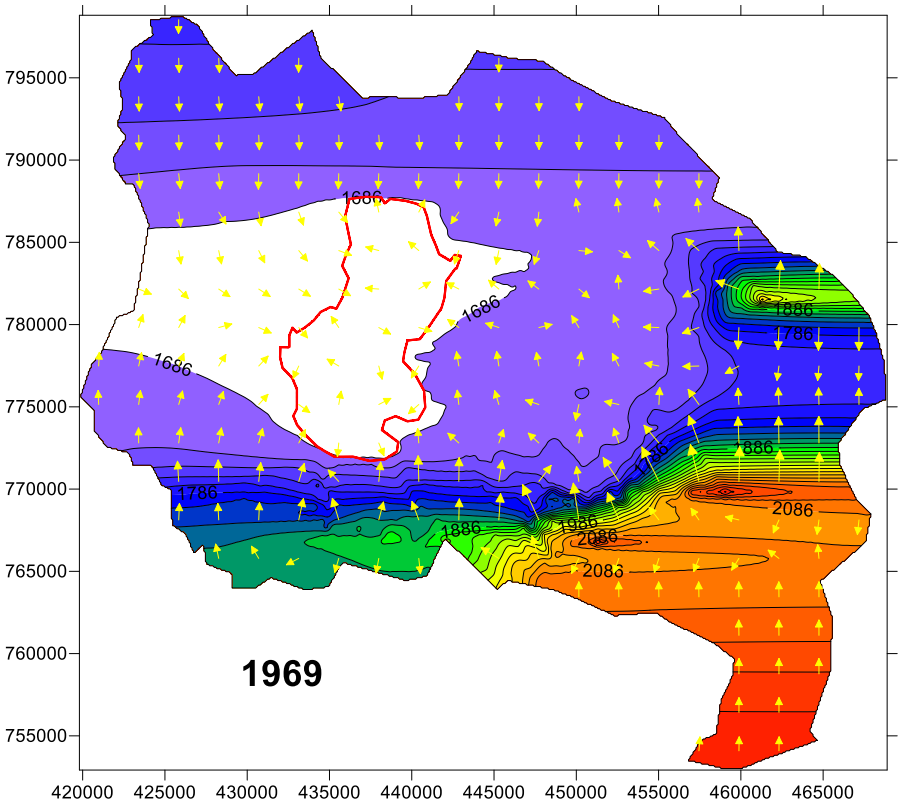


Figure 10 Groundwater level in the basin in 1969

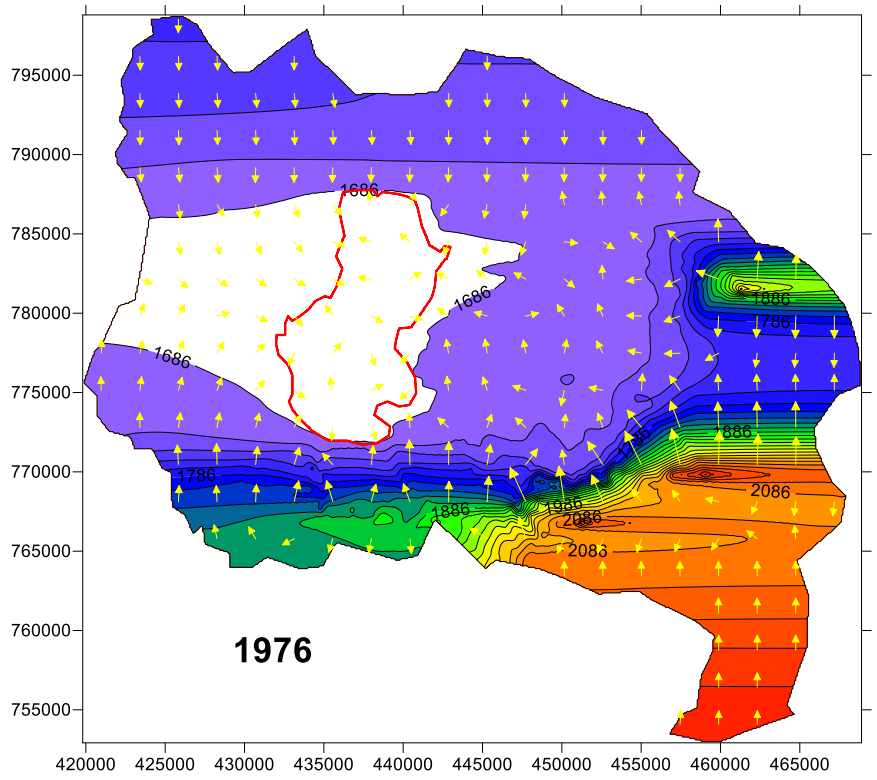


Figure 11 Groundwater level in the basin in 1976

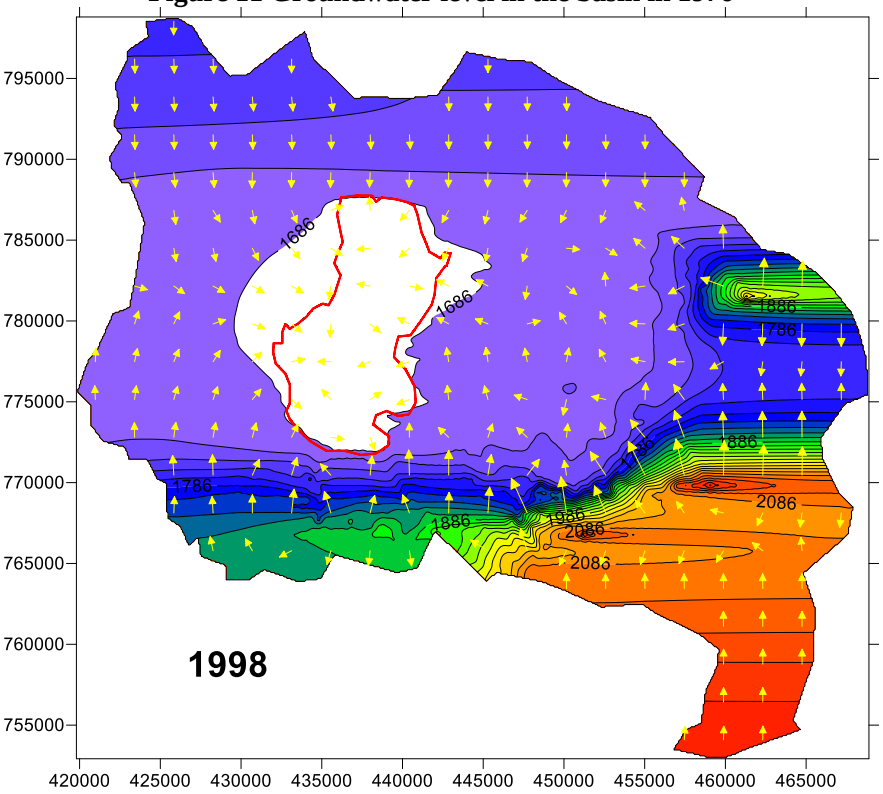


Figure 12 Groundwater level in the basin in 1998

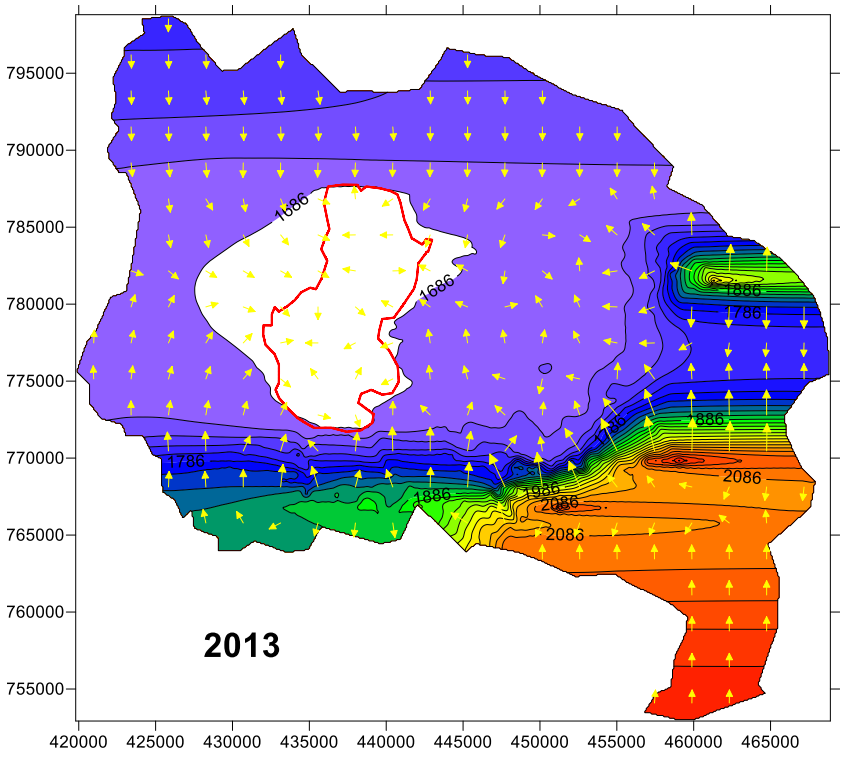


Figure 13 Groundwater level in the basin in 2013

For more insight description of the results the groundwater table level variation along East - West (E-W) and North – South (N-S) directions Figure 21, 22 and 23 are further drawn. These figures show the groundwater level variation along E – W and N – S lines..

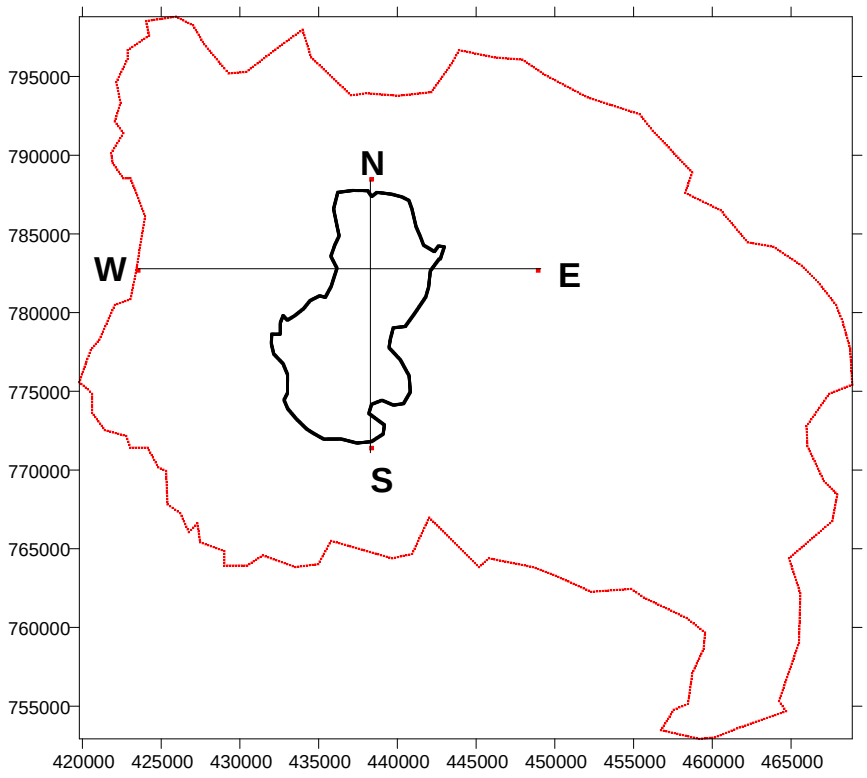


Figure 14 EWE and NS alignment Locations Layout

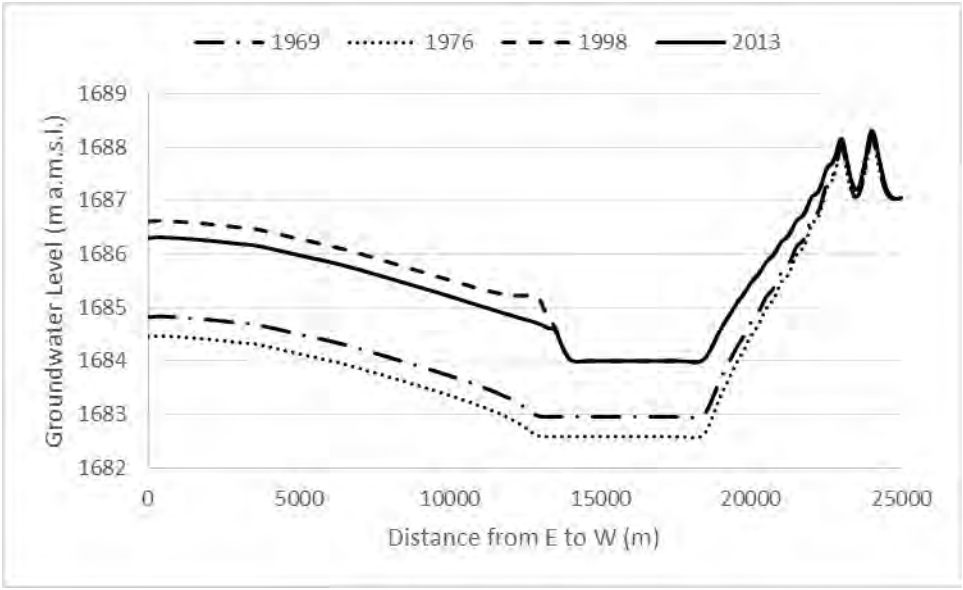


Fig. Groundwater profile along W-E alignment

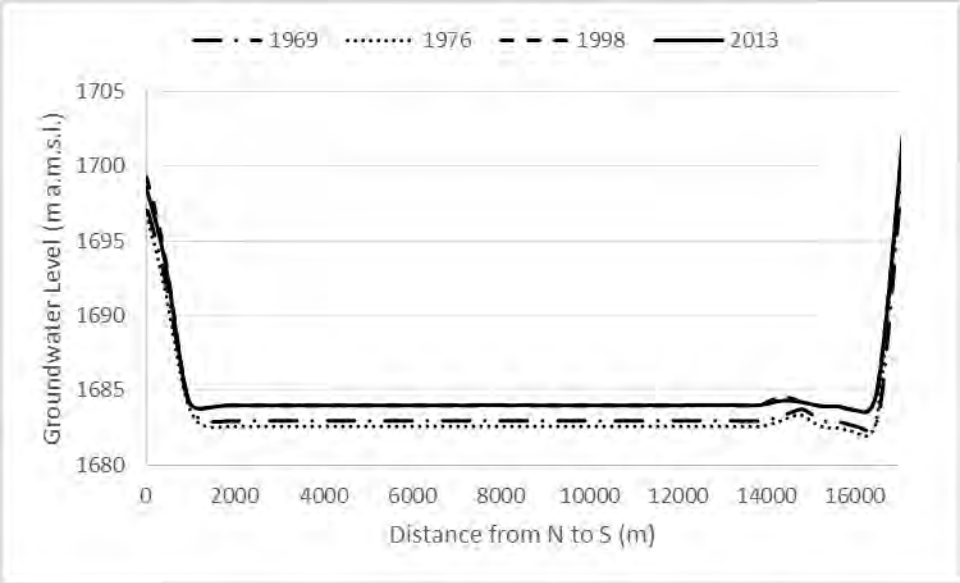


Figure 15 Groundwater profile along N-S alignment

From the above figures the hydraulic gradient in the western part of the lake is flatter than the gradient in other directions. The groundwater level variation, at locations E, and N shown in Figure 21, with respect to the lake water variation can be seen in Figure 24.

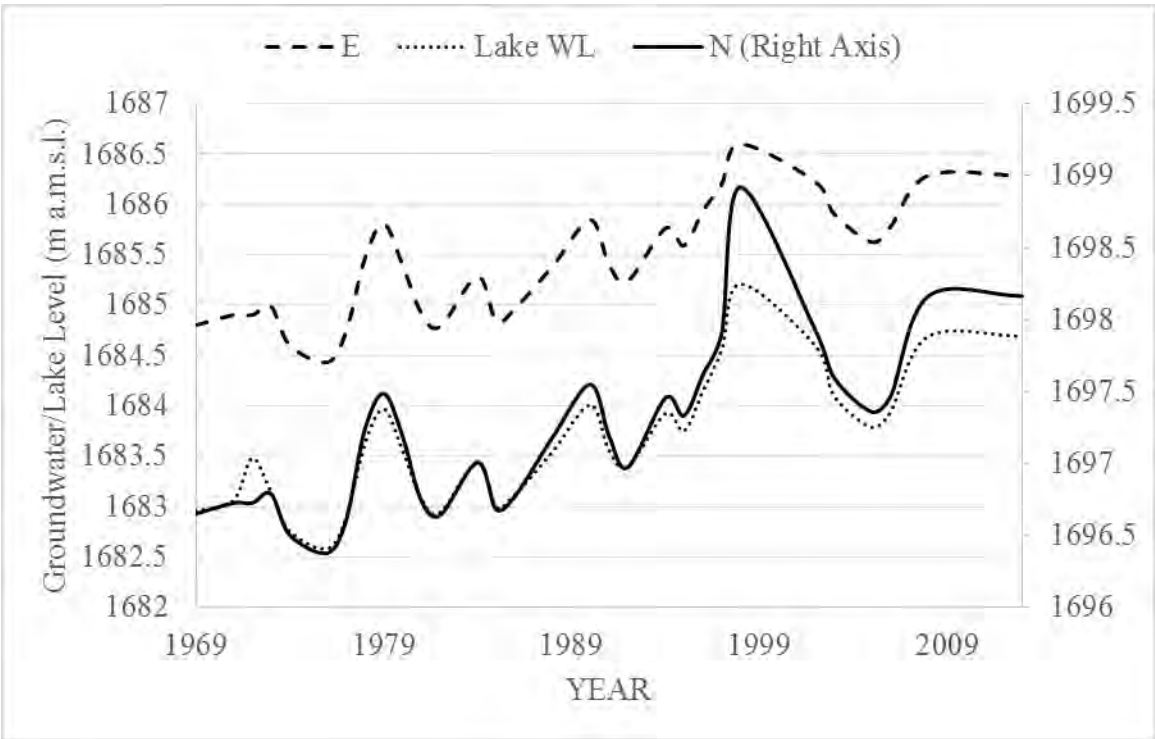


Fig. Groundwater level variation with year

Within the analysis period (1969 – 2013) the region which is not affected by the lake water variation can be seen from the following figures (Figures 23 and 24). These figures are formed by subtracting a base period say 2013, from the groundwater level observed in the years 1976 and 1998. 1976 and 1998 are years in which the lowest and highest lake water level was observed. These figures illustrate the region with no change in the groundwater level (White regions) and regions which does change in groundwater level (Shaded region) from the 2013 groundwater level. The figure illustrating the 1976 could be considered as the region which was not affected by the lake water variation. This might be due to the fact that this region is source of recharges.

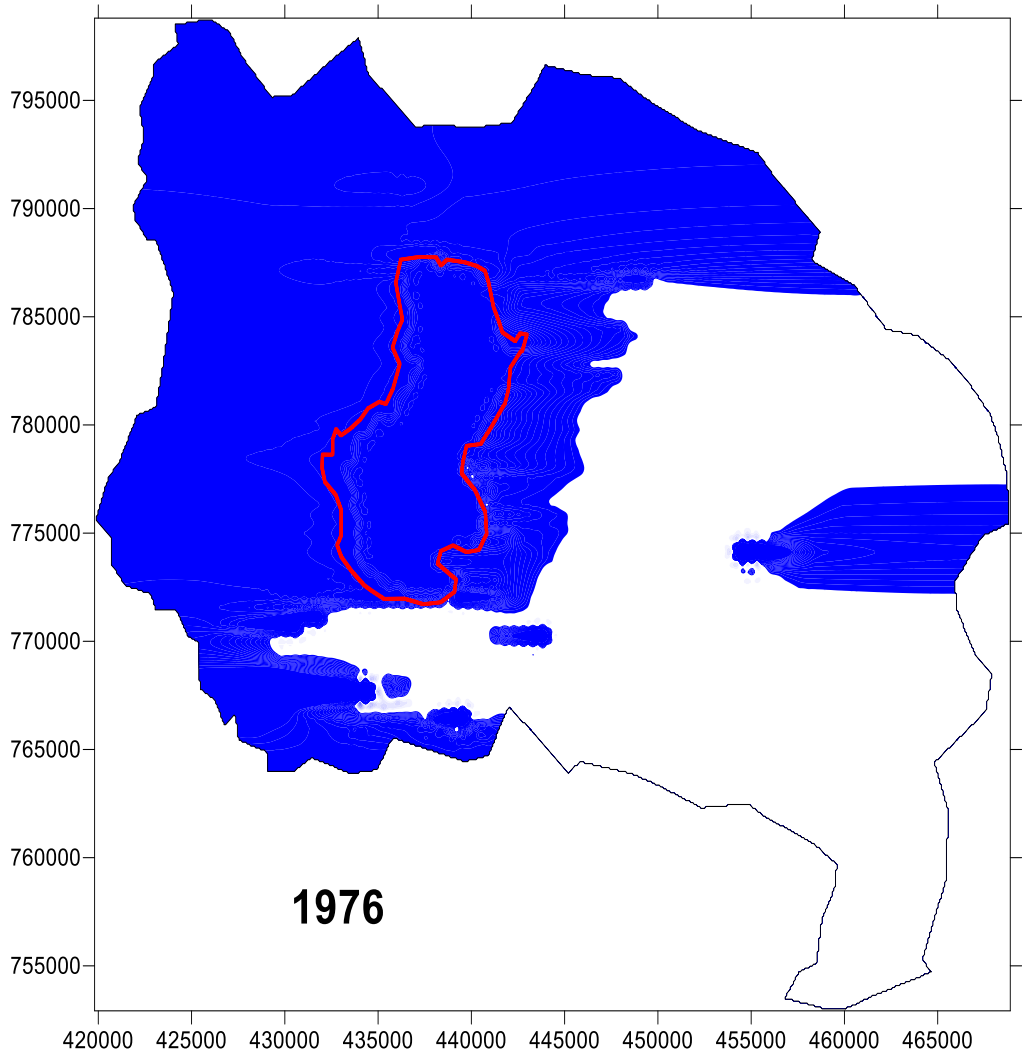


Figure 16 1976 Groundwater level change relative to current (2013) groundwater level

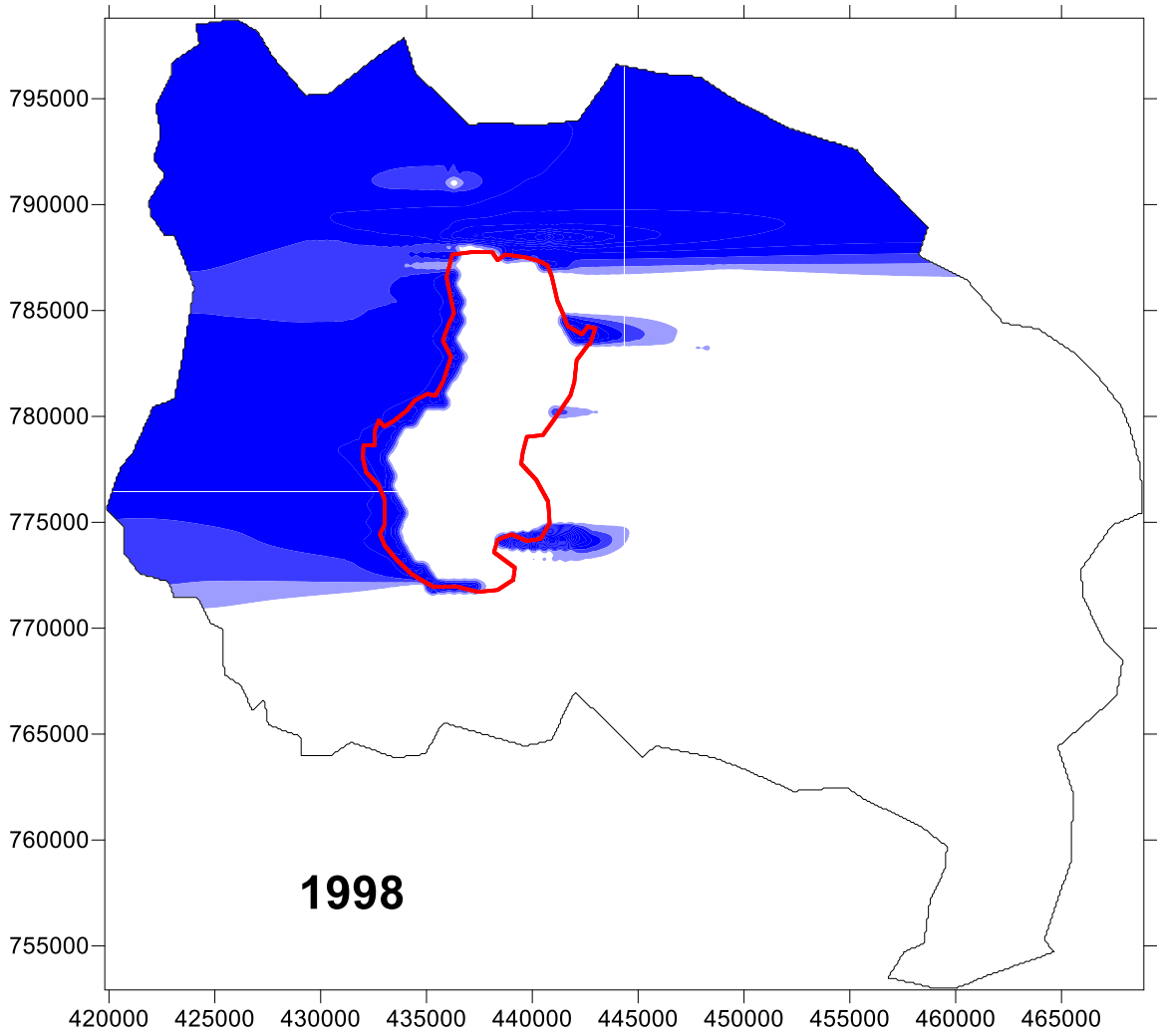


Fig. Ground water level change relative to current (2013) groundwater level

5. Conclusion and Recommendation

5.1. Conclusion

Three-dimensional models have been used extensively for groundwater modelling in Ethiopia and are generally adequate for predicting aquifer head changes. However, the three dimensional model described in this report was developed to identify the major groundwater sources of recharge over the Hawassa Lake basin and to investigate the groundwater-Lake water interaction.

The research effort was concerned with finding concrete and vital concepts for understanding the interaction of the groundwater and Hawassa Lake. To include the possible recharge to the groundwater the study area was expanded to the watershed divide of the lake basin. This study was accomplished by applying finite element numerical groundwater flow modeling software called TAGSAC. The interaction characteristics of these water sources were mainly targeted on the comparison of lake level and simulated groundwater head in response to the lake water variation within the years 1969 – 2013. The modelling effort was first started by defining of the conceptual model. To decrease the uncertainties in the conceptual model, both field data related to wells and springs were collected. These data were used to calibrate the model. With the calibrated model, it is possible to realize the behavior of the aquifer system of the lake basin.

The calibrated finite element numerical flow model of this research was simulated with evidence of groundwater level to fit the observed or measured groundwater levels collected in the lake basin. The model simulated groundwater flow direction is towards the lowest elevation of the basin (Lake Hawassa). The model result has clearly show that the groundwater level is affected more in its western part than other parts of the lake. The lake water level variation has significant effect on the groundwater on its western part than locations in the other directions. This means that larger quantity groundwater abstraction on the western part is required than other parts to bring about the same variation in the lake water level. Thus it can be suggested that lake water level variation

affects or affected by any water resources management made on the its western boundaries.

From pollution point of view the reverse is true, i.e. any pollution that takes place in the eastern part of the lake will bring about pollution at a faster rate to the lake environment. This is because of the higher gradient, there by higher groundwater velocity in this location. Unfortunately this part of the lake (eastern part) is susceptible to pollution due to the vast, economic and social development. The presence of the Hawassa city is a clear threat to the lake water pollution not only from surface water pollution but also from groundwater pollution point of view.

Within the analysis period (1969 – 2013) the region which was not affected by the lake water variation is again located in the eastern part of the lake. This region has shown no or very little change in the groundwater level. No change in groundwater level at a location implies that this location is either receives water from some other location or is itself a source. The location being at higher elevation in the lake basin can be considered as the major recharge source of the basin. The site which includes the highest development (social and industrial) makes the biggest threat to groundwater thereby lake water pollution.

As final say, for any groundwater and/or lake water planning work, the model created should be applied with caution, considering all drawback and limitations related to model input parameters.

5.2 Recommendation

In general the following recommendation listed below should get consideration for those who want to revise the model and for the planner as well as concerned organization. For future and present groundwater and surface water development / management plans in the lake basin care should be taken to make sure that the lake water and the groundwater near by the lake is polluted. When the lake water rises, the groundwater level also rises in similar fashion; however larger variation would encounter in the western part of the lake. The level rising of groundwater can saturate top of the aquifer system which causes for easily contamination of groundwater.

Further investigation on the lake water and/or groundwater could be carried out by considering this research work as their basis.

6. References

1. AG consult consulting hydrologists and Engineer, (AG Consult), 2007: The study pollution of lake and Rivers"
2. Anderson, Mary p., William W. Woessner, 1992: Applied ground water modeling: simulation of flow and advective transport – Academic press, pp. 1-143 & 295-314
3. Dr .B.B.S . Signal, 1999:, Applied hydrogeology of Fracture rock
4. Fetter, C.W., 1994: Applied hydrogeology, Prince hall in New jersey, USA 604 pp
5. Geological survey of Ethiopia(GSE), 2000, Engineering Geological study of Hawassa basin and its surroundings
6. Ghislain de Marsily; translated by Gunilla de Marsily, 1986: Quantitative hydrogeology: groundwater hydrology for engineers hard -- Academic Press, pp. 14-85
7. Jacob bear, 1992: Fundamentals of groundwater modeling, EPA groundwater ISSUE USA Environmental Protection Agency
8. Jacob Bear and Arnold Verruijt, 1987: Modeling groundwater flow and pollution: with computer programs for sample cases -- D. Reidel Pub. Co. -- (Theory and applications of transport in porous media). pp. 27-84 & 247-315
9. Jacob Bear: Hydraulics of groundwater -- McGraw-Hill International Book Co., 1979.-- (McGraw-Hill series in water resources and environmental engineering / Ven Te Chow, Rolf Eliassen, and Ray K. Linsley, consulting editors). pp. 34-189 & 436-462
10. Japan international cooperation Agency KOKUSAIKOGYO, LTD., 2012: Study on groundwater resources assessment in the rift valley lakes basin Ethiopia, Addis Ababa.
11. K.R. Ruston, 2003: Groundwater hydrology conceptual computational modeling, John & Wiley England
12. Karl Heinz Spitz, Joanna Moreno, 1996: A practical guide to groundwater and solute transport modeling. -- John Wiley, pp. 201-270
13. Kersic, Neven, 1997: Hydrogeology and groundwater CRC pres LLC, **USA**

14. Kresic. Neven, 2009: Groundwater resources sustainability, management, and restoration, MC Grawhill.
15. Kuniaki S., Yoshiaki I., 2000: Groundwater hydraulics -- Springer, pp. 15-71 & 115-140
16. Pavel Solin, 2006: Partial differential equations and the finite element method -- Wiley-Interscience, c. -- (Pure and applied mathematics).
17. Peter S. Huyakorn, George F. Pinder, 1983: Computational methods in subsurface flow -- Academic Press.
18. Rainer Helmig, 1997: Multiphase flow and transport processes in the subsurface: a contribution to the modeling of Hydrosystems -- Springer, (Environmental engineering). pp. 23-298
19. T.J. Chung: Finite element analysis in fluid dynamics -- McGraw-Hill International Book Co., c1978.
20. Tadesse D., and Zenaw T., 2003: Hydrogeology and Engineering geology Ethiopia, hydrogeology, Engineering geology and geothermal department, Addis Ababa.
21. Tenalem A. and Robert B., 2007: Comparative study of the hydrology and hydrogeology of selected Etio –Kenyan rift lakes. Addis Ababa dep. of earth Sciences & interactional institute for Geo information science and earth observation.
22. Tenalem A. and Yemane G., 2010: Application of spreadsheet hydro geological model for computing the longtime water balance of lake Hawassa
23. Tenalem Ayenew, , 2007: Hydrodynamics of topographical closed lakes in the Ethio-Kenyan rift, the case of lake Hawassa and Navaho, tonal of special hydrology val,7, No 1,springer
24. Water work design and suppression Enterprise (WWDSE), 2001: The study on lake Hawassa level rise, Addis Ababa.
25. Yemane G., 2004: Assessment of the water balance of Lake Hawassa catchment thesis for the partial fulfillment of the requirement of degree of masters
26. Imai H. and Yanagizawa K. 1990: overview of groundwater flow analysis code: TAGSAC; PNC TN 7410 90-26; in Japanese with English abstract

27. element method and neural networks for the prediction of pore pressure change **Mohammed M.,** Kunio Watanabe and Shinji Takeuchi, 2009, Combined use of finite, JSCE Annual journal of hydraulic engineering, 53, 67-72

Appendix A: Well Inventoried

The following well and spring data was inventoried. Most of these data are collected within three months (from January to march). See Figure 2 for their pictorial representation. The first 68 of the following table was used in the model

		latitude	longitude	swl
I.No.	Description of water body	northings	easting	m
1	**Haile Resort BH mean**	780229	443750	11.20
2	**Gera Requta well # 1**	771791	449214	5.63
3	**Gera Requta well # 4**	770917	449926	2.87
4	**Gera Requta well # 5**	771948	447977	10.69
5	**Gera Requta well # 6**	772643	448528	4.46
6	**Yose kulalisa # 1**	771217	447760	6.60
7	**Yose kulalisa # 2**	770948	448400	8.53
8	**Yose kulalisa # 3**	771901	448470	6.50
9	**abela wondo # 3**	769845	447560	37.90
10	**Gemeto (mite #1 2006/1999)**	770648	445603	5.55
11	**Gemeto (mite#2 2006/1999)**	770494	445304	5.50
12	**Gemeto (around Spring 1992**	771289	444637	5.13
13	**Gemeto (around tr.plt 1992**	768778	447461	56.30
14	**Gemeto (awasa 7-9 km 1994**	770924	446395	2.80
15	Gemeto (around tr.plt 1994	770254	447119	6.20

16	**Abela wondo 2006**	770333	446375	28.00
17	**boku**	771188	442184	65.00
18	**Gemeto gale/boshma #1/**	771380	443880	20.10
19	**debuniv main camp"96 #1/moenco**	780192	443980	22.35
20	**debuniv hospital"96 #2**	776754	440728	12.45
21	**debuniv main camp"96 #3**	779070	444240	26.64
22	**HawUniversity 2001 #2**	779461	444133	22.60
23	**debub univ m. camp Midrok**	779285	444865	25.30
24	**debub univ maingat#1/dormi.white hous**	779439	444885	25.39
25	**debub univ maindato#2/biglibrary**	779812	444352	27.50
26	**debub univ maindato#3/tech**	778872	444778	30.17
27	**debub univ maindato#4/staff launge**	779294	444526	24.80
28	**debub univ maindato#5/pasturization**	779258	445205	28.60
29	**well next to main gate oldbhgri research**	779732	444088	17.72
30	**HU Condominium silasie staff Res.**	781225	443285	16.40
31	**agri college new bh**	778962	441792	7.60
32	**Management institute, Civil Service**	778699	442721	28.00
33	**referal#2**	776348	441096	13.54
34	**South Road Authority**	780228	443743	22.30
35	**Hawassa Flour Factory**	782563	443455	13.72
36	**Moha Soft Drinks**	776926	444756	45.47
37	**Agrostone**	777593	445387	46.13
38	**Diary farm**	775839	442341	52.12

39	**Dashen Piaza AB**	779207	441692	12.02
40	**Enuma PLC**	779270	442888	25.60
41	**Police Garage**	780703	442971	18.50
42	**Abebe Wondimu**	778609	441936	20.20
43	**Zewde**	778881	440372	5.61
44	**zenabu abera**	778688	443288	27.72
45	**tsehaye**	**780233**	**443745**	**22.00**
46	**Zewdu**	**778694**	**443296**	**7.00**
47	**atnet**	778735	442382	26.70
48	**shell**	778737	444167	29.66
49	**debub teachers**	777249	444224	56.72
50	**paramedical**	782569	443006	15.00
51	**greenwood**	782844	443279	7.50
52	**Loke Spring**	**771938**	**436900**	**surface**
53	**Gemeto Spring/boswhima/**	**770825**	**444657**	**surface**
54	**swwce residence**	779105	441044	15.00
55	**Ambowuha**	**775226**	**453120**	**surface**
56	**Ato Wolde House**	**779191**	**441210**	**6.00**
57	**Wro. Almaz house**	**779202**	**441264**	**6.20**
58	**Ato Haile House**	**778986**	**441415**	**8.65**
59	**Korem**	**779418**	**443558**	**23.00**
60	**korem foot ball field**	**779645**	**443590**	**20.00**
61	**korem**	**779558**	**443431**	**23.00**
62	**Ato tsegye house**	**779476**	**443706**	

				22.00
63	**Mobil garage**	**780669**	**442744**	**14.4**
64	**Mobilarea**	**780839**	**444260**	**15.00**
65	**Soressa house**	**778350**	**440623**	**7.80**
66	**Mulunesh Arsado**	**770829**	**440550**	**6.80**
67	**Zemach house**	**778351**	**440487**	**7.00**
68	**Sedeka#6jawaro**	756099	439302	29.00
69	**Bahil adarah**	**779538**	**442299**	**24.00**
70	**Sedeka#5**	755899	438790	15.00
71	**Teremesa#3**	758827	439686	13.10
72	**dikticha#2**	762871	432077	45.00
73	**sheb-dikitcha #1**	762315	432044	42.00
74	**Wujigra**	766560	451697	39.14
75	**wondokosha '93 well#3**	790449	436393	40.60
76	**wondokosha '93 well#4**	790184	434965	46.33
77	**teramesa#8 bark**	758658	438753	7.10
78	**teramesa#9 school**	758116	440163	17.00
79	**Sedeka#7 dekera**	756524	439333	17.00
80	**teramesa#10 awadana**	756085	440752	8.00
81	**telamo #11 blade village**	754828	441999	16.00
82	**dulecha teberako**	767645	437317	119.00
83	**konsoro arke#1**	762584	429569	94.70