

# **Numerical Groundwater Flow Modeling of the Lake Tana Basin, Upper Nile, Ethiopia**

**A thesis submitted to the school of graduate studies  
Addis Ababa University**



**In partial fulfillment of the requirement for the degree of  
Master of Science in Hydrogeology**

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February, 2010**

# **Addis Ababa University**

## **School of Graduate Studies**

### **Numerical Groundwater Flow Modeling of Lake Tana Basin Upper Nile, Ethiopia**

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## **DECLARATION**

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in any other university and that all source of material used for the thesis have been duly acknowledged

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university advisor.

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## ABSTRACT

The Lake Tana basin embraces surface area of some 15,151km<sup>2</sup> with a prominent hydrological feature of Lake Tana that covers 3042 Sq km about 20% of the basin. The basin also embarks a number of small streams feeding the lake, Gilgel-Abay, Rib, Gumera and Megech Rivers.

Lake Tana Basin is modeled with a help numerical ground water flow Modflow 2000 to simulate hydraulic head distribution of the aquifer system. It is conceptualized with single unconfined homogeneous aquifer with the water budget of 1,756,791,794.90 M<sup>3</sup>/Y contributed from the precipitation with recharge rate ranges 0.00000520 M/D to 0.00083730 M/D.

The major hydrological feature perennial stream, Lake and ground water withdrawal considered as river, GHB and Well boundary respectively. The hydraulic parameter and recharge is spatially distributed with the available data base.

The model is calibrated with more of matching of simulated and estimated hydraulic head contour of 147 well located in and out of the region under study. And residual of not greater than 0r less than 20m of 37 well constructed 2003 after wards. The model is calibrated with absolute residual mean of 13.42 M and residual standard deviation of 12.5M.

The simulated water budget is surplus the estimated one, 1,756,791,794.90 M<sup>3</sup>/Y, by 52,212,238.60 M<sup>3</sup>/D with 2.9% deviation not too far to approximate the field situation.

The base flow discharge of simulated model is 1,563,6171,42.54 which holds 86.43% of the out flow and the major rivers recharge the aquifer with 7, 043, 7495.6 M<sup>3</sup>/Y 3.89% of the simulated inflow. The river and aquifer interaction implies huge amount discharge of ground water to the dominantly gaining streams. The hydraulic profile simulation head, under steady state, has resulted ground water flow toward major stream and finally to converge to the Lake Tana.

The lake Tana is conceptualized GHB with a simulated 243,086,633.77 M<sup>3</sup> discharge of Ground Water Lake almost 2.78% of the inflow of lake as SMEC 2007 water balance. It is a consistent result preliminary isotope studies suggested less than 7% of the total inflow is ground water (Kebede et. Al 2005).

The model is found to be with relatively more sensitive to the hydraulic conductivity than recharge. The model is simulated for increasing of pumping of ground water with 25%, 50%, 100%, 300%, 500%,700% 100%, 1200% and 1500%.The model response has been recognized for the average water level , ground water discharge to the river and GHB.

The average water level of the system shows a drawdown starting from 0.08m with 25% increment of pumping to 7.26m with 1500% increment of ground water withdrawal.

The aquifer system, with a desiccated lake, responses with a relative rise of water level by 18.17m and increase of the ground water discharge to river by 11.93 %.

# CHAPTER ONE

## 1. INTRODUCTION

### 1.1 BACKGROUND

The Lake Tana Basin is part of the upper Blue Nile Basin with presently one of the fastest growing population centers with tremendous water resource in Amhara Regional State. It is one of the high ground water prospects of young volcanic aquifer and alluvial deposit. It is considered as prospect development corner of the region. As it is a part of major Blue Nile basin of the country, there are a lot of works carried out over the region. Despite the work done so far like the most part of the country it is believed that the resource understood and managed poorly.

The Tana basin encompasses an area of some 15,151km<sup>2</sup> with a prominent hydrological feature that Lake Tana that covers 3042 Sq km surface area about 20% of the basin. It also includes a number of small stream more than 40 rivers feeding the lake, Gilgel-Abay, Rib, Gumera and Megech contribute more than 93% of the inflow of Lake Tana. (Kebede, 2008)

The government of Ethiopia launched the Tana-Beles integrated water resource development program (TBIWRDP) to promote sustainable water resource development and the management in the Lake Tana and Beles sub-basin. In fact there is a tremendous amount of surface water resource and tendency of work to deal more on the surface of water the area. However groundwater still plays significant role in the region and presently shoulder almost all town and village water supply of the sub basin. The integral approach considers both surface and sub surface water as the major resource of the region. It is reported that more than 270 boreholes are drilled over the region as community water supply source and number of hand-dug wells operate for water supply (SMEC 2007).

The research take the advantage of the works carried out before and understand the real problem of management of the ground water resource of the area. The understanding of the aquifer system in the basin is based on the previous work over the area, literatures on volcanic aquifer and field visit.

Now a days, Modeling becomes more than scientific interest rather as manual to for a wise management of ground water resource. Typically, the numeric modeling, used in the

paper, has advantageous on understanding the entire flow system of the aquifer and customize with interest of user. Modeling is an excellent way to help organize and synthesize field data having the recognition as one component of hydrological assessment and not an end in it self.

The future water management will be more reliance on calibrated mathematical simulation model at the basin scale that more rigorously account for the inherent variability in the material properties recharge rates, and ground water with drawls.

The research will maximize the out puts that have been done before in a very quantitative way and will expect to describe the ground water flow system of the region. It also facilitate water management plan over the region and helps as input for any possible after flow geochemical modeling over the basin.

## **1.2 OBJECTIVE**

The major objective of the research is to describe the ground water flow system of Lake Tana sub basin with a help of numerical flow modeling. In association with the major objective the paper will expect to full fill the following specific objective:

- To identify the possible boundary condition of the sub basin and develop a simplified conceptual model which approximates the physical field condition of the system.
- To organize and synthesize the available information and previous work
- To develop steady state numerical ground water flows modeling of the sub basin upon which post-processing modeling could be possible.
- To evaluate the input and out put of water for the identified boundary condition including the lake Tana
- To provide a steady state calibrated water level, hydraulic parameter and recharge of the hydrogeological system of the area
- To conduct sensitivity analysis of the aquifer system and identify the most influential parameter that direct future emphasis of study for the ground water management.
- To evaluate the response of the aquifer system for a possible scenario of ground water consumption
- To evaluate the water budget of the sub basin through which also to determine input and out put of major catchments

## **1.3 APPROACH AND METHODOLOGY**

The approach to achieve the objective of the research will involve the following sharpen conventional methods with tuning of the basic interest of the paper.

### **1.3.1. DATA COLLECTION**

This part of the work will include both desk and field investigation for the gathering of important data in order to achieve paper objective. It comprises the methods employed to achieve the theme.

The deskwork will carry out the essential literature review on modeling books, previous work, and water well inventory and well completion reports. It also include collection of topographic map, Geologic map, Hydrogeological map, Digital model (**DEM**), Meteorological data, hydrological data and make ready computer code that help for modeling like **Modflow**, Arc GIS (View), Surfer 8, Global Mapper 8, Aquatest, Aquachem and so on.

The field investigation made the measuring width of river and water level, observation of hydrogeological features, the confirmation of the secondary data collected at the deskwork and visit detail investigation for specific sites for confidential conceptual model. The data source was Ministry of water resource, Ethiopian Mapping agency, National Meteorological agency, Geological Survey of Ethiopia, Amhara Regional State Water Resource Development Bureau and water works construction Enterprise.

### **1.3.2 DATA ANALYSIS AND SYNTHESIS**

It involves the analysis and synthesis of the available data with a help of the numerical mathematical code of **MODFLOW** interfaced by **Ground water vista 3** software that consider the physical condition of the study area can be represented with governing equation. This part of the work embarks the modeling protocol like conceptual model development, selection of appropriate computer code, defining model geometry and boundary, assigning the hydrogeological parameter, running the model and calibration.

### **1.3.3 INTERPRETATION AND RESULT**

It is the core conducted assignment of the research to discuss on the result, screen the fact from data analysis and simulate the flow system of the aquifer. This part of the research will also comprise the conclusion and recommendation. The above listed procedure can

be summarized with the flow chart of Marry P. Anderson and William W. Woessner, 1992 shown on Fig 1.1 below.

In general, the paper approaches the problem of understanding the flow system of the Lake Tana basin with the very deterministic and Numerical model which approximation of physical law with finite difference. It is a method developed by United State Geological Survey (**McDonald and Harbaugh, 1988; McDonald and Harbaugh, 1996**). **MODFLOW** (A modular three dimensional finite difference ground water flow models). It is interfaced with **Ground Water Vista 3** for a relative facilitation of data input and out put system however data process with principle of **MODFLOW 2000**.

The paper used the power of the GIS for all spatial data and conceptual models that has been done in the research. It has developed grid independent model that can be easily modified and updated with out the disturbance of the model grid designs.

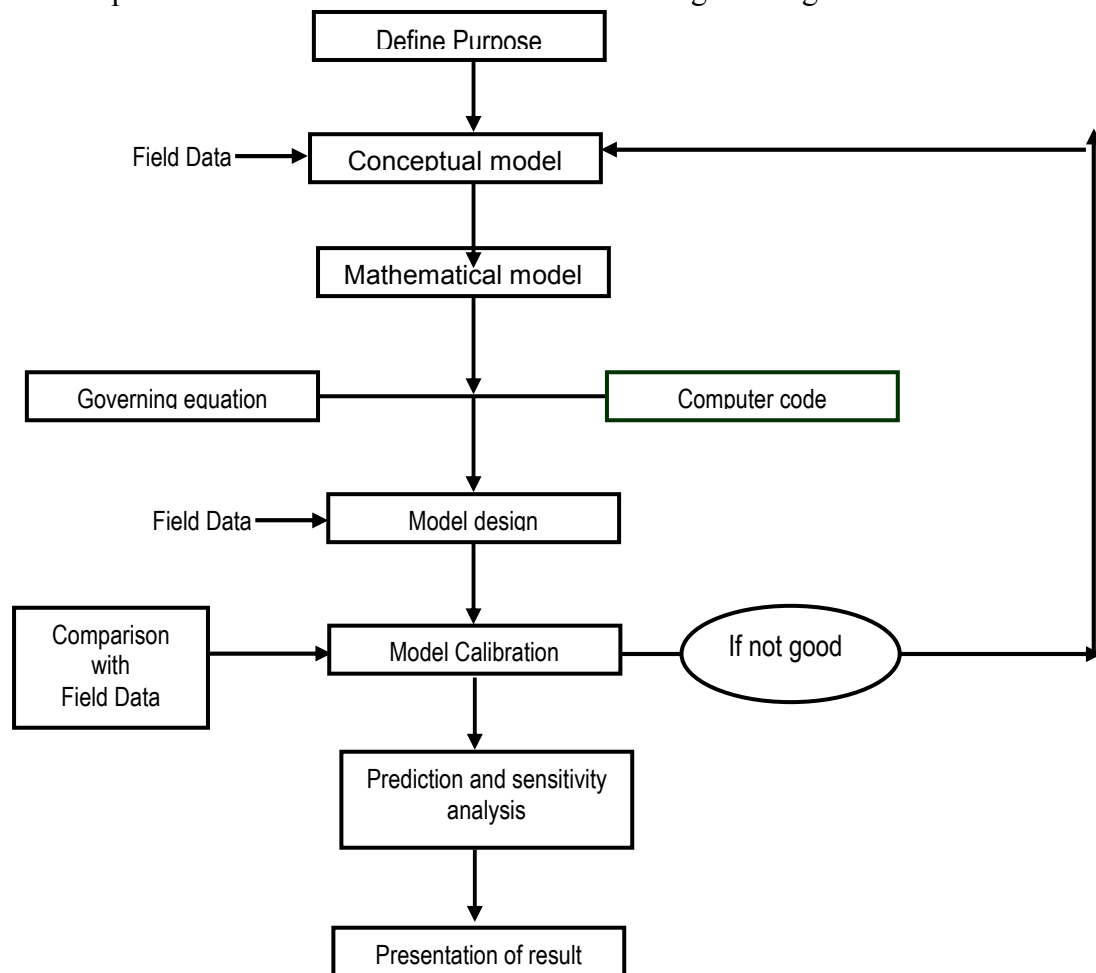


Fig 1.1. The flow chart of model protocol to be followed (Marry P. Anderson and William W. Woessner, 1992)

## **1.4. SCOPE OF THE RESEARCH**

The scope of the research will include the numerical ground water flow modeling of the Lake Tana Basin according to the boundary condition set as a result of the detail study. It used the field data and verified previous work as the input. The model used a single set of data and configured to provide a steady state ground water flow and calibrated model. It doesn't include verification of the model and localized simulation.

## **1.5. EXPECTED OUT PUT**

The research is expected to describe ground water flow system of the basin so that it will increase the knowledge on the understanding the flow system. It is also supposed to have the following out put.

- Water balance will be quantified with boundary of area of anyone interest
- The Calibrated hydraulic parameter Map will be displayed
- The available data will be synthesized will be presented in manageable way
- The sensitive hydraulic parameter will be identified for future investigation
- The flow simulation will be ready for further development scenario and contaminant plume transport
- Simulated Head distribution will be Known
- Input and out put of water for each boundary condition including Lake Tana will be quantified.

## **1.6. THESIS LAYOUT**

The paper is produced with eight chapters with a theme to describe ground water flow of the Lake Basin and associated ground water boundary interaction. The first chapter introduces the back and justification of ground water of the study. It comprises the objective and the methodology to achieve the objective is explained with scope of the work.

Chapter two is also inclined to introduce the basin Topographical and hydrological setting. In this chapter, the geographical location, climate, soil, land use and land cover have been briefed. The chapter comprises the spatial precipitation analysis with Thiessen polygon to be used as an input for recharge in the later chapters. The discharge and average level major hydrological features has been summarized.

In Chapter three, the geological and structural setting of the basin is explained. The chapter explains the major geological events that are responsible for the formation of the basin. It describes the stratigraphy of the regional geology and tries to associate with local geology of quaternary vesicular basalt, Tarmaber scoraceous basalt and recent alluvial sediments.

Chapter four is the core part of the paper that simplifies the field condition with conceptual model. In this chapter, all hydrological features represented according to their role in the aquifer system with the justification behind all the approximation. The chapter explains the hydrogeological condition of the basin with conceptual model considered in the model. It also summarizes an estimated hydraulic conductivity, recharge, boundary and water budget of the Lake Tana basin. The possible water balance component is covered with quantification. It is in this chapter the base flow of major stream summarized and quantified for basin.

In Chapter five, the mathematical model is explained with the help of governing equation and mathematical representation of boundary condition.

Chapter Six explains the calibration techniques employed, the criteria set and evaluation of the calibration. The model sensitivity for parameter of hydraulic conductivity and recharge is also explained in this chapter.

Chapter seven comprise the theme of the paper which shows the result of the modeling effort with analysis of the previous knowledge over the area. It include the simulated head and water budget of the of the Lake Tana basin. The out put expected on the paper is stated with some analysis. This chapter is also including scenario analysis with the response of the aquifer system to the abstraction of water and Influence desiccation of the Lake in the aquifer stem. The model limitation is evaluated and listed on the chapter.

In chapter eight, the paper summarized the result explained in chapter seven. It is last chapter with conclusion and recommendation with modeler view over the result and recommended future direction for study and work.

## 1.7. PREVIOUS INVESTIGATION

The Lake Tana basin has been the interest of many researcher and organization, thus a number of essential works carried out over the hydrology, hydrogeology, climate, and land use of the basin. The prominent work listed below will be reviewed for the benefit of the research. There is no flow modeling work of the aquifer system encountered yet.

- The hydrogeological map of Ethiopia 1:2,000,000 compiled by Tesfaye Chernet. (1988). It is a regional scale, classification of aquifer, standardizing the productivity of the aquifer and broad scale potential assessment. The lake Tana basin is considered as moderately productive basalt and alluvial aquifer
- Geological Map of Ethiopia 1:2, 000, 000 2<sup>nd</sup> editions (1996). It is very regional scale map showing the out line of major geologic unit. It comprises a basement of Precambrian bedrock, overlain by Mesozoic sediment, Tertiary volcanic, minor sediment, quaternary volcanic and recent alluvial sediments.
- Regional hydrogeological investigation of Northern Ethiopia, 1:100,000, hydrogeological map, compiled by Bayissa Asfaw, (2003). The report include an inventory of drilling wells, hand dug well, and springs in the study area with inclusion of Lake Tana basin. The paper recommends the quaternary basalt south of the Bahir dar to have high productivity and potential for the development thus a ea around the margin of lake Tana as potential for the future development.
- Abay Basin Master Plan. Phase 2, Sectoral studies, part3 hydrogeology (February 1998) and Annex volume, (February 2000). It include description of geology and aquifer
- Ground water resource in Lake Tana sub basin and adjacent area Rapid assessment and Terms of reference for further study” 2007 (WWCDSE). It provide the overview of the hydrogeology of lake Tana basin
- Water Balance of Lake Tana and its sensitivity to fluctuation in rainfall, Blue Nile Basin, Ethiopia (Kebede et al 2000). It is part of lake water balance investigation. It was suggested that the likely ground water flow direction is from surrounding area towards the Lake, although the ground water considered to be only a minor component of the water balance. Preliminary isotope studies suggested less than 7% of the total inflow is ground water

- Ground water recharge, circulation and geochemical evolution in the region of the Blue Nile, Ethiopia (Kebede et. Al 2005). It uses isotope and geochemical, mainly for spring and hand dug well to identify that recharging ground water migrates through short local ground water flow path to discharge as low TDS (Ca-Mg-HCO<sub>3</sub>) dominated ground water. Deeper, more regional flow systems have greater residence time in the aquifer and undergo geochemical alteration to generate higher TDS (Na-H-CO<sub>3</sub>) dominated waters.
- The Tana basin, Ethiopia. Intra-plateau uplift, rifting and subsidence. (Chorowicz et al 1998). The paper uses application of remote sensing to describe the major structural feature of the lake basin
- The structure of Mesozoic basin beneath the Lake Tana, Ethiopia, revealed by magneto telluric imaging, Hault et .al (2005)
- Remote sensing based assessment of water resource potential for lake Tana basin. Yohannes Daniel (2007)
- Hydrological and hydrogeological investigation of Tana beles sub basins, SMEC international Pty ltd. It comprise a summary of the existing hydrogeological conditions, input to water balance for lake Tana, ground water availability assessment report for the lake Tana basin and well information over the region. The study also provides hydrometric station distribution, Years hydrological and metrological data of the basin.
- Wells and Springs reference in Geological Survey of Ethiopia hydrogeology report (2003)
- Amhara regional state water resource development bureau water scheme inventory and completion report data based at Water works construction Enterprise (AWWCE)
- Miscellaneous Consultant reports (A number of water supply investigation have provided data on ground water resource for specific town (Debretabor, Dangila, Bahirdar and Woreta).

## CHAPTER TWO

### 2. GENERAL OVERVIEW OF THE AREA

#### 2.1 LOCATION

The study basin is situated in north southern part of Ethiopia about 500km from the capital city of the country, Addis Ababa and centered at **Bahir dar** where the largest lake of the country, **Lake Tana**, found. The study area is bounded with UTM Geographic coordinate of 1210493 to 141579 N and 253085 to 417083 E. It lays over Siemen Gonder, Dehub Gonder, Mierab Gojam and Agew Awi administrative zone of Amhara regional State and covers approximately 15152 sq km surface area.

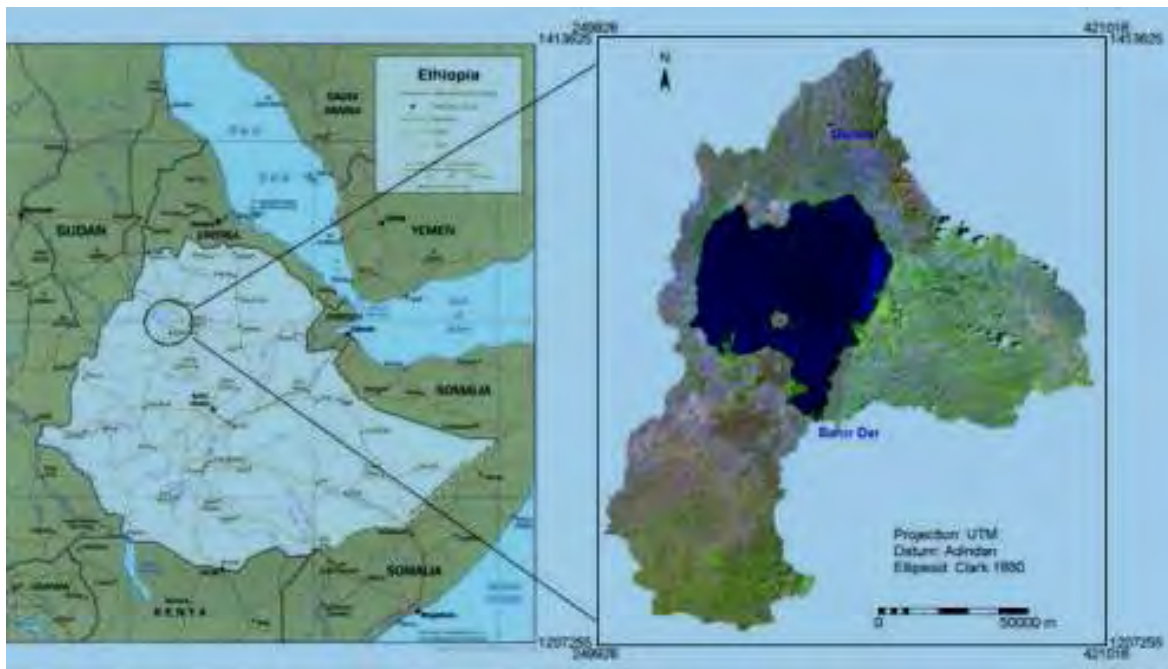


Fig 2.1. Location map of Lake Tana Basin

#### 2.2. TOPOGRAPHY

The lake Tana Basin is part of the western high land of the country and it is an elevated volcanic plateau of with an average 2900mts above m.s.l. The Eastern part of the basin is dominated by the presence of two shield volcanoes, Mt choke and Mt. Guna while the west characterized sharp drop of elevation toward the adjacent Beles and Dinder basin. The elevation ranges from **4000m** near Mt Guna to **1794 m** on the western shore of the lake and the center of the basin is identified with the largest Lake of the country, Lake

Tana, which shares about 20% of the basin and toward which all drainage system converge.

The catchment's characterized by rugged topography and relatively elevated terrain at the tip top part of Gilgel Abay, Megech and Rib. It is topographically closed volcanic ridge with a very small valley opening that let the out flow of Abay in the east part of the basin, near, Bahir Dar. There is also typical plain land near surround the lake, specifically, the Fogera plain and others

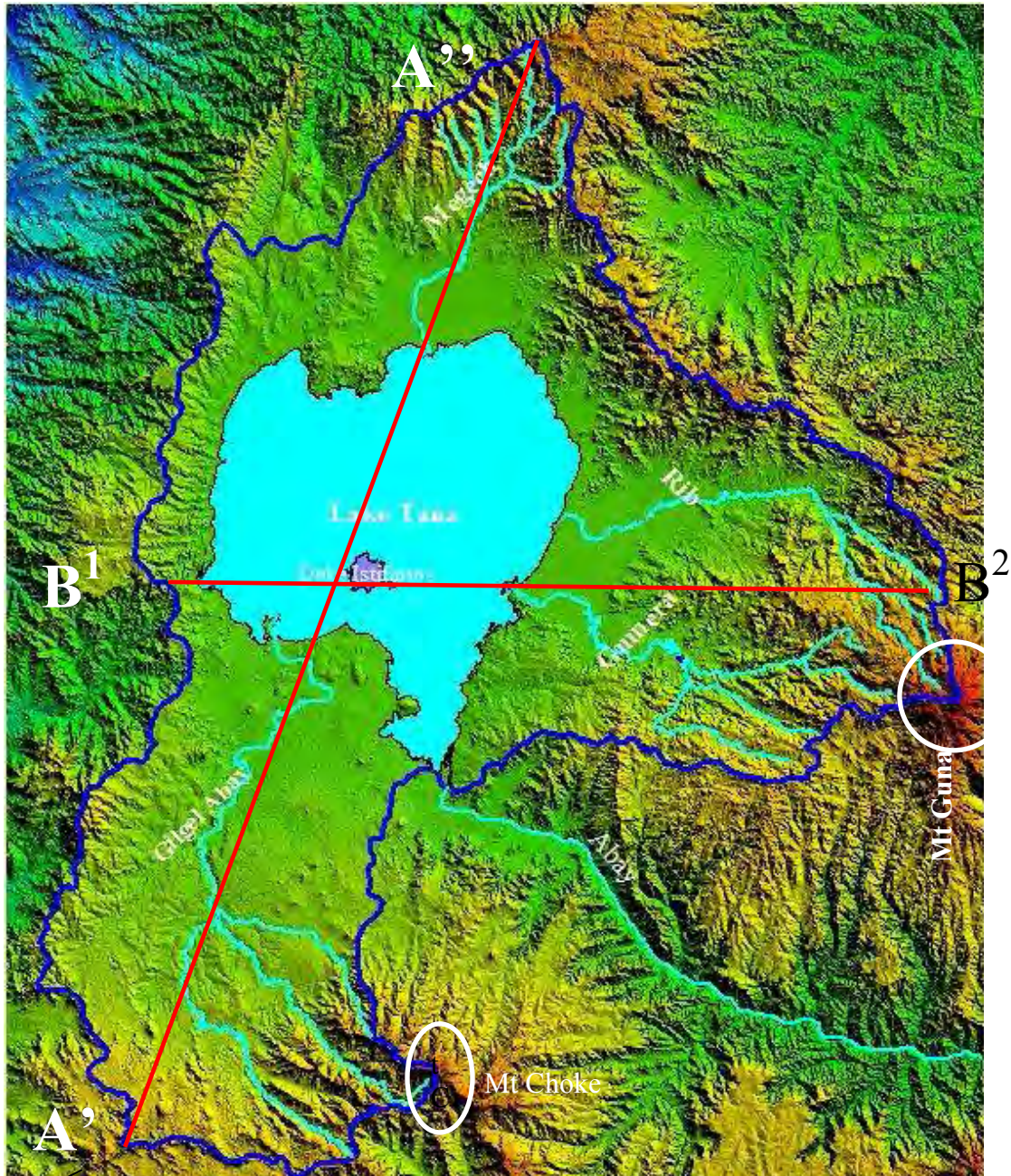


Fig 2.2 Landscape of the Lake Tana Basin with prominent topographical features

From Pos: 272529.680, 1217500.669 To Pos: 333548.246, 1405190.687

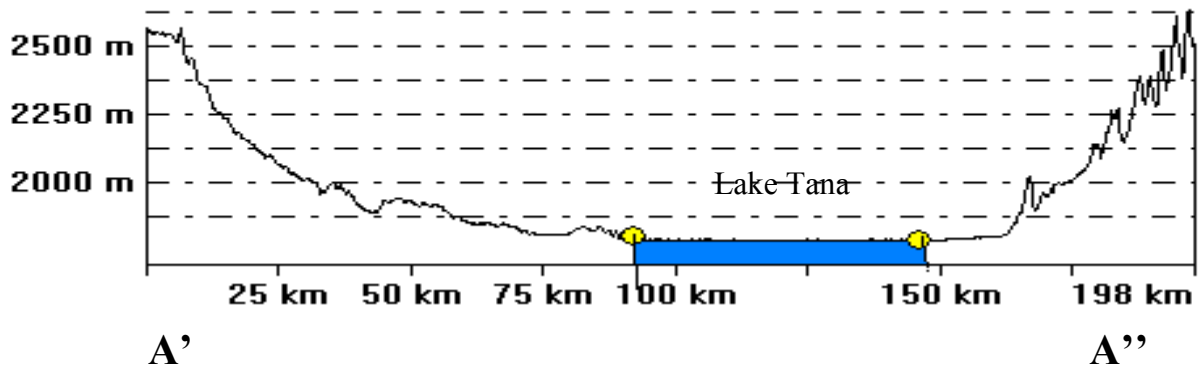


Fig. 2.3. The Topographical section of Lake Tana Basin West\_ East (A'\_A'')

From Pos: 270984.907, 1319455.741 To Pos: 413619.022, 1320485.590

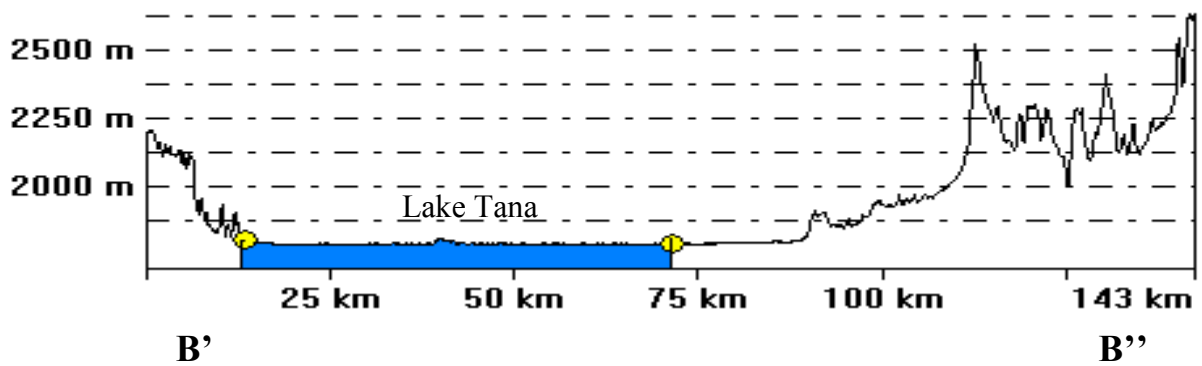


Fig. 2.4. The Topographical section of Lake Tana Basin South\_ North (B'\_B'')

### 2.3. CLIMATE

The climate of the basin ranges from cool temperate to temperate but in some peripheral part of the basin, there is particular cool area. The climate condition of the basin is highly controlled with elevation of the area which ranges b/n 1794m to 4000m. According to the climate classification of the country, it is identified with Dega and Weyna Dega and becomes Kur as the elevation rise up to 4000m.

The basin characterized by Unimodal rainfall pattern with peak rainfall season starts at mid May and end at mid September (Fig 2.4.). The monthly rain fall strike the peak at July in almost all meteorological station, with 533mm/month registered in Bahir Dar. The mean rainfall ranges from mean minimum 872mm/year registered at Delgi station to mean maximum 1805mm/year at Sekel and Aykel Station.

The mean annual rain fall of basin is 1374.60 mm/year as estimated spatial analysis of Thiessen polygon analysis method. The prominent topographic feature, Lake Tana, has annual mean rainfall nearly 70mm/yr less than the basin which is estimated same method employment 1302.79mm/year.

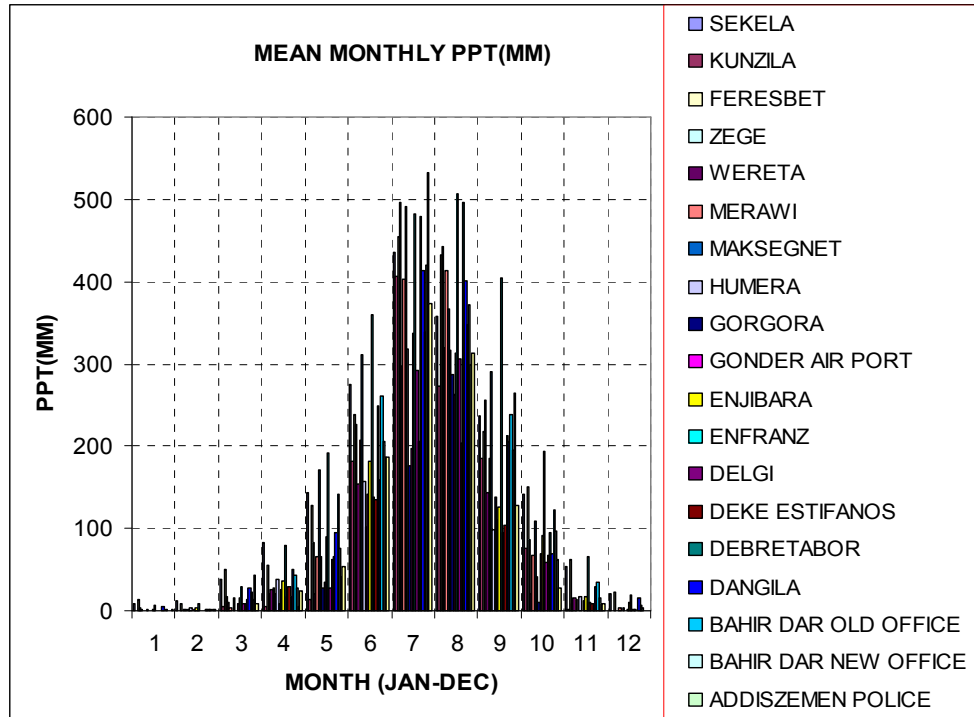


Fig. 2.5. The Mean Monthly Precipitation of Lake Tana Basin (1990\_2006)

The average annual prevailing mean minimum temperature is 12.6<sup>o</sup>c and Mean maximum temperature 27.3<sup>o</sup>c temperature. The average monthly temperature of the basin is 19.4<sup>o</sup>c with ranging 8.9 <sup>o</sup>c in Jan and Dec to 30.4 in May and April. The Mean monthly temperature diagram shown below, overview the detail.

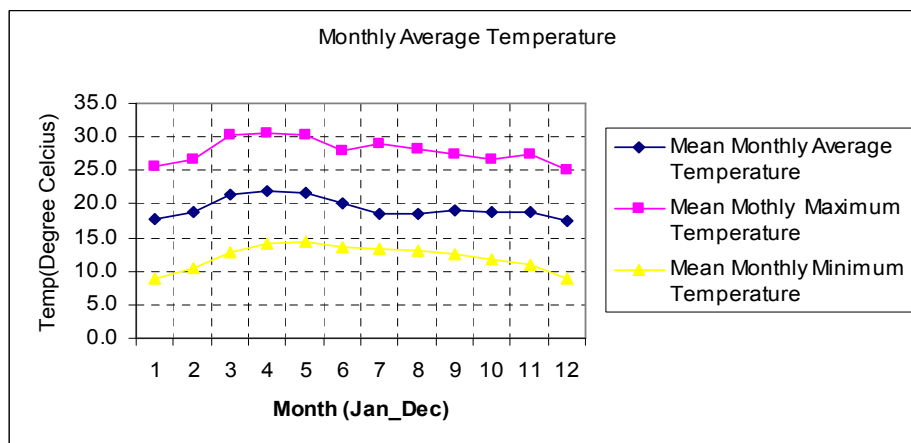


Fig 2.6. Mean Monthly Temperature of the Lake Tana Basin (1990\_2006)

The mean monthly wind speed prevailing in the basin is 1.03 m/hour with average 7.6 sunshine hours per day. The relative monthly temperature decrement is associated with low sunshine hour, high wind speed and relative humidity.

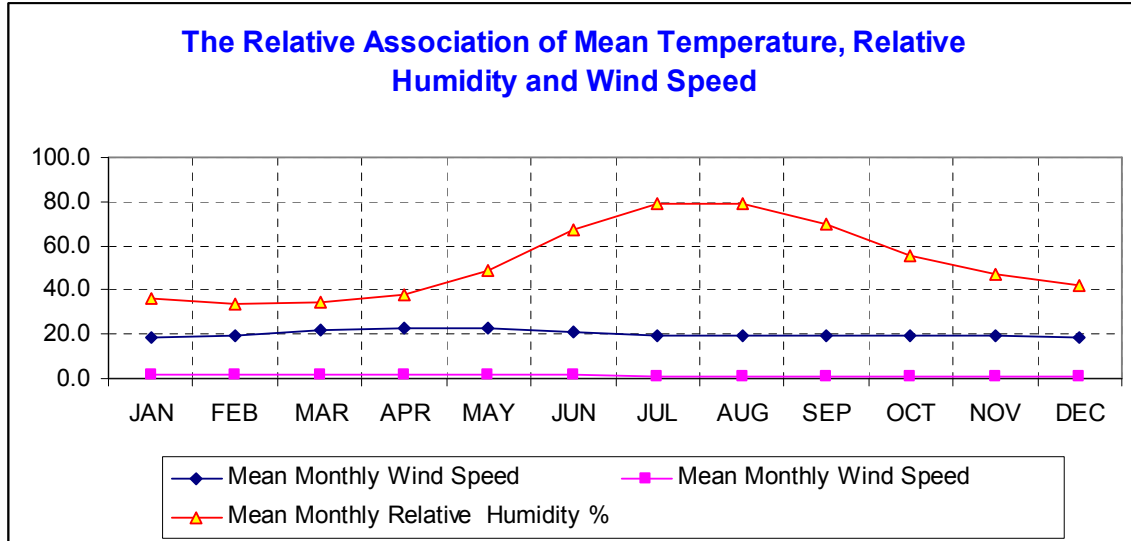


Fig.2.7. Mean Monthly Temperature of the Basin (1990\_2006)

The area is also characterized with mean monthly relative humidity of 58.3%.which ranges from 40.6 % in February up to 80.05% in August. The relative humidity shows high value b/n May to October.

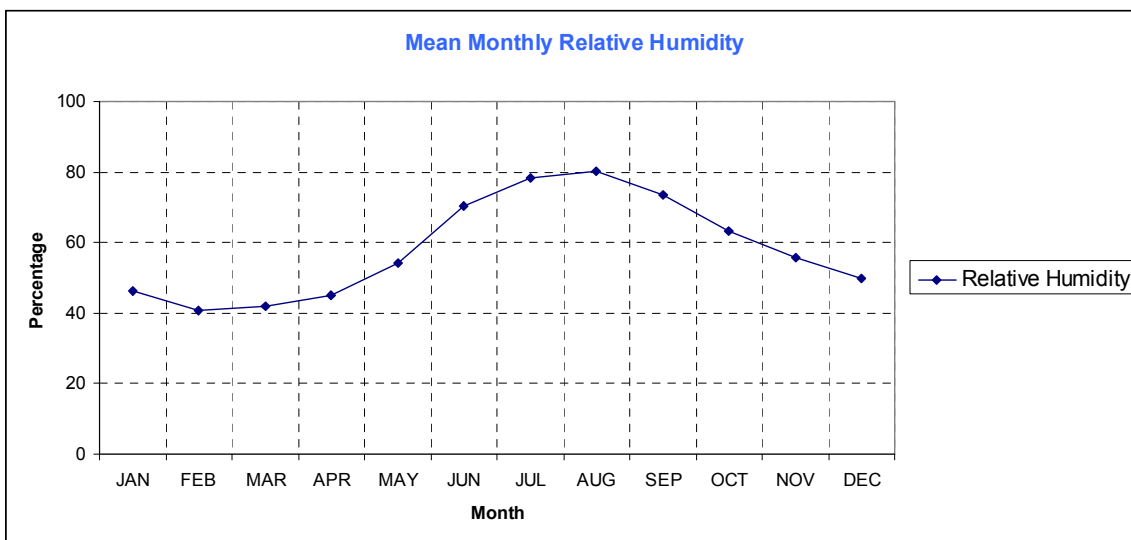


Fig.2.8. Mean Monthly Temperature of the Basin

## 2.4. SOIL

The soils in most of the Tana basin are derived from the weathered basalt profiles, and are highly variable. In low lying areas particularly north and east of Lake Tana, and along parts of the Gilgel Abbay, soils have been developed on alluvial sediments.

The Major Soil Groups, characterized base on Based on Yohannes Daniel (2007) are **Eutric Regosols** , Sandy loam to loam excessively drained, **Haplic Luvisols**, Clay to silty clay Well drained , **Chromic Luvisols**, Clay Moderately well to well drained , **Eutric Fluvisols**, Silty clay Moderately well drained , **Haplic Nitisols**, Silty clay to clay well drained , **Eutric Cambisols**, Silty clay Moderately to deep and well drained , **Eutric Leptosols** , Clay loam to clay Moderately deep to deep, **Haplic Alisols**, Clay Favorable drainage, **Eutric Vertisols**, clay Poorly drained, **Lithic Leptosols**, Loam to clay loam Moderately deep to deep Drained.

The spatial distribution of the major soil is shown on Tana soil map Fig. 2.8. (Source: MoWR).

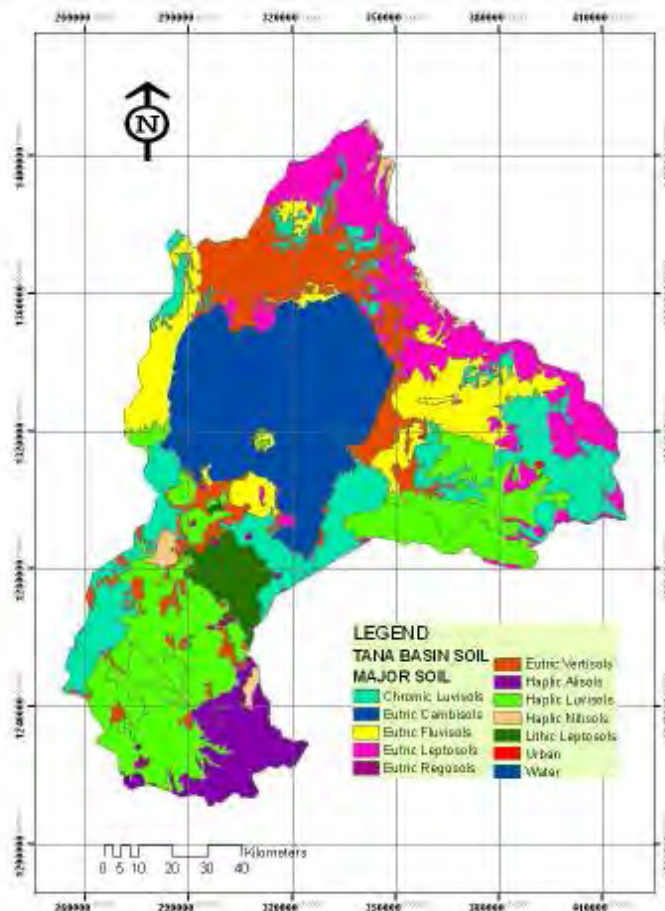


Fig. 2.9. Soil Map of Lake Tana Basin (Source: MoWR).

## 2.5. LAND COVER AND USE

The Land cover of the basin is controlled with Topographical, Climatic and ecological conditions. The Land cover has made dramatic change with the past 50 years in association with the population growth of the basin. The basin was covered with dominantly forestation but now only the scattered remains of indigenous vegetation observed.

Now, the land is covered dominantly with cultivation and very small part of the basin remains covered with grassland and forest. The major land use pattern of the basin is associated with agriculture and to some extent agro pastoral. The agriculture work is employed on production of Cereal crops. The pattern of land use is small farm yard owned by the house hold level. The detailed spatial distribution of the land cover and use of the basin is shown on the Fig. 2.9. (Source: MoWRD)

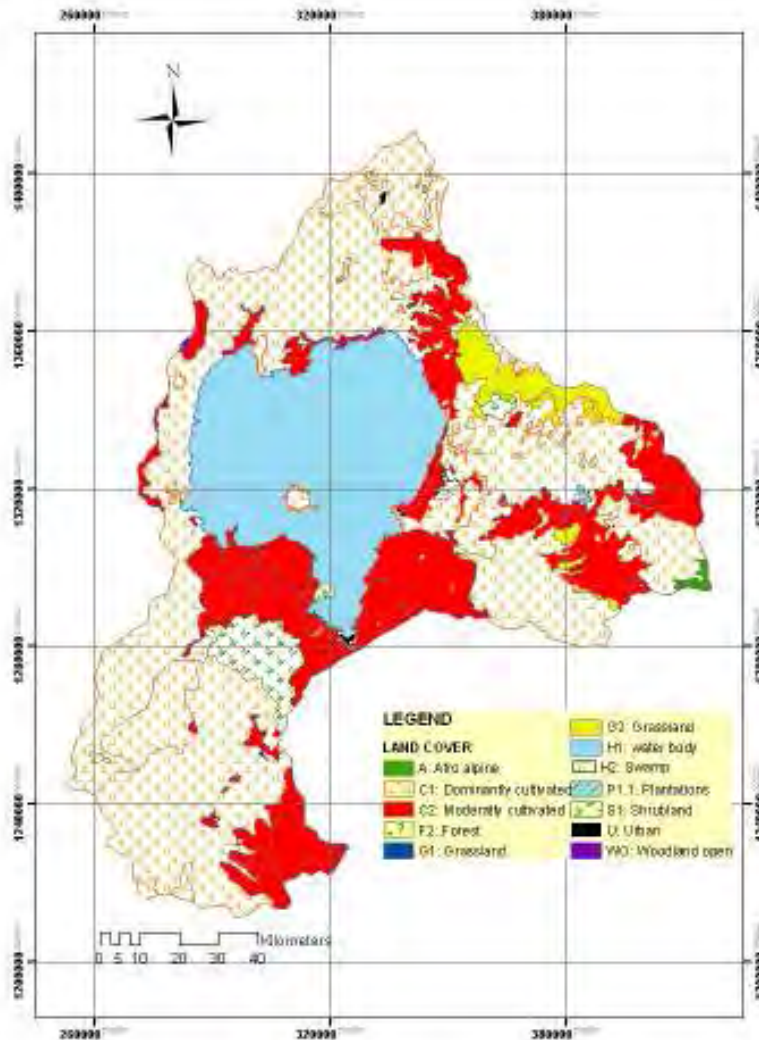


Fig. 2.10. Land Cover Map of Lake Tana Basin (Source: MoWR)

## 2.5. HYDRO METEOROLOGICAL SETTING

### 2.5.1. PRECIPITATION

The spatial and temporal variation of rainfall in is strongly controlled by the inter-annual movement of the position of the Inter Tropical Convergence Zone (ITCZ). The ITCZ represents a low-pressure area of convergence between *Tropical Easterlies* and *Equatorial Westerlies* along which equatorial wave disturbances take place. The shifting of this low pressure area governs the availability of rain driving wind direction. In Ethiopia, It is ITC occurrence at the north side of Ethiopia that the influence Equatorial Westerlies from South Atlantic Ocean and southerly wind from the Indian Ocean. It is this period that favor the occurrence of rainfall.

The major known seasons of the country are the rainy season Kiremt (June – September), the dry season Bega (October – January) and small rainy season Belg (February – May). The study basin shares the same season of the country with heavy precipitation period b/n mid may to mid September.

The rain fall analysis of the basin is the very essential part of the study which finally controls the recharge of the basin. The rainfall spatial and temporal distribution is done based on meteorological station the listed on table (2.1) and distributed on fig 2.1 below:

MET STATION	EASTING (X)	NORTHING (Y)	MEAN RAINFALL
SEKELA	305517	1216556	1805.97
KUNZILA	285406	1312938	1147.90
YIFAG	360691	1335726	1013.20
WERETA	356252	1318049	1392.47
MERAWI	298151	1261959	1697.95
MAKSEGNET	343433	1365677	1076.04
GORGORA	315087	1354781	863.93
GONDER AIR PORT	328339	1387887	1225.83
ENJIBARA	272711	1214554	2350.90
ENFRANZ	356390	1346807	957.02
DELGI	286749	1348334	827.52
DEKE ESTIFANOS	311585	1317189	1635.55
DEBRETABOR	420487	1310071	1475.95
DANGILA	263090	1244498	1560.32
BAHIR DAR OLD OFFICE	327733	1282801	1430.26
ADDISZEMEN POLICE	335170	1245152	1124.61
AYKEL	288111	1385944	1805.97
BAHIR DAR NEW OFFICE	288110	138900	1444.95
<b>ARITHMETIC MEAN</b>			<b>1353.06</b>

Table 2.1. Mean Annual Precipitation of Lake Tana Basin

## 2.5.2. SPATIAL DISTRIBUTION OF RAINFALL

In order to effectively represent point rainfall data for basin under investigation, the Thiessen polygons method is employed. This method considers point rainfall measurement station represent half way up to the adjacent gauges. It segregates the area with polygons formed by perpendicular bisector of lines joining adjacent stations.

$$P_A = \frac{\sum_{i=1}^n P_i a_i}{A_t} \quad \text{Equation 2.1}$$

Where  $P_A$ : Average rainfall for area,  $P_i$  : Measured Precipitation:  $n$ : Number of rain gauge, As the method is appropriate for an evenly gauging station distribution both fore flat and hill topography, accordingly area analysis has done with a result of an average rainfall of the **1374.60** stated on the table 2.2 **and** its spatial distribution shown in fig 2.10.

Station	Enclosed Area (Km <sup>2</sup> )	Weighted Area (%)	Mean Annual PPT(mm)	Annual Weighted PPT (mm)
SEKELA	692	4.56	1805.97	82.40
KUNZELA	893	5.89	1147.9	67.59
DANGILA	796	5.25	1560.32	81.89
MERAWI	1281	8.45	1697.95	143.41
DEKE ISTIFANOS	1557	10.27	1635.55	167.90
ZEGE	972	6.41	1641.11	105.17
DELGI	1014	6.69	827.52	55.32
GORGORA	1150	7.58	863.93	65.51
AYKEL	174	1.15	1805.97	20.72
GONDER	947	6.24	1225.83	76.54
MAKESEGNET	688	4.54	1076.04	48.81
ENFRANZE	558	3.68	957.02	35.21
WERETA	1414	9.32	1392.47	129.82
YIFAG	326	2.15	1013.2	21.78
ADDIS ZEMEN	541	3.57	1124.61	40.11
DEBRETABOR	1140	7.52	1475.95	110.94
GASSAY	654	4.31	2000.00	86.24
BAHIRDAR	370	2.44	1444.95	35.25
	15167	100.00	1372.02	1374.60

Table: 2.2 Mean annual weighted Precipitation (mm) of the Basin



Fig: 2.11. The Spatial distribution of precipitation of the Lake Tana Basin

The spatial analysis has treated the large open water body Lake Tana, prominent hydrological feature of the basin, independently with same principle of the Thiessen polygons method which results average aerial rain fall of 1302.79 mm/year by 70mm less than the average of the basin. It is listed on the table 2.3 and spatially distributed in the fig 2.12

Station	Enclosed Area by Polygon (Km <sup>2</sup> )	Weighed area (%)	Mean Annual Rainfall (mm)	Annual Weighted rainfall (mm)
Delgi_	421.00	13.86	827.00	114.65
Gorgora_	528.00	17.39	863.00	150.04
Makesegnet_	73.70	2.43	1067.04	25.90
Enfranze	208.00	6.85	957.00	65.55
Yifag	44.60	1.47	1013.20	14.88
Wereta	189.00	6.22	1392.47	86.66
Bahir Dar	36.60	1.21	1444.95	17.41
Zege	263.00	8.66	1641.11	142.12
Deke Istifanos	1273.00	41.92	1635.55	685.59
	3036.9	100.00		1302.79

Table: 2.3. The Annual weighted Precipitation of Lake Tana, Thiesen: Polygon



Fig: 2.12. Spatial distribution of precipitation over Lake Tana, Thiessen Polygon

### 2.5.3. HYDROLOGICAL SETTING

The major river catchments that result the basin are Gilgel Abay in the south (4649 sq km), the Gumera (1412 SqKm) and the Rib (1970 Sqkm) in the East and the Megech (2304 sq km) draining from the north. There is no prominent stream on the western part of the basin. The above stated major streams contribute more than 93% of the inflow of Lake Tana (Kebede 2006).

There are 5 major hydrometric stations in the Lake Tana basin and other station on the minor stream with nearly 62.2% gauged area. This paper used the data of the major five stations (on the Gilgel Abay, Koga, Gumara, Rib and Megech). Based on SMEC 2007 the

data quality assessment, The Gilgel Abay and Koga are found with high reliability while the other major station at relative less reliability at peak period. The other, minor stations need a lot to be reliable for most of the data.



Fig: 2.13. Hydro meteorological station of the Lake Tana Basin

### 2.5.3.1. GILGEL ABAY

It is the longest and largest river catchments in the southern part of the basin which drains from the high land plateau of the Gishu Abay with a gauging station that embark nearly 1664 km<sup>2</sup>. The relatively low density river pattern in association with the prevailing high rainfall implies a high ground interaction with underlying quaternary volcanic aquifer.

Gilgel Abay is major stream with mean annual discharge of **53.02 M<sup>2</sup>/sec**.The hydrographic analyses, based on above BECOEM 1996, estimates nearly 307 mm/year base flow that approximate ground water interaction. The table and figure shown below show an average 16 years hydrological summary and hydrograph respectively.

GI YEAR	Average Discharge (M <sup>2</sup> /SEC)												
	J	F	M	AP	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DE	MEAN
1990-2006	3.69	2.38	2.00	2.30	7.38	49.94	149.65	185.76	137.78	64.25	21.25	9.82	<b>53.02</b>

Table: 2.4. Mean Monthly Discharge of Gilgel Abay (1990\_2006)

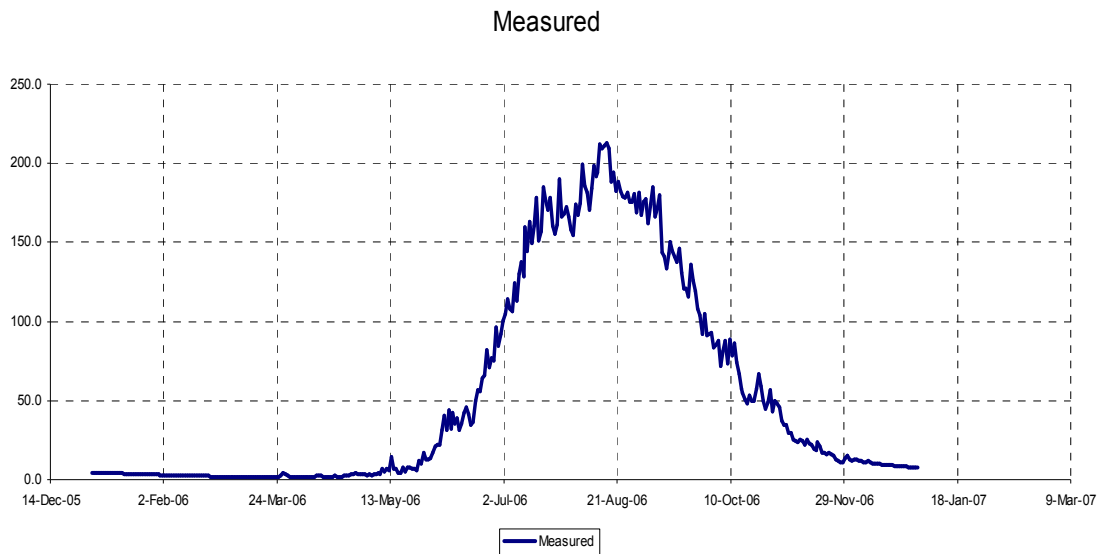


Fig: 2. 14. Hydrograph of Gilgel Abay Stream (1990-2006)

### 2.5.3.2. GUMERA

Gumera is one of the major stream with 1394 km<sup>2</sup> gauged enclosed area. It is with mean annual discharge of 35.1M<sup>3</sup> /Sec .The hydrographic analysis, based on BECOEM 1996, estimates nearly 90mm/year base flow that approximate ground water interaction.

The table and figure shown below show an average 17 years hydrological summary and hydrograph respectively.

GU_ YEAR	Average Discharge (M <sup>2</sup> /SEC)												
	J	F	M	AP	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DE	MEAN
1990-2007	3.6	2.3	2.1	1.8	2.7	16.6	87.8	157.8	93.6	33.6	12.9	6.8	<b>35.1</b>

Table: 2.5. Mean Monthly Discharge of Gumera (1990\_2006)

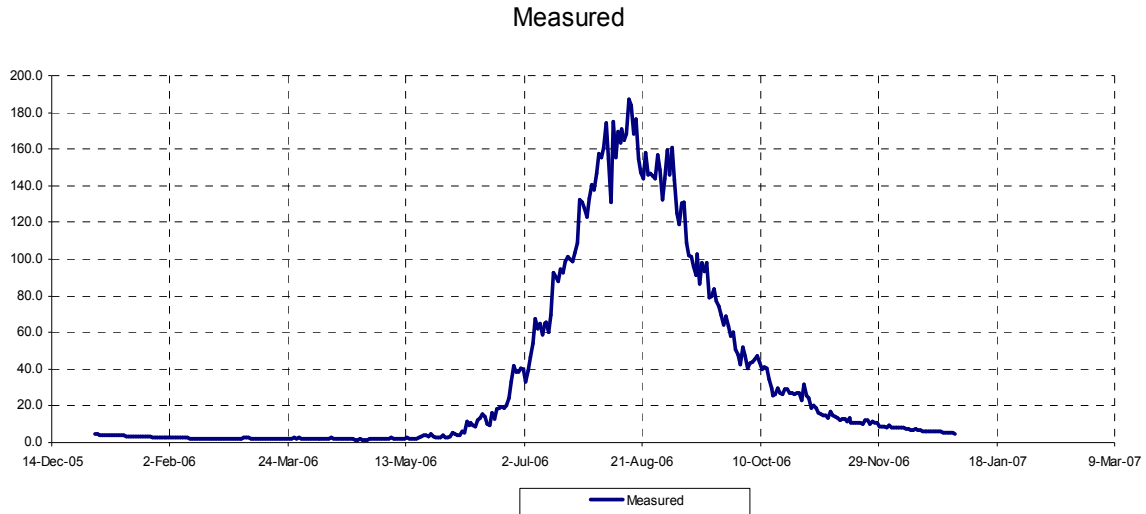


Fig: 2.15. Hydrograph of Gumera Stream (1990-2006)

### 2.5.3.3. MEGECH

The gauged part of the Megech sub basin is only the upper catchments enclosing an area of 462 km<sup>2</sup>. It is with a relative low mean annual discharge of 6.5 M<sup>3</sup>/Sec. The hydrographic analysis, based on BECOEM 1996, estimates nearly 90mm/year base flow that approximate ground water interaction. The table and figure shown below show an average 16 years hydrological summary and hydrograph respectively.

M YEAR	Average Discharge (M <sup>2</sup> /SEC)												
	J	F	M	AP	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DE	MEAN
1990-2006	1.1	1.0	1.1	1.2	1.6	4.3	15.0	32.6	11.9	4.5	2.4	1.8	<b>6.5</b>

Table: 2.6. Mean Monthly Discharge of Megech Stream (1990\_2006)

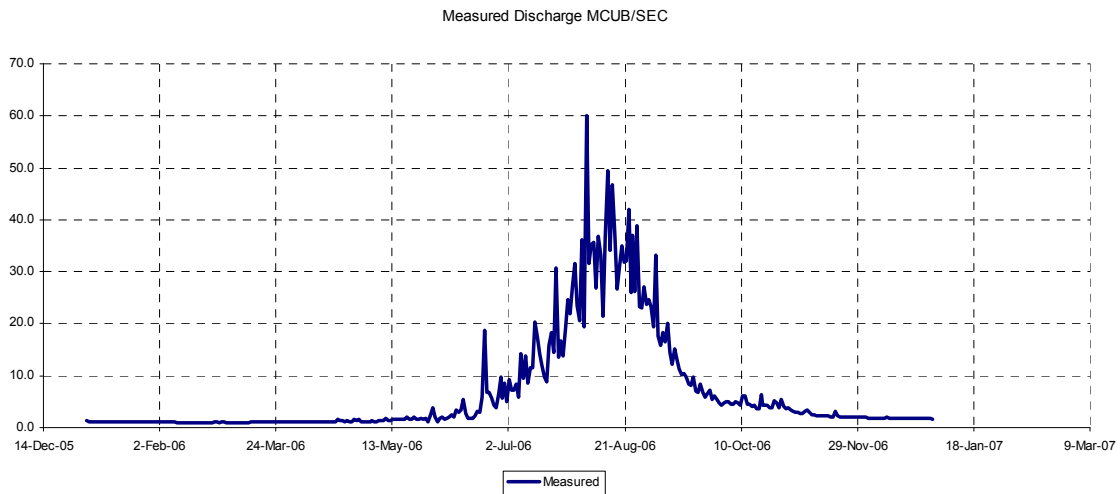


Fig: 2.16. Hydrograph of Megech Stream (1990-2006)

### 2.5.3.4. RIB

The gauged Rib river catchment's covers an area of 1592 km<sup>2</sup>. It drains from the high land of Mt Guna at south East flow toward the Lake. It is with a relative highly covered gauged area of the catchments, and with mean annual discharge of 15.4 M<sup>3</sup>/SEC.

The hydrographic analysis, based on BECOEM 1996, estimates nearly 55mm/year base flow that approximate ground water interaction. The table and figure shown below show an average 16 years hydrological summary and hydrograph respectively.

R YEAR	Average Discharge (M <sup>3</sup> /SEC)												
	J	F	M	AP	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DE	MEAN
1990-2006	1.2	0.6	0.5	0.8	1.9	6.9	45.2	70.9	38.5	10.2	5.1	2.5	<b>15.4</b>

Table: 2.7. Mean Monthly Discharge of Rib Stream (1990\_2006)

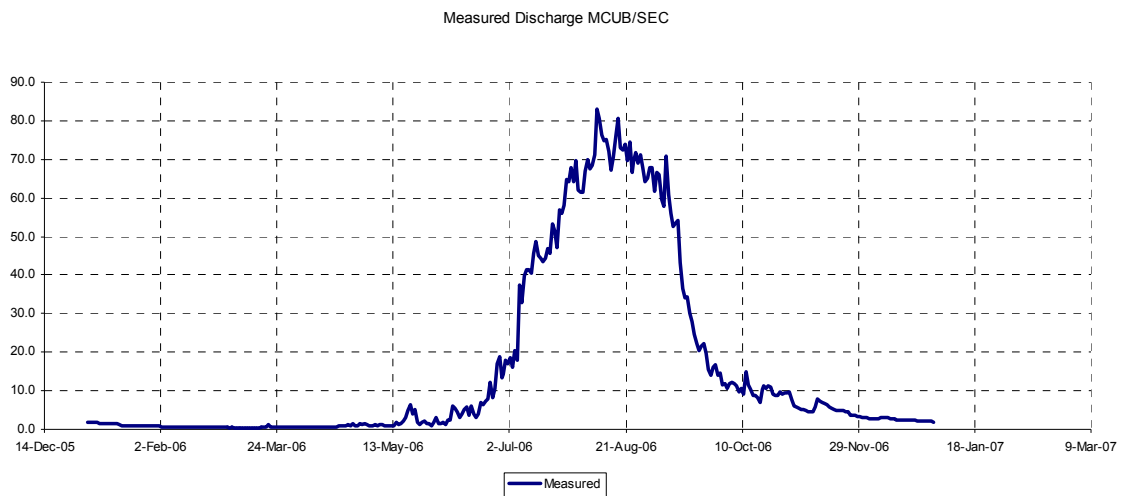


Fig: 2.17. Hydrograph of Rib Stream (1990-2006)

### 2.5.3.5. ABAY

The only surface outflow in the basin is the Blue Nile (Abay), which comprises 7% of the Blue Nile flow at the Ethio-Sudanese border (Shahin, 1988; Conway, 2000). It covers about 15321Km<sup>2</sup> gauged catchments of surface area and with an average measured discharge of 133.7 M<sup>3</sup>/Sec. The average monthly discharge and hydrograph of for a hydrological period 1990-2006 is shown below.

A YEAR	Average Discharge (M <sup>2</sup> /SEC)												
	J	F	M	AP	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DE	MEAN
1990-2006	87	70	65	65	52.3	50.6	79.3	157.3	337.6	298.5	207.2	132	<b>133.7</b>

Table: 2.8. Mean Monthly Discharge of Abay (1990\_2006)

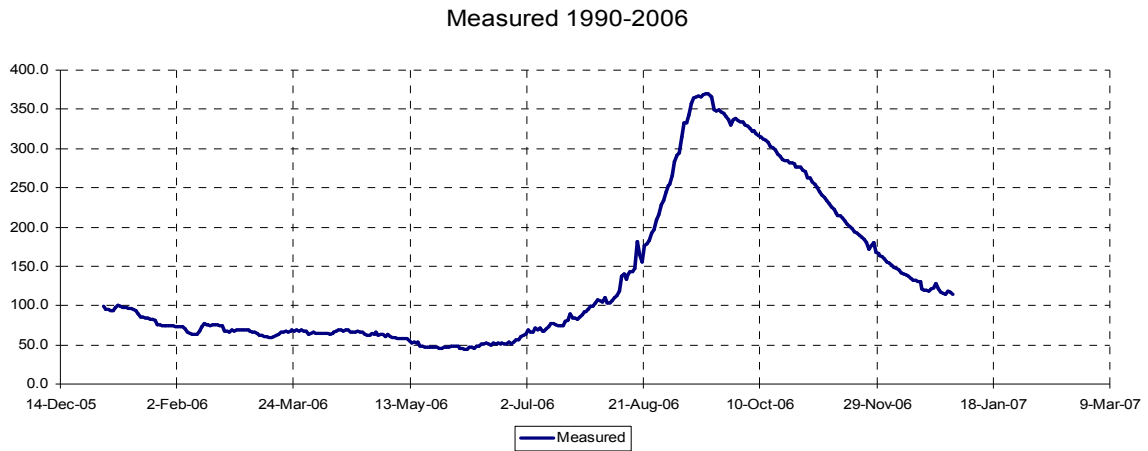


Fig: 2.18. Hydrograph of Abay River (1990-2006)

The hydrological summary of Lake Tana basin shows a share of contribution to the lake with decreasing order Gilgel Abay, Gumera, Megech and Rib. In order to see the relative comparison of dally discharge the diagram shown explains more.

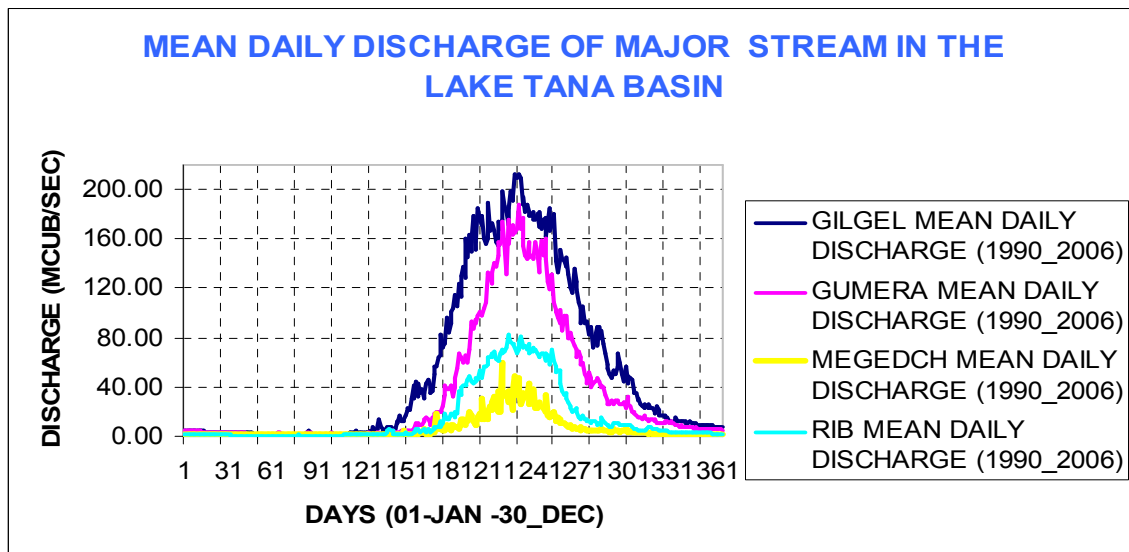


Fig: 2.19. Hydrograph of Major Stream, Lake Tana Basin (1990-2006)

### 2.5.3.6 LAKE TANA

Lake Tana is the largest lake in Ethiopia which covers nearly 306 4km<sup>2</sup> surface area of the study basin. The average water level, measured, b/n 1990 to 2006 is 1786.66m amsl. According to the a bathymetric survey carried out by Studio Pietrangeli (1990) in 1987 showed that the deepest point of Lake Tane is at an elevation of 1772 masl, which is about 14 m below the average water level 1786.66 masl).

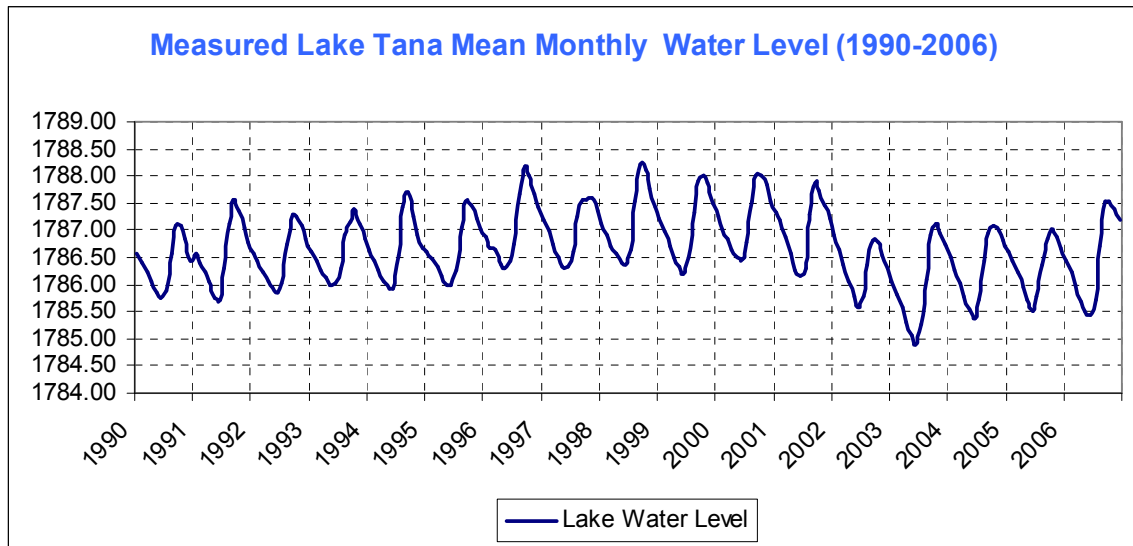


Fig: 2.17. Hydrograph of Lake Tana Water Level (1990-2006)

## CHAPTER THREE

### 3. GEOLOGICAL AND STRUCTURAL SETTING

#### 3.1. GENERAL OVERVIEW

The study area is part of the northwestern plateau of the country comprise of a basement Precambrian bed rock, overlain by Mesozoic sediments, Tertiary volcanic and minor sediment, Quaternary volcanic and recent alluvial sediments.(Geological Map of Ethiopia 1:2,000,000)

The distribution of the rock formation and current configuration of the basin controlled with tectonic activity working over the area. (Chrowicz et.al.1988). The Tana basin, northwest Ethiopia is uplifted dome possibly related to the Afar mantle Plume (Pik et al..2003), the basin was formed by faulting of mid-Tertiary basalts.

The result of the prevailed fault on the mid \_ Tertiary created three major grabens: **Debretabor** graben runs East-West, **Gonder** Graben runs North \_Northwest and **Dengel ber** Graben runs South-Southwest of the basin. The created grabens converge to ward the **Lake Tana** and highly govern the ground water flow. In association of this major garben forming events, a number of fracture and small scale faults result followed shown on the geological map.

In general, the region understudy is believed to be evolved following major regional events over and around the Lake Tana basin stated below;

- The transgression and regression of Indian ocean which is responsible for the underlying Mesozoic sediments,
- The swell Arabian plate caused by mantle pluming. The mantle pluming, initiated from a hot thermal boundary layer at base of the mantle (mantle core boundary), produced uplift, flood volcanism, and crustal extension in southeastern and northwestern Ethiopia. The tertiary trap series the covers the plateau and the quaternary lava flow and recent volcanic eruption that form the scoraceuos cone.
- The recent alluvial deposit associated with the major tributaries of the Lake sub-basin and periodical expansion and compaction of the lake to its vicinity
- The fault on the mid \_ Tertiary that created three major grabens associated fault lines that

## **3.2. REGIONAL GEOLOGY**

The regional geology of the Blue Nile, in side of which the region under investigation considered, show the occurrence and distribution of the major formation of Basement, Mesozoic sediment, Tertiary and Quaternary volcanic rocks and recent alluvial deposit

### **3.2.1. BASEMENT**

The Precambrian formation, which forms the basement formation, is mainly consisting of metamorphic rocks. It is a formation exposed on the region under study but intersect by the Abay gorge south of the study area and low land of the adjacent basin.

### **3.2.2 MESOZOIC SEDIMENTARY FORMATIONS**

It is associated with the settlement of the sediments and the accompanying compaction process following the transgression and regression of the Indian Ocean in the NW to SW

The stratigraphy of the sedimentation is controlled based on the spatial distribution and period of transgression and regression. It follows the Adigrat Sandstones, Gohatsion Formation, Lagajima Limestones, Muger Mudstones and Debre Libanos Sandstones (Getaneh, 1981, 1991; Russo *et al*, 1994).

This Mesozoic sediment is not exposed in the study area but it is believed that a considerable thickness covered by the recent volcanic flow. However, the study conducted by geophysical survey of the study basin indicates 200mts an estimated thickness of the Mesozoic sediments underlies the prevailing volcanic rocks and quaternary sediments. The regional studies finding conducted by a number of researchers' shows Mesozoic sediment comprise of number of unit that is summarized below:

- The Adigrat Sandstones (Permian-Lower Jurassic): its thickness ranges from few meters to 300 m. It typically includes yellowish to pink fine to medium grained, non calcareous, well sorted, cross bedded quartz sandstone.
- The Abbay Beds (Middle Jurassic): it is described as alternating gypsum, limestone, dolomitic limestone, sandstone and shale; in relation with the importance of the shales and evaporites.

- The Antalo limestone (Callovian-Upper Jurassic): its thickness ranges from 300 to 350 m. It can include thick beds of marls.
- The Amba Aradam Sandstones (Lower Cretaceous): It ends the sedimentary Mesozoic sequence. The lower unit consists of interbedded shale siltstone, sandstone and dolomite of tidal to brackish environment. The upper unit is a thick, homogeneous member of deltaic to alluvial sandstone. This unit consists of well washed, porous, weakly consolidated sandstone.

### 3.2.3 PALEOCENE AND MIOCENE VOLCANIC SERIES

The Tertiary basalt cover in the Tana area is assumed to average 500 - 15000 m in thickness (Jespen and Athearn, 1961; Pik et al., 2003). (USBR, 1964) The thickness of the trap series in north-western Ethiopia averages 1000–1500m (Pik et al., 2003), and in the Blue Nile gorge, Kidane et al. (2002)

- BLUE NILE BASALTS: they are 500 m thick and consist in 6 flows of columnar alkaline basalts. They form the top of the Abbay Canyon East, South and Southeast of the Mangestu Mountains. They are only observed in the central part of the **Blue Nile** basin, on both side of the Abbay gorge.
- ASHANGI BASALTS: poorly defined and deeply weathered basalt flows.
- AMBA AĪBA BASALTS: flood basalt in thick flows with scarce tuffs.
- TARMABER BASALTS: It covers most of the Northern Ethiopian Plateau and can be described as superimposed basalt lava flows with intercalated tuffs, scoriaceous strata and typical red paleo-soils.

### 3.2.4 PLIO-QUATERNARY SERIES

It includes the volcanic and sedimentary series:

- Basalt lava flows connected to volcanic centers: it covers a large area South and South-west of Lake Tana. These basalts are generally porphyritic with subordinate doleritic and glassy texture. Basaltic breccias and tuffs are also present.
- Sedimentary formations: Lacustrine and swamp deposits: which mainly cover Dabus swamps and Lake Tana vicinity. In the latter case, field

observations performed by the project show that residual deposits located in the south and the east of the lake are reduced in thickness and consist mainly of alluvial and swamp deposits in the river mouths. The volcanic substratum remains always shallow.

In general, The local geology of the sub basin comprise of a basement Precambrian bed rock, overlain by Mesozoic sediments, Tertiary volcanic and minor sediment, Quaternary volcanic and recent alluvial sediments.(Geological Map of Ethiopia 1:2,000,000) . The dominant out cropping geology over the sub basin is basaltic volcanic and alluvial deposit.

Based on the field observation, the southern part of the lake basin is covered dominantly with quaternary volcanics which is characterized by its blocky and fractured vesicular basalt, with a porphyritic, glassy texture, as well as some basaltic breccias and tuffs. It is believed it overlie the older tertiary volcanics.

And also the Northern, Eastern and western part of the lake basin is dominantly covered by the tertiary basalt characterized by the fracturing.

The quaternary alluvial deposit also covers the **Fogera** plain, along the bank main perennial stream and Lake Tana. The deposit is up to 60m near Woreta, which is part of Fogera plain. This is deposit composed of clay to gravel. The lacustrine deposit fine silt and clay covers the bed of Lake Tana overlying the tertiary basalt. The previous investigation aided with drilling on the lake floor shows the occurrence of indicates stiff clay up to 80m depth (Kebede, pers comm., 2007).

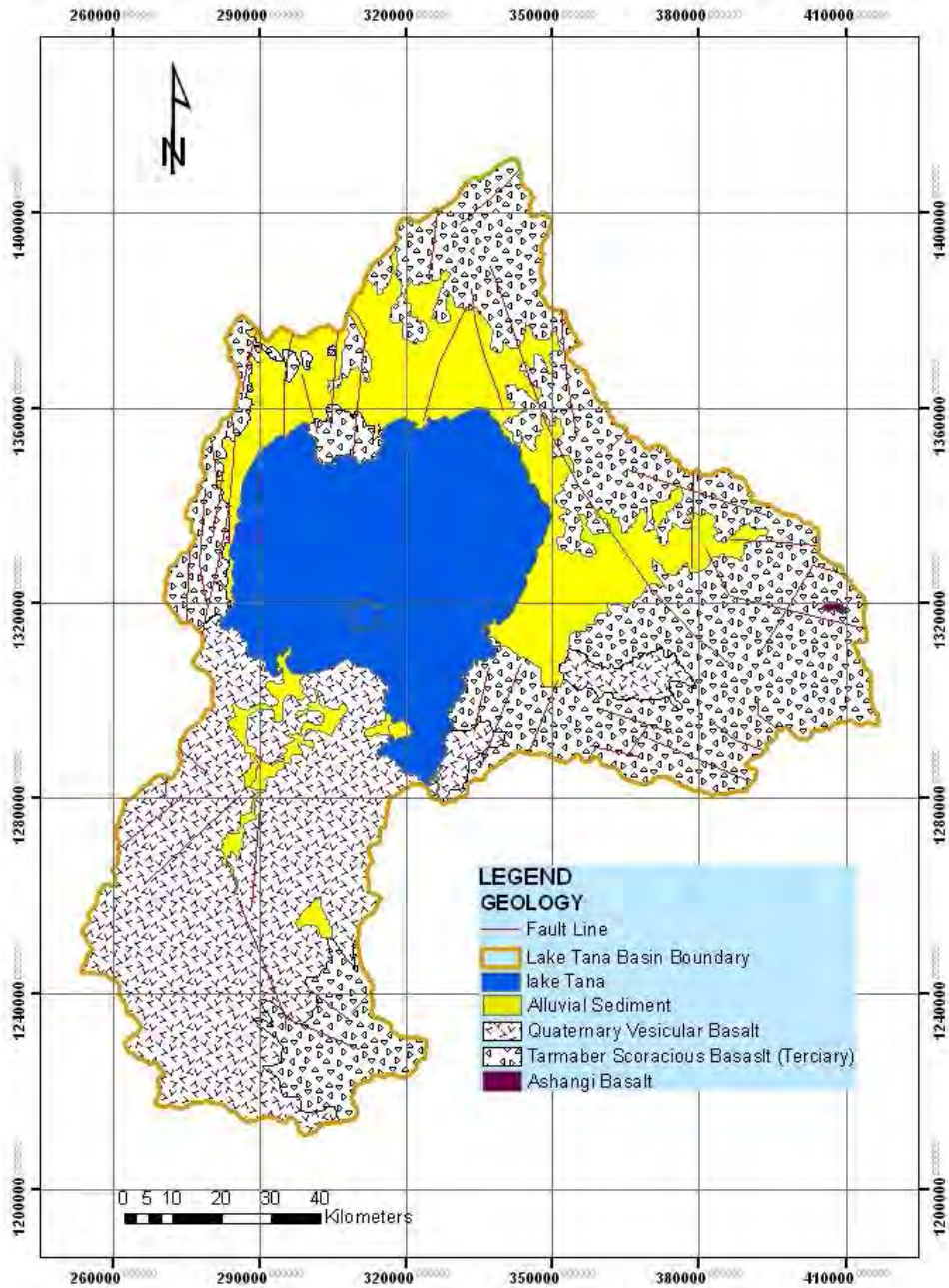


Fig: 3.1. Geological Map of Lake Tana Basin, (Simplified Based on BCOEM, 1998)

## **CHAPTER FOUR**

### **4. CONCEPTUAL MODEL**

#### **4.1. GENERAL OVERVIEW**

Conceptual model is the very ideal representation the major hydro geological setting of the study area with a purpose of providing the pictorial representation of field situation. It is a very essential and controlling factor of the modeling effort.

The concept of Numerical modeling build on the fact that every field situation can be represented with governing physical laws and these laws can be explained in equations to represent the material mathematically. The conceptual model intend to maintain the mathematical representation by identifying the available major system, the possible boundaries and aquifer characteristic which results an input data base , cross section and simplified map for the modeling.

Conceptualizing of field situation needs a thorough understanding of hydrogeological and Geological frame work of the field situation. It needs an expression of fact in very simple but still best approximation of major field situation according to the scope of the purpose. The conceptual model also understand the mathematical constraints of numerical modeling despite the Pro found fact of almost every field situation can be represented mathematically.

In ground water flow modeling, the main features of physical facts to be considered on conceptualizing the flow system are; Boundary condition, Aquifer Characterization (type of aquifer and quantitative and spatial distribution of Hydraulic Conductivity, Storativity and Leakage coefficient), Water Table and Potentiometric Map, Hydrology of the main water bodies, the rate and distribution of Recharge, stress on the aquifers, springs, possible contaminant source and so on)

Unlike the ambition to make a closer approximation of field situation for accurate numerical modeling, it is a very practical to consider major systems behavior that control the flow with the most possible simplification.

The development of this conceptual model take in to account the fact stated above and followed the major steps of defining hydrostratigraphic unit , Analyzing Water budget

component and defining flow system as of Marry P. Anderson and William W. Woessner, 2002, procedure of building conceptual model.

The conceptual model of the lake basin, the region under study, consider every previous verified investigation, Hydrometeorological data, Boreholes and literature review with judgment of the modeler.

## **4.2. HYDROGEOLOGY**

The major Aquifer systems in the Lake Tana basin are defined according to the geological units. The three major aquifer systems comprise the Tertiary Volcanics (mostly including the Ashangi, Aiba and Tarmaber basalts), the Quaternary Basalt aquifer and the Quaternary alluvial deposits. (SMEC, 2007)

Despite the suggestion of presence of Mesozoic sediments that can bear other aquifer system Hault et. Al (2005) and the assumption of an easy access Mesozoic sedimentary aquifers at the southern and eastern side of the Lake (Engida ZA, Yilma S & A. Tuinhof July 2007), quoting the thickness of the tertiary volcanic rocks in this area is estimated about 250m (Yarer, 2006). It is not considered as major aquifer until the interception of the Mesozoic sediment with boreholes.

Many of the world's largest aquifers reside in fractured consolidated media. Studies have shown that even media traditionally considered to be of low permeability, such as shales and granites, are fractured to the extent that significant groundwater flow may occur. (P. A. Lapcevic and K. S. Novakowski National Water Research Institute Burlington, Ontario E.A. Sudicky University of Waterloo)

The region under study is also can be categorized with dominant aquifer reside in a fractured consolidate media which is volcanic with a limited unconsolidated media of the quaternary alluvial deposit. The groundwater flow is largely related to the intensity of fracturing in the rock mass

Based on the Hydro geological study of Abay River Basin Integrated Development Master Plan Project, Phase 2, 1997, BCEOM et al, the Tertiary basalts and recent lava flows which are widely distributed in the Tana sub basin are grouped as extensive aquifer with fracture permeability.

The Quaternary basalts south of Bahir Dar are inferred to have high productivity and potential for development. Areas around the margins of Lake Tana are also reported as potential areas for future development. Regional Hydrogeological Investigation of Northern Ethiopia, including 1:100,000 hydro geological map Compiled by Bayissa Asfaw, (2003)

The above fact is also shown on the hydro geological log of boreholes drilled in the basin. The unconsciousness of the importance of spatial reference in borehole made the data in very unusable format.

According to the Evaluation of Boreholes (SMEC, 2007), the boreholes data are available are generally limited to depths of around 125 to 150m and 60% are less than 75m with deepest bore which at a depth of obtained data is 188m from a well at Gondar. There are few wells drilled to less than 35m. Most bores encounter the various Tertiary and Quaternary basaltic aquifers, and there are limited data on the alluvial aquifers. As noted previously no bores have intersected the complete sequence of basalts and encountered the Mesozoic bedrock.

#### **4.2.1 TERTIARY VOLCANIC AQUIFER SYSTEM**

The Tertiary volcanic aquifer system is scoriaceous basalt which covers upper Southern tip part the lake basin, spreading from the Mt. Choke and most parts of the north part of the basin spreading from Mt. Guna. (Hydrogeological map compiled by Bayissa Asfaw, 2003. It encompasses the commonly known Tarmaber, Ashangi and Aiba basalt.

The productivity of this aquifer is highly controlled with intensity of the fracture and the presence of the major structure affecting the area. It is aquifer with a relatively moderate productivity. As it is complex pattern of volcanic aquifers with close distance variation of the Transmissivity, it ranges from 0.1 -11 M<sup>2</sup>/Day with up to 32 M<sup>2</sup>/D at sole Gonder well (SMEC, 2007).

The Yields of Tertiary volcanic aquifers are in the order of 0.7 -17 L/sec, with a mean of 3.63 L/sec for the Tarmaber Basalt and 4.2 L/sec for the Ashangi and Aiba basalts. Specific capacity ranges are generally low, with average values of 0.25 and 0.27 L/sec/meter. (SMEC, 2007)

There is a tendency of productivity increment as one goes toward **Lake Tana** from the North and west.

## **4.2.2. QUATERNARY BASALT**

The very productive aquifer system is characterized with plenty of vesicles and highly weathering. The relative occurrence of high discharge springs and wells implies its potential for bearing of high ground water. The major springs of Areka and Lomi emerge from this aquifer unit with 140l/s and 50l/s respectively.

The productivity of this aquifer unit is associated with a high primary porosity of the vesicular basalt and interconnected controlled with intensity of fracturing. This aquifer unit covers dominantly the southern part of the Lake Basin. Based on the boreholes pump test analysis, there is a tendency of productivity of increment toward the Lake from the south and to ward to center from the east and west of the Gilgel Abay Catchments.

## **4.2.3. QUATERNARY ALLUVIAL AQUIFERS**

The Quaternary Alluvial Aquifers within the Lake Tana basin occur dominantly at the eastern part of the basin following the lower Rib and lower margin of Gumera. It also covers significantly in the north part of the basin at the lower part of the Megech and Western shore of lake Tana. The distribution is limited compared to the volcanic aquifer units and with limited knowledge with shortage of ground water data.

The productivity of this aquifer is associated with the pores of unconsolidated gravels and sand .The available data on this aquifer indicate high productivity with boreholes yielding more than 6l/s with depth of up to 60m.

## **4.3. CONCEPTUALIZED FLOW SYSTEM**

### **4.3.2. UNCONFINED AQUIFER**

The field situation of major aquifer `systems confirm us a semi confined to confined volcanic aquifer and a limited unconfined unconsolidated aquifer. The volcanic aquifer is dominantly semi confined and with a limited localized confined aquifer.

Despite the fact of benefit of groundwater investigations from the development of a numerical model which is used to simulate the flow system. The complex, pattern of aquifer system, which is a combination of dominate volcanic aquifer characterized by of confined, semi confined and unconfined aquifer unit is difficult for the modeling.

Modeling approaches to simulate flow and transport in fracture networks fall into one of three categories within the range of conceptual models for fractured rock: (1) equivalent porous medium (EPM), (2) dual porosity, (3) discrete fracture representation. In addition, fracture network models may be implemented in either two or three dimensions.

Particularly the volcanic aquifer groundwater flow is primarily governed by discrete fractures at the local scale, traditional mathematical methods, in which it is assumed that the hydrogeological properties vary in a smooth and continuous fashion (a single continuum), provide a poor approximation. The other, modeling approach, which can be used to circumvent this problem, is the use of stochastic or mixed deterministic-stochastic techniques (Smith and Schwartz, 1984). However, In our case numerical models it is difficult to characterize a field site to the degree necessary to support this type of model.

In order to develop a defensible conceptual model for a ground flow system in fractured rock, some characterization of the medium is necessary. The degree of characterization and simplification is also depend on a variety of factors, including the inherent complexity of the fracture system the type of conceptual model desired, and the amount of funding available and objective of modeling.

The compromise approaches to represent the region of study is equivalent porous media (EPM). It is a model based on equivalent porous medium treat the fractured porous rock as equivalent to a nonfractured continuum. The bulk parameters of aquifer for the permeability of the rock mass are used, and the geometry of individual fractures or the rock matrix is not considered. The intensity of fractures that control the water bearing character is conceptualized by its high conductivity of the aquifer.

The objective of the model to understand flow system for a very large coverage of area could also achieved with this simplification. The other supporting facts to consider Equivalent porous media approach highly tuned with aquifer parameter includes; there is no previous study to associate the lake basin with link to the external aquifer system; the basin aquifer system is interconnected with ultimate recharge of precipitation inside the basin and the relative continuity of water level that follow the topography to converge to the lake.

Presently in the general practice of hydrogeology, the modeling of flow and transport in fractured rock systems is often conducted using EPM models particularly at a domain scale of several hundreds of meters, or more, however, prediction of groundwater flux

may be conducted with a possible error using EPM models, provided the characteristics of the major fracture zones and unfractured rock are known and appropriately represented. (P. A. Lapcevic and K. S. Novakowski: National Water Research Institute Burlington, Ontario E.A. Sudicky University of Waterloo).

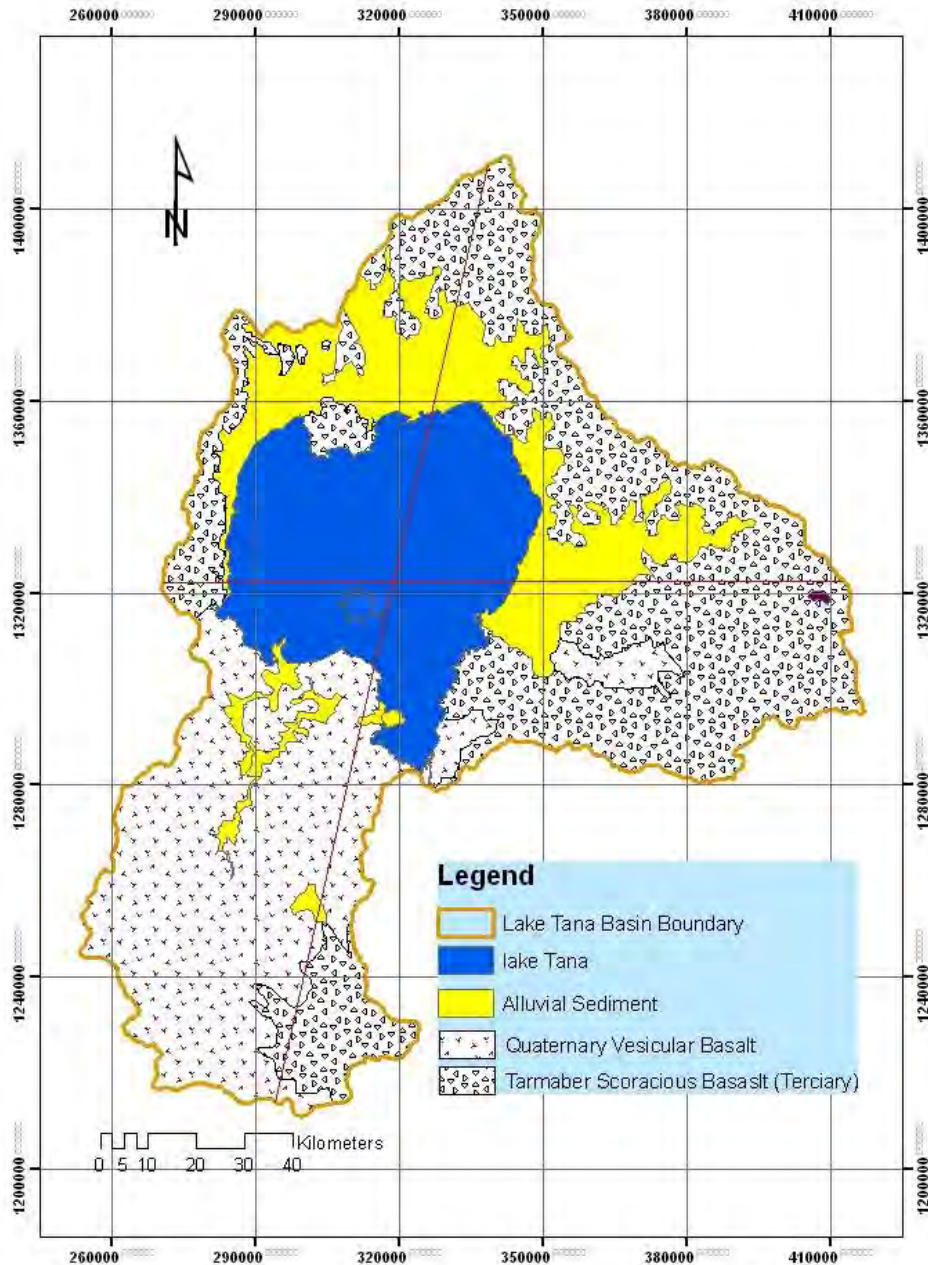


Fig: 4.1. Geological Map with S\_N and W\_E Cross section Line

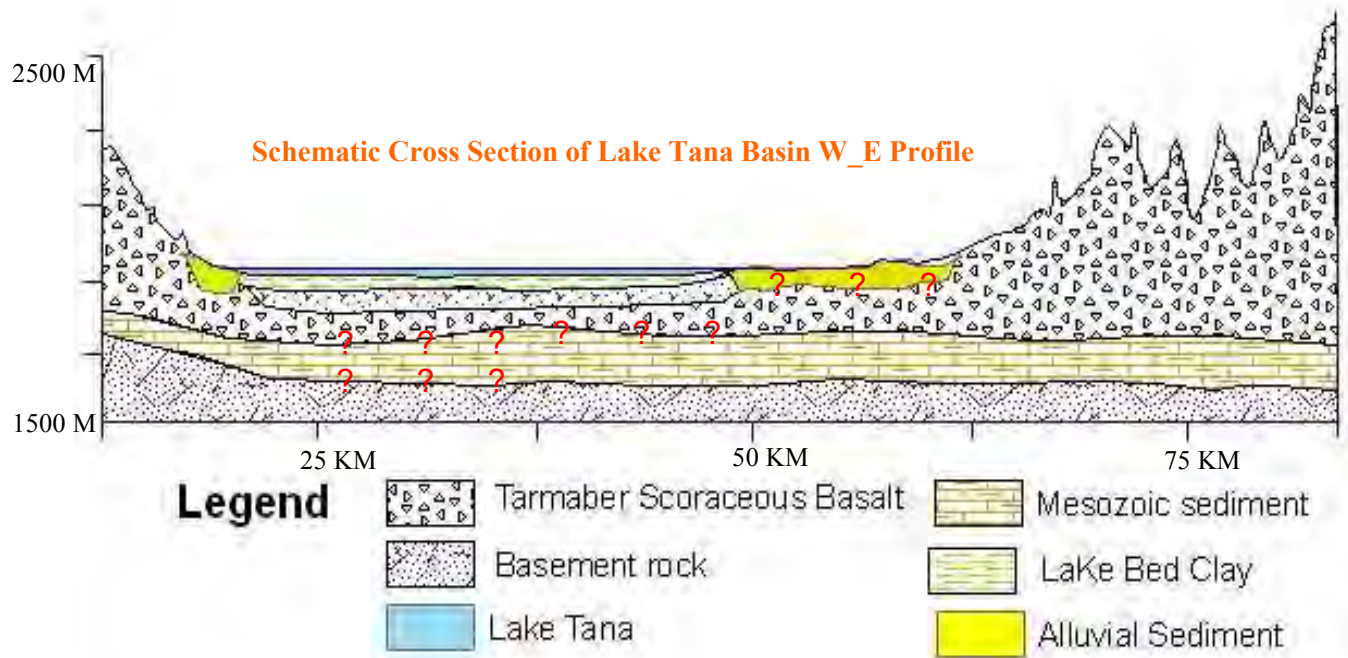


Fig: 4.2. Schematic Cross Section of Lake Tana Basin W\_E Profile

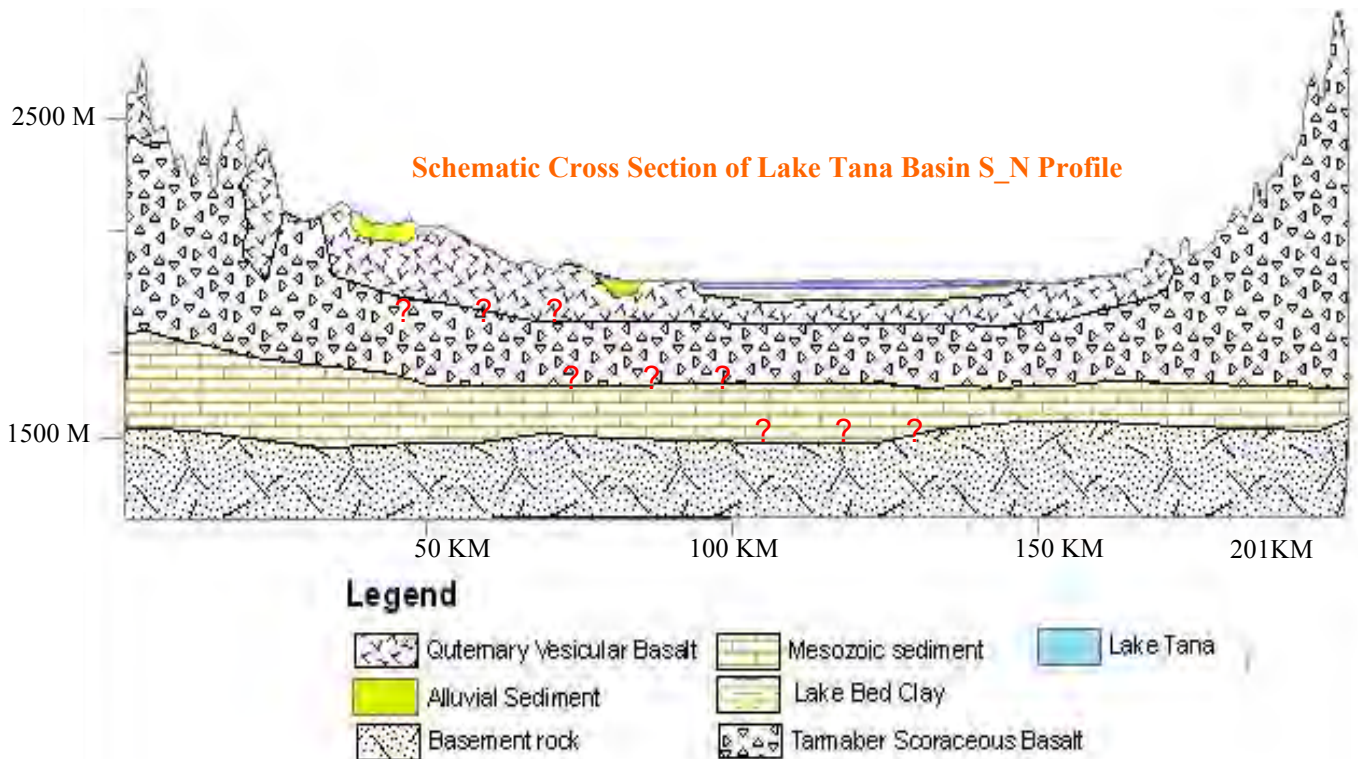


Fig: 4.3. Schematic Cross Section of Lake Tana Basin S\_N Profile

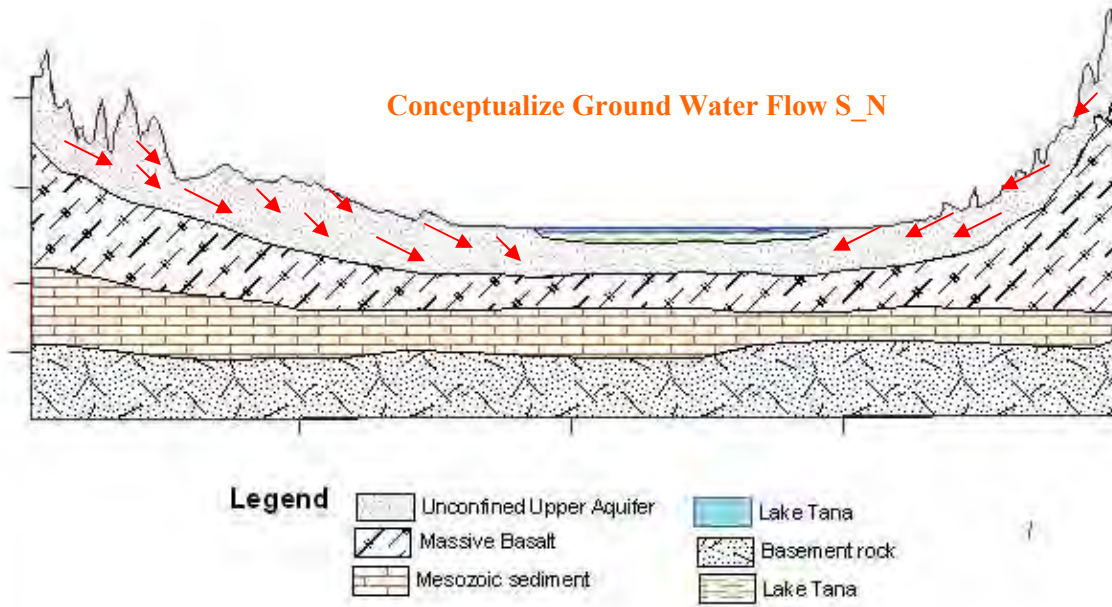


Fig: 4.4. Conceptualize Ground Water Flow S\_N

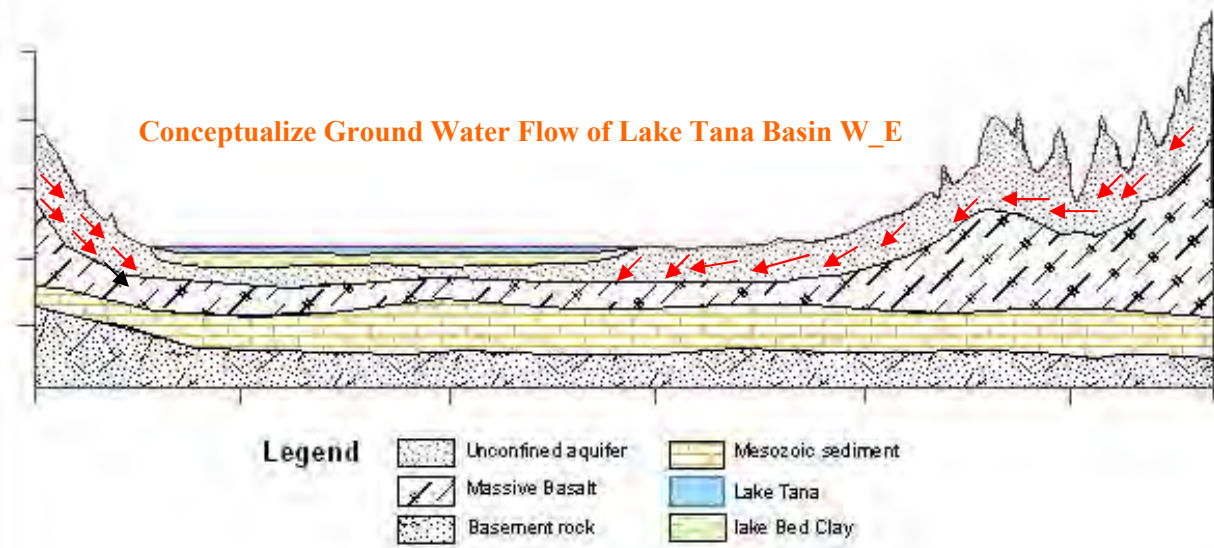


Fig: 4.5. Conceptualize Ground Water Flow of Lake Tana Basin W\_E

### **4.3.2. UNDISTURBED AQUIFER**

The aquifer system is also considered to be homogeneous, isotropic and unconfined one layer with an estimated thickness of 250m which represent the average thickness of the tertiary and the quaternary volcanic aquifers.

The lake basin is considered as not disturbed aquifer system with abstraction of the ground water taking in to account large surface area of the Lake Tana basin, poor monitoring of static water level and under exploited stage of the ground water development. Therefore, the model consider water level of boreholes with the available data at time of construction dominantly 2003 \_2006 afterward construction time.

The thickness of the aquifer is considered as the field situation is with a dominant volcanic rocks associated with fracturing openings. In this model, it is assumed that the fracturing is dying as the depth deeper and no more opening is expected after 250m.

In the aquifer system, the long period, recharge and output are equal with no significant change of the water level through time. This principle is true except in case of over abstraction which leads to a continuous depletion of the amount of water included in the aquifers. The rough estimation based on the available boreholes pumping yield with average pumping hours set according to the level of beneficiaries, it is believed no more far from the abstraction rate of 2.3M MCUB/Y which is insignificant with surface area of the study. Therefore, Regional over abstraction has not occurred yet in the Lake Tama basin.

### **4.4. HYDRAULIC CONDUCTIVITY**

Hydraulic conductivity is the most essential aquifer parameter that determines the flow system of a model. It is a measure of the ability of fluid to move through aquifer media. It is dependent on the properties of both porous media and the fluid. It is obtained through pump test analysis, laboratory and literature review. In this model, it is also obtained from the pump test analysis, the study of (BCEOM, 1996) with geologic Series and literature review.

The spatial distribution of the hydraulic conductivity of the basin is the most crucial input of the model. The initial hydraulic conductivity parameter is assigned with an overlay analysis of boreholes conductivity results aerial distribution of Thiesen polygon approach, specific yield map and hydrogeological map. The initial hydraulic conductivity

map used as an input gradually refined and updated with calibration process is shown below.

The hydraulic conductivity of an aquifer has a directional value and in this model as the model area is conceptualized as isotropic and single layer unconfined aquifer. It has no vertical flow and have same value for in x and y direction.

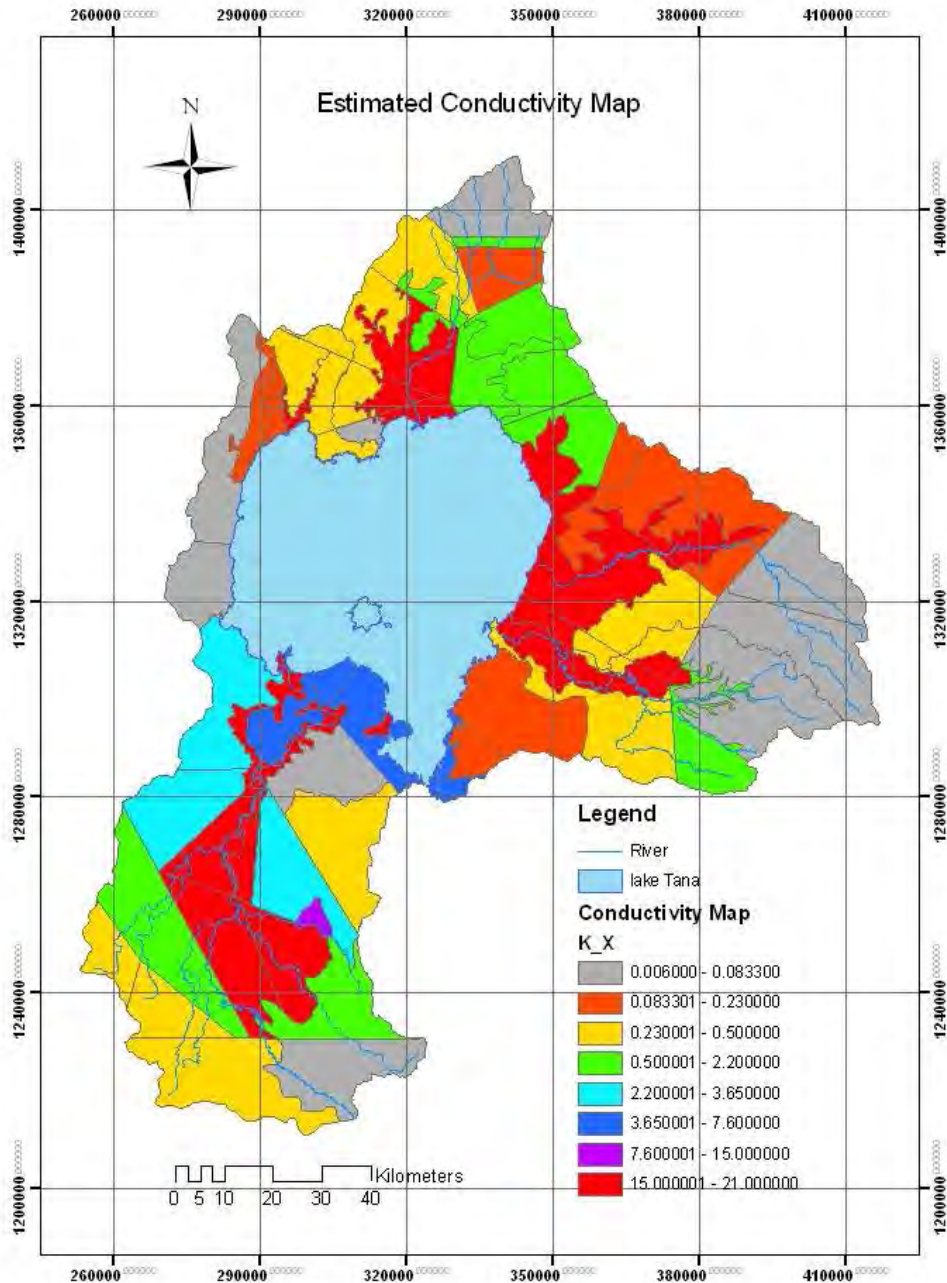


Fig: 4.6. Conductivity Map of Lake Tana Basin, Estimated

Geological series	Discharge in l/s	Specific discharge in l/s/m	Transmissivity in m <sup>2</sup> /s
Quaternary Lava Dangila Bure(QCB2 )	3.5	2.10 <sup>-4</sup>	3.10 <sup>-4</sup>
Tarmaber Basalt First Event (TTB2)	3.5	1.10 <sup>-4</sup>	2.10 <sup>-4</sup>
Basalt Flow connected with volcanic center. (QVCV)	2	5.10 <sup>-5</sup>	1.10 <sup>-5</sup>

Table: 4.1. Compiled transitivity with geologic Series BCOEM 1998

Well Name	Latitude	Longitude	Hydraulic conductivity
Addis zemen	12.133	37.7833	0.06385
Bahr Dar, Kebele 07	11.583	37.3828	4.63104
Bahr Dar, Kebele 08(1)	11.591	37.4	1.45152
Bahr Dar, Kebele 08(2)	11.588	37.3994	18.9216
Bahr Dar, Kebele 11 (1)	11.613	37.4133	9.8496
Bahr Dar, Kebele 11 (2)	11.613	37.4133	0.136512
Chuahit 1	12.3	37.2667	0.590112
Dangla 4	11.273	0	0.030931
Deghi	12.2	37.05	0.215136
Enfraz_1	12.183	37.6333	0.041904
Gorgora1	12.25	37.2833	0.205632
Hamusit	11.768	37.5511	0.045101
kola Dib Village	12.417	37.3167	1.4688
Kunzila	11.876	37.0256	0.864
Yifag	12.05	37.7167	0.179712
Yinessa, Uibeb Iyesus	11.545	37.3075	0.348192
Maksagnit	12.39047	37.56013	0.98496
Delgie	12.2	37.05	0.06817
Gasaye	11.81867	38.13138	0.635904

Table: 4.2. Conductivity of Wells Compiled from previous work

Borehole Name	Longitude	Latitude	Transmissivity	Aquifer Type
Addis zemen	12.13	37.78	1.91	Tarmaber Basalt
Angerb 2(Gondar)	12.58	37.47	3.28	Ashangi Basalt
Angerb 4(Gondar)	12.62	37.47	2.50	Ashangi Basalt
Angerb 5(Gondar)	12.60	37.47	32.83	Ashangi Basalt
Azezo Meat Factory	12.57	37.42	6.15	Tarmaber Basalt
Bahr Dar, Kebele 07	11.58	37.38	55.56	Quaternary Basalt
Bahr Dar, Kebele 08(1)	11.59	37.40	29.12	Quaternary Basalt
Bahr Dar, Kebele 08(2)	11.59	37.40	455.33	Quaternary Basalt
Bahr Dar, Kebele 11 (1)	11.61	37.41	147.74	Quaternary Basalt
Bahr Dar, Kebele 11 (2)	11.61	37.41	3.23	Quaternary Basalt
Bahr Dar, Kebele 11 (3)	11.60	37.42	59.10	Quaternary Basalt
Bahr Dar, Kebele 13 (1)	11.61	37.38	181.40	Quaternary Basalt
Bahr Dar, Kebele 13 (2)	11.59	37.38	155.50	Quaternary Basalt
Bahr Dar, Kebele 13 (3)	11.60	37.38	82.90	Quaternary Basalt
Bahr Dar, Kebele 14)	11.58	37.38	79.40	Quaternary Basalt
Bahr Dar, Kebele 15)	11.59	37.38	27.14	Quaternary Basalt
Bahr Dar, Pedagogue	11.57	37.40	20.40	Quaternary Basalt
Chuahit 1	12.30	37.27	10.63	Tarmaber Basalt
Dangla 1	11.26	36.85	1.79	Quaternary Basalt
Dangla 2	11.26	36.85	9.26	Quaternary Basalt
Dangla 4	11.27	36.86	1.24	Quaternary Basalt
Deghi	12.20	37.05	2.58	Tarmaber Basalt
Enfraz_1	12.18	37.63	8.39	Alluvium
Gorgoral	12.25	37.28	3.29	Tarmaber Basalt
Hamusit	11.77	37.55	1.72	Tarmaber Basalt
kola Dib Village	12.42	37.32	19.09	Tarmaber Basalt
Kunzila	11.88	37.03	15.55	Alluvium
Wetet Abay	11.37	37.04	59.10	Alluvium
Yifag	12.05	37.72	2.70	Quaternary Basalt
Yinessa,Uibeb Iyesus	11.55	37.31	3.68	Quaternary Basalt
Maksagnit	12.39	37.56	32.66	Alluvium
Delgie	12.20	37.05	1.23	Quaternary Basalt
Gasaye	11.82	38.13	7.31	Tarmaber Basalt

Table: 4.3. Compiled transmissivity with major available borehole aquifers SMEC (2007)

#### 4.5. AQUIFER SYSTEM BOUNDARY

The determination of the boundary is an initial step in ground water flow modeling, which is also governed on the purpose and interest of the modeler.

The Boundary of aquifer system determines the relation of the model system with its adjacent environment. The lake basin model of the aquifer is bounded at the top by the water table, laterally by the volcanic ridge considered as no flow which is defined as no recharge and no conductive. The base of the model is assumed as no flow by the dying of the fractures as depth increased; massive bed rock emerges at no less than 250m depth.

The model system is conceptualized as if there is no ground water out flow from the system. In fact, there is no evidence of the previous study that confirm the out flow yet. Most studies confirm the convergence of the ground water flow to the lake like a natural dam with small valley gate that let the Abay out flow from system. No earth material is completely impervious to water. Many earth materials, however, have very low hydraulic conductivities and thus contribute relatively small amounts of water to adjacent permeable ground-water systems.

Depending upon the conceptualization of the system and the objectives of the study, a boundary between a permeable groundwater system with appreciable flow and a surrounding body of earth material of low-hydraulic conductivity that contributes a negligible amount of water commonly is treated as a no-flow boundary.

The objectives of the study and the relative magnitudes of the flow in the bounding material, as compared to the flow in the aquifer material, are keys to assessing the assumption of negligible flow that can be approximated as no flow.

In some systems, assuming a no-flow boundary may be reasonable for flow-system analysis, but such an assumption may not be appropriate for transport analysis in which the actual path of a particle is important. (Conceptual system boundary, USGS)

The Model under the study consider the volcanic ridge surface water divide as the no flow boundary and the same time the decreasing of the conductivity down the depth of the aquifer as bottom no flow boundary.

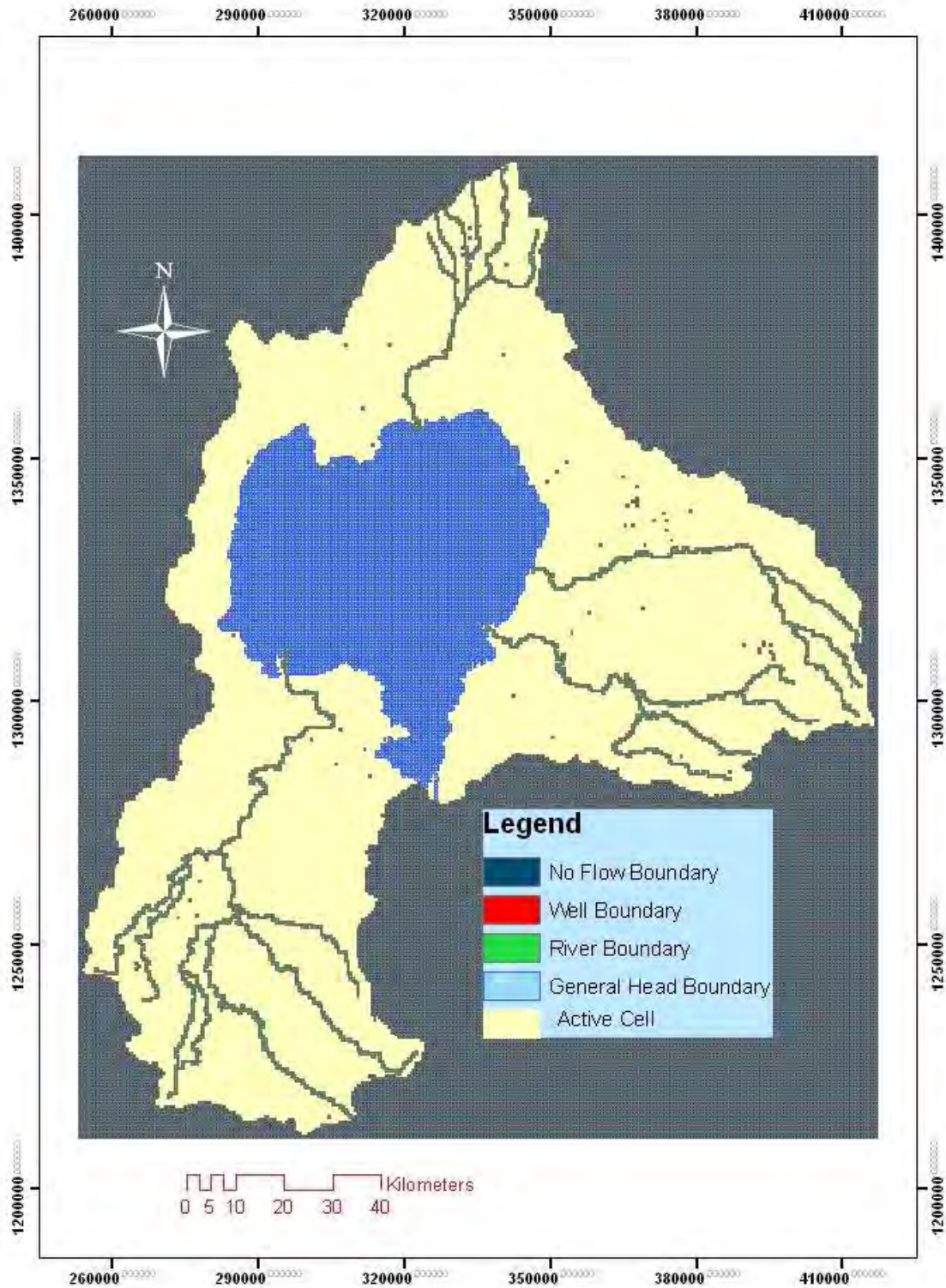


Fig: 4.7. Map Boundary of the Aquifer System Boundary of Lake Tana

#### **4.6. GROUND WATER LEVEL AND MOVEMENT**

Ground water flows from areas of recharge to areas of discharge. Discharge may occur to the atmosphere by transpiration from plants rooted below the water table; to streams, lakes, and other surface-water bodies; or to pumping wells.

The balance between ground-water recharge and discharge controls ground-water levels and storage in a manner analogous to how deposits and withdrawals control savings in a bank account

The country, in common practice of borehole construction, use to position the screen in various depth of the borehole and difficult to identify the water level water level for particular aquifer system in a multi-aquifer geological profile.

Ground water contour stand for the same water level head of the aquifer system. It helps to understand the general trend of the ground water flow as the ground water flow from high head to lower head with perpendicular direction to the contour line. In this study, the contour developed with 147 deep borehole static water levels taken during the borehole construction time. There is no ground water level monitoring system and easy access to measure the water level for most well not provided with the observation pipe.

The depth of the water level ranges from the 1785.00 to 2996.50 and a tendency to converge to ward the lake in each direction. The lowest water level is observed near the lake which is 1785 on the Fogera plain almost similar to the lake level. The hydraulic gradient is high at the high land margin of the basin and lower to ward the lake side.

Ground water recharge, circulation and geochemical evolution in the region of the Blue Nile, Ethiopia (Kebede et. Al 2005). It uses isotope and geochemical, mainly for spring and hand dug well to identify that recharging ground water migrates through short local ground water flow path to discharge as low TDS (Ca-Mg-HCO<sub>3</sub>) dominated ground water. Deeper, more regional flow systems have greater residence time in the aquifer and undergo geochemical alteration to generate higher TDS (Na-H-CO<sub>3</sub>) dominated waters to ward the lake.

## 4.7. RECHARGE AND SPATIAL DISTRIBUTION

Recharge is the volume of the water that joins the saturated zone of the aquifer. It is a term used to describe many of the processes involved in the addition of water to the saturated zone (Wilson and Moore, 1998).

Ground water recharge is one of the most difficult input data to quantify and distribute spatially in precision. It is highly governed with the amount of precipitation that is not lost by the evapotranspiration and run off, the vertical hydraulic conductivity that determine the volume of the water joining the saturated zone and the water moving ability of the aquifer and hydraulic gradient.

Recharge from precipitation is frequently an important source of water to ground-water systems. In many if not most locations, precipitation (rainfall or snowmelt) soaks into the ground and recharges the water table over the aerial extent of the aquifer system. The recharge rate is usually then incorporated into ground-water flow models as a specified flow boundary condition along the top boundary of the ground-water model.

In this modeling; the ultimate source of the recharge is precipitation and expressed as flow per unit area (L<sup>3</sup>/l<sup>2</sup>). It is believed that parts of the precipitation join the aquifer system and become recharge over the area. In fact this works particularly for the unconfined and semi confined aquifer system.

Unlike this, there is also the possibility of recharge from inter aquifer system with adjacent basins. The inter aquifer system recharge in this model is ignored as the aquifer system is conceptualized with no in or out flow ground water from the system. It is also assumed that recharge will affects the upper most surface of the layer only as the system boundary considers no ground water interconnection of adjacent basin.

There is no standard techniques to evaluate quantitatively and spatial distribution. However, ground water recharge is often estimated with a help of the fractioning of the precipitation. Precipitation occurs evenly over a large area with a relatively easily spatial distribution compared to the recharge factors stated above and it plays major role. In this study, it is considered as a tool and an initial estimate of the average distributed recharge. However, the final recharge estimation will be drawn through a ground water flow modeling calibration.

The study of (BCEOM, 1996) which result the association of rainfall infiltration coefficient (I) derived from the ratio aquifer recharge over rainfall depth within each sub-basin and the estimation of this parameter derived from the calculation of the rainfall infiltration coefficient related to each geological series which almost result similar result taken as the major devise for the conceptualizing the recharge of lake Tana basin. Please refer the tables that show the infiltration coefficient of the gauged part of sub basin.

Sub basin	Catchments' Enclosed Gauged Km <sup>2</sup>	Runoff		Rainfall	Groundwater		Infiltration coefficient
		Mm3/y	mm	mm	Mm3/y	mm	
Gilgel Abbay	1664	1849	1111	1700	507	305	18%
Koga	244	156	637	1550	49	203	13%
Ribb	1592	421	264	1490	56	35	2%
Gumara	1394	864	620	1235	125	90	7%
Megech	462	225	487	1000	26	55	6%

Table: 4.4. Rainfall infiltration coefficient derived from groundwater contribution to surface flow ((BECOM, 1996)

It No	Description of the Geology	Sub Basin	Infiltration coefficient
1	Basalt lava flows connected to volcanic centers of Bure-Dangila lava flows, quaternary basalt that cover most southern part of the Lake Basin	Gilgel Abay	20%
2	Basalt lava flows connected to volcanic centers Injjibara-Santil ridge, Tertiary basal that cover the most part of the North and west part of the Bsin	Part of koga , Rib , Gumera	10%
3	Tarmaber Basalts	Small part of the Gumera	5%
4	Metamorphic basement	Not shown in the basin	3%

Table: 4.5. Rainfall infiltration coefficient derived from Geologic Series to surface flow ((BECOM, 1996)

In this model, the quantification and the spatial distribution is made based on the study of (BCEOM, 1996) in association with current aerial distribution of rainfall of the basin. The study also assumed that the ungauged part of the sub basin hold similar distribution as long as same geologic series prevailed in the area.

The Lake Tana basin (BCEOM, 1996) study results that aquifer recharge ranges from 50 up to 300 mm and its distribution seems to be strongly linked to the rainfall geographic distribution. The rain fall and the recharge amount are highly correlated. Therefore, the quantitative and spatial distribution of recharge of the lake basin drawn from overlay analysis stated above used for model input is mapped as follow.

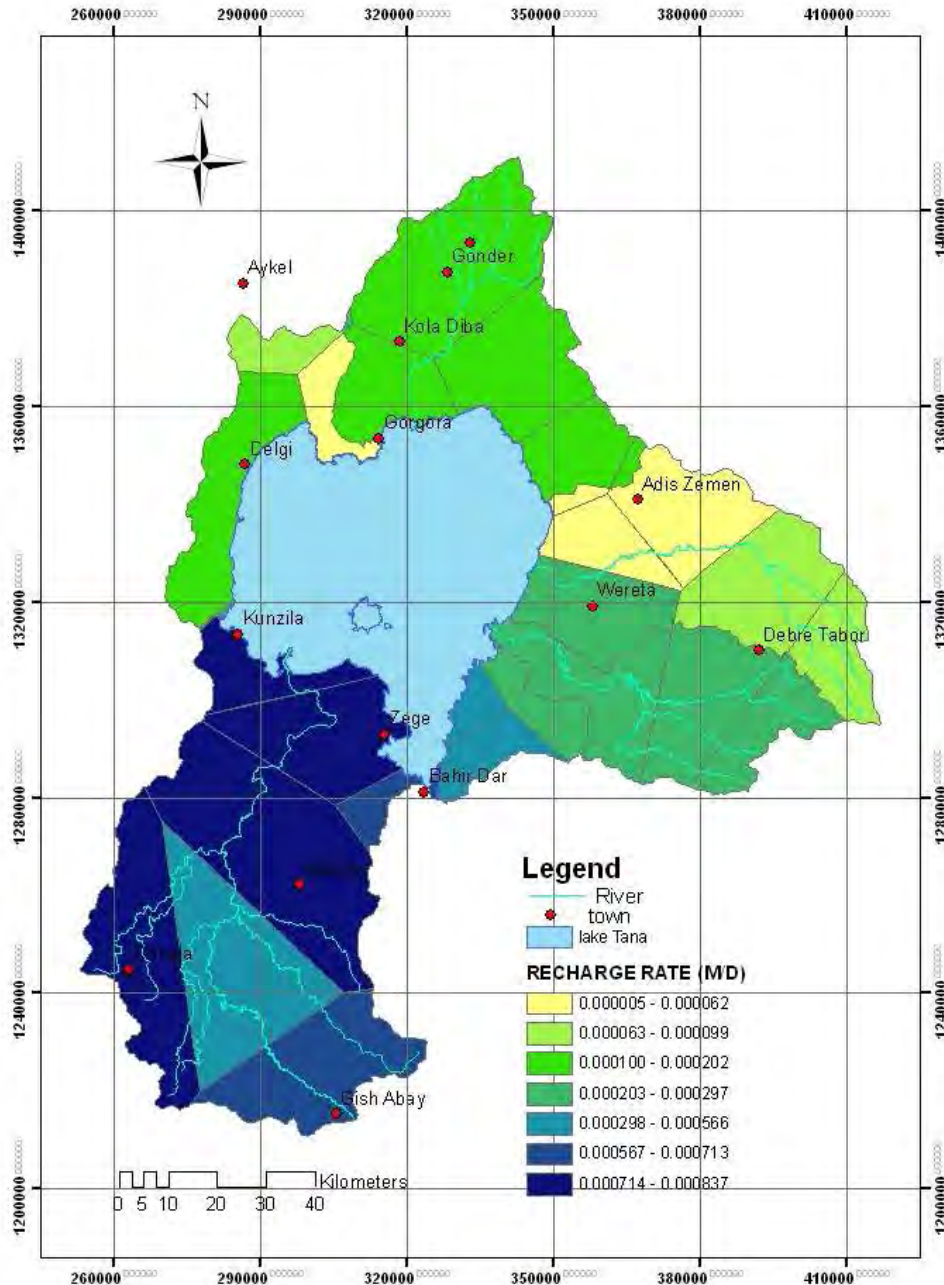


Fig: 4.8. Spatial distribution of Recharge of Lake Tana Basin

## **4.8. GROUND WATER DISCHARGE**

Aquifer system is not only with an input of a recharge but also releases its resource out of the system. The major removal ground water from aquifer system of the lake basin is possibly occurred through abstraction of water wells, springs, Base flow to surface water body, Inter basin or aquifer system transfer and Evapotranspiration.

In evapotranspiration of Lake Basin, the water is supposed to leave the aquifer system from shallow water level at which the solar energy able to reach or accessed with deep rooted plants. In this model, it is conceptualize as negligible discharge compared to the size of the basin and its pronounced effect on open water body.

In this model, the lake basin aquifer system is considered as unconfined and single layer bounded with no interaction with adjacent aquifer system. As it is also assumed to be single layer, there is no possible way to release its resource to lower or upper aquifer system and no subsurface out flow is conceptualized. The abstraction well, springs and base flow to surface water body is considered in the model described below.

### **4.8.1. SPRING DISCHARGE**

Springs typically are present where the water table intersects the land surface. Springs represent a discharge from the ground-water system. When the head in the aquifer becomes lower than the land surface opening of the spring, the spring dries up. The higher the head in the aquifer above the altitude of the spring opening, the more water discharges from the spring. Thus, springs are usually treated as nonlinear head dependent discharge boundaries that have zero flow when the head in the aquifer becomes lower than the altitude of the spring.

In the region under study, there are a number of small springs with discharge less than 0.25l/s which is almost insignificant discharge and a very few prominent springs with large discharge.

### **4.8.2. WELL WITHDRAWAL**

Ground water use in the basin is limited to domestic water supply consumption for the town and village of the basin. There is no prominent practice to use for the industry as the basin is not industrially developed and the same is true for the use of groundwater for irrigation.

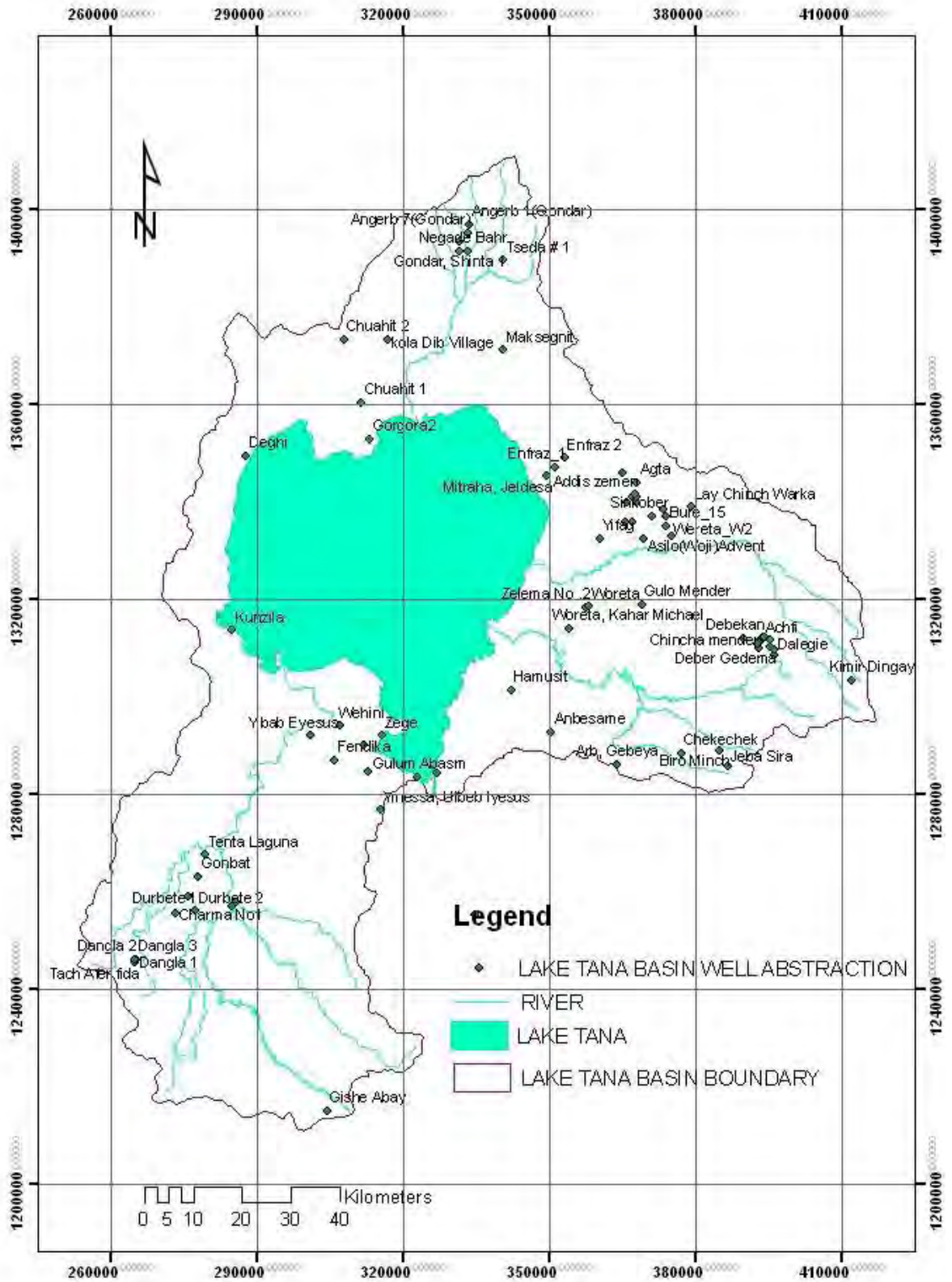


Fig: 4.9. Spatial distribution of Ground water Abstraction well

The common practice to abstract the ground water is with hand dug well, shallow well and deep boreholes with motorized scheme. The model only considers the motorized deep borehole with the assumption that boreholes abstract a relative significant amount of water from the aquifer system

The actual yield of the borehole is for there is no a responsible body and centralized system to collect such important task. In this model, the abstraction amount of boreholes analyzed based on the combining mean pumping rate of the boreholes major aquifer and assuming an average pumping eight hours for major towns and four the rural village.

Aquifer	Specific Capacity (L/sec/metre)			Pumping rate (L/sec)		
	Range	Mean	Median	Range	Mean	Median
Quaternary Alluvials	0.02 - 0.53	0.28	0.33	1.3 – 6.5	4.14	4.06
Quaternary Basalts	0.034 – 6.43	0.65	0.11	1 - >10	3.85	3.10
Termaber Basalt	0.018 – 3.31	0.25	0.14	0.7 – 16.8	3.63	2.78
Ashangi and Aiba Basalts	0.008 - 1.49	0.27	0.11	0.67 -17	4.20	2.68

Table: 4.6. Summary for specific capacity and pumping rate of the borehole in major aquifer of the Lake Tana basin, (SMEC, 2007)

Based on the above stated analysis factor, the abstraction of the ground water simulated with well package with an average withdrawal of 6327.9M<sup>3</sup>/D. The detail description of the boreholes considered and the amount water with drawn from the aquifer system is stated on the annex III of the paper.

### 4.8.3. BASE FLOW

The base flow represent the interaction of the aquifer system with the perennial stream with a concept of ground water maintain the flow of stream during dry season. Based on this concept, Groundwater base flow has been considered as an estimated by base flow recession analysis method for the Gilgel Abbay, Koga, Megech, Rib and Gumara catchments (BCEOM 1998).

Perennial River	Station	Latitude		Longitude		Catch. Km <sup>2</sup>	Groundwater		Recession slope
		°	'	°	'		Mm <sup>3</sup> /y	mm/y	
Gilgel Abbay	Bahir Dar	11	22	37	02	1664	507	<b>305</b>	0.005880
Koga	Merawi	11	22	37	03	244	50	<b>203</b>	0.002941
Rib	Addis Zemen	12	00	37	43	1592	56	<b>35</b>	0.008138
Gumara	Bahir Dar	11	50	37	38	1394	125	<b>90</b>	0.005797
Megech	Azezo	12	29	37	27	462	26	<b>55</b>	0.010648

Table: 4.7. Summary Base flow Analysis Result of Major River (BCEOM 1998)

The base flow analysis is conducted on the gauged catchments of five major river shows the occurrence of high interaction of the river and the aquifer system. The quaternary formation, which covered the Gilgel Abay Catchments, releases the highest base flow to the stream (507 Million  $M^3/Y$ ). The other river catchments aquifer also release a significant amount of ground water to the aquifer system.

The interaction of the river and the aquifer system is mutual relation to feed either of the rivers or the aquifer system based on the relative difference of stage of stream and the adjacent aquifer system. The one with a higher hydraulic head is expect to feed the lower hydraulic head. The interaction is also governed with the presence and degree of conductance the river bed and aquifer system.

The model considers the high interaction of the river and aquifer system with conceptualizing perennial stream with river package which consider the stated hydraulic head and the stage of river.

#### **4.9. LAKE AND GROUND WATER INTERACTION**

The regional groundwater flow of the area clearly shows the movement of ground water to ward to the lake. The previous knowledge of the interaction is indirect or assumption that tried to explain quantitatively with analytical approach. In fact, there is no monitoring data in the immediate vicinity of the lake, the mechanism of any groundwater discharge to or from the lake is not clear.

The bed thickness of Lake Tana floor is expected to be 80m -70m thick clay layer as the direct drilling on the floor revealed. The lake bed thickness and formation is the most essential knowledge to consider the lake floor with likely low hydraulic conductivity with the underlying aquifer system.

The analytical analysis of the SMEC, 2007 with assumption of an average lake level of 1785m and even with an underlying head of say 1800m, the vertical leakage through the 80m thick clay, with a vertical hydraulic conductivity of 0.0001m/day would suggest a leakage rate of 7mm/yr (**58397.2M<sup>3</sup>/D**). The assumption take a head in the aquifer beneath the lake with a relative high magnitude, but vertical leakage to and from the lake into the underlying aquifer is considered negligible.

The analytical analysis of the lateral interaction of the aquifer system and the lake with the prevailing low hydraulic gradient between the Lake and the aquifers in areas

surrounding the Lake, which is not likely to lead to significant lateral leakage into or out of the lake. Applying the regional gradients from the groundwater elevation contour ranging from 0.02 to 0.005 towards the lake, assuming discharge into the lake from a 50m thick aquifer with hydraulic conductivity of 1m/day, the discharge into the lake will be less than 1mm/yr (**8342.47 M<sup>3</sup>/D**) (SMEC, 2007)

The analytical analysis can be summarized with nearly **66,739.67M<sup>3</sup>/D**, which is inconsiderable compared with perennial stream interaction but still hard to be considered in the water budget.

The other important finding of Lake and ground water interaction is the predicted by isotope geochemical studies of groundwater in the vicinity of the Lake which show little evidence of mixing lake water with the adjacent aquifers (Kebede et al 2005). The same study predicts less than 7% Lake Inflow is the ground water.

#### **4.10. WATER BALANCE OF THE LAKE TANA BASIN**

The water balance is the budget of the aquifer system upon which the model is governed quantitatively. It is the most quantitative part of the hydrogeology. In a steady state aquifer system, the inflow and outflow of groundwater from the aquifer system is balanced throughout the hydrological period. It is identified and quantified with an annual base. The major component of the water budget is inflow and outflow. In a steady state, it is assumed that the inflow and outflow of groundwater in the aquifer system is equal with negligible change in storage in the hydrological year usually a year.

##### **4.10.1 IN FLOW**

The precipitation recharge is the governing inflow to the aquifer system but not the sole inflow. The other possible recharge from the subsurface of adjacent aquifer, the leakage of Lake Tana and artificial recharge has been simulated according to the conceptual model. There are also other possible inflows to the system like the subsurface inflow from adjacent aquifer, stream yielding to aquifer, large water body (Lake Tana) leak to system and artificial recharge.

The model considers the precipitation recharge as the inflow component and other inflows will be treated based on the conceptual model. The ultimate source of the recharge is precipitation which is with a relative convenience to quantify and spatially distribute. Based on the precipitation analysis of the 1990\_2006 the Lake Tana basin is privileged

with **20,827,682,820.00 M<sup>3</sup> /Y** estimated rain water. The figure includes the precipitation up on the lake annual precipitation **3,956,442,951.00 M<sup>3</sup>/Y**.

In this model, Water balance of the Lake Tana Basin derived from the BCEOM study of the Abbay Basin (1998). The study used base flow recession data to calculate groundwater contribution to the stream flow and then applied this as the recharge rate to the aquifer. This paper also used BCEOM finding in association with 1990\_2006 spatial distribution of precipitation. Accordingly, it results a recharge of **1,756,791,794.90 M<sup>3</sup>/Y**, which is the ground-water savings account of the aquifer system.

The above stated recharge could be explained with the precipitation recharge nearly 10.5% of the precipitation on the land side of Lake Tana Basin and 8.43% of the Lake Tana basin.

The other possible recharge from the subsurface of adjacent aquifer, the leakage of Lake Tana and artificial recharge has been simulated according to the conceptual model. Particularly, The lake inflow or out flow is not clearly quantified excepting the qualitative concept of the poor interconnection with aquifer system, and so that it is not considered with in flow for its insignificant impact either for recharge or discharge.

#### **4.10.2. OUT FLOW**

The out flow component of the grounds water incur the expense of the ground water reserve of the aquifer system. It includes the out flow from ground to perennial stream, out flow from the aquifer system to the adjacent aquifer, discharge from spring and withdrawal of ground water with pumping well.

The main out flow component of the aquifer system is discharge of ground water to feed the stream during the dry period when no direct run off is present. It can be explained with base flow which occurs as stage of stream is less than the hydraulic head of the aquifer system water table. The Gilgel Abbay, Koga, Megech, Rib and Gumara are prominent perennial stream to be considered to share the of the ground water reserve of the aquifer system.

In Lake Tana basin, the base flow is quantified based on the BCEOM study of the Abbay Basin (1998). The BCEOM study made the analysis only for gauged part of the perennial stream. And this paper extrapolates the result to ungauged part the major stream

catchment. Accordingly, the base flow analysis for major perennial streams are estimated and stated below.

CATCHMENT	Catchments' Enclosed Km <sup>2</sup>	Runoff		Groundwater Discharge	
		Mm <sup>3</sup> /y	mm	Mm <sup>3</sup> /y	Mm
GILGEL ABBAY	4671.55	1849	1111	1,423.36	304.6
RIBB	2225.8	421	264	78.29	35.16
GUMARA	1413	864	620	126.70	89.67
MEGECH	2348.58	225	487	132.17	56.28
<b>TOTAL</b>		<b>7799.09485</b>		<b>1760.53</b>	

Table: 4.8. Extrapolated Base flow analysis for the Ungauged Major River Catchments

The total Base flow considered in the basin is estimated to be **1,760,532,262.09 M<sup>3</sup>/D** with **3,740,467.19M<sup>3</sup>/Y** surplus of the ground water reserve of the aquifer system from precipitation recharge. This is perhaps due to the unconsidered possible in flow from adjacent aquifer system, the discharge of lake to aquifer system or the assumption of the gauged area base flow could be extrapolate to the un gauged one. It needs further study the justify on the case stated above

The other important ground water out flow from the aquifer system is occurred with the ground water withdrawal of the pumping well and springs. It is quantified with nearly **2309718 M<sup>3</sup>/Y**. The Evapo transpiration is also a possible out flow which is assumed to be negligible taking the prevailing low temperature and water table depth that is not this much vulnerable for the vaporization.

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITAION RECHARGE	<b>4,813,128.21</b>		<b>1,756,791,794.90</b>	
II	GROUND WATER WITHDRAEWAL		<b>6327.99</b>		<b>2,309,718.57</b>
III	SUBSURFACE FLOW	-	-	-	-
IV	BASE FLOW		<b>4,823,376.06</b>		<b>1,760,532,262.09</b>
	<b>TOTAL</b>	<b>4813128.21</b>	<b>4829704.05</b>	<b>1,756,791,794.90</b>	<b>1,762,841,980.66</b>

Table: 4.9. Summary of Estimated Water Balance

## CHAPTER FIVE

### 5. NUMERICAL MODELING

#### 5.1. GENERAL OVERVIEW

Groundwater flow of the Lake Tana aquifer system is simulated using the USGS three-dimensional finite-difference groundwater flow model **MODFLOW** (Harbaugh and other, 2000). It uses version of MODFLOW-2000 is a modified version of MODFLOW (Mc Donald and Harbaugh, 1988) Interfaced with Ground water vista \_3 that facilitates input and out put of parameters to define model input, the calculation of parameter sensitivities and the modification of parameter values to match observed heads, flows or advective transport using the observation, sensitivity and parameter estimation processes described by Hill and others (2000).

The MODFLOW employs a numerical modeling with widely used, tested and verified model which simulate each hydrologic feature independently with its modules grouped package. It is deterministic model approaches which assume the stage or response of aquifer is predetermined by the help of physical laws governing the ground water flow. Unlike the analytical model which solves one equation of ground water flow at a time, provide solution for the entire flow of the study area at the same time.

The MODFLOW use a cell which subdivided the study area in to small partition and the ground water flow equation is solved for each cell. The ultimate result of the MODFLOW is the distributions of the hydraulic head at point of node which locate at the center of the rectangular cells represent the cell.

The basic principle of the MODFLOW depends on the approximation or replacing of the partial differential the governing equation, boundary and initial condition in to algebraic equation and the algebraic equation which can be explained in matrix equation is solved with a numerical approach through the iterative process.

In this model, the matrix is solved with preconditioned Conjugated Gradient 2 (PCG2) and of Mod flow with convergence criteria of 0.001m. The simulation of the model is expected to upgrade the understanding of the ground flow system and will be ready to after flow model analysis.

## 5.2. GOVERNING EQUATION

The original mathematical model is started with governing equation which controls the ground water flow of the aquifer system. It is a representation the physical law that controls the ground water flow and derived by the combined concept of the conservation of Mass and Darcy law. It is used in the computer model to describe groundwater flow is:

$$\frac{\partial}{\partial x}\left(K_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz} \frac{\partial h}{\partial z}\right) - W = Ss \frac{\partial h}{\partial t} \quad \text{Equation 5.1}$$

Where:

$K_x$ ,  $K_y$  and  $K_z$  : are the values of hydraulic conductivity along x, y and z coordinate axes and are assumed to be parallel to the major axes of hydraulic conductivity, in meters per day;

$h$  : is hydraulic head, in meters;

$W$  : is a volumetric flux per unit volume and represents sources or sinks or both of water, such as well discharge, recharge and water removal from the aquifer by drains, per day ;( $LT^{-1}$ )

$Ss$  : is the specific storage of the porous materials, per meter ;( $L^{-1}$ )

$t$  : is time, in days.(T)

In order to simulate Lake Tana basin aquifer system, equation 5.1 is updated according the prevailing field condition. Based on the assumption of the conceptualized model as steady state unconfined aquifer and single layer with no possible flow in Z direction, the above equation can be simplified and rewritten in to the following equation: The governing equation is assumed to be aquifer system model and considers the flow of ground water in both vertical and horizontal direction with continuous manner and allow two or three dimensional. (Anderson and Woessner, 1992).

$$\frac{\partial}{\partial x}\left(K_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} \frac{\partial h}{\partial y}\right) - W = S_y \frac{\partial h}{\partial t} \quad \text{Equation 5.2}$$

$S_y$  is specific yield the equivalent of the Specific storage and the steady state is characterized with no storage or change of head through the hydrological year.

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) = +(-)R \quad \text{Equation 5.3}$$

Where: R is a general sink or source intrinsically positive for to represent recharge and negative for withdrawal of ground water from aquifer system.

### 5.3. SPATIAL DICRETIZATION

The ground water flow equation considers both the vertical and horizontal flow which requires continuity in space and time. In the numerical modeling, the continuous problem domain is replaced by dicretized model consist of an array of nodes and associated finite difference cell (Block). (Anderson and Woessner, 1992).

A finite-difference model is constructed by dividing the model domain into square or rectangular regions called **blocks** or **cells**. Head or concentration is computed at discrete points within the model called **nodes**. The network of cells and nodes is called the **grid** or **mesh**. The region under study is also defined by discretized aquifer system in to finite difference grid and single layer. It is consist of a three dimensional array of the nodes know as model grid. The model grid is formed with two set of parallel lines that are orthogonal to each other.

This model follows the block center grid which defines the hydraulic head and represents an average result of the cell. It uses the assumption of the homogeneity of the hydraulic and hydro geologic character. The grid orientation has tried to meet the lowest possible number of inactive cell to reduce the load on the memory of the computer.

The surface area of the region under investigation and the size of cell determine the number of cell required. The study area covers 15152 sq km and the model dicritize with a uniform size of 500m by 500m. The model size is large but meets the objective to understand the regional ground water flow system. It is also considered a uniform cell size to ease the computation, the accuracy of the model and better convergence of the model simulation. The model extent defined with **164km** width and **201.50km** height.

The Origin of the Model spread from the lower left corner of the grid with geographic coordinate of UTM 37N 253085.76E and 1210493.47N. The model makes up an array of a cell with 403 rows and 328 columns. The model used a total number of **132,184 cells** in a single layer of which only **60,268** are active and effective to compute the hydraulic head. The remaining **71,916** number of cells are in active with no computation will be carried out in this part of the model.

The irregular shape of the region under study treated with rectangular finite difference model approach may increase the number of inactive cell and reduce the number of active cell in the model.

#### **5.4. TOP OF THE LAYER**

The top of the aquifer layer is assumed to be the ground elevation and drawn from the 90m\*90m resolution digital elevation model. The model uses a single layers defined by horizontal and vertical collections of rows and columns. The DEM data is processed to generate grid file to be in a format compatible to the GV3 and imported to the model with elevation referenced according to its geographic position. The imported grid elevation converted to zone with an elevation range of 1500M to 4009 m.

#### **5.5. BOTTOM OF THE LAYER**

The bottom of the layer in association of the top layer determines the thickness of the aquifer. In this model, the bottom of the layer is determined with a consideration of 250m depth from the ground elevation. It is developed with a help of **SURFER 8** deducting 250m from the top layer grid data. In fact there is a deficient in information to delineate the basin aquifer thickness; however it assumed the aquifer forming fracturing decrease with depth and die after the depth of 250m. This also has been imported to the modeling the same manner of the top layer with grid format and distribute the data in zoning spatially with geographical reference.

#### **5.6. BOUNDARY CONDITION**

In steady state simulation, the boundaries largely determine the flow pattern. Setting the boundary is the critical step on the modeling and controls the water entrance and exit point of the model system. Boundary could be the geographical separation of the modeled system or the hydrological process boundary that is controlled with the physical law represented by the mathematical code. All boundary condition in the model initially

converted with spatial and attribute shape file and imported to be simulated with is mathematical code analogous to the boundary.

### **5.6.1. GEOGRAPHICAL BOUNDARY**

The geographical boundary determined based on the objective, physical boundary and the impact of stress to be simulated .In this model, the geographical separation of the model system is largely determined with following the topographical divide which actually assumed to coincide with the ground water divide and there is no planned stress to be simulated to by pass the boundary too.

Geographically, the lake basin is surrounded with a relatively low hydraulic conductivity volcanic ridge. And also topographically dip and converge to ward the Lake Tana in all direction.

The same convergence is observed in the static water levels maps too. This is for the case of the lateral boundary of the aquifer system with adjacent basin. It is simulated with no flow boundary for all side of the basin. As far as previous study concerned, there is no quantified ground water exchange with adjacent basin expecting the speculation of in flow of ground water to the system in around Mt Choke and Mt Guna of Gilgel and Gumera catchments respectively.

The model upper boundary is open to the flux of the recharge and evapotranspiration and assumed to be the water level of the unconfined aquifer system. The lower boundary with impermeable bed of massive volcanic rock with a dying effect of the opening as depth of the formation increased and simulated with no flow boundary.

### **5.6.2. HYDROLOGICAL PROCESS BOUNDARY**

This Boundary condition is a mathematical model that determines how and where the ground water in and out of the aquifer system. The boundary specifies the dependent variable or the derivative of the dependent variable at boundary problem domain. (Anderson and Woessner, 1992). This Boundary conditions fall into one of five categories: specified head or Dirichlet, specified flux or Neumann, mixed or Cauchy boundary conditions, free surface boundary, and seepage face (Franke et al.1987).

GV interface modeling supports the use of the first three types, specified head, specified flux, and mixed type boundary conditions. Specified head boundary cells are called

constant head cells. Specified flux boundary cells are represented using no-flow, wells, or recharge. The latter flux is actually defined as a parameter. Mixed-type boundary conditions are called rivers, drains, general-head boundaries, streams, or evapotranspiration. The latter is treated like recharge as property for its aerial distribution. The lake Tana Basin Modeling uses the specified flux for no flow boundary, wells or recharge and Mixed type boundary for the river and general head boundary.

The terminology used to describe boundary conditions is consistent with the MODFLOW usage (McDonald and Harbaugh 1988). Constant head boundary conditions are assigned a head and/or concentration that do not vary throughout the simulation. GV3 also to specify whether a constant head cell refers to head, concentration, or both. In mod flow, specified head cells are represented by assigning value less than zero (-ve) and usually -1 to entries IBOUND array.

Constant flux boundary conditions are called wells in GV. You will specify a constant flux in a cell by entering the volumetric flow rate in our case  $M^3/D$  that the model (e.g. MODFLOW) will extract or inject into that cell. The sign of the flow rate (positive or negative) depends upon the model. For example, MODFLOW assumes that negative flow rates indicate pumping and positive refers to injection. Recharge is a form of constant flux boundary conditions; however, it is normally distributed over large areas of the model and is thus categorized as a parameter in GV

No-Flow boundary conditions, a form of constant flux boundaries, are applied to cells that are outside the computational domain of the model. These are termed inactive cells in MODFLOW (IBOUND = 0). Head and concentration are not computed in cells designated as no-flow.

In the case of active cells, the MODFLOW assign values greater than one which is usually 1. In block centered finite difference grids, specified boundaries are located directly at the node but flux boundaries are located at the out side edge of the block.

The Lake Tana model imports all boundaries and they are defined by spatial coordinates rather than row-column layer coordinates. These boundary conditions are assigned to model nodes (row, column, layer) when model data sets are created.

### 5.6.2.1. MIXED-TYPE BOUNDARY

In this model GV3 used three types of mixed-type or head-dependent flux boundary conditions which include **drain**, **river** and **general-head**. Evapotranspiration is another form of head-dependent flux boundary condition; but ignored in this modeling. The head dependent boundary uses the assigning of the boundary head and a conductance term. In most models, the flux of water into or out of the cell is then computed as follows:

$$Q = C (H_b - H_m) \quad \text{Equation 5.4}$$

Where:         $Q$         = flux into or out of boundary cell (L<sup>3</sup>/T),  
                   $H_b$         = boundary head (L),  
                   $H_m$         = head computed by model (L), and  
                   $C$          = boundary conductance (L<sup>2</sup>/T).

The conductance term is a coefficient that is usually computed using an equation similar to the following:

$$C = K_b A / B \quad \text{Equation 5.5}$$

Where:         $K_b$         = hydraulic conductivity of the boundary material (L/T),  
                   $A$          = area of the boundary (L<sup>2</sup>), and  
                   $B$          = thickness or width of boundary (L).

For example, the conductance term for the MODFLOW river boundary type is computed using the hydraulic conductivity of the river bed material, the area of the river bottom within the finite-difference cell, and the thickness of the river bottom (McDonald and Harbaugh 1988).

The generic form of the head-dependent flux boundary condition (general-head boundary in GV and MODFLOW) computes the flux of water into or out of the model and assigns that flux to the cell. The other types of head-dependent boundary conditions (drains, rivers, and streams) modify this flux term depending upon the relationship of boundary head to model-computed head in the cell. The drain boundary condition will only allow water to be removed from the system; if the head computed by the model is less than the head in the boundary (drain), the boundary condition is turned off. The river boundary condition also limits the amount of water injected into the aquifer if the aquifer head drops below the bottom of the river (McDonald and Harbaugh 1988).

### 5.6.2.2. RIVER BOUNDARY

The major perennial streams are the most essential river boundary in the lake basin that holds the surface water and aquifer system interaction. It is believed that Gilgel, Koga, Gumera, Rib and Megech streams and their major tributaries sustain their dry period of flow with the contribution of the ground water. These streams are also expected to feed the ground water during the wet period when the stage of the river exceeds the adjacent aquifer system head.

In order to simulate the interaction of the surface and ground water interaction the model used the river package. The river package is used to simulate the flow between an aquifer and an overlying or under lying source of reservoir but usually river. Despite the weakness of the discharge of water from the stream is independent of the actual discharge, it simulates the river with the available data. The interaction of the river and aquifer can be mathematically represented by the MODFLOW by the relation of hydraulic head of model and the stage of river both on the upper table and bottom of river shown below.

$$Q_{RIV} = C_{RIV} (H_{RIV} - H_{AQU}), \text{ When } H_{AQU} > R \quad \text{Equation 5.5}$$

$$Q_{RIV} = C_{RIV} (H_{RIV} - R_{BOT}), \text{ When } H_{AQU} < R_{BOT} \quad \text{Equation 5.6}$$

Where:

$Q_{RIV}$ : The rate of leakage through the river bed

$H_{RIV}$ : Head in the river

$H_{AQU}$ : Head in the aquifer or the model

$R_{BOT}$ : Elevation of bottom of the river

$C_{RIV}$ : Conductance of river bed expressed

$$C_{RIV} = KLW/M \quad \text{Equation 5.7}$$

Where:

K: Hydraulic conductivity of the river bed

L: Length of the river reaches

W: Width of the river reaches

M: Thickness of the river bed

In order to fulfill mathematical model that govern the interaction of the surface water and aquifer, the physical characteristics range used for each major river is summarized below.

S/N	Major Stream	Conductivity M/D	Thickness Bed (M)	Head of the River (M)	Width (M)
1	Gilgel and Tributary	0.00831- 0.08700	0.05_0.6	1789.7- 2555.9	4_40
3	Gumera and Tributary	0.001295- 0.003090	0.1- 1	1787.14- 2153.56	5-22
4	Rib	0.013633-0.076660-	0.1-0.98	1796.23-3348.992	5-19
5	Megech	0.000033-0.189699	0.1- 1	1787.0 - 2660.61	0.1-19

Table: 5.1. Major Stream Model Input Summary

### 5.6.2.3. GENERAL HEAD BOUNDARY

Lake and reservoirs are usually hydraulically connected to ground-water flow systems and can be significant physical features of the flow system. The manner in which they are represented in a numerical model is important to accurately reproduce their role in the actual ground-water system. Their role is similar to that of streams in those lakes and reservoirs can lose water to the ground-water system, gain water from the ground-water system, or do both. In some situations, Lakes and reservoirs can be simulated with the same boundary conditions as those used for streams. In some instances, however, where the lake or reservoir level and area are dependent upon the interaction with ground water, a more complex approach is required.

In ground-water models, a lake or reservoir may be represented as: A specified-head boundary, A head-dependent or ‘leaky’ boundary, Nonlinear variations of the ‘leaky’ boundary.

In this model, the Lakes is considered as water body simulated with general head boundary which is a head dependent with the surrounding aquifer system. For cases in which the lake or reservoir is large and no change in stage is expected for the stresses to be imposed on the model, the specified-head and head-dependent boundary conditions may be appropriate. (Conceptualizing Aquifer System, USSG Report)

The function of the general head boundary package is mathematically similar to that of the river and the drain package. It is mathematically represented by the flow to the boundary ( $Q_b$ ) is calculated as the product of the conductance of the boundary ( $C_b$ ) and the head at or beyond the boundary ( $h_b$ ) and in the aquifer ( $h$ )

$$Q_b = C_b(h_b - h)$$

Equation 5.8

Unlike the river package, the general head boundary assumes a continuous linear discharge or leakage but still lacks to consider the volume of the lake. In order to meet the mathematical code of the general head boundary, the general head boundary of 1786m and lake bed conductance of 0.001 M/D facts.

#### **5.6.2.4. SPECIFIC FLUX BOUNDARY**

It is a boundary with known flux which allows constant volume abstraction or addition of ground water in the aquifer system. In MODFLOW, Recharge, evapotranspiration, No flow boundary and wells are considered as a specific flux. The GV3 model categorizes recharge and evapotranspiration as property for keeping the MODFLOW mathematical code with no difference than nomenclature and convenience of simulation. In this report the recharge is described under the model property with no conceptual difference of the MODFLOW.

The well package simulates pumping or injection wells using rates (Q) based on the estimated actual abstraction or injection with for a given period of stress. In this model, the wells are simulated for abstraction with negative discharge rate. It is simulated fore a cell and wells in same cell simulate with sum up of the rates falling in the same cell.

The available pumping wells the rate of assumption based on the conceptual simulate the well abstraction.

On the Other hand, Specific flux across which zero flow is considered as no flow boundary. Accordingly as specified by the conceptual model the no flow boundary surround the model peripheries except the upper boundary.

#### **5.7. INITIAL CONDITION**

Initial condition refer to the head distribution every where in the system at the beginning of the simulation. (Anderson and Woessnner 2002).Initial heads are known as Starting Heads in the MODFLOW manual and are given the variable name SHEAD. These heads are written in the BASIC Package to start the simulation. In this model, the preliminary potentiometric map developed used as an initial condition and imported as grid surfer file format.

For steady-state simulations, the model will run much faster if the starting heads are close to the final answer and helps on computing leakance (VCONT), the correct value of leakance for an unconfined upper layer (i.e., layer 1) can only be calculated if the starting heads (and hence the top of the layer) represent the water table. For the case of Lake Tana modeling initial condition helps to fasten the simulation.

## 5.8. MODEL PROPERTIES

The model defines different properties that are represented in the model in zones or equal value. Many of these parameters are hydraulic or transport properties, of which the following: hydraulic conductivity, storage coefficient (including specific yield and porosity), layer bottom elevation, layer top elevation and Other types of parameters include boundary conditions and initial conditions, as follows: recharge and evapotranspiration are used.

The Property Values operates on the database of parameter values. The database contains a property value assigned to each zone number used in the model. The database contains from one to three parameter values for each property.

The very essential parameter in the aquifer system is the hydraulic conductivity that defines the flow rate of the ground water in the aquifer system. The model imports the spatial and an attribute of hydraulic map described in the conceptual model. The model used a range of conductivity 0.006 MD to 21 M/D all other properties also imported with both spatial and attribute to form the properties database of the model.

Recharge is a specific flux boundary which is independent of the head of the in the cell but GV3 consider it as a property for spatially distributed all over the model area. The recharge stated used on the conceptual model is also used as an input to model parameter. In order to remind the in put data the recharge with spatial distribution of Fig: 4.8. with a range of 0.00000520 M/D to 0.00083730 M/D used.

The recharge is implemented with recharge package of **MODFLOW** 2000.As It is a boundary property, the recharge has a mathematical code that assume the volumetric rate of flow in to cell described with multiplication of the recharge rate by the horizontal area of the cell.

$$Q \text{ Recharge }_{ijk} = I_{ijk} (\text{DELR}_j)(\text{DELC}_i)$$

Equation 5.9

Where:  $I_{ijk}(\text{L/T})$  is the recharge rate (or infiltration rate) ,  $\text{DELR}_j$  the dimension of the  $j^{\text{th}}$  column along the row direction and  $\text{DELC}_i$  the dimension of the  $i^{\text{th}}$  column in the column direction , and  $Q\text{Recharge}_{ijk}$  the volumetric recharge of the rate on the rectangular area whose dimension is  $\text{DELR}_j$  and  $\text{DELC}_i$ .

# CHAPTER SIX

## 6. MODEL CALIBRATION AND SENSITIVITY

### 6.1. GENERAL OVERVIEW

Ground water flow model calibration is the process of adjusting selected model parameters within an expected range until the difference between model-predicated heads and the field observed heads within selected criteria for performance .(Mercer and Faust,1981)

Calibration is a tool to refine the hydrogeologic character until it meets the field observation with in specific criteria. It needs the adjustment or modification of the hydraulic conductivity; net precipitation recharge rate, Thickness of aquifer, boundary condition.

The calibration process requires observed value up on which the modeler will attempt to match. This observed value known as calibration target. It is a point in space and time where one of the model dependent variables has been measured. Calibration targets provide a means of assessing calibration quality because an error term, called residual, is computed for each target location. A residual is computed as the field measurement minus the model-computed value. The range of errors helps you determine whether the quality of the calibration is adequate for your purposes.

Calibration targets may be measurements of head, concentration, drawdown, or groundwater flow (called flux in the following discussion). Targets may be steady-state or may have an associated time value (called transient targets). One limitation is that flux targets must be steady-state. Head, drawdown, and concentration targets may be either steady-state or transient.

In general, there are two major calibration achieving method known as inverse and forward problem solving. The inverse solving method approaches a problem to get a set of hydrogeologic parameter in order to meet observed value and the forward solving method use an aquifer system parameter to calculate the head.

In this model the calibration target is taken with observed hydraulic head or the static water level measured on the production well. The model applies inverse solving method to use calibrated head of the aquifer system to determine essential refined hydrogeological parameter.

## 6.2. CALIBRATION METHOD

### 6.2.1. CALIBRATION TARGET

The model is calibrated to steady state condition with observed head measured at the available production well. Unfortunately, the ground water level measurement is taken during the construction and inventory time of the borehole. In fact, there is no practice of monitoring the existing well standing water level and no accessing means like an observation pipe installation to easily measure the water level.

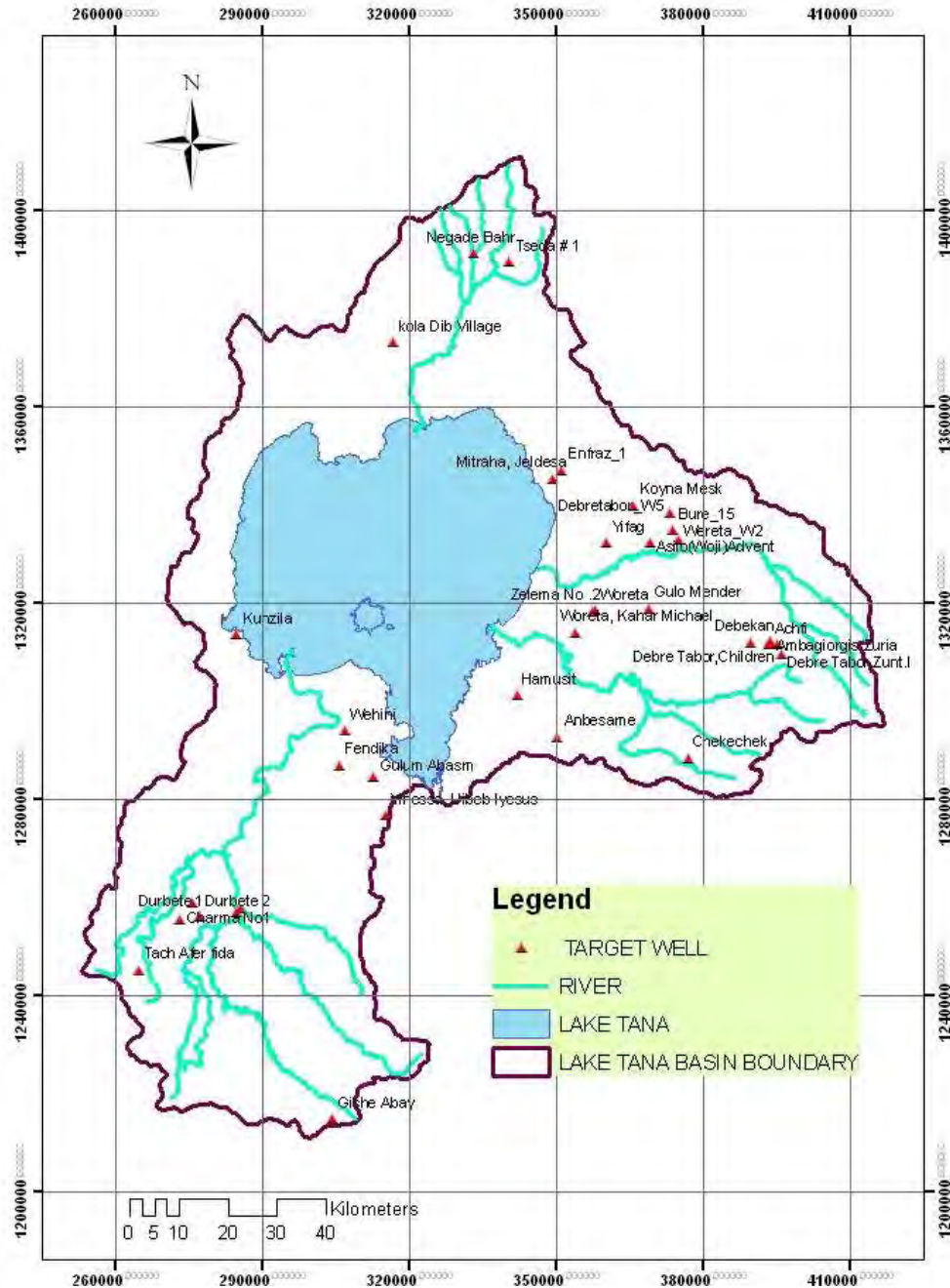


Fig: 6.1. The Spatial distribution of Target Well of the Model

The majority of the observation of water level is taken from different part of the basin during 2003-2006 borehole construction times. The model uses 37 calibration target distributed with in the basin. The model tolerates the possible error introduced by the different time measurement of the heads, head derivation from 90m\*90m resolution DEM.

### **6.2.2. CALIBRATION TECHNIQUES**

The calibration criteria set by the modeler is to match the simulated ground surface and hydraulic gradient with estimated one. Taking in to account the variation of hydraulic conductivity of volcanic aquifer in small distance, the model relies on matching the simulated ground surface with the estimated one too.

The model calibration accounts the matching of the calibration target with simulated head with a permissible residual head of  $\pm 20$ meter. The criteria set is almost 1.5 percent of the difference of the maximum and the minimum measured water level head. It is almost tolerable difference with respect to the gradient, the objective to understand ground water flow pattern and the very diversity hydraulic nature of volcanic aquifer.

The calibration process is also maintain the estimated base flow on the gauged part of the major stream, water budget and other important inflow and out flow component of a steady state aquifer system.

In this model, Parameter estimation is essential synonymous with the model calibration, which is synonymous with solving the inverse problem.

The model calibration is expected to fulfill the criteria set stated above and uses inverse solving method technique. Basically, there are two way of finding model parameter to achieve calibration of inverse solving method: **(1) Manual trail and error calibration** **(2) Automated parameter estimation.** (Anderson and Woessner, 1992).

The model of the region under investigation is calibrated with a help of the modeler high judgment participation manual trail-and –error adjustment.

### **6.2.2.1 MANUAL TRAIL AND ERROR CALIBRATION**

This calibration technique relies on the modeler prior information and knowledge about the area. The modeler uses his knowledge to evaluate the response of aquifer parameter or boundary changes on the simulated head to match the observed head.

The model tries to determine the aquifer parameter with information of the head distribution over the aquifer system. It results a set of aquifer system parameter that minimize the difference between the simulated and observed head.

In trail – and –error calibration, the aquifer parameter will be modified or adjusted until the sequential model run match simulated head to calibration target. Accordingly, the model use adjustment, dominantly, in the hydraulic conductivity and minor adjustment on the recharge and river conductance.

In this calibration process, it is found that the simulation is responsive to particular change of hydraulics conductivity. The model uses the prior information of the about area that the hydraulic conductivity tend to increase to ward the lake in all direction and also to ward the major stream and Lineament structure.

## **6.3. EVALUATION OF CALIBRATED MODEL RESULT**

The result of the calibration is evaluated both quantitatively and qualitatively. Now days, there is no standard protocol for evaluating the calibration process. This model tries to use the (Anderson, Woessner, 2002) protocol suggestion to evaluate the calibration. These include matching of contour map of measured and simulated head, calibration statistics and scatter plot used to evaluate the trial.

### **6.3.1. CONTOUR MAP COMPARISON**

This type of evaluation uses comparison between contour map of measured and simulated head. It is uses a visual scan and qualitative evaluation with very s very subjective approach. The map of simulated and measured contour map is displayed for the help of judgment.

Lake Tana Basin Modeling is could be categorized as regional studies and matching simulated and measured map trend is very essential to calibrate the model. Accordingly, the model simulated contour of the hydraulic head is approach to match the measured contour one.

The simulated head follows the trend and hydraulic gradient of the measured one. However, it will be very unpractical to achieve identical simulated and measured contour in the context of volcanic aquifer with inherited nature of head difference in small distance and poor ground water data management of the country.

The simulated heads is found to follow almost the same trend as of the observed ground water contour. The simulated head approximate the observed contour with reasonable accuracy.



Fig: 6.2. Map of Observed Vs Simulated Hydraulic head of Lake Tana Basin

### 6.3.2. CALIBRATION STATISTICS

Calibration statistics are computed by first calculating the error associated with each target and then calculating simple statistics on the population of targets. The error is called a residual and is computed by subtracting the model-computed value (head, drawdown, concentration, or flux) from the target value. Negative residuals indicate that the model is calculating the dependent value too high and a positive residual is where the model value is too low.

Prior to computing calibration statistics or plotting residuals, the calibrated model run that satisfied the criteria and computation of statistics has been conducted to evaluate the calibration.

The types of statistics computed and statistics computed from the simulated head and observed head are described below.

- Sum of squared residuals
- Residual mean
- Residual standard deviation
- Absolute residual mean
- Residual standard deviation divided by range in target value

The sum of squared residuals is computed by squaring all residuals and adding them together. This statistic is meaningless by itself but is useful to plot on sensitivity curves or when judging several different simulations. The sum of squared residuals is used by inverse models in the automated calibration process. In this model, the sum of the square residual is 7940.

The residual mean is computed by dividing the sum of residuals by the number of residuals. Because both positive and negative residuals are used in the calculation, this value should be close to zero for a good calibration. In other words, the positive and negative errors should balance each other. The model of the region under investigation has a residual mean of -8 that is not too far for regional modeling to close good calibrated model.

The absolute residual mean, on the other hand, is calculated using the absolute value of the error (only positive values) and is a measure of the average error in the model. The residual standard deviation is a measure of the overall spread of residuals. Think of it as value. The model results an absolute residual mean of 13.42 which is below the residual

criteria set before the calibration process. It closes a fine calibration for the fulfillment objective of the model.

The residual standard deviation can be compared to the overall range in target value (e.g., head) as a further comparison. For head targets, this value shows how the errors relate to the overall gradient across the model. Normally, this value should be less than 10 to 15 percent for a good calibration. The model has resulted residual standard deviation of 12.5 which is in the permissible range of the good calibration.

### 6.3.3. PLOTTING CALIBRATION RESULTS

#### 6.3.3.1. SCATTER PLOTS

Three types of plots are useful in assessing the quality of calibration simulations. The first is the scatter plot where observed target values (measurements) are plotted versus the values computed by the model. In an ideal calibration, the points will fall on a straight line with a 45 degree slope; i.e., that the computed value equals the measured value. The degree of scatter about this theoretical line is a measure of overall calibration quality. In this modeling, It is most difficult to match the theoretical line matches the plot, but follows a straight line with  $\pm 20$ mts.

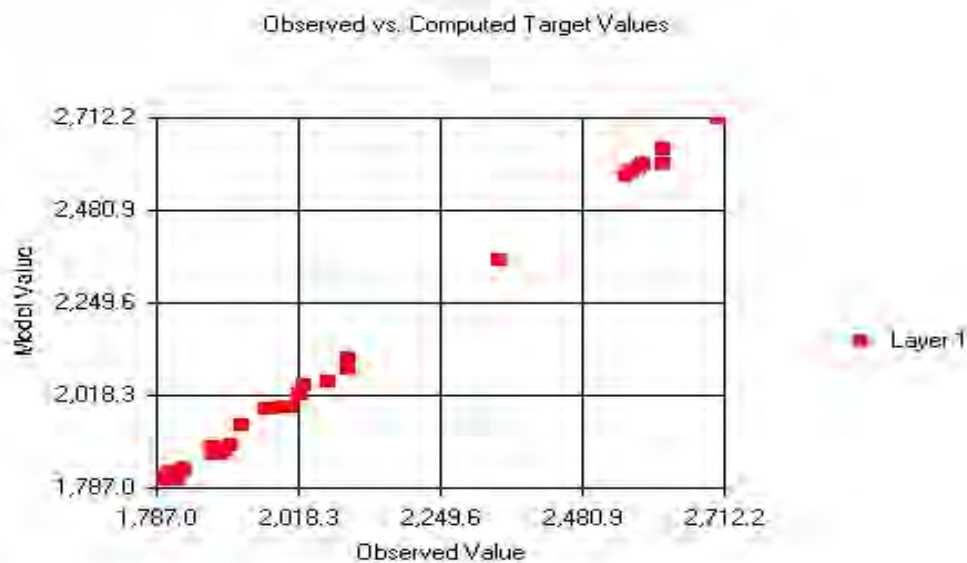


Fig: 6.3. Observed Vs Computed Target Value Chart

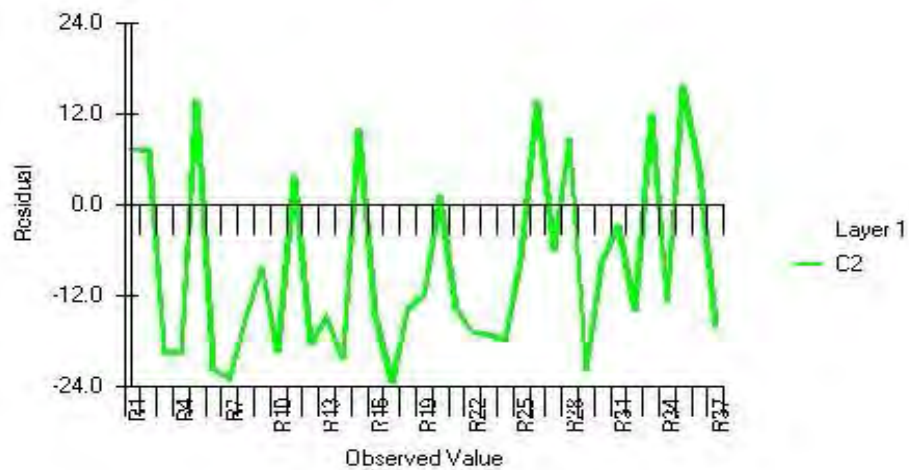


Fig: 6.4. Residual Vs Observed Value Chart

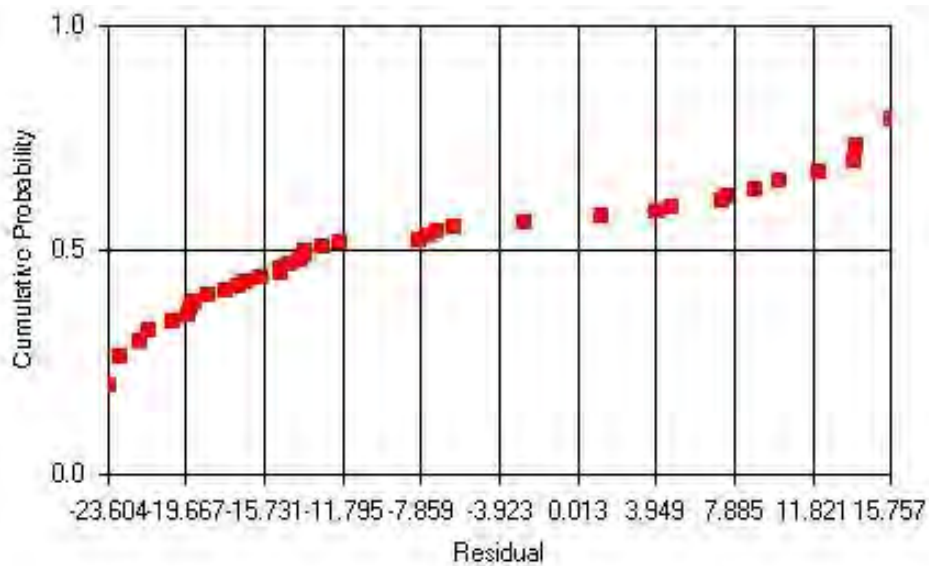


Fig: 6.5. Cumulative Probability Vs Residual Chart

### 6.3.3.2. POST RESIDUAL ON CONTOUR MAP

Another type of plot that is useful in assessing calibration quality is a contour map of the model dependent variable (e.g., head) with residuals posted on the contours. This type plot posts the target residual on simulated ground surface map and help on understanding the calibration quality over spatial distribution. These residual posting maps are useful in pointing out spatial bias in the distribution of errors. Based on the posted residual, we can easily understand areas where residuals are all too high or too low.

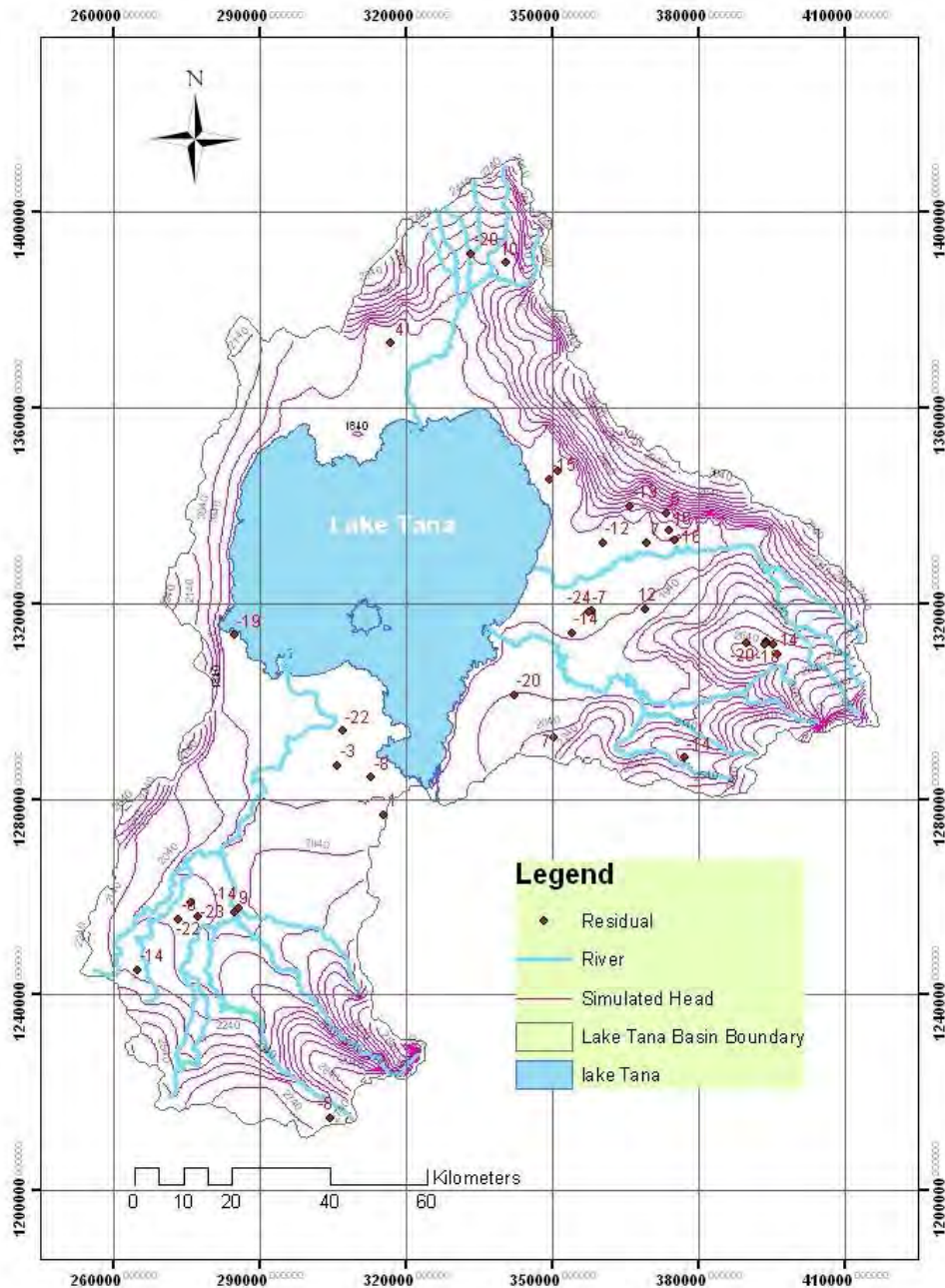


Fig: 6.6. Post residual of Target Well of the Model

#### 6.4. MODEL SENSITIVITY ANALYSIS

The purpose of sensitivity analysis is to quantify the uncertainties in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Anderson and Woessner, 1992).

Sensitivity analysis is the process of identifying the model parameters that have the most effect on model calibration or on model predictions. Sensitivity analysis is generally conducted by varying hydraulic conductivity, storage coefficient, specific yield, recharge, layer thickness, boundary location and their condition.

It is a relative rate change of selected out put caused by unit change in the input. The more change in out put caused by the input, the model is more sensitive to that input. In fact the model make up also determine how sensitive to an input parameter. For instance, model with low permeability is less sensitive to recharge. Sensitivity analysis evaluates the effect of a change in a model parameter or boundary condition on the calibration statistics.

The calibration process to some extent shows the major sensitivity parameter of the model how the model response to fulfill the calibration criteria. Based on the calibration process, it is found that the model is very sensitive to change in hydraulic conductivity and to some extent the model is also responsive to recharge change where estimated high hydraulic conductivity. The other sensitive parameter during calibration of the model is stream bed conductance which governs the most influential interaction of the aquifer system and the surface water.

The interface of this model GV3 has two methods of performing a sensitivity analysis, (1) single sensitivity runs, and (2) an automated sensitivity analysis. This model has used an automated sensitivity runs. The automated sensitivity analysis has been conducted both for the hydraulic parameter property and boundary condition. The detail sensitivity analysis of hydraulic conductivity, recharge, ground water withdrawal, GHB, stream conductance of the model is annexed with the paper so that to facilitate a further data organizing direction.

The sensitivity of the model to hydraulic conductivity was determined with multiplier of 0.2, 0.5, 1, 1.5, 2 which include both increment and decrement by 20% and 50% with a reference of the calibrated model out put. On the other hand , the model sensitivity to recharge is evaluated with multiplier of 0.25 , 0.5, 1, 1.25,1.75,2 which include lowering of parameter with 80%,50% and rising of parameter with 25%,75%,100%.

The upper Gilgel river show an intermediate sensitivity with more responsive to the lowering of the parameter near Gish Abay and more sensitive with the rising of parameter as one goes from south to north.

The Upper Gilgel catchment is less sensitive to the recharge and the model reacts to rising of the recharge unlike the conductivity. It can be generalized that the upper Gilgel is more sensitive to hydraulic conductivity than the recharge and sensitive to rising of recharge and lowering of conductivity. The representative sensitivity analysis chart is shown on fig 6.7 and fig 6.8

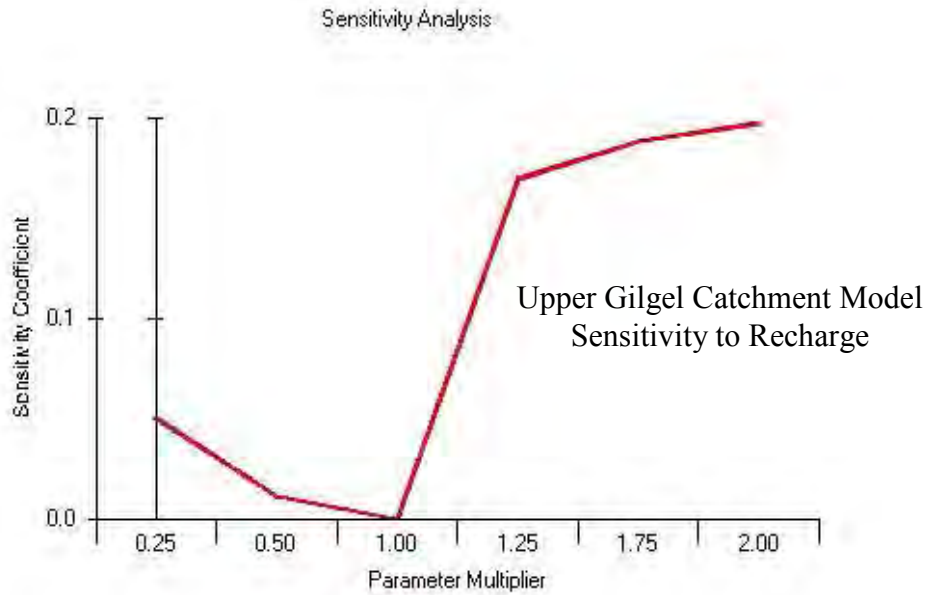


Fig: 6.7. Upper Gilgel Catchments Sensitivity to recharge

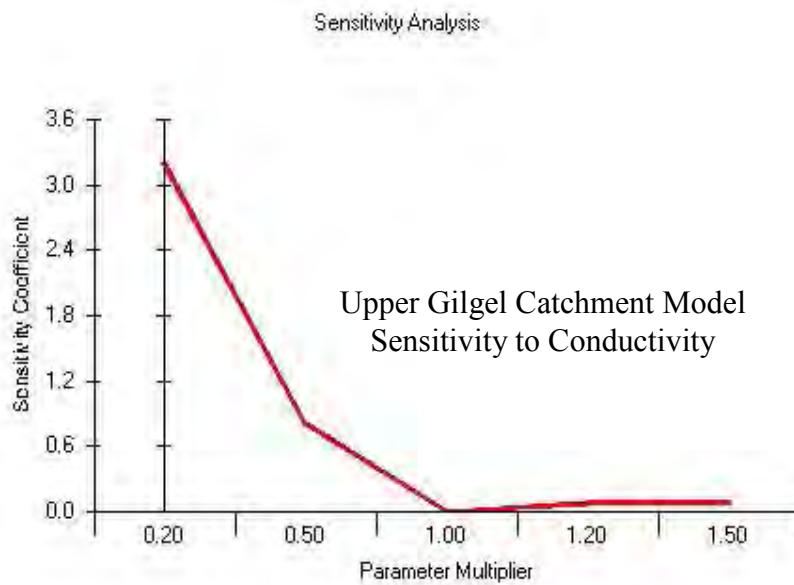


Fig: 6.8. Upper Gilgel Catchments Sensitivity to Conductivity

The Middle Gilgel characterized with relative less sensitive to hydraulic conductivity compared with the Upper Gilgel one and sensitivity increase with the rising of conductivity. The same effect is recognized on the sensitivity of the model to change of recharge parameter value, the model is more responsive with the rising of the recharge value. The representative sensitivity analysis chart is shown on fig and fig

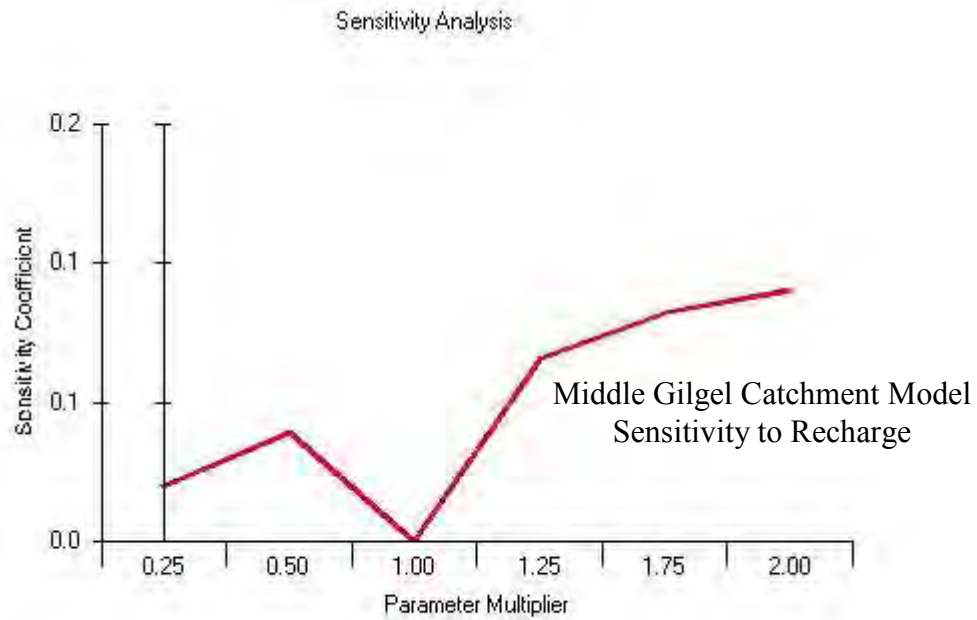


Fig: 6.9. Middle Gilgel Catchment Sensitivity to Recharge

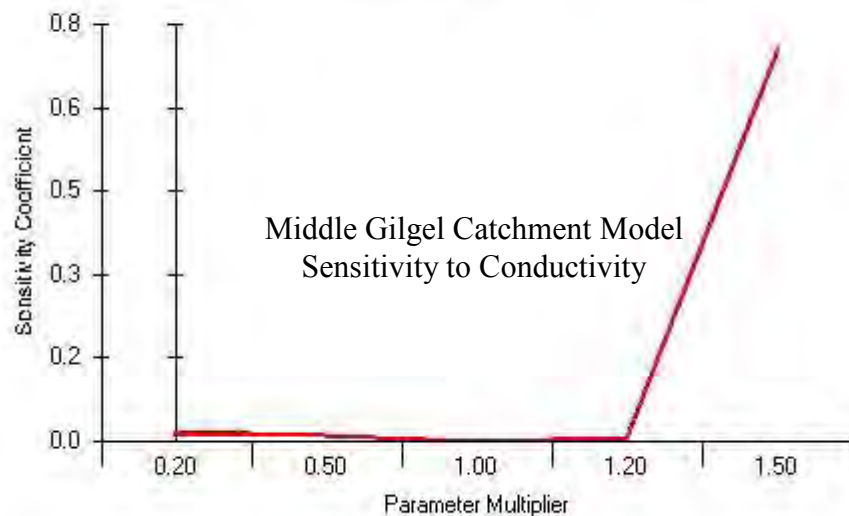


Fig: 6.10. Middle Gilgel Catchments Sensitivity to Conductivity

The most part of the lower Gilgel area is sensitive to increment of the conductivity parameter and the eastern part of the lower Gilgel need special attention with its very anomaly sensitivity to change. The same unusual response of the model is also seen in the recharge of the same area. This is may be as the result poor available calibration data for the conductivity or the presence of the elevated scoraceous cone result discrepancy of the model as the model consider same thickness of the aquifer.

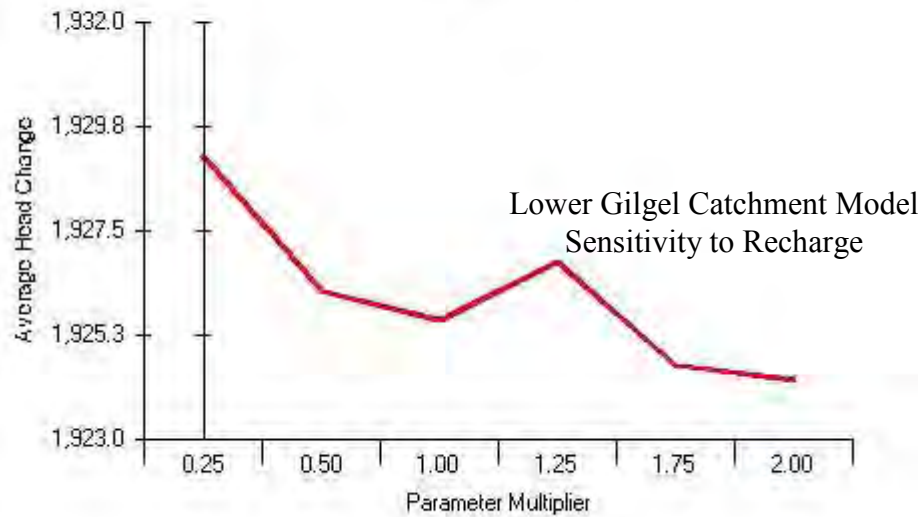


Fig: 6.11. Lower` Gilgel Catchments Sensitivity to Recharge

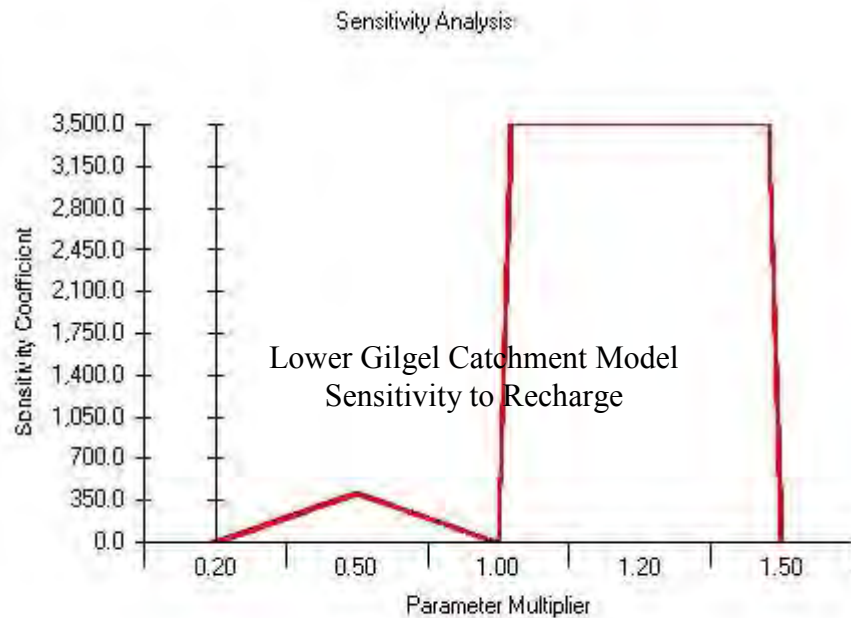


Fig: 6.12. Lower Gilgel Catchments Sensitivity to Recharge

The Upper Gumera catchments are very sensitive to the conductivity with reducing of the calibrated conductivity value and the adjacent Upper Rib Catchments is dominantly less sensitive to the conductivity except the southern part of the upper where the catchments share same sensitivity like the Gumera.

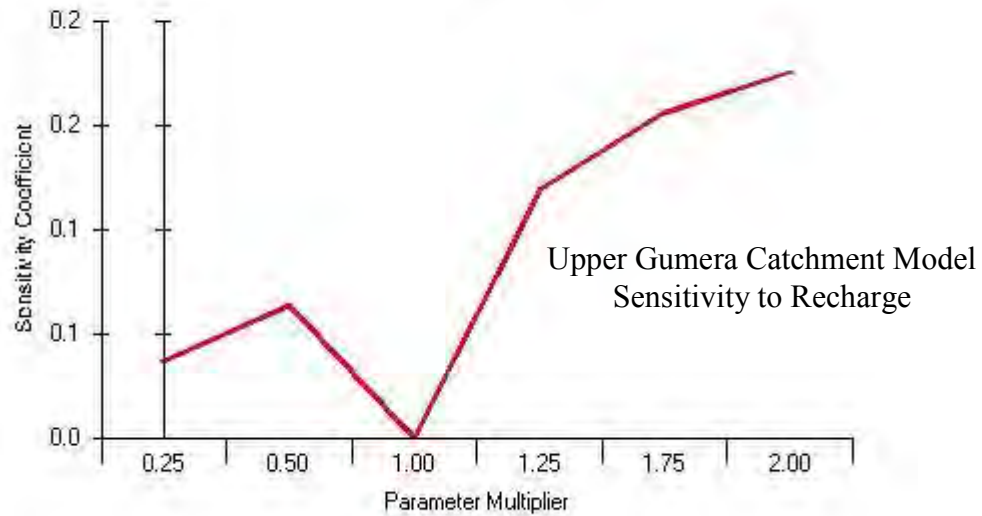


Fig: 6.13. Upper Gumera Catchments Sensitivity to Recharge

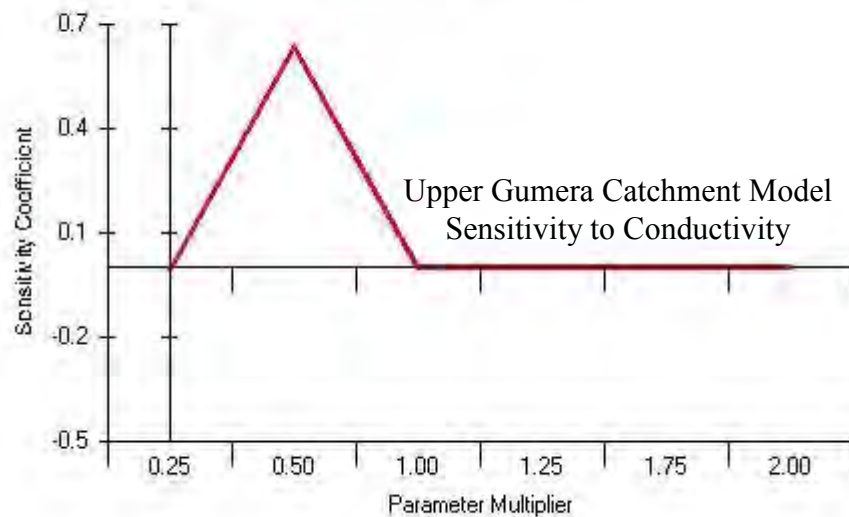


Fig: 6.14. Upper Gumera Catchments Sensitivity to Conductivity

The lower part of both catchments characterized with the alluvial plain which is a significant sensitivity to the decrement of conductivity and need caution on detail data acquisition.

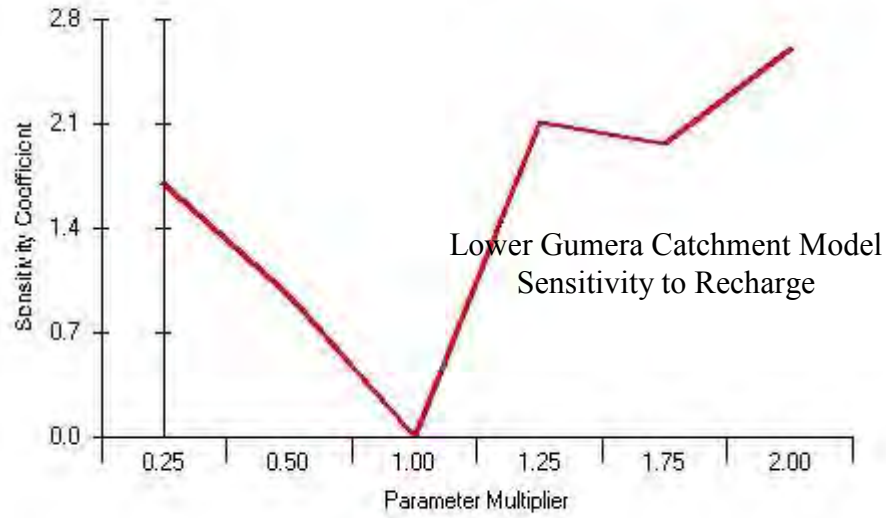


Fig: 6.15. Lower Gilgel Catchments Sensitivity to Recharge

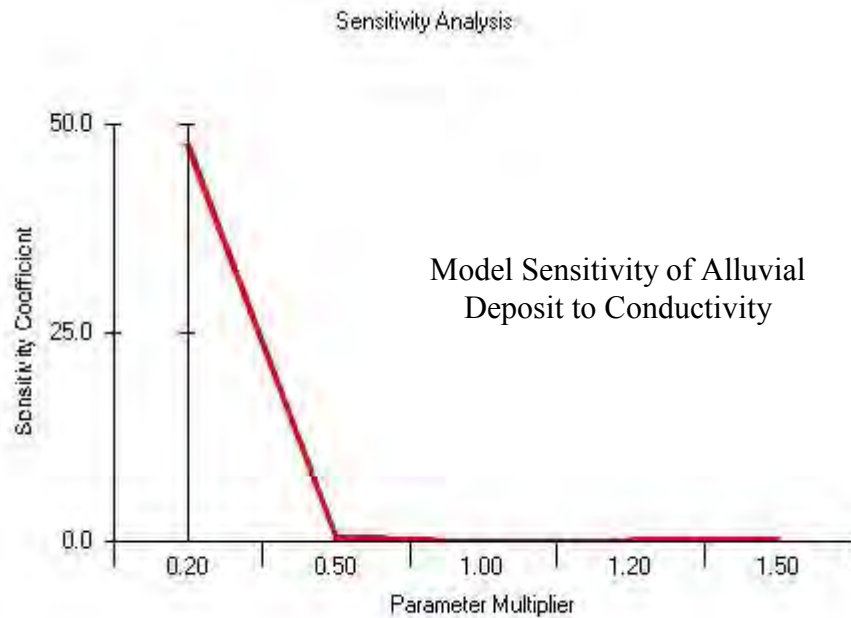


Fig: 6.16. Alluvial Sediment Sensitivity to Conductivity

The Upper Megech and the Southern flank of the Megech catchments is a relatively less sensitive to the conductivity with a better sensitivity to recharge whereas the lower and the middle part of the catchments sensitive to conductivity than the upper one. The model is sensitive to the recharge too.

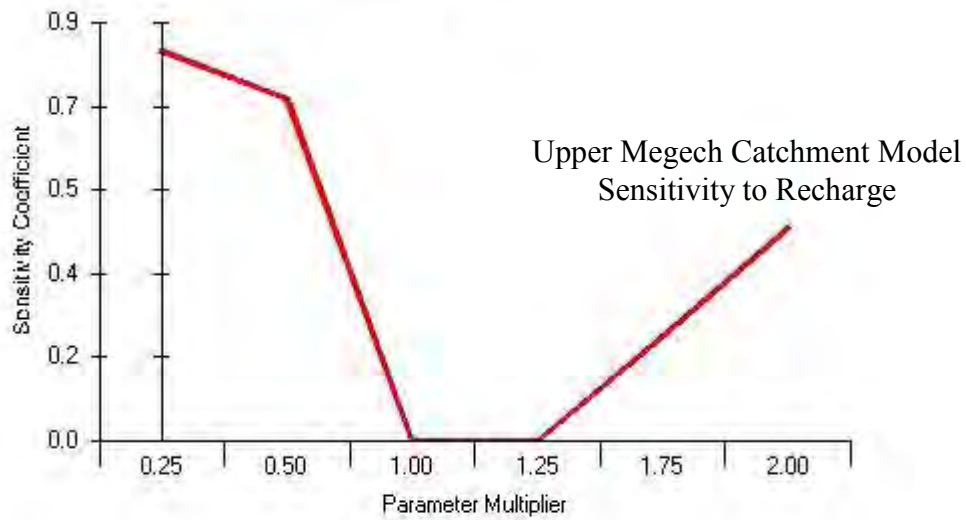


Fig: 6.17. Upper Megech Catchments Sensitivity to Recharge

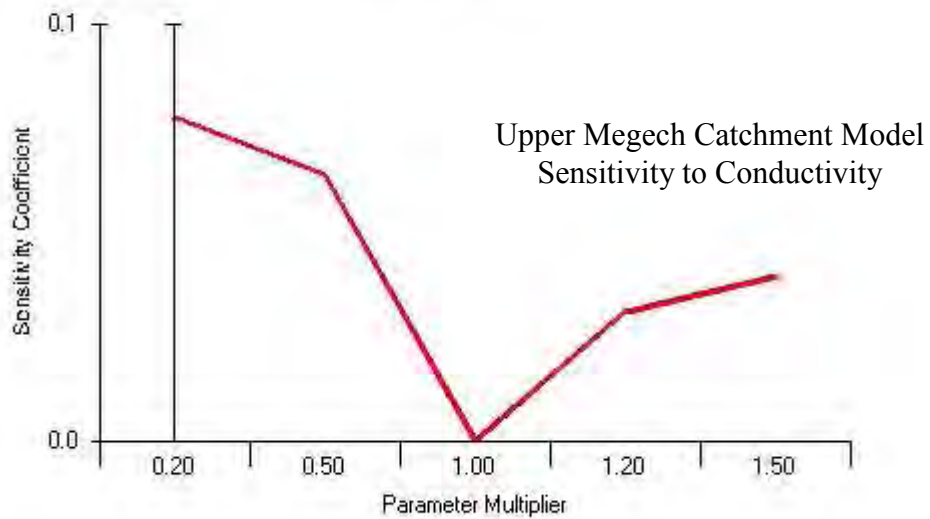


Fig: 6.18. Upper Gilgel Catchments Sensitivity to Conductivity

In general, the model is very sensitive to change of conductivity and the sensitivity is manifested on the hydraulic head and water budget distribution of the boundary. The whole sensitivity analysis the show details manifestation of the parameters change is documented quantitatively on the annex V\_VII.

# CHAPTER SEVEN

## 7. MODEL RESULT AND ANALYSIS

### 7.1 GENERAL OVERVIEW

The final result of the model is a calibrated steady state ground water flow model with simulated head of ground water surface. The model can be manipulated and simulated with user define interest. The primary result is to satisfy the theme of the paper stated on the objective. The whole effort was to make the following major out put listed below.

### 7.2. SIMULATED GROUND WATER FLOW

The **MODFLOW** calculates the hydraulic heads distribution of the ground water surface. The simulated head distribution shows the ground water surface follow the topographical contour flow directions also coincide with surface water catchments flow.

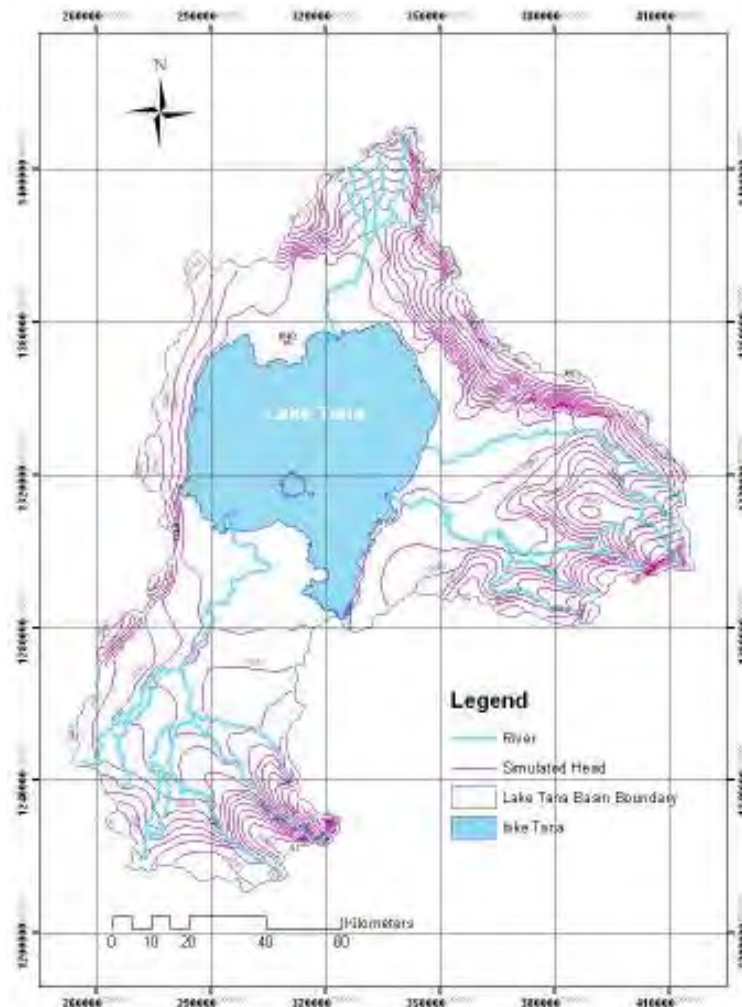


Fig: 7.1. Spatial distribution of Simulated Head of Lake Tana Basin

### 7.3. SIMULATED WATER BUDGET

#### 7.3.1. SIMULATED BASIN WATER BUDGET

The simulated water budget of the Lake Tana basin ground water flow modeling is a total of 1,811,313,752.07 M<sup>3</sup>/Y with -0.00052 percent of error. The simulated water budget is surplus the estimated on, 1,756,791,794.90 M<sup>3</sup>/Y, by 54,521,957.17M<sup>3</sup>/D.

The difference of the water budget could be due to the uncertainties of the estimation of the recharge and the other parameter. Despite the fact of the water budget difference, the model is believed to approximate the field ground water flow with reasonable 3.1% deviation from the observed one.

The simulated out flow of the model is 1,809,013,494.88 M<sup>3</sup>/Y which is lower from the simulated inflow by 9461.37145 M<sup>3</sup>/Y with - 0.00052301% percent of error. The base flow discharge of simulated model hold 86.43% of the out flow but still with lower volume than the estimated one. This high share of base flow implies the discharge of ground water to the dominantly gaining streams and high interaction of surface and aquifer system.

The simulated base flow of the model is under estimated with possible error introduced during poor estimating the conductivity river bed, derivation of head from the DEM, thickness and over whole width of stream and Coarse grid design of the model.

The detail water budget analysis of the basin is illustrated below with the table and the chart stated below.

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITAION RECHARGE	4763195.99		1738566536.79	
II	PUMPING WELL	-	6327.99		2309716.35
III	RIVER IN FLOW	192979.44		70437495.6	
IV	RIVER OUT FLOW	-	4283882.58		1563617142.54
VI	GHB LAKE		665990.78		243086633.77
	TOTAL	4956175.43	4956201.35	1809004033.51	1809013494.88
	PERCENT OF ERROR		-0.00052301		-0.00052301

Table: 7.1. Simulated Water Budget of lake Tana Basin

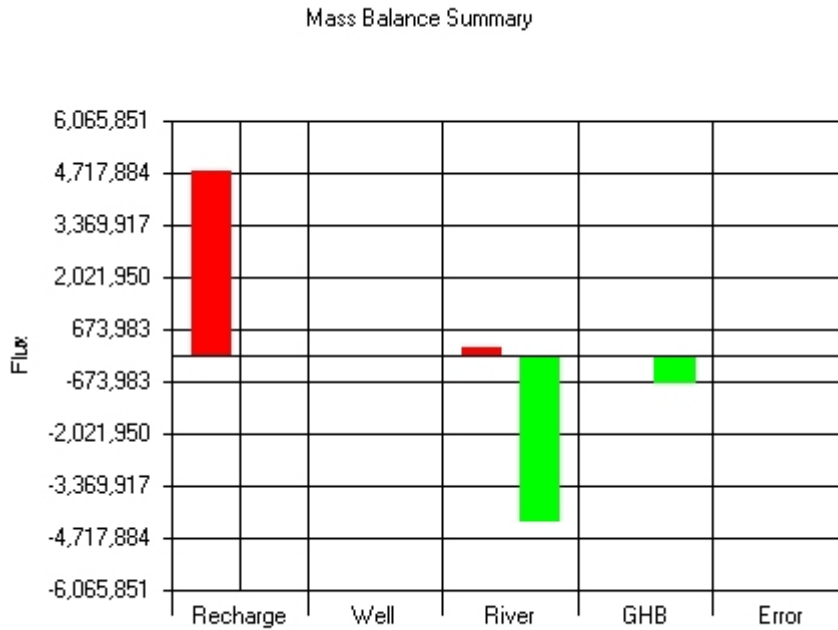


Fig: 7.2. Mass Balance Chart of the Lake Tana Basin

### 7.3.2. SIMULATED WATER BUDGET OF THE CATCHMENT

The Lake Tana basin is comprised of four major catchments and a number of subcatchment. The numerical ground water flow modeling is empowered with computation of water budget. The simulated water budget is computed for the major catchments of Gilgel, Gumera, Rib and Megech as the aerial coverage of fig 7.2 shown above and summarized with the pi chart below.

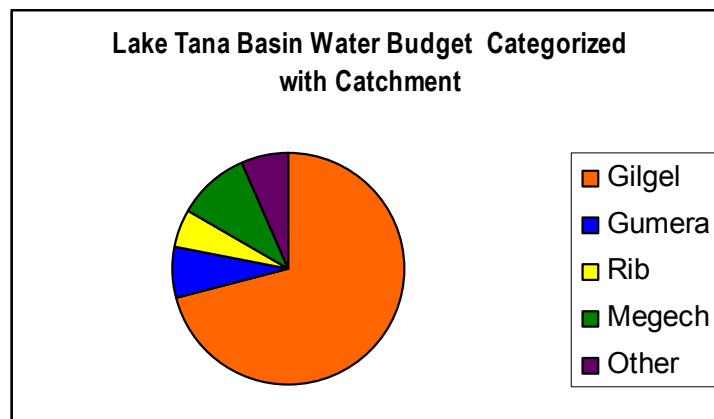


Fig: 7.3. Lake Tana Basin Water Budget Categorized with major Catchments

### Major Catchment Of Lake Tana Basin

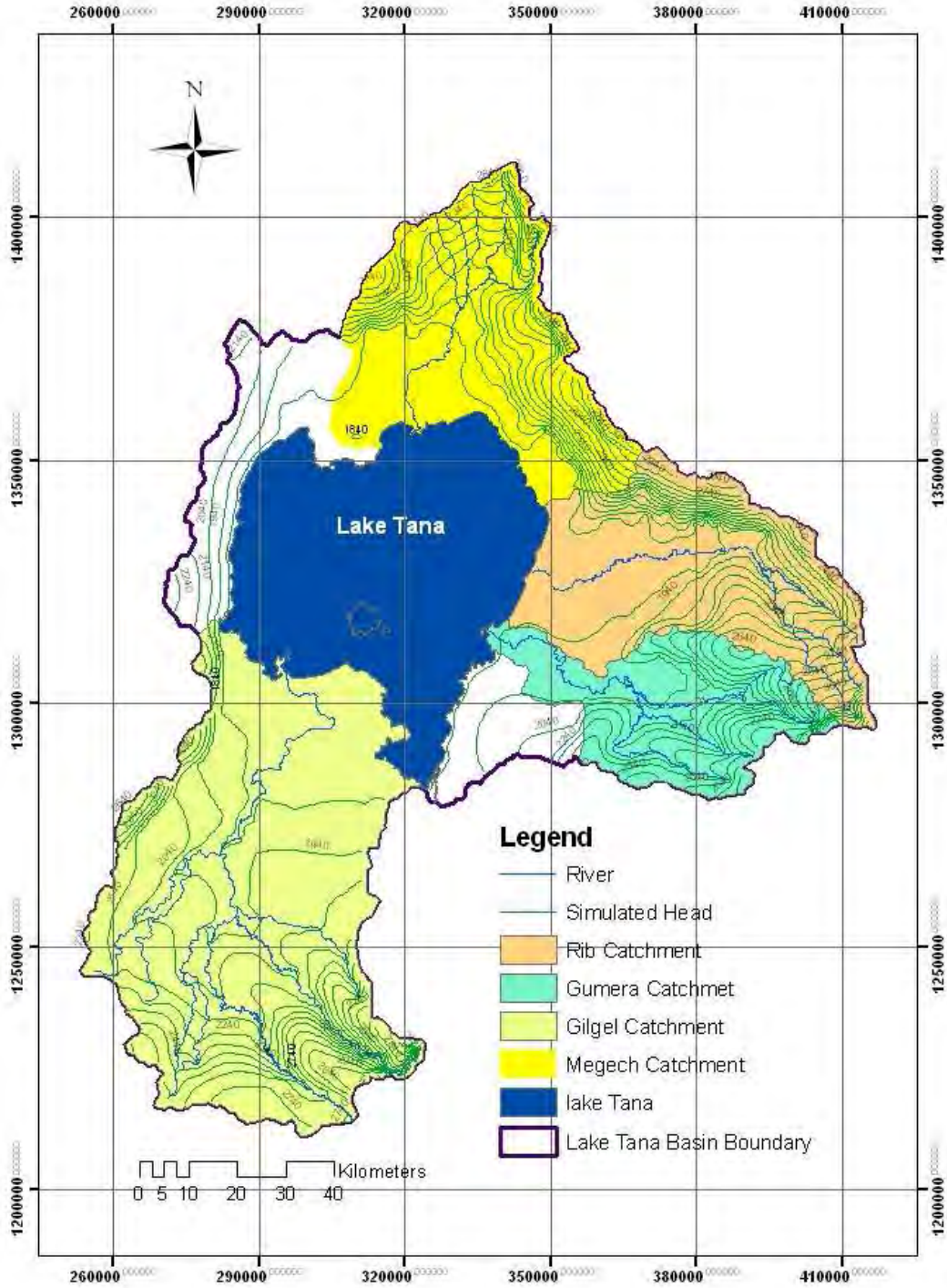


Fig: 7.4. Lake Tana Basin major Catchments considered for water budgeting

### 7.3.2.1. GILGEL CATCHMENT

The Gilgel Catchments shares about 70.85% of the water budget of the Lake Tana basin with an out flow 288807.23  $M^3/Y$  to lake. The Catchments is simulated with downing of the out flow 5.5% perhaps due to boundary condition assigned around the catchmet is not closed to make an equated inflow and out flow. The simulated ground water discharge to major stream is **1207M  $M^3/Y$**  less than the estimated one with 216.36  $M^3$  with possible uncertainties of the river parameter.

The hydraulic head is characterized with very steep hydraulic gradient on the upper Gilgel, particularly, near Mt choke and with a relative an intermediate gradient higher on the west part than the East. The hydraulic gradient is getting low toward lower part of the catchments where a relative high conductivity is observed.

The detail result is illustrated on the simulated Hydraulic head map, Mass balance Summary and chart shown below.

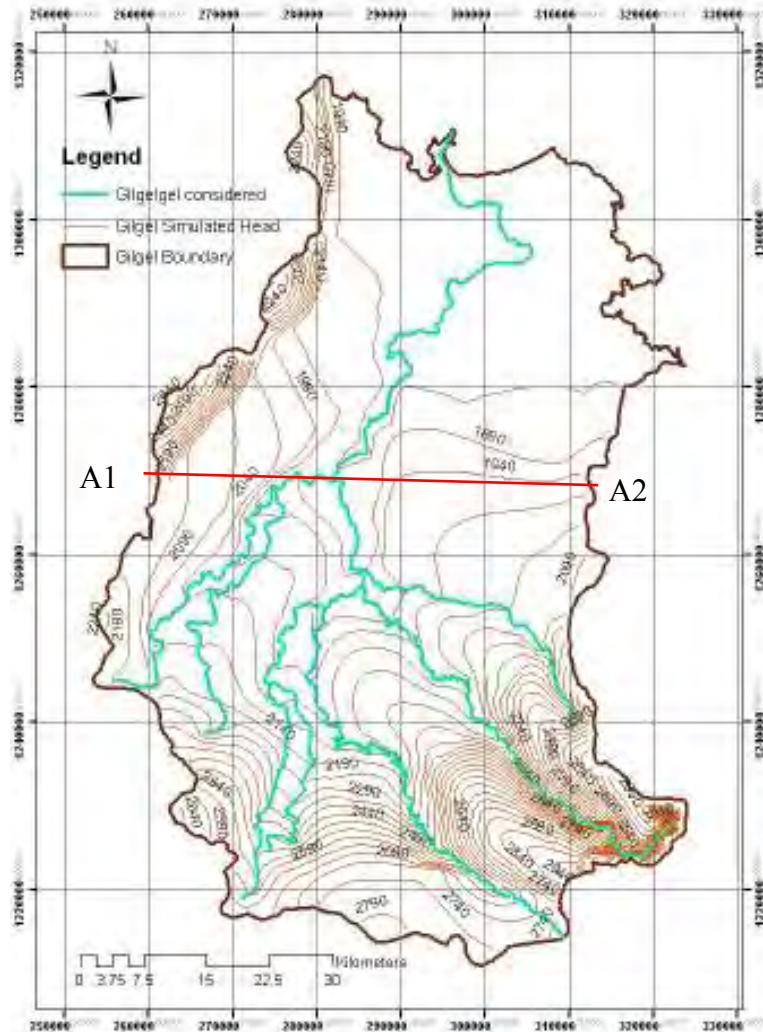


Fig: 7:5. Gilgel Catchments simulated head with W\_E cross section Line

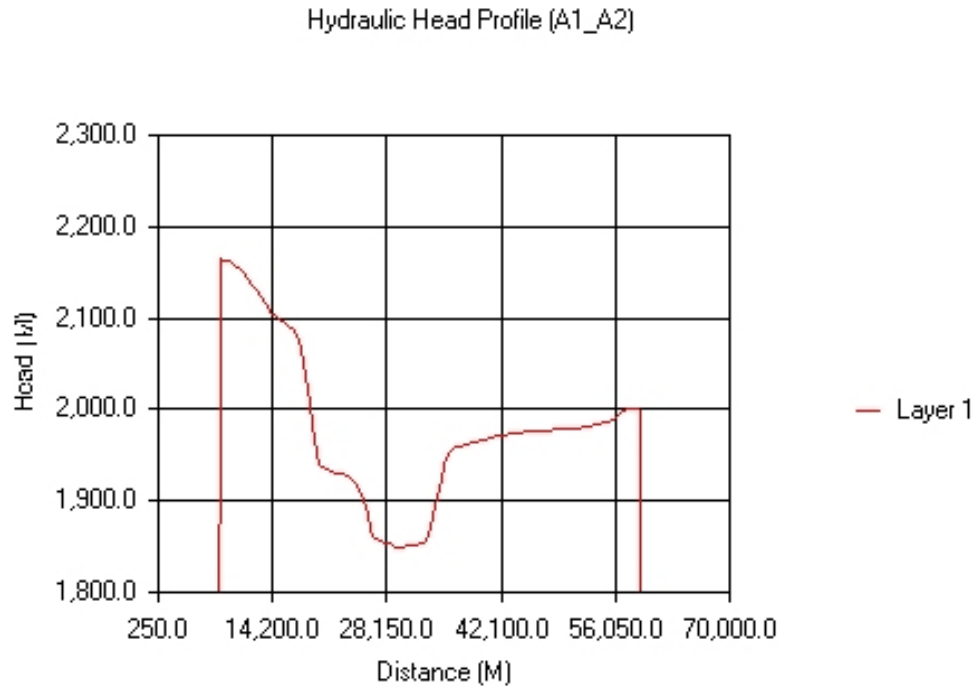


Fig: 7:6. Gilgel Catchments W\_E Profile of simulated Hydraulic head

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITAION RECHARGE	<b>3373902.02</b>		<b>1231474238.13</b>	
II	PUMPING WELL		<b>2495.55</b>		<b>910876.50</b>
III	SPRING				
IV	SUBSURFACE FLOW	-			
V	RIVER IN FLOW	<b>138019.46</b>		<b>50377103.26</b>	
	RIVER OUT FLOW	-	<b>3308536.74</b>		<b>1207615910.1</b>
VII	<b>GHB LAKE</b>		<b>5499.44</b>		<b>2007298.09</b>
	TOTAL	<b>3511921.48</b>	<b>3316531.73</b>	<b>1281851340.2</b>	<b>1210534081.45</b>
	PERCENT OF ERROR		<b>-5.56%</b>		<b>-5.56%</b>

Table: 7.2. Simulated Water Budget of Gilgel Abay Catchments

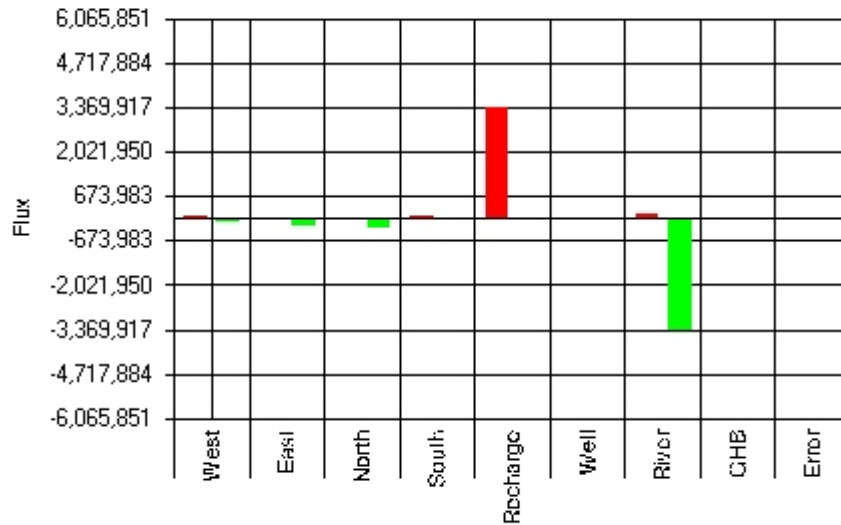


Fig: 7:7. Gilgel Catchments Mass Balance chart

### 7.3.2.2. GUMERA CATCHMENT

The Gumera catchment is simulated with a base flow of **128.71M m<sup>3</sup>/Y** which is very equivalent with **126.70M m<sup>3</sup>/Y** observed one. This catchment is simulated with a relatively low deviation 1.5% from the estimated base flow. The catchment shares 7.25% of the over all water budget.

The catchment is also simulated to discharge ground water of 0.28 M m<sup>3</sup>/Y. The hydraulic head is characterized with steep and high gradient on the upper Gumera and flat and low to ward the Fogera plain. The result is illustrated with the simulated head map, Mass Balance Summary Table, Chart and profile shown below.

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITAION RECHARGE	<b>359031.87</b>		<b>131046632.55</b>	
II	PUMPING WELL		<b>268.69</b>		<b>98071.850</b>
III	RIVER IN FLOW	<b>299.67</b>		<b>109380.80</b>	
IV	RIVER OUT FLOW		<b>352649.50</b>		<b>128717070.82</b>
VI	GHB LAKE		<b>791.25</b>		<b>288807.23</b>
	TOTAL	<b>359331.54</b>	<b>353709.44</b>	<b>131156012.1</b>	<b>129103945.6</b>
	PERCENT OF ERROR		<b>-1.56%</b>		<b>-1.56%</b>

Table: 7.3. Simulate Water Budget of Gumara Catchment

### Mass Balance Summary

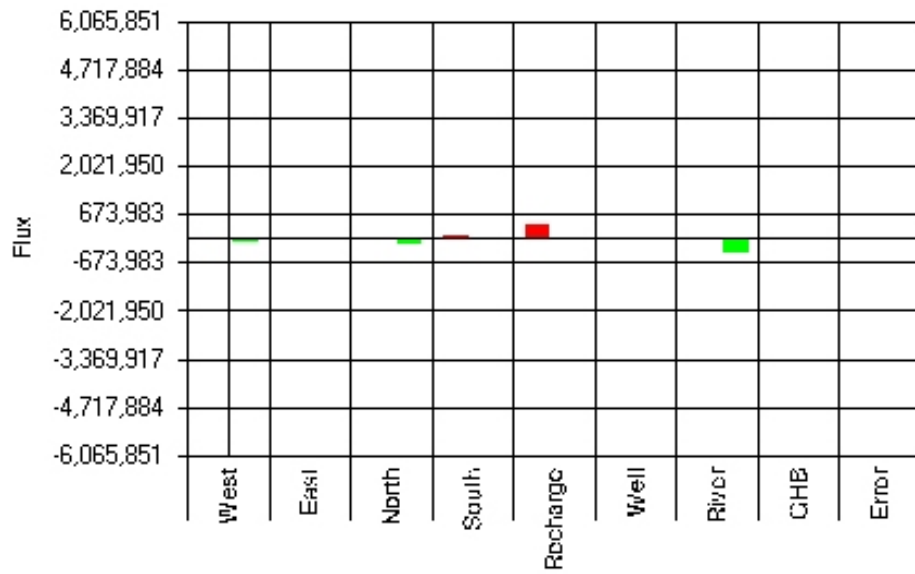


Fig: 7.8. Gumera Catchments Mass Balance chart

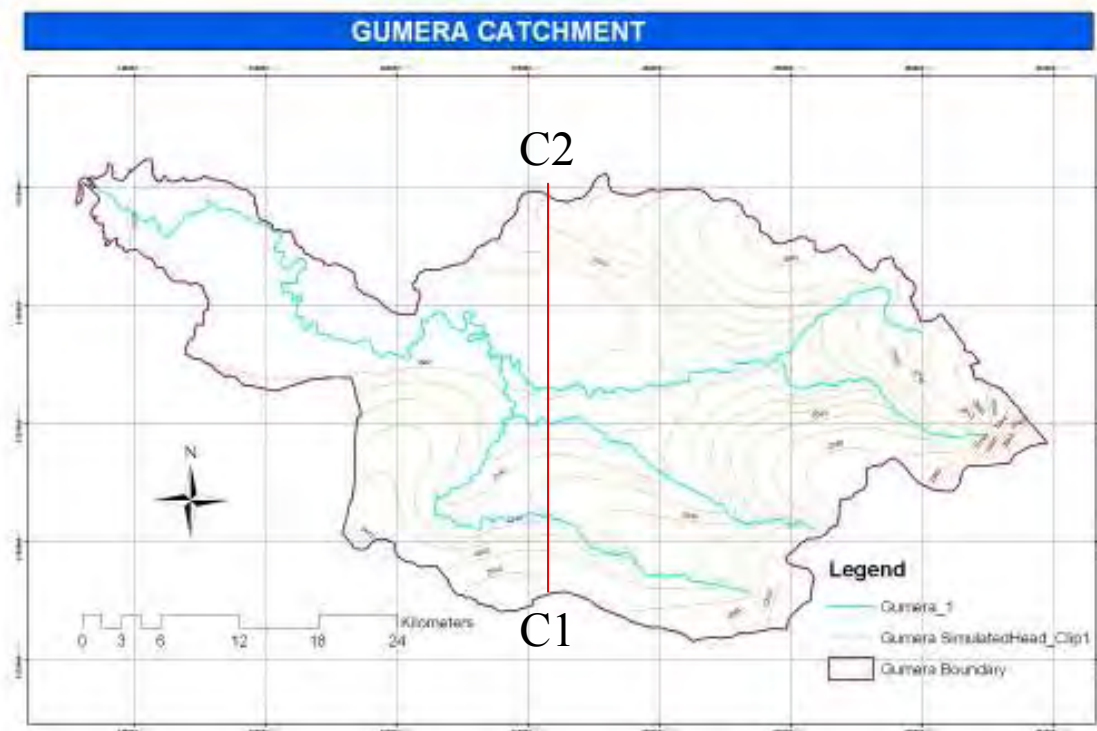


Fig: 7.9. Gumera Catchments simulated head with S\_N cross section Line

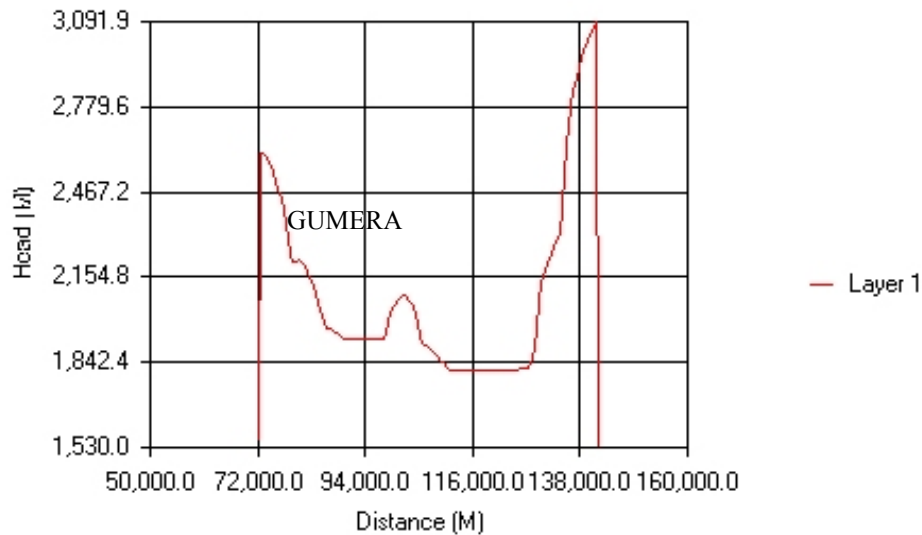


Fig: 7.10. Gumera Catchments S\_N Profile of simulated Hydraulic Head

### 7.3.2.3. RIB CATCHMENT

The Rib catchment is simulated with 96.6 M M<sup>3</sup>/Y with surplus 18.31M M<sup>3</sup>/ Y the estimated one. It is due to the possible error introduced with uncertainty of river and other parameter.

The simulated hydraulic head is characterized with a relatively very steep gradient compared with the other catchments and share same behavior as of the other with dropping of gradient to ward the lake. The catchment shares 5.25% of the water budget of the Basin.

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITATION RECHARGE	251961.048		91965782.52	
II	PUMPING WELL		1776.32		648358.99
III	RIVER IN FLOW	8166.24		2980677.99	
IV	RIVER OUT FLOW		264720.12		96622845.70
VI	GHB LAKE		678.62		247696.78
	TOTAL	260127.288	267175.06	94946460.12	97518896.9
	PERCENT OF ERROR		2.70%		2.70%

Table: 7.4. Simulate Water Budget of Gumara Catchment

Mass Balance Summary

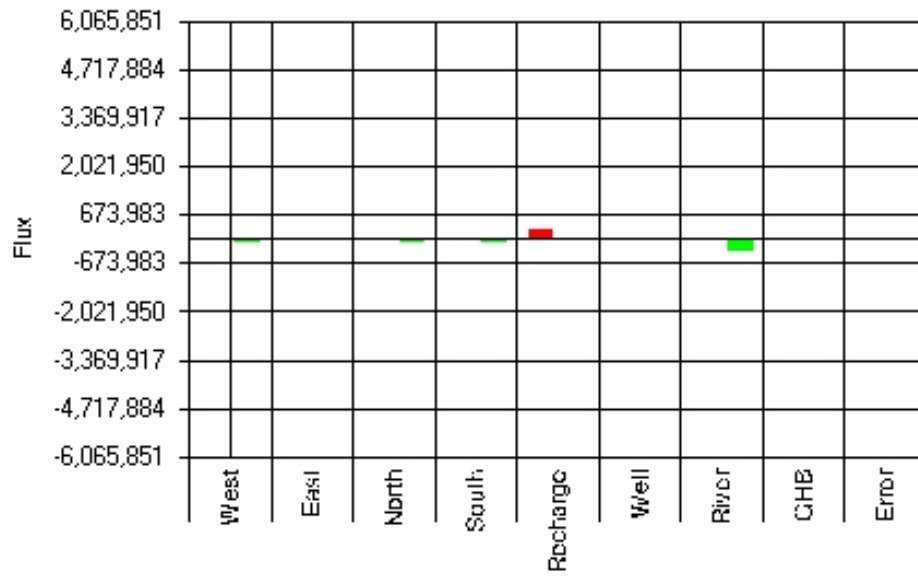


Fig: 7.11. Rib Catchments Mass Balance Chart

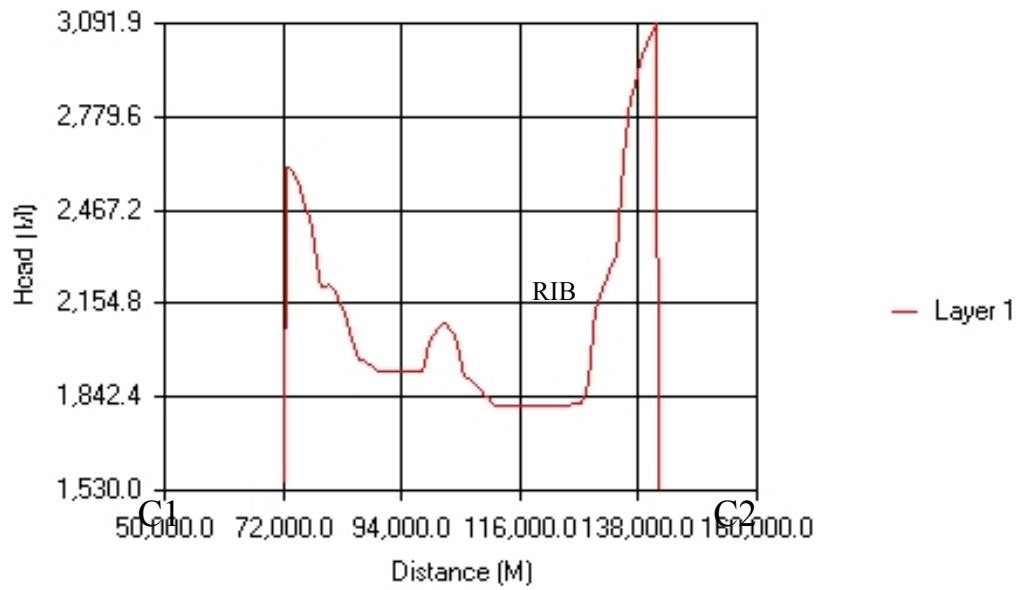


Fig: 7.12. Rib Catchments S\_N Profile of simulated Hydraulic Head

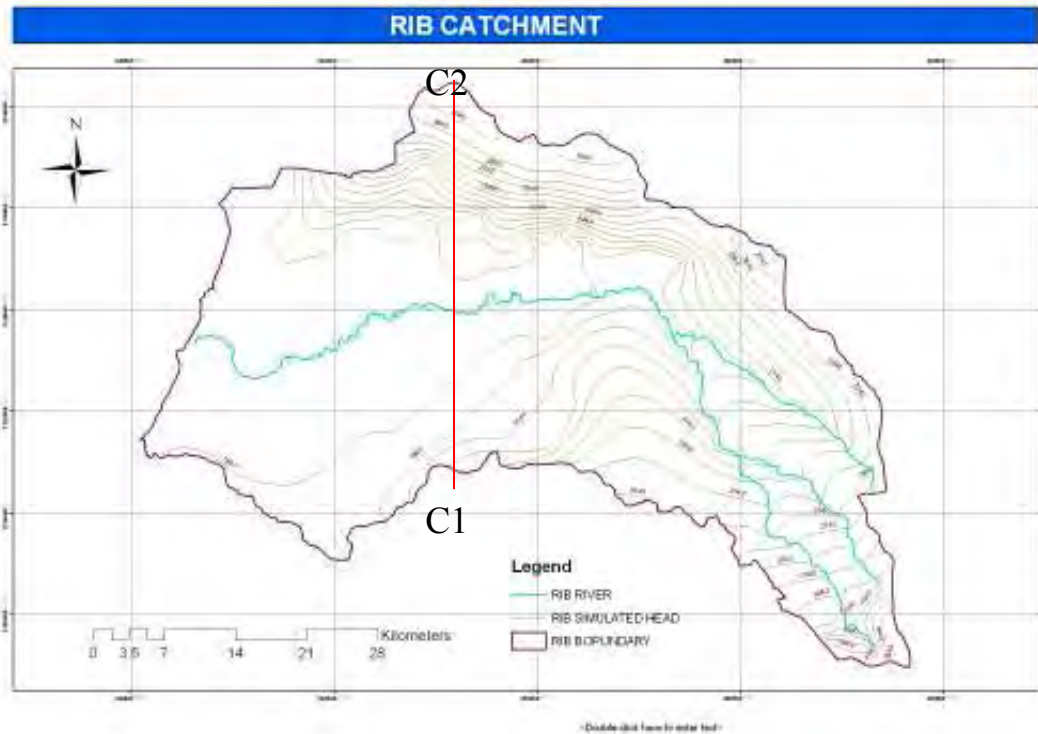


Fig: 7.13. Rib Catchments simulated head with S\_N cross section Line

### 7.3.2.4. MEGECH CATCHMENT

The Megech catchment shares 9.05% of the water budget of the basin with a simulated base flow of 123.15 which is equivalent with the estimated 132.17 M M<sup>3</sup>/Y a deficiency deviation of 9.02% from the estimated.

The over all water budget accuracy is poor perhaps a closed boundary condition is not provided the customized budget area. The customized Megech catchment is also over extended to embark the surrounding sub catchment that increase the recharge aerial distribution and quantity compared with the base flow.

NO	WATER BALANCE COMPONENT	DAILY		ANNUAL	
		IN FLOW (M <sup>3</sup> /DAY)	OUT FLOW (M <sup>3</sup> /DAY)	IN FLOW (M <sup>3</sup> /YEAR)	OUT FLOW (M <sup>3</sup> /YEAR)
I	PRECIPITATION RECHARGE	402307.17		146842117.79	
II	PUMPING WELL		1123.89		410222.77
V	RIVER IN FLOW	46484.23		16966746.28	
	RIVER OUT FLOW		337420.20		123158374.93
VII	GHB LAKE		3452.14		3452.14
	TOTAL	448791.4	341996.23	182252429.62	182252656.59
	PERCENT OF ERROR		-23.7		-23.7

Table: 7.5. Simulate Water Budget of Megech Catchment

Mass Balance Summary

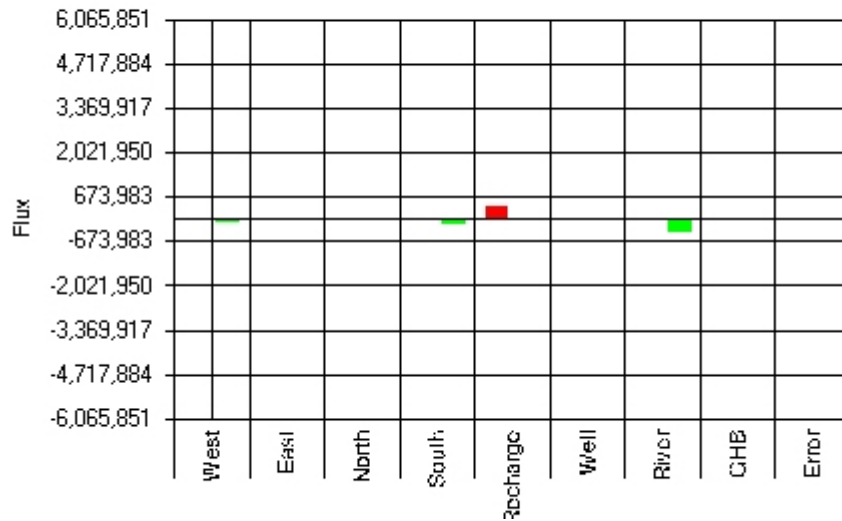


Fig: 7.14. Megech Catchments Mass Balance chart

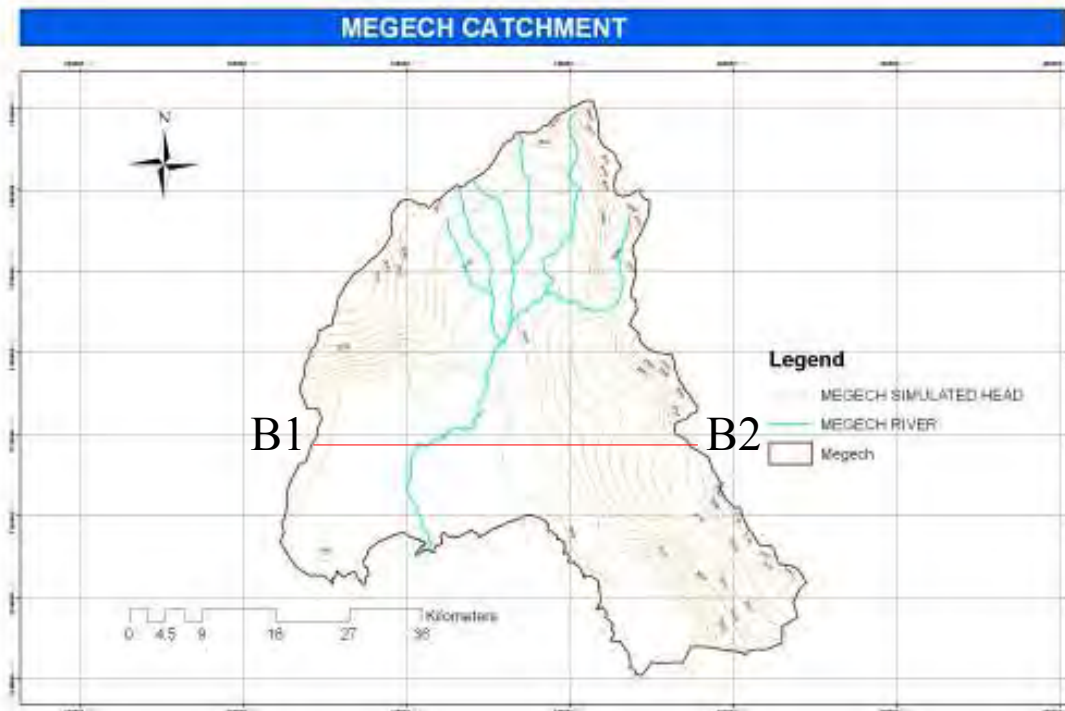


Fig: 7:15. Megech Catchments simulated head with S\_N cross section Line

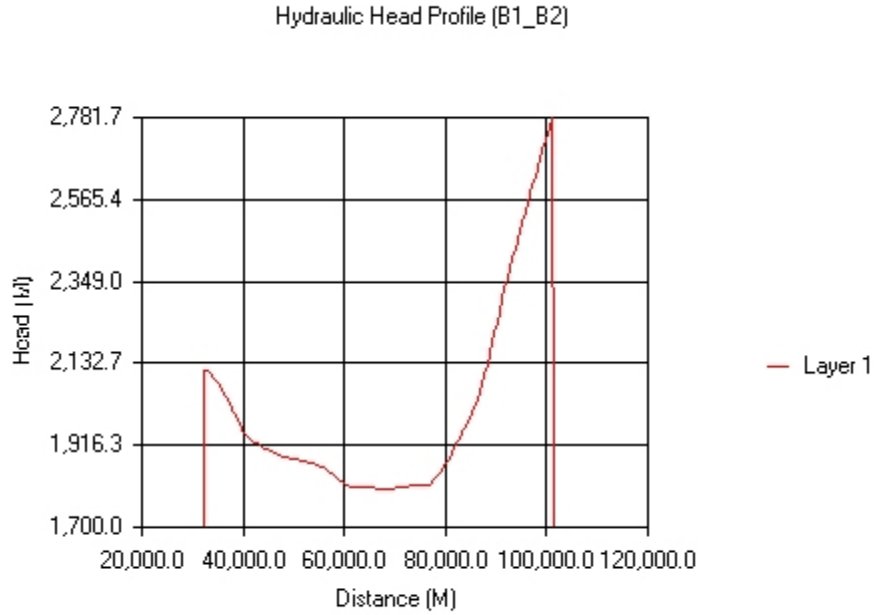


Fig: 7.16. Megech Catchments S\_N Profile of simulated Hydraulic Head

#### 7.4. LAKE TANA AND THE AQUIFER SYSTEM

Lake Tana is a major hydrologic feature of the basin with poor interaction with the aquifer system. It is represented with the GHB and found with gaining of 243.08 M M<sup>3</sup>/Y ground water from the aquifer system.

Based on a recent water balance conducted by SMEC 2007, the total Inflow to the lake is estimated 8723 M M<sup>3</sup>/ Y. The calibrated ground water flow modeling under steady state shows of 2.78% of the contribution could be ground water discharge to the Lake.

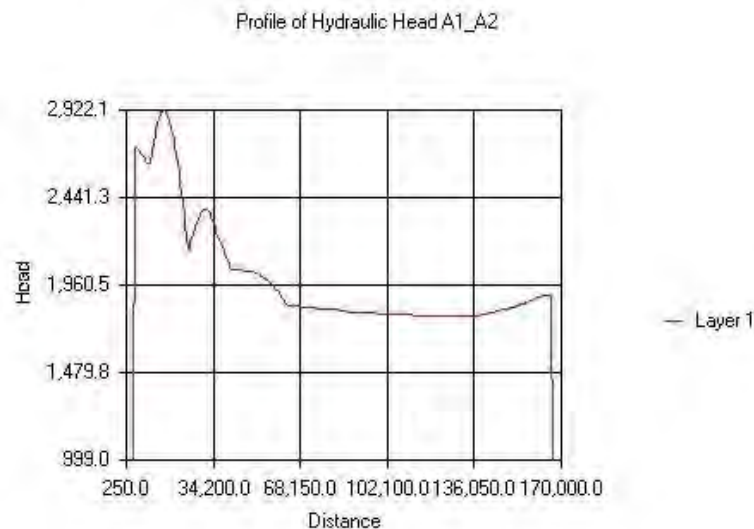


Fig: 7.17. Lake Tana Basin S\_N Profile of simulated Hydraulic Head

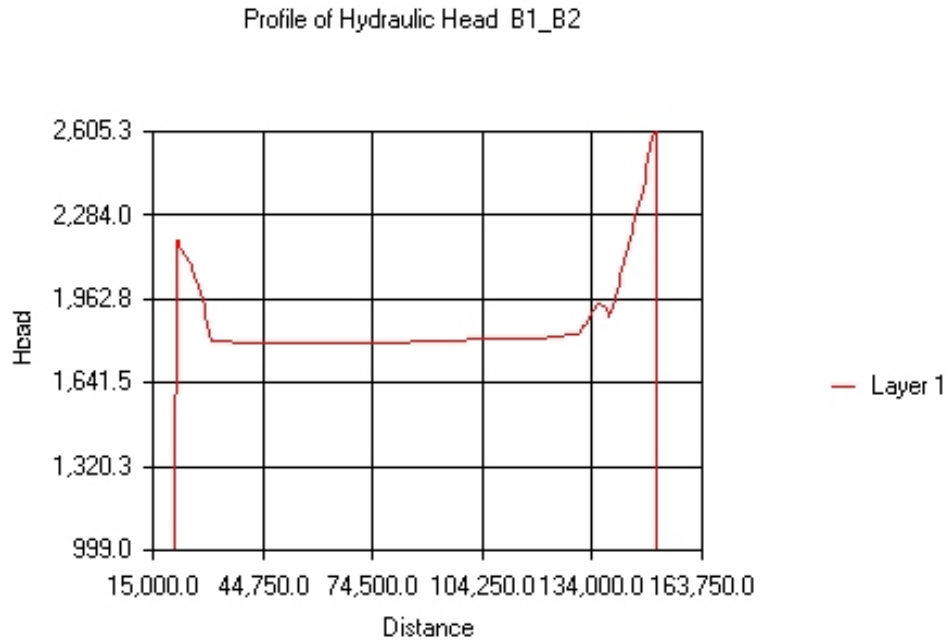


Fig: 7.18. Lake Tana Basin W\_E Profile of Simulated Hydraulic Head

The ground water flow direction and the cross section of the head confirm the flow of the ground water to ward the Lake. Despite the fact of ground water flow of the basin to ward lake, the Lake Tana shares very small amount of the ground water of the aquifer system. This is also suggested by the previous work over the area.

Water Balance of Lake Tana and its sensitivity to fluctuation in rainfall, Blue Nile Basin, Ethiopia (Kebede et al 2000). It was suggested that the likely ground water flow direction is from surrounding area towards the Lake, although the ground water considered to be only a minor component of the water balance. Preliminary isotope studies suggested less than 7% of the total inflow is ground water.

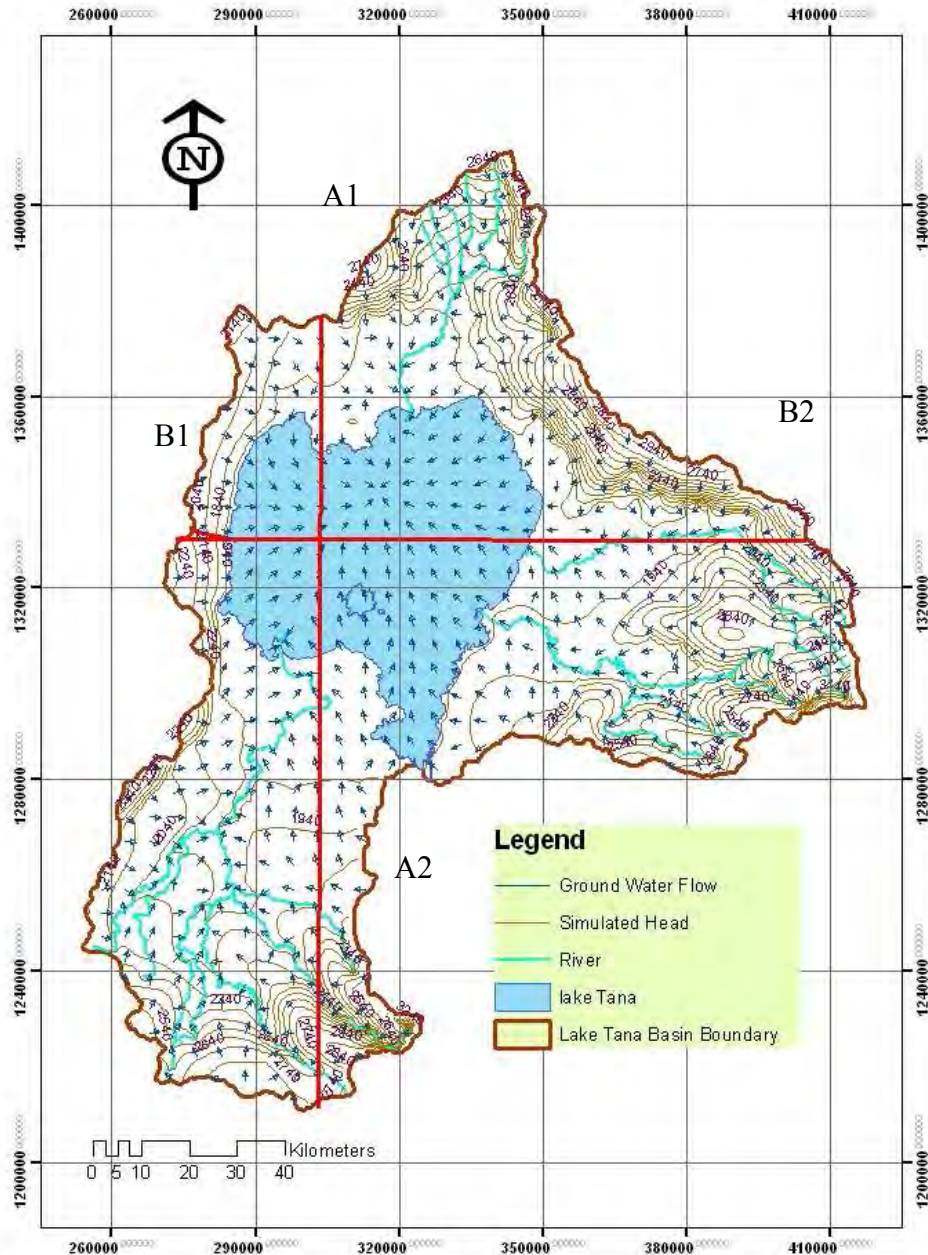


Fig: 7.19. Lake Tana Basin ground water flow vector direction

## 7.5. CALIBRATED AQUIFER SYSTEM PARAMETER

### 7.5.1. CALIBRATED HYDRAULIC CONDUCTIVITY

The Model is calibrated with trial and error method with the most sensitive parameter of dominantly the hydraulic conductivity. In the Calibration process, the modeler considers the fact of the increment of conductivity as one goes to ward the lake, Intensity of

fracturing, the regional maximum and minimum conductivity of the quaternary vesicular basalt, Tarmaber Scoraceous basalt (Tertiary) and alluvial Sediment formation.

As the estimated hydraulic conductivity used a scarce data resource in very spatial controlled volcanic aquifer system, it was very difficult to refine the parameter value. The change of made on conductivity on the shore of the lake on the quaternary basalt and alluvial sediment were large as compared to of the basin volcanic ridge escarpment. The calibrated hydraulic conductivity of the steady state model is shown the map shown on the Fig below.

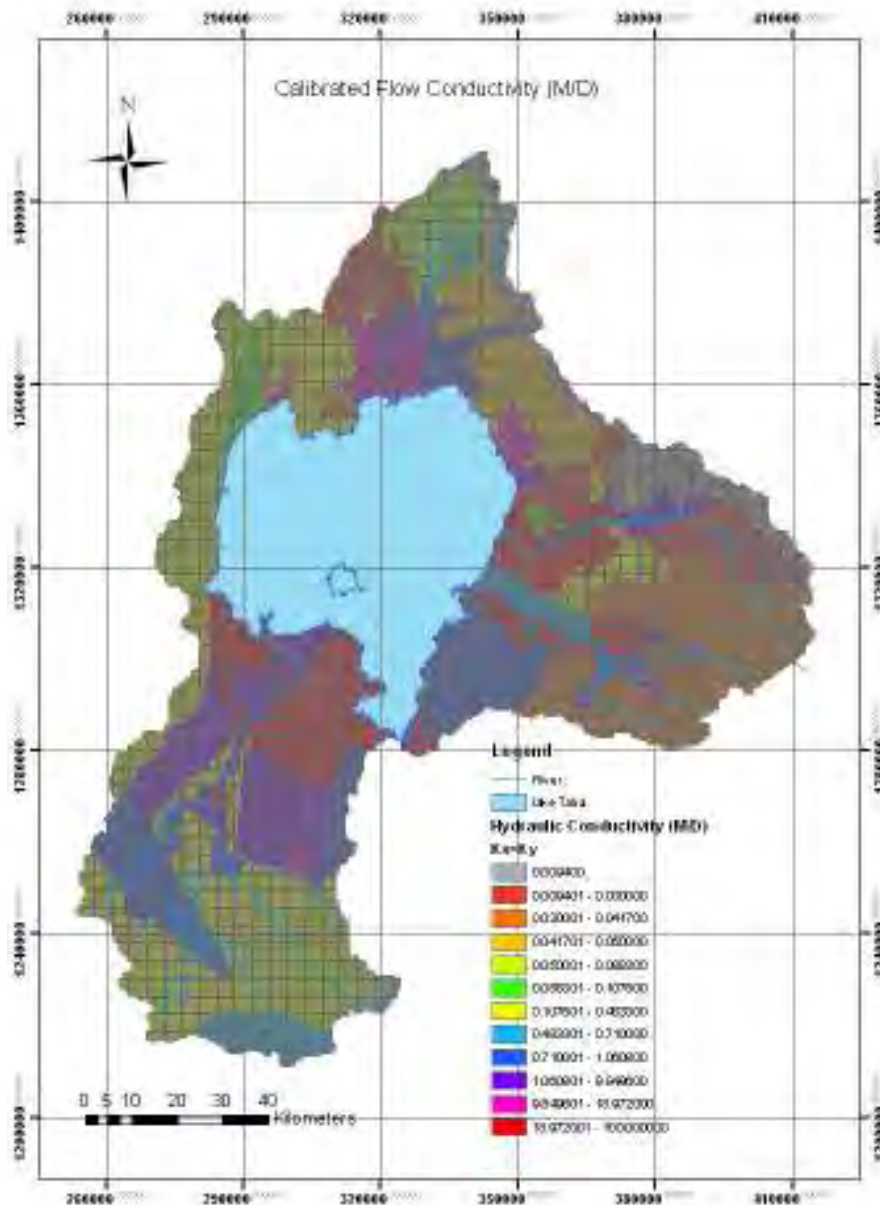


Fig: 7.20. Calibrated Conductivity Map of Lake Tana Basin

### 7.5.2. CALIBRATED RECHARGE

The recharge is the most essential parameter of the aquifer system that governs the water budget system. During calibration, the model was not as sensitive as the hydraulic conductivity. There is almost no change between calibrated and the estimated parameter. The calibrated recharge map of the area is shown on blow.

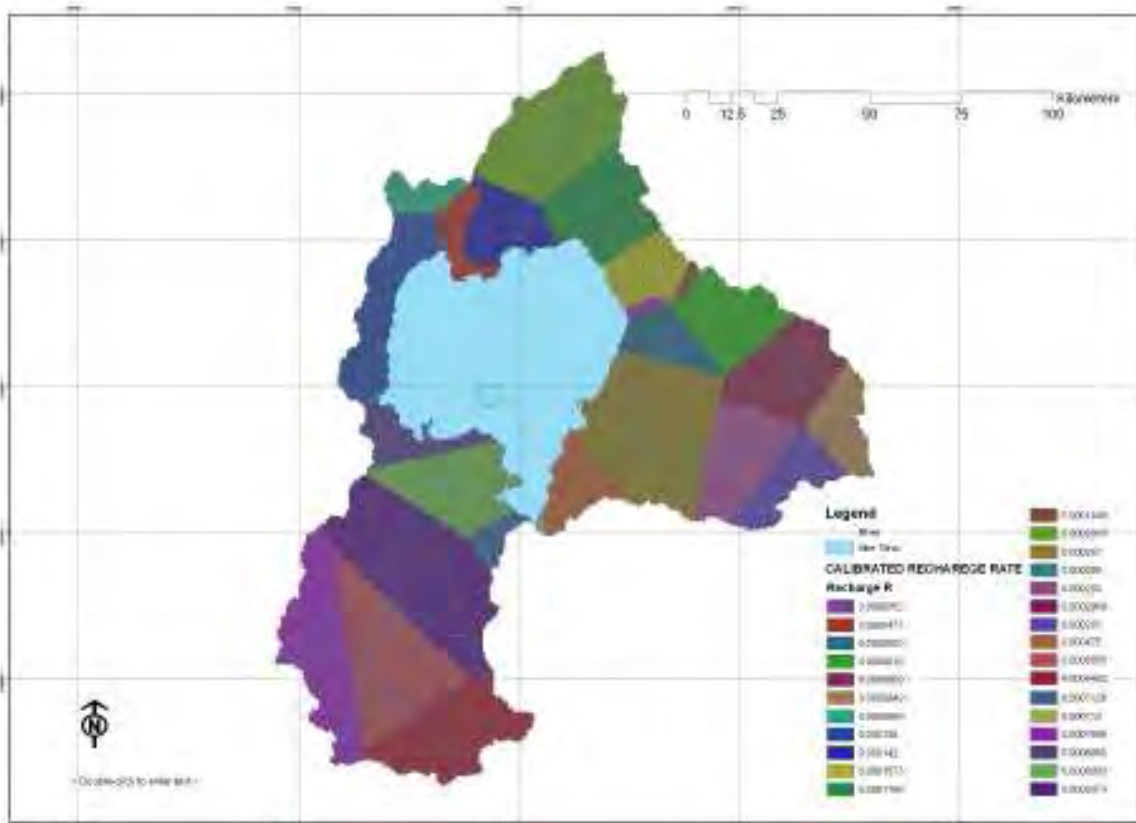


Fig: 7.22. Calibrated Recharge Rate of Lake Tana Basin

### 7.6. SCENARIO ANALYSIS

The main advantage of numerical ground water flow modeling is to customize the result for a different scenario analysis. The calibrated flow model helps as a tool to evaluate the response of the aquifer system to different stress. Even If, It is not major objective to simulate to different scenario but the paper has tried for the simulation of two scenarios with the abstraction of the ground water and the lake influence over the aquifer system.

This part of model analysis has ability to predict the response of the system to change in the future events. As we all know the tendency of the country to use its ground resource

for the domestic and Irrigation projects, it is interesting to see the response of the water level to ground water withdrawal.

Despite the very regional study approach of the research to describe the ground water flow, it has the ability to show a relative aquifer system response to high ground water abstraction.

The model is simulated for increasing of pumping of ground water with 25%, 50%, 100%, 300%, 500%, 700%, 100%, 1200% and 1500%. The model response has been recognized for the average water level, ground water discharge to the river and GHB

The average water level of the system shows a drawdown starting from 0.08m with 25% increment of pumping to 7.26m with 1500% increment of ground water withdrawal. As the percentage of the increment is dramatic at 1200% the aquifer system is also response a radical change too.

The increment of ground water withdrawal has also great effect on the discharge of water from the aquifer system to the River and GH boundaries. The same increment percentage of pumping well results the decrease of the water to discharge to the River and to the GHB.

There will be a change on the discharge of ground water to river` the with a relative lowering of 0.02% with pumping increment by 25% and lowering of 1.99% by pumping increment 1500%.

The increment of the ground water withdrawal will also have an impact of the lake that is represented by the GHB in the model. The ground water discharge will decrease from 0.05 % with 25% increment to 1.63% with 1500% increment of pumping ground water withdrawal.

The detail response of the aquifer system to the ground water withdrawal is summarized in the table 7.8. and Fig 7.23. Chart show below.

<b>GROUNDWATER VISTAS SENSITIVITY ANALYSIS</b>					
<b>PARAMETER: WELL DISCHARGE    ZONE: BASIN</b>					
<b>RUN</b>	<b>MULTIPLIER</b>	<b>DRAW DOWN</b>	<b>RIVER (Q) %</b>	<b>GHB Q (%)</b>	<b>SENSITIVITY</b>
1	1	0.00	0.00	0.00	0.00
2	1.25	0.08	-0.02	-0.05	0.25
3	1.5	0.14	-0.02	-0.05	0.22
4	2	0.27	-0.09	-0.11	0.15
5	3	0.56	-0.18	-0.22	0.00
6	5	1.08	-0.36	-0.43	0.36
7	7	1.49	-0.51	-0.65	0.50
8	10	1.83	-0.77	-0.96	2.40
10	12	2.08	-0.94	-1.17	1.99
11	15	7.26	-1.99	-1.63	2.09

Table: 7.6. Ground Water Withdrawal Scenario Lake Tana Basin

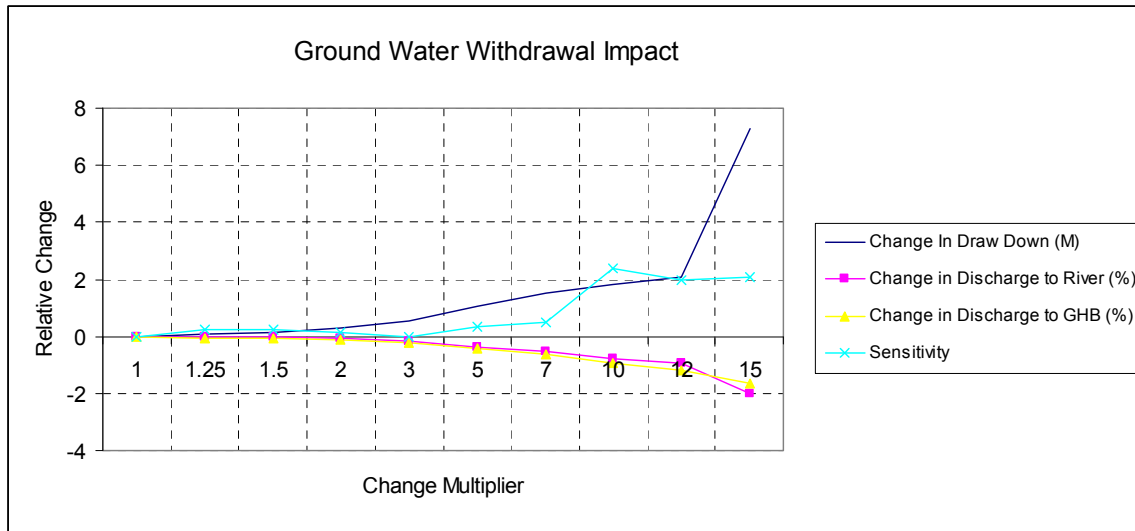


Fig: 7.21. Ground water withdrawal impact chart on the lake Tana basin

The Lake Tana is a major hydrological feature that will have a great effect on the aquifer system. According to the previous studies conducted on the Lake Tana, the lake had been exposed to of the different climate change that lead to desiccation.

If we take the history of the lake in to account, and assumed the same change disconfigure the hydrological set up of the basin with desiccated lake. There will be scenario of the model with no GHB, this achieved by the model with nil GHB conductance. The aquifer system, with a desiccated lake, responses with a relative rise of water level by 18.17m and increase of the ground water discharge to river by 11.93 %.

The model is also simulated for the response to the decrease of Lake Bed conductance by 70% and 90%. It is found to increase the Average water level by the 1.78 M and 9.48 M respectively. The same scenario will have an increment change to ground water discharge to river with rising by 4.69% and 9.48% and dropping of ground water discharge to GHB by 74% and 44% respectively.

The GHB is a head dependent boundary with similar effect of constant head as the conductance is increase. The aquifer system response for the increase of the conductance between by the 25% and 9500 % resulted dropping of the water level from 0.27M to 5.77M ; dropping ground water discharge to river from 1.16% to 12.21%; and rising of discharge to GHB from 8.27 to 81.42% .

The aquifer system response to the increase and decrease GHB conductance is illustrated with table and the Chart stated below.

<b>GROUNDWATER VISTAS SENSITIVITY ANALYSIS</b>					
<b>PARAMETER: GHB CONDUCTANCE</b>			<b>REACH: 0</b>		
<b>RUN</b>	<b>MULTIPLIER</b>	<b>RESIDUAL MEAN</b>	<b>WATER LEVEL (M)</b>	<b>RIVER (Q) (%)</b>	<b>GHB (Q) (%)</b>
1	0	18.17	13.53	11.93	-100
2	0.30	15.48	1.78	4.69	-44
3	0.10	16.46	9.48	9.07	-74
4	1	13.42	0	0	0
5	1.25	13.14	-0.17	-1.16	8.27
6	5	12.07	-3.01	-8.75	58.87
7	6	12.03	-4.57	-9.75	65.54
8	7	12.34	-8.33	-11.34	71
9	8	11.98	-5.59	-11.3	75.6
10	9	11.96	-5.73	-11.93	79.6
11	9.5	11.95	-5.77	-12.21	81.42

Table: 7.7. The Lake Tana Influence Scenario on the Basin

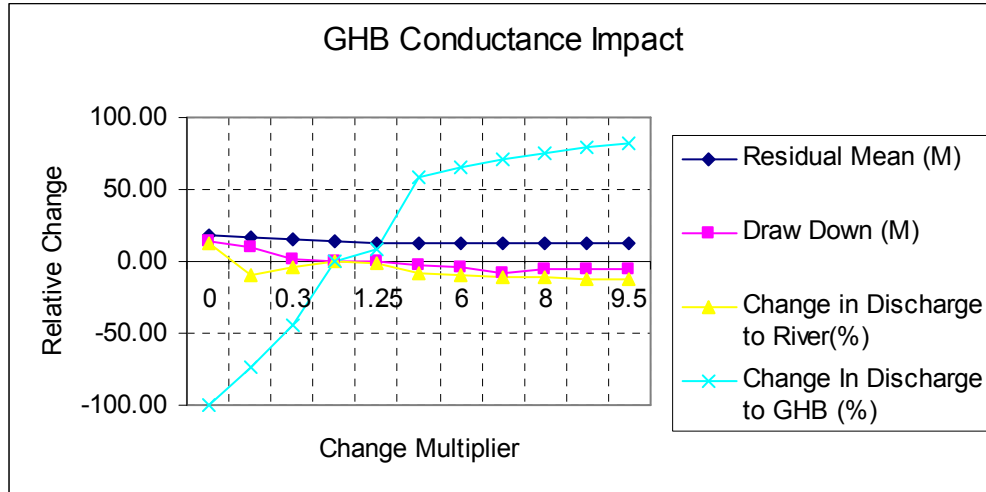


Fig: 7.22. Lake Tana Influence chart on the basin

### 7.7. MODEL LIMITATION

A ground-water model is a simplified approximation of actual conditions. The accuracy of the ground-water model results depends on the accuracy of the input data. The groundwater flow model for this study was constructed with available site specific hydrologic data to determine groundwater flow direction.

The database management of the hydro geologic of the country is so poor and with scarce essential parameter. Therefore the user of the model should consider the deficiency of the data that encountered the modeler.

Model parameters such as hydraulic conductivity and recharge are applied uniformly to a model cell. The assumption of homogeneity can cause inaccuracies because geologic materials and climatic conditions are typically heterogeneous.

The ground-water flow model was discretized using a grid with cells measuring 500 m by 500 m. Model results were evaluated on a relatively large scale and cannot be used for detailed analyses such as simulating water-level drawdown near a single well. A grid with smaller cells would be needed for such detailed analysis.

The Grid size of the model is also has a discrepancy effect on sharing same parameter over this large representation of the field situation in the model.

The resolution of any numerical model is limited by the level of discretization used to create the model. The level of discretization used in the Lake Tana basin is too coarse for studying effects at a local scale, but the discretization is adequate for studying groundwater withdrawal effects at the regional scale.

The model is also assumed a single layer unconfined homogeneous aquifer system which is ignoring the inherited heterogeneity of the earth and the user is expected to take in to account all the assumption used on the paper.

The model calibration relies more on the matching the simulated and observed head distribution than the residual. The user of the model should also consider the scope and tolerance taken on the paper in order to customize the model.

# CHAPTER EIGHT

## 8. CONCLUSION AND RECOMMENDATION

### 8.1 CONCLUSION

In this model, a numerical ground water flow Modflow 2000 is applied to simulate hydraulic head distribution of the aquifer system. It is conceptualized with single unconfined homogeneous aquifer with the water budget of 1,756,791,794.90 M<sup>3</sup> /Y contributed from the precipitation.

The major hydrological feature perennial stream, Lake and ground water withdrawal considered as river, GHB and Well boundary respectively. The hydraulic parameter and recharge is spatially distributed with the available data base.

The model is calibrated more of with matching of simulated and estimated hydraulic head contour of 147 well in and out o of the region under study. And residual of not greater than 0r less than 20m of 37 well constructed 2003 after wards. The model is calibrated with absolute residual mean of 13.42M below the criteria set and residual standard deviation of 12.5M. During the process of calibration, change is made on the hydraulic conductivity, recharge, and river bed conductance with qualitative knowledge of the area.

Based on the conceptual model and calibration stated above, the model is simulated to result water budget of the Lake Tana basin inflow 1,809,004,033.50 M<sup>3</sup>/Y with - 0.00052% percent of error with out flow 1,809,013,494.88 M<sup>3</sup>/Y.

The simulated water budget is surplus the estimated one, 1,756,791,794.90 M<sup>3</sup>/Y, by 52,212,238.60 M<sup>3</sup>/D with 2.9% deviation from the observed one. It is deviation associated with uncertainties of the estimation of the recharge and the other parameter but taking the size of the basin, the model is believed to approximate the field ground water flow.

The base flow discharge of simulated model is 1,563,6171,42.54 which hold 86.43% of the out flow but still with lower volume than the estimated one. The river recharge the aquifer with 7, 043, 7495.6 M<sup>3</sup>/Y 3.89% of the simulated inflow. The river and aquifer interaction implies huge amount discharge of ground water to the dominantly gaining streams. The ground water the basin is highly depleted with discharge of the ground water to the stream.

The simulated base flow of the model is under estimated with possible error introduced during poor estimating the conductivity river bed, derivation of head from the DEM, thickness and over whole width of stream and Coarse grid design of the model.

The lake Tana is conceptualized GHB with a simulated 243,086,633.77 M<sup>3</sup> discharge of Ground Water Lake almost 2.78% of the inflow of lake as SMEC 2007 water balance. It is a consistent result with previous work over poor interaction of the lake and the aquifer

system and preliminary isotope studies suggested less than 7% of the total inflow is ground water (Kebede et. Al 2005).

The hydraulic profile simulation head, under steady state, has resulted ground water flow toward major stream and finally to converge to the Lake Tana. The simulation shows the gaining river from the ground water unlike the paradox of convergence of ground water toward the lake but still with poor contribution. It was suggested that the likely ground water flow direction is from surrounding area towards the Lake, although the ground water considered being only a minor component of the water balance. (Kebede et al 2000).

The model sensitivity is also carried out and found to be more sensitive to the hydraulic conductivity than recharge but being sensitive to the recharge too. The Model is also found to be sensitive to river conductance. The sensitivity conducted on the lake bed conductivity is found to be very sensitive to control the interaction. As Water Balance of Lake Tana and its sensitivity to fluctuation in rainfall, Blue Nile Basin, Ethiopia (Kebede et al 2000) show how the lake separated from the ground water contribution. The high sensitivity of the model to lake bed conductivity bridges the separation of the lake with the aquifer system.

The model is also simulated for two major scenarios with ground water withdrawal increment considering the growing tendency of ground water abstraction and the impact of Lake Tana over the aquifer system with GHB conductance taking the desiccation history of the lake in mind.

The model is simulated for increasing of pumping of ground water with 25%, 50%, 100%, 300%, 500%, 700%, 100%, 1200% and 1500%. The model response has been recognized for the average water level, ground water discharge to the river and GHB.

The average water level of the system shows a drawdown starting from 0.08m with 25% increment of pumping to 7.26m with 1500% increment of ground water withdrawal. While The change on the discharge of ground water to river with a relative lowering of 0.02% with pumping increment by 25% and lowering of 1.99% by pumping increment 1500%. The increment of the ground water withdrawal will also have an impact of the lake that is represented by the GHB in the model. The ground water discharge will decrease from 0.05 % with 25% increment to 1.63% with 1500% increment of pumping ground water withdrawal.

The aquifer system, with a desiccated lake, responses with a relative rise of water level by 18.17m and increase of the ground water discharge to river by 11.93 %. The model is also simulated for the response to the decrease of Lake Bed conductance by 70% and 90%. It is found to increase the Average water level by the 1.78 M and 9.48 M respectively. The same scenario will have an increment change to ground water discharge to river with rising by 4.69% and 9.48% and dropping of ground water discharge to GHB by 74% and 44% respectively.

The GHB is a head dependent boundary with similar effect of constant head as the conductance is increase. The aquifer system response for the increase of the conductance between by the 25% and 9500 % resulted dropping of the water level from 0.27M to 5.77M ; dropping ground water discharge to river from 1.16% to 12.21%; and rising of discharge to GHB from 8.27 to 81.42%.

Finally, the model is able to achieve a simulated hydraulic head that govern the ground water flow with possible approximation of the field situation. The model is also able to show water budget of major catchments with good approximation of the estimated. The model is very good way to describe ground water flow and with refined data the same model can mange scenario with a better accuracy.

## **8.2. RECOMMENDATION**

The objective of the model was to describe the ground water flow of the lake basin in association with the major objective to identify the possible boundary condition and their interaction with the aquifer system. After this all work. It is my recommendation to further work over area.

- The conceptual model is simplified the field condition but there is still a room to refine the flow system, for instance, the base flow of the river surplus the recharge could be conceptualized with identifying possible adjacent aquifer recharge out side the aquifer system.
- The model could be represented with more than single layer to see three dimensional flows.
- The same model could be more appropriately represented with highly sensitive hydraulic characteristics refined and better data set. The basin is still in need of conductivity map with a better accuracy.
- The quantifications and spatial distribution of recharge of the basin still demand attention to work on it.
- The model could be manage with fine grid size or sub divide to different catchments as the modeling is more feasible as the size of the model decreased. The subdivision of the basin may treat the alluvial sediment aquifer independently.
- Modeling is a result of the information era which is best way of ground water management. It demands organized data set so the concerned body, MoWRD, should provide a centralized monitored data for water level, conductivity, ground water withdrawal and pumping test data with usable format i.e. referenced spatially and time seriously.

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# Annex I

Mean Monthly Precipitation (1990\_2006)

GAUGE STATION	JAN (MM)	FEB (MM)	MAR (MM)	APR (MM)	MAY (MM)	JUN (MM)	JULY (MM)	AUG (MM)	SEP (MM)	OCT (MM)	NOV (MM)	DEC (MM)	YEARLY MEAN
SEKELA	8.11	11.29	38.31	83.54	142.95	275.53	435.87	357.62	236.93	141.58	52.82	21.42	1805.97
KUNZILA	0.50	0.00	5.80	6.00	13.60	180.70	405.50	273.10	185.00	76.70	1.00	0.0	1147.90
FERESBET	14.51	9.03	50.25	55.10	128.31	238.06	453.93	432.23	217.14	150.64	62.84	23.15	1835.18
ZEGE	4.16	0.13	16.65	20.69	82.49	226.67	496.37	442.53	256.44	86.48	8.14	0.36	1641.11
YIFAG	1.45	2.50	10.05	26.55	21.60	154.40	297.35	319.35	144.00	20.30	15.65	0.00	1013.20
WERETA	0.10	0.86	3.88	28.52	65.93	208.29	402.85	413.16	184.34	68.26	13.29	2.99	1392.47
MERAWI	0.40	1.35	0.80	20.40	171.25	310.80	490.90	367.10	290.95	109.60	0.00	0.00	1697.95
MAKSEGNET	1.73	2.74	15.13	38.05	65.33	157.18	318.67	316.29	98.17	41.50	17.78	3.47	1076.04
HUMERA	0.63	0.00	0.77	8.53	26.93	101.25	176.92	286.60	137.50	10.15	0.58	0.00	749.85
GORGORA	0.00	1.00	8.30	25.35	34.23	141.13	197.40	263.13	111.20	68.30	12.63	1.25	863.93
GONDER AIR PORT	2.47	3.80	16.01	35.81	89.76	182.09	336.93	312.52	126.33	91.98	17.71	10.42	1225.83
ENJIBARA	7.45	8.74	28.81	80.02	192.48	360.44	481.79	507.17	404.45	193.60	66.54	19.41	2350.90
ENFRANZ	0.70	0.75	8.48	17.30	27.62	137.50	292.95	306.28	94.52	59.15	9.79	1.98	957.02
DELGI	0.39	0.75	8.03	29.16	62.67	134.86	205.71	204.74	104.44	67.23	8.46	1.08	827.52
DEKE													
ESTIFANOS	0.35	0.35	14.05	16.83	66.19	248.91	478.41	495.65	212.08	94.92	7.82	0.00	1635.55
DEBRETABOR	4.38	2.52	27.25	50.73	95.04	159.27	413.74	401.51	206.61	69.26	30.11	15.53	1475.95
DANGILA	0.73	2.33	22.65	43.22	142.11	260.95	338.72	347.74	238.58	122.43	34.73	6.13	1560.32
BAHIR DAR OLD OFFICE	1.20	2.57	14.41	26.89	76.84	205.24	420.60	370.95	196.10	97.38	14.71	3.38	1430.26
BAHIR DAR NEW OFFICE	0.35	0.05	43.40	4.95	41.10	187.30	533.20	299.85	263.70	62.70	8.35	0.00	1444.95
ADDISZEMEN POLICE	0.00	0.99	8.32	23.55	54.36	187.16	373.23	312.27	127.61	27.41	9.18	0.53	1124.61
AYKEL	0.72	2.14	14.65	35.6	113.28	193.2	280.16	240.63	164.04	98.21	14.76	0.38	1157.767

## Annex II

### Mean Monthly Temperature (1990\_2006)

STATION	MEAN MONTHLY TEMPERATURE (°C)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ADDIS ZEMEN	17.7	19.7	20.5	20.9	19.7	19.7	17.5	18.4	18.9	18.8	18.4	14.2
DEBRETABOR	15.8	15.4	17.5	17.9	17.6	16.1	14.3	14.4	14.7	14.8	14.9	14.7
GORGORA	25.5	26.7	26.6	27.9	25.1	22.4	21.1	20.7	21.5	23.4	22.7	23.8
MERAWI	8.6	9.5	19.9	20.5	20.8	19.1	18.5	18.5	18.9	19.0	18.0	16.7
ZEGE	17.3	17.8	20.5	21.3	21.2	20.2	18.6	19.0	18.8	19.0	18.6	17.9
BAHIR DAR	17.1	18.8	20.7	21.6	21.8	20.3	18.8	18.7	18.9	19.0	18.2	16.6
DANGILA	16.3	14.7	18.4	19.0	18.5	17.7	16.8	16.9	17.2	17.1	16.4	15.6
ENFRANZE	20.8	22.2	23.6	25.1	24.3	21.6	19.7	18.2	19.4	13.9	20.6	15.7
GONDER	19.3	20.5	22.0	22.4	21.8	19.7	18.0	17.9	18.8	19.3	19.4	19.3
MAKSEGNTTE	17.9	19.5	22.9	22.9	22.8	20.7	19.1	19.5	19.8	20.3	20.1	17.3
WERETA	15.5	17.7	19.7	19.3	21.1	20.1	19.4	19.0	19.5	18.3	19.3	17.9
KUNZILA	17.7	19.3	23.2	22.5	23.5	20.8	19.15	19.5	20.45	19.55	18.45	17.75
HUMERA	27.6	29.8	32.3	34.3	34.1	30.6	27.3	26.9	27.8	28.5	28.0	27.0
DEKE ISTIFANOS	20.7	21.6	22.2	23.2	22.6	21.5	20.1	20.0	20.5	21.1	20.9	20.5
MEAN OF LAKE TANA BASIN	18.4	19.5	22.1	22.8	22.5	20.8	19.2	19.1	19.7	19.4	19.6	18.2

## Annex III

### Mean monthly maximum temperature (°c) (1990-2006)

STATION	MEAN MAXIMUM TEMPERATURE (°C)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ADDIS ZEMEN	30.9	33.0	33.0	32.7	31.7	28.0	25.2	25.5	27.2	28.9	29.7	19.4
DEBRETABOR	23.4	22.1	24.7	24.8	24.2	22.3	19.1	19.2	20.4	21.1	21.8	21.7
GORGORA	31.0	32.3	32.5	31.5	31.0	27.8	25.5	25.2	26.5	28.4	29.2	29.2
MERAWI	14.3	15.0	30.3	29.9	27.9	25.5	23.6	23.8	25.1	26.6	27.3	27.3
ZEGE	27.5	27.7	30.8	31.2	30.2	28.1	25.4	24.6	25.6	26.3	27.0	27.7
BAHIR DAR	26.5	27.9	29.4	29.7	28.9	26.6	23.9	23.8	25.1	25.8	26.2	25.6
DANGILA	26.5	23.8	28.1	27.8	25.7	24.1	21.6	22.4	23.8	24.3	25.0	25.8
ENFRANZE	28.6	30.2	30.7	31.3	30.4	26.4	23.7	24.2	25.7	18.1	28.0	21.7
GONDER	27.5	28.7	29.6	29.5	28.3	25.3	22.5	22.6	24.8	26.1	26.7	26.9
MAKSEGNTTE	26.2	27.7	32.0	31.1	30.6	27.5	24.4	25.2	26.8	28.4	29.2	25.6
WERETA	23.5	25.9	28.0	26.6	28.6	27.1	26.1	25.0	26.6	25.5	25.7	26.8
KUNZILA	26.3	27.4	30.85	29.4	31.1	26.3	24.2	24.7	27.7	27.4	26.6	26.1
HUMERA	36.7	39.2	39.8	42.0	41.1	38.6	34.3	32.0	33.8	35.8	37.8	36.8
Deke Istifanos	21.1	23.1	33.2	40.7	46.6	47.0	90.9	79.7	51.9	37.8	34.4	22.1

## ANNEX IV

### Mean Monthly Minimum Temperature (°C) (1990\_2006)

STATION	Mean Minimum Temperature (°C)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ADDIS ZEMEN	4.5	6.4	8.0	9.1	10.0	11.4	9.8	10.1	10.7	8.7	7.8	3.7
DEBRETABOR	8.7	8.9	10.5	11.0	10.9	10.1	9.4	9.6	9.0	8.6	8.3	8.0
GORGORA	19.9	21.1	20.7	22.5	19.2	17.1	16.8	16.2	16.6	18.3	16.3	15.2
MERAWI	2.9	3.9	9.5	11.1	13.6	12.7	13.5	13.3	12.6	11.5	8.7	6.0
ZEGE	7.1	7.9	10.2	11.4	12.2	12.2	11.9	13.3	12.0	11.7	10.1	8.0
BAHIR DAR	7.5	9.2	11.9	13.3	14.4	14.0	13.6	13.5	12.8	12.3	10.4	7.7
DANGILA	4.7	5.0	7.4	9.3	10.3	10.8	11.4	11.1	10.3	9.4	7.0	4.8
ENFRANZE	8.7	14.2	16.5	18.9	18.1	16.8	15.7	12.2	13.1	9.6	13.1	9.7
GONDER	11.0	12.2	14.3	15.3	15.2	13.8	13.3	13.0	12.6	12.3	11.7	10.9
MAKSEGNTTE	9.6	11.9	14.5	15.6	15.6	14.4	14.2	14.2	13.5	13.0	11.8	9.8
WERETA	7.5	9.5	11.4	12.1	13.7	13.1	12.7	13.1	12.5	11.1	12.9	8.9
KUNZILA	9.1	11.3	15.7	15.6	15.9	15.3	14.1	14.3	13.2	11.7	10.3	9.4
HUMERA	15.4	17.3	21.0	24.2	24.8	22.8	20.7	20.2	19.9	19.5	18.2	16.6
DEKE												
ISTIFANOS	14.5	15.2	16.0	17.0	16.6	15.9	15.5	15.4	15.4	15.8	15.3	14.3

## ANNEX V

### MEAN WIND SPEED (IN M/S) AT 2 METERS A.S.L (1990\_2006)

STATION NAME	MEAN WIND SPEED (IN M/S) AT 2 METERS A.S.L											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
DEBRETABOR	1.0	1.2	1.2	1.2	1.3	1.1	1.1	1.2	1.0	0.8	0.9	0.9
BAHIR DAR	0.6	0.7	0.8	0.9	0.9	0.9	0.7	0.7	0.7	0.7	0.6	0.5
DANGLA	0.9	1.0	1.1	1.2	1.3	1.2	1.1	1.1	0.9	0.8	0.7	0.8
GONDER	1.4	1.4	1.6	1.5	1.7	1.7	1.1	1.1	1.2	1.1	1.1	1.0

## ANNEX VI

### MEAN MONTHLY RELATIVE HUMIDITY (%) (1990\_2006)

STATION NAME	MEAN MONTHLY RELATIVE HUMIDITY (%)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
DEBRETABOR	41.9	38.6	40.8	47.5	51.9	68.1	79.8	77.9	70.7	59.3	50.6	45.3
Bahir Dar	52.4	45.8	42.5	43.4	52.4	66.9	76.2	77.2	72.1	63.1	56.2	52.9
Dangla	54.5	44.6	49.0	51.2	63.9	80.1	77.6	85.7	81.7	75.8	69.2	58.9
Gonder	36.2	33.5	34.7	37.9	48.6	67.1	79.2	79.4	70.1	55.4	46.9	42.1

## ANNEX VII

### MEAN MONTHLY SUNSHINE HOURS (HOURS/DAY) (1990\_2006)

STATION NAME	MEAN MONTHLY SUNSHINE HOURS (HOURS/DAY)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
DEBRETABOR	8.5	9.7	9.3	7.4	7.2	6.7	5.0	5.6	6.4	7.9	8.2	9.9
BAHIR DAR	9.6	9.6	9.1	8.9	8.3	7.0	4.6	4.5	6.5	8.5	9.5	9.8
DANGLA	9.1	9.0	8.2	8.2	7.7	6.2	4.2	4.3	6.3	6.6	8.4	8.8
GONDER	9.5	9.0	8.1	7.7	7.0	4.5	4.4	5.0	7.0	7.6	8.8	9.2

## ANNEX VIII

### Ground` Water withdrawal from Pumping well and static water level

Name	X_m	Y_m	SWL	Top layer	Bottom layer	Q_m3_d)
Addis zemen	367607	1341556	1972.00	1	1	-104.54
Adet	334754	1246924	2130.00	1	1	-104.54
Anbesame	350344	1292749	2127.72	1	1	-52.27
Angerb 1(Gondar)	333468	1397039	2159.22	1	1	-120.96
Angerb 7(Gondar)	333457	1395269	2160.00	1	1	-120.96
Arb, Gebeya	363821	1286050	2230.98	1	1	-52.27
Arbaya	373290	1396833	1760.28	1	1	-59.616
Asilo(Woji)Advent	369384	1332368	1934.00	1	1	-52.27
Aykel, Antra	289943	1388143	2175.00	1	1	-104.54
Azena 1	260578	1190629	2157.00	1	1	-52.27
Azena 2	260578	1190629	2108.40	1	1	-111.74
Bahr Dar, Kebele 07	323665	1280943	1795.13	1	1	-111.74
Bahr Dar, Kebele 11 (1)	327010	1284243	1786.51	1	1	-111.74
Bahr Dar, Kebele 11 (2)	327010	1284243	1787.80	1	1	-111.74
Bahr Dar, Kebele 13 (1)	322829	1283492	1793.00	1	1	-111.74
Bahr Dar, Kebele 14)	323664	1280722	1786.00	1	1	-111.74
Bahr Dar, Kebele 15)	323605	1281828	1798.85	1	1	-111.74
Bichena1	417848	1153937	2371.00	1	1	-111.74
Bure 1	287118	1183591	2094.50	1	1	-111.74
Bure 2 (M.W)	289370	1183245	2093.50	1	1	-111.74
Chagni -1	228954	1212008	1705.00	1	1	-111.74
Chagni -2	227021	1213574	1747.02	1	1	-111.74
Chuahit 1	311499	1360335	1787.00	1	1	-52.27
Chuahit 2	307952	1373302	1785.00	1	1	-52.27
Debre Tabor, Ajibar	392745	1310820	2681.97	1	1	-104.54
DebreTabor, Ajibar02	395373	1311695	2566.50	1	1	-104.54
Dabat, Besekos	364340	1417227	2586.00	1	1	-52.27
Dangla 1	265471	1245919	2123.20	1	1	-111.74
Dangla 2	265046	1246033	2119.24	1	1	-111.74
Dangla 3	265046	1246033	2127.98	1	1	-111.74
Debre Markos	358947	1143621	2333.50	1	1	-104.54
Debre Markos 1	354410	1142644	2322.90	1	1	-104.6
Debre Markos 2	359238	1142293	NA	1	1	-104.54

Name	X_m	Y_m	SWL	Top layer	Bottom layer	Q_m3_d)
Debre Markos 3	359152	1142625	2320.70	1	1	-104.54
Debre Markos 5	359153	1143067	2322.30	1	1	-104.54
Debre Markos 6	358692	1142737	2361.50	1	1	-104.54
Debre Markos 7	358694	1143180	2325.80	1	1	-104.54
Debre Mewi	328629	1253040	2270.00	1	1	-111.74
Debre Tabor,Children	389873	1311936	2638.00	1	1	-52.27
Debre Tabor,Zunt.l	396064	1309702	2632.69	1	1	-52.27
Debre Work 1	327574	1178935	2405.30	1	1	-52.27
Deghi	287845	1349433	1791.00	1	1	-52.27
Dembecha	335672	1168056	2038.10	1	1	-52.27
Durbete 1	277370	1256013	1988.00	1	1	-55.87
Durbete 2	277370	1256013	1987.00	1	1	-55.87
Enfraz_1	351310	1347164	1894.00	1	1	-55.87
Enfraz 2	353137	1349035	1893.00	1	1	-55.87
Fenote Selam	310297	1180798	1824.00	1	1	-111.74
Feres Bet	347430	1200407	2987.80	1	1	-52.27
Gedebghi	362600	1431947	2612.83	1	1	-52.27
Gishe Abay	304381	1214903	2708.50	1	1	-52.27
Gondar, Chinese 1	331621	1391518	2124.68	1	1	-104.54
Gondar, Chinese 4	331632	1393399	2123.76	1	1	-104.54
Gondar, Shinta 1	331621	1391518	2145.40	1	1	-104.54
Gonji	354830	1239527	2210.00	1	1	-59.61
Gorgora2	313258	1352911	1880.25	1	1	-52.27
Hamusit	342125	1301307	1994.80	1	1	-111.74
Ibnat	394813	1341447	2220.30	1	1	-52.27
Jeba Sira	386595	1285627	2492.00	1	1	-52.27
Keranyo	386850	1212968	2457.57	1	1	-52.27
Kessa 1	278865	1204665	2530.00	1	1	-59.61
Kimir Dingay	411939	1303459	2996.50	1	1	-52.27
Kokit 1	210552	1422047	NA	1	1	-60.48
kola Dib Village	317020	1373243	1845.66	1	1	-60.48
Kunzila	284932	1313605	1799.53	1	1	-59.61
Maksegnit	340560	1371224	1940.30	1	1	-104.54
Mitraha, Jeldesa	349495	1345403	1794.60	1	1	-119.232
mota1	377761	1225276	2396.66	1	1	-52.27
Nefas Mewcha # 1	436432	1293446	3050.00	1	1	-52.27
Nefas Mewcha # 2	436474	1313351	3050.80	1	1	-52.27
Negade Bahr	333436	1391508	2075.30	1	1	-60.48
Rob Gebeya	364994	1166600	2860.00	1	1	-52.27
Shehdi	223099	1408968	NA	1	1	-60.48
Shindi	257380	1178038	2051.40	1	1	-55.87
Smada	422718	1256653	2516.64	1	1	-52.54
Tiilli	283820	1199764	2447.00	1	1	-55.87
Tseda # 1	340662	1389696	1964.25	1	1	-59.616
Wada Yessus	319923	1163932	1954.30	1	1	-52.27
Wetet Abay	285691	1257947	1965.10	1	1	-55.87
Woreta	358040	1318483	1790.00	1	1	-119.232

Name	X_m	Y_m	SWL	Top layer	Bottom layer	Q_m3_d)
Woreta, Kahar Michael	354087	1314078	1867.00	1	1	-119.232
Yechereka	327537	1171635	1967.00	1	1	-55.87
Yedwuha	427491	1154026	2374.80	1	1	-55.87
Yifag	360316	1332409	1846.28	1	1	-119.232
Yinessa, Uibeb Iyesus	315428	1276787	1971.20	1	1	-55.87
Zege	315606	1292052	1816.87	1	1	-55.87
Guber	287735	1183421	1975.00	1	1	-1119.23
Tach Afer fida	264910	1245387	2005.00	1	1	-1119.23
Dalegie	396071	1308601	2657.00	1	1	-52.27
Deber Gedema	395127	1310133	2020.00	1	1	-52.27
Debekan	393828	1312208	1906.00	1	1	-52.27
Ambagiorgis Zuria	393696	1311911	2934.00	1	1	-52.27
Achfi	393598	1311599	1804.00	1	1	-52.27
Chincha mender	394055	1312407	1958.00	1	1	-52.27
Zelega No .2	357597	1318403	1789.50	1	1	-52.27
Gonbat	278000	1263000	1813.00	1	1	-55.44
Debregenet	276000	1259000	1809.00	1	1	-55.44
Tenta Laguna	279500	1267500	2000.50	1	1	-55.44
Charma No1	273500	1255500	1850.00	1	1	-55.44
Galadula No 1	285000	1257000	1819.00	1	1	-55.44
Gulit	350000	1412000	1912.40	1	1	-55.44
Yibab Eyesus	301000	1292000	1767.00	1	1	-119.23
Adisambo	313000	1269000	1991.00	1	1	-119.23
Alefa (Azemer)	312000	1290000	1995.00	1	1	-119.23
Durbete	316000	1178000	NA	1	1	-119.23
Wehini	307000	1294000	2012.00	1	1	-119.23
Werkmidir (Alefa well )	335000	1283500	2009.00	1	1	-119.23
Gulum Abasm	313000	1284500	1950.00	1	1	-119.23
Fendika	306000	1287000	1959.00	1	1	-119.23
Argaba	317000	1277000	1926.00	1	1	-119.23
Bachanges	316000	1178000	1988.00	1	1	-119.23
Denbun no .1	286000	1170000	2028.00	1	1	-59.61
Denbun no .2	286000	1175000	2045.00	1	1	-59.61
Gindaba	297000	1112000	2130.00	1	1	-59.61
Muksan	300000	1192000	1933.00	1	1	-59.61
Wember	285500	1174000	1983.00	1	1	-59.61
Agona	292000	1169000	3208.00	1	1	-59.61
Erobgebeya	292000	1171000	2340.00	1	1	-59.61
Licha	293000	1168000	2310.00	1	1	-59.61
Mickre	289000	1174000	2424.00	1	1	-59.61
Wefchame	283000	1176000	2298.00	1	1	-59.61
Debretabor	282000	1176000	2673.00	1	1	-59.61
Awramba	298000	1189750	1892.00	1	1	-59.61
Abegziabher	291000	1173000	1950.00	1	1	-59.61
Ambomeda	293000	1170700	2014.00	1	1	-59.61
Atse Mesaferia	415000	1283000	1944.70	1	1	-52.27

Name	X_m	Y_m	SWL	Top layer	Bottom layer	Q_m3_d)
Biro Minch	385000	1289000	1882.00	1	1	-52.27
Chekechek	377000	1288500	2105.70	1	1	-52.27
Chinca Warka	409000	1272000	1875.00	1	1	-52.27
Enberewary well no 1	385000	1252000	1985.00	1	1	-52.27
Enberewary well no 2	393000	1310000	1975.00	1	1	-59.61
Gulo Mender	369000	1319000	1836.00	1	1	-59.61
Koyna Mesk	366000	1340000	2061.00	1	1	-52.27
Lay Chinch Warka	379000	1339000	1993.00	1	1	-52.27
Sinkober	371150	1337150	2075.00	1	1	-52.27
Washa Endrias	365500	1336000	2440.00	1	1	-52.27
Agta	368000	1344000	1832.00	1	1	-52.27
Bure_15	374000	1335000	1980.00	1	1	-52.27
Debretabor_W1	367000	1341000	2102.23	1	1	-52.27
BH_W1	368000	1341000	2580.00	1	1	-52.27
BH_W2	367000	1336000	2607.00	1	1	-52.27
BH_W3	368000	1340000	2542.50	1	1	-52.27
BH_W4	373500	1338500	2535.30	1	1	-52.27
BH_W5	374000	1337000	2540.40	1	1	-52.27
BH_W6	365000	1346000	2494.44	1	1	-52.27
Wereta_W2	375000	1333000	1785.00	1	1	-52.27

## ANNEX IX

### Observed Vs Computed Water Level

Name	X	Y	Observed	Computed	Residual	Remark
Anbesame	350344	1292749	2064.12	2056.68	7.44	
Asilo(Woji)Advent	369384	1332368	1817.20	1810.02	7.18	
DebreTabor Ajibar02	392745	1310820	2549.50	2568.73	-19.23	
Debre Tabor Children	389873	1311936	2614.40	2633.91	-19.51	
Debre Tabor Zunt	396064	1309702	2612.09	2598.15	13.94	
Durbete 1	277370	1256013	1963.90	1985.50	-21.60	
Durbete 2	277370	1256013	1962.50	1985.50	-23.00	
Enfraz_1	351310	1347164	1799.20	1814.17	-14.97	
Gishe Abay	304381	1214903	2704.20	2712.23	-8.03	
Hamusit	342125	1301307	1925.30	1944.86	-19.56	
kola Dib Village	317020	1373243	1813.46	1809.52	3.94	
Kunzila	284932	1313605	1800.53	1819.09	-18.56	
Mitraha Jeldesa	349495	1345403	1796.80	1811.75	-14.95	
Negade Bahr	333436	1391508	2024.50	2044.85	-20.35	
Tseda # 1	340662	1389696	2097.65	2087.60	10.05	
Wetet Abay	285691	1257947	1878.20	1892.68	-14.48	
Woreta	358040	1318483	1787.00	1810.60	-23.60	
Woreta K/ Michael	354087	1314078	1803.10	1816.89	-13.79	
Yifag	360316	1332409	1796.78	1808.78	-12.00	
Yinessa Uibeb Iyesus	315428	1276787	1875.10	1873.96	1.14	

Name	X	Y	Observed	Computed	Residual	Remark
Tach Afer fida	264910	1245387	2098.20	2112.00	-13.80	
Debekan	393828	1312208	2562.50	2579.29	-16.79	
Ambagiorgis Zuria	393696	1311911	2571.50	2588.55	-17.05	
Achfi	393598	1311599	2579.70	2597.40	-17.70	
Zelema No .2	357597	1318403	1803.40	1810.53	-7.13	
Debregenet	276000	1259000	2003.00	1989.20	13.80	
Charma No1	273500	1255500	2016.40	2022.62	-6.22	
Galadula No 1	285000	1257000	1905.10	1896.18	8.92	
Wehini	307000	1294000	1803.70	1825.77	-22.07	
Gulum Abasm	313000	1284500	1827.00	1834.60	-7.60	
Fendika	306000	1287000	1828.80	1831.53	-2.73	
Chekechek	377000	1288500	2344.00	2357.98	-13.98	
Gulo Mender	369000	1319000	1887.00	1874.89	12.11	
Koyna Mesk	366000	1340000	1974.60	1987.44	-12.84	
Bure_15	374000	1335000	1897.90	1882.14	15.76	
Debretabor_W5	373500	1338500	1994.10	1989.39	4.71	
Wereta_W2	375000	1333000	1805.30	1821.24	-15.94	