

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES DEPARTMENT OF
EARTH SCIENCES



**NUMERICAL GROUNDWATER FLOW MODELING OF THE
NORTHERN RIVER CATCHMENT OF THE LAKE TANA**

By: - Nigussie Ayehu

**A Thesis Submitted to the School of Graduate Studies of Addis Ababa
University in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Hydrogeology**

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Advisor: - Tenalem Ayenew (Prof.)

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DECLARATION

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

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The Thesis has been submitted for examination with my approval as university advisor.

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ABSTRACT

The study area is found North Western plateau in the North Gondar zone, Amhara regional state. Its total surface coverage is 1887km². The study area boundary was delineated from 90m Shuttle Radar Terrain Mapping (SRTM) digital elevation model (DEM) using Global Mapper 8 software. This boundary was served as the divide line of groundwater flow while stream networks were used as internal drainage lines. Input parameters such as hydraulic conductivity and recharge were obtained from past studies and modelers knowledge. Based on geologic information of the study area, unconfined subsurface flow condition was considered and simulated using MODFLOW 2000.

The model calibration accounts the matching of the 58 observation point with simulated head with a permissible residual head of ± 10 m. 75% of the difference the observed and measured water level head in the study area is 5m. . The model was calibrated with mean error 0.506, absolute mean error 4.431m and standard deviation 6.083m.

The sensitivity of the major parameters of the model was identified during calibration process. Based on the calibration process, the model is very sensitive in decreasing order change in recharge, hydraulic conductivity, and stream bed conductance respectively.

The simulated water budget has been computed for the study area. The simulated out flow of the model is 205733827.88m³/year which is nearly equal to simulated inflow with difference 2887.5 m³/year. The base flow simulated discharge holds 35.75% of the out flow. It also contributed as recharge in to the aquifer that accounts to 15.30% of the inflow. This share of base flow implies the discharge of the groundwater to the dominantly gaining streams and high interaction of surface and aquifer systems.

Two scenarios of increased groundwater withdrawals have been conducted. In the first scenario, five increased withdrawals amounts were distributed among existing wells in proportion to the current contribution of each source to the daily withdrawal rate. Steady state withdrawal rates were increased by 15%, 35%, 55%, 75% and 100% to study the response of the system in this scenario. From the above five simulation results, one can observe that the development of a new groundwater sources would not pose appreciable impact in case of 15% and 35% withdrawal the head declines in this case is insignificant relative to the steady state withdrawal rate and the natural discharges were not altered highly. In the second scenario, increased groundwater withdrawal in Gondar-Azezo town and its periphery well fields were simulated. The simulation result indicated that the stream leakage decreased by 7.9% relative to the whole steady state value, but showed 14.9% decrease for Angereb, Keha, and Shinta river segments near the well field area. The water tables decline by 3.57m to 18.81m in head observation in the well field area. The lower Angereb well field head decline is significant when compare with other near well fields.

This scenario simulates also decreasing recharge to aquifers that result from environmental changes, expansion of agriculture, deforestation and town expansion. The steady state simulated recharge was decreased by 32% and the simulation results showed on average head decrease of 8.06m over the whole area; with the highest fall 32m in wells to north and a minimum of about 1m in wells to the south. In addition, the stream leakage, compared to the simulated steady state value and it was decreased by 75.36%.

The effect return flow of irrigated water and development of Megech reservoir were simulated simultaneously to see the effects on groundwater level changes and stream leakage. In the simulation the response of the system was compared with the steady state simulated water levels and stream leakages. The differences showed the effect of development of Megech reservoir and irrigation on the groundwater. The simulated value showed an average 2.74m increased head over the whole area. High difference values were observed at Tseda (7.83m) and Koladiba (7.3m). The minimum difference 1.08m was recorded at Angereb well field (observation 94). In addition, the stream leakage increased by 87.43%.

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I would also like to express my appreciation to all earth science department staffs that helped me directly or indirectly during my stay in AAU.

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CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Ground water is an invisible resource, both the dynamic of the resource base and the services it produces are not well known. It is poorly understood resource, yet one that is critical to a wide variety of social, economic and environmental services. Pollution and declining water levels represents direct threat to the sustainability of the environment, domestic, agricultural, and industrial, uses dependent on ground water flow. In addition, as demands grow and the limits of sustainable extraction become evident, competition between agricultural and other users is increasing rapidly. This can generate competitive extraction between individuals. Each person extracts as much ground water as possible in order to capture benefits for themselves before the resource is exhausted. The net result can be a spiral of growing demands and decreasing availability. Competition is, thus, a critical social issue that must be addressed in order to manage groundwater on a sustainable basis.

A critical challenge in interpreting both quantity and quality problems are related to understanding of the resource base and its dynamics. Many individuals, ground water professionals included, conceptualize ground water as flowing smoothly through the earth with rapid recharge from rainfall and relatively uniform water quality. In reality, however, complex rock formation and differential recharge rates results in far more complicated dynamics. These, in turn, greatly complicate understanding of resource conditions.

It is important to recognize that overdraft and water level declines typically affects the sustainability of uses that are dependent on groundwater long before the resource base itself is threatened with physical exhaustion. One of the primary objectives of most groundwater resource studies is the determination of the maximum possible pumping rates that are compatible with the hydrogeologic environment from which the water will be taken. (Allan freeze %john a.chry, 1979). Many uses and environmental values depend on the depth to water not the volume theoretically available. Beyond overdraft and water level declines lie the

questions of water quality and pollution. Pollutions or quality declines causes reduction in water availability that are far less reversible than over draft.

Since the occurrence of ground water flow is invisible and the velocity of ground water flow is much smaller, studies of ground water under both natural and artificial conditions have employed modeling techniques.

Groundwater modeling is being used more frequently as a tool to help answer optimum water management questions because it can lead to a better understanding of how the real system behaves and it can be used to make predictions about the systems future behavior. This in turn helps to develop operational and regulation strategies that will secure the sustainable development of strategically important water resource.

Numerical modeling is being used increasingly to quantify the water resource availability of our complex, dynamic groundwater /surface water systems and to take account of the environment impact of abstraction. However, to be credible, modeling tools must be technically valid and agreed representation of the real system. Therefore, one of the key objectives of any resource study is the process of developing a shared understand (conceptual model) of the essential flow mechanisms. Only then can the numerical model be used as a predictive tool to investigate different future conditions (Eg. New abstraction regimes and changes in climate).

1.2 THE IMPORTANCE OF THE STUDY

Because of climatic change, deforestation and construction activity, recharge to ground water has been decreasing, and because of increasing population size water demand is increasing at alarming rate. This is true for the catchment because of the increasing of Gondar city construction activity, climatic change and deforestation the recharge to ground water is decreasing, and the increasing of population in the catchment results the increasing of water demand. To meet the increasing demand of pure and adequate water in the area, several investigation works have been done in the catchment and out of the catchment to surface and subsurface water.

The current water supply system of the city was designed to have two water sources that are Angereb reservoirs and boreholes. According to the design, Angereb reservoir serves as the

primary source while additional boreholes serve as supplementary sources. (Tropic consulting Engineering in 1998)

The actual average annual water production capacity of the existing system is 1,514, 734 m³. But the annual projected average water demand of Gondar city is 3,963,024 m³. Hence, the difference between the estimated average annual water demand and present water supply capacity is 2,448,290 m³. The service coverage is only 38.2%. The figure indicates that the water supply coverage of the city is very low and far from sufficiency which is due to low capacity of existing system. (Amhara National Regional State Bureau Agriculture & Rural Development, 2005)

In the Megech River basin ground water is exploited by different industries and institutions, in addition to wells that are operated by Gondar Water Supply and used for public services. In long terms, extended and uncontrolled withdrawals may result in water declines, which cause imbalances among hydrologic stresses. One of the important significant of imbalance hydrologic stresses is the decreasing of Megech river flow which will affect the reservoir water in the Megech dam. Generally groundwater in the catchment would be inadequate resource for large scale, sustainable ground water based irrigation development (SEMEC 2007, Engda Z, Yilma S & Albert T, 2007).

The other most important reason to develop the flow modeling of the catchment is to evaluate the impact of irrigation on groundwater. On the proposed irrigation site, Megech plain, the depth of groundwater table is between 4 to 10m and the possible annual water table rise is 2 to 3m (MOWR, 2009). This means it could take 2 to 4 years for the water table to rise to the surface, thus causing salt accumulation in the top soil and hampering plant growth. It is therefore very important to closely monitor changes in groundwater table and identify the most vulnerable areas and adopt low volume irrigation systems (sprinklers and drippers).

This thesis work will give insight about the response of the catchment groundwater flow system to different possible occurring stresses like decrease or increase in recharge and change in groundwater-surface water interactions. So this model may be used as a tool as water resource management to assess the regional effect of change in stress to the steady state system. In addition, it improves the understanding of ground water system and the general effects of different ground water use alternatives on the water resources of the catchment.

The scientific community may use the result of this thesis as input for further investigation to develop detailed numerical groundwater flow model, transient and 3D model, and to study the behavior of contaminant transport in the aquifers, as this area is susceptible to pollution from irrigated lands, industries and domestic sources.

1.3 PERVIOUS WORKS

Like other parts of Tana basin such as Gilgel Beles and Gumera, Megech basin has been investigated in some extent both from geological and hydrogeological point of view to water supply for domestic and irrigation purpose. The investigation was conducted in the area either on regional scale or hydrogeological scale and geophysical investigation for specific institution, organizations, private companies, irrigation projects and town water supply for constructing dams and locating borehole sites without considering the detail characteristics of all the catchment area.

The most important geological and hydrogeological investigations carried on are the following:

Regional hydrogeological investigation of Northern Ethiopia, EFDR, Minister of Mines Geological survey of Ethiopia, Hydrogeology, Engineering geology & Geothermal Department (Bayissa Asfaw, 2003)

Gondar city Water Supply & Angereb Integrated Watershad Development Project, EFDR, Amhara National Regional State Bureau of Agriculture and Rural Development (2005)

Integrated Approach for Hydrogeologic Investigation of Megech River Catchment, North Western Ethiopia. M.Sc. Thesis. AAU Unpublished.

Hydrological Balance of Lake Tana Upper Blue Nile Basin, Ethiopia (Abyou Wale, 2008).

Numerical Groundwater Flow Modeling of the Lake Tana Basin, Upper Nile, Ethiopia (Samson, 2010).

1.4 OBJECTIVES

The general objective of the study is numerical simulation of the groundwater flow system of the Northern river catchment of Lake Tana to evaluate the response of the hydrogeologic system to different stress so that the resulting consequence on the system can be projected.

Different stresses of increased withdrawals and decreased recharge will simulate using processing MODFLOW 2000, (Harbaugh and McDonald, 1988) to study the system response, the result of which can be used as a tool to understand the future risk of groundwater over exploitation.

Specifically, this work will focus on

- Construct a model to compute the natural steady state head distribution and flow direction of the sub basin.
- Identifying the most sensitive parameter of the hydrogeologic system.
- Effects of increased groundwater withdrawals on the study area.
- Effects of Altered Recharge on the study Area.
- Effects of dried Angereb reservoir.
- Effects of development of Megech reservoir.
- Evaluating the effect of irrigation on groundwater in Megech irrigation project area.

1.5 APPROACH AND METHODOLOGY

1.5.1 MATERIALS USED

To accomplish the objectives mentioned above, the following materials and equipments were used:

- The 1:50,000 scale topographical map used to give good morphological picture of the area.
- Magellan GPS-15 used to locate specific location of well and river data
- Land satellite images that help to identify the study area boundary and conceptualize the boundary conditions.
- Geological and hydrogeological maps with relevance and available scale
- Various computer softwars (MODFLOW 2000, ArcGIS 9.2, Global Mapper 8, Surfer 8 and others).

- Deep meter; is device that used to measure water level in the well.
- Current meter; is instrument that used to measure the river discharge.

1.5.2 DATA COLLECTION

The field work was conducted to perform the following activities:

- ❖ Observing and mapping outcrops of different lithological units and soil types in the study area.
- ❖ Visual observation of geological structures and interpreted/ inferred structures.
- ❖ Observing Land use/ land cover practices.
- ❖ Identification of perennial and intermittent streams.
- ❖ Measuring discharge, width and depth of the rivers at representative site
- ❖ Measuring the water level on representative well.

1.5.3 DATA ANALYSIS AND SYNTHESIS

In order to achieve the objective of this work the following activities were done:

- Collecting and adjusting primary and secondary data
- Identify the study area boundary and conceptualize the boundary conditions.
- Construct hydrologic database of the area for model input parameter.
- Carry out model sensitivity analysis test from which the most sensitive model input parameters can be known so that they might be treated with caution for further calibration in future studies.
- Build conceptual model for the hydrogeologic system of the study area.

Data analysis and synthesis of the available data with the help of the numerical mathematical code of MODFLOW consider the physical condition of the study area can be represented with the 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; Summarized from M Anderson and Woessner, 1992.

Groundwater flow in the Northern River Catchment of Lake Tana aquifer system has been simulated using a modular three dimensional finite- difference groundwater flow model of the U.S Geology Survey which describe and predict the behavior of the flow system.

MODFLOW, the USGS modeler three dimensional finite difference, groundwater flow model, is an international standard for groundwater modeling.

Ground water flow modeling software, Modflow-2000(McDoland and Hrbauph, 1988 as developed by USGS) is used to simulate numerical ground water flow system in the area under study. The general groundwater flow modeling protocol and methodology followed during data assembly and the simulation processes in this work is given below.

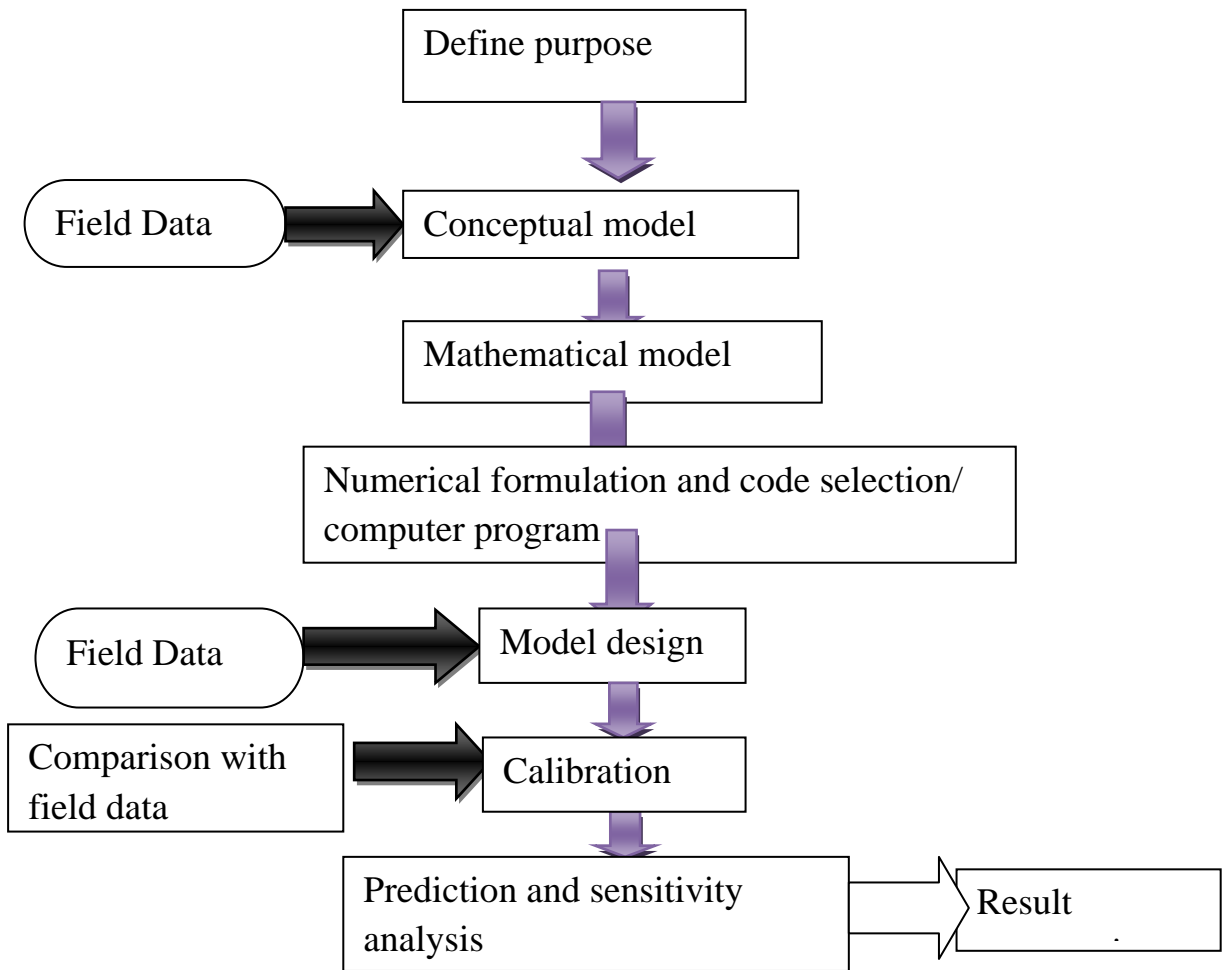


Figure 1.1 The general methodology followed (Anderson and Woessner, 1992)

CHAPTER TWO

2 GENERAL OVERVIEW OF THE STUDY AREA

2.1 LOCATION AND ACCESSIBILITY

The study area is found in the North Gondar Zone of the Amhara region. This catchment is located about 748km and 180km from Addis Ababa and Bahardar respectively. Geographically it lies between UTM coordinates of 1353412N-1410544N latitude and 305000E-357099E longitude with an approximation altitude range 1785m to 2920m above sea level.

The area covers a total surface of 1887 km². The Northern, Eastern and Western part of the catchment has characteristics of rugged topography and with a chain of ridges bordering sub catchments with in the area and the southern part of the catchment is characterized by gently sloping and plain surface which is an outlet of Megech River to Lake Tana.

The main roads that connects Addis Ababa city with Sudan passes through the catchment. The other rout extends from Gondar town to Humera and Mekele in northern direction, North West to Chilga, Metema, Sudan and in the south west to Dembia. There are also some all weather and dry weather roads in the catchment that connects small towns. Since the area is highly rugged and mountainous, most of the area is not accessible to vehicles especially the north and east of the catchment.

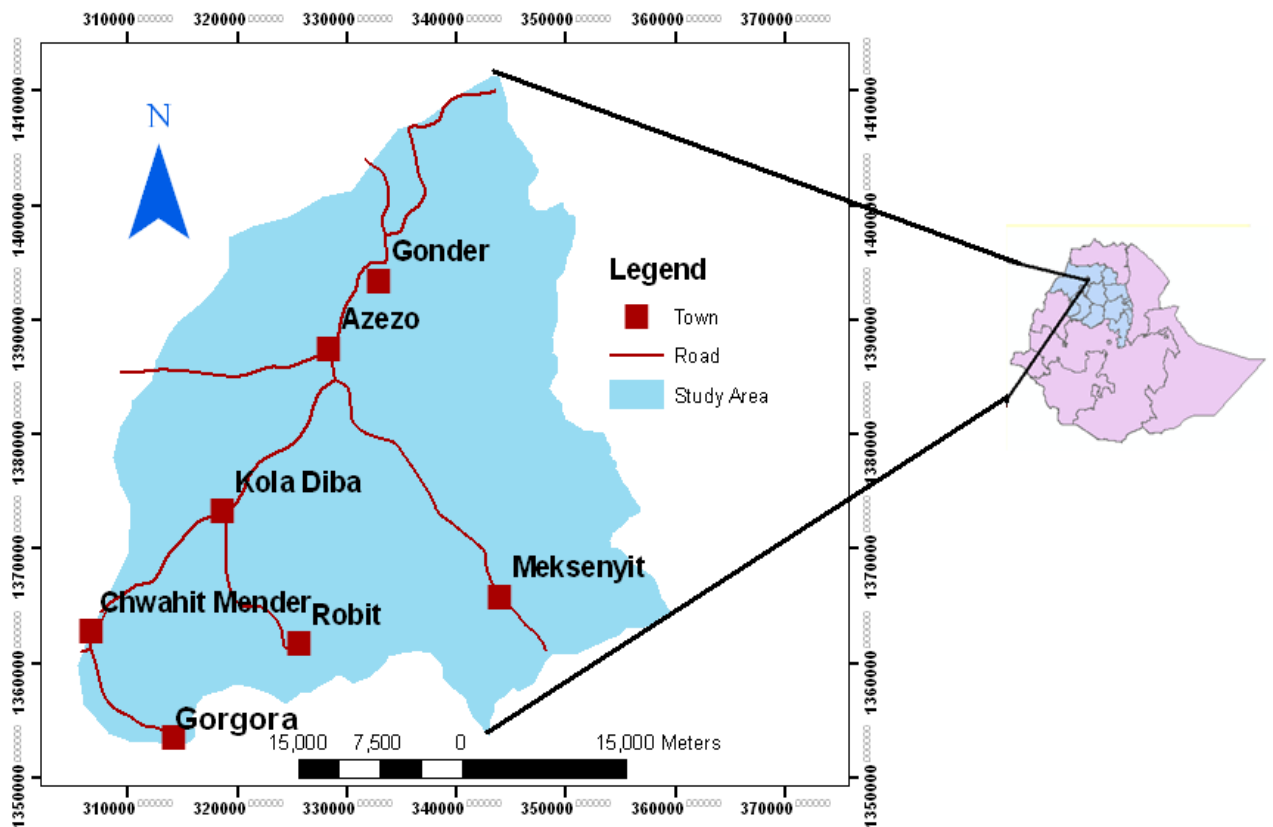


Figure 2.1 Location of the study area, Amhara region, North western Ethiopia.

2.2 CLIMATE

Similar to the other parts of the region, the rainfall of the catchment area is erratic. According to the general classification of Agro- climate zone (on the bases of annual rainfall, temperature, length of growing period and plant types) used in Ethiopia the study area is located within “Moist Weyina Dega” zone. The amount of rainfall in Ethiopia is influenced by the location of the place relative to the source of moisture, the direction of winds and topographical relief (Admassu Gebeyehu, 1996 and Andarge Yitbarek, 2002).

Based on the rainfall, the climate of the area can be categorized in to two broad seasons; the dry season (winter) which covers the period from October to May and wet season (summer) extends from Jun to September, with slightly rainfall during Autumn and Spring. The annually mean maximum, mean, and mean minimum temperatures are 24.5, 19.08, and 13.35 $^{\circ}\text{C}$ respectively.

2.3 PHYSIOGRAPHY

The major landform of the watershed comprises chains of hills with mountainous ridge, which include most of what is designated in north central massif. This catchment can briefly be expressed by mountainous rugged south facing topography. It is almost semi oval in shape with dendrite drainage pattern, steps ridges at boundary, numerous convex hills inside the catchment and steep gorges. The present rugged landform of the area is due to volcano-tectonic activities that formed the plateau and followed by later erosion and river dissection. The slope classes in the watershed encompasses very steep to gentle topography. The northern and eastern part of the catchment has very rugged topography and steep slopes. There is the large elevation difference within the watershed. Elevations range from 1785m (at south tip of study area, Lake Tana) to 2920m (North Extreme of the catchment).

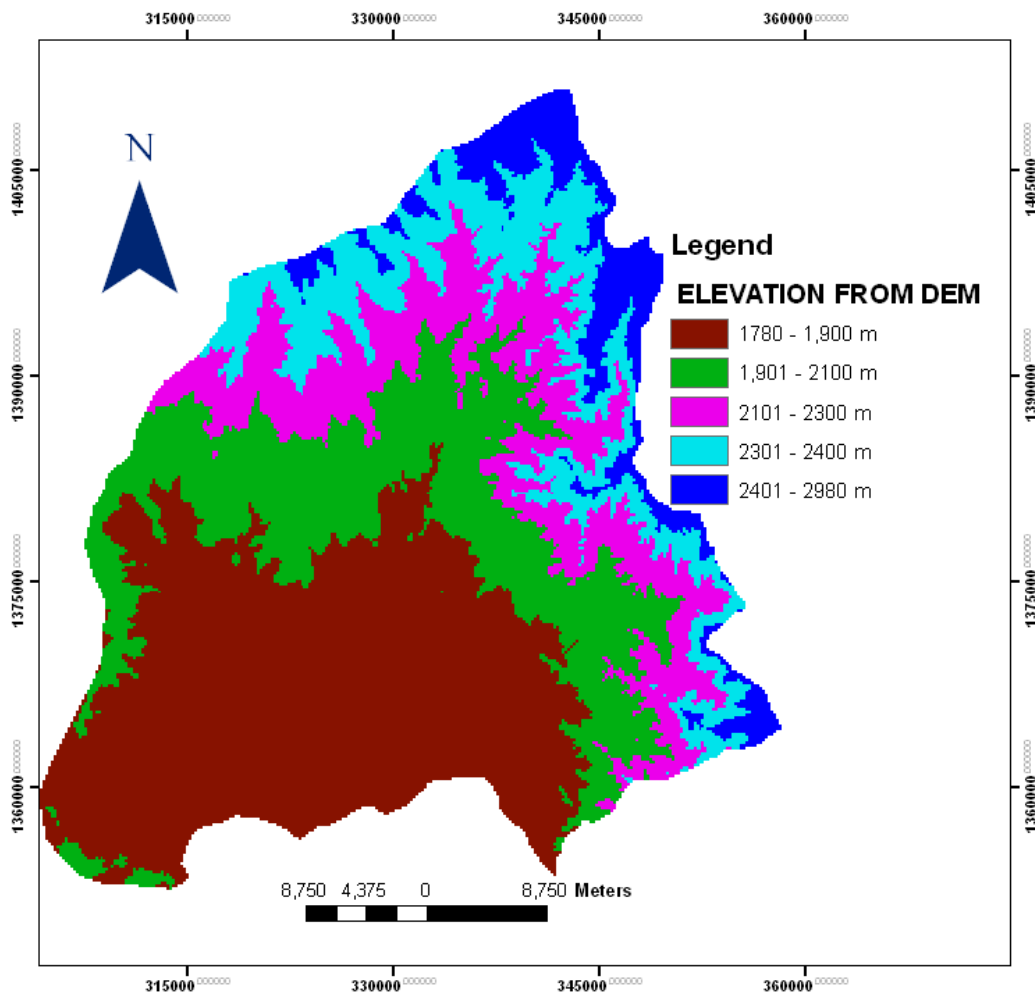


Figure 2. 2 Elevation Map of the Study Area

2.4 DRAINAGE

Northern river catchment of Lake Tana Sub basin comprises of numerous small rivers. The major one is Megech River, which drains in the central part of the study area. The main tributaries of Megech River; Angereb, Keha, Shinta, Dimaza, Gilgel Megech, and Wizaba, have cut deep trenches that divide the watershed in to sub catchments(Fig.). There are also other two intermittent river catchments that have been included in the study area; Gumero and Derma.

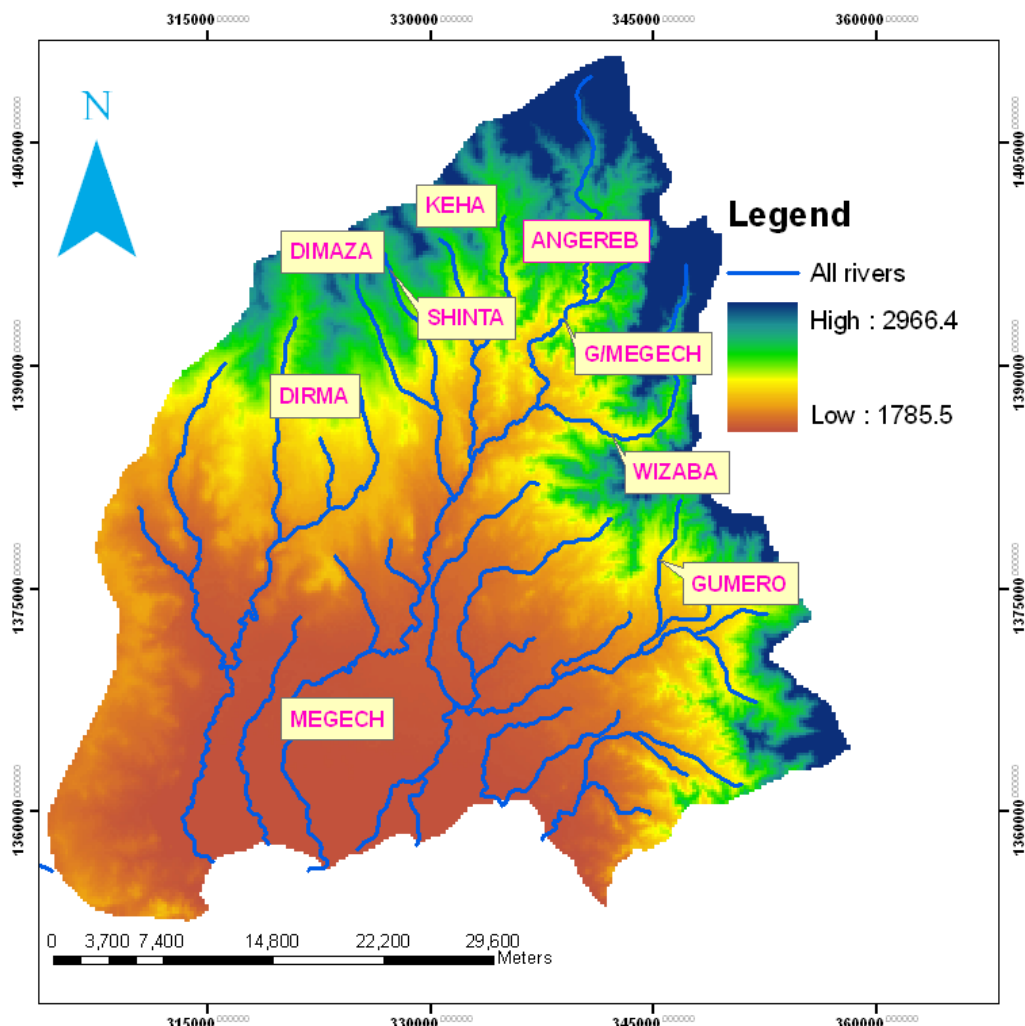


Figure 2.3 Physiographic and Drainage Pattern Map

The study area is characterized by well developed dendritic drainage pattern. Most of the streams originate from the surrounding volcanic chained hills, which are surface as well as believed to be groundwater divides. The drainage patterns are dense in the high topographic and less dense in the lowland area. The drainage of an area is affected by numerous factors

among which, rainfall, slope, rock type and tectonic activity, vegetation, soil type and thickness, infiltration capacity etc. In the northern part of the catchment the drainage forms relatively steep narrow gorges that can attributed to high rainfall, small depth soil and high topographic elevation. Where there are volcanic ridges, drainage radiates in all directions forming radial or parallel system. It is known that area with high permeability have lower drainage density that intern may decrease the surface run off.

2.5 LAND USE AND SOIL TYPE

2.5.1 Land Use and Land Cover

From the Environmental Impact Assessment (EIA) of this watershed study, human population density was 382.4/km². The same study of socio-economic section shows that the population distribution was not even, thus some area have highly pressure while others are with fewer burdens. Most of the areas are used for cultivation. Also from aspect of land suitability, steep slopes carry than their capability. Most of the inhabitants live on the hill and mountainsides, and the houses are moderately scattered all over the watershed. According to the intensity of cultivation and land coverage, it is divided in to five groups. Those are dominantly cultivated, moderately cultivated with bushes, moderately cultivated with trees, wood land with sparse plots and urban.

2.5.2 Soil Type

In most of the northern part of the catchment, the soils are shallow Leptosols underline by unconsolidated medium sized gravels with loose joints, which in turn underline by watertight rocky layers. These layers are easily visible in some healing gullies and steeper part of the river beds (DEVECON, 1989)

The dominant soil colour for this watershed is brown. Of course, there are some black soils on lower flat lands and foot of hills and patch of red soil. The colour and the texture of the soils of the area characterized by moderate acidity, high available of potassium, calcium and magnesium contents (DEVECON, 1989). The dominant textures identified in this area are silt clay loam and silt clay. Soil depth refers the depth of the soil above a layer of hard rocks, stones or other materials, which hinder root penetration. In this watershed, all the soil depth classes are found but the dominant soil depths are between 25 cm to 200cm.

The physiographic position, parent materials, drainage characteristics and soil depth are the key to classify the soils in the study area. Texturally, clay soils are considered to be heavily textured, loams to be medium textured, and sandy and loamy sands to be light textured. According to FAO-UNESCO-ISRIC soil classification the soil units of the study area fall on four main groups these are Leptosols, Vertisols, Cambisols and Fluvisols.

Infiltration and hydraulic conductivity of the soil

Infiltration is one of the important soil characters to be considered in estimation of recharge. The rate at which water enters the soils is termed as infiltration rate. Each kind of soil has its own intake characteristics but differences between some soils are small that for practical purposes several soils can be grouped together.

Table 2. 1 Summary of infiltration result (cm/h) of Megech by major soil type.(BECON,1998)

No	Major soil type	Mean	Range
1	Moderately well drained fluvial-lacustrin plain soil cm/h	1.25	1-2.3
2	Poorly to very poorly drained bottom land soils	0.42	0.2-0.6
3	Imperfectly to poorly drained vertisols	1.6	1.1-2.9
4	Medium to heavy textured shallow soils	11.65	11.5-11.8

Soil hydraulic conductivity is the rate at which water passes through a given area of soils. Considering soils moisture movement permeability is the hydraulic conductivity of saturated soils. Permeability is determined mainly by size and continuity of the pores. Hydraulic conductivity results provide information on permeability and drainage characteristics of different soils. According to BECON, 1998 general results for the moderately well drained cambisols in the study area indicate slowly to moderately slow class of hydraulic conductivity, with a mean value of 0.35 to 0.72 m/days. The poorly to very poorly drained gleysols showed a moderately slow in topsoil and very slow in subsoil, with mean value of 0.71m/day and 0.04m/day. The hydraulic conductivity of the vertisols indicates a slow class, with mean value of 0.24 and 0.31 m/day. The hydraulic conductivity rates of <0.2m/day are classified as very slow.

2.6 HYDRO METROLOGY

The analysis of the components of the hydrologic cycle in the study area, an average of 15 years data has been collected from four stations located within and in the vicinity of the study area. The stations are located at Azezo Airport, is located at the north western, Maksegnet at south eastern, and Gorgora at south western of the study area. The other one is located out of the catchment but at a reasonable distance, Ambagiworgis is located at the northern extreme of the study. From these four catchments hydro metrological data was analyzed. Azezo is Class 1 standard metrological station which records (Temperature, precipitation, evaporation, relative humidity, wind speed and sunshine). The other three are Class 3 that records precipitation and temperature only. Wind speed, Sunshine hours and relative humidity are considered exclusively from Azezo Station. The most important data that was calculated and used to achieve the objective of the research are as follows:

2.5.1 Precipitation

Precipitation is any form of water that falls on the surface of the earth by the process of condensation & sublimation. There are different forms of precipitation. Out of this rainfall is the important form of precipitation in hydrologic cycle. The study area is characterized by unimodal rain fall pattern with peak rainfall season starts at the mid of May and ends at the end of the September. The monthly rainfall strike the peak at July in three (Azezo, Maksegnet, and Ambagiworgis) and August in Gorgora metrological station. The highest peak recorded in July at Azezo metrological station with 315.2mm/month. The mean annual rainfall ranges from 863.93mm/year recorded at Gorgora to 1225.83mm/year at Azezo station.

Table 2. 2 Mean monthly distribution of RF (mm) in the study area

Station	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Azezo	4.4	5.1	18.3	39.2	92.1	158.2	315.2	292.5	117.8	64.1	23.2	12	95.18
Ambagiwor gis	5.1	5.1	22.8	41.9	91.3	127.3	287.7	162.5	94.6	46.7	24.9	3.7	76.13
Maksegnet	2.2	2.1	11.4	25	70	14.55	271.1	270.7	10.7	44.3	23.2	3.8	80.82
Gorgora	0	1	8.3	25.4	34,2	141.1	197.4	263.1	111.2	68.3	12.6	1.3	71.99

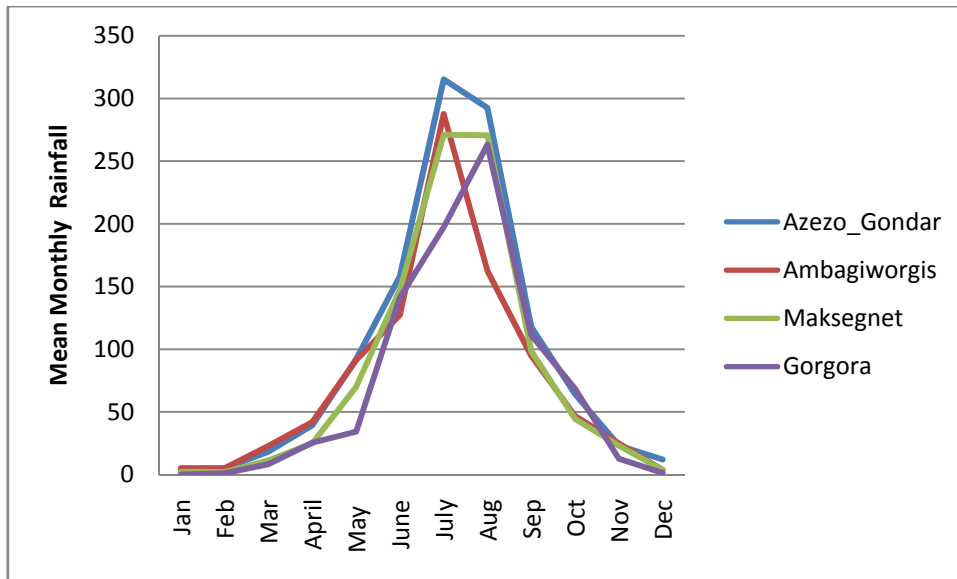


Figure 2.4 Mean monthly distribution of rain fall on the study Area.

In order to represent point rainfall data for the study area, the Thiessen polygon method is employed. This method gives good result when the rain gauges are not evenly distributed over the area in both flat and hilly terrain. This method considers point rain fall measurement represents half way up to adjacent gauges. It is formed around each precipitation station by drawing perpendicular bisector of the lines joining adjacent stations.

The average depth of precipitation over the total area is given by:

$$P_A = \frac{\sum_{i=1}^n P_i a_i}{A}$$

Where P_A - average rainfall for total area

P_i - Measured precipitation at station n - Number of rain gauge

a_i . The area of polygon associated with P_i

According to Thiessen polygon method analysis the mean annual rainfall of the study area is 1100.4 mm/year.

Table 2. 3 The Annual weighted rainfall of study area based on Thiessen Polygon Method.

Gauge station	Mean annual RF (mm)	Area (km ²)	Weighted area	Annual weighted RF (mm)
Gondar-Azezo	1225.83	853.34	0.4522	554.35
Maksegnet	1076.04	541.02	0.2867	308.51
Gorgora	863.93	339.78	0.1801	155.56
Ambagiworgis	1013	152.66	0.0809	81.95

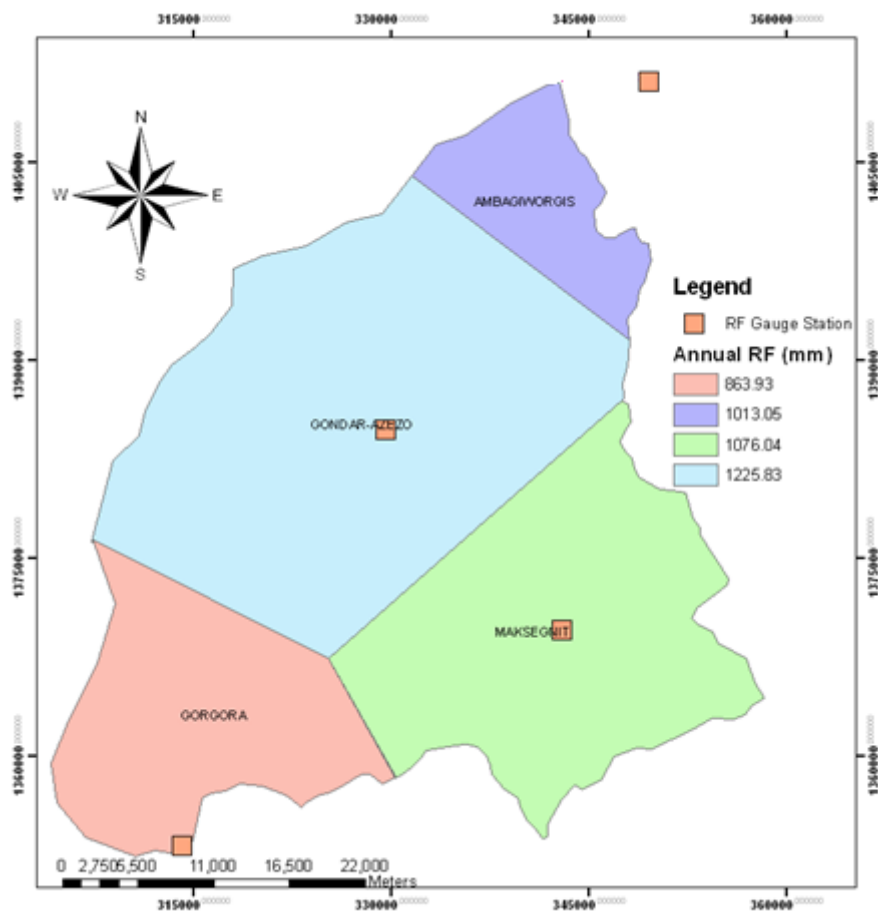


Figure 2.5 Spatial distribution of rainfall base on Thiessen Polygon Method.

2.5.2 River Discharge

The Megech river, which is about 75km long, has a drainage area of about 850km² and an average annual discharge of 11.1m³/s (TAHAL, 2009). The gauged part of the Megech sub basin is only the upper part of the catchment enclosing an area of 462km². It has mean annual discharge 6.67m³/sec. .

The table and the figure shown below show an average thirty nine years hydrological summery table and hydrograph respectively.

Table 2. 4 Mean Monthly Discharge of Megech River

Year	Average Discharge m ³ /s												
	Jan	Feb	Mar	Ap	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1965-2006													
Measured	0.83	0.72	0.75	0.92	1.31	5.00	16.25	34.2	11.4	4.62	2.44	1.61	6.67

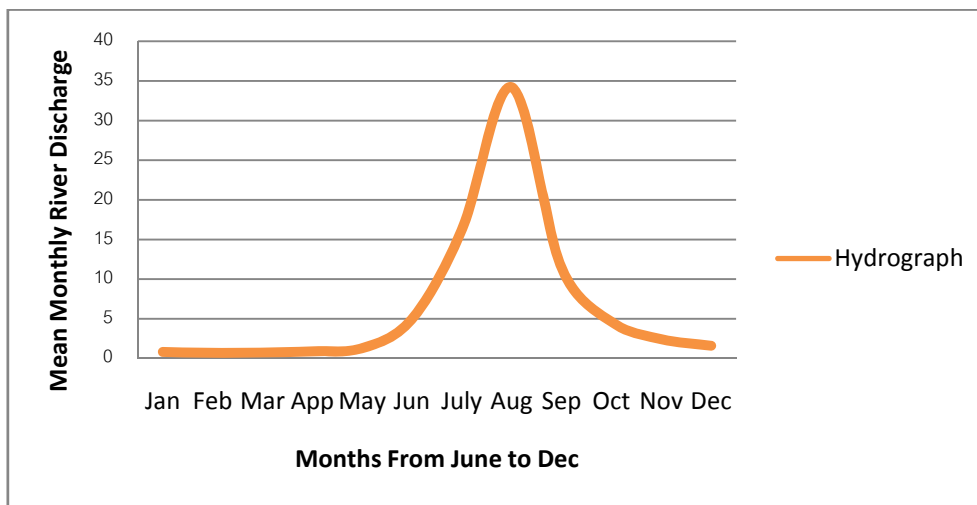


Figure 2.6 Hydrograph of Megech River (m³/s)

2.5.3 Temperature

Temperature of the catchment area is used to quantify the potential and the actual evapotranspiration of the data that helps to evaluate the water balance of the catchment.

Table 2.5 Mean monthly temperature (0C) in the study area.

Gauge Station	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Azezo	18.9	20.5	21.2	22.5	20.8	19.5	17.3	16.7	18.1	19.1	19.2	18.6
Ambagiworgis	12	12.8	13.4	14.4	14.3	13.0	11.9	11.9	12.6	12.3	11.7	11.6
Maksegnet	19.9	20.7	21	21.4	20.8	20.13	19.9	20.0	20.2	20.2	20.3	20.1
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

Table 2. 6 Mean maximum monthly temperature (0C) in the study area.

Gauge Station	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Azezo	26.9	28.6	28.1	29.3	26.7	25.3	21.4	20.4	23.6	26.0	26.6	26.8
Ambagiworgis	18.6	19.1	19.2	20.5	19.9	17.3	5.3	15.5	17.1	18.0	17.7	18.1
Maksegnet	25.3	26.3	27	27.2	26.3	25.6	25.1	25.2	25.6	25.6	25.6	25.4
Gorgora	31	32.3	32.5	31.5	31	27.8	25.5	25.2	26.5	28.4	29.2	29.2

Table 2. 7 Minimum monthly temperature (0C) in the study area

Gauge Station	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Azezo	10.9	12.4	14.3	15.7	14.9	13.7	13.3	13.0	12.5	12.2	11.7	10.9
Ambagiworgis	5.4	6.5	7.7	8.2	9.0	8.8	18.4	8.4	8.1	6.6	5.7	5.1
Maksegnet	14.5	15	15	15.5	15.2	14.6	14.8	14.7	14.8	14.9	14.9	14.7
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

2.5.2 Relative Humidity

The absolute humidity of a give air mass is the number of grams of water per cubic meter of air. The maximum amount of moisture that the air can hold at a given temperature is saturation humidity. The relative humidity of the air mass is the percent ratio of the absolute humidity to the saturation humidity (Fetter, 1994). The relative humidity of the area is used to calculate evapotranspiration that helps to evaluate the recharge of the study area. The

maximum relative humidity corresponds to the rainy seasons and the minimum to the dry months.

Table 2. 8 Mean monthly relative Humidity (%) at Gondar-Azezo Station. (Andarge 2002)

	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	42.9	39.6	39.6	41.2	52.7	64.7	79.6	80.2	73.1	61.2	52.6	47.7
Min	25.7	21	25.3	23.3	29.3	53.7	69.3	71	58.3	40.3	36	32
Max	67	69	65	59.7	79.3	89.0	90	90	85.7	79.7	73.3	73

2.5.3 Wind Speed

The direction and speed of the wind are most important features of the weather. As far as evapotranspiration is concerned, the speed of the wind is an important parameter. Wind removes moist air and leaves the air dry in which the evapotranspiration process continues to feed the air with moisture. The mean monthly wind speed calculated from Gondar-Azezo station ranges from 1.32m/s to 2.0 m/s. The wind speed reaches its maximum in the dry season and minimum in the rainy season.

Table 2. 9 Monthly wind speed at Azezo (m/sec) (Andarge, 2002)

	Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	1.7	1.85	2.0	1.9	1.9	2.0	1.5	1.3	1.5	1.5	1.6	1.6
Min	1	1.1	1.3	1.2	1.7	1.6	1.2	1.1	1.3	1.2	1.4	1.5
Max	1.9	2.2	2.2	2.1	2.2	2.3	1.9	1.7	1.7	1.6	1.7	1.8

CHAPTER THREE

3. GEOLOGY

3.1 GENERAL OVER VIEW

The geological frame work of lake tana basin as out lined on the 1:2000000 Geological Map of the Ethiopia (2nd Ed.1996) comprises a basement of Precambrian bed rock, over line by Mesozoic Sediments, Tertiary Volcanic and minor sediment, Quaternary Volcanic and recent Alluvial sediments. Ongoing tectonic activities has controlled the distribution of the rock formation and controlled the current configuration of the basin (Chorowicz et.al 1998, SMEC 2007). These lithological and tectonic features have important role in groundwater regime of the study area (Groundwater flow, Depth of Circulation, Ground Water Potential, Recharge Processes, and Hydraulic Conductivity etc.)

3.2 GEOLOGICAL STRUCTURES

In the context of the regional tectonics (Fault formation in Mid-tertiary) Lake Tana Basin is situated at the graben; Gondar graben (Exposed by erosion) runs N-NW, Dengel Ber (Buried) runs S-SW and Debretabor graben (Reactivated) runs E-W (chorowicz et .al 1998, Engeda,2007). Reactivation of faults occurred in Late Miocene to Quaternary, superimposed down-faulted the N-S trending Gondar graben, which is exposed by erosion in the north of the basin, the N-S Dengel, buried beneath the Quaternary volcanic and the eastern part of the basin, the essentially E-W Debretabor graben. The created graben converge toward the Lake Tana, and highly controls the ground water flow.

The approximate elevation of the base of Tertiary basalts differs across the region. In Blue Nile it is around 2000m. Around eastern boundary boundary of the Gilgel Abay basin the base of the basalt is inferred Mgnetotellic investigation by Hautot et.al (2006) to be at depth of around 250m. To the north at Gondar, a minimum thickness of 210m has been encountered in bores, although the base of the basalt was not intersected (SMEC, 2008).

It appears that within the basin, the geological structures suggests inward tilting fault blocks and an essentially flat base of the basalt dips away from the Tana basin in the area

surrounding the basin (SMEC, 2008). This needs to be confirmed by drilling geological mapping and more detailed geophysical investigation in the Tana Basin.

Detailed remote sensing investigation have shown the down faulting to form the Gondar graben has resulted in fault blocks 1-4km wide dipping in to towards the Lake. Although individual fault blocks, dip steeply, the staggered arrangements provide an overall relatively flat structure in to the basin for the base of the basalt (chorowicz et.al 2005, SMEC 2007).

Mesozoic sediments up to 1.5-2.0 km thick are interpreted to occur beneath volcanic in NW-SE trending sedimentary basin (Hautot et.al 2006, Yirgalem, 2008). The structure is consider to be a half graben thickness increases by as much as 1km over a 30-40km wide section. The geophysics also describes the presence of thick dikes and sills penetrating the Mesozoic Sequence.

3.3 STRATIGRAPHY

The geology of the Lake Tana region is dominated by out crops of the basaltic volcanic rocks in the highland areas surrounding the Lake, with alluvial deposits around the Lake margin.

3.3.1 Basement Rock

The basement rocks in the region comprise metamorphic and granitic rocks which occur only subsurface in the Tana basin. The oldest rocks in the area are the Alphe group (AR1) and Baro group (ARb) Archean age. They consists biotite, calc-silicate, muscovite gneiss and migmatite with minor metasedimentary gneiss. In places this gneiss is moderately to well layered units of mafic and metasedimentary gneiss. They are introduced by alkaline granite (gt5), post tectonic granite and syenite (gt4), and late to post tectonic granite (gt3).

3.3.2 Mesozoic Sediment Formation

Mesozoic sediments formation is created by the settlement of the sediments and accompanying compaction process following the transgression and regression of the Indian Ocean in NW to SW. The stratigraphy of the Mesozoic sediment is highly depending on the spatial distribution and period of transgression and regression. It follows the Adigrat Sandstone, Gohatsion formation, Lagasima Limestone, Muger mudstone and Debrelibanos sandstone (Getaneh 1981, 1991, Russo et.al 1994, SMEC 2009).

Recent geophysical studies south and east of the Lake Tana (Hautot et al. 2006) have indicated up to 1.5 to 2km thickness interpreted to be Mesozoic sediments preserved in a northwest trending half graben structure beneath the Tertiary volcanic cover. The thickness identified in the geographical profiling appears to be consistent with the section exposed in the Blue Nile gorges. The Mesozoic sediments have not been confirmed beneath the basin by intersection in boreholes but their presence beneath the basalt cover is inferred from the geophysical studies and geological structure.

The regional studies finding conducted by a number of researchers shows Mesozoic sediment comprise or number of unit that is summarized below:

Adigrat Formation (Ja)

The adigrat sandstone includes the whole succession of classic rocks resting unconformable on the Precambrian Metamorphic. It comprises sandstone with minor lenses of siltstone and conglomerate with laterite up to 2m thick at the top. The formation is typically yellowish to pink in color and comprised of fine to medium grained, well sorted, crossbedded quartz sandstone. It is non calcareous except at the top near the contact with the overlying Antalo Formation (Jt). The age is Triassic to middle Jurassic (Bayissa Asfaw 2003).

Abbay Beds (Jb)

It includes alternating beds of limestone, shale and gypsum of middle Jurassic age. It occurs in the south-eastern part covering a very small percentage of a map area. The exposure mainly occurs along Abbay gorge. Thickness is reported to be 450m.

Antalo Limestone

Antalo limestone is fossiliferous yellow limestone containing thin beds of marly and calcareous shale, and occasional arenaceous sands near the top. It is exposed in Abbay gorge. Antalo limestone underlies the Amba Aradam formation. The total thickness is reported to be 430m. age of Antalo formation is middle to late Jurassic, and is deposited during the first cycle of regression in Ethiopia.

Amba Aradam Formation

Amba Aradam formation consists of the interbedded shall, siltstone, sandstone, marl and dolomite of tidal to brackish environment. The upper unit is thick, homogeneous member of deltaic to alluvial sandstone. This unit is consists of well washed, porous and friable sandstone. Its thickness reaches 450 to 600 meters. This formation is deposited during the second regression event of late cretaceous sea.

3.3.3 Tertiary Volcanic Rocks (PNtb)

Much of the study area is covered by Tertiary volcanic rocks. These consists a number of different Tertiary Volcanic units which overlay the sedimentary and basement complexes. The volcanic vary in character based on composition, structure and degree of weathering.

The major volcanic units recognized in the study area are:

Ashangi Basalt

Ashangi basalt represents the earliest fissural flood basalt volcanism on the North West plateau. The basalts are thick strongly weathered, crushed, tilted basalts which lies below the major Pre-Oligocene unconformity (Zanetin, 1980 Assefaw, 2003). The Ashangi formation consists of predominantly mildly alkaline basalt with interbedded pyroclastics and is commonly injected by dolerite sill and dykes. The upper part of Ashangi is more tuffaceous and contains interbedded Lacustrine deposits with Lignite seams

Aiba Basalts (P_{3a})

The Aiba Basalt represents the second major pulse of fissural basalt volcanic on the north western plateau. They are generally aphyric, compact rocks, in places showing stratification and contain rare interbedded basic tuffs. The Aiba Basalt conformably overly the Ashangi basalts and attain a thickness of about 200-600m. The basalt show distinctive tholeiitic nature with transitions to mildly alkaline varieties (Zanetin, 1980, Kazhin, 1979, Bayissa 2003).

Tarmaber Basalts (PNtb)

Tarmaber formation represents Oligocene to Miocene basaltic shield volcanism on the north-western plateaus. Tarmaber basalts in contrast to tholeiitic and mildly alkaline nature of the

earliest Aiba flood basalts are typically alkaline in nature. On the North-western plateau the Tarmaber shield volcanoes become progressively younger from the north to south. Thus the classification Tarmaber Gussa formation (PNtb) for shield volcano of the northern Ethiopia plateau with absolute age range of 26 to 16 MY (Kazmin, 1979, Bayisa 2003).

3.3.4 Quaternary Volcanic Rock and Sediment

3.3.4.1 Quaternary Volcanic Rocks

Quaternary basalts and trachytes were erupted along the pre-existing structure in the North-western plateau. It overlies the old Tertiary Volcanic. The quaternary volcanic sequence comprises blocky and fractured vesicular basalt, with a porphyritic, glassy texture, as well as some basaltic breccias and tuffs. In the study area there is the probability to be found in southern side at prefer of Lake Tana, but it has not study well using drilling.

3.3.4.2 Quaternary Sediments

It comprises alluvial and Lake deposits. The alluvial sediments occur at lower reach of the Lake Tana tributaries, mainly in the North and East of Lake Tana in the Megech, Ribb and Gumera flood plains. They range in lithology from clay to gravel of not clearly known thickness and extent.

Lacustrine deposits comprising dominantly fine silt and clay cover the Lake Tana. These deposits have been identified from high resolution seismic studies, supported by extensively analysis of cores drilled up to 9.5m deep (Lambetal 2007, SMEC 2007). The geophysics shows that the thickness varies across the lake, from a minimum of 9m across the entire Lake bed to at least 40m at the Northern end of the Lake. Several stiff silt horizons have been mapped across the Lake. Resent drilling information (Kebede,pers comm;2007, Zenaw 2010) indicates that up to 80m of stiff clay covers floor of Lake.

3.3.4.3 Recent Deposits

These include alluvial deposits, sands, silt, clay, limestone, and beach sand. It is wide spread in the area. However considerable deposits are found around the Lake Tana and following Angereb and down Megech River. It is deposited as fluvial out wash deposit. It is light grey,

gravelly medium to course grained sand. The age of this sediment is Pleistocene to Holocene (Geology of Ethiopia, reand Ed 1996).

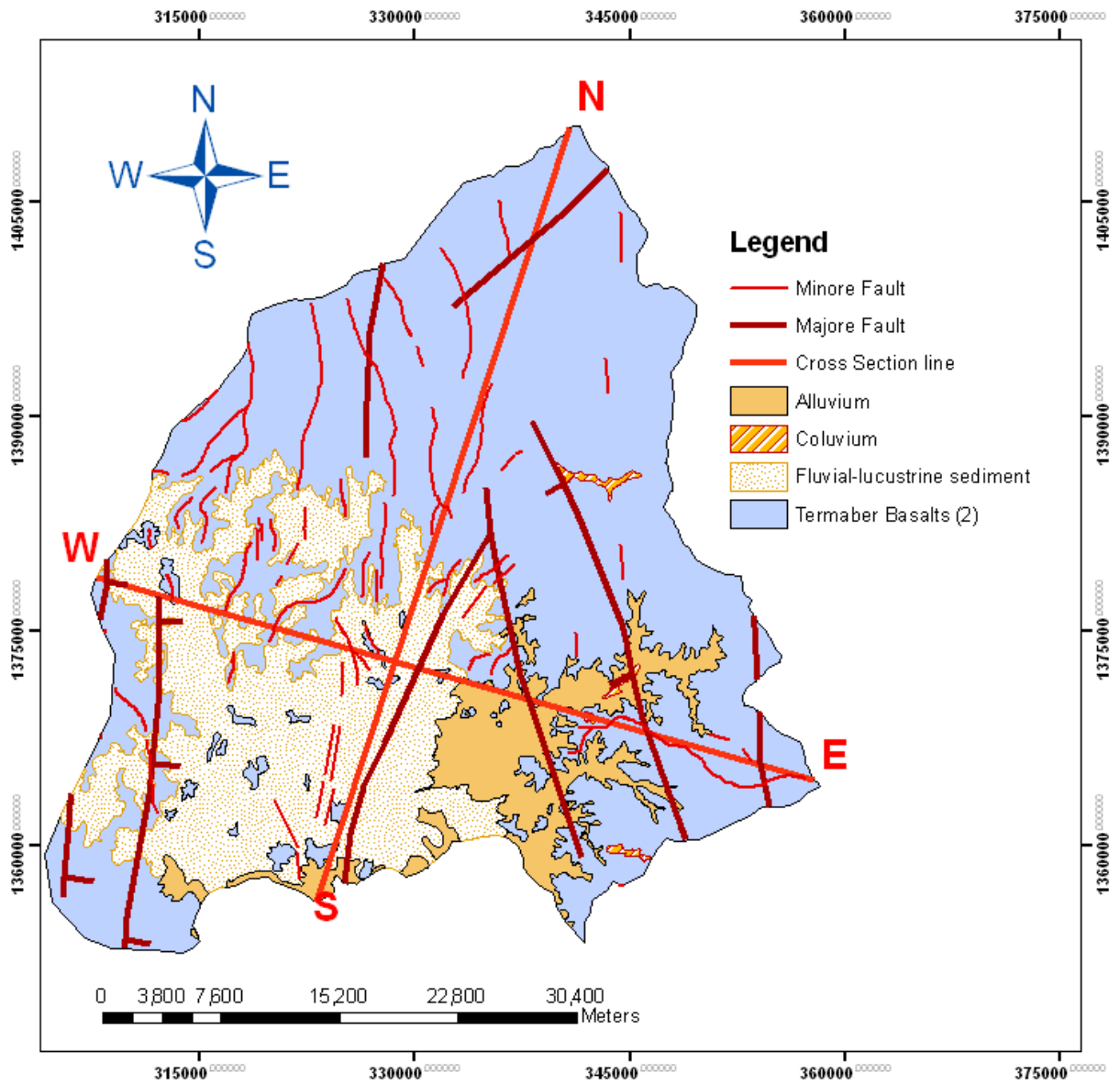


Figure 3.1 Geological Map of the study Area with N_S and W_E Cross sectional Line (Edited from BECOM)

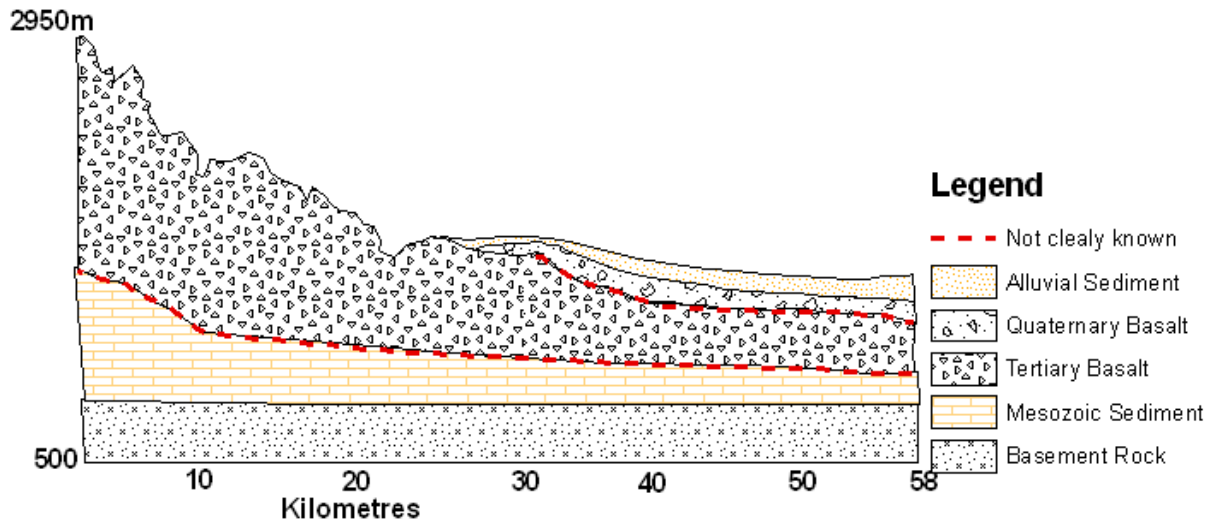


Figure 3.2 Schematic Geologic Cross Section of the Study Area N_S Profile (Refined from USBR 1964)

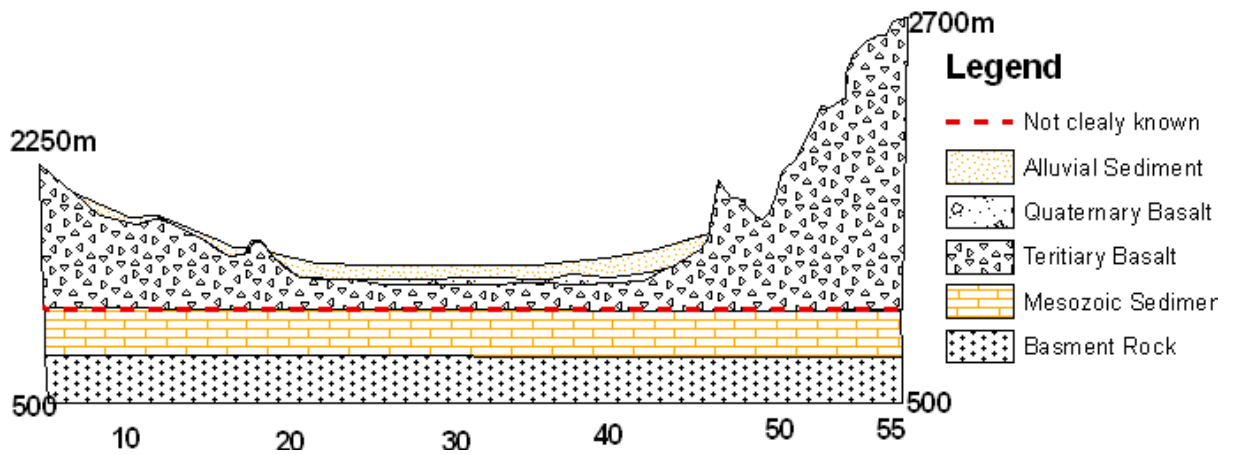


Figure 3.3 Schematic Geologic Cross Section of the Study Area W_E Profile (refined from USBR, 1964)

CHAPTER FOUR

4. CONCEPTUAL MODEL DEVELOPMENT

4.1 GENERAL OVER VIEW

Conceptual model is a pictorial representation of the ground water flow system, frequently in the form of a block diagram or a cross section (Anderson and Woessner, 1992). The nature of conceptual model will determine the dimensions of the numerical model and the design of the model. The development of conceptual model is the most important stage in ground water flow modeling as it simplify the field problems and organize the field as result the system can be analyzed readily.

Model conceptualization is the process in which data describing field condition of the study area are assembled in a systematic way to describe groundwater flow at a site. It is very important controlling factor of the modeling result. It must be based on detailed quantitative analysis of field data. It is always remembered that a model is only as good as the data up on which it is built.

The first step in formulating the conceptual model is to define the area of interest, i.e. to identify the boundaries of the model.

The important steps in building the conceptual model include

- Defining boundary condition
- Defining hydrostratigraphic units
- Preparing a water budget
- Defining the flow system

Hydrostratigraphic units for conceptual model are defined from geologic information combined with information on hydrogeologic properties. In modeling regional flow system, aquifers and confining beds are defined using the concept of hydrostratigraphic unit. Several geologic formations may be combined in to a single hydrostratigraphic units or a geologic formation may be subdivided in to aquifers and confining units (Anderson and Woessner, 1992)

The source of water to the system as well as the expected flow direction and exit points should be a part of conceptual model. The field estimated inflow may include groundwater recharge from precipitation or recharge from surface water body. Out flows may include spring flow, base flow to the streams and pumping. A water budget should be prepared from the field data to summarize the magnitude of these flows.

The hydrostratigraphic forms the framework of the conceptual model. Hydrologic information is used to conceptualize the movement of groundwater through the system. Hydrologic information on precipitation, evaporation and surface water runoff, as well as head data and geochemical information are used in this analysis. Water level measurement are used to estimate the general direction of groundwater flow, the location of recharge and discharge areas, and the connection between the aquifers and surface water systems (Anderson and Woessner,1992).

4.2 SYSTEM BOUNDARY CONCEPTUALIZATION

The initial step in any groundwater flow modeling is the definition of the boundary of the study area. To have a good conceptualization of a hydrologic system, it is essential to identify and assign system boundaries appropriately.

System boundaries are classified in to two: Physical boundaries and Hydraulic boundaries (Anderson & Wessner, 1992). Physical boundaries of a ground water flow systems are found by the physical presence of impermeable body of rock or large body of surface water. Hydraulic boundaries are result of hydrologic conditions, are invisible and they may include ground water dived and streams.

In groundwater flow modeling, boundary conditions influence the extent of flow domain to be analyzed or simulated. The extent of the flow domain is initially determined by the extent of the area of concern and it's preferable if it is bounded by physically observable features. Moreover, it should be noted that correct conceptualization of boundary is important to select an appropriate mathematical representation in the model so that the effect of the boundary on flow can be correctly understood.

In Northern River Catchment of Lake Tana, the system boundary has carefully delineated based on the DEM data, field visit and existing works. The geographic boundary of the study area groundwater flow model approximately corresponds closely with natural hydrologic boundaries across which groundwater flow was assumed to be negligible (Andersen and Woessenr, 1992). This assumption was also done for the study area boundary system. The Northern, Eastern and Western boundary of the catchment of the model coincide with surface water divide line of the study area which is considered as no flow boundary. It should be remembered that groundwater divide is not a really a boundary in nature, but as groundwater on either side of the divide flows away from the divide and not across it, the divide itself acts as a no flow boundary.

The objective 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.

The model under 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.

The model also consider specified head boundary which is simulated by setting the head at the relevant boundary nodes equal to known values. For lakes and reservoirs the boundary is described by constant head condition. The southern part of the study area is coinciding with Lake Tana. As result southern part of the study area boundary considered as specific head boundary.

4.3 HYDRO-STRATIGRAPHIC UNITS

In the various formations the variation in groundwater storage, transmission and yield are the basis for the classification of the aquifer. Lithology, topography, area coverage, fracture, weathering etc. are considered for the qualitative classification of the aquifer. The occurrence of groundwater depends not only on the nature of the rocks but also in their geologic history. Aquifers in the area of investigation are classified based on qualitative and quantitative factor.

In area where hydrogeological data are not available field observations such as distribution and magnitude of springs, degree of fracturing of the rocks, grain size, rounding and sorting type and degree of cementation, depth and extent of weathering are taken in to consideration.

Pumping test though limited in number is taken from different sources and are reintegrated and used in the classification of the aquifers. In bore holes where only yield and draw down data are available, transmissibility and permeability values are calculated for some boreholes. Almost all boreholes in the study area are drilled on Tertiary and alluvial deposit. According to hydrogeological study of Abbay River Basin Integrated Development Master Plan Project, Phase 2, 1998 (BCEOM et al.) the Tertiary basalts and recent lava flows which are widely distributed in Tana Sub-basin, are grouped as an extensive aquifer with fracture permeability.

The major aquifer systems in Northern Lake Tana sub basin are defined according to the geologic units. The two major aquifer systems comprise the Tertiary Volcanic (including, Ashangi, Aiba, & Tarmaber basalt) and quaternary alluvial deposits.

Despite the suggestion of presence of Mesozoic sediments that can bear other aquifer system Haut 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 tertiary volcanic rocks in this area is estimated about 250m (Yarer, 2006). It is not considered as a major aquifer until the interception of the Mesozoic Sediments with boreholes

Table4.1 Yield and specific capacity of major Aquifers (Bayisa, 2003)

Aquifer	Specific capacity l/s/m			Pumping rate (l/sec)		
	Range	Mean	Median	Range	Mean	Median
Quaternary Alluvial	0.02-0.53	0.28	0.33	1.3-6.5	4.14	4.06
Tarmaber Basalt	0.018-3.31	0.25	0.14	3.0-5.2	3.65	3.8
Ashangie and Aiba Basalt	0.008-1.49	0.025	0.022	0.3-6.78	2.72	2.68

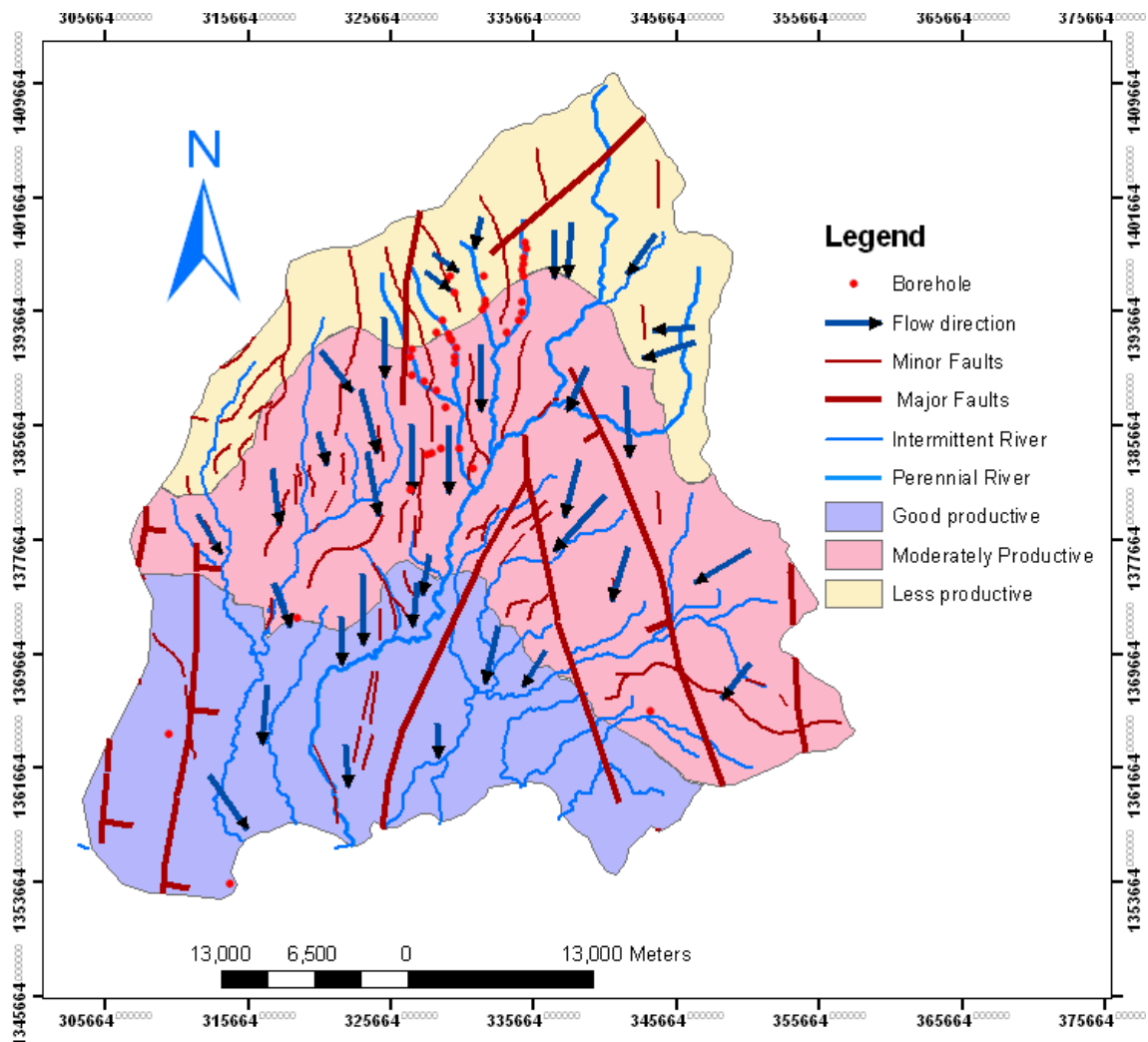


Fig.4.1 Hydrogeological Map of the Study Area.

4.3.1 Tertiary Volcanic Aquifer System

The tertiary basalt aquifers are fractured rocks systems in which groundwater flow is largely related to the intensity of fracturing in the rock mass. They have a wide range of the aquifer properties and yield.

AShangi Basalt Aquifer is fissured flood basalts commonly injected by dolerite and dykes and sills. They cover some part of the Northern part of the study area. They are thick, deeply weathered and fractured. They are mostly considered as highly water yield formation and often big springs are found in the formation. The discharge of the springs in this unit is vary from place to place from 0.5 to 6.78 l/s and mostly it is greater than 2 l/s with a mean of 2.72

l/s. Yield of boreholes range from very low ($5.42\text{m}^3/\text{d}$) to very high ($168\text{m}^3/\text{d}$). The unit is considered low to moderate (Baisa Assefaw, 2003).

Aiba Basalt unit is jointed and highly weathered. Yield of boreholes vary from 1.5 to 6.78 l/s and the discharge of the springs vary from 0.2 to 5 l/s. In fractured and areas of thick alluvial or soil cover, groundwater storage is high and could be productive aquifer having low to moderately productive water yield zone (Baisa Assefaw, 2003).

Tarmaber Basalt covers large part of the study area. They consist of basalts with tuff and scoriaceous lava flows interbedded with palaeosols. The discharges of most of the springs range from 3 to 5 l/s. This unit is generally classified as moderate productive aquifer.

4.3.2 Quaternary Basalt Aquifers

The transmissivity and specific capacity of the quaternary basalts appears to be greater than the Tertiary volcanic. It consists with very fractured and scoriaceous nature of basalt. This aquifer is not exposed in study area, it is anticipated to exist underneath Quaternary sediment.

4.3.3 Quaternary and Alluvial Aquifers

The quaternary alluvial aquifers occur dominantly north of Lake Tana, Southern part of the study area. The distribution is limited compared to the volcanic aquifer units and with limited knowledge with shortage of groundwater data. It consists of alluvial and lacustrine sediments. It is gravelly medium to coarse sand. Borehole data at Infraze indicates that the alluvium is composed of alternate beds of clay, sand and conglomerate. The sand and conglomerate are the aquifers. The mean specific capacity and transmissivity is 0.78l/s/m and $53\text{m}^2/\text{day}$ respectively (Baisa Assefaw, 2003). Therefore, it is grouped as moderate productive aquifer.

Table 4.2 National Aquifer Productivity Classification (SMEC, 2008)

Productivity Range	Specific capacity l/s/m			Estimated optimum yield in l/s based on 20m draw down				
	Range	80% middle value	Mean	Median	Range	80% middle value	Mean	Median
High	0.2-7.6	3.3	2	1.8-68.4	29.7	18		
Moderat	0.05-1.1	0.53	0.13	0.45-9.9	4.8	1.2		
Low	0.006-0.5	0.1	0.04	0.05-4.5	0.9	0.4		

The following cross section is comes out from Geological Map of the study Area with N_S and W_E Cross sectional Line (Fig 3.2)

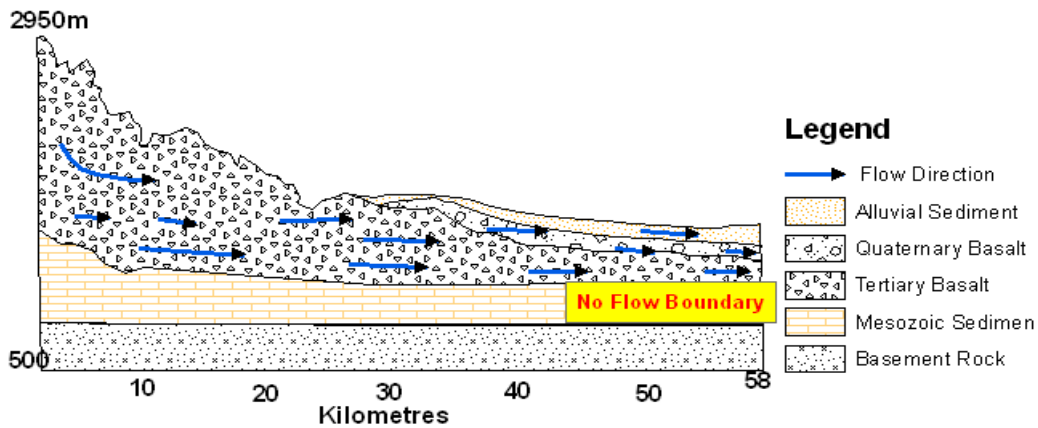


Figure 4.2 Conceptual Hydrostratigraphic and Groundwater Flow of the Study Area N_S Profile (Edited From USBER)

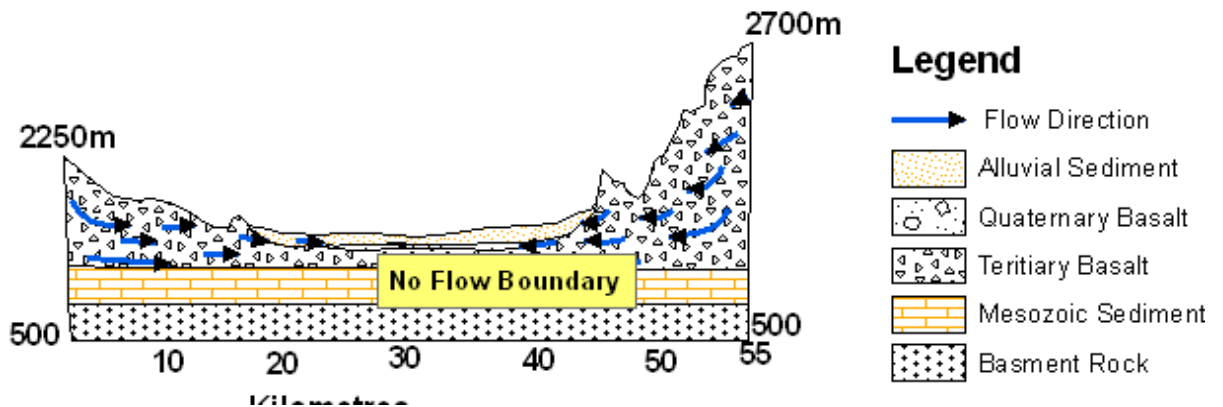


Figure 4.3 Conceptual Hydrostratigraphic and Groundwater Flow of the Study Area E_W Profile (Edited from USBER)

4.3.3 Hydraulic conductivity

The permeability of the soils or rock materials consisting the porous media is a function of their effective porosity, structure, texture and geological history. Hydraulic conductivity (K) is a measure of the ability of fluid to move through interconnected void spaces in the sediment or rock. It is a function of both the medium and the fluid.

Hydraulic conductivity is the most essential parameter that determines the flow of the system of a model. It is obtained through pump test analysis, laboratory and lithologic type and geologic history study review. In this model, it is obtained from the pump test analysis data and the study of geologic series (BCEOM 1996, SMEC 2008) and literature review.

The spatial distribution of the hydraulic conductivity of the basin is the very important input of the model. It is assigned with an over lay analysis of borehole conductivity results of Thison polygon approach, geologic map, and hydrogeologic 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 is conceptualized as isotropic and single layer unconfined aquifer. It has no vertical flow (Z direction) and have the same value in X and Y direction.

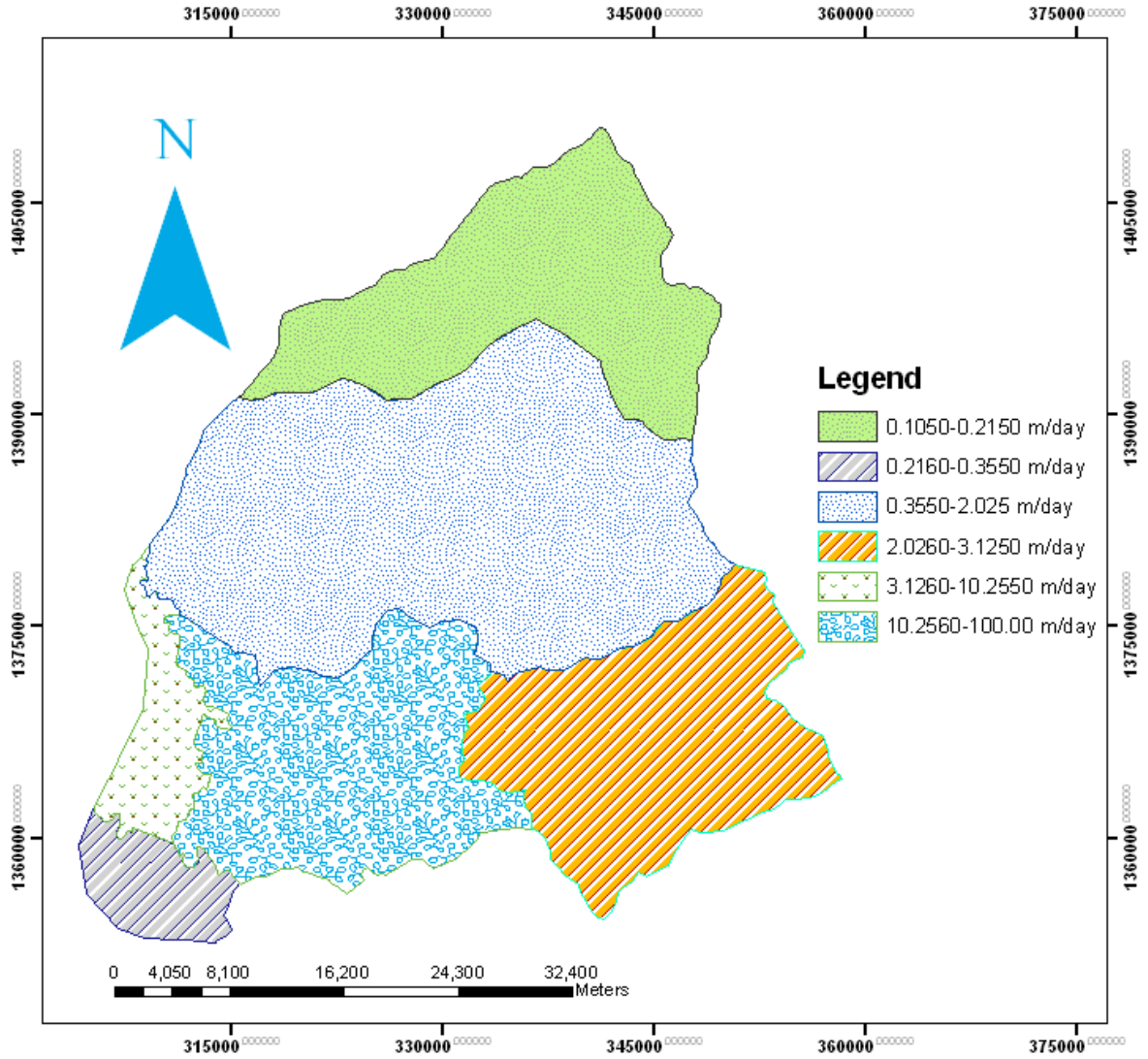


Figure 4.4 Hydraulic Conductivity Map of the Study Area

Table 4.3 Hydrogeologic characteristics of the aquifer (From SMEC, 2008)

Bh Name	Easting UTM	Northing UTM	Tranmitivity (m ² /d)	Hydraulic conductivity m/d	Specific capacity l/s/m	Aquifer type
Angereb 2	333792	1391173	3.28	-	0.047	Ashangi Basalt
Angereb 4	333805	1393386	2.5	-	0.013	Ashangi Basalt
Azezo Meat	328353	1390487	6.15	-	0.187	Tarmaber
Gorgora	312911	1354794	3.29	0.205632	0.034	Tarmaber
Chuahit	311858	1360332	10.63	-	0.241	Tarmaber
Koladiba	317381	1373573	19.09	1.4688	0.533	Tarmaber
Maksegnat	354330	1370045	32.66	1.98496	-	Alluvium

4.4 CONCEPTUALIZED GROUNDWATER INFLOWS AND OUTFLOW SYSTEM

4.4.1 Recharge and Spatial Distribution

The rate of replenishment of the water table in aquifers (mainly by rainfall) is known as groundwater recharge rate. This is the most important parameter required in the successful development of groundwater resource that can safely be abstracted as safe yield from wells and boreholes from aquifers.

There are a number of methods of estimating the groundwater recharge rate to an aquifer: they are catchment water balance method, soil water budget model, lysimeter method, darcy method, tracers profile method etc.

Groundwater recharge is one of the difficult input data to quantify and distribute spatially in precision. It is highly governed with precipitation (not lost by evapotranspiration and run off) vertical hydraulic conductivity that determines the quantity of water joining the saturated zone and water moving ability of the aquifer and hydraulic gradient.

There is no a standard technique to evaluate quantitatively and spatial distribution, but estimating methods. Mostly groundwater recharge is often estimated with a help of fractioning of precipitation. These precipitation fractionation recharge estimation methods of the study area depends on the geologic character, topography, soil type, land use and other recharge control factors.

The study of recharge 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 these parameter derived from the calculation the rainfall infiltration coefficient related to each geological series which almost similar result taken as the major devise for the conceptualizing the recharge of Lake Tana basin (BCEOM 1999, SMEC 2007).

The study result of rainfall infiltration coefficient derived from groundwater contribution to surface water flow in gauged site of the study area (Gauged area 462km², infiltration coefficient 6%, groundwater 55mm and rainfall 1000mm). The study result also showed rainfall infiltration coefficient derived from geologic series to surface flow (BCEOM 1996, SMEC 2007).

The recharge quantification and spatial distribution is made based on precipitation distribution, geologic character, soil type, land cover, topography of the study area. Recharge, as estimated by base flow separation is 105mm, which is 10% of the annual rainfall amount of the study area based on the gauged catchment and it has been extended to ungauged area based on the geologic character. In general, this recharge is 5-20% of annual rainfall amount of the Tana basin (TAHAL, 2009, Getachew, 2002). The recharge of the Tana basin based on chemical data (Chloride Method), was found to vary from 75 to 155mm. The overall recharge was determined to be between 70 and 120mm per year (TAHAL 2009, Getachew, 2008). The recharge has quantity and its distribution has been estimated by overly analysis of the above most important parameters. These recharge map has been modified in quantity and special distribution during the calibration process.

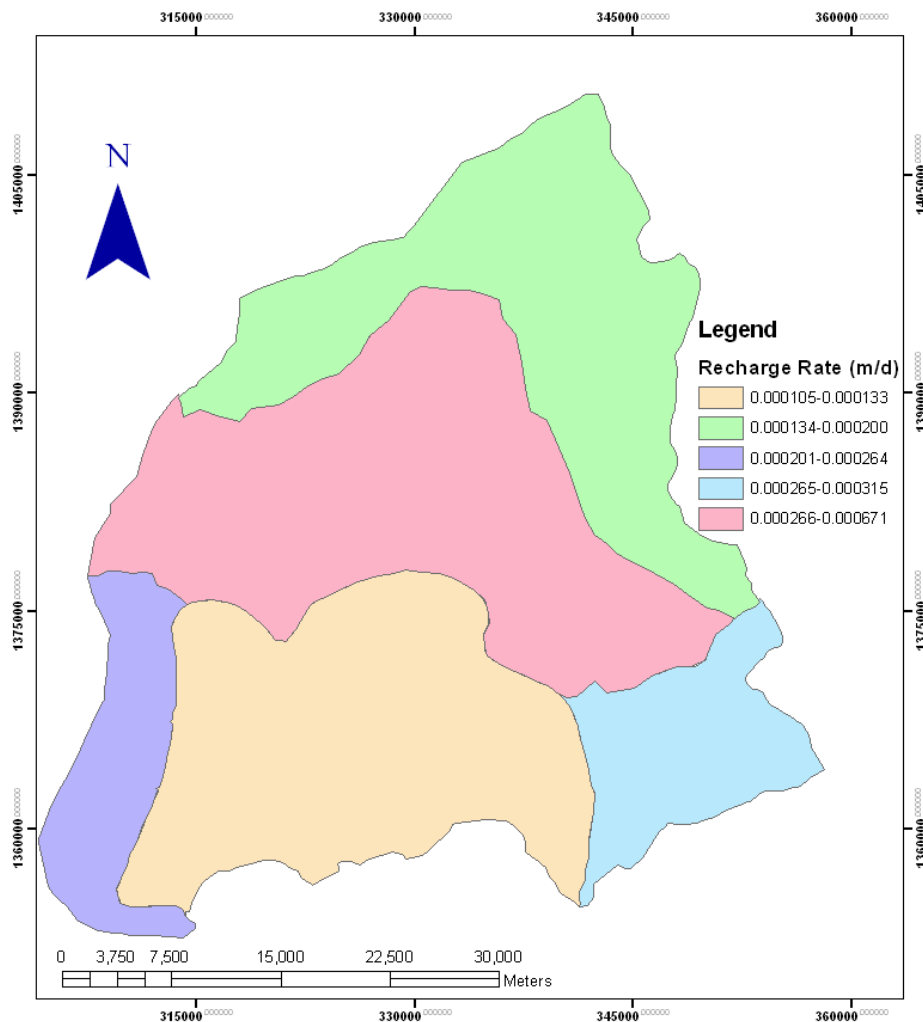


Figure 4.5 Recharge Distribution Map of the Study Area.

4.4.2 Ground Water Discharge

Groundwater discharged by spring or seepage effluent streams (baseflow), dug wells, boreholes, evaporation, springs and where the water table is expected to the surface (swamps) are the most important sources of discharge on the high relief areas. Groundwater abstraction by boreholes is also another source of discharge. But the yield of most boreholes being very low, the effect is insignificant compared to the available groundwater reserve. Evapotranspiration can be considered as one of the discharge mechanisms of subsurface water in near land surface aquifers and from unsaturated soil moisture storage zone. But in the model groundwater level is found at significant depth, as a result it has been neglected.

4.4.2.1 Spring discharge

Springs typically occur where water table intersects the land surface. It represents 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.

A number of low discharge are emanating in the catchment. Two exceptional springs with relatively high discharge are, shollaye spring with an estimated discharge of 5l/s and used for Azezo Military Camp supply. Korebreb spring with estimated discharge of 4l/s and used for Gondar Water Supply. The two springs are believed to be controlled by the NNW-SSE springs trending lineaments.

The springs in the area can be classified in to fault controlled, contact and depression, but dominant once are the contact springs that emanate at the contact of the highly weathered, fractured and friable basalt and/or alluvial deposit and relatively less weathered underlying basalt. The discharge of the springs increases during the rainy season and gradually decreases reaching minimum discharge during the peak dry season. The total estimated amount of water discharged in the form of springs is 16.6l/s. It is insignificant comparing with the volume of groundwater discharged in the study area. As a result it has been neglected in the model.

4.4.2.2 Well withdrawal

Groundwater use in the study area is limited to domestic water supply consumption for the town of the basin. Most of the boreholes are drilled for water supply system of Gondar-Azezo Town and Dashen beer industry. They are located in the vicinity of the town in the three well

fields (Angereb, Keha and Shinta). There are also three borehole in Maksegnet, Koladiba and Gorgora.

In this model, the abstraction amount of boreholes analyzed based on the yield of the boreholes and the average pumping eight hours for towns and rural villages.

The abstraction of groundwater simulated with well package with an average withdrawal of $125.75\text{m}^3/\text{day}$. The total amount of groundwater abstracted in the study area is 4681.8. The detailed description of the boreholes considered and the amount of water withdrawal from the aquifer system is stated on the annex of the paper.

4.4.2.3 Hand dug wells

Both the rural and urban community in the catchment is using a number of hand-dug wells. Most of the wells have depth 6-9m. Almost all the wells tap the weathered basalt and/or the alluvial and colluvial deposit. The yield of hand dug wells increased during the rainy season and gradually reaching minimum discharge during the peak dry season. Since its total amount yield is insignificant comparing to the volume of groundwater discharged in the study area, it did not considered during the modeling.

4.4.2.4 Base flow

One can use water level surface in rivers to predict the mode of interaction of the groundwater and surface water as the one with higher hydraulic head feeds the other with lower head provided that there is a material with higher conductance between the river bed and the aquifer. Previous works show that groundwater and surface water in the study area have interactions and the aquifer system feeds perennial rivers in most streams reaches in the catchment.

Based on this concept, groundwater base flow has been considered as an estimated by base flow recession analysis method for Megech Catchment (BCEOM 1998). This gauged catchment has area 462km^2 and $55\text{mm}/\text{year}$ and 0.010648 groundwater and recession slope respectively.

In this study area, the base flow is quantified based on study of BCEOM the Abbay basin, 1998 and SMEC 2007. The both of the studies made the analysis only for gauged part of the perennial stream. And this model extrapolates the result of ungauged part of the major stream and

other small stream catchments. The hydrographic analysis, based on (BCOEM 2006, Samson 2010) estimates nearly 90mm/year base flow that approximates groundwater interaction.

4.4.2.5 Sub Surface out Flow

The out flow component of the groundwater incur the expenses of groundwater reservoir of the aquifers. It includes the out flow from aquifer system to adjacent aquifer system. In the southern part of the catchment the groundwater discharges in to the Lake Tana. The water surface elevation of Lake Tana, 1785m, was assumed to be the lowest elevation of water table of the catchment area. As a result groundwater will drains toward Lake Tana.

4.5 GROUND WATER FLOW SYSTEM

In developing a conceptual model of a flow system, it is important to consider the topographic setting and geology of the area. The hilly topography produces numerous sub systems within the major flow system. Water that enters the flow system in a given recharge area may be discharged in the nearest topographic lower or transmitted to the regional discharge area in the bottom of the major valley.

Subsurface stratigraphy and the resulting of subsurface variations in hydraulic conductivity can exist in an initial variety. This geological heterogeneity can have a profound effect on regional groundwater flow. It can also affect the interrelation ship between local and regional systems, surficial pattern of recharge and discharge areas and the quantities of flow that are discharged through the systems (Freeze and Cherry, 1979).

In order to develop better conceptual modal for a groundwater flow system in fractured rock, some characterization of the medium is necessary. The degree of characterization and simplification is depends on the inherent complexity of the fracture system, the type of conceptual model desired, the amount of funding available and objective of the modeling (Freeze and Cherry, 1979).

Despite the fact of the benefit of groundwater investigations from the development of numerical model which is used to simulate the flow system. The complex, pattern of aquifer system, which is a combination of dominant volcanic aquifer characterized by confined, semi confined and unconfined aquifer unit is difficult for the modeling. The study area aquifer system is considered to be homogenous, isotropic and unconfined one layer with an estimated

thickness of 250m which represents the average thickness of the tertiary and quaternary alluvial aquifers.

The compromise analysis of flow study area can be carried out continuum approach. As with granular porous media, the continuum approach involves the replacement of fractured media by a representative continuum in which spatially defined values of hydraulic conductivity and porosity can be assigned. This approach is valued as long as the fracture spacing is sufficiently dense that the fractured media acts in a hydraulically similar fashion to granular porous media. As field investigation and geological logs depict, the study area is highly weathered and intensively fractured. The object of the model to understand the flow system for a very large coverage area could achieved with this simplification.

The study area catchment groundwater flows from the recharge area to discharge area following the morphology. The head difference between the maximum and the minimum water level in wells used as the head observation point is about 395m. This shows high hydraulic relief and existing high hydraulic gradient between the points.

CHAPTER FIVE

5. NUMERICAL GROUNDWATER FLOW MODELING

5.1 GENERAL CONCEPT AND MODELING APPROACH

Groundwater modeling is being used more frequently as a tool to help answer optimum water management questions because it can lead to a better understanding of how the real system behaves and it can be used to make predictions about the systems future behavior. This in turn helps to develop operational and regulation strategies that will secure the sustainable development of strategically important water resource.

Numerical modeling is being used increasingly to quantify the water resource availability of our complex, dynamic groundwater /surface water systems and to take account of the environment impact of abstraction. However, to be credible, modeling tools must be technically valid and agreed representation of the real system. Therefore, one of the key objectives of any resource study is the process of developing a shared understand (conceptual model) of the essential flow mechanisms. Only then can the numerical model be used as a predictive tool to investigate different future conditions (Yirgalem and Assefa 2008).

In recent years, numerical ground water modeling has become a major part of projects dealing with groundwater exploitation, protection, remediation and it is the most useful tool to study the response of hydrogeologic system to any scenario or to predict system response. Numerical models describes the entire flow field of interest at the same time providing solutions as many data points as specified by the user, the area of interest is subdivided in to many small areas(usually referred to as cells or elements) and basic groundwater flow equation is selected to solve for each cell. The solution of a numerical model is the distribution of the hydraulic heads at points representing individual cells. Similarly to most numerical groundwater flow models, Northern River Catchment of Lake Tana, groundwater flow model developed in this work was simulated to study the response of the system to different hypothetical scenarios of the withdrawal, recharge or any other parameters under steady state condition.

This numerical model developing approach includes the definition of system boundary, estimation of base flow, estimation well withdrawal, compilation of water level data, groundwater level counteracting, compilation and develop previously estimated recharge and hydraulic conductivities, selection of an appropriate computer code/ governing equation for simulation, calibration of calculated heads to field observed heads and simulation under different scenarios to understand the response of the system. The concept of approach used was that an understanding of related basic principles and an accurate description of the specific system under study will enable an accurate quantitative understanding of the cause and effect relationship. This quantitative understanding of the relationships allows one to understand the response of the system under consideration to any proposed scenario or to make prediction for any defined set of conditions.

Groundwater flow in the Northern River Catchment of Lake Tana aquifer system has been simulated using a modular three dimensional finite- difference groundwater flow model of the U.S Geology Survey which describe and predict the behavior of the flow system. The MODFLOW were originally designed to simulate three dimensional groundwater flows through pervious medium. Since its design concept did not include solving equations other than the groundwater flow equations, various computer codes for solving specific problems have been developed by numerous investigators.

The most recent version, MODFLOW 2000, which is used in this model, attempts to incorporate the solution of the multiple related equations in to a single code. To achieve the goal, code is divided in to entities called process. Each process deals of a specific equation. These codes are often called packages, models or sometimes simply programs. Packages are integrated with MODFLOW; each package deals a particular technique for solving the system of equations or a specific feature of the hydrologic system to be simulated. A model or a program is not embedded in MODFLOW, but communicates with MODFLOW through data files.

MODFLOW, the USGS modeler three dimensional finite difference, groundwater flow model, is an international standard for groundwater modeling. In addition, MODFLOW is a basis from which other models can be considered. MODFLOW is widely used, tested, verified and water balance computation incorporated model which simulates all hydrologic

features independently using its grouped package. It is deterministic model approach which assumes the stage or response of aquifer is predetermined by the help of physical laws governing the groundwater flow. In MODFLOW, the continuous problem domain is replaced by a discretized domain consisting of an array of nodes and associated finite difference blocks. The ultimate result of the MODFLOW is the distribution of the hydraulic head at point node which locate at the center of the rectangular cells represent of the cell.

The basic principle of the MODFLOW is the approximation that means replacing of the partial differential equations (the governing equations, boundary and initial condition) in to algebraic equation. The algebraic equation which can be written in matrix equation is solved with a numerical approach through the iterative process. These numerical approaches, in finite difference approximation involve applying Taylor's expansions the flow equations and approximating derivatives in the equation. Finite difference methods compute a value for the head at the node which is the average head for the cell (block) that surrounds the node. In this case no assumption is made about the form variation at the head from one node to the next.

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

5.2 GOVERNING EQUATION

The movement of groundwater through porous media is described and solved on the basis of partial differential equation, governing equation. It is the representation of physical law that controls the groundwater flow, which is based on Darcy's law and the law of mass conservation. It is used in computer model to describe groundwater flow is:

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

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.

To model the study area, Northern river catchment of Lake Tana, aquifer system the above governing equation has been adjusted according to the prevailing field condition. Since the conceptualized model is steady state unconfined aquifer and a single layer with no possible in the Z direction, the equation can be simplified and rewritten in to the following equation. This equation assumes flow system view point that allows both vertical and horizontal component of flow throughout the system and there by allows treatment of flow in two dimensional profiles (Anderson & Weossener, 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 DISCRETIZATION AND GRID LAYOUT

In numerical model, the continuous problem domain is replaced by a discretized domain consisting of the array of nodes and associated finite difference blocks (cell). The nodal grid forms the frame work of the numerical model. There are two types of finite difference grids,

block-centered grid and the mesh centered grid. The difference between them lies mainly in the way in which the flux boundaries are handled. In the block centered approach flux boundaries always are located at the edge of the block. In mesh centered grid, the boundary coincides with the nod. In most computer codes, including MODFLOW the finite difference mathematics for boundaries are more easily treated with the block centered approach.

The grid should be drawn on an overlay a map of the area to be modeled. The horizontal plane of the grid should be aligned so that the X and Y coordinate axes are collinear with K_X and K_Y . In a finite difference model it is also important to orient the grid to minimize the number of nodes that fall outside the boundaries of the modeled area. These nodes are called inactive nodes, where as nodes that fall within the modeled area are active nodes. Inactive nodes are not part of the solution but still use up storage space in the array need by the code. Fitting the grid to boundaries, care should be taken that the nod falls directly on the boundary. In a finite difference block-centered, the grid is designed so that the flux boundaries fall on the edge of the blocks and specified head boundaries fall on the node.

The other important in grid design is the size of the nodal spacing. The size of the nodal spacing in the horizontal dimension is a function of the expected curvature in the water table or potentiometric surfaces. Finer nodal spacing will be required to define highly curved surfaces. The overall size of the modeled area also affects the selection of the nodal spacing. A grid with a small number of nodes is preferred in order to minimize data handling, computer storage and computation time. Yet, it is desirable to use a large number of to represent a system accurately. Then need to select meaningful boundary may also require modeling a large area.

In this work, the extent of the study area in north-south and east-west is 58800 and 54400m, respectively. The catchment covers 1887km² and the model discrete with a uniform size of 200m X 200m with 294 row and 272 column arrays in a single layer. The origin of the model spread from the lower left corner of the grid with geographic coordinate of UTM 37N 304069E and 1352300N. The model uses a total number of 79968 cells in which only 39780 are active and used to compute the hydraulic head. The remaining number of cells are inactive with no computation will be carried out in this part of the cell.

5.4 BOUNDARY CONDITION

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain (Anderson and Woessner, 1992). The boundary chosen for the model describe mathematically how the simulated groundwater system interacts with the surrounding hydrologic system. Computer simulation of groundwater flow system numerically evaluates the mathematical equations governing the flow of the fluids through porous media. This equation is the second order partial differential equations with head as dependent variable. To determine the unique solution of such mathematical problem, it is necessary to specify boundary conditions around the flow boundary domain for head or its derivatives. One requirement for the solution of mathematical equation that describes groundwater flows is that boundary conditions must be prescribed over the boundary of the study area domain. It is important to note that in solving groundwater flow problem, boundary conditions are not simply mathematical constraints. They generally represent the sources and sinks of water within the system. In addition, their correct selection, the location of boundaries and their numerical representation in the mode, is critical to the development of an accurate model that can simulate system response correctly under proposed scenario.

In mathematical analysis of the ground water flow system, three common mathematical boundaries conditions are specified (Anderson and Woessner, 1992). These are specified head, specific flow and head dependent flow. In this model two boundary conditions were applied; specified head and specified flow/ no flow. Nodes that represented specified head boundary in the model were simulated with a head that is unchanging. Such heads represented an inexhaustible supply of water that is; the groundwater system may pull water from the boundary or may discharge water in the boundary without changing head at the specified head nod. In this model, the southern part of the study area boundary is coincides with Lake Tana. As result its boundary has been specified head and such nodes assigned by -1 value to entries of I-BOUND array in MODFLOW. This water surface elevation of Lake Tana, 1785m, was given as initial heads to cells representing such constant head nodes. Angereb reservoir also considers as constant head with water surface elevation 2155m.

The upper boundary of the system was simulated as specified flux as recharge was applied to the water table. Such nodes has assigned by 1 value to entries of I-BOUND array in

MODFLOW. The lower boundary was assumed to be a no flow boundary. In the northern, western and eastern boundaries of the catchment model coincides with the surface of the water divide lines of the study area which is considered as no flow boundaries. The value 0 was assigned to the cells at the external of such boundaries to make them inactive and no flow occurs across such boundaries. Head values are not calculated for cells represented as inactive cells.

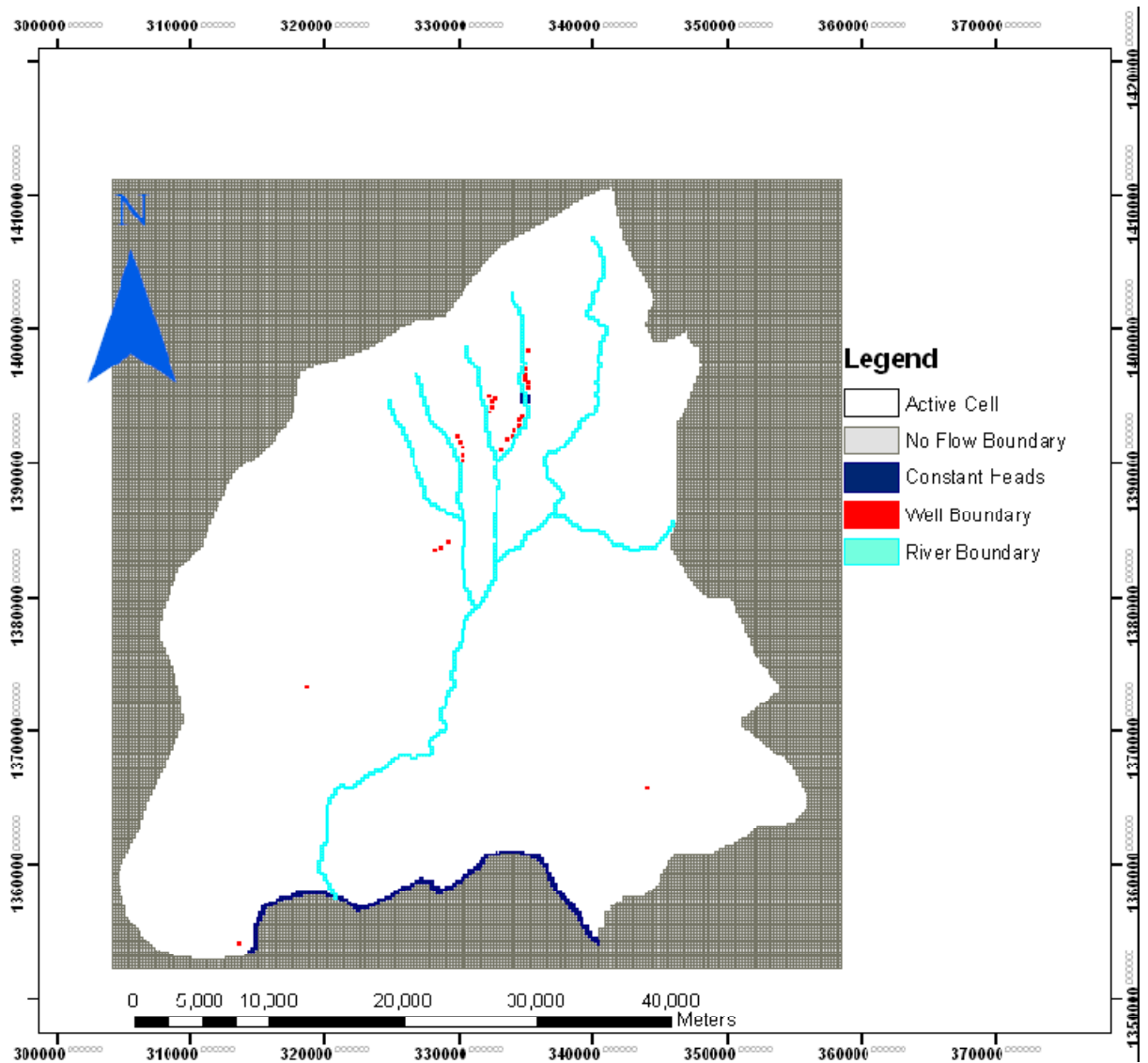


Figure 5. 1 Boundary Condition of the Study Area

5.5 TOP OF MODEL LAYER

Top layer is the top elevation of the aquifer under considerations. The top layer of unconfined aquifer is the water table and not the land surface (topography). In this model, the aquifer was assumed to be a single layer unconfined aquifer. Generally, the top layer elevation was considered to be the elevation of water table. The nodal values of ground surface elevation were interpolated from DEM data. The interpolation was done at the resolution of 200m X 200m and then loaded in to the MODFLOW top elevation array by subtracting surface elevations above from the interpolated water table.

5.6 BOTTOM OF MODEL LAYER

Bottom layer is the bottom elevation of the aquifer layer being modeled. In this study, the aquifer thickness lies within the range 210m to 300m in most parts of the catchment except along the boundaries where ridges with high elevation are found. Elevated zones were simulated by giving relatively higher thicknesses at the cells in order to avoid drying of cells during simulations. In fact, the thicknesses of the aquifers are varying as it has not yet been determined exactly for the aquifers and was modified a bit in few areas during model calibration process.

5.7 INITIAL AND PRESCRIBED HYDRAULIC HEAD

Initial and prescribed hydraulic heads are values of the hydraulic head for each active and constant head cell in the model. They must be higher than the elevation of the cell bottom and are necessary for the start of iterative model calculations. Initial hydraulic heads for steady state condition only constant head cells must be actual (realistic). In this model, the initial hydraulic heads was obtained by subtracting constant number accordingly with the topographic and interpolated water table elevation. The real value of water level elevation was given as initial heads in cells represented by constant heads.

5.8 MODEL STRESSES AND FLUX

Water may enter or leave a model in one of two ways through the boundaries, as determined by the boundary conditions, or through sources and sinks within the interior of the grid (Anderson and Woessener, 1992) the flux in to or out of the aquifer system of Northern River Catchment of Lake Tana as applied in to the model and simulated by MODFLOW 2000 are summarized under the following sub section. Various MODFLOW packages were used to

simulate model stresses. The modeled stresses include recharge to the aquifers discharge to rivers and well withdrawal.

5.8.1 Recharge Package

The rate of replenishment of water table in aquifers (mainly by rainfall) is known as ground water recharge rate. The recharge package is designed to simulate distributed recharge to the groundwater system. Recharge is defined by assuming the following data to each vertical column of cells. The input parameters are assumed to be constant during a given stress period. As it was pointed out under recharge section, the catchment was subdivided into different zones of recharge based on the amount of precipitation, rock type, land cover/land use, topography, soil type etc. and in fact based on recharge amount of the catchment. The recharge was simulated as specific flux by using recharge package of MODFLOW 2000 with the option recharge “application on the top grid layer” and is not expected to change with water level changes.

MODFLOW 2000 uses I_R to calculate the recharge flow rate Q_R applied to the model cell:

$$Q_R = I_R \cdot \text{DELR} \cdot \text{DELC} \quad \text{Equation 5.4}$$

Where - DELR, DELC is the map area of a model cell.

- I_R is recharge flux

In MODFLOW, the recharge rate Q_R is applied to a single cell within the vertical column of cell. In this model, the top layer is designated as unconfined and an array of recharge flux I_R is specified for the layer. Recharge of the model was the only expected inflow component to the aquifers. The recharge value was modified during the calibration process.

5.8.2 River Package

One can use water level surface in rivers to predict the mode of interaction of the groundwater and surface water as the one with higher hydraulic head feeds the other with lower head provided that there is a material with higher conductance between the river bed and the aquifer. The major perennial stream was most essential river boundary in the model area that holds the surface and aquifer system interaction. In the study area Megech River and its tributaries sustain their dry period of flow with contribution of the groundwater. This river

also expected to feed the groundwater where the stage of the river exceeds the adjacent aquifer system head.

The interaction of the river and aquifer can be mathematically represented by the MODFLOW relation of hydraulic head of model and the stage of the river both on the upper table and the bottom of the river as shown below:

$$Q_{riv} = C_{riv} (h_{riv} - h) \quad \text{if } h > B_{riv} \quad \text{Equation 5.5}$$

$$Q_{riv} = C_{riv} (h_{riv} - B_{riv}) \quad \text{if } h < B_{riv} \quad \text{Equation 5.6}$$

$$C_{RIV} = K_{riv} L W_{riv} / M_{riv} \quad \text{Equation 5.7}$$

Where:

Q_{riv} : Flow rate between the river and groundwater

h_{riv} : Head in the river

h : Head in the aquifer or the model

B_{riv} : Elevation of bottom of the river bed

C_{riv} : hydraulic conductance of river bed

K_{riv} : Hydraulic conductivity of the river bed

L : Length of the river within the cell

W_{riv} : Width of the river

M_{riv} : Thickness of the river bed

5.8.3 Well Package

Most of the boreholes are drilled for water supply consumption for water supply system of Gondar-Azezo town and Dashen beer industry. There are also other three wells at Koladiba, Gorgora and Maksegnt. In this model, the abstraction amount of the boreholes analyzed based on the yield of the boreholes and average pumping eight hours for towns and rural villages. The abstraction of groundwater was simulated using well package.

In this model pumping wells was defined using Cell-by-Cell input method. The injection or pumping of the rate of a well is independent of both the cell area and the hydraulic head in the cell. MODFLOW assumes that a well penetrates the full thickness of the cell. To simulate withdrawal of water from aquifers through well package, negative value of the rate of daily abstraction (m^3/d) was assigned to the entry recharge in well Package MODFLOW.

CHAPTER SIX

6. CALIBRATION AND SENSITIVITY ANALYSIS

6.1 GENERAL OVER VIEW

Calibration of a flow model refers to a demonstration that the model is capable of producing field measured heads and flows which are calibration values (Andersen & Woesser). It is accomplished by finding the set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that much field measured value with in prescribed range of error. Calibration is carried out to demonstrate that the calibrated model can reproduce measured heads or fluxes, and groundwater flow modeling is usually intended to produce a model that can accurately simulate future conditions for area where no head data are available. To make good projection and to understand system dynamics, model calibration was done to acceptable error range by considering realities in the area. Field measured values can be measurements of head, concentration, drawdown or groundwater flow (flux).

Calibration can be achieved in two ways; the forward and inverse problem solutions. In an inverse problem the objective is to determine values of the parameters and hydrologic stresses from information about heads, where as in forward problem system parameters such as hydraulic conductivities, specific storage, and hydrologic stresses like recharge rate are specified and the model calculates the head.

Sensitivity analysis is the processes of quantifying the calibrated model caused by the uncertainty in the estimates of aquifer parameters, stresses, and boundary condition.

6.2 CALIBRATION TECHNIQUES

Parameter estimation is essentially synonymous with model calibration, which is synonymous with solving the inverse problem. There are basically two ways of finding model parameters to achieve calibration; manual trial and error adjustment of parameters and automated parameter estimation. Manual trial and error calibration was the first technique to be used and still the technique preferred by most practitioners (Anderson and Woelsson, 1992). In trial and error calibration, parameter values are initially assigned to each nod in the grid. During

calibration, parameter values are adjusted in sequential model runs to match simulated heads and flows to the calibration targets.

In this model, calibration was performed by the traditional trial and error processes in which model parameters and hydrologic stresses were adjusted manually within reasonable limits of existing data and field hydrogeological observation to achieve the best model fit. Additionally, hydrologic stresses literature review and point hydraulic conductivity and transmissivity data was used as initial guessing during calibration of hydraulic conductivity. Since the available hydraulic conductivity and transmissivity data reliability are very low due to the faller of pumping test, they did not take as control during calibration of hydraulic conductivities.

The calibration criteria set by the modeler is to match simulated ground surface and hydraulic gradient with estimated one by taking in to account the variation of hydraulic conductivity of volcanic aquifers in small distance.

The model calibration accounts the matching of the 58 observation point with simulated head with a permissible residual head of $\pm 10\text{m}$. The criteria set is almost 75% of the difference the maximum and minimum measurement water level head in the study area which is about 5m. It is almost with tolerable difference with respect to the gradient, the objective to understand the groundwater flow pattern and the diversity of hydraulic nature of volcanic aquifer.

The model was assumed calibrated when the fit between observed and calibrated heads was within this criteria and calibration evaluated based on final spatial distribution of the difference between the observed and simulated heads.

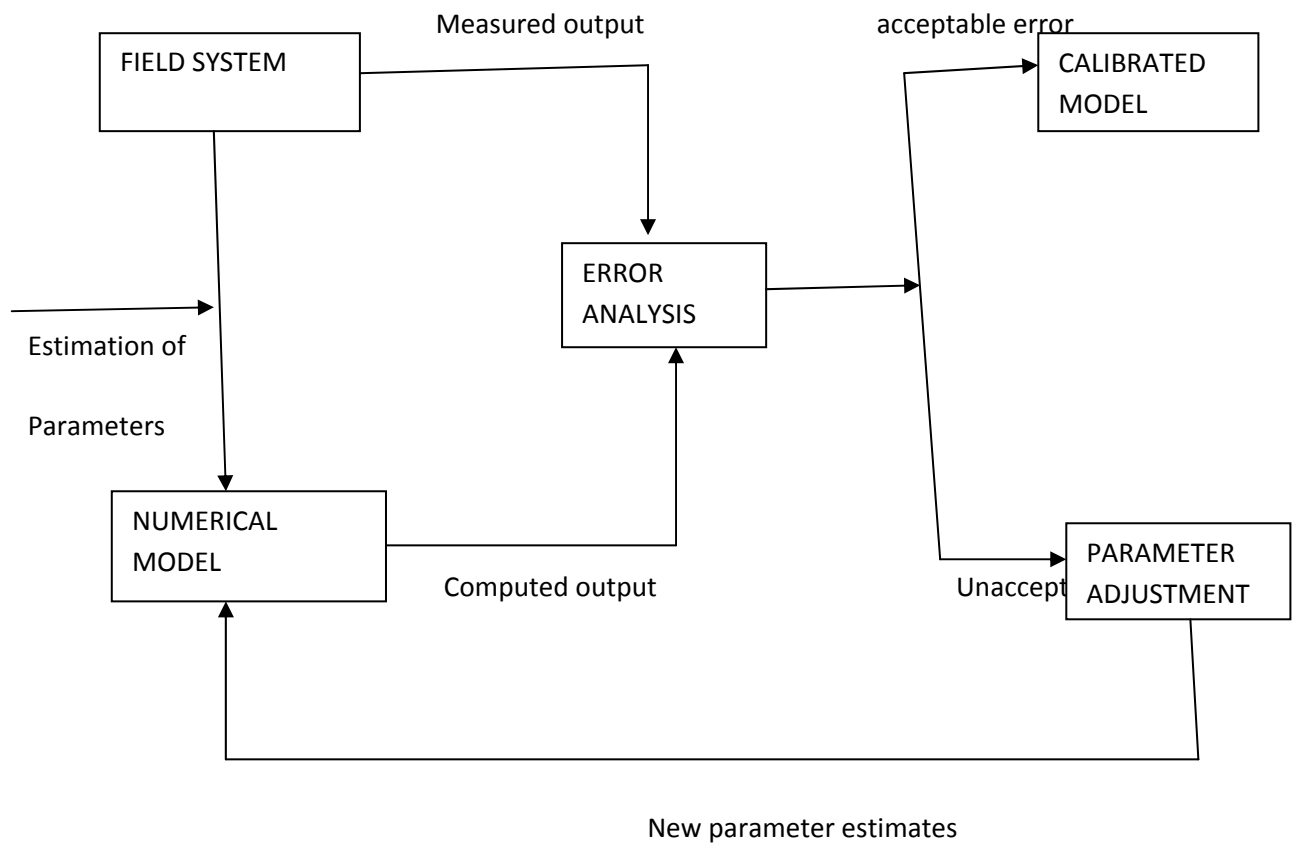


Figure 6. 1 Trial-and-error calibration procedure (Anderson and Woessner, 1992)

6.3 DATA USED FOR CALIBRATION

The model is calibrated to steady state condition with observed head measured at the available production well. Most of the groundwater measurements were taken during construction and inventory times of the borehole. There was no practice of monitoring existing well standing meter except where fails and needs maintenance. Observation points were not evenly distributed throughout the model domain but clustered geographically in Gondar-Azezo town and their peripheries. And there were also a few observation points at Koladiba, Makesnet and Gorgora. Hand dug wells were used to as observation points on the Megech plain catchment area.

Groundwater heads contours were constructed from these water levels/heads and matching field contours with calculated contours was made during model calibration.

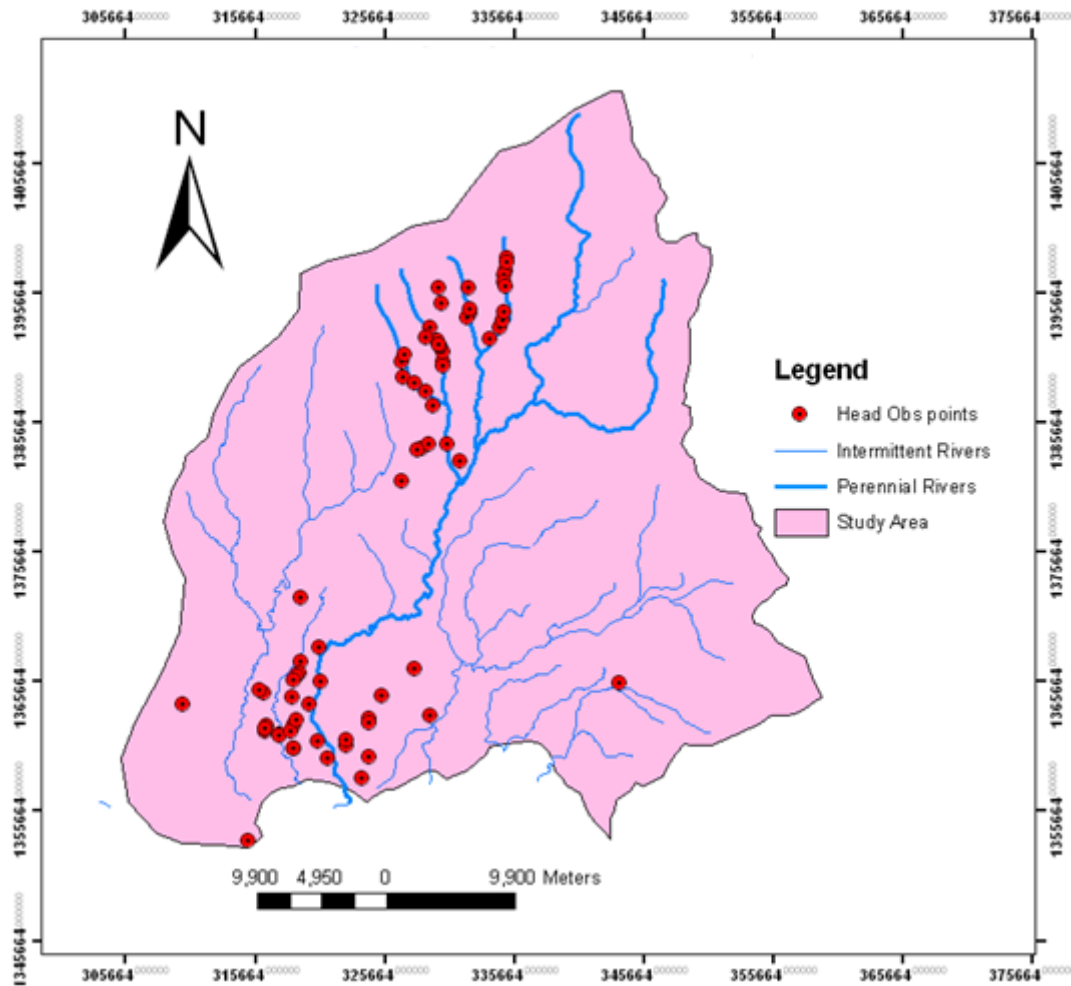


Fig 6.2 Location of Observation points used for head calibration.

6.4 EVALUATION OF CALIBRATED RESULT

The result of calibration should be evaluated both qualitatively and quantitatively. The efficiency of calibration process was evaluated by comparing measured heads with simulated heads for each observation wells used. Three types of calibration techniques were set for this model calibration evaluation.

6.4.1 Calibrated Statistics

A listing of measured and simulated heads with their differences and some type of average of the differences is common way of reporting the calibration result. This difference is called error or residual. It is computed by subtracting the model computed value (head, draw down, concentration) from the target value. Negative residual indicates that the model is calculating the dependent value too high and the positive residual is where model value is too low.

The following types of statistics computed to express the average difference between simulated and measured heads are commonly used.

Mean Error (ME) is the mean difference between the measured heads (h_m) and simulated heads (h_s). n is the number of calibration value.

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

The ME is simple to calculate but is usually not a wise because both negative and positive differences are incorporated in the mean and may cancel out of the error. Hence a small mean may not indicate a good calibration. The model of the area under investigation has a mean error of 0.506m that is not too far to be good calibrated model.

Mean Absolute Error (MAE) is the mean absolute value of the difference in measured and simulated heads.

$$MAE = \frac{1}{n} \sum_{i=1}^n |h_m - h_s|_i$$

It is the measure of the average errors in the model. The model results an absolute residual mean of 4.431m which is bellow the residual criteria set before the calibration process.

The Root Mean Squared (RMS) Error or the standard deviation is the average of squared differences in measured and simulated heads.

$$RMS = \left[\frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i^2 \right]^{1/2}$$

It is the measure of the overall spread of errors. It can be compared the overall range of in the observed value as further comparison. For head observations, this value show errors related to the overall gradient across the model. The model has resulted (6.083m) error of standard deviation which is good range in calibrations.

6.4.2 Plotting Calibrated Results

Two types of plots are useful in assessing the quality of calibration simulations. The first is the scatter plots where observed values are plotted versus the value computed by the model. In an ideal calibration the points will fall on the straight line with a 45 degree slope that

means the computed value equals with the measured value. In this model, it was difficult to match the theoretical line with the plot, but follows a straight line with ± 10 mts.

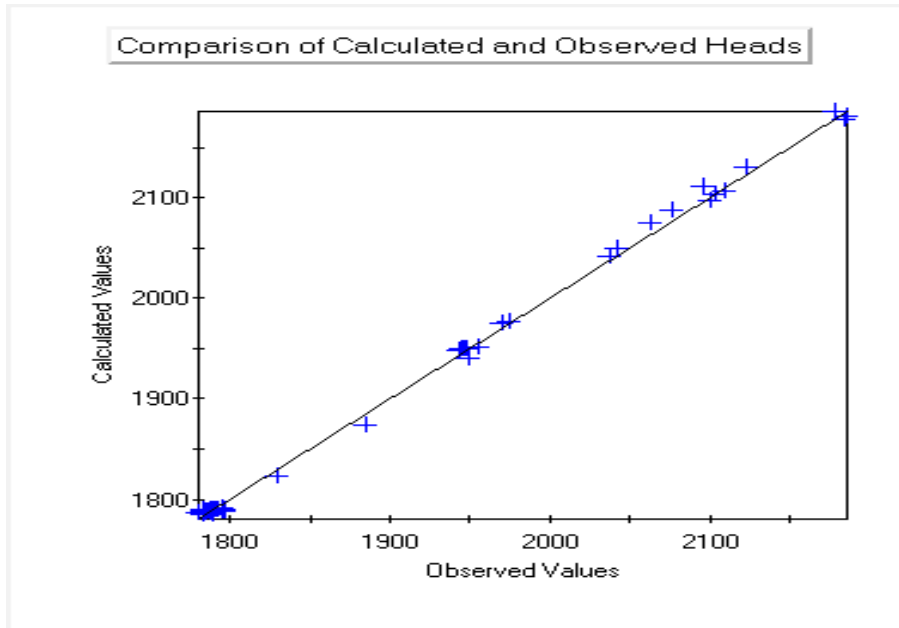


Figure 6.3 Scatter Plot of Head Distribution of Calibrated Model

6.4.3 Histogram of Calibrated Result

This helps to observe clearly the distribution of the absolute value of the difference between observed and simulated hydraulic heads and the frequency occurrence. Absolute head difference above 10m can be attributed to uncertainty in estimated stresses and hydraulic parameters.

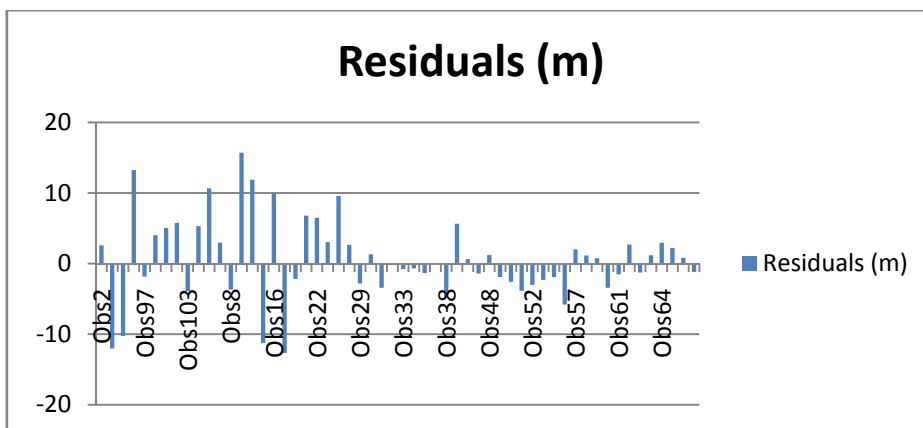


Figure 6.4 Histogram showing error distributions

6.4.4 Post Errors on Counter Map

This is also one type of useful plot to assess the calibration quality by posting the error on the counter map of the model dependent variable (head). This type of plots posts the target errors on simulated ground surface map and help to understand the calibration quality over spatial distribution. This is important to indicate spatial bias in the distribution of the errors. Based on the posted error, we can easily understand the areas where errors are all too high or too low.

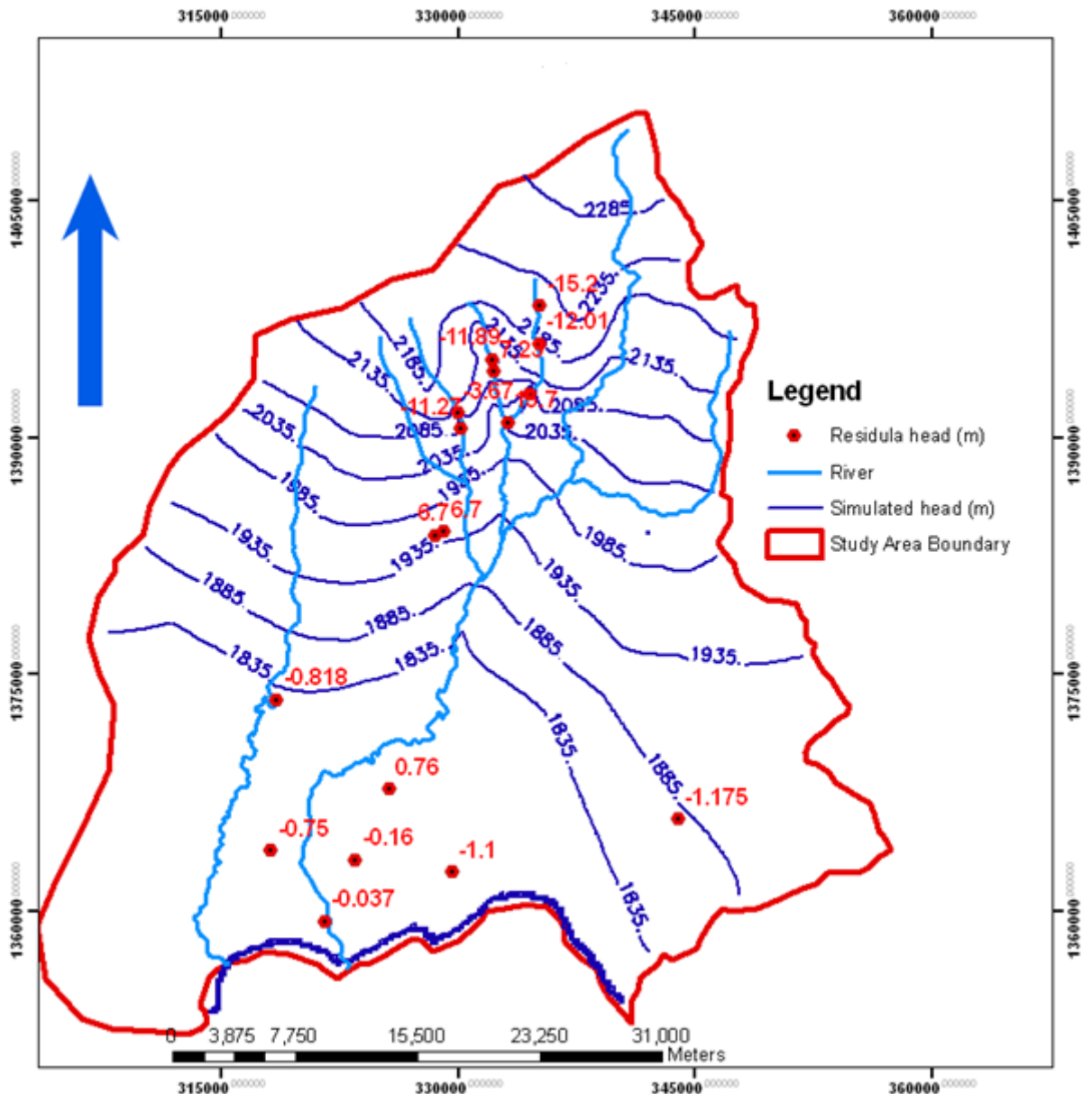


Figure 6.5 Post residual selected target wells of the model

6.5 SENSITIVITY ANALYSIS

The purpose of sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimated of the aquifer parameters, stresses, and boundary condition (Anderson & Weossner, 1992). During sensitivity analysis, calibrated value for hydraulic conductivity, storage parameters, recharge and boundary conditions are systematically changed with in the previously established plausible range. The magnitude of change in head or flux from the calibration solution is a measure of the sensitivity of the solution to that particular parameter. In fact the model make up also determines how sensitivity to an input. Generally, sensitivity analysis in the processes of identifying the model parameters that that have the most effect on model calibration or on model prediction.

The results of sensitivity analysis are reported as the effect of the parameter change on the average measure of errors or residual selected as calibration criterion (calibration statistics). The effect on the spatial distribution of head residual is also examined. The sensitivity of the major parameters of the model was identified during calibration process. Based on the calibration process, the model is very sensitive to change in recharge, hydraulic conductivity, and stream bed conductance respective general decreasing order.

The calibration value of recharge, hydraulic conductivity, and stream bed conductance were varied by 5%, 15%, 30%, and 50% increase and decrease at different times to test the sensitivity of the model to the parameters. The total of twenty four model runs were conducted by changing the above listed parameters by specified percent, and the respective root mean head and the river leakage by percent changes from the calibrated are shown in the table below.

In all sensitivity analysis, it was observed that the model was less sensitive to parameter change in alluvial sediment aquifer (southern part of the catchment) compared with volcanic aquifers (Northern part of the catchment), that is, absolute mean water level changes were minimal to alluvial plain in all sensitivity simulation. The sensitivity of the volcanic and alluvial sediment aquifers to change of all the above listed parameters has been shown in the table.

The following tables and plots show the result of sensitivity of the model to changes in recharge, hydraulic conductivity, and stream bed conductance on the hydraulic heads and river leakage.

Table 6. 1Result of Sensitivity Analysis test on water level

Multiplier Factor	Hydraulic conductivity (%)	Recharge (%)	Stream Conductance (%)
0.5	107.76	253.37	81.07
0.7	65.39	84.15	22.52
0.85	12.91	23.1	5.84
0.95	0.92	3.41	0.71
1	0	0	0
1.05	1.10	0.41	0.62
1.15	7.45	6.02	0.87
1.3	22.42	31.31	7.50
1.5	53.82	75.73	15.53

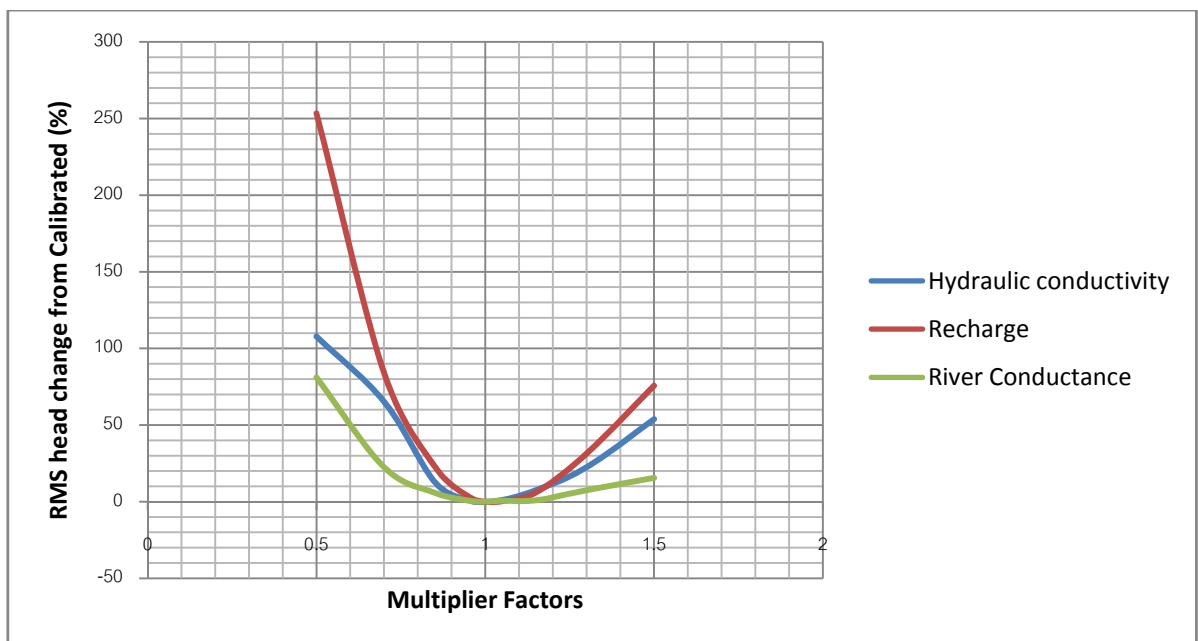


Figure 6.6 Plot of the result of Sensitivity Analysis Test on Heads.

Table 6. 2 Result of Sensitivity Analysis test on Stream Leakage

Multiplier Factor	Hydraulic conductivity (%)	Recharge (%)	Stream Conductance (%)
0.5	69.04	-76.72	11.99
0.7	30.80	-74.97	6.64
0.85	14.02	-37.79	3.47
0.95	4.46	-12.65	1.21
1	0	0	0
1.05	-4.31	12.73	-2.02
1.15	-12.68	38.48	-4.18
1.3	-24.64	77.72	-8.95
1.5	-39.47	131.29	-15.64

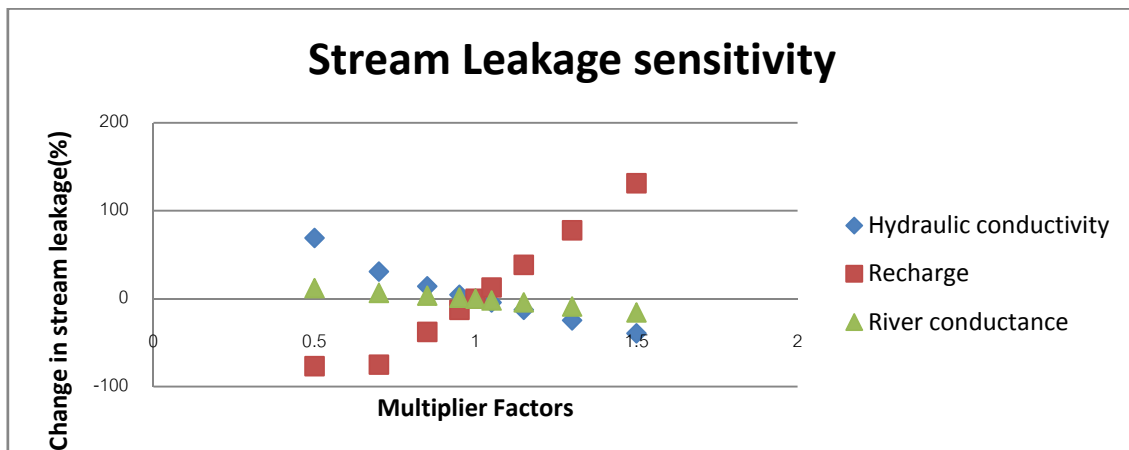


Figure 6.7 Plot of stream leakage Sensitivity Result

6.6 MODEL RESULT AND ANALYSIS

The final result of the model is a calibrated steady state groundwater flow model with simulated head of groundwater surface. Once the model is calibrated it can be manipulated and simulated with users' defined interest.

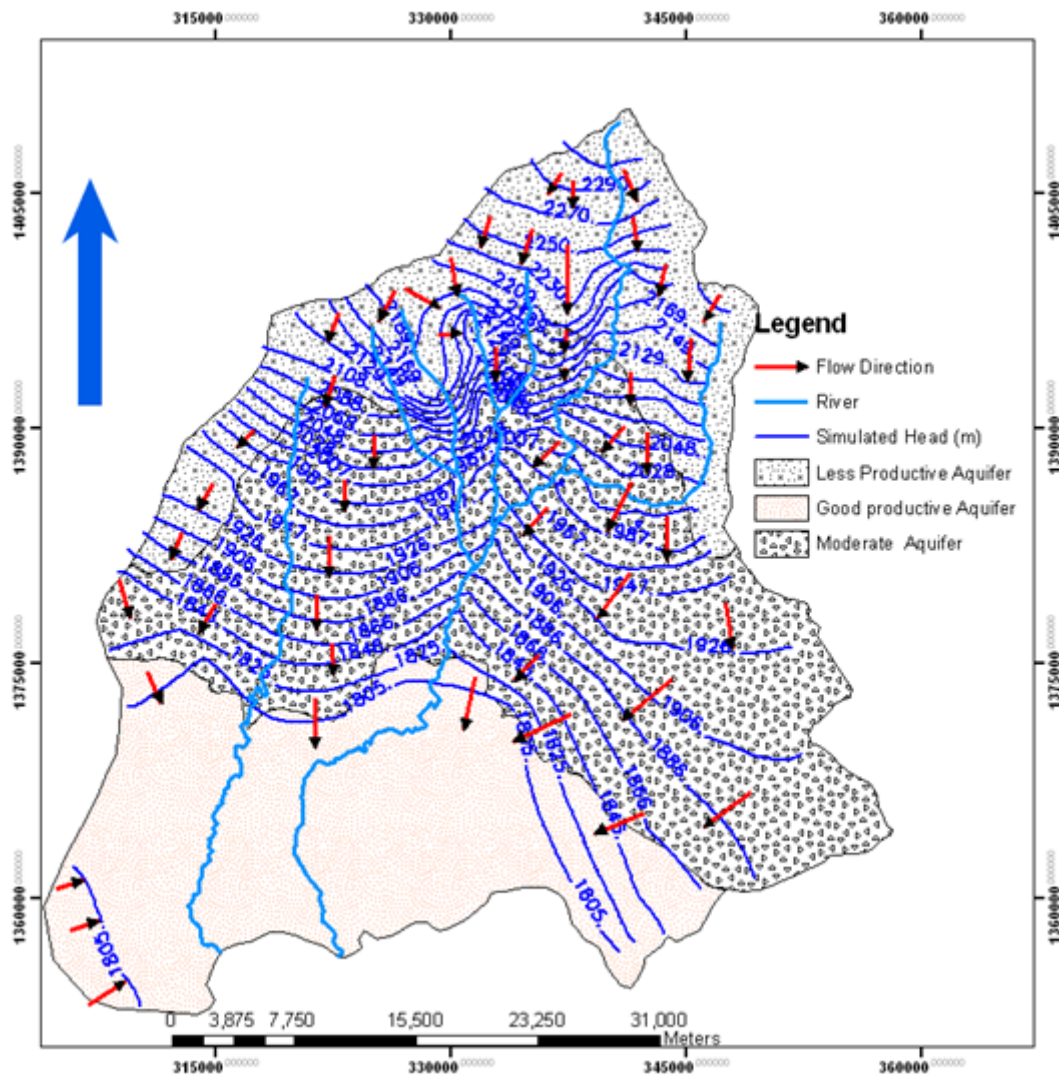
The numerical groundwater flow modeling is empowered with computation of water budget. The simulated water budget has been computed for the study area. The simulated out flow of

the model is 205733827.88m³/year which is nearly equal to simulated inflow with difference 7.9m³/day and 0% of error. The base flow simulated discharge holds 35.75% of the out flow. It also contributed as recharge in to the aquifer that accounts to 15.30% of the inflow. This share of base flow implies the discharge of the groundwater to the dominantly gaining streams and high interaction of surface and aquifer systems.

Table 6.3 Detail water budget analysis of the study area is shown below with table.

No	Water balance component	Daily		Annually	
		Inflow (m ³ /d)	Out flow (m ³ /d)	Inflow (m ³ /d)	Outflow (m ³ /d)
I	Constant head	227.16	356946.84	83026.98	130464070.02
II	Wells		4681.80		1711197.90
III	Recharge (Precipitation)	476551.50		174179573.25	
IV	River Leakage	86112.44	201254.59	31474096.82	73558552.65
	Total	562891.13	562883.25	205736708.02	205733827.88

The study area catchment groundwater flows from the recharge area to discharge area following the morphology. The MODFLOW calculates the hydraulic head distribution of groundwater flow surface. The head distribution shows the groundwater surface follows the topographic contour and it coincides with surface water flow.



Figure

Fig 6.8 Groundwater head contour and flow direction

6.7 SCENARIO ANALYSIS

The main advantage of numerical ground water flow modeling is to customize the result for different scenario analysis. Having a calibrated model that was tested for sensitivity as a capable of simulating water level elevations or fluxes and given its associated limitations, it is possible to use the model to simulate the resulting changes in water levels and fluxes due to new proposed scenario and project the likely effects. As it has been clearly stated in objectives, numerical groundwater flow model simulated in this study was intended to test the response of the hydrologic system to different scenarios. System responses were evaluated by using fluxes and heads of the calibrated model as base line and compared with resulting changes in stream leakage and changes in water table elevation in the new scenario simulation.

Changes in water levels and fluxes caused by increased groundwater with drawl in the whole catchment and effective of local increase groundwater local withdrawal of Gondar-Azezo town and its peripheries were simulated by the model. The effect of changes in water levels and fluxes caused by decreased recharge due to less than normal precipitation that may result from weather modification and deforestation was also simulated. The increasing of the recharge due to irrigation project area has also been simulated using the model. In addition, the response of the system in the absence and development of reservoirs with groundwater has also been tested using the numerical model.

It should be noted that the results of the scenarios depends on the future land use, population growth, weather condition, hydrologic stresses etc, and may not be used as predictive tool to generate absolute amounts in the future, but used primarily to test the response of the system. In general, the results of the scenarios or their accuracy depend on the validity of the assumptions behind the scenarios. Moreover, errors introduced due to limitations associated with numerical model also affect the results of the scenario and should be taken in to consideration during interpretation and application of the results. In the following section results of each scenario is discussed.

6.7.1 Effects of Increased Groundwater Withdrawals

Gondar-Azezo town expanding, industries flourishing and population are increasing in the study area, it is reasonable to assume that the water demand will increase too. In addition the main water supply source of Gondar, Angereb dam yield is decreasing due to sedimentation of the reservoir site. To meet increasing demand and decline of exciting water supply scheme yield, it is must that the existing boreholes should be pumped a greater rate or with new boreholes with higher capacity should be drilled in the future. This truth can be seen from large number of wells drilled since recently in the catchment at the peripheries of Gondar-Azezo town. So it is logical to think that groundwater withdrawal will increase in the catchment and it is necessary to project its future effects on groundwater table and fluxes of the area so that the appropriate water management practices that could mitigate the likely adverse effect of increased withdrawal may be proposed. To evaluate this condition, two scenarios of increased groundwater withdrawals have been conducted.

In the first scenario, five increased withdrawals amounts were distributed among existing wells in proportion to the current contribution of each source to the daily withdrawal rate. The current withdrawal rate estimated under steady state simulation was 4681.8m³/day. The current estimated groundwater withdrawal rate from the catchment can be considered as the minimum reasonable amount.

Generally, as withdrawal rate is increased, initially it induces decline in water level but eventually, if stress continues, the increasing groundwater pumping will begin reduce natural discharge of groundwater. This can be manifested by reduced stream leakage in the study area. In addition, it also can induce recharge from surface water bodies such as streams or reservoirs.

The steady state withdrawal rates were increased by 15%, 35%, 55%, 75% and 100% to study the response of the system in this scenario. These increased are equivalent to withdrawing 5384.1, 6320.4, 7256.8, 8193.15, and 8336.6 m³/day over the whole catchment respectively and the increased withdrawal rate distributed among the existing wells. Model simulated results of stream base flow and water table elevations in the scenarios were compared with the model calculated steady state results, and the difference showed the response of the system to the assumed scenarios.

Table 6.4 System response to increased groundwater withdrawal

Multiplier	Decreasing groundwater (m)			Decreasing stream leakage (%)
	Mean	Min	Max	
1.15	0.11	0	0.57	0.37
1.35	0.78	0.002	1.85	0.84
1.55	1.35	0.004	2.50	1.50
1.75	1.85	0.074	3.23	2.00
2.00	2.46	0.102	3.98	2.67

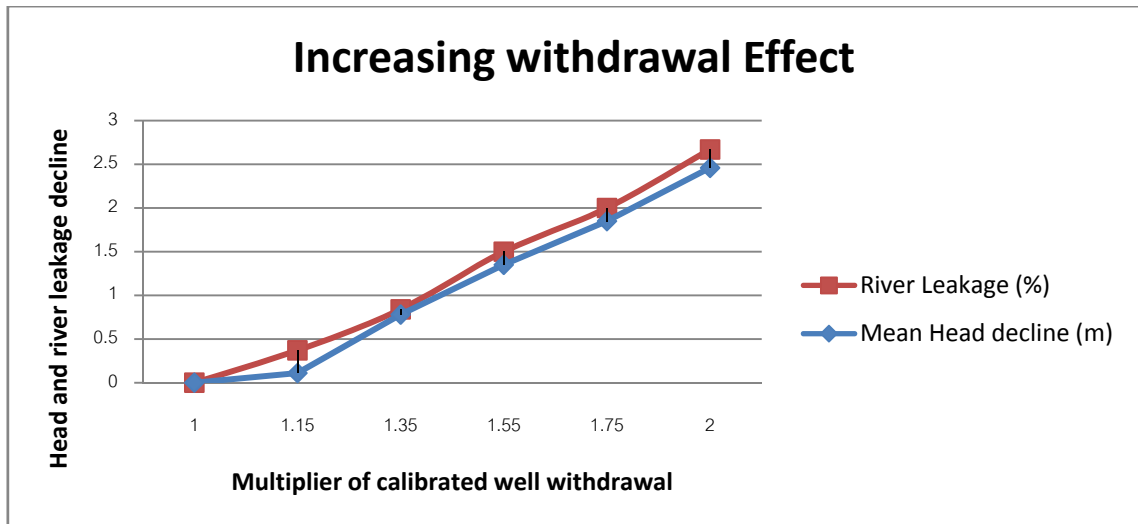


Figure 6.9 Trend of System response to increased groundwater withdrawal Rates

Thus, additional groundwater pumping would most likely result in decline of groundwater levels and reductions in natural discharge based on intensity of pumping. These observed changes simply represented regional effects of the proposed groundwater withdrawals. In fact, water levels in individual pumped wells likely lowered depending on local aquifer properties, well construction and well location relative to surface water bodies. Water level changes in individual wells can be exaggerated or dimensioned relative to the regional representation value. From the above five simulation results, one can observe that the development of a new groundwater sources would not pose appreciable impact in case of 15% and 35% withdrawal the head declines in this case is insignificant relative to the steady state withdrawal rate and the natural discharges were not altered highly.

In the second scenario, increased groundwater withdrawal in Gondar-Azezo town and its periphery well fields were simulated to see the effects on groundwater level changes and stream reaches. In this case the current withdrawal of the well field from active wells was increased to $-23409\text{m}^3/\text{day}$ for scenario test, which is about five fold increases. Here the additional withdrawal was assigned as a new hypothetical with various discharges in the Angereb, Keha, and Shinta well fields. The simulation result indicated that the stream leakage decreased by 7.9% relative to the whole steady state value, but showed 14.9% decrease for Angereb, Keha, and Shinta river segments near the well field area. The water tables decline by 3.57m to 18.81m in head observation in the well field area. The lower Angereb well field head decline is significant when compare with other near well fields.

Generally, if future water demand conditions force groundwater to be withdrawn at rates simulated in these scenarios, other parameters not changed, these will be hydrologic imbalance between groundwater inflow and outflow conditions that may cause pollutants to enter the groundwater system from polluted surface water sources. The effects of withdrawal on four well fields in decreasing order are as follows; Lower Angereb well field, Shinta well field, Upper Angereb well field and Keha well field.

6.7.2 Effects of Altered Recharge

This scenario simulates a case of decreasing recharge to aquifers that may result from lower than normal precipitation (environmental changes), expansion of agriculture, deforestation and town expansion. It is a real that changes in climatic condition from time to time are affecting precipitation amounts in the country adversely and are reducing recharge to groundwater as the main source of recharge is precipitation. Although difficult to quantify other factors assumed unchanged, the future decrease in recharge amount will be inevitable and rough estimates made above can be used to study system response.

Based on the decline of dry period base flow (1.0648%/ year; BCEOM, 1998), that may approximate maximum recharge decline roughly, a 30 years period was assumed to study the system response. There for in this scenario the simulated response of the system to decreased recharge was compared with the steady state simulated water levels and stream leakage, and the differences showed changes induced due to the decrease recharge. The steady state simulated recharge was decreased by 32% and the simulation results showed on average head decrease of 8.06m over the whole area; with the highest fall 32m in wells to north and a minimum of about 1m in wells to the south. In addition, the stream leakage, compared to the simulated steady state value and the changes was about 75.36%.

As it has been seen the decreasing of recharge has adverse effect on the groundwater table and stream leakage. So, solutions should be forwarded to tackle such environmental unfriendly problem. On this catchment there is one proposed dam that has been on going to be constructed. To provide ample amount of water to the dam, different remedial measures should be developed to increase the recharge of the catchment that flourishes water to the river. The most important measures that should be taken are decreasing the expansion of agriculture, afforestation, constructing soil and water conservation structures etc.

6.7.3 Effect of Dried Angereb Reservoir

The source water stored in Angereb reservoir is either from run off during precipitation or leakage from groundwater systems. In this numerical model simulation, the reservoir was considered as constant heads. Angereb reservoir is artificial surface water bodies constructed for domestic water supply purposes for Gondar town.

The maximum water demand of the town was estimated to be 346.8 l/sec. the analysis on the adequacy of the current source, if used throughout the year, could only satisfy the water demand of the town up to 2014 GC. And this holds true if and only if sediment flourishing is done as per the design and the watershed is treated with different conservation measures. These two important reasons indicate that the reservoir will dried if the people use excessively to satisfy the demand.

The reservoir has direct or indirect influences on groundwater of the area. Hence, this scenario is intended to test the response of the system in the absence of interaction of groundwater system with this surface water bodies. The simulation results showed an average reservoir peripheries area rise in ground water level by 0.901 m compared to the steady state simulated water level, with maximum value of 4.75 m in wells near the reservoir (observation well3, 800m from the reservoir). Leakage to rivers increased by 1.85% compared to the steady state simulated amount, which might be due to elevated groundwater relative to stream bottom elevation.

6.7.4 Effect of Development of Megech Reservoir

Ethiopian minister of water resource has proposed to construct a dam on Megech River. The designed dam is 76.5m high and 864m long. The total amount of water that will be stored in the reservoir is 182Mm³. The elevation of the dam is 1952m and the designed live storage elevation is 1947.1m. The total areal coverage of the reservoir is 2.55M m².

This reservoir is artificial surface water bodies constructed for the purpose of irrigation water and Gondar Water Supply and have direct and indirect influences on the groundwater of the area. Hence the Scenario is intended to test the response of the system in the presence of interaction of groundwater system with these surface water bodies. The simulation results showed an average rise in groundwater level by 0.38m compared to the steady state simulated water level, with maximum value of 5.042m in well near the Megech reservoir (observation

well 24, 1.8km from the reservoir). The influence of the reservoir with radius 2.6 km is greater than 1.25m from simulated water level.

Leakage to streams increased by 45 % compared to the steady state simulated amounts, which might be due to elevated groundwater level relative to the stream bottom elevation, dominantly at the reservoir and its periphery area. The leakage to Lake Tana decreases by 11.75% compared to the steady state simulated amounts that may be due to the increased leakage to the streams.

6.7.5 Effect of Irrigation Water on Megech Command Area

This scenario simulates in case of increasing recharges to the aquifer that result from irrigation water to the command area. The proposed Megech irrigation project will develop more than 14,600ha of irrigable land. The irrigation demand of the command area is 116M m³. The return flow from irrigation water is approximately 30% of the irrigated water (TAHAL, 2009). That means the total amount of return flow is 34.8M m³ or 0.238m/year or 0.0006525m/day.

There for in this scenario the simulated response of the system to the increasing recharge was compared with the steady state simulated water levels and stream leakages, and the difference showed changes induced due to the increasing recharge. The simulated recharges on the command area was increased by 0.238m/year and the simulated recharge showed an average head increase of 2.47m over the whole area with highest rise 7.28m in Koladiba well and minimum of 1.07m in the north at Angereb well field. Besides the stream leakage compared with the steady state value the change was about 47.78%.

In the second scenario, increased recharge (return flow of irrigated water) and development of Megech reservoir were simulated simultaneously to see the effects on groundwater level changes and stream leakage. In the simulation the response of the system was compared with the steady state simulated water levels and stream leakages. The differences showed the effect of development of Megech reservoir and irrigation on the groundwater. The simulated value showed an average 2.74m increased head over the whole area. High difference values were observed at Tseda (7.83m) and Koladiba (7.3m). The minimum difference 1.08m was recorded at Angereb well field (observation 94). In addition, the stream leakage compared with the steady state value the change was about 87.43%.

6.8 MODEL LIMITATION

Since model is a tool that represents an approximation of the real situation, there may be limitation associated with it. Numerical groundwater flow models are approximation of a natural system and have uncertainties. So it is important to any groundwater model to be interpreted. In this model some of the associated limitations are as follows:

- The system was represented as single layer, unconfined and steady state condition. Its transient condition was not known due to lack of long term monitoring well data. Its detail geologic condition is also not clearly known because of its complex geologic history specially the basalt part.
- Hydrologic and hydrogeologic input parameters used in this model were estimated by approximation of their field situation. Uncertainty was large due to spatial variability of parameters like hydraulic conductivity and recharge distribution. In this model hydraulic conductivity and recharge were represented as uniform in discrete mode over the large area.
- The model was calibrated with target wells mostly found at the north-south central axis of the catchment and recorded during construction time. So uncertainties are expected due to unevenly distribution and not well monitored wells.
- Calibration relies more on residual errors that matching the simulated and observed head distribution.

In general the model output should be interpreted and applied by considering all the above limitations and the modeler experience. Therefore, the results of simulations considered under different scenarios reflect the error or uncertainty in the model and the outputs are used as general guides to help understand how the system will respond to new stresses and should not be considered as exact prediction.

CHAPTER SEVEN

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The study area is found North Western plateau in the North Gondar zone, Amhara regional state. Its total surface area is 1887km². In the study area, the main source of domestic water supply of Gondar town was on the Angereb Dam. But today because of the increasing population and deterioration of Angereb reservoir due to sediment, the water supplier is in the processes of shifting to groundwater. Therefore the potential of groundwater should be assessed and managed using different hydrogeological investigation methods like flow model. In addition, there is a proposed irrigation site that should be evaluated its effect on groundwater.

The study area boundary was delineated from 90m Shutter Radar Terrain Mapping (SRTM) digital elevation model (DEM) using Global Mapper 8 software. This boundary was served as the divide line of groundwater flow while stream networks were used as internal drainage lines. Based on geologic information of the study area, unconfined subsurface flow condition was considered and simulated using MODFLOW 2000.

Input parameters like hydraulic conductivities and recharge rate of the area has been derived from previous studies integrated with the modeler's knowledge and its individual characteristics of the parameter.

The Megech river and groundwater withdrawal were simulated as river and well boundary respectively.

The model calibration accounts the matching of the 58 observation point with simulated head with a permissible residual head of ± 10 m. 75% of the difference (observed and measured water level) head in the study area is 5m. The model was calibrated with mean error 0.506, absolute mean error 4.431m and standard deviation 6.083m. The calibration was done by adjusting hydraulic conductivity, recharge, river conductance and aquifer thickness.

The sensitivity of the major parameters of the model was identified during calibration process. Based on the calibration process, the model is very sensitive in decreasing order change in recharge, hydraulic conductivity, and stream bed conductance respectively.

The numerical groundwater flow modeling is empowered with computation of water budget. The simulated out flow of the model is $205733827.88\text{m}^3/\text{year}$ which is nearly equal to simulated inflow with difference $7.9\text{m}^3/\text{year}$. The base flow simulated discharge holds 35.75% of the out flow. It also contributed as recharge in to the aquifer that accounts to 15.30% of the inflow. This share of base flow implies the discharge of the groundwater to the dominantly gaining streams and high interaction of surface and aquifer systems.

The study area catchment groundwater flows from the recharge area to discharge area following the morphology. The MODFLOW calculates the hydraulic head distribution of groundwater flow surface. The head distribution shows the groundwater surface follows the topographic contour and it coincides with surface water flow.

The main advantage of numerical ground water flow modeling is to customize the result for different scenario analysis.

Two scenarios of increased groundwater withdrawals have been conducted. In the first scenario, five increased withdrawals amounts were distributed among existing wells in proportion to the current contribution of each source to the daily withdrawal rate. The current withdrawal rate estimated under steady state simulation was $4681.8\text{m}^3/\text{day}$. Steady state withdrawal rates were increased by 15%, 35%, 55%, 75% and 100% to study the response of the system in this scenario. These increased are equivalent to withdrawing 5384.1, 6320.4, 7256.8, 8193.15, and $8336.6\text{m}^3/\text{day}$ over the whole catchment respectively. From the above five simulation results, one can observe that the development of a new groundwater sources would not pose appreciable impact in case of 15% and 35% withdrawal the head declines in this case is insignificant relative to the steady state withdrawal rate and the natural discharges were not altered highly.

In the second scenario, increased groundwater withdrawal in Gondar-Azezo town and its periphery well fields were simulated to see the effects on groundwater level changes and stream reaches. In this case the current withdrawal of the well field from active wells was

increased to $-23409\text{m}^3/\text{day}$ for scenario test, which is about five fold increases. Here the additional withdrawal was assigned as a new hypothetical with various discharges in the Angereb, Keha, and Shinta well fields. The simulation result indicated that the stream leakage decreased by 7.9% relative to the whole steady state value, but showed 14.9% decrease for Angereb, Keha, and Shinta river segments near the well field area. The water tables decline by 3.57m to 18.81m in head observation in the well field area. The lower Angereb well field head decline is significant when compare with other near well fields.

This scenario simulates a case of decreasing recharge to aquifers that may result from lower than normal precipitation (environmental changes), expansion of agriculture, deforestation and town expansion. In this scenario the simulated response of the system to decreased recharge was compared with the steady state simulated water levels and stream leakage, and the differences showed changes induced due to the decrease recharge. The steady state simulated recharge was decreased by 32% and the simulation results showed on average head decrease of 8.06m over the whole area; with the highest fall 32m in wells to north and a minimum of about 1m in wells to the south. In addition, the stream leakage, compared to the simulated steady state value and the changes was about 75.36%. As it has been seen the decreasing of recharge has adverse effect on the groundwater table and stream leakage. So, solutions should be forwarded to tackle such environmental unfriendly problem.

The Angereb reservoir has direct or indirect influences on groundwater of the area. Hence, this scenario is intended to test the response of the system in the absence of interaction of groundwater system with this surface water bodies. The simulation results showed an average reservoir peripheries area rise in ground water level by 0.901 m compared to the steady state simulated water level, with maximum value of 4.75 m in wells near the reservoir (observation well3, 800m from the reservoir). Leakage to rivers increased by 1.85% compared to the steady state simulated amount, which might be due to elevated groundwater relative to stream bottom elevation.

Megech reservoir is artificial surface water bodies that would be constructed for the purpose of irrigation water and Gondar Water Supply and have direct and indirect influences on the groundwater of the area. Hence the Scenario is intended to test the response of the system in the presence of interaction of groundwater system with these surface water bodies. The

simulation results showed an average rise in groundwater level by 0.38m compared to the steady state simulated water level, with maximum value of 5.042m in well near the Megech reservoir (observation well 24, 1.8km from the reservoir). The influence of the reservoir with radius 2.6 km is greater than 1.25m from simulated water level. Leakage to streams increased by 45 % compared to the steady state simulated amounts, which might be due to elevated groundwater level relative to the stream bottom elevation, dominantly at the reservoir and its periphery area. The leakage to Lake Tana decreases by 11.75% compared to the steady state simulated amounts that may be due to the increased leakage to the streams.

This scenario simulates in case of increasing recharges to the aquifer that result from irrigation water to the command area. The simulated recharges on the command area was increased by 0.238m/year and the simulated recharge showed an average head increase of 2.47m over the whole area with highest rise 7.28m in Koladiba well and minimum of 1.07m in the north at Angereb well field. Besides the stream leakage compared with the steady state the value was increased by 47.78%.

In the second scenario, increased recharge (return flow of irrigated water) and development of Megech reservoir were simulated simultaneously to see the effects on groundwater level changes and stream leakage. In the simulation the response of the system was compared with the steady state simulated water levels and stream leakages. The differences showed the effect of development of Megech reservoir and irrigation on the groundwater. The simulated value showed an average 2.74m increased head over the whole area. High difference values were observed at Tseda (7.83m) and Koladiba (7.3m). The minimum difference 1.08m was recorded at Angereb well field (observation 94). In addition, the stream leakage increased by 87.43%.

7.2 RECOMMENDATIONS

The general objective of the study is numerical simulation of the groundwater flow system of the Northern river catchment of Lake Tana to evaluate the response of the hydrogeologic system to different stress so that the resulting consequence on the system can be projected. The following recommendations were forwarded for groundwater management and further study.

- As it has been seen the decreasing of recharge has adverse effect on the groundwater table and stream leakage. So, solutions should be forwarded to tackle such environmental unfriendly problem. On this catchment there is one proposed dam that has been on going to be constructed. To provide ample amount of water to the dam, different remedial measures should be developed to increase the recharge of the catchment that flourishes water to the river. The most important measures that should be taken are decreasing the expansion of agriculture, afforestation, constructing soil and water conservation structures etc.
- According to the model on the proposed irrigation site, Megech plain, the depth of groundwater table will increase from 2.74 to 7.83m. So in this area the irrigation schemes should be low volume irrigation (Drip and Sprinkler) or well designed drainage system. If not water logging and/or accumulation of salts on plant root zone will be the major problem.
- Sufficient and evenly distributed groundwater level monitoring wells should be placed in the whole catchment in order to understand the general head pattern and fluctuations in groundwater levels. This helps to carry out better steady and transient groundwater flow modeling, so that system response can be predicted with better confidence.
- Detailed recharge estimates has to be carried out by combining different methodology like Soil water budget model and catchment water balance method to conduct detail model simulation. Because recharge is the most influential model input parameter in the area as seen in sensitivity and recharge scenario.
- The model still needs appropriate hydraulic conductivity map with better accuracy.
- To represent the system in a more realistic condition, it is important to divide the aquifer system in to different layers and estimates their respective hydraulic conductivity parameters.

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ANNEX I

Ground water withdrawal from pumping wells

Name of well	Easting	Northing	Yield (m ³ /day)
Old Angereb Well1	335026	1397495	76.32
Old Angereb Well2	334986	1397091	59.04
Old Angereb Well 3	335144	1395982	115.2
Old Angereb Well 4	335236	1395580	57.6
Old Angereb Well 5	334934	1396639	144
Old Angereb Well 6	335160	1398499	77.76
Old Angereb Well 7	334673	1393121	864
Azezo meat fac.	330210	1390487	28.8
Gondar China 1	332300	1394139	62.208
Gondar China 2	332461	1394631	33.696
Gondar China 4	332597	1394758	133.632
Gondar Yugoslav	332240	1394903	74.304
Gondar Shinta 1	329765	1392082	70.56
Gondar Shinta 2	330279	1391160	201.6
Gondar Shinta 3	329980	1391691	86.4
Fuel dipo well	332100	1393853	28.8
EWCA well	335045	1396219	86.4
Azezo well 1	330093	1382102	112.32
Azezo well 2	329624	1381671	190.08
Azezo well 3	330858	1382914	117.792
Azezo well 6	330233	1390128	129.6
New Angereb Well	333182	1391108	57.6
New Wngereb Well 2	333656	1391730	184.32
New Angereb Well 3	333945	1391982	184.32
New Angerb Well 4	334090	1392433	219.744
New Angereb Well 5	334581	1392865	438.624
New Angereb Well 6	334785	1393410	48.096
Test well 1	328605	1383715	288
Test well 2	329204	1384103	288
Test well 4	328216	1383638	259.2

ANNEX III

Observe Vs Simulated Water Level.

Well ID	Site Name	OBS points	Easting	Northing	Calculated	Observed	Obs- Calc	/Obs- Calc ² /n
	Old Angereb							
OAW1	Well1	Obs2	335026	1397495	2174.905	2177.5	2.595	2.595
OAW3	Old Angereb3	Obs3	335144	1395982	2155.965	2143.95	-12.015	12.015
AZMF	Azezo meat fac.	Obs8	330210	1390487	2078.669	2075	-3.669	3.669
GC1	Gondar China 1	Obs9	332300	1394139	2088.097	2103.8	15.703	15.703
GS2	Gondar Shinta 2	Obs14	330279	1391160	2071.444	2083.33	11.886	11.886
GS3	Gondar Shinta 3	Obs15	329980	1391691	2103.276	2092	-11.276	11.276
FDW	Fuel dipo well	Obs16	332100	1393853	2090.055	2100	9.945	9.945
EWWCA	EWWCA well	Obs17	335045	1396219	2158.185	2145.5	-12.685	12.685
AZW7	Azezo well 7	Obs19	330725	1386589	1977.186	1975	-2.186	2.186
DW1	Dashen Well 1	Obs21	328575	1383748	1938.603	1945.4	6.797	6.797
DW2	Dashen Well2	Obs22	329198	1384107	1941.821	1948.3	6.479	6.479
DW2	Dashen Well2	Obs23	328246	1383668	1941.566	1944.6	3.034	3.034
CAW	Civilavation well	Obs24	330525	1384050	1939.189	1948.75	9.561	9.561
DDW2	Guramba	Obs26	320755	1365764	1789.701	1792.35	2.649	2.649
DDW6	Kurtit	Obs29	323991	1358237	1785.366	1782.56	-2.806	2.806
DDW7	Guramba	Obs30	319915	1364043	1788.825	1790.15	1.325	1.325
DDW8	Seraba	Obs31	316631	1361911	1787.672	1784.25	-3.422	3.422
DDW9	Mahal Woinit	Obs32	316486	1361878	1787.66	1787.5	-0.16	0.16
DDW11	Mahal Woinit	Obs33	316557	1362100	1787.781	1787	-0.781	0.781
DDW12	Mahal Woinit	Obs34	316584	1362812	1788.182	1787.5	-0.682	0.682
DDW13	Jankura	Obs35	325468	1364643	1788.938	1787.6	-1.338	1.338
DDW14	Jankura	Obs36	326065	1365996	1789.837	1789.8	-0.037	0.037
DDW17	Seraba	Obs38	318727	1362359	1787.872	1783.2	-4.672	4.672
DDW18	Guramba	Obs43	319187	1366397	1790.063	1795.7	5.637	5.637
DDW18	Guramba	Obs44	318942	1366156	1789.961	1790.6	0.639	0.639
DDW21	Guramba	Obs45	318724	1365841	1789.812	1788.4	-1.412	1.412
DDW26	Seraba	Obs48	316680	1363016	1788.295	1789.5	1.205	1.205
DDW27	Seraba	Obs49	316680	1365142	1787.9	1786	-1.9	1.9
DDW28	Seraba	Obs50	316572	1362087	1787.774	1785.2	-2.574	2.574
DDW29	Seraba	Obs51	316715	1362241	1787.856	1784	-3.856	3.856
DDW30	Seraba	Obs52	317573	1361700	1787.515	1784.5	-3.015	3.015
DDW31	Seraba	Obs53	317606	1361503	1787.411	1785.1	-2.311	2.311

Hospital Well	332355	1394468	188.5
Dashen Well 1	328575	1383748	223.5
Dashen Well2	328246	1383668	235.54
Koladiba3	318630	1373350	316.5
Maksegnet	343951	1365765	201.6
Gorgora	313614	1361132	99.56

DDW32	Seraba	Obs54	318460	1361914	1787.616	1785.7	-1.916	1.916
DDW34	Seraba	Obs56	318738	1360587	1786.807	1781	-5.807	5.807
DDW35	Seraba	Obs57	318803	1364407	1789.072	1791.1	2.028	2.028
DDW36	Guramba	Obs58	318603	1364591	1789.14	1790.3	1.16	1.16
DDW37	Seraba	Obs59	318955	1363020	1788.252	1789	0.748	0.748
DDW38	Seraba	Obs60	318884	1362802	1788.127	1784.7	-3.427	3.427
DDW39	Seraba	Obs61	319328	1362450	1787.919	1786.4	-1.519	1.519
DDW40	Achera	Obs62	320622	1361137	1787.099	1789.8	2.701	2.701
DDW42	Achera	Obs63	321356	1359788	1786.275	1785	-1.275	1.275
DDW43	Adisgie	Obs66	322817	1361132	1786.828	1788	1.172	1.172
DDW44	Adisgie	Obs64	322745	1361132	1787.057	1790	2.943	2.943
DDW46	Adisgie	Obs65	324513	1361132	1786.181	1788.4	2.219	2.219
KD	Kolladiba	Obs91	318630	1361132	1828.182	1829	0.818	0.818
Mak	Maksegnit	Obs93	343951	1361132	1886.775	1885.6	-1.175	1.175
	New Angereb							
NAW1	Well	Obs94	333182	1361132	2026.449	2008.2	-18.249	18.249
	New Wngereb							
NAW2	Well 2	Obs95	333656	1361132	2013.988	2027.25	13.262	13.262
	New Angerb							
NAW4	Well	Obs97	334090	1361132	2012.881	2011.04	-1.841	1.841
	New Angereb							
NAW7	Well7	Obs100	333184	1361132	2028.486	2032.5	4.014	4.014
	Test well							
TW1	1	Obs101	328605	1361132	1938.775	1943.8	5.025	5.025
	Test well							
7W2	2	Obs102	329204	1361132	1941.849	1947.6	5.751	5.751
	Test well							
TW3	3	Obs103	330914	1361132	1974.789	1970.9	-3.889	3.889
	Test well							
TW4	4	Obs104	328216	1361132	1940.998	1946.3	5.302	5.302
	Test well							
TW5	5	Obs105	334274	1361132	2035.651	2046.3	10.649	10.649
GOR	Gorgora	Obs107	313614	1361132	1786.525	1789.5	2.975	2.975
							0.505839	4.430661