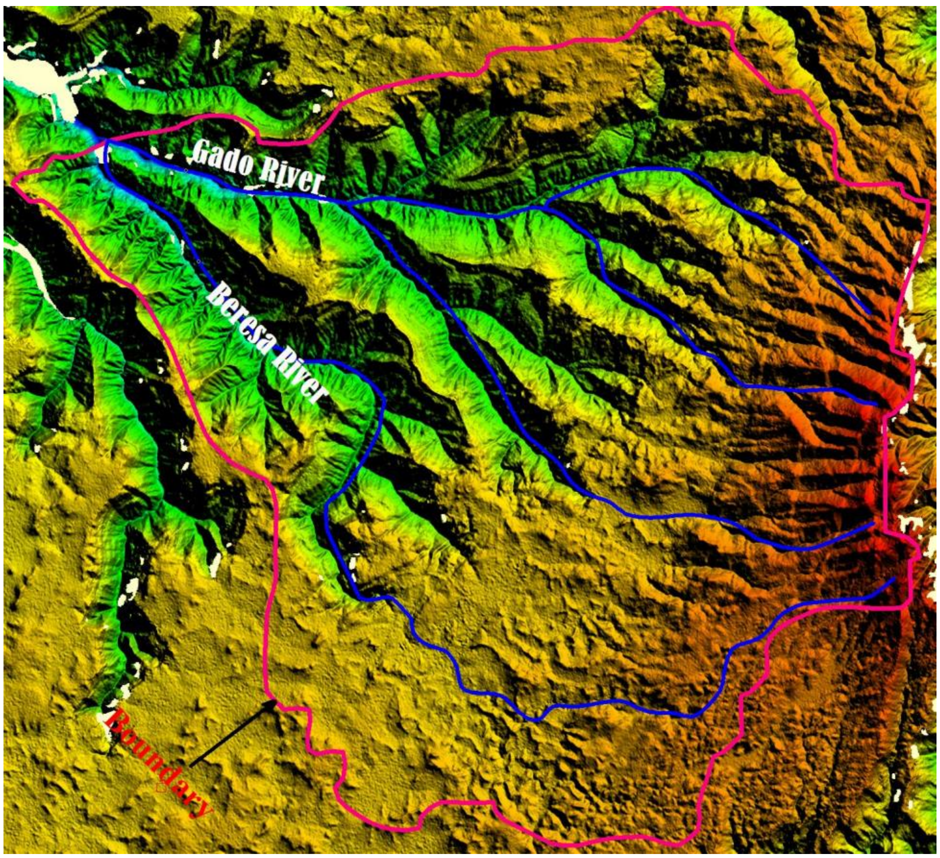
NUMERICAL GROUNDWATER FLOW MODELING OF BERESA AND GADO RIVERS CATCHMENT, DEBRE-BIRHAN AREA, NORTH SHOA ZONE, AMHARA REGIONAL STATE



Tadesse Shewakena

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

February, 2013

Addis Ababa

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By: - Tadesse Shewakena

Advisor: - Tenalem Ayenew (Prof.)

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Addis Ababa University School of Graduate Studies Faculty of Science Department of Earth Sciences

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Approved by the Board of Examiners:

Chairman ___________________________________

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Examiners ___________________________________

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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.

Tadesse Shewakena Weldemelak

School of Graduate Studies (AAU)

February, 2013

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

Tenalem Ayenew (Prof.)

Addis Ababa University

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ABSTRACT

The study area is found in Amhara regional state at the Beresa and Gado rivers catchment. Its total surface area coverage is 1062.2km^2. This research is conducted with the objective of to simulate the groundwater flow system of the area and to evaluate the response of the hydrogeologic system to different stress, so that the resulting consequence on the system can be estimated. Input parameters such as hydraulic conductivity, recharge, and discharges were obtained from previous works. Based on geologic information of the study area, unconfined subsurface flow condition was considered and simulated using MODFLOW-2000. The area is characterized by Tertiary volcanic rocks and Quaternary superficial deposits. Tertiary volcanic rocks are mainly exposed on the plateau and along the NE-SW trending rift margin. Quaternary superficial deposits are mostly found on the plateau covering flat lying and gentle topography. The simulation is made in a one layer, unconfined aquifer with spatially variable recharge and hydraulic conductivity under well-defined boundary condition in a model grid design of 200 rows and 220 columns. The model calibration accounts the matching of the 19 observation point with simulated head of a permissible residual head of ±10m and 100% of the difference between the observed and calculated water level head of the study area is below 10m. The model was calibrated with variance of 14.95, mean error -0.88, absolute mean error 3.25, and root mean square value of 3.93, which is an indicator of good calibration. The calibrated model is used to forecast the groundwater flow pattern, and evaluate the behavior of the groundwater system under possible future utilization scenarios. The sensitivity of the major parameters of the model was identified during calibration process. Based on calibration process, the model is very sensitive in both changes in recharge and hydraulic conductivity and less sensitive to river bed conductance. The simulated water budget has been computed for the study area. The simulated inflow of the model is 1.3466171E+06m^3/day which is nearly equal to simulated outflow 1.3465134E+06m^3/day with difference 1.0364551E+02m^3/day and 0.01% of error. The river leakage simulated discharge holds 94.3% of the out flow. It also contributed as recharge in to the aquifer that accounts to 54.98% of the inflow. This share of river leakage implies the recharge of the groundwater dominantly from the losing streams. The simulation result indicates that the groundwater flows from the recharge area to discharge area following the morphology of the area.

1. Introduction

1.1. Background

Groundwater is the safest and economical water source used in the water supply. However, the demand for groundwater, in terms of both quantity and quality has increased rapidly, not only for drinking water source, but also industrial and agricultural uses. In addition to these, the recently ever-growing groundwater utilization associated with rapid population growth, industrial water demand and the trends in expanding future proposed projects demanded detailed hydrogeological studies that will assist in the development and the management of groundwater resources.

The present study area is located in Jemma drainage basin of the Beresa and Gado rivers catchment around Debre-birhan area. The main objective of the study is numerical simulation of the groundwater flow system of the area to evaluate the response of the hydrogeologic system to different stress so that the resulting consequence on the system can be estimated.

The above generalization is true for the Beresa and Gado rivers catchment as the zonal town Debrebirhan and other small towns in this area are expanding in alarming rate. To meet the increasing demand of pure and adequate water in the area, few investigation works were carried out to use groundwater for water supply.

In order to utilize the groundwater safely more study should be done in the area, it includes understanding of the spatial and temporal groundwater distribution, surface water and groundwater interactions, the mechanisms and rate of recharge. This needs understanding of the various hydrological processes and their relation with the geological environment. Therefore, developing predictive groundwater flow models for sustainable groundwater use and management is very important.

Numerical Groundwater flow modeling is a tool used to analyze the effects of different water abstractions and asses the dynamics of hydrological system. A groundwater modeling can be used to examine effects from pumping on water levels, spring flows, and directions of groundwater flow. These effects can affect water availability and the movement of contaminants. It can be also a valuable tool for managing the groundwater resources and addressing complex socioeconomic and political issues resulting from conflict water uses.

This study will provide more detailed result that can readily be used for groundwater development and management that will lead to sustainable and environmentally sound groundwater utilization practises.

1.2. Importance of the Study

This research work provides basic information on the groundwater flow direction and the response of the hydrogeologic system to different stress. It can be also used to examine effects of pumping on water levels, spring flows, and directions of groundwater flow. Some of the applications of the results are:

- Characterization of heterogeneous hydrogeological systems plays an important role in groundwater protection and proper utilization. In such cases, numerical groundwater flow modeling techniques can provide a better characterization of such complex hydrogeological systems.
- Based on the model output, it is possible to know how to allocate and use the groundwater by applying management of a groundwater system in which decision will be made with respect to water use. Thus a tool like groundwater modeling is needed to provide information for the decision maker about the future response of the system to the different stresses.
- The towns and rural villages within the study area, especially Debrebirhan town can use this result to manage the groundwater development, use and the movement of contaminants.
- This work can also used as one input for other researcher, who wants to work on the area of groundwater potentials, development and any other related works, can use this result as a reference.

1.3. Objectives

The General Objectives

- The numerical simulation of the groundwater flow system of the area to evaluate the response of the hydrogeologic system to different stress so that the resulting consequence on the system can be estimated.

Specific Objectives

- Constructing conceptual map of the aquifer parameters and the hydrological condition of the study area
- Construct a model to show the natural steady state head distribution and flow direction of the area.
- Identifying the most sensitive parameter of the hydrogeologic system.
- Evaluate the effects of pumping or increased groundwater withdrawals on the study area.
- Evaluate the effects of changed recharge on the study area.
- To calculate the water budget of the area in steady state condition.

1.4. Approach and Methodology

1.4.1. Materials Used

- The 1: 50,000 scale topographic map
- Satellite image (LANDSAT) and Digital elevation model /DEM/ 30m resolution.
- Geological map Debre-birhan area 1: 250,000 scale and hydrogeological maps of Ethiopia.
- Various computer software /MODFLOW-2000, Arcgis-9.3, Erdas9.2, Global maper8, Sufer8, Spreadsheet…/
- Deep meter
- GPS
- Previous research works, study reports, reference books, and journals

1.4.2. Data Collection

Office work

- Collecting and reviewing of modeling books, previous works, water well inventory reports, and well completion reports from different organization
- Collecting and reviewing of topographic map, geological map, hydrogeological map, Digital Elevation Model (DEM), meteorological data, hydrological data and others

- Preliminary data interpretation using remote sensing and GIS techniques
- Preparation of different maps and data analysis using different software

Field work

- Observing, identifying, and examining of different geological outcrops, and soil types in the study area.
- Visual observation of geological structures and inferred structures.
- Observing land use and land cover types.
- Measuring of rivers width, depth and water level at representative site
- Measuring the water level on representative wells.
- Cross checking the secondary data and updating existing information.

1.4.3. Procedures of Data Analysis

Once it has been collected all the required data from the field and different sources, it is necessary to bring those data in to model design, and then following relatively a well-defined series of steps for applying groundwater model. 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).

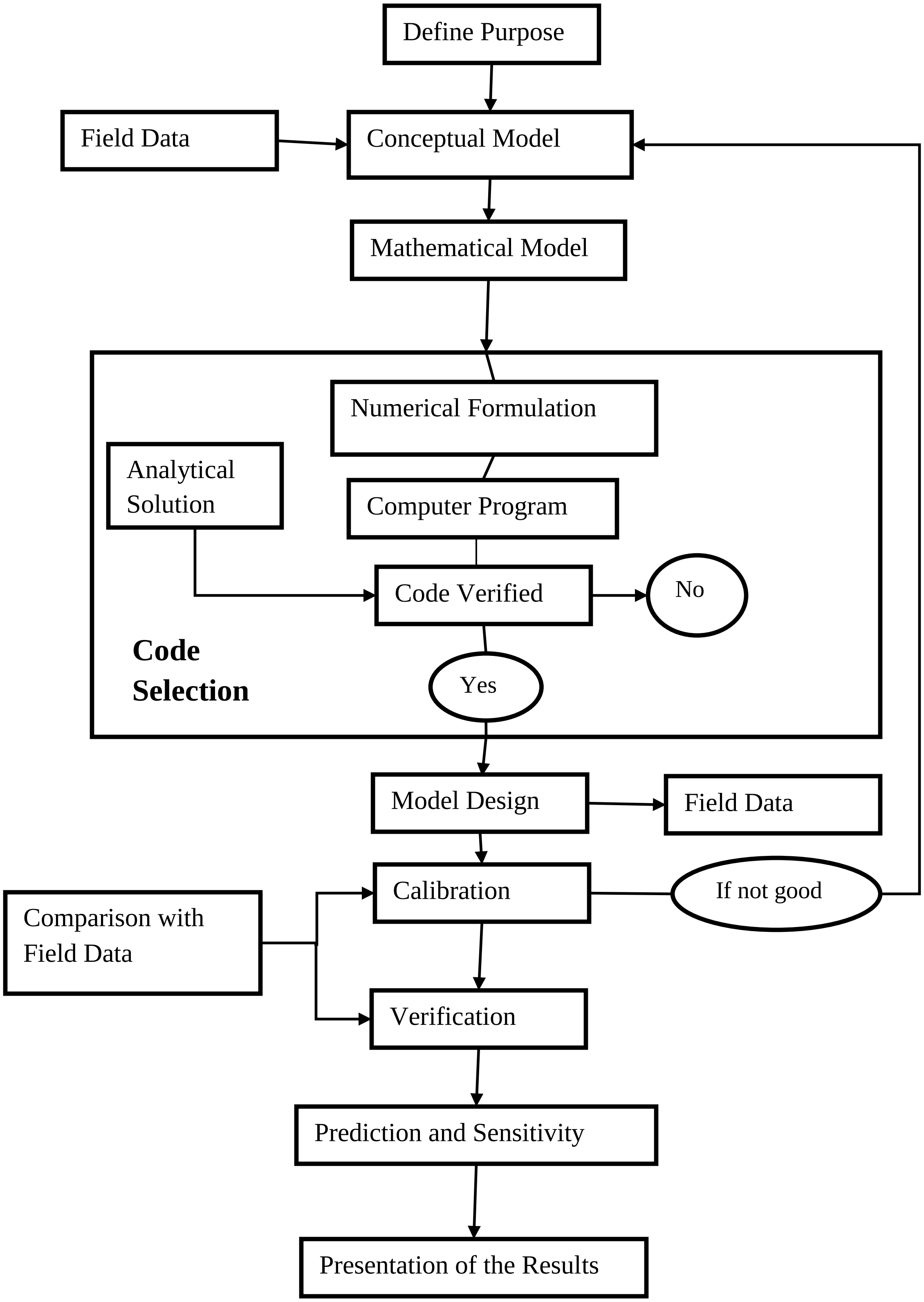

Figure 1.1 Model application process (Anderson and Woessner, 1992)

2. General Overview of the Area

2.1. Location and Accessibility

The study area is situated in the North Shoa zones of Amhara National Regional States. It is about 130 km far from Addis Ababa. It is located on the central parts of North western Ethiopian plateau and southeastern parts of the Jemma river basin. Its eastern part is bounded by the rift margin.

Geographically, the area is found between UTM coordinate of 1058000N-1098000N and 538000E-582000E, and it approximately covers an area of 1062.2 sq. km (Figure 2.1). The altitude of the area ranges from 1750 to 3600 m.a.s.l, in deeply dissected valleys of Beresa river and in the mountain ranges respectively. The study area can be accessed by a number of all-weather and dry weather gravel roads. The Addis Ababa-Debre Birhan-Tarmaber road is the main asphalted road that runs through the area.

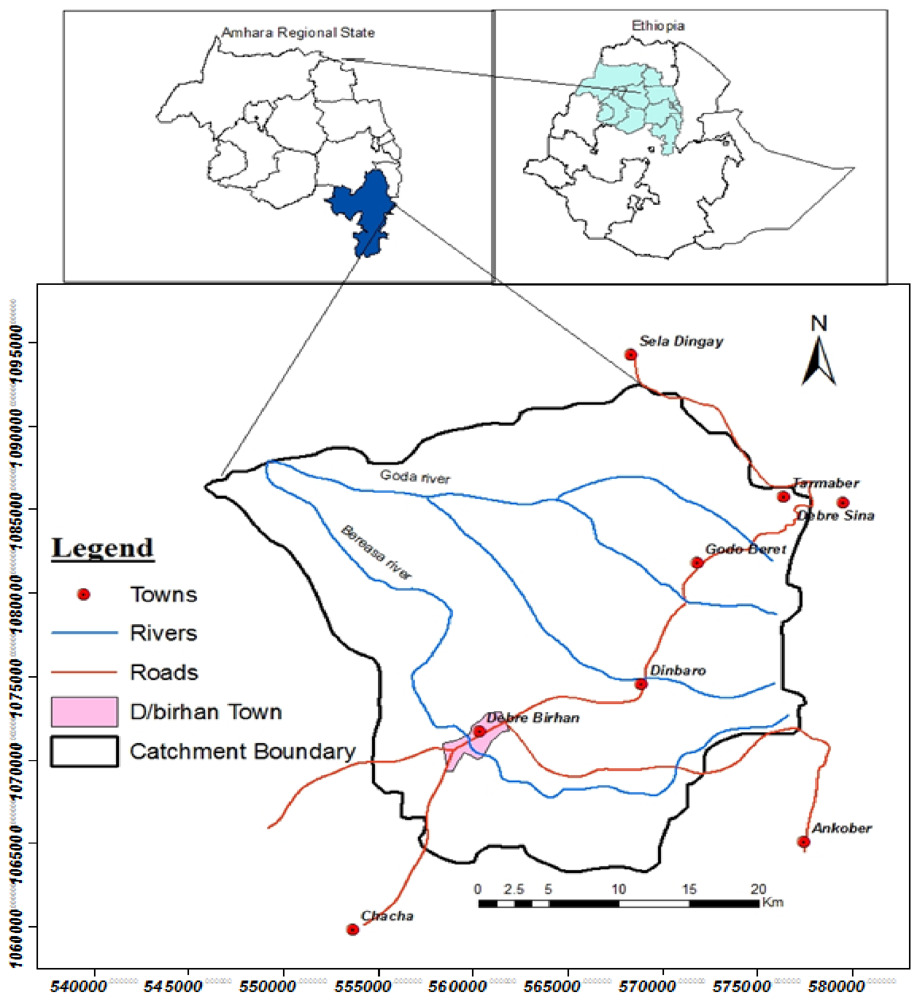

Figure 2.1: Location map of the Beresa and Gado rivers catchment

2.2. Physiography and Drainage

2.2.1. Physiography

The study area is found in the central parts of north western Ethiopia plateau and western most part of the rift margin. The morphology of the area is divided into two physiographic divisions: (1) Plateau, (2) Escarpment

Plateau

The plateau covers the central part of the area that includes Debre Birhan, Dinbaro and Sela Dingay localities. It is largely characterized by flat lying topography (up lifted up to 2800 m.a.s.l.) with some undulating ridge chains and deeply dissected valleys in the downstream of the plateau. The flat lying topography is mostly represented by the Tertiary basalts and Quaternary sediments with sporadic small hills formed by trachyte and erosion remnant of ignimbrites. The undulating ridges are represented by Tarmaber basalts. The deeply dissected valleys located at the northwestern parts of the area are represented by Beresa and Gado rivers and its tributaries.

Escarpment

The escarpment is located in the eastern parts of the area which is the rift margin and It starts from the Seladigaye-Tarmaber and passes through southeast of Dinbaro and Debere Birhan towns. It reaches up to 3600 m.a.s.l in the mountainous area.

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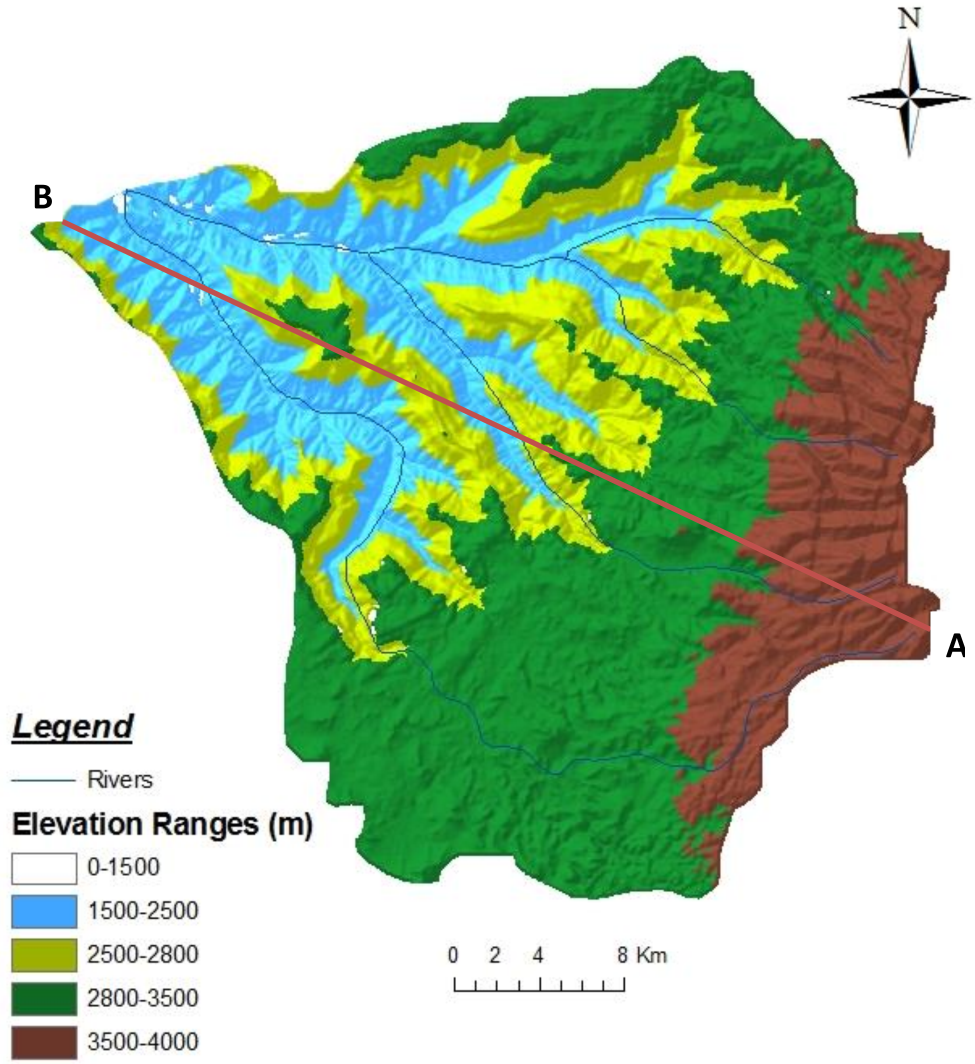

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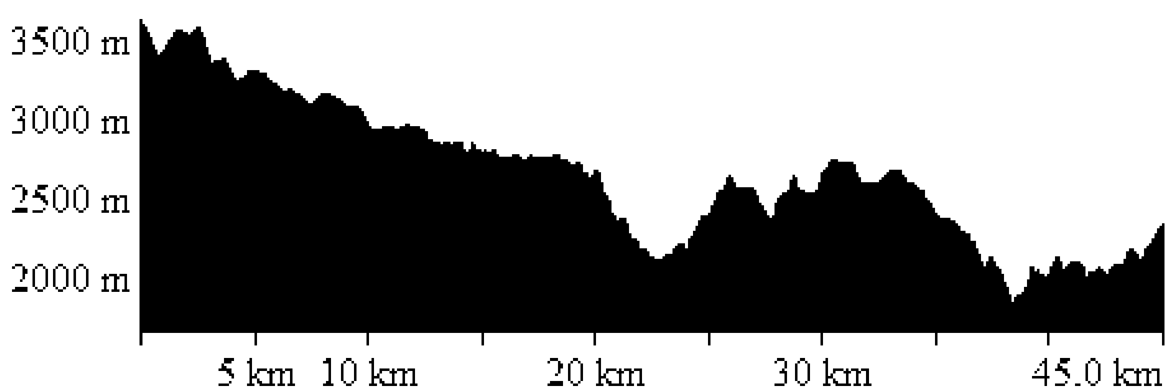

Figure 2.2 (a).Digital Elevation Model and (b).East-West Vertical Profile of the area (A-B)

2.2.2. Drainage

The area is highly drained and dissected by well-developed rivers and matured streams which form the Jemma drainage basin. Streams and rivers in the area starts from the eastern part of the plateau and escarpment drained from east to west towards Jemma river. The stream includes intermittent (Derk Wenz,) and perennial (Gado, Gedemsa, Legeyida, Dalecha and Beresa) rivers. The streams and rivers form sub parallel to dendritic drainage patterns (Figure 2.3).

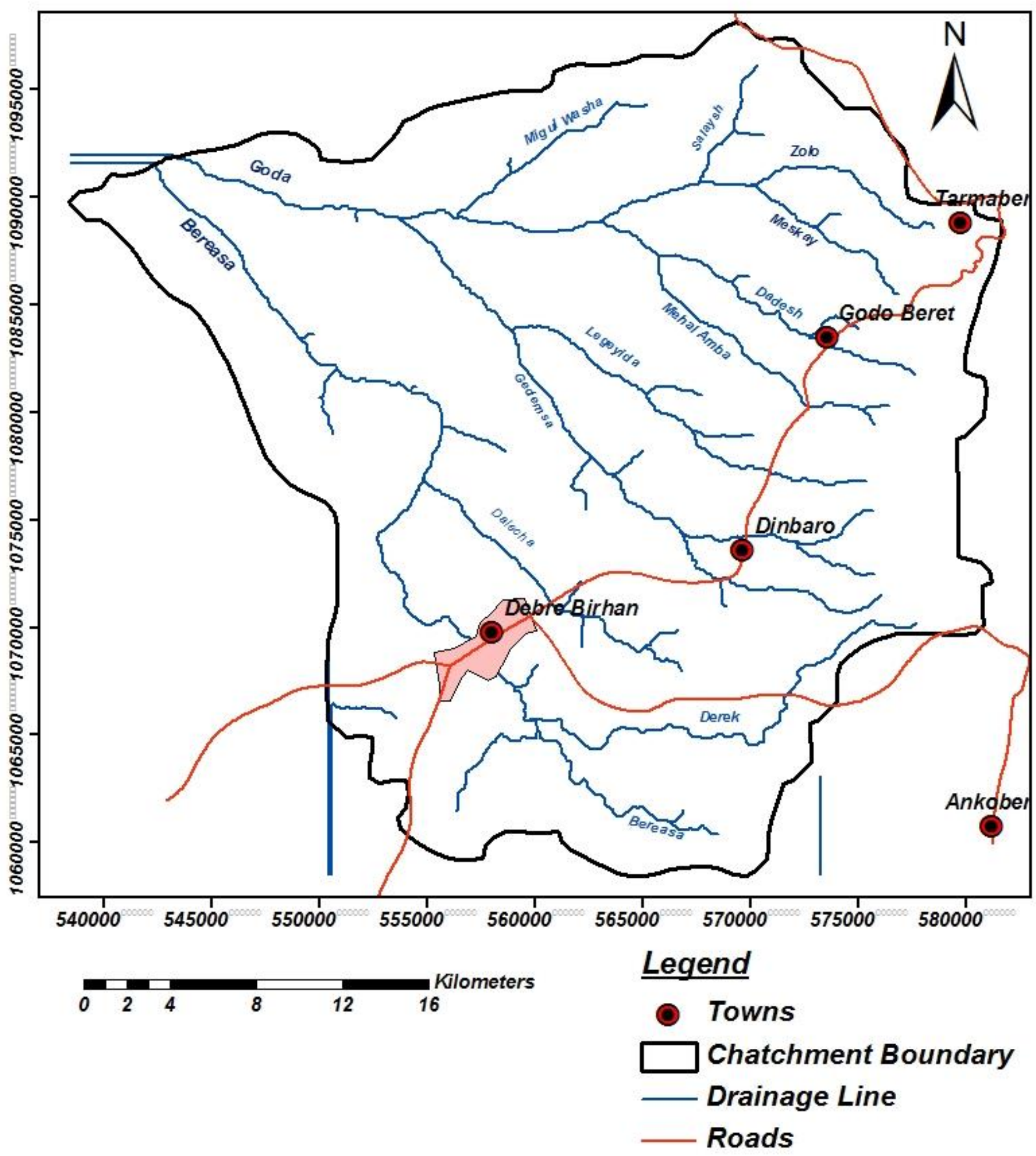

Figure 2.3 Drainage map of the Beresa and Gado rivers catchment

2.3. Climate

The climate of the area is mostly dependent on altitude. The area is mainly characterized by a wet temperate climate in which the main rainy season passes from July to September. Based on long term observations made by the Debre Birhan station (1987-2008), the mean maximum annual temperature, the mean minimum annual temperature, and the mean annual rain fall of the area is 19.7 °C, 6.2 °C and 886.44 mm respectively.

According to Tamiru Alemayeu (2006) classification of climate based on altitude and temperature the climate of the area ranges from cool/kur/ to temperate/Weina Dega/climatic zones.

2.4. Soil

The soil type of the area is mostly eluvium soil or soils that are derived by in-situ weathering or weathering plus gravitational movement and accumulation. It is formed by the gradual weathering of the basalt, ignimbrite and rhyolite. There are rock fragments of basalt, ignimbrite and rhyolite within the soil. It is silt to clay sized, light/dark gray to reddish brown fertile soil. It is highly ploughed by the local people.

According to the soil map obtained from the Ministry of Agriculture, the area is covered by five soil types (Fig. 2.4).

Eutric leptosols cover most of the eastern plateau and highlands in the area. Eutric leptosols are very weakly developed soils in unconsolidated materials. They are extensive in eroding lands.

Eutric Vertisols occupy the plateau in the northern parts of the study area. Vertisols are found in regions of high temperature, where bacteria destroy organic residues. Therefore the humus content is low. Alternate wet and dry seasons lead to the alternate swelling and shrinking of these soils.

Vertic Cambisols cover in the southern part of the area.

Lithic Leptosols cover the central and western parts of area. This soil type is the most abundant type of soil in the area. Lithosols are soils of a humid climate in which soluble salts and minerals are leached out of the upper layers and are cemented or compacted at lower levels. They are shallow, consisting of imperfectly weathered rock fragments limiting their agriculture capability.

Eutric Cambisols exist in northeastern parts of the plateau. Cambisols are soils with a characteristic lack of horizon development or accumulation of humus, clay or soluble salts.

Because of their favorable aggregate structure and high content of weatherable minerals, they usually can be exploited for agriculture subject to the limitation of terrain and climate.

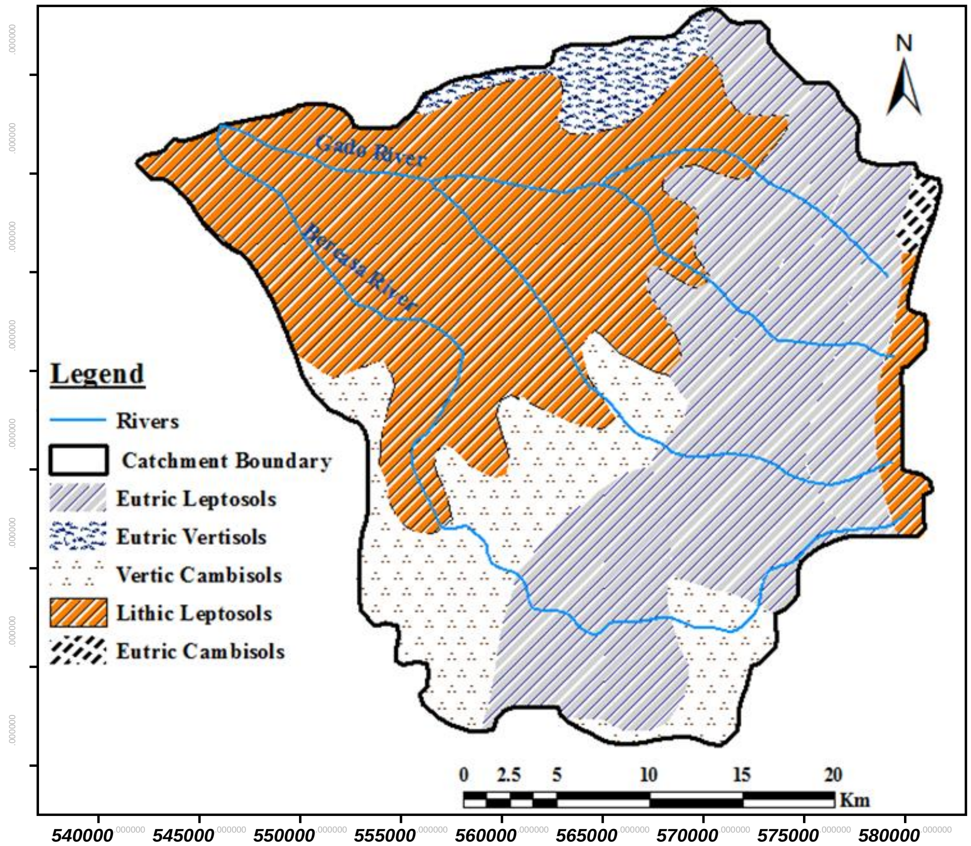

Fig- 2.4 Soil map of the Beresa and Gado rivers catchment (Source FAO, 1998)

2.5. Land Use and Land Cover

The land use and the land cover of the area is mostly controlled by climatic factors, landscape, land use practice and agricultural activities of the area. The elevated and plateau area dominantly covered by eucalyptus trees, small shrubs and many undifferentiated ever green plants. Dense eucalyptus trees are found at highly elevated areas in the eastern parts of the study area. There are usually also eucalyptus trees amongst the houses rendering the villages virtually study area. The most of the gentle slops and the plateau lands are mostly cultivated. Steeper slopes are usually used for grazing where the soil cover is often heavily degraded. Forests occupy only a very small area. Settlements are dispersed throughout the area. Apart from Debre Birhan and a few larger centers along asphalted and other all-weather roads, the villages consist of a lower number of small houses often with thatched roofs.

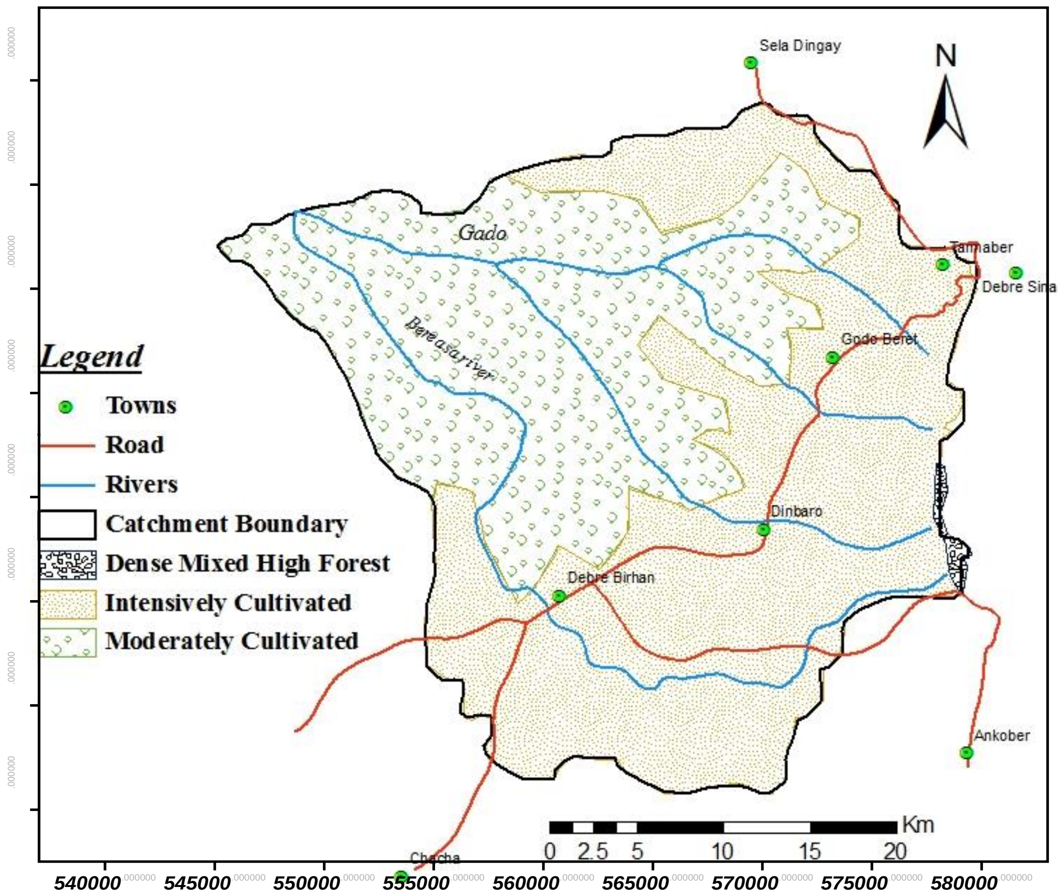

Figure 2.5 Land use and land cover map the Beresa and Gado rivers catchment (source FAO, 1998)

2.6. Hydro-Meteorological Setting

2.6.1. Precipitation

The area is characterized by three distinct seasons, and bimodal precipitation patterns with small peaks in April and the main rainy season during mid-June to mid-September with peaks in July. The three distinct seasons locally known as Bega (October to January), Belg (February to May) and Kiremt (June to September). The maximum volume of precipitation is observed during Kiremt when the area receives 90% of the annual rainfall.

Form the monthly rainfall data the monthly peak rainfall is 432.6mm and the maximum mean rainfall is 302.46mm/month in July at Debrebirhan station. There are six metrological stations within and around the research area. The mean annual rainfall ranges from 882.93mm/year recorded at Chacha station to 1852.07mm/year at Debresin station. (Table2.1)

Table 2. 1 Metrological stations within and around the study area

No	Stations	Location (UTM)			Annual Rainfall(mm)	Recording periods(years)
		Northing	Easting	Elevation		
1	Debrebirhan	556250	1068300	2780	886.44	1987-2008
2	Chacha	549500	1053650	2770	882.93	1987-2005
3	Debresina	586139	1086890	2680	1852.07	1987-2008
4	Gudoberet	574500	1083300	3100	1117.82	1988-2008
5	Ankober	580400	1060400	2970	1786.20	1974-2008
6	Seladingay	570450	1092920	2850	1081.01	1982-2006

Table 2.2 Mean monthly distribution of RF (mm) within and around the study area (1974-2008)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debrebirhan	11.60	20.55	43.00	54.97	36.44	52.41	302.46	270.28	82.45	18.75	6.69	4.93
Chacha	10.38	13.42	32.76	36.66	24.91	56.38	281.34	296.61	97.29	24.69	5.41	3.08
Debresina	65.73	55.26	120.95	159.10	92.13	69.87	366.69	431.42	202.93	116.95	98.24	72.82
Gudoberet	19.98	19.38	39.06	48.05	39.41	75.64	348.84	318.23	127.78	50.29	23.33	7.83
Ankober	82.26	55.26	167.92	164.06	88.04	86.16	350.51	385.28	181.36	109.49	62.99	52.84
Seladingay	11.80	17.27	46.82	51.93	47.41	54.73	339.84	341.53	117.40	28.38	13.27	10.66

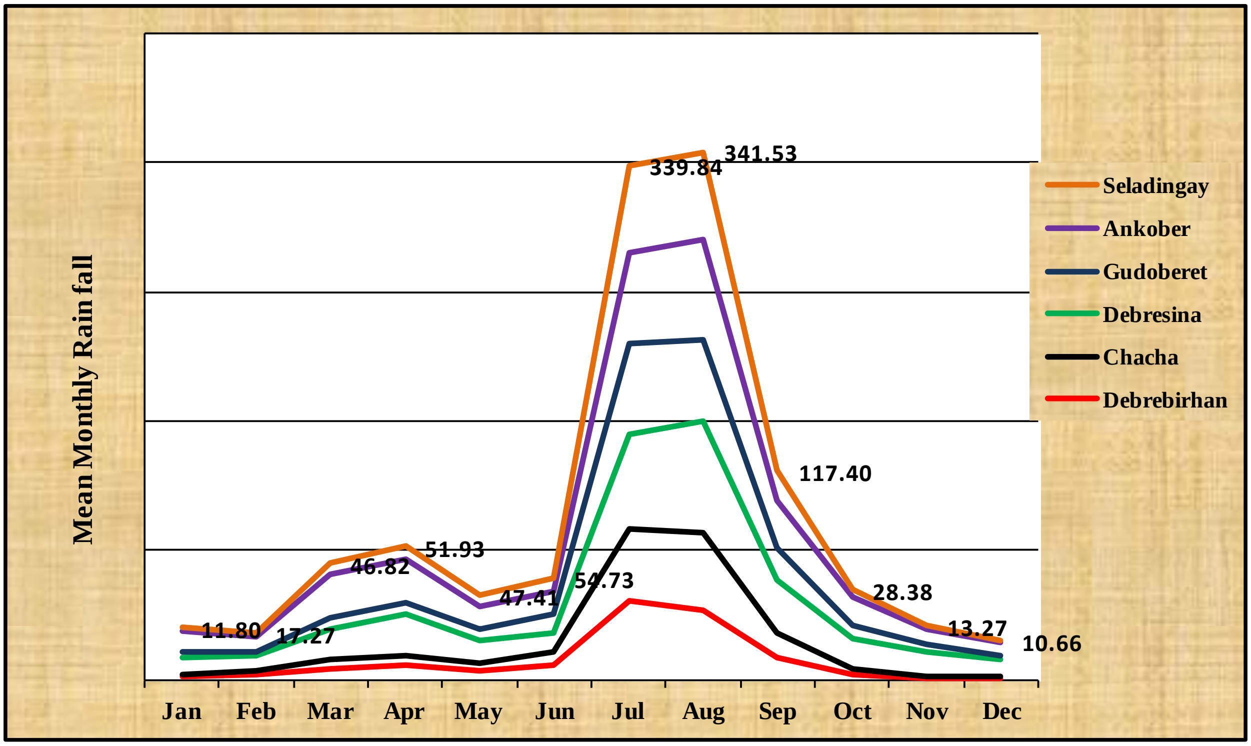

Figure 2.6 Mean monthly distribution of rain falls within and around the study area at six stations.

2.6.2. River discharges

There are perennial and intermittent rivers draining the study area. Some of the river discharges are monitored by river gauging stations with in and nearby the study area. The stations flow recorded data on the Beresa river near the Debre-birhan town and on the Chacha river near Chacha town are used for comparison of runoff characteristics.

The flow measurements or the gauging stations on the rivers are located on the plateau. It can provide enough data on surface flow and base flow on the plateau and can be used for characterization of aquifers outcropping.

The flow records from the stations reflect the fact that the river discharge is directly proportional to the intensity of rainfall within the water shade. There is a high discharge fluctuation between wet and dry seasons of the year. The highest flow period is from June to October and peak flow for all rivers is usually recorded in August (Kiremt rainy season). Discharge data also shows a small increase of flow during small rainy season (Belg) in the period from March to May.

Table 2.3 Mean Monthly Discharges of Beresa River

Years(1962-2008)	Average Discharges(m3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Measured Values	1.26	1.39	1.47	1.54	1.69	1.68	11.91	26.98	7.58	1.98	1.27	1.13

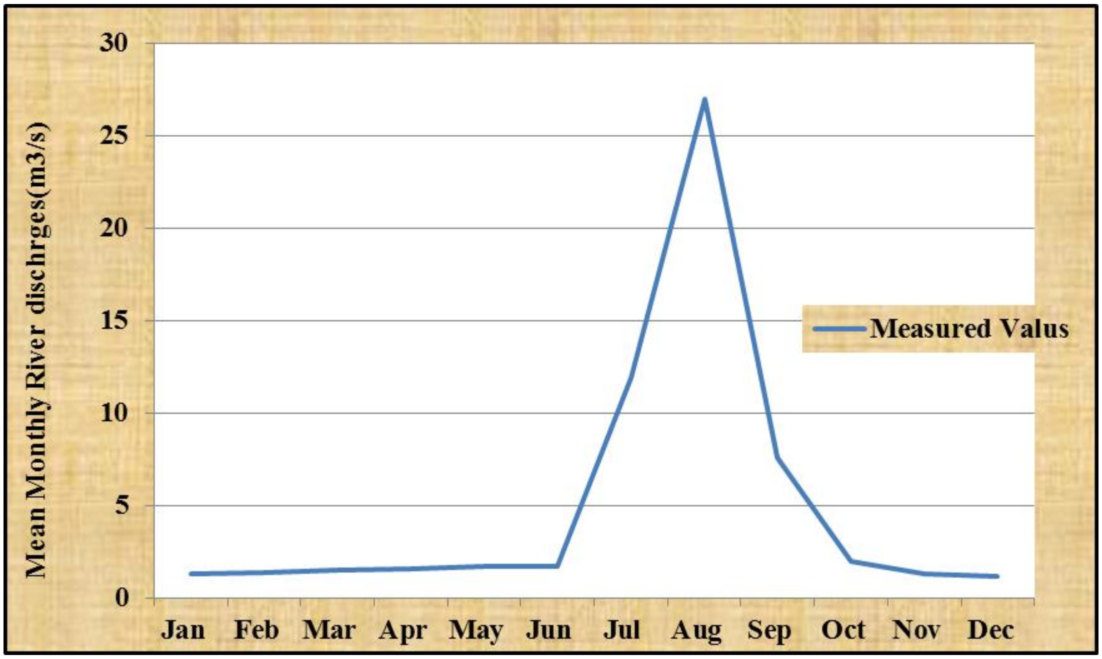

Figure 2.7 Hydrograph of Beresa river

Table 2.4 Mean Monthly Discharges of Chacha River

Years(1962-2009)	Average Discharges(m3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Measured Values	0.13	0.13	0.21	0.29	0.23	0.25	9.90	27.78	5.75	0.78	0.35	0.16

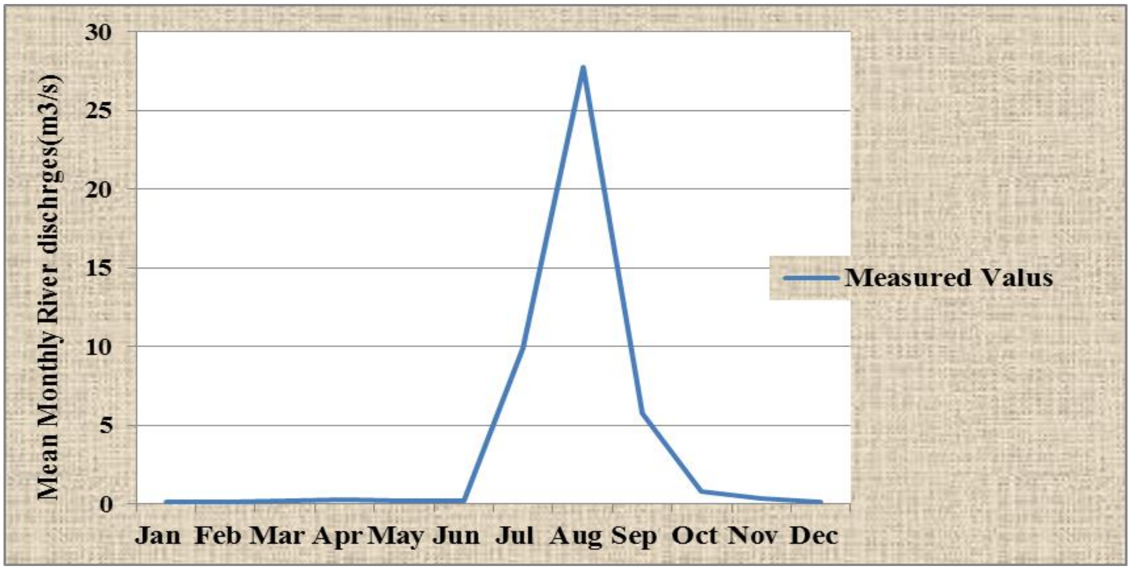

Figure 2.8: Hydrograph of Chacha river

2.6.3. Temperature

Air and water temperature are dependent on solar radiation and has direct influence on evaporation. It governs the rate at which water molecules leaves the surface and enter the over lying air. From the six metrological stations found within and nearby the study area, only two stations (D/birhan and Gudoberet) have records of monthly maximum and minimum temperature. The least minimum and most maximum air temperature is recorded in the month of November and June respectively.

Table 2.5 Monthly maximum mean and minimum mean temperature of Debrebirhan and Gudoberet stations

Mean Maximum and Minimum Temperature Year (1987-2008)													
Stations		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D/Birhan	Mean Max. Temperature	19.57	20.49	20.96	20.87	21.65	21.92	18.58	18.17	18.81	18.68	18.64	19.04
	Mean Min. Temperature	4.89	5.94	7.41	7.75	7.49	7.42	9.05	8.92	7.22	3.70	2.38	2.68
Gudoberet	Mean Max. Temperature	18.1	18.2	18.1	17.9	17.5	18.6	16.9	16.9	16.6	16	16.3	16.7
	Mean Min. Temperature	7.37	7.86	8.27	8.59	9.2	8.99	8.18	8.1	8.17	7.47	6.58	7.01

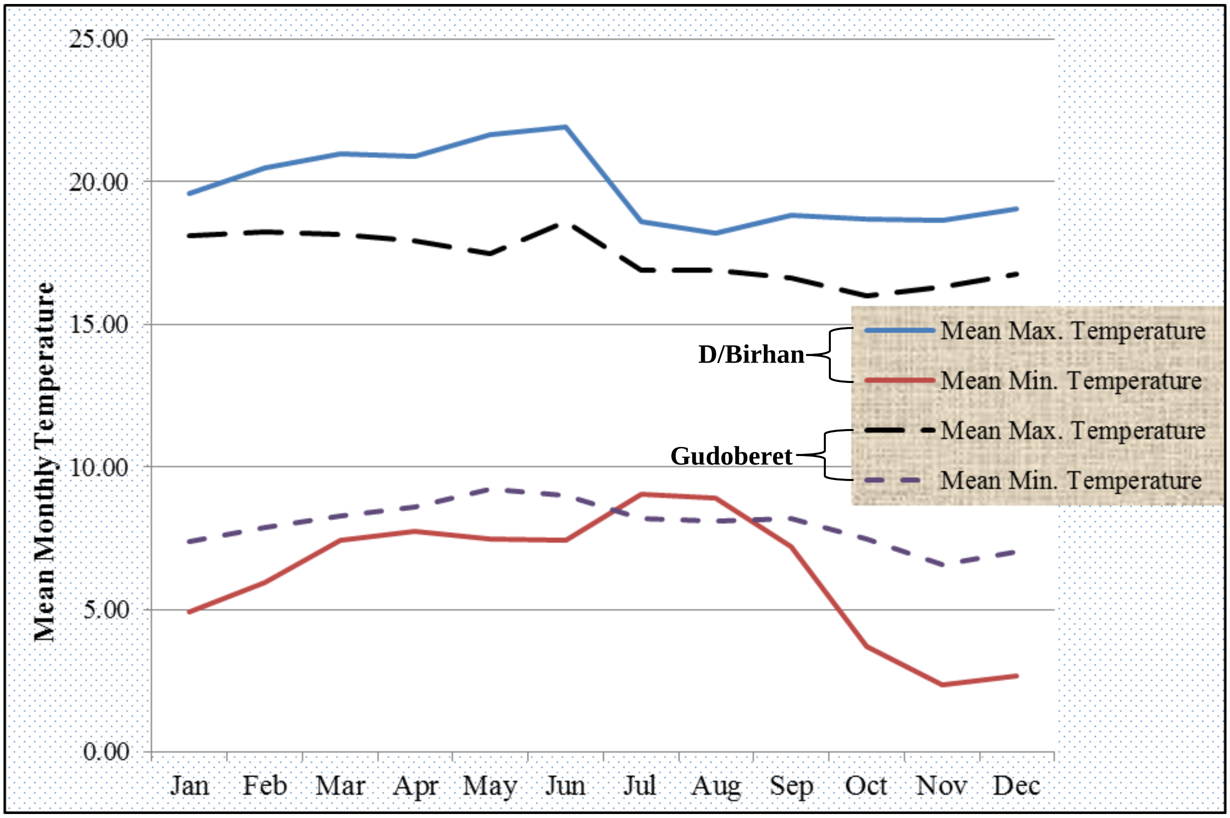

Figure 2.9: Mean Maximum and Minimum Temperature of the two stations

2.6.4. 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.

As the air humidity increases, its ability to absorb water vapor decrease and the evaporation rates slow down. For evaporation to take place there must be a difference in humidity (Tenalem Ayenew and Tamiru Alemayehu, 2001).

In the study area only one station, Debrebirhan station has relative humidity records.

Table 2.6 Monthly mean relative humidity of Debrebirhan station

Station	Jan.	Feb.	Mar.	Apr	May	Jun.	Jul	Aug	Sep	Oct	Nov	Dec
600	83.62	82.55	84.52	86	84.4	86.55	93.42	94.05	92.52	90.56	84.34	80.56
1200	55.62	54.89	56.86	58.09	49.9	49.44	75.63	79.16	68.76	58.74	56.81	56.49
1800	64.76	57.55	60.67	61.05	53.52	52.71	75.42	79.71	70.86	64.72	61.69	62.75
Average	68	65	67.35	68.38	62.61	62.57	81.49	84.31	77.38	71.34	67.63	66.60

2.6.5. Wind Speed

One of the factors of evaporation is wind speed. Any decrease in wind speed, resulting in the non-removal of saturated vapor, affects the evaporation rate. The wind speed at the Debre Birhan station reaches its peak in February and the wind is relatively calm in the month of July and August.

Table 2.7 Monthly wind speed of Debre Birhan Station (in m/s) 2m above ground surface

W/Speed	Jan.	Feb.	Mar.	Apr	May	Jun.	Jul	Aug	Sep	Oct	Nov	Dec
Max	3.2	3.3	3.4	3.6	4.6	3	2.2	2.1	2.3	2.2	2.6	2.9
Min	1.2	1.5	1.3	1.3	1.2	0.2	0.8	0.7	1	0.1	1.3	1.4
Ave.	2.4	2.6	2.6	2.3	2.6	2.1	1.6	1.5	1.7	1.7	2.1	2.3

2.6.6. Sunshine Hours

The total daily evapotranspiration rate is dependent on the total daily sunshine hours. It has direct relationship with evaporation. At Debre Birhan station the mean maximum sunshine hours is recorded in January and November whilst the mean minimum is registered in July and August. It has direct relationship with dry and rainy season.

Table 2.8 Monthly Sunshine hours of Debre Birhan station

Sunshine	Jan.	Feb.	Mar.	Apr	May	Jun.	Jul	Aug	Sep	Oct	Nov	Dec
Max	10.4	11	10	10	9.9	9.6	7	8.1	7.4	10.1	10.4	10.5
Min	6.9	4.8	4.2	4.7	6.4	5.6	3.4	2.8	4.3	5.4	6.5	6.8
Ave.	9.3	8.42	7.41	7.07	8.29	7.52	5.12	5.32	6.14	8.08	9.21	9.07

3. Geological and Structural Setting

3.1. Regional Geology

According to Daniel Meshesha et al, 2010, the geology of the study area falls under Cenozoic age and consists of two litho-stratigraphic units, Tertiary volcanic rocks and Quaternary superficial deposits (Table3.1).

Table 3.1 Classification of lithologies and stratigraphy of the study area

Age		Lithio-Stratigraphic Units	Lithologies
Cenozoic	Quaternary	Superficial Deposits	Eluvium(Qel)
	Tertiary	Volcanic rocks	**Tarmaber-Megezez basalt (Ttb**) plagioclase phyric and olivineplagioclase phyric basalts with minor olivine phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric and aphanitic basalts. **Sela Dengay-Debre Birhan-Gorgo ignimbrite (Tdig)** ignimbrite, tuff, rhyolite, aphanitic basalt, tuffaceous sediments, ash, agglomerate **Kesem basalt (Tkb)** aphanitic basalt intercalated with plagioclase phyric basalts and thin beds of ignimbrite

The Cenozoic volcanic rocks cover the area are grouped into Tertiary and Quaternary superficial deposits, based on their mode of occurrences and previous works in the area. The Tertiary volcanic rocks are mainly exposed along the plateau (e.g., high lands of Tarmaber, Debre Birhan, Saya Debir, Weberi, Wenoda, Sheno and Sendefa) and the NE-SW trending rift margin (Debre Sina, Ankober, Aliyu-Amba, Gorgo, Megezez and Meteh Bila). The rocks mainly consist of thick succession of basalts and ignimbrites with sporadically distributed trachyte, rhyolite and scoria cones. Texture, mode of occurrence and stratigraphic sequence are the main criteria used to subdivide the major age groups into different subunits (Table 3.1). In addition to compositional and textural criteria of each subunit, mostly known localities where the unit is predominantly exposed and attains its maximum thicknesses, is used here for nomenclature purpose (Zanetiine et al., 1974; Kazmin, 1979; Kazmin et al., 1980; Tefera et al., 1996 as citied by Daniel Meshesha et.al, 2010)

Daniel Meshesha et.al, (2010) also stated that the Tertiary volcanic rocks are the earliest volcanic rocks in area that occur along the plateau bordering the rift, which were erupted from fissures due to extensional tectonic activity. The rocks consist of thick succession of aphanitic basalts and ignimbrites which are overlain by central volcano (plagioclase phyric basalts). Within the Tertiary volcanic rocks, thin beds of volcanoclastic sediments (Tertiary sediments) are also found. Acording to Geological Survey of Ethiopia, (2010), these tertiary volcanic rocks are classified as Kesem Basalt, Sela Dengay-Debre Birhan-Gorgo ignimbrite and Tarmaber-Megezez basalt and described as follows;

Kesem basalt (Tkb)

The Kesem basalt is found at the lower stratigraphic sections of Kesem and Jema (Bersina, Derk Wenz, Chira, Chacha, Mofer Wuha and Beresa) drainage basins. The Kesem basalt is strongly fractured, irregularly to columnarly jointed, spheroidally weathered, aphanitic to porphyritic in texture and forms very steep cliffs. In the Jema drainage basin, the contact with the underlying Mesozoic sandstone is sharp and marked by the presence of baked and dark brown soil horizon (palaeosoils). The Kesem basalt consists of dominantly aphanitic basalt intercalated with plagioclase phyric basalts and thin beds of ignimbrite. The aphanitic basalt is the most abundant, fine grained, dark gray to black (fresh color) to bluish gray (weathering color), columnarly jointed and it contains petrified wood at Wintaf river (north of Inewari town). It is characterized by different phases of basaltic flows separated by randomly exposed reddish palaeosols (0.6mt thick) and Sediments (1-4 mt, west of Lizib Dingay Gebreal area)

Aphanitic basalt, its groundmass is dominated with plagioclase microlaths and exhibit trachytic to seriated texture. The plagioclase phyric basalt is exposed mostly at the top most part of the aphanitic basalt and forming a steep cliff. It is coarse to very coarse grained, dark gray and phyric. The ignimbrite is very limited in its vertical extent as compared to the aphanitic basalt. It is found at the middle and sometimes on top of the aphanitic basalt with varying thickness at different localities. It is fine to medium grained, bluish gray to gray, friable and composed of small rock fragments.

Sela Dengay-Debre Birhan-Gorgo ignimbrite (Tdig)

Sela Dengay-Debre Birhan-Gorgo ignimbrite is exposed mainly at Sela Dengay, Sefi Beret, Debre Birhan, Ankober, Aliyu Amba, Gorgo, Shembeko Ber, Alem Gebaya and Sendafa localities, covering most of the study area (Figure 3.1). It has sharp contacts with the overlying (Tarmaber-Megezez) and underlying (Kesem) basalts. It comprises ignimbrite, rhyolite, Tertiary sediment, tuffaceous sediment, aphanitic basalt, agglomerate and ash.

The ignimbrite forms gentle to steep cliffs, elongated ridges and sporadically distributed isolated hills (e.g., Kotu Gebya and Cheki). It is medium to coarse grained, light/bluish/brownish gray to gray (fresh color) to dull/dark gray (weathering color), highly consolidated to welded tuff and bedded with columnar joint; vertical joints, and fractures. It contains rock fragments of rhyolite and basalt ranging up to 2cm in diameter and elongated fibrous glass shards (fiamme), whereas the amount of rock fragments significantly varies from place to place. At Awajo Gebrial (2km north of Mezezo town), there is two distinct layers of ignimbrite. The upper layer is white to light yellow while the lower one is dark and contain basaltic rock fragments.

The rhyolite is found around Deneba, northeast of Debre Birhan (Beriyo Baleweld), Shola Gebya and Gina Ager. It is fine to medium grained, bluish/light/greenish gray (fresh color) to dull gray, light/dark brown (weathering color). It is highly fractured and vertically jointed at northeast of Debre Birhan (Beriyo Baleweld).

Tertiary sediment mainly exposed in and around Jema (Mofer Wuha, Aboya Jema, Chacha and Ayserawem river sections), Kesem (e.g., Argu, Uroa Wiha and Meti), Awash (Mote and Mensa) tributaries and Nito Debri locality (north of Debre Birhan), consisting of an alternating bed of tuffaceous sediments and sandstones. There are two different layers of Tertiary sediment, the upper and lower layers. The upper layer is only exposed in the upper part of Chacha, Bersena river vallyes and Nito-Wydeme (Nito Debri locality) and has a maximum thickness of 65mt and pinches out at Metkoria and Amora Gedel localities. The sediment in general forms gentle slope and the lower sediment attains its maximum exposed thickness (~120mt) around Mafud locality. The tuffaceous sediment is light gray to pinkish gray, coarse grained with basaltic rock fragments and laminated (at Moya Mariam and Goshe Bedo).

Plagioclase is altered to sericite. It shows angular to sub rounded and inequant grains of feldspar and quartz within clay (ash) matrix. The sandstone layer is sandwiched within the tuffaceous sediment and has different exposure thickness and characters. In the Mofer Wuha river section, the sediment (80mt thick) is characterized by alternating layers of sandstones and tuffaceous sediments, whereas at Aboya Jema section, there is only 60mt thick sandstone with 10cm thick grayish green and fissile shale. South of Lizib Dingay Gebriel (southeast of Aleltu) and around Sar Amba Silase (east of Gina Ager) the sandstone has 2-5mt thickness. The sandstone is medium grained, reddish brown, brownish gray to light yellow, sorted, cross-bedded (only around Menyet village and Metekoria area) and conglomeratic. There are also coal bearing sediments confined within the tuffaceous sediments at Mush valley (3mt thick, 30km north of Debre Birhan town) and Shirer Libanos (1-2mt thick; west of Koremash town) but the lateral extents of the two coal bearing sediments are obscured.

The aphanitic basalt is fine grained, black/dark/gray, irregularly fractured, slightly jointed, columnarly jointed and rarely shows a massive appearance that forms a steep morphology. It is strongly deformed at south of Abo Danse locality.

The Agglomerate contains fragments of ignimbrite and vesicular variety of dark gray porphyritic to aphanitic basalts cemented by white ash. It is loose and highly weathered with angular rock fragments from cobble to pebble size and forming low slope angle than other rocks.

The ash is forming mostly gentle slope and flat topography. It is white, light yellow, pink and light brown (fresh color) to red, yellowish gray and black (weathering color). It contains small fragments of basalts and pumice.

Tarmaber-Megezez basalt (Ttb)

Tarmaber-Megezez basalt is dominantly exposed on the western (Wenoda, Sendafa and Megezez) and north central (Debre Sina, Termaber and Ankober) part of the plateau in the area (Figure 3.1). It forms a series of linear ridges and high mountains (Mt. Megezez, 3595m a.s.l.)

and Mt. Yekur (3400m a.s.l.). It has sharp contact with the underlying Sela Dingay-Debre Birhan-Gorgo ignimbrite.

Termaber-Megezez basalt includes fine, medium to coarse grained, dark gray (fresh color) to light/reddish/dark/yellowish brown (weathering color) and aphanitic to porphyritic basalts. It is characterized by different phases of basaltic flows separated by randomly exposed reddish palaeosols and reddish brown scoriaceous basalts (0.5-8mt thick). It is dominantly represented by plagioclase phyric varieties (plagioclase phyric and olivine-plagioclase phyric basalts) together with minor olivine phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric and aphanitic basalts.

Plagioclase phyric basalt is the most abundant rock type and mostly occupies the highlands of Debre Sina, Tarmaber, Ankober and Wenoda including Mt. Megezez and Mt. Yekur where it attains its maximum thickness. It is medium to coarse grained and dark gray, containing plagioclase phenocyrsts up to 5cm in length. The plagioclase phyric basalt shows randomly distributed and faint columnar jointing (at north of Debre Birhan and south of Mezezo town).

In the plagioclase phyric basalt, the Plagioclase and olivine grains are altered to sericite and iddingsite. The groundmass is dominated with plagioclase and pyroxene microlaths. The rock exhibits trachytic, porphritic, ophitic to seriated textures.

Olivine-plagioclase phyric basalt is mostly exposed around Berek-Chancho ridges (north of Sendafa), between Beke and Aleltu, and around Gina Ager localities. It is medium to coarse grained, dark gray (fresh color) to dull gray (weathering color), phyric with dominant plagioclase and few olivine phenocrysts. It is massive and blocky in appearance, exhibiting spheroidal weathering. Plagioclase and olivine are altered to sericite and iddingsite (mostly along fractures) respectively. The groundmass is composed of microcrystals of olivine, plagioclase, and opaque minerals. The rock exhibits porphyritic to seriated textures.

Olivine-phyric basalt is exposed northeast of Shola Gebeya (Gorfo village) and southeast of Mt.Yekur. At Gorfo village, the olivine phyric basalt forms a ridge with blocky appearance. The rock is coarse grained, greenish gray (fresh color) to gray (weathering color).

In general, the dominant Tarmaber-Megezez basalt (plagioclase phyric basalt) gradually ranges to aphanitic basalt with no or few phenocrysts from the center to the periphery along Mt. Megezez, Mt. Yekur, Chancho-Berek and Tarmaber ridges. There are also randomly distributed patchy outcrops of such aphanitic basalt throughout Tarmaber-Megezez basalt (Sembo, Chacha, Mendida and Deneba). The aphanitic basalt is fine grained, black and dark/light gray (fresh color) to gray and dull gray (weathering color), columnarly jointed. North of Sheno and along the road of Kotu Gebya-Hageremariam, there are also scoria deposits associated with the aphanitic basalt.

Quaternary superficial deposits /Eluvium Soil/ (Qel)

The recent litho-stratigraphic unit in the area is superficial deposits. It is mostly found on the plateau and escarpment of the study area, occupying flat lying and gentle topography (Figure 3.1). It is formed by the gradual weathering of the basalt, ignimbrite and rhyolite. There are rock fragments of basalt, ignimbrite and rhyolite within the eluvium soil. It is silt to clay sized, light/dark gray to reddish brown fertile soil. It is highly ploughed by the local people.

3.2. Local Geology

This section provides a brief description of the geology of the Beresa and Gado rivers catchment and this description is conducted by modifying geological maps with the field observations. As shown in Figure-3.1 the geology of the study area which is extracted from Daniel Meshasha et.al, (2010), is classified in to the following classes.

3.2.1. Lower Basalt

The lower most part of the lithologic unit of the study area is characterized by basalt. This formation is located in the rivers gorge forming steep cliffs at north western part of the study area. The successive flow of this formation deeply eroded by rivers determining steep cliffs alternating with shoulder shaped gentle slope. This rock unit is highly jointed and fractured by minor local faults. It has dark gray color and aphanitic texture. This rock is similar with Kesem basalt described in the regional geology section.

3.2.2. Ignimbrite, Rhyolite, Trachyte, Tuff

On the top of the lower basaltic unit silicic volcanic product of ignimbrite, rhyolite, and tuff have been out cropped in the area as the second major volcanic rock units. The ignimbrite and rhyolite rock units are highly weathered and fractured. The coarser grain ignimbrite rock contains phenocrysts of quartz and feldspars. The fresh rock have got light grey, light greenish and white colour. These rock units are similar with Sela Dengay-Debre Birhan-Gorgo ignimbrite unit described in above.

3.2.3. Upper Basalt

The other main volcanic rock units overlaying on the top of Ignimbrite, rhyolite, trachyte, and tuff is the basalt. This rock unit is highly weathered and fractured. The main phenocrysts are plagioclase feldspars. There are paleosoil in between different flows and its thickness varies from place to place. This unit covers the upper and middle parts of the study area. Its textural feature very similar with the Tarmaber basalt described in above section.

3.2.4. Superficial Deposits

The topographic nature of the area is undulating, most of the stream and river beds outcrops rock units. On the gentle slope of the area, there is a wide area of cultivated land having brown clay and silt residual soil with an average thickness of 0.5m overlaying on the ignimbrite, rhyolite and basaltic bed rocks. This thin thickness residual soil unit described and mapped as the bed rock lithologic type. But there are some soil patch mapped as soil unit which covers relatively wide area along the flat rivers and small valley coarse.

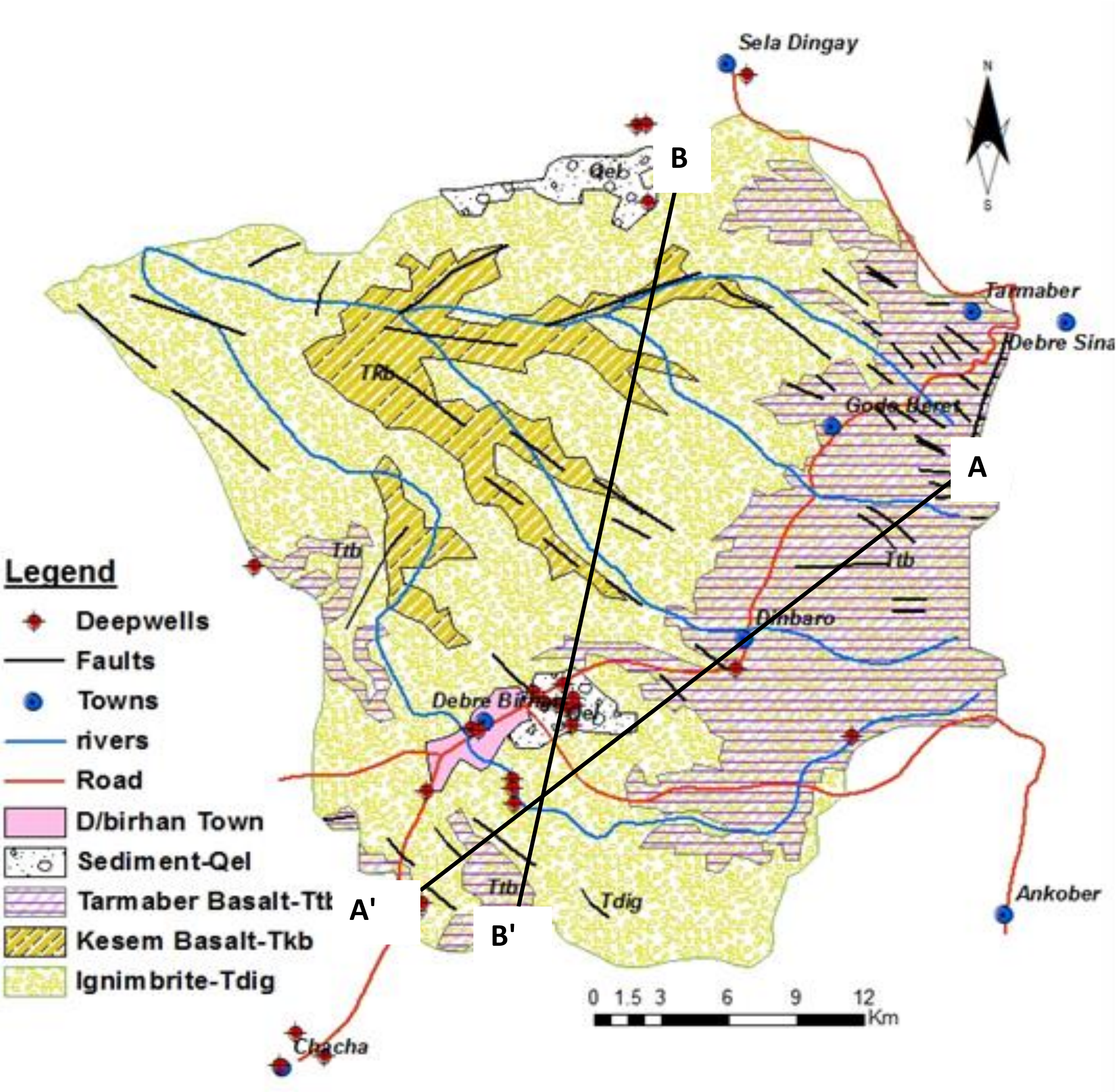

Figure 5.1 Geological Map of the Beresa and Gado rivers catchment (Modified from Daniel Meshesha et.al 2010)

4. Conceptual Model Development

4.1. General Over View

Conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross section (Anderson and Woessner, 1992). A conceptual model describes how water enters an aquifer system, flows through the aquifer system and leaves the aquifer system. Briefly, it describes the hydrologic system with respect to aquifer properties, flow characteristics and boundary conditions.

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 important steps in building the conceptual model include

- Defining boundary condition

- Defining hydro-stratigraphic units

- Defining the flow system

To develop the conceptual model, some simplifying assumptions were made. The assumptions include: the model consists of a single layer, the model is two dimensional, the aquifer is unconfined with varying thickness and, the groundwater flow is horizontal.

In principle the groundwater flow and contaminant transport in porous medium domain are three-dimensional. However, when considering regional problems, one should note that because of the ratio of aquifer thickness to horizontal length, the flow in the aquifer is practically horizontal. The horizontal dimension may be from tens to hundreds of kilometers with a thickness of tens to hundreds of meters (Bear J. and H.D. Cheng, 2010).

Simplification is important because complete reconstruction of the filed system is not feasible. The conceptual model should be simplified as much as possible while it is still remains complex enough to represent the system behavior (Anderson and Woessner, 1992). In this study, to simplify the complex nature of the area, a simplified conceptual hydrogeological model of the groundwater system was developed based on information about geology, hydrogeology and hydrology.

The groundwater flow system comprises the subsurface water, the porous geologic media containing the water, the flow boundaries, the sources (outcrop areas, streams for recharge to the aquifer), and the sinks (springs, inter-aquifer flow, and wells for flow from the aquifer). The groundwater flow through the volcanic rocks that cover the highland part of the studied area is mainly localized to the fractured and faulted zones. It is more likely through those structures that the groundwater flows from the highland to the low laying valley fill alluvial deposits and the underlying fractured volcanic rocks.

The hilly topography produces numerous subsystems within the major flow system. Water that enters into the flow system in a given recharge area may be discharged in the nearest topographic low or it may be transmitted to the regional discharge area in the bottom of the major valley (Freeze and Cherry, 1979). The simplified conceptual groundwater flow system of the area is shown in figures below.

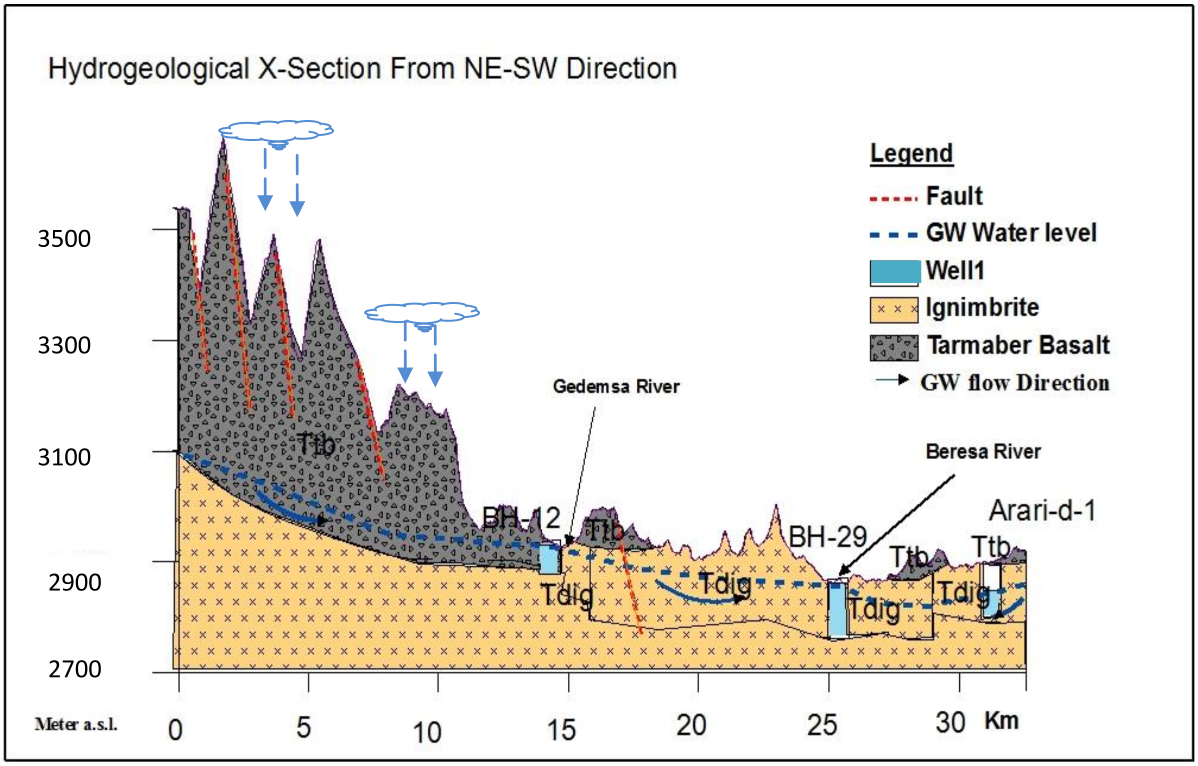

Figure 4-1: Hydrogeological Cross-section from NE-SW Direction (A-A') from Geological map of the area.

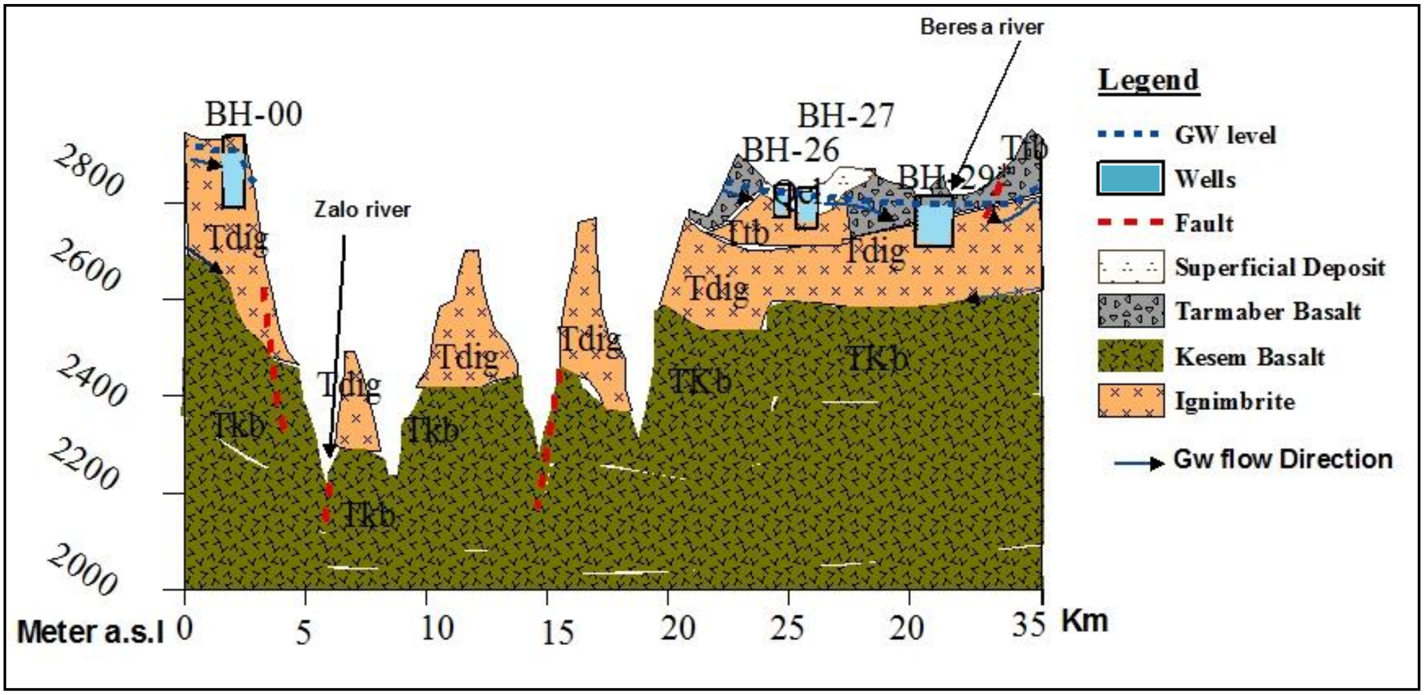

Figure 4-2: Hydrogeological Cross-section from N-S Direction (B-B')

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 and Woessner, 1992). Physical boundaries of groundwater flow systems are formed by the physical presence of an impermeable body of rock or a large body of surface water. Hydraulic boundaries are a result of hydrologic conditions, are invisible and they may include groundwater divides and streamlines.

In groundwater flow modeling, boundary conditions influence the extent of the 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 is 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 the Beresa and Gado rivers catchment, the system boundary was carefully assigned based on field visits, existing works and extracted from the DEM data.

The groundwater flow direction in the catchment coincides with the topography following the surface water flow direction because small intermittent and practically perennial rivers form local drainage basins and shallow aquifers. The flow is partly controlled by the structure and partly by the geomorphology of the area. Most of the springs emerging from tertiary volcanic rocks are topographically controlled and others emerge along structures indicating that the groundwater flow is controlled by both factors. Local groundwater flow directions vary from place to place according to the local topography.

The northwestern tip of the catchment was represented as head dependent boundary because there is groundwater outflow. Flux is approximated to occur in this side of the catchment based on the head in the aquifer and the external source head. In this study the head in the external source is lower than the head in the aquifer, so groundwater is expected to be discharged from the aquifer system.

In addition, the upper boundary of the modeled catchment was assumed to be the water table and recharge was used to represent the boundary flux. Although not known to exact, the lower boundary was considered as a no flow because the aquifer was assumed to be underlain with an impermeable rock body.

In general, the boundary systems used for the purpose of this modeling work are selected to coincide with groundwater divide features in the actual systems.

4.3. Hydro-Stratigraphic Units

4.3.1. Hydrogeological Characterization

According to Jiri Sima et al. (2009), the qualitative division of lithological units is based on the hydrogeological characteristics of various rock types using water point data, including data from pumping tests of various boreholes obtained from different organization. The lithological units were divided into groups with dominant porous and fissured permeability and impermeable rocks. This division served for definition of the catchment aquifer/aquitard system. Since quantitative data such as permeability, aquifer thickness and yield are not adequate or evenly distributed enough to make a detailed quantitative potential classification; analogy was used for characterization of rocks without the adequate number of water points. Hence, the hydrogeological characterization of the study area reveals the following Aquifer/Aquitard system:

Porous permeability units, where groundwater is accumulated in and is flowing through pores of an unconsolidated or semi-consolidated material. Porous materials of Quaternary and Tertiary age are represented by fluvial and colluvial sediments developed in depressions and/or along valleys of former and existing rivers. The pyroclastic rocks between lava flows are generally porous but usually less permeable due to poor sorting. Layers of paleosoil of various thicknesses in between lava flows are also less permeable and consist usually of clay material.

Fissured permeability units, where groundwater is accumulating in and flowing through the weathered and fractured part of volcanic rocks. The porosity of lava flows may be high but the permeability is largely a function of a combination of the primary and secondary structures (joints and fissures) within the rock. In addition, the permeability of lava flows tends to decrease with geological time. Pyroclastic rocks associated with lava flows as well as paleosoils in between lava flows are generally porous but not very permeable because of poor sorting and the abundance of fine materials. Hence, extensive volcanic ash beds may form semi-horizontal barriers to water movement (infiltration) resulting in lower productivity of basaltic units located at greater depth.

Impermeable units, like fresh rhyolite, trachyte and ignimbrite, particularly when forming mountains, represent impermeable layers and/or layers with limited groundwater resources within the study area.

4.3.2. Superficial Deposits Aquifer

The general distribution of the deposits with porous permeability in the study area is localized to a gentle undulating plateau and along rivers. The thickness of these deposits is variable from place to place. Elluvial sediments of the plateau consist of silty to clayey soil. Aquifers in these sediments are recharged directly by infiltration of rain and can also be recharged by rivers during high discharge. Groundwater of aquifers in the sediments is drained by small springs and rivers. Plateau Quaternary deposits also recharge the underlying aquifers. Dug wells sunk into the plateau’s Quaternary deposits supply the local community but in some situations where the elluvial cover is thin the wells fail during the dry season after pumping for only a few hours. The groundwater level is about 1–2 m below the surface in some places.

Perennial springs with variable yield depending on sediment thickness, degree of consolidation and extension of eluvilal and/or alluvial sediments were seen on some of the inter-mountain plains. The safe yield of wells sunk into Quaternary deposits is estimated to be about 0.5 l/s.

4.3.3. Moderately Productive Fissured and Mixed Aquifers of the Plateau Area

Volcanic rocks of the plateau represent large and moderately productive fissured aquifers which are the principal aquifers in the area. Groundwater is mostly under water table conditions, however, semi-confined conditions can be found in a number of the wells. This semi-confined condition is a result of vertical as well as lateral inhomogeneity of volcanic rocks partly intercalated by various sediments.

The basalt is tectonically affected by the NNE-SSW trending normal faults following the rift structure and by a system of NE-SW faults which are following by rivers in the southeastern part of the plateau. Most of the springs of this unit are fracture controlled usually emerging at the intersection points of fractures or faults with a topographical depression. Dry period discharge varies from 0.01 to 17 l/s. Koso spring which emerges at the contact between the phyric basalt and underlying impermeable volcanic rock has a discharge of 3.2 l/s while the Gudoberet spring has a discharge exceeding 17 l/s. The boreholes drilled in the basalt also have good yield more than 7 l/s is good example of the high potential of the aquifer in the eastern corner of the study area.

Due to the relatively good yield and constant discharge rate of the springs emerging from this unit, they are widely used for small scale irrigation purposes in addition to being a sustainable community water supply. This aquifer is recharged directly by infiltration of precipitation and/or by infiltration from a porous aquifer developed in Quaternary sediments covering the plateau area and rivers. The plateau sediments retain rainwater for a longer time and create favorable conditions for infiltration through a highly weathered, jointed and permeable upper layer.

Groundwater is drained by shallow rivers and also recharges the underlying aquifers. The groundwater is probably under water table conditions. Recharge is enhanced along rift related NNE-SSW structures.

The static water level measurements of boreholes in the Basalt are in the range of 6 to 37.44.m below the surface.

4.3.4. Ignimbrite /trachyte/ basalt/ rhyolite/ tuff /ash aquifer

The highly fractured volcanic rocks of the plateau consisting of ignimbrite, basalt, rhyolite and/or trachyte are one of the major water bearing formations in the area. It covers large gently undulating areas of the eastern plateau. Ignimbrite and trachyte form a non-homogeneous hydrogeological environment, with the amount of groundwater in these rocks varying from place to place depending on the frequency, intensity and distribution of the fracturing system. According to production wells drilled for the Debre Birhan water supply, the inter-bedded volcanic rocks act as a semi-confined aquifer. This aquifer is recharged directly by infiltration of rainfall and/or infiltration from a porous aquifer developed in Quaternary sediments covering the plateau area. The formation is drained by perennial and seasonal rivers like the Beresa, Dalecha, and Gado. The discharge of springs and wells from the mixed aquifer varies from 0.03 to 17.0 l/s.

Boreholes sunk in the fractured ignimbrites for the most part have transmissivity between 0.05–266.4m2/day. The fractured ignimbrite /trachyte/ unit generally has moderate permeability and productivity. Transmissivity, hydraulic conductivity and storativity data of wells located mainly in the fractured ignimbrite and basaltic rocks of Debre Birhan area are summarized in Table 4-1. The boreholes through fractured ignimbrite/trachyte have a static water level between 6 and 91.86 m below the surface.

Porous sediments in between lava flows form a body that can accumulate a large volume of groundwater by drainage of surrounding fissured aquifers and contribute to the yields of well developing groundwater from this mixed aquifer, which is more productive than fresh basalt, ignimbrite, trachyte and rhyolite that are normally considered as rocks with very low permeability.

The fissured and mixed aquifers on the plateau are the most important hydrogeological unit of the area and the basic statistics of these two important aquifers are summarized in table 4.1. The yields of 17 wells representing fissured and mixed aquifers vary from 1.5 to 18 l/s.

Table 4.1 Hydraulic conductivity, Transmissivity and Storativity of wells in area

Id	E	N	Elva	Depth	SWL	Yield	Transmissivity (m2/day)	Hydraulic Conductivity (m/day)	Storativity	Lithology
BH-2*	559277	1067055	2766	100.5	6.25	15	98.8	2.6928	$2.96x10^{-1}$	Rhyolite / ignimbrite
BH-3*	560716	1070578	2790	108	7.92	12	165.6	3.3984	$1.93.1^{-8}$	Rhyolite / trachyte
BH-21*	562016	1070480	2801	108	12.79	7	10.8	0.3024		Ignimbrite / trachyte /sand
BH-22*	561928	1070820	2799	95.56	11.68	8	98.064	2.5776	$6.68x10^{-4}$	Ignimbrite / trachyte /gravel
BH-23*	561901	1069500	2798	125	9.2	4	0.05	0.00104112	$5.01x10\text{-}^{3}$	Trachyte
BH-24*	574362	1069000	2795	150	7.4	3.5	0.2	0.00335	10.00	Trachyte / ignimbrite
BH-25*	561507	1071446	2797	72	11.45	15	244.6	7.272		Trachyte / ignimbrite
BH-28*	559242	1066637	2760	92	6.25	18	266.4	5.302		Rhyolite and Ignimbrite
BH-29*	559340	1065876	2765	102	8	15	76.9	1.805		Rhyolite and Ignimbrite
BH-00	565324	1093842	2851	151	32.35	7.2	37.44	0.63648		Basalt
Arari-1	555236	1061291	2802	98.42	8.4	7	68.43	1.9008		Trachyte
Go01	547775	1076918	2772	175	91.86	3.25	11	0.3056		Ignimbrite / trachyte
Bbh4	559369	1067258	2780	106.49	5.3	15.3	80.78	2.21		Ignimbrite / trachyte
Dbf1	560800	1071004	2830	153	11.72	1.5	1.54	0.05		Ignimbrite
BH-16	550872	1054157	2778	96	6.6	5	0.1	0.00175		Ignimbrite/ basalt/sand
STBH-1	564836	1097392	2865	100	27.3	14	203.04	5.8896	6.09	Ignimbrite
STBH-2	565227	1097476	2868	119	28.45	5	11.7072	0.32544	$2.10x\ 10^{5}$	Ignimbrite

4.4. Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of a fluid to move through interconnected void spaces in sediments or fractures in rocks. It is a function of both the fluid and the medium. The higher the hydraulic conductivity of a rock/sediment, the higher the water yielding capacity of the rock is. The hydraulic conductivity of fractured rocks depends largely on the density of the fractures and width of their apertures. Accordingly the geology of the area is Tertiary volcanic rocks and Quaternary alluvial deposits. Previous works in and around the area show that all aquifer types exist is the area, but as this study considered a single layer of an unconfined aquifer system the hydraulic conductivity is expected to vary horizontally, not vertically. Most pumping test and other well data found in the area were not to the standard field hydrogeological test of a carefully monitored pumping test with observation wells. Few attempts have been made in the past to estimate the transmissivity and hydraulic conductivity of the area by different authorities and individuals from pumping test data, some of which are: Nigussie Kebede (2005) calculated the estimates of transmissivity and hydraulic conductivity of the boreholes with in the Beresa river catchment and the result is in the range of 10-332m^2/day and 0.3-7.8m/day. According to Jiri Sima et al. (2009) the hydraulic conductivity and transmissivity of the Jemma aquifers lies in the range of 0.00104 to 1.53 m/day and 0.05 to 380 m^2/day. Because of the point hydraulic conductivity obtained from well data does not cover the whole catchment; it creates difficulty in mapping the hydraulic conductivity of the area. Therefore, an effort has been made to estimate the hydraulic conductivity in this study, based on the geology of the area and the degree of fracturing and weathering of the rocks, collecting and analyzing the existing borehole data and referencing previous works mentioned above, the research area was subdivided in to six different zones of different hydraulic conductivity values (Figure 4-3).The value is low in the mountain escarpment and highly dissected valley areas especially where acidic volcanic rocks are exposed and also less fractured & less weathered basalts are found. The flat laying and plateau area, where the quaternary sediment and highly weathered and fractured ignimbrite/trachyte, the hydraulic conductivity is relatively higher. Highest values of hydraulic conductivity in the catchment are attributed to the Debirebirhan town water supply well field area, which was found to have a value of about 7.272m/day. The aquifer in this area is made up of quaternary sediment and weathered and fractured ignimbrite/trachayte that have higher productivity. These calculated hydraulic conductivity values may adjusted during the model calibration step.

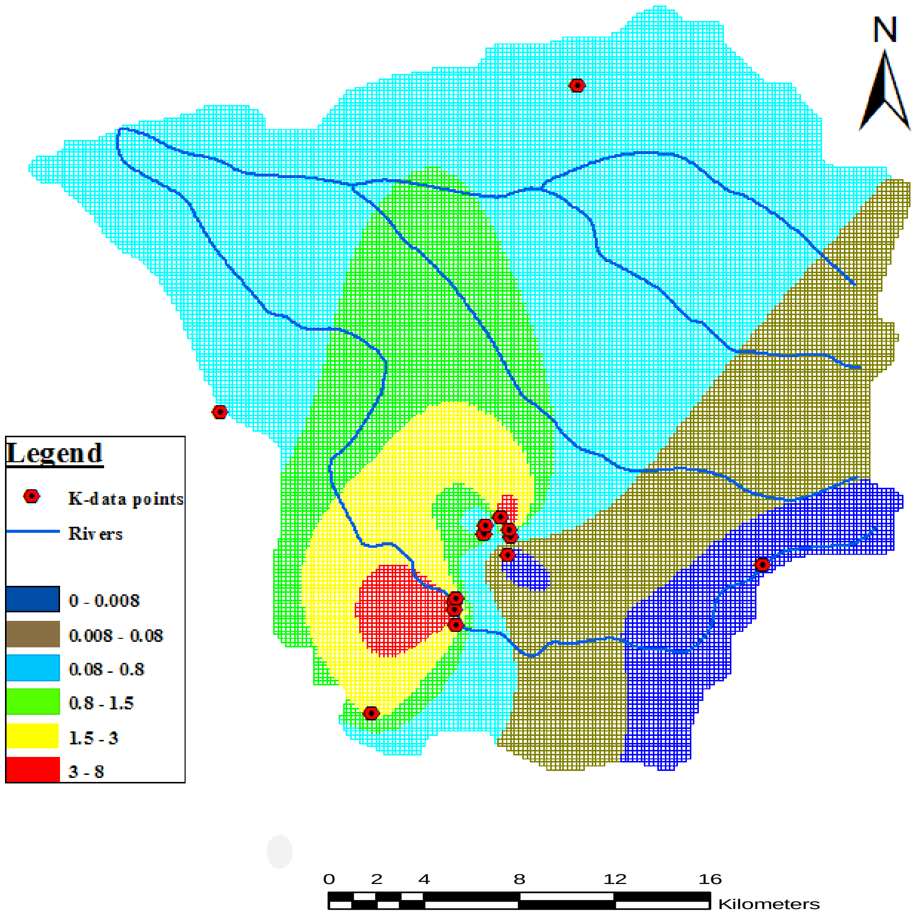

Figure- 4.3 Hydraulic Conductivity map of the Beresa and Gado river catchment

4.5. Groundwater Inflow and Outflow Conceptualization

4.5.1. Recharge and its Spatial Distribution

In nature different types of recharges occur together, which lead to different recharge estimation techniques and this makes the quantification process difficult. In this study, direct recharge from precipitation was considered and it occurs in this area as there is a surplus of rainfall over evapotranspiration. The groundwater level of an area is directly influenced by the amount of water that enters to the aquifer system, that is, areas with higher recharge amount have shallow groundwater level and in general, groundwater flows from recharge areas to discharge areas.

The spatial distribution of recharge is affected by a number of natural and anthropogenic factors, some of which are climatic factors, geology, and vegetation cover, topography and land use/cover. Based on all these factors, the global net recharge estimated for the whole country ranges from 50-150mm (Tesfaye Cherinet, 1988). Some researchers and institutions have made an estimate of the recharge amount in the area and in general the values estimated lie within this global range.

In this study, recharge to groundwater was spatially grouped into various zones with different recharge values, according to the works of Nigussie Kebede (2005) the annual recharge of the Beresa river catchment estimated by WATBAL method is about 122.46mm/yr which is about 10.9% of precipitation of the area. And according to Jiri Sima et al. (2009) the annual recharge of the area using soil water balance method calculation is 122mm/yr. Groundwater recharge to aquifers in the area is derived from precipitation, mostly during intensive precipitation from June to September.

The recharge zonation map shown below in figure-4.4 was mapped based on the above data and the geomorphology of the study area.

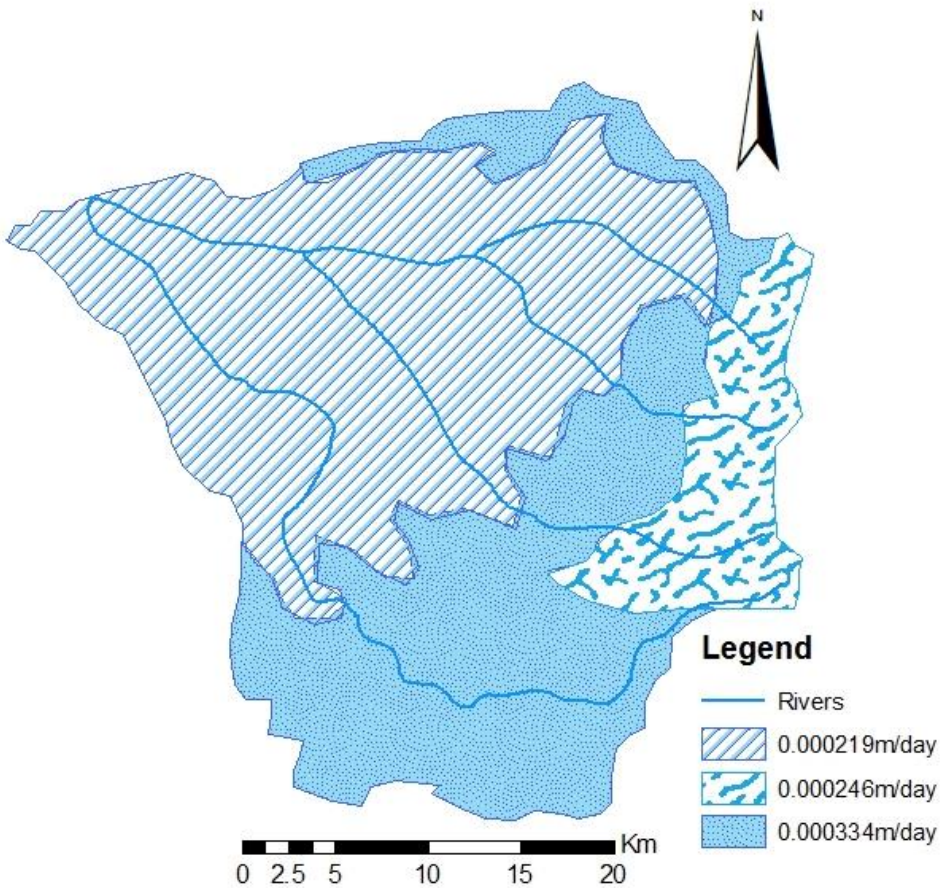

Figure-4.4 Recharge map of the Beresa and Gado rivers catchment

4.5.2. Groundwater Discharge

Groundwater is removed from the aquifer in the catchment by withdrawal through wells for human consumption, springs, dug wells, subsurface outflow, and base flow to the rivers, and evapotranspiration. Evapotranspiration can be considered as one of the discharge mechanisms of subsurface water in shallow aquifers and from unsaturated soil moisture storage zone. But in this model groundwater loss from the aquifer through evapotranspiration was considered to be negligible.

4.5.2.1. Spring Discharge

Springs are typically occurring where groundwater table intersects with the land surface. It represents the elevation of the groundwater level. A number of low discharging springs are emanating in the catchment. The discharges of most of the springs are lower and were not directly considered in the model. But relatively higher discharge and perennial springs are incorporated in numerical simulation, which have discharge of 1.0l/s and above that used for community water supply purpose.

The springs in the area are contact, depression, and structure controlled, but dominant once are the fractured and contact springs that emanate at the contact of the highly weathered, fractured and friable volcanic rocks and/or alluvial deposit and relatively less weathered underlying basalt. The discharge of springs especially springs which have low yields, increases during the rainy season and gradually decreases reaching minimum discharge during the peak dry season.

4.5.2.2. Well Withdrawal

Most of the boreholes are drilled in the Beresa and Dalocha well fields for the purpose of Debrebrihan town water supply and industries in the town. And also there are boreholes drilled in the catchment that used for community water supply of small towns and rural villages. The discharge of the boreholes varies from 1.5l/s to 18l/s.

In this model, the abstraction amount of boreholes analyzed based on the yield of the boreholes. The abstraction of groundwater simulated with well package with an average withdrawal of 610.71m3/day. The total amount of groundwater abstracted in the study area is 11,344.32m3/day. The detailed description of the boreholes considered and the amount of water withdrawal from the aquifer system is summarized in table-4.2

Table- 4.2 Wells and their discharges in the study area

Id	Locality	N	E	Elva	depth	SWL	Yield (l/s)	Yield m3/day
BH-2*	Beresa well field	559277	1067055	2766	100.5	6.25	15	1296
BH-3*	Dalecha well field	560716	1070578	2790	108	7.92	12	1036.8
BH-4	Aquasafe / Debre Birhan	560171	1071077	2801	153	11.72	1.5	129.6
BH-21*	Dalecha well field	562016	1070480	2801	108	12.79	7	604.8
BH-22*	Dalecha well field	561928	1070820	2799	95.56	11.68	8	691.2
BH-12	Bakelo	569176	1072153	2847	50	12.5	3	259.2
BH-23*	Dalecha well field	561901	1069500	2798	125	9.2	4	345.6
BH-24*	Dalecha well field	574362	1069000	2795	150	7.4	3.5	302.4
BH-25*	Dalecha well field	561507	1071446	2797	72	11.45	15	1296
BH-26	Dalecha well field	561688	1070292	2800	70	6.66	5	432
BH-27	Dalecha well field	561233	1070521	2796	83	6	5	432
BH-28*	Beresa well field	559242	1066637	2760	92	6.25	17	1468.8
BH-29*	Beresa well field	559340	1065876	2765	102	8	15	1296
BH-00	Aysofe	565324	1093842	2851	151	32.35	7.2	622.08
Arari--1	D/birhan-research	555236	1061291	2802	98.42	8.4	7	604.8
BH-01	Marine camp	555400	1066500	2785	90	11.9	4	345.6
BH-02	TTI	557442	1069410	2800	67	33.5	3.5	302.4
BH-03	Divine ProS	557750	1069300	2785	111	29.6	1.6	138.24
							Total	**11,344.32**
							Mean	**610.71**

4.5.2.3. Hand Dug Wells

Hand dug wells are very shallow groundwater which is dug by hand manually at shallow groundwater table area. In the study area, most of the rural community is using a number of hand pump fitted hand-dug wells for domestic water supply purpose. Most of the wells have depth 4-9m. Almost all the wells tap from the alluvial and residual silt clay soil and some from highly weathered and fractured volcanic rocks (ignimbrite/trachyte). 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.

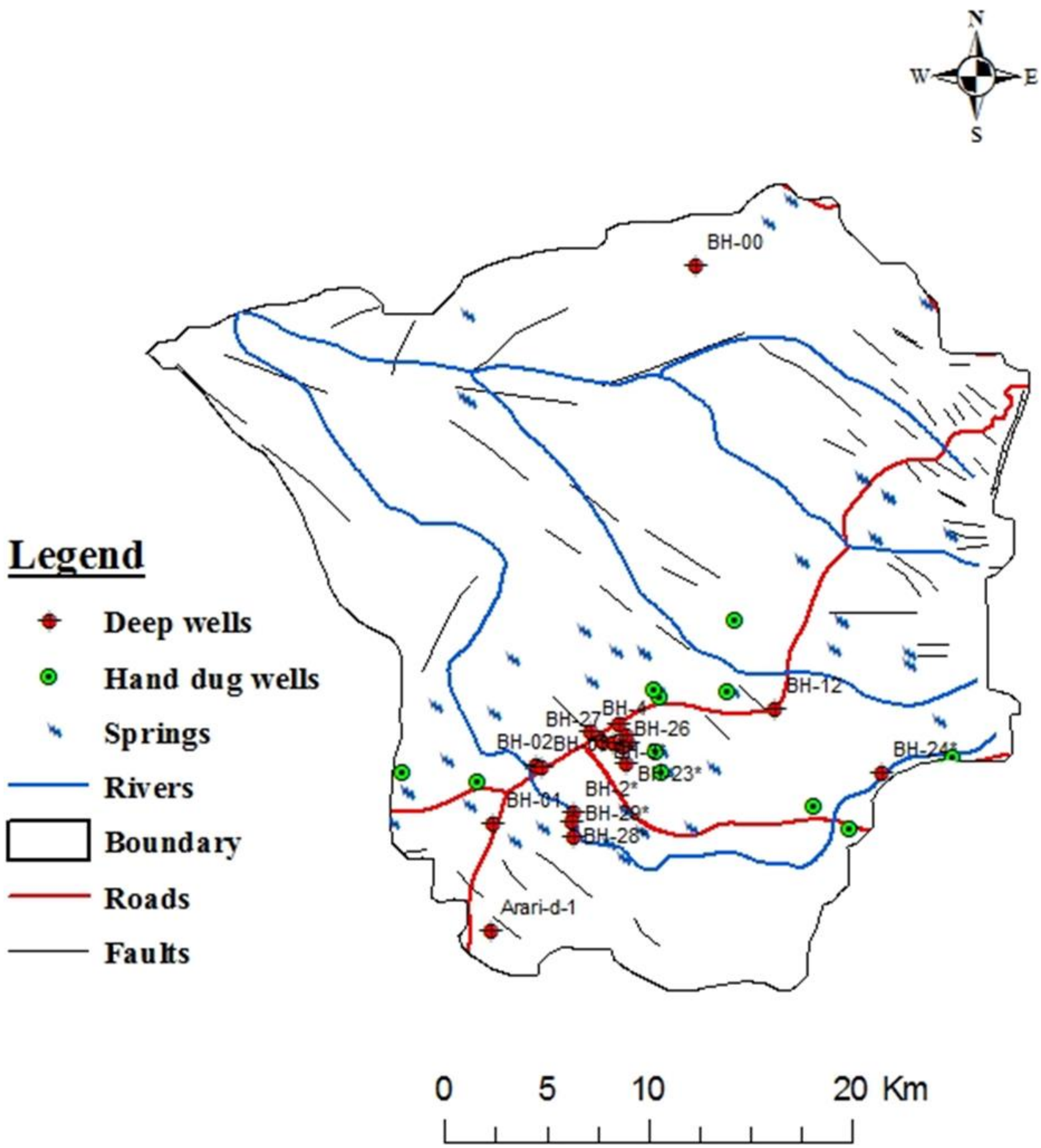

Figure 4.5 Water points in the Beresa and Gado rivers catchment

4.5.2.4. 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 in the catchment.

From gauged Beresa river, groundwater base flow has been estimated using TIMPLOT method. The annual base flow and surface runoff Beresa river catchment is 149mm and 265.93mm respectively.

4.5.2.5. Sub-Surface out flow

The subsurface 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. The Northwestern tip of the catchment is the only boundary along which groundwater is expected to flow out of the aquifers in the area. The groundwater discharges into the deep valley of the perennial Beresa river. The water surface elevation of the river is about 1715m.a.s.l and it is assumed to be the lowest elevation of water table of the study area, thus the groundwater is drained toward the river.

4.6. Groundwater 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 interrelationship 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 are difficult for the modeling. The study area aquifer system is considered to be homogenous, isotropic, unconfined and one layer with an estimated thickness of 200m which represents the average thickness of the tertiary and quaternary alluvial aquifers.

The compromise analysis of flow of the 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.

Minor aquifers with local and limited groundwater resources are found in mountains forming the peak of the plateau. They are developed along the catchment watershed, particularly along the escarpment. Runoff is relatively fast and infiltration is limited. The rest of the plateau area is covered with various volcanic rocks forming a gently undulating plain that receives adequate rainfall and has moderate run-off resulting in good infiltration and formation of extensive and moderately productive or locally developed and highly productive fissured aquifers. Infiltration is particularly good in areas where the plateau is covered by thick sediments. Aquifers outcropping in the plateau area also feed deeper fissured aquifers developed in underlying rocks.

The groundwater flow direction in the area coincides with the topography following the surface water flow direction because small intermittent and particularly perennial rivers form local watersheds and shallow aquifers. The flow is partly controlled by the structure and partly by the geomorphology of the area. Most of the springs emerging from tertiary volcanic rocks are topographically controlled and others emerge along structures indicating that the groundwater flow is controlled by both factors. Local groundwater flow directions vary from place to place according to the local topography.

Outcrops of deeper aquifers can be found only in deep valleys and therefore the possibility for direct recharge in the Beresa and Gado rivers catchment is limited. These aquifers are recharged from the upper overlying layers. Groundwater flow direction is mainly vertical and only limited groundwater emerges as springs in deep valleys. Utilizing the potential of the extensive fissured aquifers is difficult due to their thick cover. The prevailing vertical groundwater flow results in a lack of springs in the valleys. The limited possibility for direct infiltration and the dominant vertical flow of the groundwater manifested by the lack of springs are the reasons for classifying these layers as low productive aquifers.

5. Numerical Groundwater flow Modeling

5.1. General overview and Modeling Approach

Numerical groundwater flow modeling helps to have a good understanding of the current or to predict the long term tendency of a hydrogeological system and it allows an analysis of the movement of water through hydrogeologic unit that constitute the groundwater flow system.

It is mandatory to have good initial data on boundary conditions, fluxes and aquifer hydraulic parameters for a model to give simulation output that approaches the real situation. In other words, models can only be good if the input data is good enough. Especially, input parameters that have the most control on the model output have to be carefully investigated and correctly estimated. In this work, a shortage of standard hydrogeological data has been encountered especially in downstream parts of the catchment to have good estimates of these parameters but collection and assemblage of relevant hydrogeological data in the conceptual model has been made.

In recent years numerical groundwater flow 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 a hydrogeologic system to any hypothetical scenario or to predict system response. Numerical models describe the entire flow field of interest at the same time providing solutions for as many data points as specified by the user. The area of interest is subdivided into many small areas (usually referred to as cells or elements) and a basic groundwater flow equation is selected to solve for each cell. The solution of a numerical model is the distribution of hydraulic heads at points representing individual cells. Similarly to most groundwater flow models, Numerical groundwater flow modeling of Beresa and Gado rivers catchment was developed in this work, to study the response of the system to different hypothetical scenarios of the withdrawal, recharge, hydraulic conductivity or any other parameters under steady state condition.

This numerical model developing approach includes the definition of system boundary, measuring and compilation of wells and springs withdrawal, compilation of water level data, compilation and develop previously estimated recharge, hydraulic conductivities, base flow, 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.

Groundwater flow of the study area aquifer system is simulated using MODFLOW-2000. MODFLOW is a modular three-dimensional finite-difference groundwater model published by the U. S. Geological Survey. The first public version of MODFLOW was released in 1988 and is referred to as MODFLOW-88. MODFLOW-88 and the later version of MODFLOW-96 were originally designed to simulate saturated three-dimensional groundwater flow through porous media. 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 into a single code. To achieve the goal, code is divided into 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 model, the matrix is solved with Preconditioned Conjugated Gradient 2 (PCG2) and of MODFLOW with convergence criteria 0.001m.

5.2. Governing Equations

Models are simplified descriptions of physical reality and can be verbal descriptions, graphical representations, physical or mathematical expressions. Physical models such as laboratory sand tanks simulate groundwater flow directly, whereas mathematical models simulate flow indirectly by means of a governing equation that represents the physical processes that occur in the system (Anderson and Woessner. 1992). Groundwater flow equations that describe three-dimensional groundwater movement in a porous medium are developed from the application of Darcy's law and the continuity equation. The concept of the continuity equation explains that the sum of all inflows into and out of the cell equals the rate of change in the storage within the cell (McDonald and Harbaugh, 1988). The water balance equation is mathematically combined with Darcy's law to derive the following equation that describes the three-dimensional subsurface groundwater flow process in porous medium (Anderson and Woessner. 1992).

$$\frac{\partial}{\partial x}\left[Kxx\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[Kyy\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[Kzz\frac{\partial h}{\partial z}\right]-W=Ss\frac{\partial h}{\partial t} \qquad Equation\ (5.1)$$

Where: *Kxx*, *Kyy* and *Kzz* are the values of hydraulic conductivity along the *x*, *y* and *z* coordinate axes (L/T)

h is the hydraulic head (L)

W is a volumetric flux per unit volume representing sources and/or sinks of water, where *negative* values are extractions, and *positive* values are injections (LT−1)

SS is the specific storage of the porous material (L−1); and

t is time (T)

In this case, numerical groundwater flow modeling of the Beresa and Gado rivers catchment, 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.

$$\frac{\partial}{\partial x}\left[Kxx\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[Kyy\frac{\partial h}{\partial y}\right]-W=Sy\frac{\partial h}{\partial t} \qquad Equation\ (5.2)$$

Sy 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.

$$\frac{\partial}{\partial x}\left[Kxx\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[Kyy\frac{\partial h}{\partial y}\right]-W=0 \qquad Equation\ (5.3)$$

Where: W is a general sink or source basically positive for to represent recharge and negative for withdrawal of groundwater from aquifer system.

5.3. Spatial Discretization and Grid Layout

In a numerical model, the continuous problem domain is replaced by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells). The nodal grid forms the framework of the numerical model (Anderson and Woessner, 1992). A critical step in grid design is the selection of the size of the nodal spacing as the horizontal dimension depends on the expected curvature in the potentiometric surface and the change in head in the vertical direction influences the vertical nodal spacing. Other factors that influence the size of nodal spacing are the availability of data, variability of aquifer properties and the size of the area to be modeled.

The extent of the study area catchment in the north-south and east-west is 40,000m and 44,000m respectively. This single layer model grid has 200 rows and 220 columns with surface area of 1062.2 square kilometer. A uniform spacing of 200m (both rows and columns) is used, that is each cell is 40,000 meter square. A regular grid has been adopted for the entire catchment and each cell has homogeneous property. The groundwater flow equation discussed above is formulated at the center of each model cell. Flow area and gradient used to determine flow through the cell are determined at the center of each cell and represent the average area and gradient through the cell. Because finite difference model grid must be rectangular, certain cells represent areas outside the modeled area (may have any shape). The model uses a total number of 44,000 cells in which only within the catchment 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. Such inactive cells (Fig-5.1) are identified by assigning a value of "0" to entries of I-BOUND array in boundary condition & groundwater flow equation is not solved for such cells. A single aquifer of one layer system was considered for the purpose of groundwater flow simulation in this study.

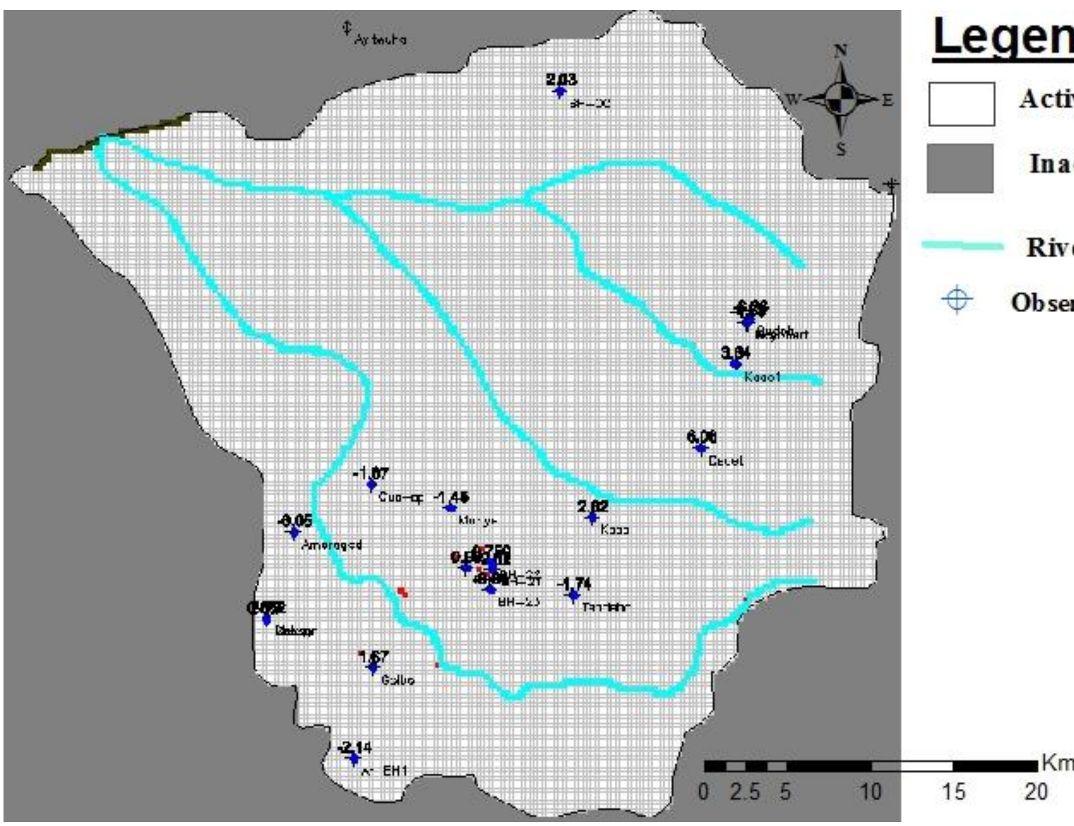

Figure-5.1 Model Grid layout

5.4. Boundary condition

The first 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 correctly.

For groundwater system of the given area, there are two types of aquifer boundaries which control the groundwater flow direction (Anderson and Woessner, 1992). These boundaries are: Physical boundaries of groundwater flow system which are formed by physical presence of an impermeable body of rock or a large body of surface water. Other boundaries form as a result of hydrologic conditions. These invisible boundaries are hydraulic boundaries that include groundwater divides and streamlines.

In groundwater flow modeling, boundary conditions influence the extent of the 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 is 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 this study, the system boundary was carefully assigned based on field visits made and existing works. The geographic boundaries of the Beresa and Gado rivers catchment groundwater flow model approximately corresponds closely with natural hydrologic boundaries across which groundwater flow was assumed to be negligible. This is true for the eastern, northern, southern, and southwestern boundaries of the area. In the eastern boundary of the catchment the model coincides with the Abay and Awash basin water divide. On other sides, the watershed or the topographic divides were assumed to coincide with groundwater divides. It should be remembered that groundwater divide is not 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 Northwestern tip of the study area was represented as head dependent boundary because there is groundwater outflow to the Beresa river gorge. Flux is approximated to occur in this side of the catchment based on the head in the aquifer and the external source head. In this study the head in the external source is lower than the head in the aquifer, so groundwater is expected to be discharged from the aquifer system.

In addition, the upper boundary of the modeled catchment was assumed to be the water table and recharge was used to represent the boundary flux. Although not known to exact, the lower boundary was considered as a no flow because the aquifer was assumed to be underlain with an impermeable rock body.

5.4.1. Top of the Model Layer

As it is explained earlier, in this model the catchment will be treated as single unconfined aquifer which is represented by a two dimensional horizontal model. The top layer elevation was considered to be the elevation of ground surface (topography). The nodal values of ground surface elevation were interpolated from the digital elevation model (DEM) of the model domain was derived from the Shuttle Radar Topography Mission (SRTM) satellite data and specified as the top elevation of the aquifer. The interpolation was done at a resolution of 200m by 200m and then loaded into MODFLOW top elevation array.

5.4.2. Bottom of the Model Layer

The bottom layer elevation is used by the model to identify when a cell is drained or goes dry. The average thickness of the aquifer is estimated from lithologic logs of boreholes and used to derive the bottom elevation from the DEM of the area. In this modeling work, the catchment is represented by an average aquifer thickness of 200m 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. Hence bottom elevation was obtained by subtracting a range of 200-450m from top elevation in most parts of the catchment. In fact, the thicknesses of the aquifer have not yet been determined exactly and were modified a bit in few areas during model calibration process

5.5. Initial and Prescribed Hydraulic Head

Initial and prescribed hydraulic heads are values of the hydraulic head for each active cells and it must be between the top and the bottom of the model layer. It is essential to start the iterative model calculations. In this model, the initial hydraulic heads was obtained by subtracting the depth of water level from the land surface value of the DEM data. The difference increases as topography increases.

Based on this, the initial and prescribed hydraulic head for the model was assigned for each cell of the model layers by the following methods:

- areas where land surface elevation ranges from 1700m-2000m hydraulic head was assigned by land surface elevation minus 10m,
- areas where land surface elevation ranges from 2000m-2500m hydraulic head was assigned by land surface elevation minus 15m,
- areas where land surface elevation ranges from 2500m-3600m hydraulic head was assigned by land surface elevation minus 25m.

5.6. Model Stress and Fluxes

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 fluxes into or out of the aquifer system in the Beresa and Gado rivers catchment of the study area as applied into the model and simulated by MODFLOW 2000 are summarized under the following subsections. Different MODFLOW packages were used to simulate model stresses. The modeled stresses include recharge to the aquifers, discharge to rivers, and well withdrawal and spring discharges, and subsurface outflows.

5.6.1. 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 in to 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 IR to calculate the recharge flow rate QR applied to the model cell:

$$QR = IR * DELR * DELC \qquad \text{Equation 5.4}$$

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

- IR is recharge flux

In MODFLOW, the recharge rate QR is applied to a single cell with in the vertical column of cell. In this model, the top layer is designated as unconfined and an array of recharge flux IR 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.

5.6.2. River Package

The purpose of the River package is to simulate the effect of flow between groundwater systems and surface water features, such as rivers, lakes or reservoirs. One can use water level surface in rivers to predict the mode of interaction of the groundwater and surface water. The one with higher hydraulic head feeds the other with lower hydraulic head provided that there is a material with higher conductance between the river bed and the aquifer. The major perennial rivers were most essential river boundary in the model area that holds the surface water and aquifer system interaction. In the study area Beresa and Gado rivers and its tributaries sustain their dry period of flow with contribution of the groundwater. These rivers also expected to feed the groundwater where the stage of the river exceeds the adjacent aquifer system hydraulic head.

The input parameters are assumed to be constant during a given stress period. Using the Data Editor, a river is defined by using the Cell-by-Cell input methods to assign parameters to model cells. Since the river package requires the input of Head in the river (Hriv), Elevation of the Riverbed bottom (Briv), and river hydraulic conductance (CRIV) to each cell of a river.

The value Criv is obtained by:

$$Criv = \frac{\mathrm{Kriv} * \mathrm{L} * \mathrm{Wriv}}{\mathrm{Mriv}} \qquad \text{Equation 5.5}$$

Where: Kriv is hydraulic conductivity of riverbed (L/T)

L is the length of the river within a cell (L)

Wriv is the width of the river (L)

Mriv is the thickness of the riverbed (L)

In a model cell containing river parameters, the flow rate (Qriv) between the river and groundwater is calculated by Equation 5.6 & 5.7. If the groundwater hydraulic head (h) is greater than RBOT, the leakage rate Qriv from the river to the aquifer is calculated by

Qriv = Criv*(hriv - h)   if h > Briv   Equation 5.6

The value of Qriv is negative if the hydraulic head h is greater than Hriv It means that water flows from the aquifer into the river and is removed from the groundwater system. When h falls below the bottom of the riverbed, the leakage rate through the riverbed is given by:

Qriv = Criv * (hriv - Briv)   if h < Briv   Equation 5.7

Where: Qriv: Flow rate between the river and groundwater (L/T)

hriv : Head in the river(L)

h: Head in the aquifer or the model(L)

Briv : Elevation of bottom of the river bed(L)

By default, MODFLOW saves the calculated flow rates in the BUDGET.DAT, which can be used for water balance calculations.

5.6.3. Well Package

The boreholes in the study area are drilled for the purpose of water supply, the abstraction amount of the boreholes analyzed based on the yield of the boreholes and average daily pumping hours for towns and rural villages. The abstraction of groundwater was simulated using well package. The input parameters are assumed to be constant during a given stress period. In this model pumping wells was defined using Cell-by-Cell input method. The pumping 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 (m3/day) was assigned to the entry. There are no recharging wells.

6. Model Calibration and Sensitivity Analysis

6.1. General Over View

Groundwater flow model calibration is the process of adjusting selected model parameters within an expected range until the difference between model predicated heads and the field observed heads within selected criteria for performance.

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

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

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

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

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

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 Methods

6.2.1. Calibration Targets

The model is calibrated to steady state condition with observed head measured at the available production wells and springs. Unfortunately, the ground water level measurement is taken during the wells construction and inventory time of the water points. Observation points where not evenly distributed throughout the model domain but clustered geographically in D/birhan town area and their peripheries. There were also a few observation points around seladingay town. The model uses 19 calibration targets (wells and springs) within the study area. The model calibration accounts the matching of these observation points with simulated head with a permissible residual head range of ±10m. The criterion set is 100% of the difference between the maximum and minimum measurement water level head in the study area is less than 10m. Groundwater heads contours were constructed from these water levels/heads and matching field contours with calculated contours was made during model calibration.

6.2.2. 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 node 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 manual 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 previous work reviews, point hydraulic conductivity and transmitivity data was used as initial guessing during calibration of hydraulic conductivity.

The model calibration accounts the matching of 19 observation point with simulated head with a permissible residual head of ±10m. The criterion set is all (100%) of the difference of the maximum and the minimum water level head in the study area is less than 10m.

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.

6.2.3. 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.

The calibration results are evaluated by using qualitative and quantitative performance measures. Qualitative assessment (pattern matching) involves comparisons of contour maps and hydrograph of measured and simulated head, while quantitative performance measure involves mathematical or statistical description of residuals (Middlemis, 2001).

The performance of any model should be evaluated by combining both qualitative and quantitative measures. The water balance is one of the quantitative performance measures that are used to check solution accuracy or the total residual error in the calibration solution by comparing total simulated inflows and outflows. The water balance error is expressed in percentage, representing the difference between total inflows and total outflows including change in storage divided by total inflows or outflows. The error should be less than 1% for the entire model to ensure the calibration solution is numerically stable and acceptable (Anderson and Woessner, 1992; Middlemis, 2001).

Lumped-sum comparison methods are the other commonly used quantitative measures employed to measure the average difference of residuals. However, these performance indicators provide lumped measures of calibration that do not indicate the spatial or temporal distribution of the error (Anderson and Woessner, 1992). These methods include mean error of residuals, absolute mean error to the residuals, and root mean squared error.

Accordingly, in this work, steady-state calibration was made using water level observations of 6 wells and 13 springs. The effectiveness of calibration was evaluated by visual matching of measured groundwater level contours with simulated ones, the water balance error and lumped quantitative performance measures such as the mean error, the mean absolute error, and the root mean square error.

6.2.3.1. 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, drawdown, and 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 (hm) and simulated heads (hs), and n is the number of calibration value.

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

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 head error of -0.88m 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.

$$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}|(\mathrm{hm}-\mathrm{hs})\mathrm{i}|$$

It is the measure of the average errors in the model. The model results an absolute residual mean error of 3.25m head which is below 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.

$$RMS = \left\{\frac{1}{n}\sum_{i=1}^{n}(hm - hs)_i^2\right\}^{0.5}$$

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 3.93m error of standard deviation which is good range in calibrations.

Table 6.1 Comparison of Calculated and Observed Head Values for Steady-state Simulation

Head Observations	**Calculated Head (C)**	**Observed Head(O)**	**O-C**	**|O-C|**	**(O-C)^2**
GUS-SP	2482.673	2481	-1.67	1.67	2.80
WEYN	2984.628	2980	-4.63	4.63	21.42
KOSO	2808.179	2811	2.82	2.82	7.96
MEKGN	2777.338	2778	0.66	0.66	0.44
AMORAGED	2496.053	2490	-6.05	6.05	36.64
GUDOBERE	2986.262	2980	-6.26	6.26	39.21
BH-3	2781.15	2782.08	0.93	0.93	0.86
BH-21	2790.226	2788.21	-2.02	2.02	4.06
BH-22	2786.561	2787.32	0.76	0.76	0.58
BH-23	2797.444	2788.8	-8.64	8.64	74.72
BH-00	2816.621	2818.65	2.03	2.03	4.12
AR-BH1	2795.737	2793.6	-2.14	2.14	4.57
GUDOBERT	2984.713	2980	-4.71	4.71	22.21
DEDET	2916.944	2923	6.06	6.06	36.68
KOSO1	2973.156	2977	3.84	3.84	14.78
MUZIYE	2702.445	2701	-1.45	1.45	2.09
CHEKGN	2777.269	2781	3.73	3.73	13.92
TENDEHA	2823.745	2822	-1.74	1.74	3.05
GOLBO	2787.327	2789	1.67	1.67	2.80
			-16.81	61.82	292.89
			-0.88	**3.25**	15.4152
			ME	AME	**3.93**
					RMS

6.2.3.2. Plotting Calibrated Results

There are three types of plots which are useful in assessing the quality of calibration simulations.

6.2.3.2.1. The scatter plot Calibrated Result

The first is the scatter plots where observed values are plotted versus the simulated values 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 ±10mts.

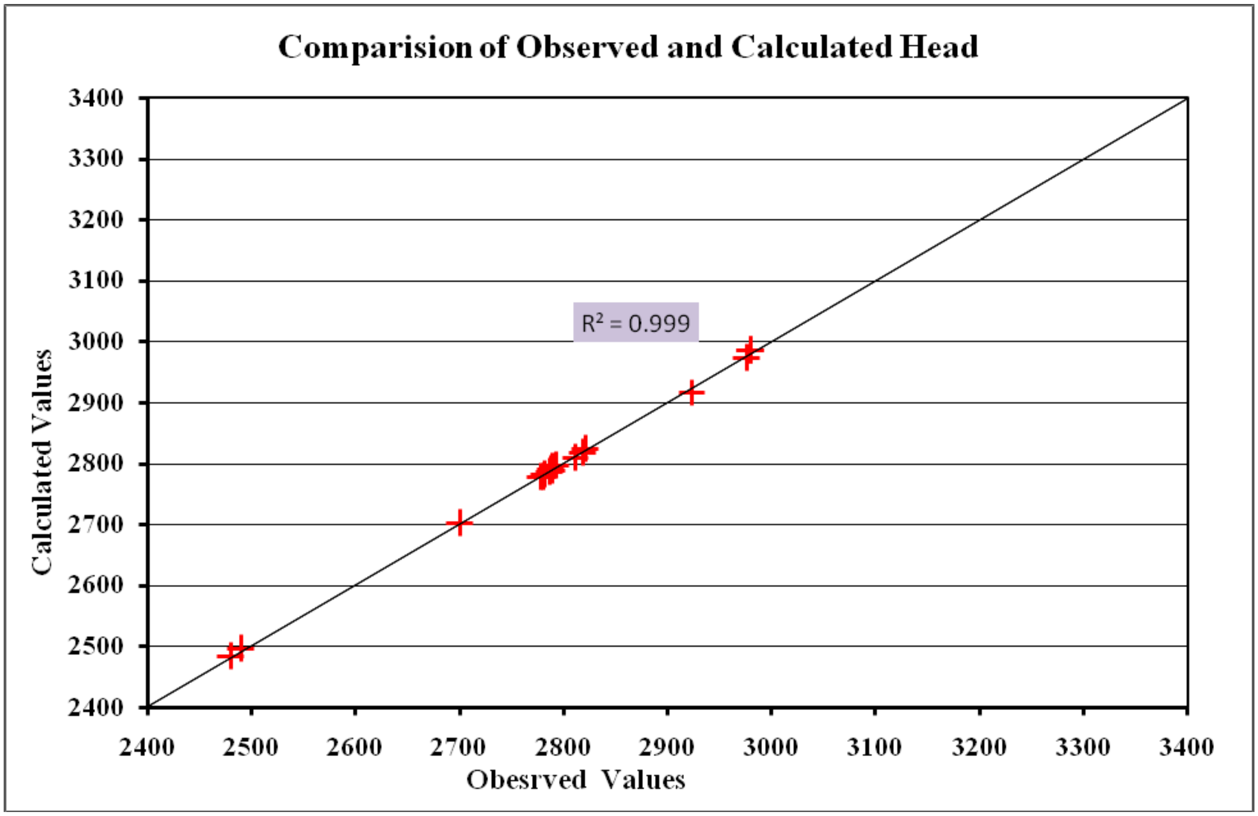

Figure 6.1 Scatter Plot of Head Distribution of Calibrated Model

6.2.3.2.2. 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 of occurrence. Absolute head difference above 10m can be attributed to uncertainty in estimated stresses and hydraulic parameters.

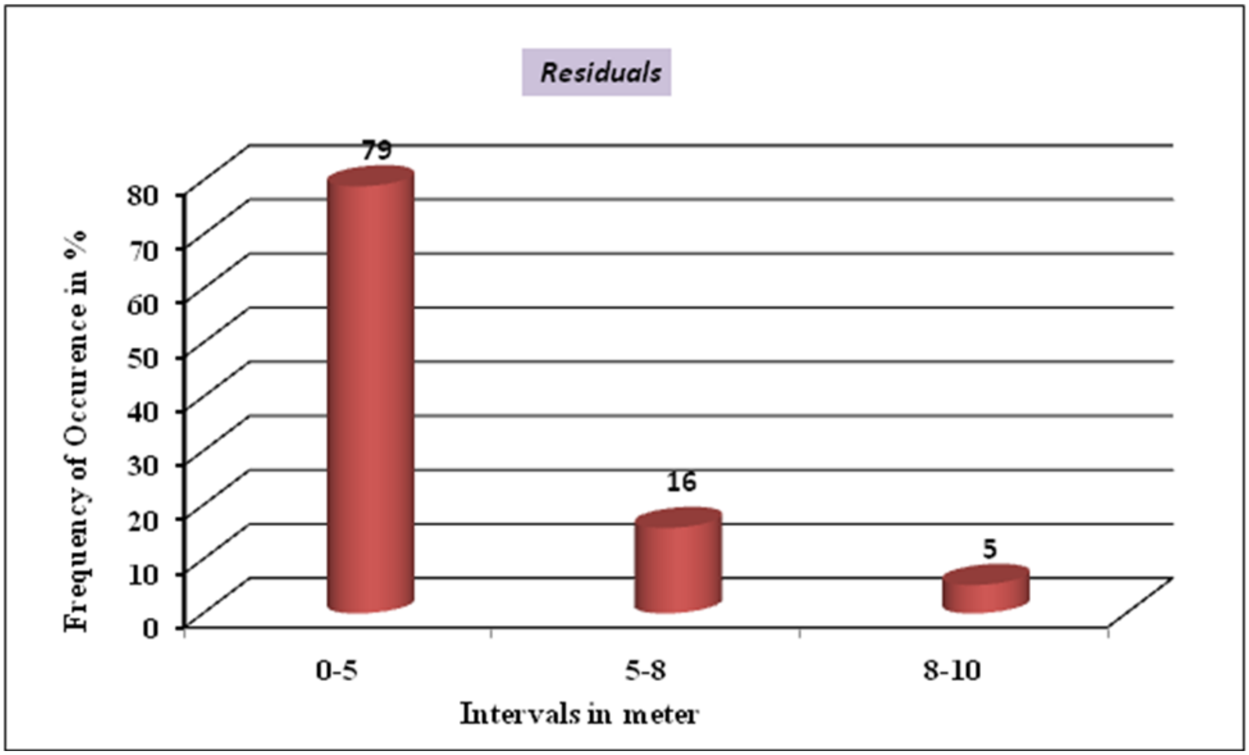

Figure 6.2 Histogram showing the frequency of error distributions

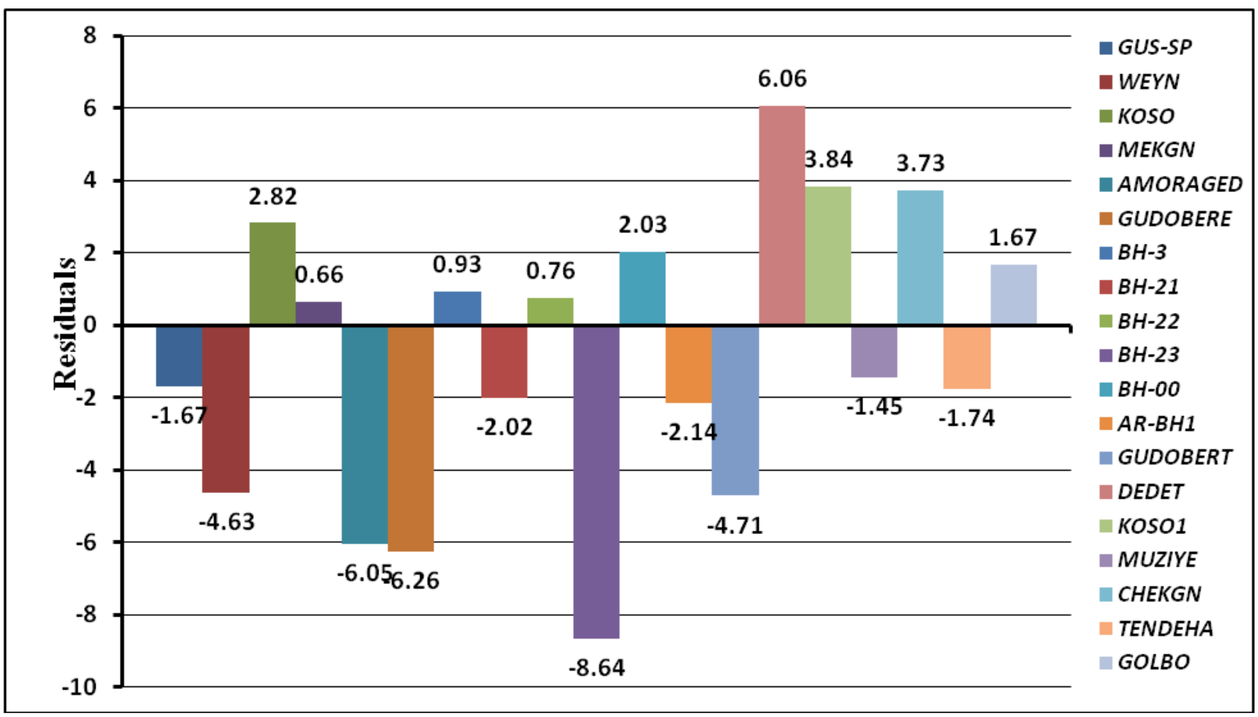

Figure 6.3 Histogram showing error distributions

6.2.3.2.3. **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 too high or too low

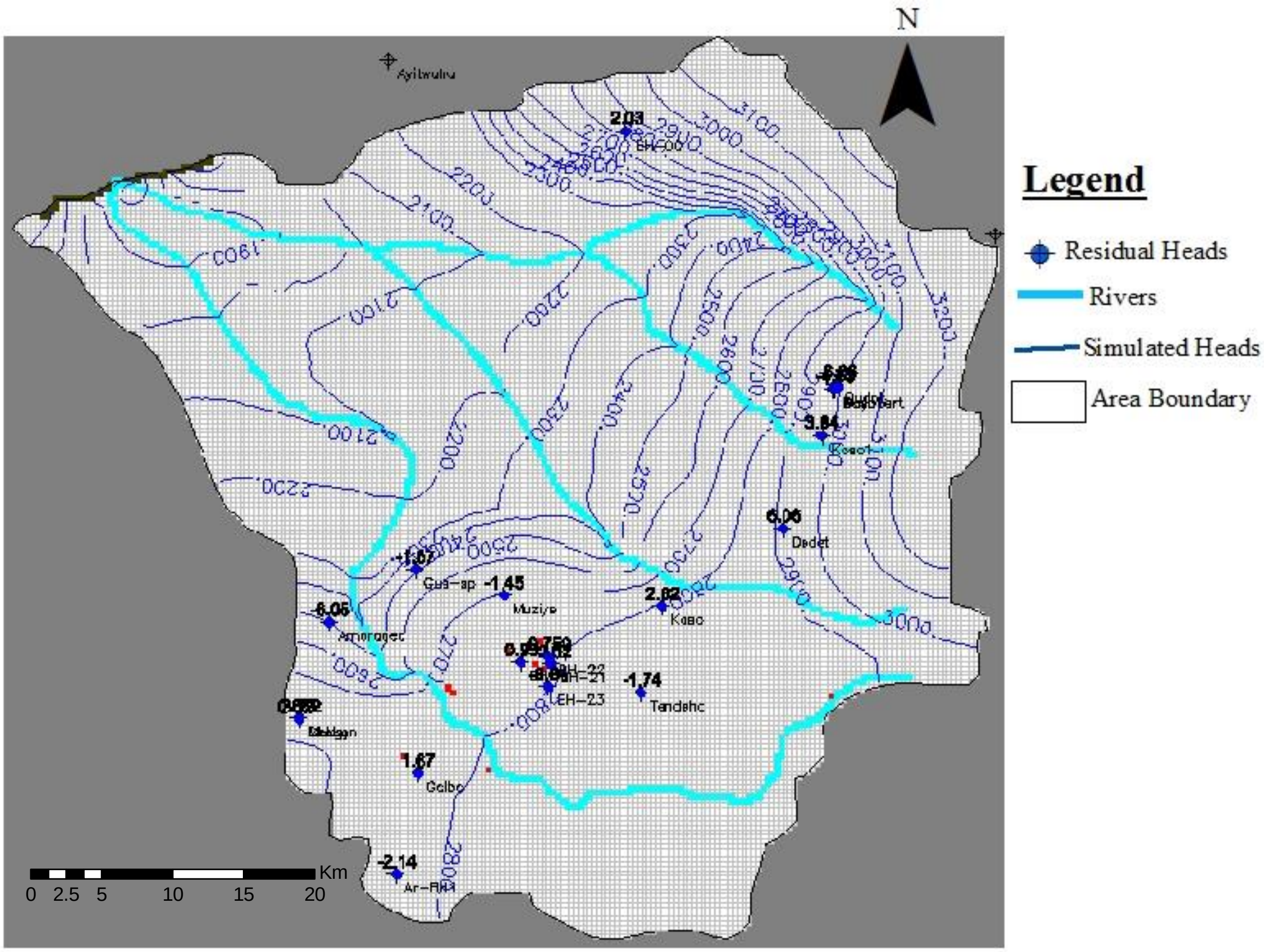

Figure 6.4 Post residual of target wells of the model

6.3. 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 reasonable 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 is the processes of identifying the model parameters 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 calibration process, the model is very sensitive in both changes in recharge and hydraulic conductivity and less sensitive to river bed conductance.

The calibrated value of recharge, hydraulic conductivity, and river bed conductance were varied by 5%, 15%, 50%, and 90% increase and decrease at different times to test the sensitivity of the model to the parameters. The totals of twenty four model runs were conducted by changing the above listed parameters by specified percent. When the parameters increased in the specified percent the model is more sensitive to recharge, moderately sensitive to hydraulic conductivity and less sensitive to river bed conductance. Whereas the parameters decrease as the specified percent the model is more sensitive to hydraulic conductivity, moderately sensitive to recharge and less sensitive to river bed conductance and the respective head mean error, mean absolute error and root mean squared error changes from the calibrated are shown in the table 6.2 and figure 6.4 below.

In all sensitivity analysis, it was observed that the model was less sensitive to parameter change in plateau and sediment aquifer (southern and northern part of the catchment) compared with volcanic aquifers in the escarpment and valley area (western and eastern part of the catchment), that is, absolute mean water level changes were minimal to sediment plateau in all sensitivity simulation. The sensitivity of the volcanic and sediment aquifers to change of all the above listed parameters has been shown in the table 6.2

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

Table 6.2 Result of Sensitivity Analysis test on water level

Change in Parameters in %	ME, MAE and RMS Values for the Parameters								
	Hydraulic Conductivity			Recharge			River Bed Conductance		
	ME	MAE	RMS	ME	MAE	RMS	ME	MAE	RMS
90%	47.29	47.29	65.45	-69.11	69.11	97.07	-1.04	4.99	6.61
50%	30.84	30.85	42.26	-39.98	40.05	56.93	-0.87	4.58	6.00
15%	10.54	11.33	16.05	-12.90	13.66	18.99	1.57	3.60	5.14
5%	3.30	5.68	7.10	-3.25	5.28	6.56	-0.60	3.91	5.08
0%	-0.88	3.25	3.93	-0.88	3.25	3.93	-0.88	3.25	3.93
-5%	-4.70	6.57	8.25	3.67	5.81	7.43	0.63	3.89	5.02
-15%	-14.06	14.87	21.06	16.93	17.75	33.66	0.09	3.50	4.49
-50%	-69.25	69.25	101.69	48.99	48.99	70.78	1.88	5.17	5.69
-90%	-274.31	274.31	345.70	84.32	84.32	118.72	48.71	12.16	13.18

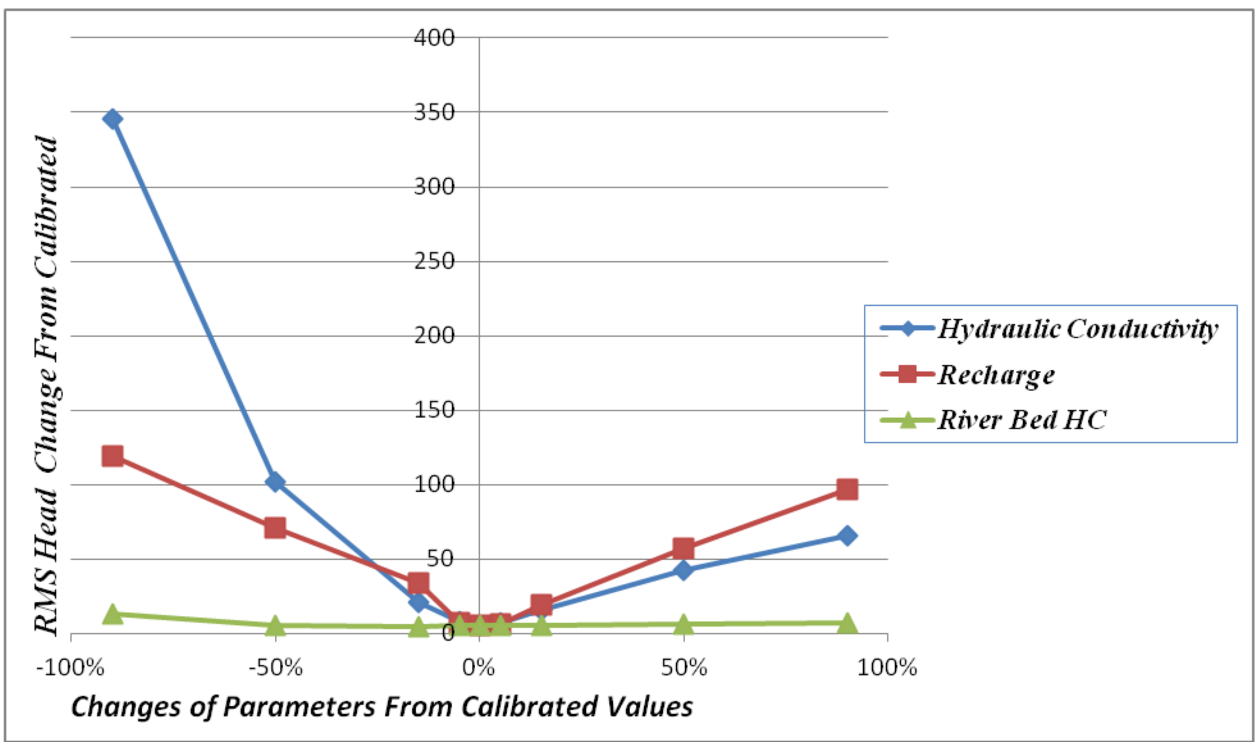

Figure 6.4 Plot of the result of sensitivity analysis test on heads.

6.4. 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 inflow of the model is 1.3466171E+06m^3/day which is nearly equal to simulated outflow1.3465134E+06m^3/day with difference 1.0364551E+02m^3/day and 0.01% of error. The river leakage simulated discharge holds 94.3% of the out flow. It also contributed as recharge in to the aquifer that accounts to 54.98% of the inflow. This share of river leakage implies the recharge of the groundwater dominantly from the losing streams and high interaction of surface and aquifer systems.

Table 6.3 Detail water budget analysis of the study area

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Water Budget of the Whole Model Domain in M^3/Day:

==

Flow Terms	In	Out	In-Out
Wells	0.0000000E+00	1.1344319E+04	-1.1344319E+04
Recharge	5.4283881E+05	0.0000000E+00	5.4283881E+05
River Leakage	7.4038100E+05	1.2698649E+06	-5.2948388E+05
Head Dep. bounds	6.3397254E+04	6.5304227E+04	-1.9069727E+03
Sum	**1.3466171E+06**	**1.3465134E+06**	**1.0364551E+02**
Discrepancy [%] 0.01			

In the study area, the 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 flow follows the topographic contour and it coincides with surface water flow.

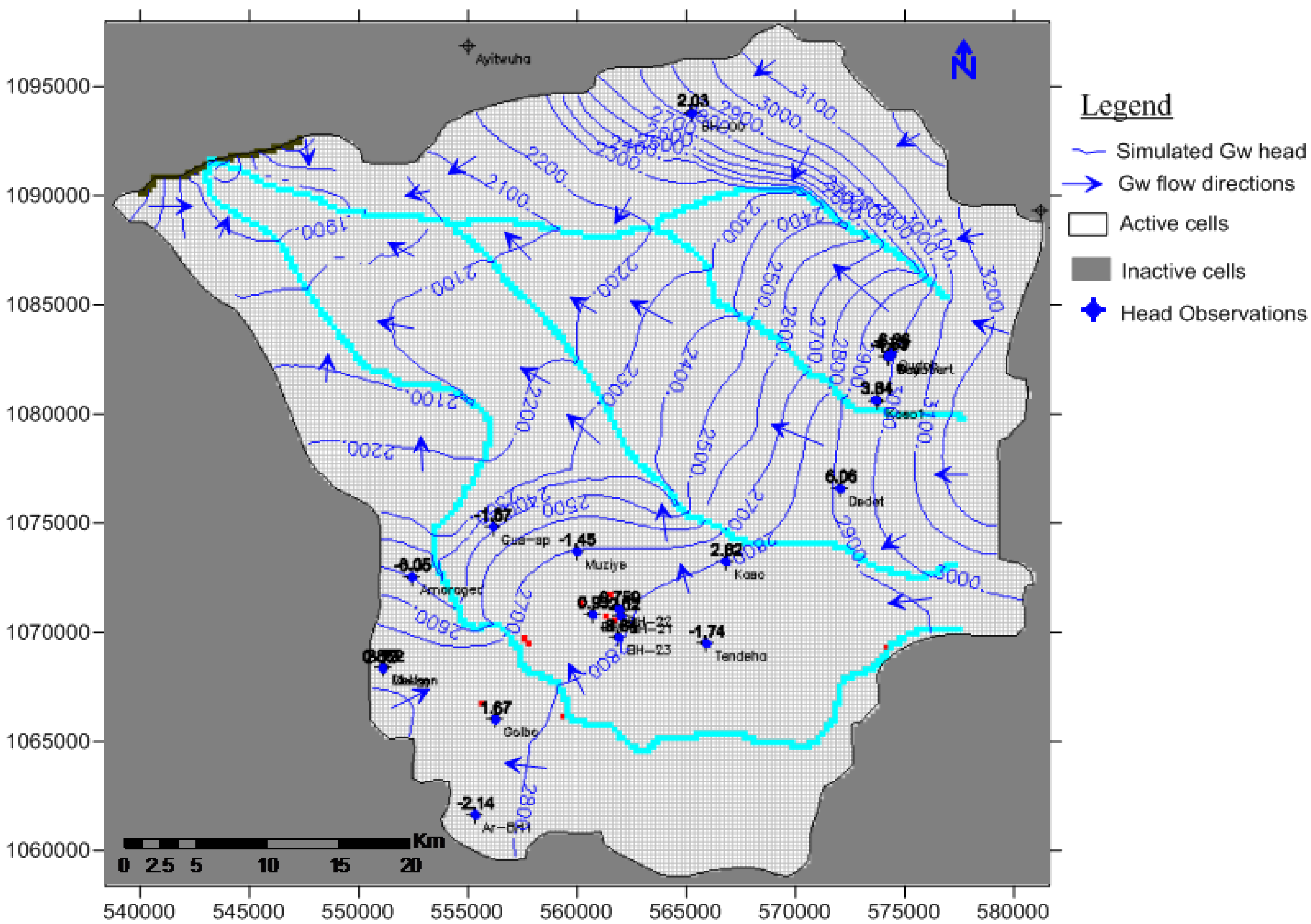

Fig 6.5 Groundwater head contour and flow direction

6.5. Scenario Analysis

The main advantage of numerical groundwater 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 river leakage, water table elevation and subsurface outflow in the new scenario simulation.

Changes in water levels and fluxes caused by increased groundwater withdrawal in the whole catchment and especially the effective of local increase groundwater withdrawal of Debrebirhan town well fields 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.

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 all scenarios, other model parameters were kept to the steady state values except the stress for which the projection was carried out and the resulting changes in water levels and fluxes were interpret as the response of the system to the changes introduced on it. In the following sections, result of each scenario is discussed.

6.5.1. Effects of Increased Groundwater Withdrawals

Debrebirhan and other small towns are expanding; industries or factories are flourishing in the study area, it is reasonable to assume that the water demand will increase as well. To meet this increasing demand, it is must that the existing boreholes should be pumped at greater rates or new boreholes with higher capacity should be drilled in the future. Thus, 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 an appropriate water management practices that could mitigate the likely adverse effects of increased withdrawal may be proposed.

The demand of groundwater, in terms of both quantity and quality has increased rapidly, not only for drinking water source, but also industrial and agricultural uses. In addition to these, the recently ever-growing groundwater utilization associated with rapid population growth, industrial water demand and the trends in expanding future proposed projects demanded testing of the system for different scenario that will assist in the development and management of groundwater.

Current and the projected future water demand of the catchment shows that the demand of water will increase in each five year on average by 60%. The per capital water demand will also vary with time. The main reasons are the improvement of living condition or standard of the population.

Population projection

The present population of the catchment is about 187,335 according to North Shoa Zone Finance and Economic development office.

The future population is calculated by the formula

$P_n = P_p\,(1+G)^n$ Where Pn = population at the n-year

Pp = present population

G = annual growth rate (4.1%)

n = year (up to 15 year)

Table 6.4. The Current and Future Water Demand of the catchment

no	***Description***	***Year***			
		2013	2018	2023	2028
1	Population	187,335	229,019	279,979	342,378
2	Average Domestic Water demand (l/c/d)	20	25	30	40
3	Domestic Water Demand(DWD) (P_n* capital water demand) in m^3/d	3,747	5,725	8,399	13,695
4	Public Water Demand(20% of DWD) in m^3/d	749	1,145	1,680	2,739
5	Industria1 Water demand (10% DWD) in m^3/d	375	573	840	1,370
6	Agricultural water Demand(10-100 h/r) in m^3/d	864	1,728	4,320	8,640
7	***Total Water Demand (3+4+5+6) in m3/d***	***5,735***	***9,171***	***15,239***	***26,444***

So, using the flow model, the scenarios of increased groundwater withdrawals were tested. In this scenario, three increased withdrawal rates were simulated by considering all active wells in the catchment and the increased withdrawal 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 11,344.32m^3/d. Therefore, 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 the stress continues, the increasing groundwater pumping will begin to reduce natural discharge of groundwater. This can be manifested by reduced stream leakages, spring discharges, and subsurface groundwater outflows.

The steady state withdrawal rate was increased by 20%, 75% and 150% to study the response of the system in this scenario. These increases are equivalent to withdrawing additional 2268.86m^3/d, 5672.16m^3/d and 17,016.48m^3/d over the whole catchment, respectively and the increased withdrawals were distributed among the existing wells. Model simulated results of river base flow, water table elevations and subsurface outflow in the scenarios were compared with model calculated steady state results, and the differences showed the response of the system to the assumed scenarios.

Accordingly, increasing the steady state withdrawal rate by 20% resulted in reductions of river leakage by about 0.08%, subsurface outflow by 0.1% and average ground water level by 1.1m compared to the steady state value. Increasing the steady state well discharge by 75% resulted in reductions of river leakage by 0.28%, subsurface outflow by 0.37% and average water level by 4.16m (with a maximum of 16.98m and a minimum value of 0.007m). Similarly, increasing the steady state withdrawal by 150% resulted in reduction of river leakage by 0.56%, average ground water level by 8.41m, and subsurface outflow by 0.74%. This result is summarized in table 6.4.

Thus, additional groundwater pumping would most likely result in a decline of groundwater levels (loss of storage) and a reduction in natural discharges based on the intensity of pumping (shown in figure 6.6 and 6.7). These observed changes simply represented regional effects of the proposed groundwater withdrawals. In fact, water levels in individual pumped wells are 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 diminished relative to the regional representative value. From the above three simulation results, one can observe that the development of new groundwater sources would not pose appreciable impact in case of 20% increase in withdrawal as the head decline in this case is insignificant relative to the steady state withdrawal rate and the natural discharges were not altered highly.

Table 6.5 System response to increased groundwater withdrawal

No.	Increase in groundwater withdrawal from steady state value, in %	Change in head, in m /Drawdown/	Change in river leakage		Change in sub surface outflow(Reduction)	
			in %	m3/day	in %	m3/day
1	20	1.1	0.08	962.5	0.1	1306.4
2	75	4.16	0.28	3563.4	0.37	4944.8
3	150	8.41	0.56	7104.9	0.74	9907

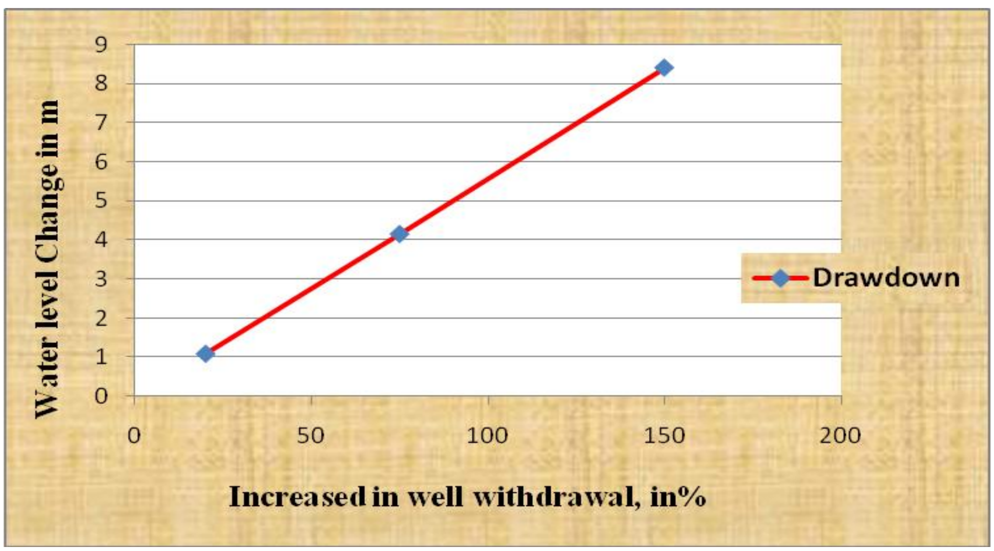

Figure 6.6 Trend of System Response to Increased Groundwater Withdrawal Rates for water level

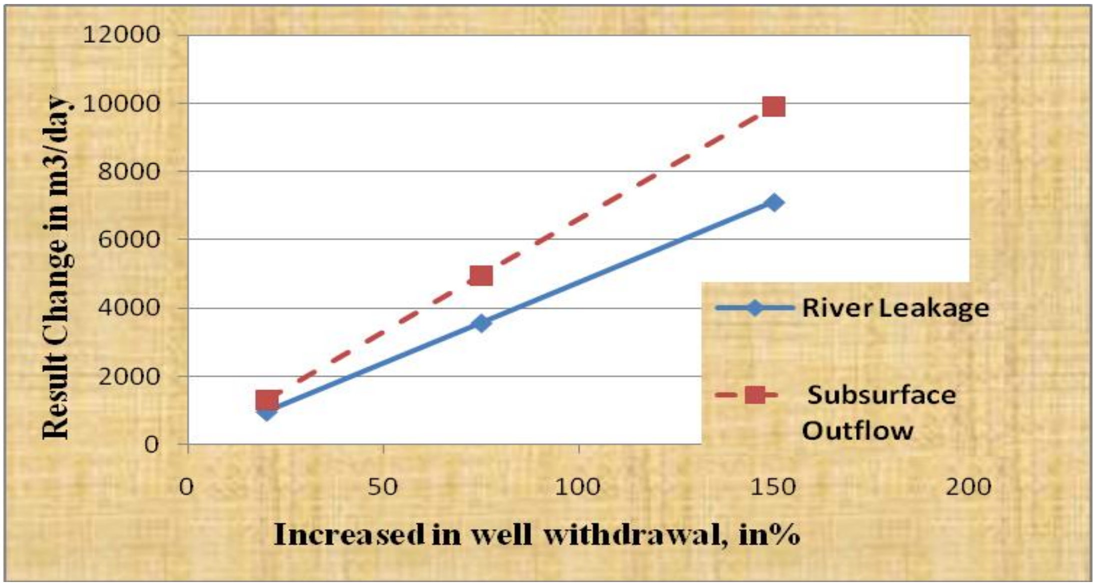

Figure 6.7 Trend of System Response to Increased Groundwater Withdrawal Rates for River leakage and Ssubsurface outflow

Generally, if future water demand conditions force groundwater to be withdrawn at rates simulated in these scenarios, other parameters not changed, there will be hydrologic imbalance between groundwater inflow and outflow conditions that may cause sustainable decline in groundwater level. This in turn results not only in source depletion but also may cause pollutants to enter the groundwater system from polluted surface water sources.

6.5.2. Effects of Altered Recharge

In 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.

Therefor in this scenario the simulated response of the system to decreased recharge was compared with the steady state simulated water levels the differences showed changes induced due to the decrease recharge. The steady state simulated recharge was decreased by 15%, the simulation result shows on average head decrease of 11.61m over the whole area. Decreasing the recharge by 50% the simulation result shows on average head decrease of 45.78m over the whole area.

Therefore the decreasing of recharge has adverse effect on the groundwater table. So, solutions should be forwarded to tackle such environmental unfriendly problem. In this catchment there are some artificial recharge structures that used to facilitate infiltration and other different remedial measures should be developed to increase the recharge of the catchment that flourishes water to the ground and the river. Some of the most important measures that should be taken are decreasing the expansion of agriculture, afforestation, constructing soil and water conservation structures.

6.6. Model Limitation

Model is a tool that approximate the real system or field condition, 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.
- 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 and springs mostly found at the southern and northern parts of the catchment and not well spatially distributed. Some of the wells water level measurements were recorded during construction time. So uncertainties are expected due to unevenly distribution of targets 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 help to understand how the system will respond to new stresses and should not be considered as exact prediction.

7. Conclusion and Recommendation

7.1. Conclusion

This research describes a conceptual model of groundwater flow in the aquifer and calibration of a numerical model to simulate groundwater flow. The approaches to achieve the objective of the research involve data collection, analysis and synthesis with understanding the flow system of the Beresa and Gado rivers catchment with the very deterministic and numerical model which approximates physical law with finite difference. It is a method developed by US Geological Survey (McDonald and Harbaugh, 1988). The study area boundary was delineated from 30m Shutter Radar Terrain Mapping (SRTM) digital elevation model (DEM) using Global Mapper 12 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.

Fundamental input parameters used for conceptual model development, MODFLOW simulation and calibration of the steady state groundwater model required layer top elevation taken from DEM and layer bottom elevation is found by subtracting the aquifer thickness which varies from 200 to more than 450 meter. The dominant aquifers property of the study area is unconfined. The second input to the model is boundary conditions, for active cell 1 is assigned which includes all working area, for inactive cell 0 is assigned for area outside the catchment. The other input parameter is initial hydraulic head that is specified to each cell and the first steady-state simulation uses initial and prescribed hydraulic head by subtracting 10-25m from top of layer. The other important parameter in the model is horizontal hydraulic conductivity and for first simulation a value of 0.00104m/day to 7.272 m/day is used. The flow packages treated in the model are recharge, wells, general head boundary, and river package. In recharge package recharge from direct precipitation is specified to each cell that varies from 0.000219 m/day in Western desiccated valleys of the catchment to 0.000334 m/day in Southern and Northern High land plateau. In well package 20 abstraction wells are treated varying from 129.6m3/day to1468.8 m3/day in a cell. The Beresa and Gado rivers are treated with river package and the outflow the in northwestern part of the rivers is also simulated by general head boundary.

The model calibration accounts the matching of 19 observation point heads with simulated heads with a permissible residual head of ±10m. And 100% of the difference (observed and calculated water level) heads in the study area is below 10m. The model was calibrated with mean error

-0.88, absolute mean error 3.25m, standard deviation 3.93m, and variance 14.95. The calibration was done by adjusting hydraulic conductivity, recharge, and river conductance.

The sensitivity of the major parameters of the model was identified during calibration process. Based on the calibration process, when increasing recharge, hydraulic conductivity, and stream bed conductance, the model is more sensitive to recharge, moderately sensitive to hydraulic conductivity and less sensitive to river bed conductance. Whereas decreasing the same parameters, the model is more sensitive to hydraulic conductivity, moderately sensitive to recharge, and less sensitive to river bed conductance.

The numerical groundwater flow modeling is empowered with computation of water budget. The simulated inflow of the model is 1.3466171E+06m^3/day which is nearly equal to simulated outflow1.3465134E+06m^3/day with difference 1.0364551E+02m^3/day and 0.01% of error. The river leakage simulated discharge holds 94.3% of the out flow. It also contributed as recharge in to the aquifer that accounts to 54.98% of the inflow. This share of river leakage implies the recharge of the groundwater dominantly from the losing streams and high interaction of surface and aquifer system.

In the catchment the 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 flow 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 and altered recharge have been conducted. In the first scenario, three increased withdrawal 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 11,344.32m3/day. Steady state withdrawal rates were increased by 20%, 75%, and 150%, to study the response of the system in this scenario. These increased are equivalent to withdrawing of additional 2268.86m3/d, 5672.16m3/d and 17,016.48m3/day over the whole catchment respectively. From the above three simulation results, one can observe that the development of a new groundwater sources would not create appreciable impact in case of 20% and 75% withdrawal, the head declines in this case is insignificant relative to the steady state withdrawal rate which is an average decreasing of 1.1m to 4.16m respectively and the natural discharges were not altered highly. But increased groundwater withdrawal by 150%, the water tables decline with an average by 8.41m in head observation, this can affect highly the natural discharges.

The second 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. The steady state simulated recharge was decreased by 15% and 50% the simulation results showed on average head decrease of 11.61m and 45.78m over the whole area. As it has been seen the decreasing of recharge has adverse effect on the groundwater table. So, solutions should be forwarded to tackle such environmental unfriendly problem.

7.2. Recommendation

The general objective of the study is numerical simulation of the groundwater flow system of the Beresa and Gado rivers catchment 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. So, solutions should be forwarded to tackle such environmental unfriendly problem. The most important measures that should be taken are decreasing the expansion of agriculture, afforestation, constructing soil and water conservation structures etc.
- 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 and recharge maps with better accuracy, because the prepared hydraulic conductivity map is produced based on the collected pumping test data from regional water bureau, and were corrected during

calibration. And the initial recharge for the model was taken from previous work and the recharge map is prepared by considering the geomorphology of the area

- To represent the system in a more realistic condition, it is important to divide the aquifer system into different layers and estimates their respective hydraulic conductivity parameters.
- Although numerous boreholes were constructed by different bodies (governmental, non-governmental organizations, individuals, firms, etc.), a central groundwater database, either in a national and/or regional level should be established to organize the records generated during the construction of these wells. Data should be collected in a standardized and systematic manner.

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Annex-1 List of Water points within and around the study area

1. Wells and its Discharge

Id	Locality	N	E	Elva	Depth	SWL	yield	K	T	Lithology
BH-2*	Beresa	559277	1067055	2766	100.5	6.25	15		98.8	Rhyolite/ignimbrite
BH-3*	Dalecha	560716	1070578	2790	108	7.92	12		165.6	Rhyolite/trachyte
BH-4	D/Birhan	560171	1071077	2801	153	11.72	1.5	0.05	1.54	Ignimbrite
BH-21*	Dalecha	562016	1070480	2801	108	12.79	7		10.8	Ignimbrite/trachyte
BH-22*	Dalecha	561928	1070820	2799	95.56	11.68	8		98.064	Ignimbrite/trachyte
BH-1	Chacha	548910	1053759	2784	80		5			Ignimbrite/basalt
BH-11	WV/ADP/	549590	1055218	2790	90					Ignimbrite
BH-12	Bakelo	569176	1072153	2847	50	12.5	3			Rhyolite/ignimbrite
BH-15	Tsdkane	569688	1099723	2829	184		3			Rhyolite/ignimbrite
BH-16	Chacha	550872	1054157	2778	96	6.6	5		0.1	Ignimbrite/basalt/sand
BH-23*	Dalecha	561901	1069500	2798	125	9.2	4	0.05	0.00104	Ignimbrite/trachyte
BH-24*	Dalecha	574362	1069000	2795	150	7.4	3.5		0.06	Trachyte/ignimbrite
BH-25*	Dalecha	561507	1071446	2797	72	11.45	15		244.6	Trachyte/ignimbrite
BH-26	Dalecha	561688	1070292	2800	70	6.66	5			Ignimbrite
BH-27	Dalecha	561233	1070521	2796	83	6	5			Trachyte/ignimbrite
BH-28*	Beresa	559242	1066637	2760	92	6.25	17		266.4	Rhyolite/Ignimbrite
BH-29*	Beresa	559340	1065876	2765	102	8	15		76.9	Rhyolite/ignimbrite
BH-00	Aysofe	565324	1093842	2851	151	32.35	7.2	0.636	37.44	Basalt
Arari-1	D/birhan	555236	1061291	2802	98.42	8.4	7		0.0478	Trachyte
BH-01	Marine camp	555400	1066500	2785	90	11.9	4			Ignimbrite/trachyte
BH-02	TTI	557442	1069410	2800	67	33.5	3.5			Ignimbrite/trachyte
BH-03	Divine ProS	557750	1069300	2785	111	29.6	1.6			Ignimbrite/trachyte
Go01	Goshebado	547775	1076918	2772	175	91.86	3.25	0.3056	11	Ignimbrite/trachyte
STBH-1	Seladingay	564836	1097392	2865	100	27.3	14	203.04	5.8896	Ignimbrite
STBH-2	Seladingay	565227	1097476	2868	119	28.45	5	11.7072	0.32544	Ignimbrite

2. Hand dug wells and its Discharges

Name	E	N	Elv	Discharge	
				L/sec.	m3/day
Kirte	546891	1076728	2782	0.33	9.504
Eri-begilo	554622	1058987	2798	0.38	10.944
Koso-Meda	566882	1073028	2811	2	57.6
Al-ski	544627	1065010	2749	0.33	9.504
Alalat	545703	1064414	2761	0.34	9.792
Gebi	542588	1059208	2745	0.5	14.4
Guya minch	547501	1067737	2768	0.5	14.4
Mekegn	550969	1069087	2778	6	172.8
Gamegna	567260	1076524	2807	0.412	11.8656
Godguadit	577339	1069388	3237	0.33	9.504
Weyira	548509	1070973	2767	0.37	10.656
USAID	549961	1068788	2775	0.33	9.504
Grar	549981	1071109	2774	0.3	8.64
Berye	563580	1072744	2851	0.4	11.52
Abdel	563290	1073108	2857	0.4	11.52
Chefa	571078	1067470	3083	1.3	37.44
krcha	546891	1076728	2782	0.33	9.504
Eribe	554622	1059185	2798	0.38	10.944
Ribrib	572865	1066380	3104	1	28.8
Durmesk	575843	1068454	3161	1	28.8
Duri	575435	1068760	3159	1	28.8
Belg	577867	1069844	3249	1.1	31.68
Regreg	554631	1068650	2777	0.3	8.64
Mesno	563618	1069081	2798	4	115.2
Tulu	563354	1070119	2802	3	86.4
Fila	545771	1099228	2680	0.45	12.96
Kechine	568094	1097991	2867	0.392	11.2896

3. Springs and its Discharges

Name	E	N	Elv	Disharge	
				L/sec.	m3/day
Shola	572829	1054165	2600	0.71	61.344
weses-wuha	573612	1058005	2885	1.25	108
Margja	574549	1056695	2790	1.2	103.68
Bahir-zaf	574710	1058851	2800	0.5	43.2
May mekjia	579142	1063556	3203	0.5	43.2
Shinet	573224	1083428	2939	0.689	59.5296
Likanos	570212	1079376	2898	0.42	36.288
Dedet	572197	1076436	2923	1	86.4
Chefa	575470	1074346	3245	0.33	28.512
Abo-tsebel	562560	1074854	2726	0.494	42.6816
Wentaf	530353	1092025	1946	0.339	29.2896
Bein	574438	1082548	2980	4.7	406.08
Koso	573847	1080517	2977	4	345.6
Ahiya Megalebia	577504	1080703	3374	0.498	43.0272
Mesk	570391	1054678	2669	0.35	30.24
Gus	556073	1074643	2481	0.5	43.2
Mesk	570391	1054678	2669	0.35	30.24
Shir	572829	1054165	2600	0.711	61.4304
Weses	573612	1058005	2885	1.25	108
Mefgeja	574549	1056695	2790	1.2	103.68
Mitak	574710	1058851	2800	0.5	43.2
Mesno	553212	1059185	2799	0.5	43.2
Dansa1	553995	1087228	2190	0.3	25.92
Mekawnz	553711	1087408	2180	0.33	28.512
Weyn	574438	1082548	2980	4.7	406.08
Timch	540010	1066311	2770	0.32	27.648
Koso	566882	1073028	2811	1.5	129.6
Mehl	574998	1062948	3121	0.52	44.928
Totat	545291	1062694	2774	0.3	25.92
Mekgn	550969	1068087	2778	6	518.4
Wekegn	549941	1069894	2772	0.4	34.56
May	579142	1063556	3203	0.5	43.2
Guduad	577339	1069388	3237	0.33	28.512
Kus	573847	1080517	2977	4	345.6
Shint	573224	1083428	2939	0.7	60.48
Ahiyamega	577504	1080703	3374	0.5	43.2
Likanos	570212	1079376	2898	0.42	36.288
Dedetm	572197	1076436	2923	1	86.4

Ayino	550199	1071887	2768	0.31	26.784
Amoraged	552312	1072332	2490	1.04	89.856
Enjir	571798	1075110	3055	0.675	58.32
Chefa	575475	1074876	3245	0.33	28.512
Abotse	562560	1074854	2726	0.5	43.2
Akdela	563290	1073108	2857	0.4	34.56
Shinkurt	576957	1071617	3305	1	86.4
Guramba	575980	1067965	3206	1	86.4
Wentaf	530353	1092025	1946	0.34	29.376
Gudoberet	574438	1082548	2980	4.7	406.08
Faji	553301	1062284	2891	0.77	66.528
Zanjira	559620	1075959	2745	0.3	25.92
Muziye	559956	1073509	2701	1.5	129.6
Kore	561174	1074960	2728	0.3	25.92
Chekegn	550966	1068090	2781	5	432
Tikurgedel	550207	1072883	2764	0.3	25.92
Weldetnsa	552839	1069677	2776	0.5	43.2
Tulu	550260	1066583	2780	0.3	25.92
Adade	553979	1067425	2808	0.4	34.56
chele	555193	1071938	2776	0.4	34.56
Tendeha	565976	1069251	2822	1	86.4
Awale	563401	1070100	2997	2	172.8
Harater	564823	1066332	2835	3	259.2
Tachburl	563619	1069164	2797	3	259.2
Atakilt	561596	1067148	2845	0.3	25.92
Qura	562460	1066161	2937	0.5	43.2
Meka	561540	1064838	2781	3	259.2
Mesno	560753	1065629	2768	1	86.4
Golbo	556178	1065700	2789	3	259.2
Misreta	557532	1066308	2765	0.5	43.2
Talale	563647	1097841	2836	0.476	41.1264
Ameraro	563040	1100379	2789	0.5	43.2
Mesno-amba	558811	1099015	2747	0.33	28.512
Jor	563387	1099517	2834	0.33	28.512
Lemesk	561062	1099419	2794	1.125	97.2
Mesno-mi	569660	1097055	2856	0.354	30.5856
Mehal-wenz	567246	1098833	2863	0.36	31.104
Shinet	555597	1095463	2744	0.84	72.576
Banba-wuha	553927	1095941	2737	0.5	43.2
Dildisa	568545	1099767	2801	1.82	157.248
Abachala	576296	1091995	2760	0.31	26.784

Alekatri	562399	1096371	2865	0.3	25.92
Mesno-fit	570008	1098813	2830	0.85	73.44
Kega	568611	1095914	2816	0.397	34.3008
Adis-Amba	560369	1103112	2337	1	86.4
Regrg	568645	1103388	2460	0.386	33.3504
Sholawuha	553858	1091475	2381	0.386	33.3504
Kurie	553013	1103911	2359	0.33	28.512
Adinat-2	581538	1089315	3196	1.1667	100.80288
Boled-1	581437	1089989	3110	0.33	28.512
Anbagr	552143	1099041	2519	0.3	25.92
Gedam	547292	1097993	2628	0.7	60.48
Ayit-wuha	554919	1097032	2743	1.44	124.416
Ambo	573222	1101625	2395	0.3348	28.92672
Shola	572945	1102119	2427	0.9773	84.43872

Annex-2 Monthly Beresa River flows (m3/s)

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962	0.121	0.112	0.187	0.218	0.224	0.352	8.504	17.036	7.467	0.645	0.502	0.282
1963	0.159	0.117	0.227	0.445	0.785	0.395	10.215	24.572	3.085	0.418	0.431	0.332
1964	0.11	0.072	0.084	0.274	0.192	0.252	15.896	18.608	4.574	0.369	0.133	0.086
1965	0.234	0.351	0.314	0.823	0.341	0.431	1.517	9.077	3.155	0.447	0.781	1.367
1966	0.175	0.248	0.234	0.432	0.322	0.654	2.101	21.795	8.707	0.325	0.23	0.232
1967	0.227	0.214	0.39	0.549	1.072	0.567	11.171	18.724	2.408	2.67	1.106	0.495
1970	0.154	0.112	0.251	0.143	0.238	0.211	1.122	23.899	2.92	0.344	0.097	0.128
1971	0.108	0.064	0.076	0.158	0.292	2.132	8.283	41.371	3.563	0.15	0.14	0.178
1972	0.141	0.161	0.102	0.137	0.125	0.35	3.136	17.943	4.686	0.322	0.167	0.126
1973	0.121	0.112	0.089	0.129	0.194	0.196	7.715	22.484	7.704	0.222	0.179	0.132
1974	0.145	0.107	0.149	0.204	0.148	0.221	15.746	19.701	5.289	0.479	0.2	0.192
1975	0.122	0.105	0.122	0.221	0.109	0.456	5.681	21.641	15.612	0.344	0.249	0.092
1976	0.048	0.044	0.145	0.169	0.293	0.136	6.87	28.541	5.813	0.198	0.413	0.175
1977	0.172	0.127	0.104	0.092	0.148	0.179	9.327	10.435	0.53	1.612	0.32	0.157
1978	0.166	0.133	0.203	0.169	0.205	0.214	6.07	17.218	6.944	1.426	0.192	0.279
1979	0.207	0.12	0.125	0.191	0.392	0.403	9.058	11.82	0.854	0.268	0.037	0.048
1980	0.061	0.094	0.126	0.129	0.125	0.096	1.791	16.785	13.6	2.014	0.202	0.074
1982	0.169	0.231	0.203	0.425	0.341	0.332	1.744	52.859	4.299	2.994	0.312	0.254
1983	0.117	0.089	0.137	0.252	0.72	0.439	2.607	16.978	1.639	0.191	0.135	0.106
1984	0.091	0.074	0.069	0.07	0.319	0.505	6.294	2.94	2.031	0.199	0.128	0.079
1986	0.102	0.117	0.411	0.339	0.195	0.323	11.366	34.939	8.148	0.265	0.19	0.168
1987	0.151	0.175	0.224	0.476	0.622	0.26	0.22	6.058	0.442	0.619	0.216	0.2
1988	0.209	0.199	0.242	0.29	0.337	0.367	6.234	36.702	10.625	0.605	0.197	0.171
1989	0.17	0.16	0.178	0.308	0.19	0.243	3.121	14.522	4.142	0.31	0.225	0.243
1990	0.203	0.251	0.28	0.676	0.297	0.254	8.137	12.462	16.994	0.413	0.156	0.155
1991	0.152	0.143	0.154	0.204	0.304	0.394	6.58	45.344	5.006	0.308	0.144	0.13
1992	0.137	0.143	0.129	0.154	0.138	0.166	3.939	30.649	10.376	0.438	0.177	0.138
1993	0.118	0.162	0.125	0.306	1.792	0.313	31.103	7.414	1.889	3.255	0.203	0.15
1994	0.14	0.133	0.169	0.195	0.284	0.377	19.481	51.566	18.404	0.301	0.288	0.246
1995	0.223	0.214	0.244	0.377	0.384	0.415	7.951	37.402	11.041	0.36	0.342	0.365

1996	0.349	0.32	0.577	0.978	1.894	1.556	27.779	42.341	2.949	0.593	0.56	0.485
1997	0.478	0.457	0.534	0.834	0.677	1.323	28.732	20.569	0.721	4.164	0.805	0.337
1998	0.44	0.304	0.309	0.556	0.877	0.609	13.322	42.155	8.258	0.852	0.248	0.182
1999	0.155	0.119	0.156	0.128	0.172	0.358	21.42	36.81	4.827	1.465	0.096	0.049
2000	23.294	23.573	23.227	23.886	25.742	25.348	52.343	103.63	50.147	35.389	26.049	23.375
2001	23.754	28.618	31.113	28.046	29.331	27.265	77.173	97.07	30.623	17.963	17.198	15.84
2002	0.382	0.363	0.42	0.331	0.411	0.563	2.154	24.399	6.872	0.266	0.192	0.228
2003	0.216	0.249	0.182	0.783	0.374	0.545	9.336	11.722	3.165	0.241	0.016	0.029
2004	0.014	0.433	0.618	0.764	0.658	1.315	8.318	20.882	2.62	0.405	0.171	0.129
2005	0.122	0.103	0.11	0.173	0.308	0.326	9.01	12.596	4.839	0.359	0.222	0.261
2006	0.241	0.26	0.284	0.357	0.353	0.397	6.116	16.903	4.988	0.289	0.241	0.253
2007	0.207	0.215	0.222	0.477	0.302	0.653	10.692	26.186	9.137	0.424	0.278	0.227
2008	0.215	0.191	0.165	0.203	0.322	0.433	12.95	13.422	4.661	0.33	0.343	0.263
Total	54.32	59.589	63.41	66.071	72.549	72.324	512.325	1160.17	325.754	85.251	54.511	48.438
Mean	1.26	1.39	1.47	1.54	1.69	1.68	11.91	26.98	7.58	1.98	1.27	1.13

Annex-3 Metrological Data at Debrebirhan Station

1. Mean Monthly Maximum Temperature (^{O}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	19.5	20.9	19.5	19.7	19.5	22.0	22.4	19.5	19.8	19.5	19.8	20.1
1988	18.9	18.7	21.5	20.6	22.1	22.1	17.0	17.6	18.0	17.4	17.9	18.3
1989	19.0	18.5	19.7	18.1	20.5	21.4	18.8	18.3	18.2	18.0	x	x
1990	19.0	x	x	20.1	22.6	23.0	18.6	18.9	18.4	18.2	18.5	18.8
1991	19.9	20.0	20.6	20.8	22.0	22.5	18.0	17.8	19.0	18.2	18.6	18.3
1992	18.1	18.9	21.7	21.5	21.6	22.6	18.3	16.6	17.5	17.3	17.3	18.7
1993	18.9	18.7	20.6	19.4	19.9	21.9	18.5	18.9	17.7	18.0	18.2	18.9
1994	19.7	20.9	20.4	21.4	22.0	21.4	19.4	17.6	18.1	x	19.3	19.8
1995	20.9	20.8	21.3	20.8	22.1	23.6	x	18.7	19.4	19.2	19.8	19.7
1996	19.1	21.0	20.7	21.2	20.1	19.2	18.5	18.6	19.6	18.9	18.7	18.4
1997	18.6	20.1	21.2	19.8	21.3	21.1	18.0	18.3	19.3	18.3	x	x
1998	19.8	20.9	20.9	21.4	22.4	23.3	17.8	17.7	18.7	18.6	18.4	18.4
1999	19.4	21.5	20.5	21.8	22.6	22.4	17.1	18.1	18.5	17.9	17.7	18.5
2000	19.7	20.5	21.5	20.8	21.8	22.7	18.3	17.7	18.5	18.4	18.5	19.4
2001	19.9	20.8	19.2	21.2	22.2	21.5	17.9	17.6	19.6	19.9	19.6	19.3
2002	19.5	21.2	20.7	21.4	23	22.8	21.5	17.5	18.6	19.6	19.8	19.3
2003	20.3	21.4	21.2	20.8	21.8	22.5	18	18.3	19	19.4	18.5	19.4
2004	20.7	20.4	21	20.4	23.1	21.2	18.7	18.7	19.1	18.6	19.5	19.6
2005	20.1	22.1	22	21.3	20.4	21.6	18.3	18.9	19.3	19	18.8	18.9
2006	20	21	20.5	20	21.9	22.6	19	18	18.6	19.6		19.1
2007	19.9	20.6	21.8	20.8	22.7	21.2	18.0	18.2	18.7	19.0	18.6	20.0
2008	19.4	20.2	22.0	20.8	21.3	21.2	18.9	19.0	19.4	19.2	18.4	19.1

2. Mean Monthly Minimum Temperature (^{O}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	3.4	6.6	8.8	8.0	10.7	7.7	8.2	8.9	7.6	5.5	4.2	5.0
1988	6.6	6.7	8.4	8.2	7.0	6.6	12.8	9.0	7.4	4.0	1.8	1.1
1989	0.5	6.2	7.4	8.1	5.5	6.3	8.8	9.2	9.4	X	1.2	6.7
1990	3.1	9.2	7.1	6.8	5.5	5.9	8.6	8.9	7.3	2	2.1	0.2
1991	5.3	6.1	8.4	7.7		7.4	9	8.8	7.1	1.6	1.7	0.8
1992	6.8	7.9	8.5	7.3	6.5	6.9	7.9	9	7	3.6	3.9	4.2
1993	5.8	6.9	5.8	8.2	6.8	6.5	8.8	8.6	7.8	4.5	1.5	2.5
1994	3.6	5.1	8.7	8	7.1	7.1	8.6	7.8	6.7		0.8	2.5
1995	2.8	7.5	6.7	8.7	6.4	6.7		9.2	7	2.7	1.2	5.8
1996	6.3	4.6	7.4	7.1	8	7.9	8.2	8.5	6.4	1.4	2.1	3.2
1997	6.1	2.2	8.2	7	6.7	8.5	8.6	8.1	7.1	6.1	4.3	2.3
1998	7.7	8.4	9.3	9.6	7.7	7.2	9.3	9.5	7.3	3.7	-1	-2.1
1999	2.2	3.1	5.9	5.2	5.8	6.3	8.6	8.6	6.2	4.6	-1.2	1.8
2000	1	3.4	4.8	7	7.1	5.7	8.6	8.1	6.8	3.3	1.7	1
2001	1.5	4.5	8.3	6	8.2	8	9.2	9.2	6.4	3.3	2.9	4.6
2002	5	6.3	8.4	7.6	7.7	7.6	9.1	9.1	7.5	3.1	2.8	7.2
2003	5.3	6.9	7.9	9.5	7	8	9.4	9.6	8.1	3	2.7	1.6
2004	5	4.4	5.6	8.9	6.7	8.1	9.2	9	7	3.3	2.7	5.2
2005	5.3	7.3	8.3	9.2	9.2	7.8	9.2	9.2	8.3	3.9	2	1.7
2006	5.9	8	7.5	8.5	7.4	8.2	9.8	9.8	7.4	5.4		4.7
2007	6.6	7.5	7.7	8.5	8.1	9.0	9.6	9.2	7.5	3.4	3.9	1.5
2008	5.4	5.0	5.5	7.7	8.6	8.5	8.6	9.2	7.0	4.2	4.0	4.6

3. Monthly Total Rainfall in mm

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1987	5.0	19.2	108.1	51.7	100.2	0.0	32.3	309.5	47.5	18.7	0.0	6.3	698.5
1988	10.6	34.6	16.9	83.1	16.2	16.0	286.2	290.0	152.5	12.1	0.0	0.0	918.2
1989	2.3	40.5	97.6	42.7	1.4	41.1	211.3	177.4	67.7	18.6	0.0	30.7	731.3
1990	0.0	62.2	20.7	59.5	0.9	1.6	321.0	217.2	168.7	0.6	0.0	0.0	852.4
1991	4.8	8.3	64.6	21.0		63.7	215.6	387.5	86.6	6.4	0.0	6.4	864.9
1992	30.3	26.7	19.4	80.2	19.3	13.3	307.6	267.6	92.9	41.9	0.5	1.8	901.5
1993	4.3	63.2	0.0	116.9	60.5	9.1	405.5	168.4		43.2	0.0	1.1	872.2
1994	0.0	0.0	95.6	0.0	23.2	92.7	281.7	222.9	101.7		36.5	0.0	854.3
1995	0.0	28.5	19.1	68.4	26.3	23.3		233.8	60.4	5.1	0.0	1.7	466.6
1996	20.7	2.8	75.4	9.7	129.2	138.0	328.4	252.5	24.3	0.0	3.0	0.0	984.0
1997	29.5	4.0	41.2	82.4	25.9	96.9	272.1	200.6	34.8	89.7			877.1
1998	23.1	13.2	14.9	49.3	43.0	13.5	337.3	289.0	70.6	5.2	0.0	0.0	859.1
1999	6.9	0.0	26.5	2.8	11.0	48.9	362.4	365.1	52.4	59.6	1.4	0.0	937.0
2000	0.0	0.0	25.9	47.3	37.1	45.8	352.4	317.5	105.2	28.5	18.8	6.8	985.3
2001	0.0	33.8	71.2	18.8	64.6	34.9	406.7	260.4	32.2	4.1	0.0	3.4	930.1
2002	18.1	28.0	60.6	46.1	18.4	29.1	214.4	294.8	109.1	3.1	0.0	8.4	830.1
2003	15.6	36.3	60.2	85.7	3.8	99.5	334.1	288.7	74.2	0.0	0.0	7.4	1005.5
2004	24.4	9.7	29.7	113.3	5.6	99.7	334.7	301.3	78.9	14.1	11.8	0.0	1023.2
2005	34.3	4.5	28.6	49.5	76.4	91.1	310.7	228.3	106.8	0.7	1.5	0.0	932.4
2006	17.3	24.4	61.0	38.3	19.8	35.2	432.6	224.2	59.8	8.6		26.3	947.5
2007	0.3	30.4	8.9	71.8	13.6	93.2	309.9	414.6	128.5	4.9	5.7	2.0	1083.8
2008	0.3	1.7	0.0	34.6	68.9	66.4	397.7	234.8	76.6	9.9	54.6	1.2	946.7
Total	247.8	472.0	946.1	1173.1	765.3	1153.0	6454.6	5946.1	1731.4	375.0	133.8	103.5	19501.7
Mean	11.26	21.45	43.00	53.32	34.79	52.41	293.39	270.28	78.70	17.05	6.08	4.70	886.44