



ADDIS ABABA UNIVERSITY  
COLLEGE OF NATURAL SCIENCES  
SCHOOL OF EARTH SCIENCES

**NUMERICAL GROUNDWATER FLOW MODELING OF WALGA-DARGE CATCHMENTS**

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

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DECLARATION

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

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

Tenalem Ayenew (Professor) \_\_\_\_\_.

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## ABSTRACT

The area concerned in this study is situated in the Northern parts of Omo-Gibe river basin. The total surface area of the catchments is about 2915km<sup>2</sup>. In this study, the numerical groundwater flow model was used to study regional groundwater flow and the response of the groundwater system to different scenarios. The aquifer system was considered as a single layer and simulated under steady state condition using MODFLOW. The study area boundary was delineated from 30m resolution of digital elevation model (DEM) using Arc SWAT software with ArcGIS interface. The recharge rate was estimated using the semi-distributed hydrologic model Soil Water Assessment Tool (SWAT) which account for the spatial heterogeneity in climate, topography, land use and soil of the catchments. The long-term annual recharge to shallow aquifer estimated by the model is 315mm/year. The general trend of groundwater flow direction was determined as it is from the north-east to south-west following topography, with some local variations. Model calibration was carried out by manual trial and error calibration method using head observations from 121 wells. The model was calibrated to mean error -2.43m, absolute mean error 10.82m and root mean squared error 13.47m. The simulated water budget of the entire model domain is 86532382m<sup>3</sup>/year inflows and 86530619m<sup>3</sup>/year out flow with difference the of 1762.27 m<sup>3</sup>/year. Sensitivity analysis was made by taking hydraulic conductivity and recharge to understand the uncertainty in the calibrated model caused by limitations in the estimates of aquifer parameters and stresses. Decreasing and increasing the hydraulic conductivity by 20% and 40% resulted in MAE head changes from the calibrated value by 24.90, 15.54, 14.26 and 23.86 respectively. Similar changes in recharge resulted in MAE head changes from the calibrated value by 39.66, 30.32, 19.37 and 21.24. The model is more sensitive to recharge compared to hydraulic conductivity. Scenario modeling was made with increased groundwater abstraction rates and decreased and increased aquifer recharges as part of the forecast. The system responses to scenarios were evaluated by resulting changes in water level and groundwater outflow from the model domain. Increasing the steady-state well discharges up to fourfold resulted in insignificant declines in groundwater levels in most of the model domain. Decreasing and increasing of aquifer recharges has significant change in water level and fluxes.

Key words: gibe basin, MODFLOW, Numerical model, Scenarios model, SWAT, Water budget

## 1. INTRODUCTION

### 1.1. Background

The water demand in the world is rapidly increasing due to population growth, extensive industrialization and agricultural practices. Groundwater plays a significant role in the supply of ever increasing water demand. It provides fresh water for domestic, agriculture, industrial and ecological purpose. Therefore, accurate estimation of groundwater resources is a prerequisite for any sustainable water development and management.

Effective groundwater management requires, firstly, a good understanding of the aquifer system, secondly, that practical measures to control abstraction can be identified and, thirdly augment groundwater resource through artificial recharge. It is therefore essential to quantify the response of the aquifer under study to different input output stresses. Groundwater modeling study has proved to be a potential tool to study the aquifer response and thereby to evolve appropriate management schemes (Thangarajan, 2007). The use of groundwater models is prevalent in the field of environmental science. Models have been applied to investigate a wide variety of hydrogeological conditions (Kumar, 2002). Groundwater simulation modeling is recognized as a very useful tool for understanding regional groundwater systems, management of groundwater resources, and planning for future water consumption (Qiu, *et al.*, 2015). Groundwater flow models are an important tool for the management of groundwater resources as they give an approximate estimate about the various hydro-geological parameters and they similarly help in illustrating a clear picture of the flow pattern in aquifers.

The intended study area is located in the south west shoa and gurage provinces, southwestern part of central Ethiopia. The groundwater flow system for the proposed catchments has not been explored in detail and simulated, and there is little guidance on how to deal with the complicated geological conditions, boundaries and the relationship between the groundwater and rivers.

There are a number of modeling software exist to simulate groundwater flow. Among them modeling software MODFLOW was used to understanding the groundwater flow system and construct the steady state model for the study area.

## **1.2. Objectives**

### **1.2.1. General Objective**

The major objective of the study was the numerical simulation of the groundwater flow system of the Walga-Darge catchments to have a better understanding of the groundwater flow system and to evaluate the response of the hydrologic system to different scenarios.

### **1.2.2. Specific Objectives**

In association with the major objective the paper intended to full fill the following specific objective:

- ✚ To identify the possible boundary condition of the Catchments and develop a simplified conceptual model which approximates the physical field condition of the system.
- ✚ To develop steady state numerical ground water flows modeling of the catchments
- ✚ To conduct sensitivity analysis of the aquifer system and identify the most influential parameter
- ✚ To evaluate the response of the aquifer system for different possible scenario of ground water consumption and altered recharge on the study Area
- ✚ To evaluate the water budget of the entire catchment in identified boundary condition

## **1.3. Significance of the Study**

The Study was intended to describe ground water flow system of the catchment, so that it will increase the knowledge on the understanding of the flow system and its response to future stress in changing environment. Thus it can give the guideline for future groundwater resource development and management practices. Furthermore, it can serve as a reference frame work for the students, non-governmental organizations and different non-governmental organizations for those who have interest to do related work.

## **1.4. Previous Works**

Some previous studies also were conducted in the proposed study area on the hydrological, hydrogeological, hydrogeochemical, geological and structural evolution of the study area.

The geology of the Akaki Beseka area is compiled by Efreem Beshawered (EIGS, 2010). In the study both the integrated geological, geochemical and remote sensing investigation has revealed

the presence of Pre-rift, Mesozoic sediment, Oligocene to late Miocene plateau flood basalts, the syn-rift upper Miocene- quaternary of welded to partially welded pyroclastic flows, Main rift unit quaternary-Holocene young central volcanic of rhyolite and trachyte and wonji basalt and quaternary lacustrine and alluvial sediment

Hydrogeology and hydrochemistry of the Akaki-Beseka Sheet (NC 37-14) is also compiled by:- Bereket Fenatw and Mihret Manaye (EIGS, 2011). In the study, factor affecting the groundwater occurrence, the productivity of aquifer and Hydrochemical characteristics of groundwater are explained.

Kassahun Beyene (2005) studied ground water resource evaluation of Walga river basin; the study indicated ground water recharge, hydrogeological and Hydrochemical characteristics of the basin;

Abenezer Kefeni (2007) conducted his MSc. thesis on hydrogeochemical evolution in the Ambo-Woliso area, he identified the hydrogeochemical evolution towards west and along the flow path there are at least two water types, high TDS  $\text{NaHCO}_3$  and fresh(low TDS)  $\text{CaHCO}_3$  water. Low PH and high electrical conductivity water is limited to Ambo springs emerging sites, Wonchi and Woliso which are connected by NNW and SSE structures. The low PH is attributed to high  $\text{CO}_2$  supply from Mesozoic de-carbonation and Dandi-Wonchi related magma chamber degassing.

Hassen Shube (2011) was used Isotopic and geochemical data to study the hydrogeochemical evolution of thermal and hypothermal ground waters and  $\text{CO}_2$ -water-rock interaction of ground waters around Wonchi, Woliso and Ambo area.

Birhanu Haile (2015) worked on Characterizing the Ground Water Resources Potential in Omo Gibe River Basin. Finite element groundwater modeling code (TAGSAC in mat lab) is used in his work to characterize and estimate the groundwater resources potential in the Omo Gibe River Basin.

Tsegaye Abebe et al., (1998) studied the Yerer– Tullu Wellel volcano tectonic lineament: a transtensional structure in central Ethiopia and the associated magmatic activity: He mentioned that an east-west trending structure in central Ethiopia, the Yerer Tullu-Welel volcanotectonic lineament, intersects the main Ethiopian Rift and lies between latitudes  $8^{\circ}20'N$  and  $9^{\circ}05'N$ . Along this structures there are several central volcanoes concentrated

along the latitude of  $8^{\circ}45'N$ . the central volcanoes are usually located at the intersections of the above described fracture system.

## **1.5. Methodology and Material Used**

In order to fulfill the objective of the study, the following three methodologies were used: Firstly, different literatures and relevant data (hydrogeological, geological, topographic maps, meteorological, hydrological data, well inventories and satellite imageries) were collected and organized. Secondly, field characterization to understanding the hydrogeological & geological setup, field verification of the study area and determination of physical boundaries and water level collection and taking readings of borehole locations was made. Thirdly, Analysis and interpretation of field inventoried and collected hydrogeological, geological and meteorological data to prepare model input parameters.

The general groundwater flow modeling protocol and methodology to be followed during data assembly and the simulation processes in this work are summarized in figure 1.1. A protocol for modeling includes build conceptual model, formulate mathematical model and select modeling code, model design, calibration, sensitivity analysis, and finally forecasting and report preparation.

In developing a conceptual model, the relevant hydrogeological data was organized, analyzed, and synthesized, often with the help of a database tool such as a GIS.

The model was design which involves translating the conceptual model into a numerical groundwater flow model by designing the grid/mesh, setting boundaries, assigning values of aquifer parameters, and hydrologic stresses.

Model fit was assessed through history matching with field collected data. The purpose of calibration was to establish that the model can reproduce field-measured heads. It was done by trial-and-error adjustment of parameters.

Forecasting simulations used the calibrated model to forecast the response of the system to future events. Estimates of anticipated future hydrologic conditions (recharge rates and pumping rates) were used to perform the forecast. In this work, the model was limited to steady state numerical ground water, forecasting change of the head with the time had not been made.

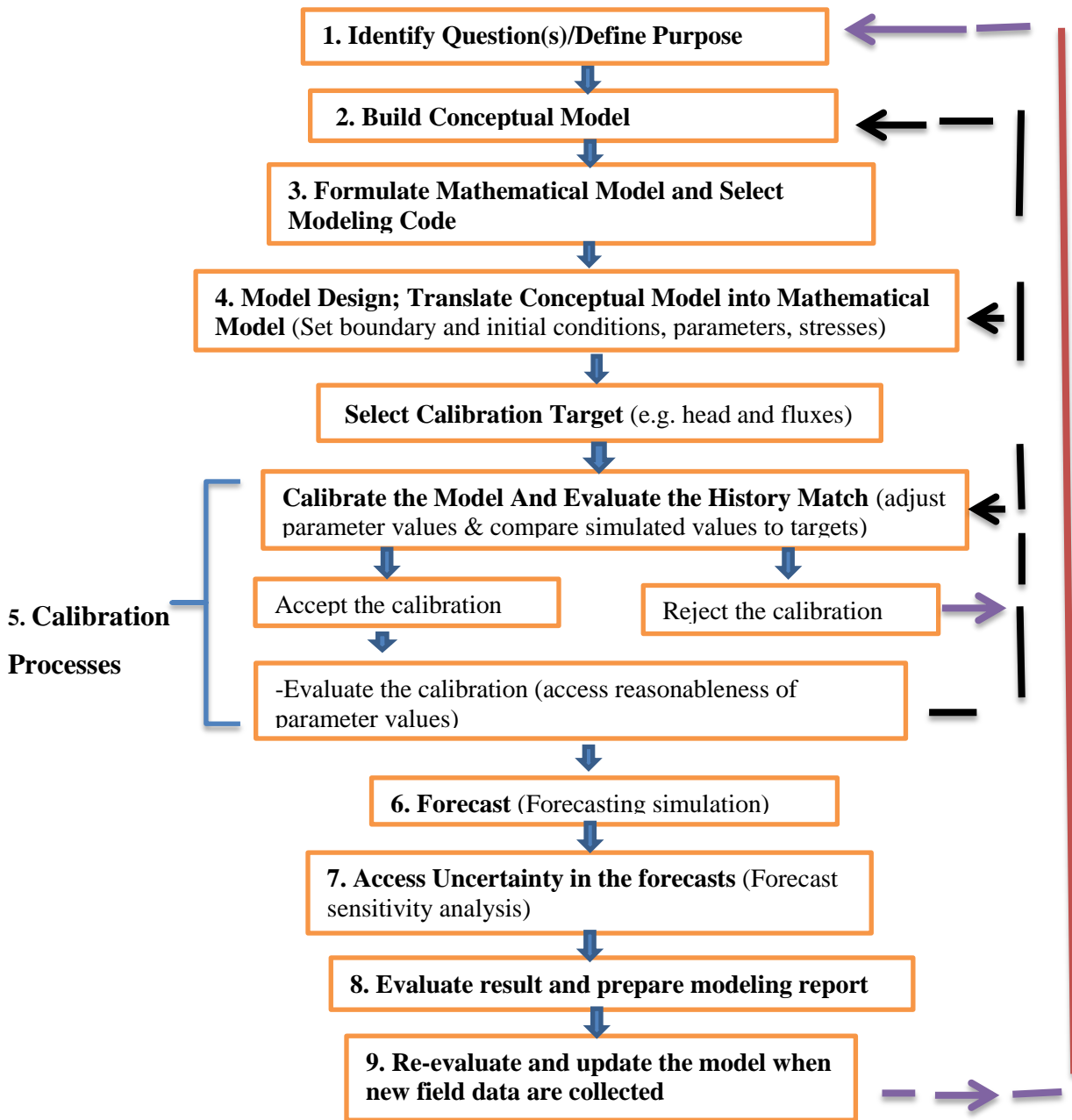


Figure 1.1: General workflow for groundwater modeling (Adapted from: Anderson.et.al. 2015)

## **1.5. Materials and Data sets**

To accomplish the objectives mentioned above, the following materials and equipment was used:

- Deep meter to measure water level of representative well
- Geological and hydrogeological maps with relevance and available scale
- GPS has been used to locate specific location of well.
- STRM DEM and Google earth that help to identify the study area boundary and conceptualize the boundary conditions.
- 1:250,000 scale topographical map was used to give good morphological picture of the area.
- Various computer software (MODFLOW, ArcGIS 10.3, Arc SWAT, ERDAS, Global Mapper 17, Surfer 10)

## **1.6. Outline of the Thesis**

1. Introduction
2. Literature Review
3. General Overview of the Study Area and Hydrology
4. Geology and Hydrogeology of Study Area
5. Conceptual and Numerical Groundwater Flow Modeling
6. Conclusion and Recommendation

## 2. LITRETURE REVIEW

A model is any device that represents an approximation of a field situation. physical models such as laboratory sand tanks simulate groundwater flow directly whereas, a mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model (boundary conditions) ( Anderson and Woessner, 2002).

Groundwater models are valuable tools that can be used to help understand the movement of water and chemical in the subsurface. The purpose the of the model is to simulate subsurface conditions and to allow prediction of chemical migration when properly applied , models can supply useful information about flow and transport processes and can assist in the design of remedial programs (<http://www.nap.edu/openbook/0309039967/html/R1.html>).

Reilly and Harbaugh (2004) identify five broad classes of problems that may initiate a hydrologic study involving a groundwater modeling: basic understanding of groundwater systems; estimation of aquifer properties; understanding the present; understanding the past; and forecasting the future. Anderson et al (2015) groups the first three of these categories into interpretive models and the last two into forecasting/hind casting models.

There are so many numerical groundwater flow modeling practice have been used in Ethiopia in previous time and to mention and review some of them; Tenalem Ayenew et al. (2007) conducted a numerical modeling study for the groundwater system in the Akaki catchment of central Ethiopia. A 3-D steady state finite difference groundwater flow model was developed to quantify the groundwater fluxes and analyze the subsurface hydrodynamics in the Akaki catchment by giving particular emphasis to the well field that supplies water to the city of Addis Ababa. The model was calibrated using head observations from 131 wells and the simulation was made in a two-layer unconfined aquifer with spatially variable recharge and hydraulic conductivities under well-defined boundary condition. The result indicated that the groundwater flows regionally to the south converging to the major well field.

Mechal et al. (2016) Studied on the Characterizing regional groundwater flow in the Ethiopian Rift: A multi-model approach applied to Gidabo River Basin. The regional groundwater flow within Gidabo River Basin, which is part of the southeastern Main Ethiopian Rift, was characterized using a multi-model approach to account for the conceptual model uncertainty

arising from the incomplete knowledge about the complex hydrogeology of the area. To account for these uncertainties fourteen different numerical models with a stepwise increase from 7 to 40 adjustable parameters were developed, calibrated against the same hydraulic head observations, and ranked according to the Akaike information criteria (AIC and AICc) and Bayesian information criterion (BIC). Based on the information criteria five plausible models were identified, all of which were successfully verified against the river baseflow. On a regional scale, the hydraulic head distributions of the plausible models agree reasonably well with the equipotential map interpolated from well observations

Tenalem Ayenew and Nardos Tilahun (2008) studied on assessment of lake–groundwater interactions and anthropogenic stresses, using numerical groundwater flow model, for a Rift lake catchment in central Ethiopia. In the study, a steady-state groundwater flow model was used to access lake and groundwater interactions in a complex rift volcanic catchment. The study also was include assessing the effects of water pumping from wells, and of variable recharges rates associated with climate and lake level changes, on the dynamics of the volcanic aquifers surrounding Lake Awassa. The model results indicated that the lakes and Rift aquifers are fed by large groundwater inputs that originate in the highlands. The lakes and rivers have important roles in recharging the aquifers in some locations. Lake Awassa receives a major groundwater inflow from its southern and eastern shorelines, while substantial water leakage from the lake occurs along the northern shoreline.

There are also many Modeling practices which have been done for academic thesis and dissertation by MSc and PhD students in different region of the country which freely available on the Addis Ababa University Depository ([www.etd.aau.edu.et/dspace](http://www.etd.aau.edu.et/dspace))(Geletu Belay, 2006 Ebaso Oljira, 2006; Samson Mengistu, 2010, Getaneh Kinfu, 2010 Nigussie Ayehu,2010; Sintayehu Mulu, 2017)

### 3. GENERAL OVERVIEW OF THE STUDY AREA AND HYDROLOGY

#### 3.1. Location and Accessibility

The area concerned in this study is situated in the Northern parts of Omo-Gibe river basin. Administratively, it also contains parts of the Oromia National Regional State and Southern Nations Nationalities. Geographically, it is bounded between 910000mN to 980000mN and 330000mE to 410000mE. The total surface area of the catchments is about 2915km<sup>2</sup>. The study area can be accessed mainly through Addis Ababa –Woliso-Wolkite roads. There is weathered gravel roads like: Woliso-Chitu-Ambo, Woliso-Chitu-Gindo-Darge, and Wolkite-Tawella-Robe gebeya-Darge.

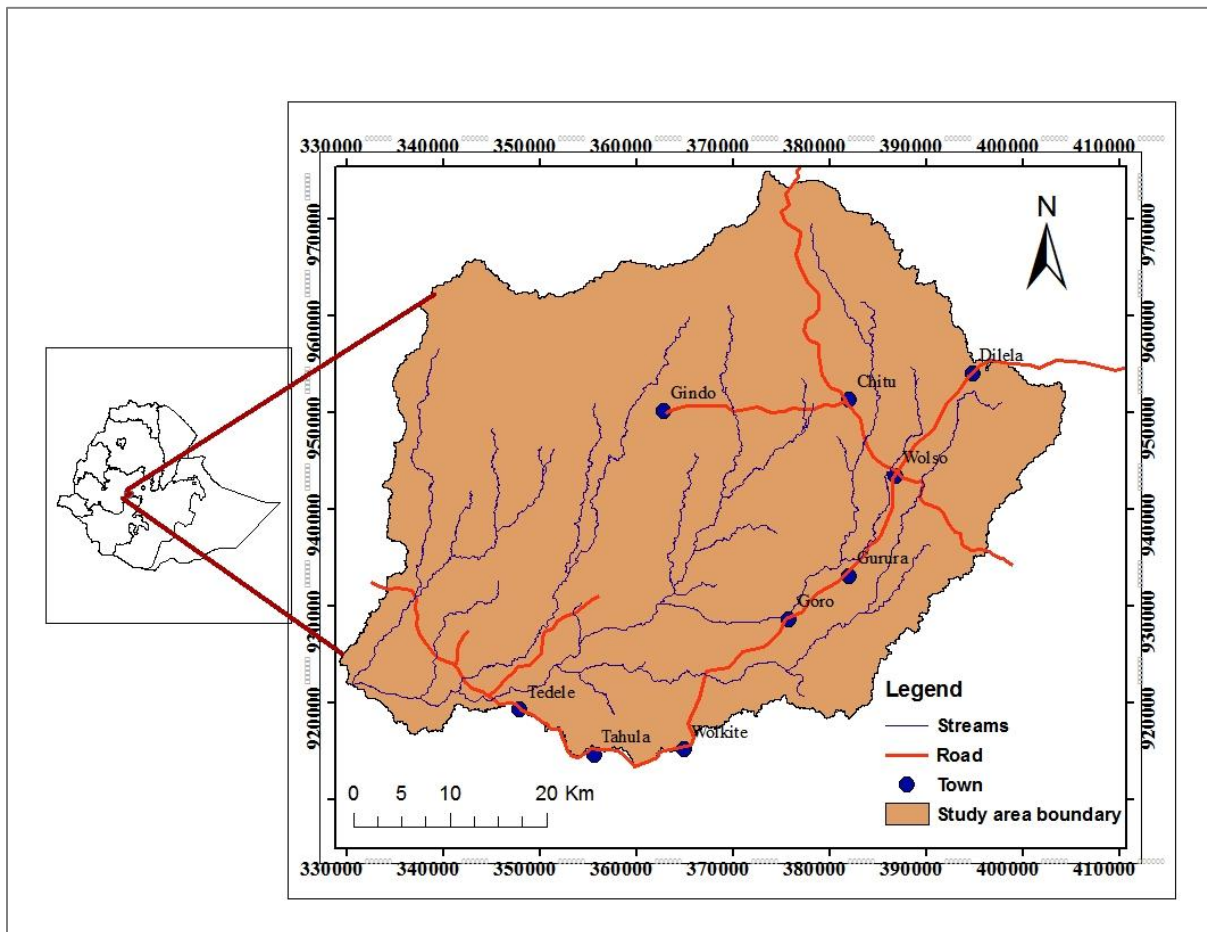


Figure 3.1: Location and accessibility of Study area

#### 3.2. Physiography and Drainage Features

The study area is characterized by large Mountains and various volcanic rocks. The elevation varies from 1164 m.a.s.l near Gibe gorge to 3360 m.a.s.l at the northern (Wonchi Caldera).

Highly elevated Volcanic Mountains and Spatter Cones are common in the northern, northeastern and northwestern parts of the study area. The central and southern portions are characterized by flat undulating plain topography. Surface water hydrology shows that the area is at a water divide of three catchments namely the Omo - Gibe, Awash and Abay catchment. The drainage pattern of the area is controlled by the rift shoulder uplifted topography and the predominant fracture systems and the central volcanoes. Most of the major rivers follow the NE-SW lineament trend. The major river that drains the study area is the Walga River. Small rivers like Amenya, Tilku Jara, Kulit and Darge flows from north to south, joining Walga river, which further drains due south west to join the Gibe river outside the study area. The deep gorges, incised river valleys, and rolling plains are a specific feature of the study area.

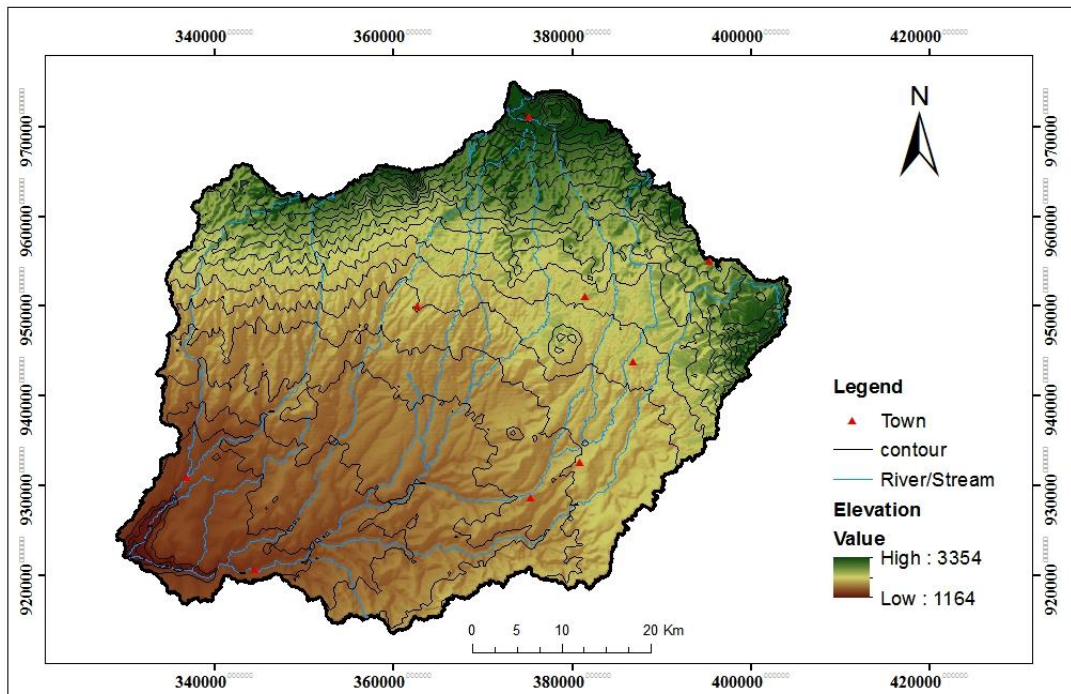


Figure 3.2: Physiography and Drainage Map of study area

### 3.3. Land use and Soil Type of Study Area

Land use is important in groundwater studies, because it is a prominent factor affecting the recharge. Dominant Land use land cover of the study area is agricultural land. There is also distributed forest, bushed shrub grassland and dense woodland.

The type and distribution of soils are highly dependent on lithology (parent source), geomorphology and climatic factor. Based on the previously conducted studies, the major soil type of study area includes vertisols, deep brown clay, deep red\_brown clay, shallow stoney soil and deep read soils the dominant textural for all types is clay.

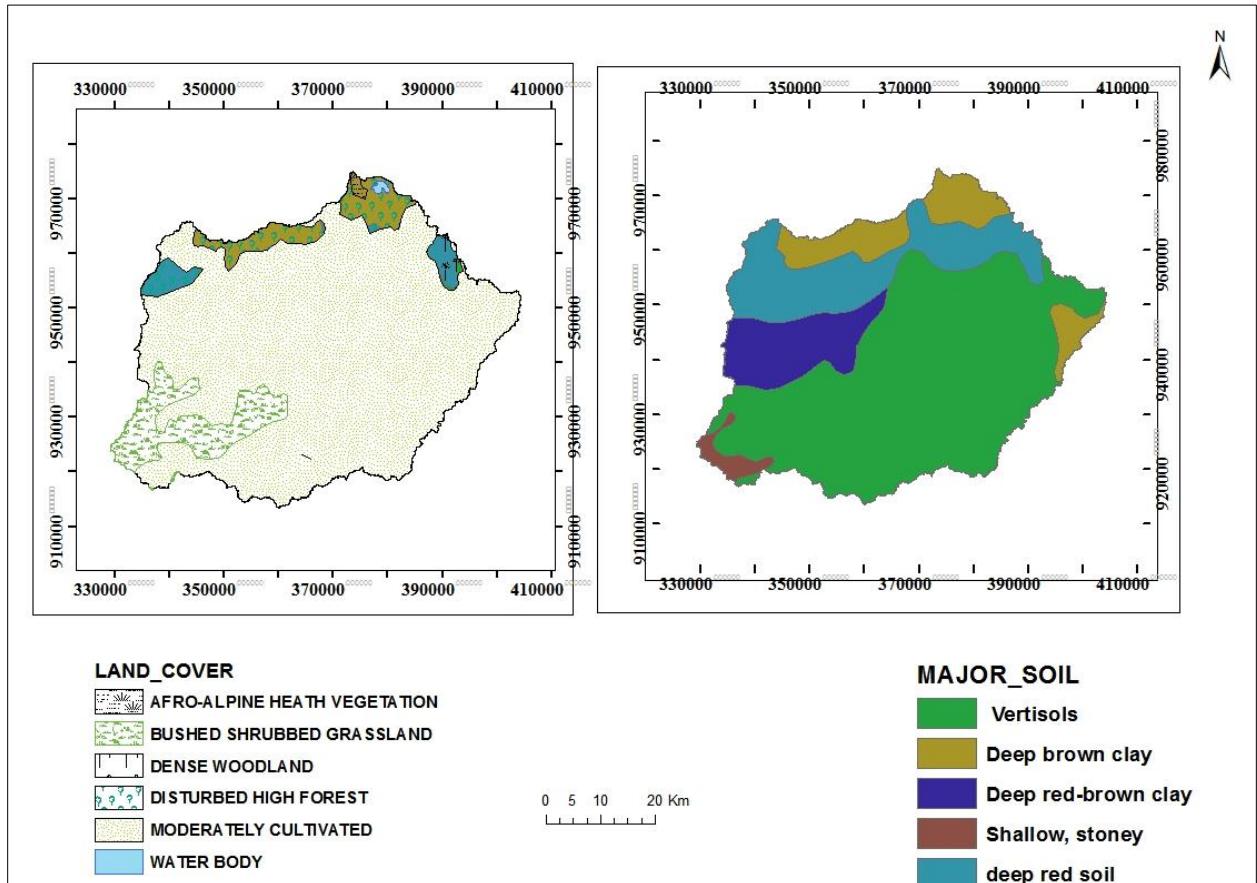


Figure 3.3: Land use (a) and Soil Map (b) of study area (Source: MoWR, 1996)

### 3.4. Climate

#### 3.4.1. Rainfall

In general, the study area is characterized by humid to semi-arid with hot humid summer and dry warm winter. The whole area, lying in a tropical climate, classified as wet, humid region with a mean annual rainfall of 1073-1478 mm per year. Figure 3.4 show that all observed stations get their maximum peak rain in July and August. Out of six observed stations the maximum rainfall is recorded at Busa and Darian stations with values of monthly peak rainfall 342 and 311 mm respectively. Records from stations Dilela and wolkite show relatively minimum rainfall even in summer. The lowest observed average monthly rainfall occurs in December. The maximum total

annual rainfall in the watershed is 1478 mm at the Dariyan gauging station & the minimum total annual is 1073.3mm at Dilella station in the watersheds.

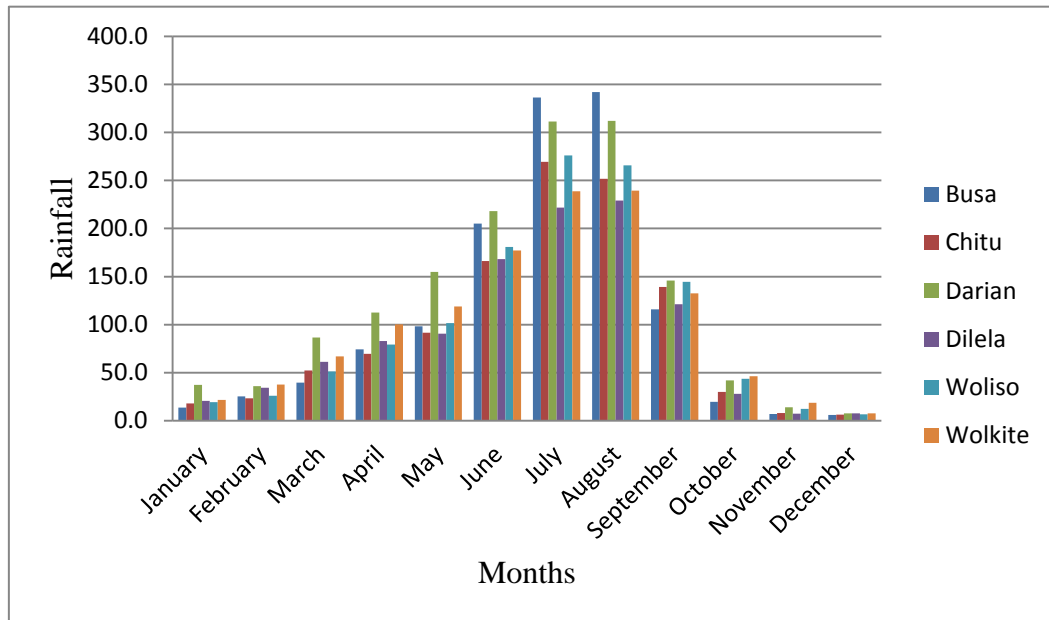


Figure 3.4: Long term (1990-2014) mean monthly rainfall distribution of study area

Table 1. Mean monthly rainfall for six stations in the study area, 1990-2014

stations	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Busa	13.9	25.5	39.7	74.3	98.1	205.0	336.4	342.0	115.8	19.7	7.2	6.2	1283.6
Chitu	17.9	23.3	52.3	69.6	91.7	166.0	269.4	251.7	139.2	30.2	8.0	6.5	1125.7
Darian	37.3	36.1	86.8	112.4	155.0	218.0	311.2	311.9	146.0	42.2	14.2	7.6	1478.4
Dilela	20.8	34.4	61.2	82.9	90.7	168.1	221.8	228.9	121.4	28.0	7.3	7.7	1073.3
Woliso	19.4	25.9	51.4	79.3	101.5	181.0	276.1	265.8	144.4	43.6	12.4	6.8	1207.6
Wolkite	21.6	37.7	67.0	100.3	119.0	177.2	238.8	239.5	132.4	46.5	18.8	7.7	1206.4

### 3.4.2. Temperature

As other elements of the climate, temperature of the study area is highly dependent on altitude. Throughout the entire area the spatial and temporal temperature varies from place to place and even in the same station at a significant rate. The average minimum, maximum and mean annual

temperature for woliso and wolkite stations are 13, 25.4 &19.2 °C and 13.6, 28.2 &20.9 °C respectively. The least mean monthly minimum temperature is recorded from November to January. Mean monthly temperature fluctuation at Waliso and Wolkite stations were shown in (Figure 3.5).

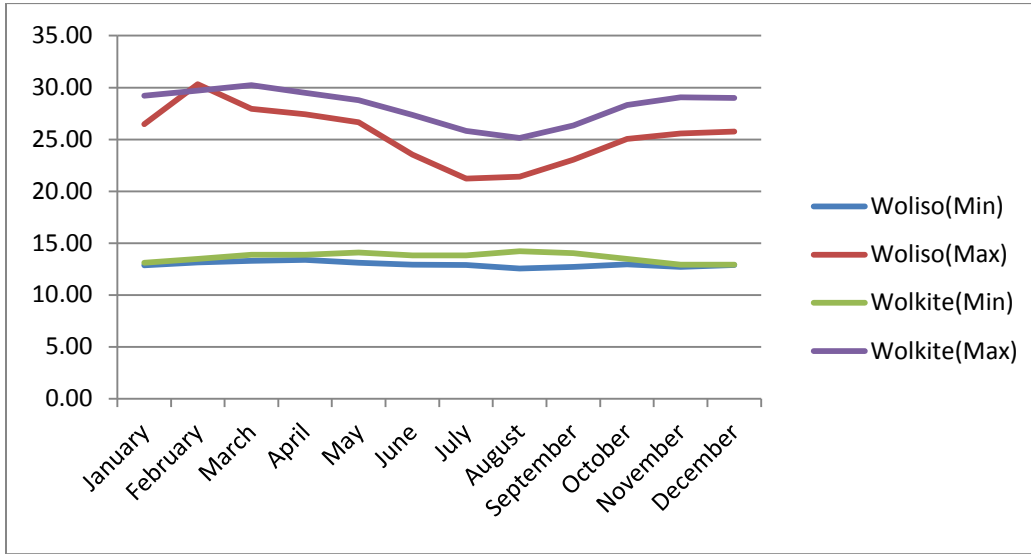


Figure 3.5: Mean monthly temperature (max. and Min) of Woliso and Wolkite stations

Table 2. Mean monthly temperature (max. and Min) of Woliso and Wolkite stations (1990-2014)

		Jan.	Feb.	Mar.	Apr.	may	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Woliso	Minimum	12.9	13.1	13.3	13.4	13.1	12.9	12.9	12.5	12.7	13.0	12.7	12.9
	Maximum	26.5	30.3	28.0	27.4	26.7	23.5	21.2	21.4	23.0	25.1	25.6	25.8
Wolkite	Minimum	13.1	13.5	13.9	13.9	14.1	13.8	13.8	14.2	14.0	13.5	12.9	12.9
	Maximum	29.2	29.7	30.2	29.5	28.8	27.4	25.8	25.1	26.3	28.3	29.0	29.0

The weather data obtained from National Metrological Agency were not enough and well distributed to drive water balance by using SWAT. Therefore, the additional weather data were

obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) website (<http://globalweather.tamu.edu/>). The geographic coordinate of these weather data is as in below table.

S/N	STATION	WLATITUDE	WLONGITUDE	WELEV
1	83375	8.274	37.5	1312
2	83378	8.274	37.813	1832
3	83381	8.274	38.125	2575
4	86375	8.586	37.5	2050
5	86378	8.586	37.813	2062
6	86381	8.586	38.125	2588

### 3.4.3. Relative Humidity

Mean monthly relative humidity on average (1990-2014) at six stations were analyzed and used for hydrological model. The relative humidity of the area is used to calculate evapotranspiration in hydrologic water balance that helps to evaluate the recharge of the study area.

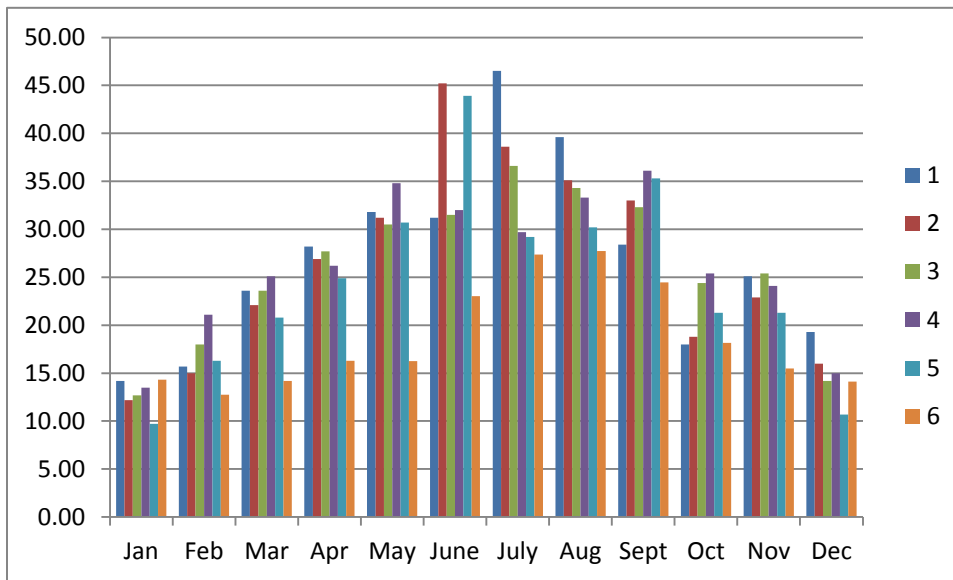


Figure 3.6: Relative Humidity (from: NCEP)

### 3.4.4. Solar Radiation

Solar radiation governs the rate of evaporation by changing large quantities of liquid water into water vapor. Consequently, the evapotranspiration process is determined by the amount of energy available to vaporize water. Mean monthly solar radiations on average (1990-2014) at six stations are shown as the following figure.

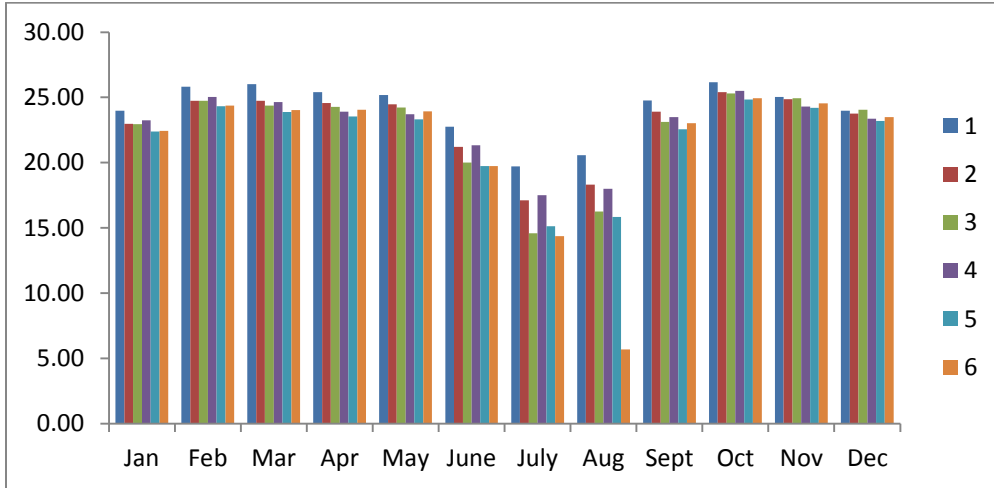


Figure 3.7: Solar radiation (MJ/m2) from: NCEP)

### 3.4.5. Wind Speed

Mean monthly wind speed on average (1990-2014) at six stations are analyzed and used for hydrological model. Wind speed is one of input parameter to estimate evapotranspiration where Penman- Monteith (Monteith, 1965) is used.

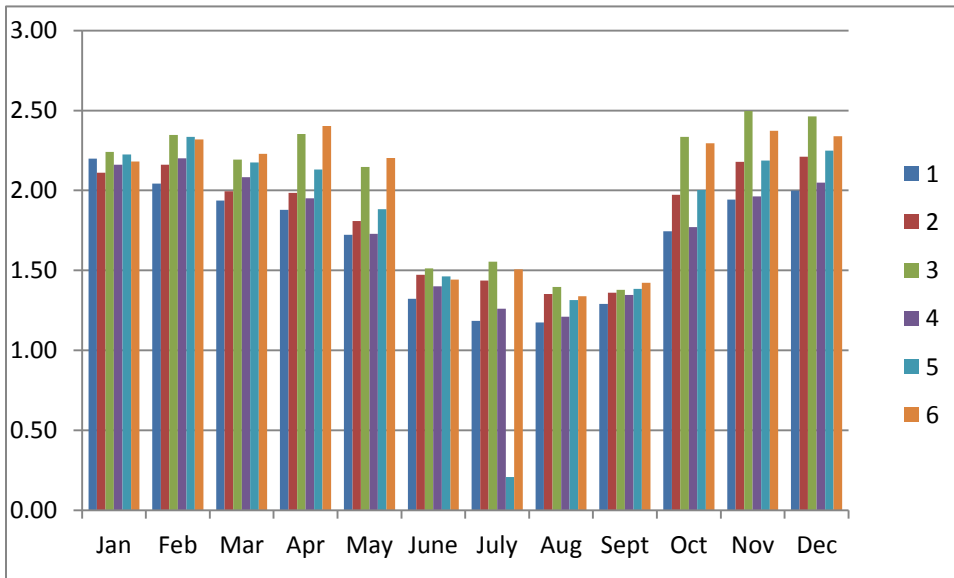


Figure 3.8: Wind speed (m/s), (from: NCEP)

## 3.5. Hydrological Model and Water Balance of the Study Area Using SWAT

SWAT (Soil and Water Assessment Tool) is a catchment or river basin scale model developed for the USDA Agricultural Research Service (ARS) (Neitsch et al., 2001). It is a physically

based model able to estimate the impact of land management practices on water, sediment and agricultural chemicals on a sub-catchment and land use unit scale over long periods of time.

SWAT is a popular model among many watershed hydrologists who are interested in studying the impact of agricultural activities and land use management on the overall watershed health including stream flow and water quality.

One of the most essential components of an efficient groundwater model is the accuracy of recharge rates within the input data. Groundwater recharge rates show spatial-temporal variability due to climatic conditions, land use, soil characteristics and hydrogeological heterogeneity. Most of these factors are not considered for the estimation of recharge rates in groundwater models. A high level of spatial variability can be simulated, since SWAT allows the division of the watershed into a large number of sub-basins (watersheds), and then further subdivided into hydrologic response units (HRUs) based on the land use, slope characteristic and soil distributions. The HRUs are used to describe spatial heterogeneity in terms of land cover, soil type and slope class within a watershed

Soil and Water Assessment Tool (SWAT) was used for recharge estimation for the catchments. The main objective of Hydrological model using SWAT is to quantify the groundwater recharge of study area.

SWAT requires four main data files to accurately simulate the discharge. These are: Digital Elevation Model (DEM) data, land use data, soil data, and weather data. The Shuttle Radar Topography Mission (SRTM) 30m resolution DEMs was used to delineate the watershed into sub-basins.

The weather variables used for driving the water balance are daily precipitation, minimum and maximum daily air temperature (degree C), wind speed (m/s), solar radiation (MJ/m<sup>2</sup>), and relative humidity (fractional). These data partly were obtained from the Ethiopian National Meteorological Agency (NMA) for weather stations located within and in close proximity to the watershed. In the northern and western where there is a lack of meteorological stations and where only rain recording station, the data were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) website (<http://globalweather.tamu.edu/>). During simulation each sub-basin is linked to the nearest weather station.

The land cover and soil data obtained from the Ministry of Water Resources of Ethiopia were used for parameterizing the SWAT model. The land uses were divided into five major groups (Fig. 3.3a): Agricultural Land-Generic (AGRL, 82.88%), Forest-Deciduous (FRSD, 6.76%), Forest-Evergreen (FRSE, 1.60%), Water (WATR, 0.17%), Range-Brush (RNGB, 8.59%). The slope of study classified into five classes as shown in figure below (Figure 3.9).

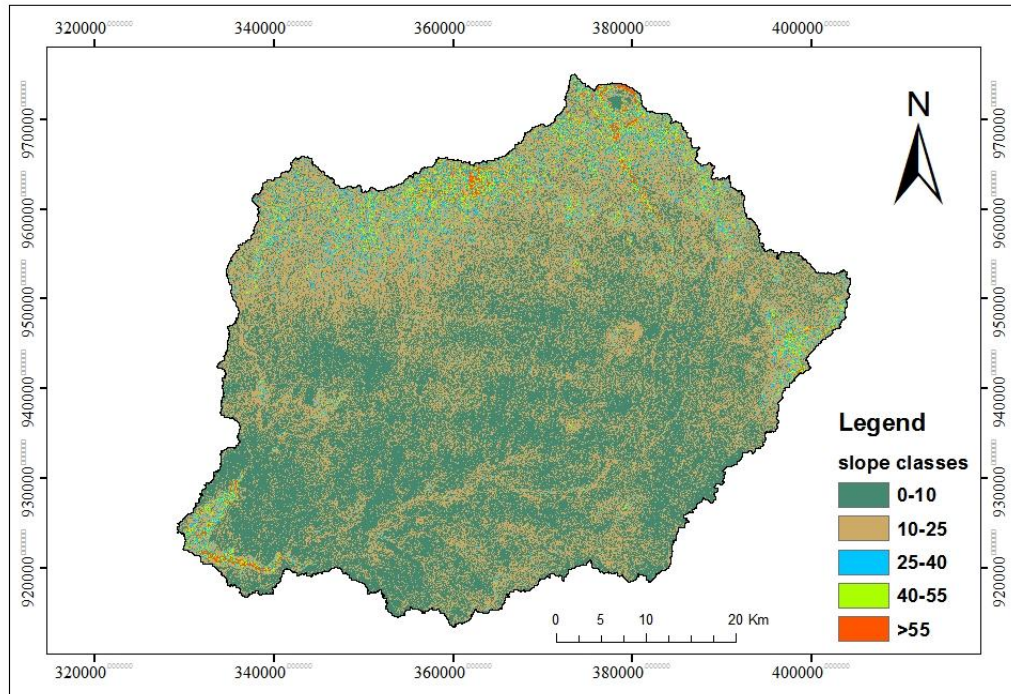


Figure 3.9: Slope map of study area

SWAT model provides three options for estimating potential evapotranspiration: Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965) (Neitsch et al., 2005). The selection of potential evapotranspiration method depends on availability of data required for these methods. In this study, potential evapotranspiration was calculated using the Penman- Monteith (Monteith, 1965).

Long term average hydrologic budget (1990-2013); precipitation, evapotranspiration & potential evapotranspiration, surface runoff and percolation to subsurface are displayed in figure 3.10 and table 3.3. Average annual ground water recharge to shallow aquifer is 315.3mm/y. The

hydrologic water budget shows that only 15.79.mm/y infiltrates to the deeper aquifers. The remaining supplies base-flow to the rivers.

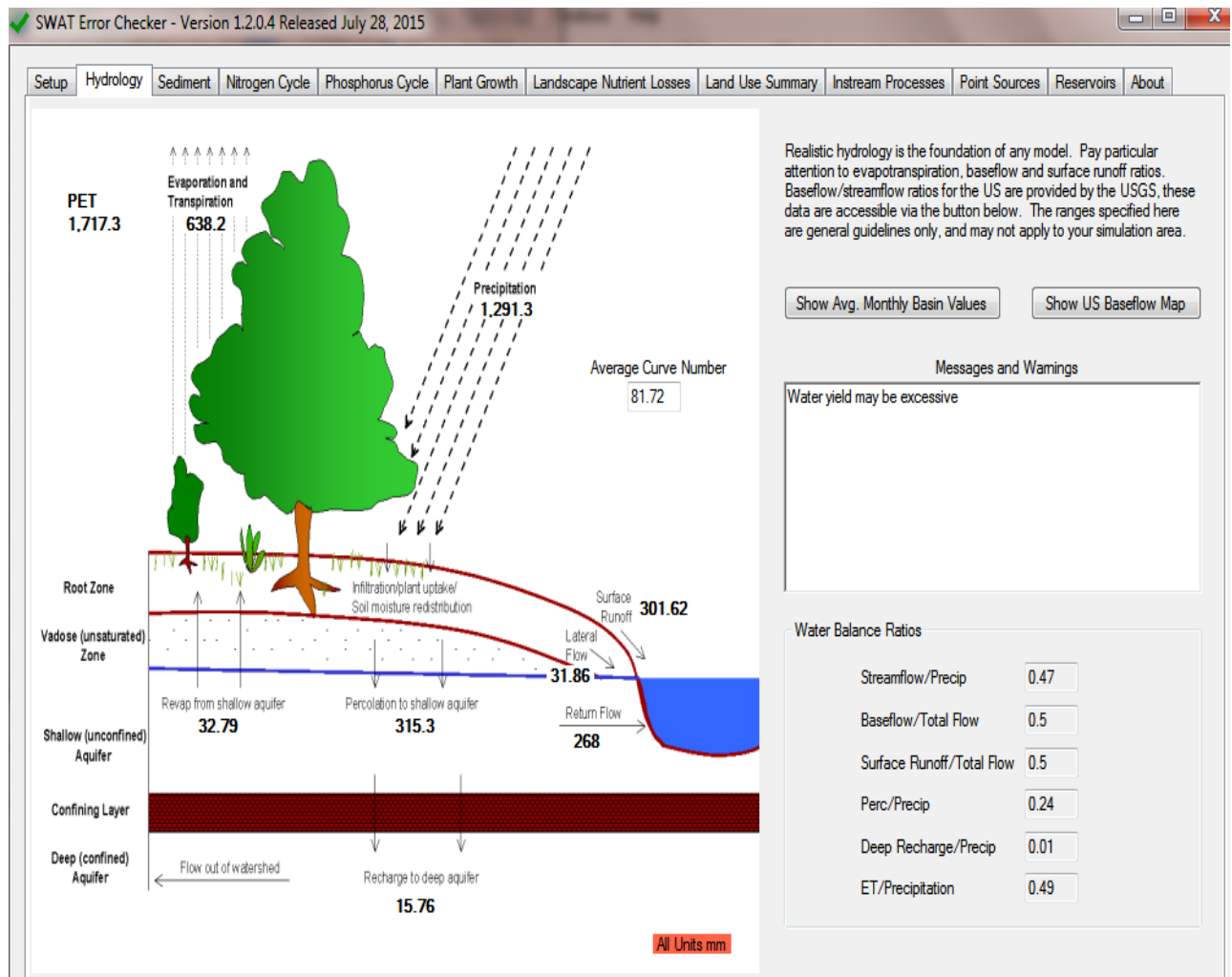


Figure 3.10: Hydrological water balance representation of the basin

A number of output files with several variables are generated in every SWAT simulation. These files are: the summary output file, (output.std), the HRU output file (output.hru), the sub-basin output file (output.sub) and the main channel or reach output file (output.reach).

The Average monthly basin value displays the average annual watershed monthly values in terms of rain fall, snow fall, surface runoff, Lateral flow, total water yield, evapotranspiration & potential evapotranspiration. It is briefly shown as table below.

Table 3. Monthly basin values of model output

Mon	Rain (mm)	Snow Fall(mm)	SURF Q(mm)	LAT Q(mm)	Water Yield(mm)	ET(mm)	Sed. Yield (mm)	PET (mm)
1	15.99	0	1.3	0.3	4.2	13.97	0.19	164.84
2	18.66	0	3.39	0.27	4.04	17.08	0.5	176.09
3	67.04	0	24.38	0.59	26.75	49.7	4.29	187.6
4	75.57	0	13.3	0.88	17.61	83.75	2.2	172.62
5	91.36	0	8.06	1.29	12.66	74.24	1.22	160.36
6	192.18	0	23.15	2.8	27.62	81.16	3.12	108.22
7	304.21	0	83.73	6.78	107.57	69.94	10.56	78.06
8	301.12	0	94.8	8.96	166.58	69.5	11.75	79.75
9	160.99	0	38.63	6.32	129.18	81.68	5.19	113.84
10	44.7	0	7.61	2.73	76.79	55.51	1.17	151.24
11	9.45	0	1.05	0.86	36.27	26.95	0.16	156.64
12	9.13	0	2.99	0.34	15.26	13.64	0.39	164.03
Total	1290.4	0	302.39	32.12	624.53	637.12	40.74	1713.29

Based on the print code selected, the output files may include all daily values, daily values averaged over the month, daily values averaged over the year, daily values averaged over an entire simulation period.

Spatial variability of recharge was extracted from GW\_RCHG output variable (output.hru) and reclassified according to sub basin. A number of variables are created with the HRU output file. The following variables (output.hru) are symbolized the water that inter to the subsurface (Arnold et al., 2012).

PERC: \_ water that percolates past the root zone during the time step (mm H<sub>2</sub>O). There is a lag time the water leaves the bottom of the root zone and reaches the shallow aquifer. Over a long period of time, these variable should equal groundwater recharge (PERC=GW\_RCHG as time is increased).

GW\_RCHG: recharge entering during time step (total amount of water entering the shallow and deep aquifer during time step) (mmH<sub>2</sub>O).

DA\_RCHG: Deep aquifer recharges (mmH<sub>2</sub>O). It is the amount of water from the root zone that recharges the deep aquifer during the time steps. (Shallow aquifer recharge = GW\_RCHG - DA\_RCHG).

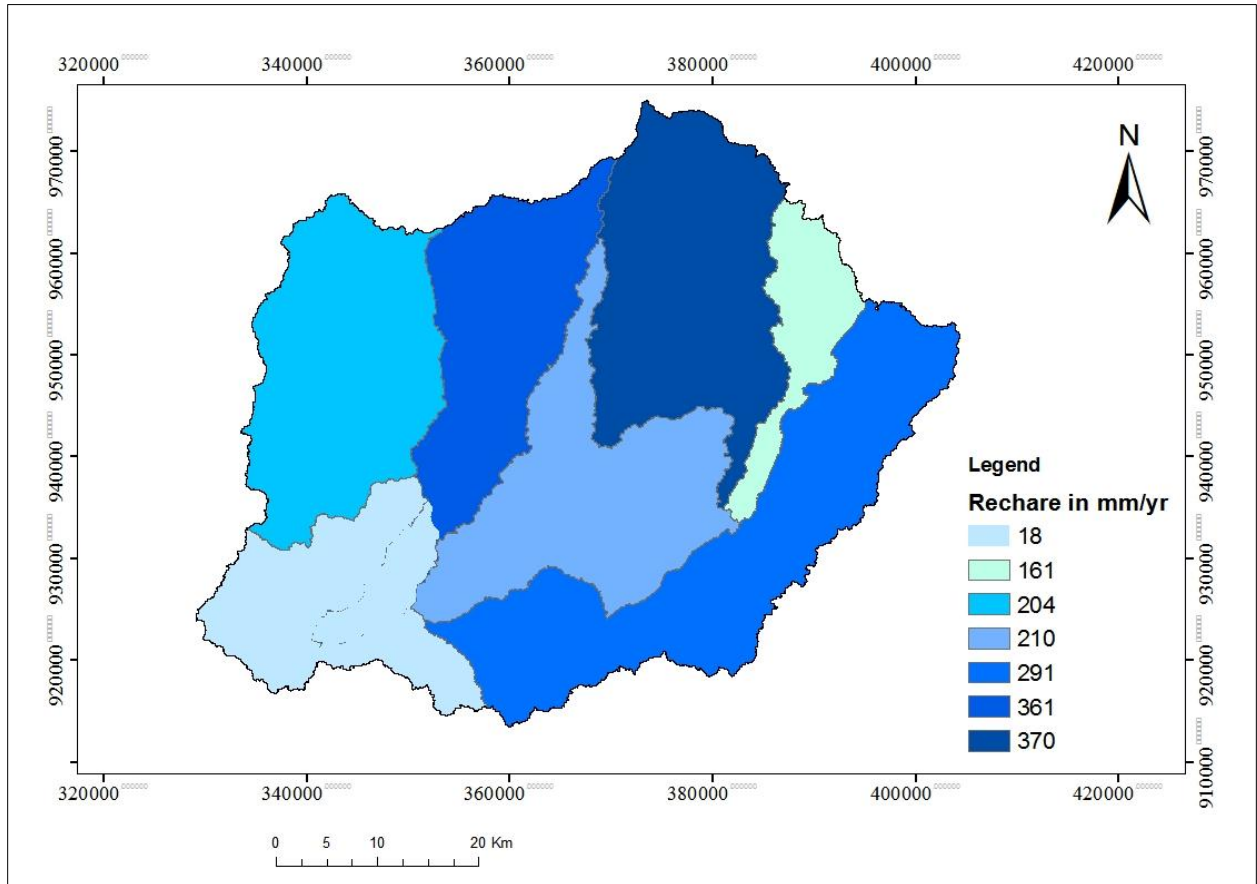


Figure 3.11: Spatial variations of simulated long average annual recharge (mm/year)

## **4. GEOLOGY AND HYDROGEOLOGY OF STUDY AREA**

### **4.1. Geologic Setup**

Dominantly the geological setup of the study area is associated with the results of volcano-tectonic activities of trap serious volcanics of Ethiopian plateau and the development of the Ethiopian rift system. A number of regional geological studies were carried out by the Geological Surveys of Ethiopian (GSE, 2010; 2014) in the study area and nearby, including the geology of: (a) Akaki Beseka area, (b) Arjo area. These areas were covered on 1:250,000 scale maps. The main lithologic units identified includes: Precambrian gneiss, Mesozoic sediments, paleogene (late Eocene to late Oligocene) fissural flood basalt with minor rhyolite, trachyte and pyroclastic flow, Neogene (Miocene-pliocene) pyroclastic, rhyolite and trachytic flow and pleistocene-holocene basic to acidic volcanic and phreatomagmatic deposits including the recent lacustrine and alluvial sediments.

#### **4.1.1. Jima Lower Basalt**

This unit, the oldest and most extensive flood basalt, is exposed along the Gibe gorge area. It usually forms flat lying plateaus, often tilted. For the most part, it is horizontally stratified. In outcrop, it is dark-grey medium to coarse-grained and partly weathered. The base of succession is highly fractured and jointed. The bottom part of succession is comprised of intercalated acidic to intermediate rocks. Attains a maximum thickness of 500 m at Akote-Gilgel Gibe section, where the base of the section is not exposed (EGS, 2010; 2014).

#### **4.1.2. Mekonen Basalt**

The name Makonnen Basalts (Volcanic rocks of pre-rift succession) was coined by Davidson (1983) for up to 700 meters thick of sub-horizontal flood basalts which cap the plateau in southern and southwestern Ethiopia (i.e. those of the Makonnen, Gecha, Nono and Gura Ferda plateaus). Outcrop of this unit is found in the western and central portion of the study area.

#### **4.1.3. Tarmaber-Magezez Formation**

The name Tarmaber Megezez Formation (Ntb) for the younger shield volcanoes which represents Pliocene to Miocene Basaltic shield volcanism in the southern part of the northwestern

plateau and the southeastern plateau has been widely used and the latter is believed to mark the initiation of rifting of the Main Ethiopian Rift (EIGS, 1999). This unit is found in the central, and extend to central west, east and south portion of the study area. It is fine-grained volcanic rock composed of plagioclase, pyroxene, and opaque minerals (EIGS, 2010).

#### **4.1.4. Wechecha Trachytes and Dendi- wenchí pyroclastic**

Exposure of this unit is found to the northeast, central north and northwestern portion of the study area. This unit is composed of trachyte and pyroclastic material. Dendi- wenchí pyroclastic materials cropping out near and around Wenchí and Dendi lakes include the products of Mount Dendi, an isolated elliptical cone having a NE-SW direction. At the summit of the cone, there are two crater lakes called Wenchí and Dendi with a diameter of ~ 2 and 1.5 km, respectively. Volcanic activity, possibly of pre-caldera formation, gave rise to a pile of ignimbrites associated with ash flows, pumice falls and surge deposits.

The product from the caldera forming eruption could have been dispersed as far as Tikur Inchini since some distal ash were observed in some river cut sediments on the plateau (WWDSE, 2015).

#### **4.1.5. Nazret Pyroclastics, Welded to Partially Welded Pyroclastic Flows**

The name Nazareth Group is assigned to the series of rhyolite-trachyte plugs, stratoid flows, ignimbrites, pumice, ash fall tuffs and characteristic lacustrine sediments containing coal and lignite deposits along the main Ethiopian Rift and adjacent plateau margins. The Nazareth Group attains a thickness of 200-300 m in the Ethiopian Rift, but is thinner on the adjacent plateau margins (MoWR, 1995; EIGS, 1999). The Group (Welded to Partially Welded Pyroclastic Flows) crops out along the south of Waliso to Welkite. It is fine grained, densely welded rock containing vitrophyric fiamme and lithic fragments with associated rhyolitic lava flows interleaved with ash and unwelded tuffs (GSE, 2010).

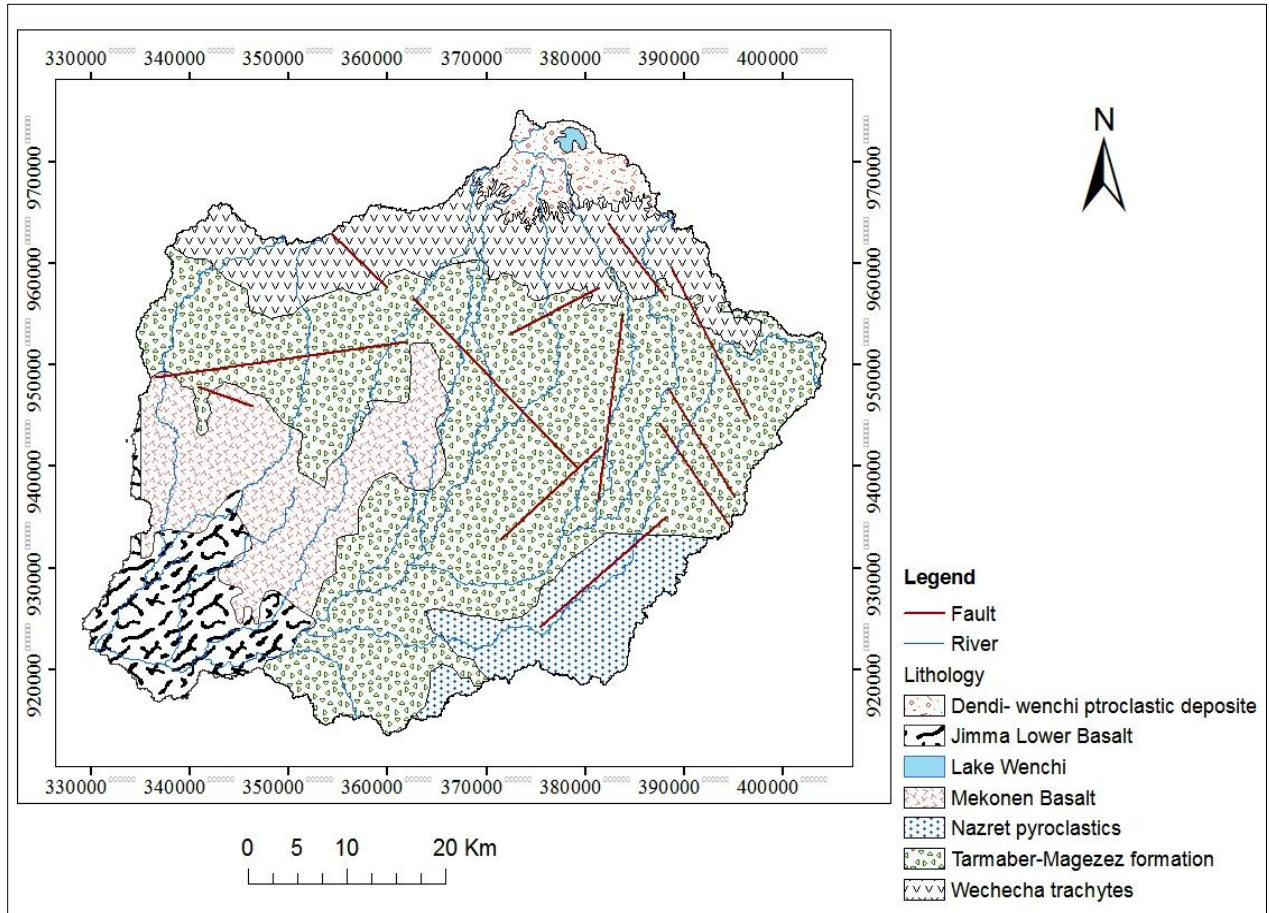


Figure 4.1: Geologic Map of study area; (Adopted from EGS, 2010 & Structures from WWDSE, 2015)

## 4.2. Hydrogeology

Ideally the occurrence, distribution, and availability of groundwater should be evaluated in terms of the distribution of aquifers and aquitards: that is, in terms of the distribution of the hydrogeological properties of the rock framework, hydraulic continuity (Toth, 2004). According to the hydrogeological characteristics, a good aquifer must be sufficiently permeable and transmissive that is porous and interconnected with enough storage to result a suitable and productive yield. Those intrinsically or secondarily openings formed within a rock which includes primary porosities and fractures or joints control the occurrence and movement of subsurface water.

In the study area many shallow source springs come out through the regolith surfaces of volcanic rocks and serve as main water supply for small communities especially in the highland areas. The spring discharge varies spatially depend on geology and the degree of fracturing.

The existing data shows that hydrogeologic system of the catchments are composed of both porous and fissured permeable volcanic aquifers typically Tertiary and Quaternary volcanics. The fissured volcanic aquifers are composed of basalts, ignimbrites and trachytes. Basalt and partially welded pyroclastic flows of Nazerate group (mainly ignimbrite) are generally highly fractured extensive and permeable and have been classified as high productive aquifers with yield up to 5-25 l/s. The transmissivity varies from 100 to 500 m<sup>2</sup>/d. High degree of weathering and fracturing is observed from geological log as well as vertical and lateral permeability's can be favored by columnar jointing and inter lava flows.

Thermal springs around Waliso and warm artesian well in the same area appears to be controlled by the E-W structures of the tectono-magmatically active YTVL and/or the Late Miocene proto-rifts with heat being derived from Pleistocene magmatism in the area (WWDSE, 2015).

Analyzing available data and previous work, groundwater yield varies with respect to geology and wells depth. Tarmaber-Magezez formation, which is fractured and weathered trap serious basalts, are the most extensive and main productive aquifer of the area. Fractured Basalt is the major water bearing formation.

As illustrated in Fig. 4.2, EGS (2011) differentiated the hydrogeological system of study area into four hydrogeological classes. These are:

- 1) Extensive and high productive fissured aquifers- (T= 100-500 sq. m/d, with well & spring yield 5-60 l/s) and includes: Tarmaber-Magezez formation and partially welded pyroclastic flows of Nazret group (mainly ignimbrite).
- 2) Extensive and porous moderately productive Aquifers-These aquifers include Dendi-wenchi pyroclastic deposit. Transmissivity varies from 50 to 100km<sup>2</sup>/d by spring and well discharge of 2-5l/s. The groundwater hosting part of this unit is the primary permeability resulted from the

availability of primary effective porosity. The ground water availability is highly dependent on the grain size, distribution as well as sorting.

3) Extensive and moderate productive fissured aquifers- These aquifers include Mekonen Basalt, Jima Lower Basalt & Nazret pyroclastics, ( $T=50-100$  sq. m/d, with well & spring discharge 2-5 l/s).

4) Extensive and low productive fissured and/or porous Aquifers- These are Wechecha trachytes. ( $T= 1-10$  m<sup>2</sup>/d with spring and well discharge 0.05-0.5 l/s. These units are minor aquifers with limited groundwater occurrence.

Based on field data together with the pumping test data analysis, the volcanic aquifer is not entirely unconfined type. Some part of the basin, typically waliso area shows Semi-confined and confined aquifer type with artesian groundwater conditions. This is presumably due to relatively thick clay (mostly altered ash) and massive basalt, as it was verified from borehole lithological logs. Previous works shows that EGS (2011) and OWWDSE (2017) the groundwater flow direction in the basin coincides with the topography following the surface water flow direction. The flow is partly controlled by the structure (Volcano tectonic lineament) and partly by the geomorphology of the area.

Table 4.4. Basic hydrogeological data from selected water points: Compiled from Well completion report

S N	Site_Name	X	Y	Z	Well_ depth, m	SWL ,m	Q,l/ s	Sc, l/s/m	T,m <sup>2</sup> /day	Safe_ yield, l/s
1	Woliso Prison	386183	943986	2032	108	6.25	5	0.06	4.16	
2	Guro	375734	926348		360	14	2.5	0.20	112	
3	Gindo	357700	944225	1835	360	23	5	0.043	24	
4	Meti-walga	383826	947387	2058	265	0	5	0.054	125	
5	Sodo Gerba	408282	939498	2314	360	22	24	1	43	
6	Wolkite town	363415	915588	1801	280	98	3	0	3	
7	galiye Rogida	358290	926080	1970	459	82	10.5	0.197	19.8	18.76
8	Meisa	370781	943250	1970	471	29.3	16.4	0.3	43.1	
9	Woliso	385801	939409	1970	474	65	60.7	2.76	6.66	48.62
10	Wesherbi	389562	922209	1931	450	98				
11	Kile	395770	936037	2117	101	5.05	2.08	0.023	1.115	1.476
12	Woliso	387657	946375	2063	133	0	2	0.017	0.5	1.46
13	Ameya	350776	948648	1899	135	29.8	4.4	0.174	0.000343	
14	Ameya	354182	939439	1725	150		4.74		0.00045	12.45
15	Hadud-10	361150	934826	1745	122	30.3		60.04	499.43	
16	Woliso	387549	945858	2058	93	1.2	5	0.956	41.51	
17	DaeWondimtu	385518	959705	2363	133	12.4	7.2	0.18	24.03	
18	Dulele Kori	384450	959524	2382	167	43	4.5	0.08	33.9	
	Goro#1	373521	924345	1758	245	2.2	12.2	0.37	205.53	
19	Goro#3	373521	924345	1758	300	4.6	5.2	0.83	5.31	
20	guraghe	352181	918205	1643	180	113	8		1.36x10 <sup>2</sup>	
21	Gerjeba	364968	915411	1899	140	17.9	7		7.11 x10 <sup>-5</sup>	
22	Ameya	366782	960280	2311	172	27.4		0.000	290	
23	S/W/S-Kota	377000	942000	1952	174	14.7	1.30	0.024	2.84	
24	Korke	399121	934755	2184	161	57	7	87.6	160	
25	Sonkole	378981	956265	2257	45	13	3			
26	weliso town	387641	946064	1962	135	2	8.3		11.3	
27	Welkite	364905	923161	1694	152	12	7		56.92	9
28	Welkite	365433	923338	1696	200	35	2		0.616	53
29	Welkite	365427	923242	1697	103	3	8		221.36	24
30	Welkite	365447	922747	1708	152	54	5		1.76	
31	Welkite	369104	915815	1835	81	22	2		4.83	2
32	Welkite	372001	916722	1848	69	12	3		13.73	12

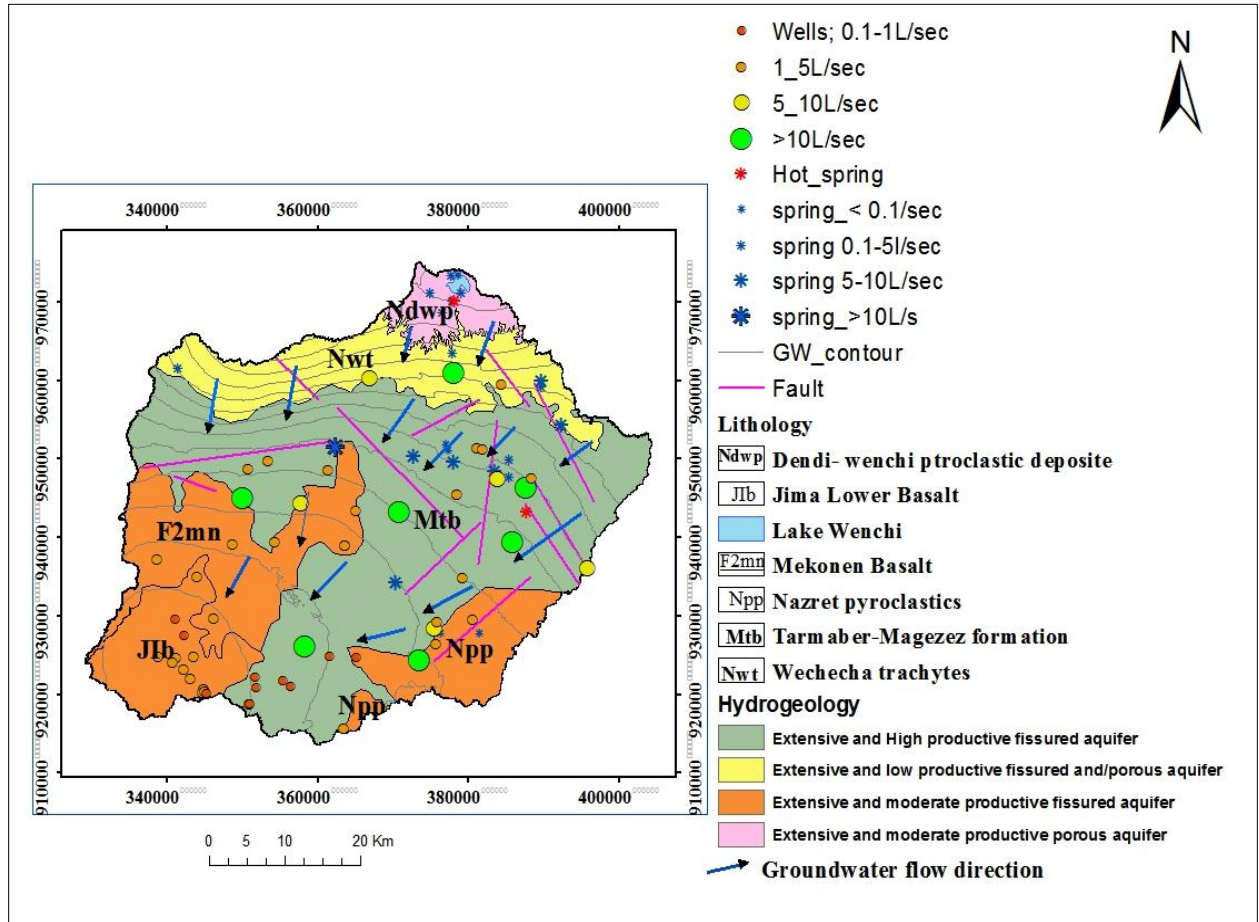


Figure 4.2: Hydrogeological Map of study area (Modified from EGS, 2011)

## **5. CONCEPTUAL AND NUMERICAL GROUNDWATER FLOW MODELING**

### **5.1. Conceptual Model**

A conceptual model defined as to be a qualitative representation of a groundwater system that conforms to hydrogeological principles and is based on geological, geophysical, hydrological, hydrogeochemical, and other ancillary information (Anderson et.al, 2015). A conceptual hydrogeological model is a mental construct or hypothesis accompanied by verbal, pictorial, diagrammatic and/or tabular interpretations and representations of site hydrogeological conditions as well as corresponding flow/transport dynamics (Neuman and Wierenga, 2002). A conceptual model may include a description of the aquifers and confining units that make up the aquifer system, boundary conditions, sources and sinks of water, flow regimes and general directions of ground-water flow (Eberts and George; 2000).

#### **5.1.1. Hydrostratigraphic Units**

Identification of hydrostratigraphic units is important in defining the number of layers controlling groundwater flow within the aquifer system. For hydrogeological investigations, geologic layers or formations are often classified into hydrostratigraphic units. A hydrostratigraphic unit is comprised of geological units of similar hydrogeological properties.

Lithological logs show variable aquifer lithology with different degrees of fracturing and weathering. The aquifer system of the area composed of different volcanic rocks: Basaltic, welded to partially welded pyroclastics and trachyte. However, due to their permeability the different hydrostratigraphic units are hydraulically interconnected. Therefore, these hydrostratigraphic units are considered as one layer. Based on pumping test data and lithological logs the aquifer system behaves as an unconfined. The following figure shows simplified hydrogeological cross section of the study area.

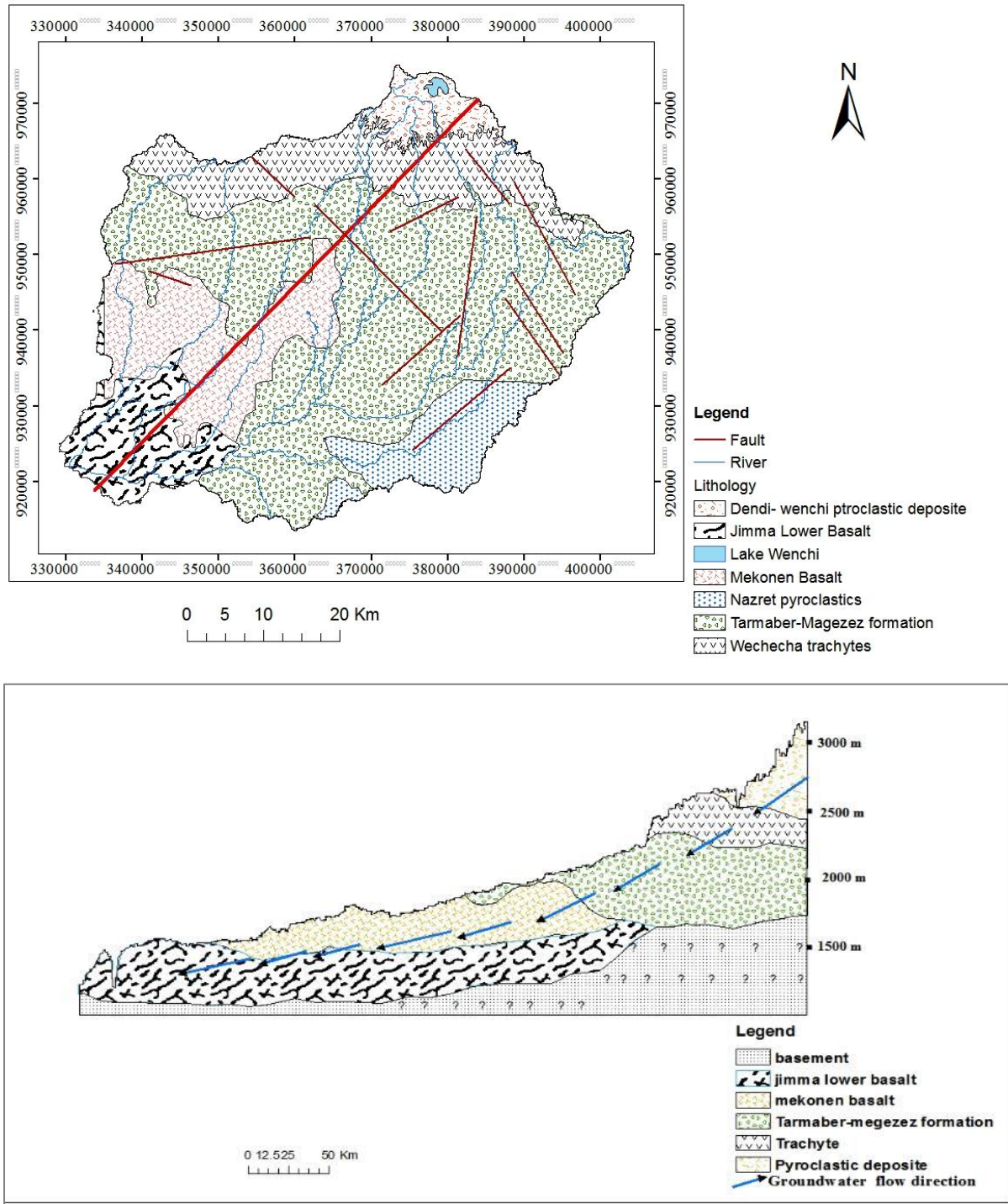


Figure 5.1: Hydrogeological Cross Section along NE\_SW profile

### 5.1.2. Groundwater Flow Conceptualization

Generalized potentiometric surfaces of the study area aquifers were estimated from water levels from observed wells in the aquifers. The potentiometric surfaces indicate a generalized southwesterly groundwater-flow direction slightly following the topography. Groundwater generally flows from areas of recharge to streams or other topographically low areas where the aquifers discharge either through stream or base flow. The general direction of groundwater flow in the study area is north- east to south west and towards the Gibe River gorge.

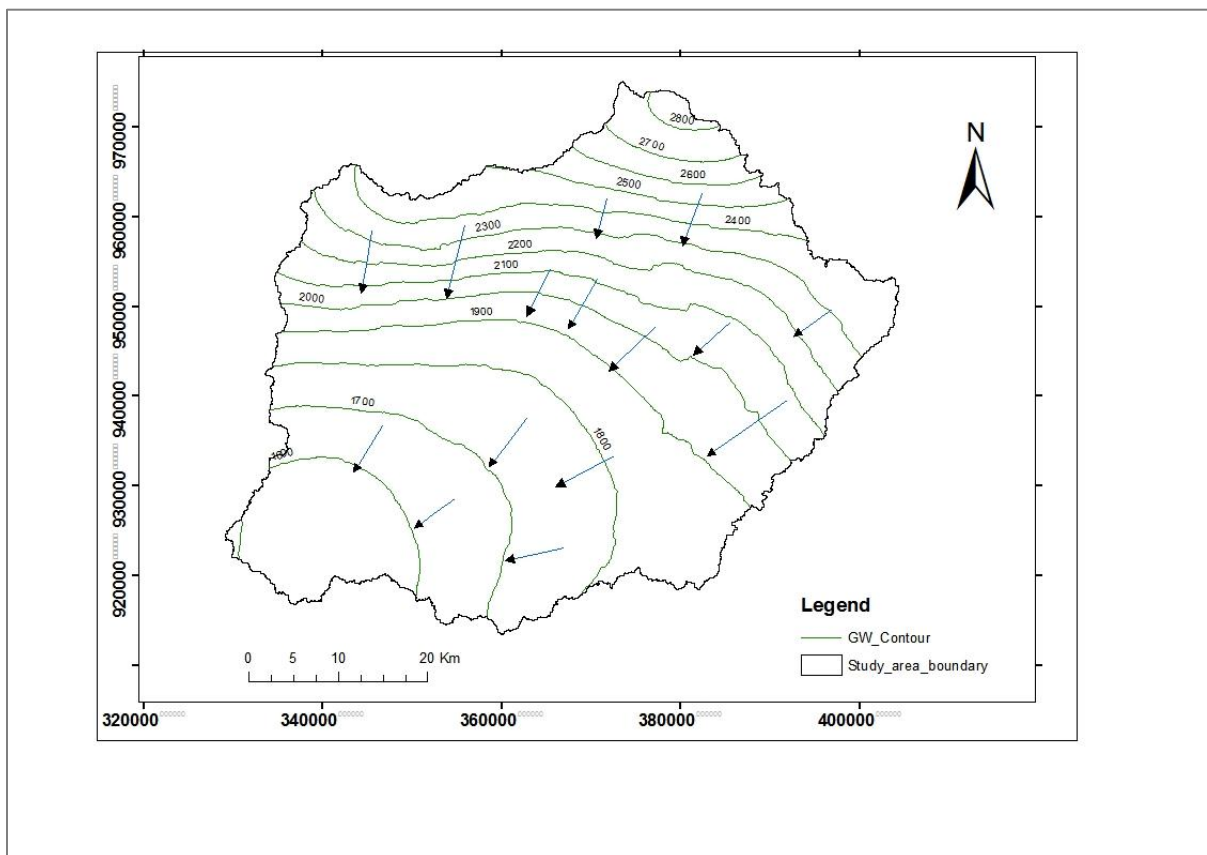


Figure 5.2: Groundwater level contour map of study area

### 5.1.3. Boundary Conditions

The hydrological conditions along the boundaries of the conceptual model determine the mathematical boundary conditions of the numerical model and are a key component of a mathematical model and strongly influence the flow directions calculated by a steady-state numerical model.

Boundaries include hydraulic features such as groundwater divides and physical features such as bodies of surface water and relatively impermeable rock. The water table usually forms the upper boundary of a three-dimensional numerical model. Ideally, lateral and bottom boundaries should be aligned with physical or hydraulic features that do not move or change as hydrologic conditions change. Boundaries are identified from potentiometric, topographic, and geologic maps of the region and site.

Mathematically, boundary conditions are classified into three types (Anderson et al., 2015).

1. Specified head boundary (Dirichlet conditions); - where head along the boundary is set at a known value. Heads along a specified head boundary may vary with space. A constant head boundary is a special case Type 1 boundary where the heads along the boundary are set to the same value.
2. Specified flow boundary (Neumann conditions); - where the derivative of head at the boundary is specified. Flow is calculated from Darcy's law. A no flow boundary is a special case Type 2 boundary where the flow across the boundary is zero.
3. Head-dependent boundary (Cauchy conditions);- where flow across the boundary is calculated from Darcy's law using a gradient calculated as the difference between a specified head outside the boundary and the head computed by the model at the node located on or near the boundary. This type of boundary condition is sometimes called a mixed boundary condition because it relates a boundary head ( $h_b$ ) to a boundary flow.

Based on potentiometric, topographic, geologic and hydrogeological maps of site, three of these boundary conditions are identified for the region. General Head Boundary is identified for south western boundary of the aquifer system. Specified flow boundary (no flow boundary) is assigned for the remaining all lateral boundaries. A Wonchi lake was considered as constant head boundary.

#### **5.1.4. Ground Water Recharge**

The recharge quantification and spatial variability was made using SWAT model based on precipitation distribution, soil type, land cover, topography (slope class) of the study area. The total groundwater recharge to shallow aquifer, as estimated using SWAT model is 315mm/yr., which is 24.4% of the annual rainfall amount of the study area. Spatial distribution of recharges

was extracted from GW\_RCHG output variable (output.hru) and reclassified according to sub basin as shown figure 3.11.

#### **5.1.3.2. Ground Water Discharge**

Discharge from the Study area aquifers occurs through discharge to streams, subsurface outflow and well withdrawals. Discharge to streams occurs as flow from springs and seeps and as base flow where the aquifers are hydraulically connected to the streams (river leakage). For the purpose of this analysis, all discharge from springs and seeps was assumed to reach a stream and contribute to base flow. Well withdrawals are for public and domestic water supplies.

#### **5.1.5. Hydraulic Conductivity**

Hydraulic conductivity is a measure of the capability of a fluid to move through interconnected void spaces in sediments or rocks. It is a function of both the fluid and the medium. The hydraulic conductivity of fractured rocks depends largely on the density of the fractures and width of their apertures.

The spatial distribution of the hydraulic properties of the aquifer is hardly known. The surface geology, Lithologic log therefore helped as a first criterion for the delineation of hydraulic conductivity zones. Yet, in some areas the results from pumping tests data obtained from WWDSE, OWWDSE, Gurhage and Southwest Shoa Zone Water Resource Development Offices display a wide range of transmissivity and hydraulic conductivity values within the same lithology. Therefore, the zonation was further modified based on the pumping test data as well as on the information about aquifer geology. As a result, the hydraulic conductivity classified into four zones for which it is assumed that despite their internal heterogeneity they can be reasonably represented by one hydraulic conductivity value at the regional scale. From existing pumping test data analysis the hydraulic conductivity values ranges from 0.000008 to 13.8m/day.

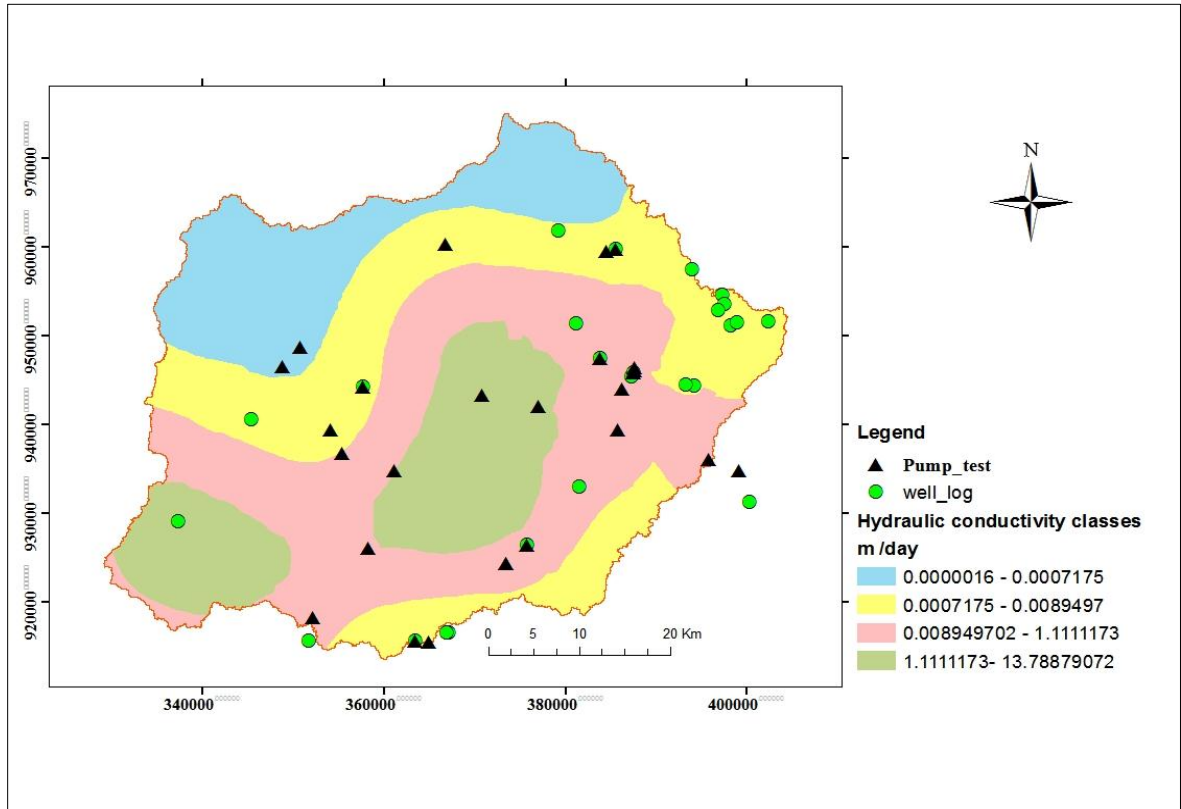


Figure 5.3 : Classified Hydraulic conductivity in m/day

## 5.2. Numerical Groundwater Flow Modeling

### 5.2.1. Governing Equation and Modeling Approach

Numerical models use an approximate form of the governing equation to calculate head at selected locations. The governing equation for groundwater flow model is derived from two basic principles: conservation of mass (i.e., water balance), which states that water is not created or destroyed; and Darcy’s law, which states that groundwater flows from high to low potential energy.

A mathematical model for groundwater flow consists of a governing equation (derived from conservation of mass and Darcy’s law) that represents processes within the problem domain; boundary conditions that represent processes along the boundaries; and, for time-dependent (transient) problems, initial conditions that specify values of the dependent variable (i.e., head) at the start of the simulation.

The steady- state groundwater flow is simulated based on the following governing differential equation under two- dimensional aerial view in unconfined aquifer (Anderson and Woessner, 1992).

$$\frac{\partial}{\partial X} \left( Kx \frac{\partial h}{\partial X} \right) + \frac{\partial}{\partial Y} \left( Ky \frac{\partial h}{\partial Y} \right) + R = 0 \quad \text{Equation 5.1}$$

Where:

Kx and Ky = Components of the hydraulic conductivity along x, and y axes [LT-1]

R = Flux per unit volume representing sources/sinks term [T-1]

h = Hydraulic head [L]

The most widely used code for solving groundwater flow problems currently is the FD code MODFLOW by the U.S. Geological Survey. This numerical modeling was performed using the interface of Processing Modflow *Pro* (*PMWIN Pro*), Version 8.0.30

### 5.2.2. Model Grid Design

Numerical groundwater models require the model domain to be subdivided (discretized) into a grid (or mesh) that defines the locations of the points, which referred to as nodes, at which heads or solute concentrations are calculated and the geometry of the cells (or elements) that controls the calculation of the volumetric or mass flow rates of water and solutes (Barnett et al., 2012).

The extent of the model in the north-south and east-west is 62,934m and 75,689m, respectively. The modeled catchment has an area of about 2915 km<sup>2</sup>. The lateral dimension of the cells is 500m by 500m on each side with 126 row and 151 column arrays in a single layer. A regular grid has been adopted for the entire catchment and each cell assumed that has homogeneous property.

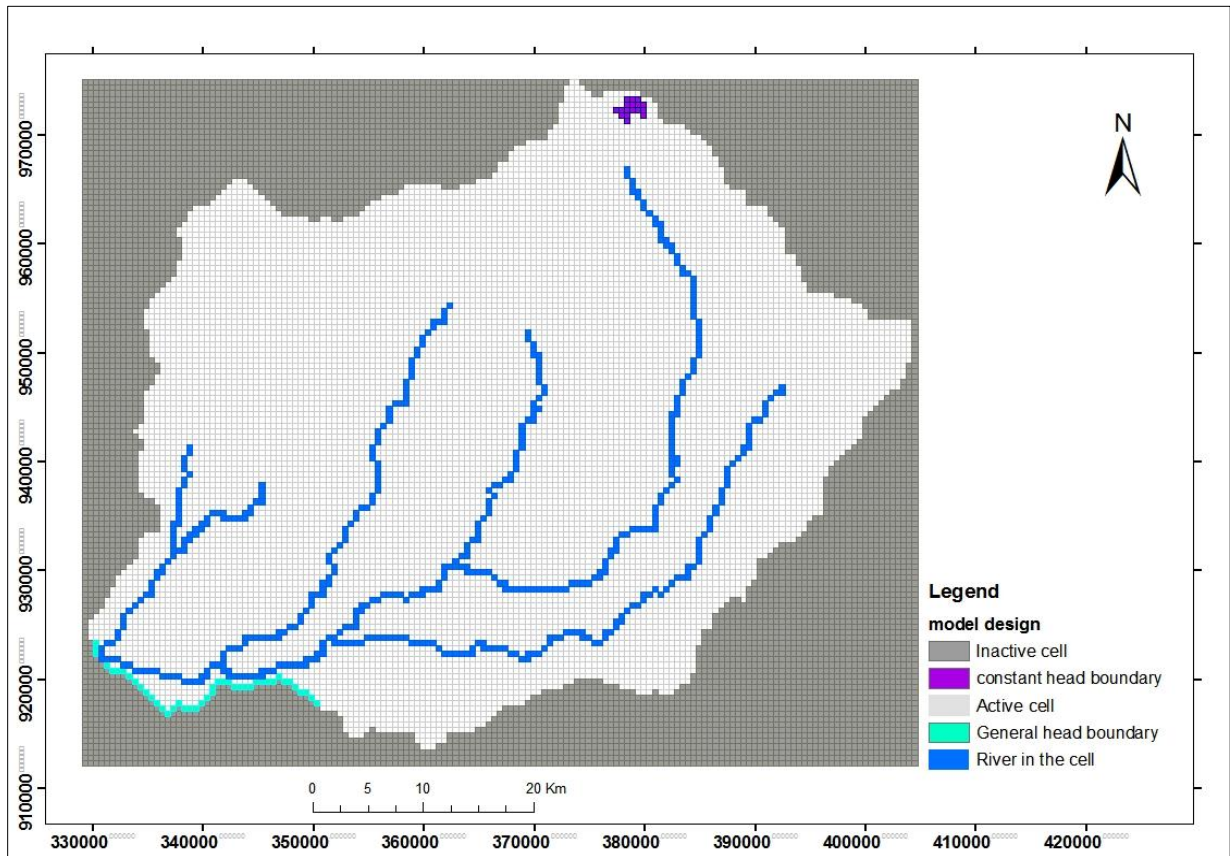


Figure 5.4: Model Grid Design

### 5.2.2.1. Top of Model Layer

In this model, the aquifer was assumed to be a single layer and unconfined aquifer. The top of the aquifer layer is assumed to be the ground elevation and the digital elevation model was used to constrain top elevations relative to approximate land surface elevations. The 30-meter resolution digital elevation model was sampled and converted to GRD surfer 6 txt (grd) format and then loaded in to the MODFLOW top elevation.

### 5.2.2.2. Bottom of Model Layer

Bottom layer is the bottom elevation of the aquifer layer being modeled and in association with the top layer determines the thickness of the aquifer. In this study, the aquifer thickness lies within the range 180m to 380m in most parts of the catchment except along the boundaries where ridges with high elevation are found. Therefore, bottom layer was acquired by subtracting a range of 180-380m from elevation top in most parts of the catchments. Whereas, elevated zones were simulated by giving relatively higher thicknesses at the cells in order to avoid drying of cells during simulations.

**5.2.2.3. Initial and Prescribed Hydraulic Head**

MODFLOW requires initial hydraulic heads for each active and constant head cell in the model at the beginning of a flow simulation. Initial hydraulic heads at constant head cells are used as specified head values of those cells and remain constant throughout the flow simulation. For transient flow simulations, the initial heads values should be obtained, wherever possible, from a previous model run (e.g. a steady state solution) to avoid spurious results at early times in the transient model run (Barnett et al., 2012). For steady-state flow simulations, the initial heads are used as starting values for the iterative equation solvers. The initial heads at the constant head cell must be actual (realistic) values while all other values can be set at an arbitrary level (Chiang, 2005). In this model, the preliminary potentiometric map was developed from measured head and used as an initial condition and imported as grid surfer file format.

**5.2.3. Model Stress Package**

**5.2.3.1. Recharge Package**

Groundwater recharge processes and estimated results are discussed in section 3.5. The recharge value was modified during the calibration process. There are no recharging wells or other artificial method in the study area. It is clear that recharge to the aquifers in the catchment is directly from precipitation during intensive rainy seasons.

The Recharge package is designed to simulate distributed recharge to the aquifer system and is defined by assigning the following data to each vertical column of cells. (Chiang; 2005)

- Recharge Flux  $IR$  [ $LT^{-1}$ ]
- Layer Indicator  $IRCH$  [-]
- Parameter Number [-]

MODFLOW uses  $IR$  to calculate the recharge flow rate ( $QR$  [ $L^3T^{-1}$ ]) applied to the model cell:

$$QR = IR \cdot DELR \cdot DELC \dots \dots \dots \text{Equation 5.2}$$

Where:  $DEL R \cdot DEL C$  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.

### 5.2.3. 2.The River Package

The River (RIV) package is intended to simulate the effect of flow between groundwater systems and surface-water features, such as rivers, lakes or reservoirs (Harbaugh, 2005; Chiang, 2005). In the River package, two elevations is specifies. One represents the elevation of the lowermost of the river bed and other represents the bottom of the river bed. If the head in the cell connected to the river drops below the bottom of the river bed, the leakage rate  $QRIV$  from the river to the aquifer is calculated by Eq. 5.3. If the head is above the bottom of the river, the water flows from the aquifer into the river and is removed from the groundwater system and calculated as Eq.5.6. A river bed conductance ( $Criv$ ) is multiplied by the difference between the head in the cell and the head in the river to determine the flux.

$$Q_{riv} = Criv (h_{riv} - h) \text{ if } h > Briv, \quad \text{Equation 5.3}$$

$$Q_{riv} = Criv (h_{riv} - Briv) \text{ if } h < Briv, \quad \text{Equation 5.4}$$

Where:

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

$h_{riv}$  : Head in the river

$h$ : Head in the aquifer or the model

$Briv$  : Elevation of bottom of the river bed

$Criv$ : hydraulic conductance of river bed

$Kriv$ : Hydraulic conductivity of the river bed

$L$ : Length of the river within the cell

The major perennial stream was most essential river boundary in the model area that holds the surface and aquifer system interaction. In the study area Walga River and its tributaries, Kulit and Darge sustain their dry period of flow with contribution of the groundwater. Based on some sample site observation during the field work and estimation, river bed sediment thickness has been assumed to vary between 0.25 to 1 m. River widths range from 3 to 15m. River length in a cell has been roughly estimated, based on the relative length in the cell. The hydraulic conductance of the river bed sediments has been calculated using the relation:

$$Criv = \frac{Kriv.L.Wriv}{Mriv} \quad \text{Equation 5.5}$$

Where;

$Criv$  = hydraulic conductance of the river bed [L<sup>2</sup>T<sup>-1</sup>]

$Kriv$  = hydraulic conductivity of the riverbed material [LT<sup>-1</sup>]

$L$  = length of the river within a cell [L]

$Wriv$  = river width within a cell [L]

$Mriv$  = thickness of the riverbed [L]

### 5.2.3. 3.The General Head Boundary (GHB) Package

General-Head Boundary (GHB) Package is head-dependent flux boundary package to simulate flow into or out of a cell from an external source in proportion to the difference between the head in the cell and the head assigned to the external source. The reference head and constant of proportionality is called the boundary conductance is specified by user. Thus a linear relation between flow into the cell and head in the cell is established (Harbaugh, 2005):

$$QB_n = CB_n (HB_n - h_{i,j,k}) \quad \text{Equation 5.6}$$

Where

$n$  is a boundary number,

$QB_n$  is the flow into cell  $i,j,k$  from the boundary (L<sup>3</sup>T<sup>-1</sup>);

$CB_n$  is the boundary conductance (L<sup>2</sup>T<sup>-1</sup>);

$HB_n$  is the head assigned to the external source (L); and

$h_{i,j,k}$  is the head in cell  $i,j,k$  (L).

In the study area the heads at or outside the boundary is less than the head in the aquifer, which results in loss of water from the groundwater system. Heads at or beyond the boundary were approximated by the water level altitude Gibe river gorge and head in aquifer was calculated during simulations.

### 5.2.3.4. Well Package

In this model, the abstraction volume of the boreholes was analyzed based on the yield of the boreholes and average pumping hours. The abstraction of groundwater was simulated using well package. The sum of pumping rate of each well was considered in the cases of two or more wells were assigned into a single cell.

## **5.2.4. Model Calibration and Sensitivity Analysis**

### **5.2.4.1. Calibration**

Calibration of a flow model refers to a demonstration that the model is capable of producing field-measured heads and flows which is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error (Anderson and Woessner, 1992).

In order to calibrate the model, calibrate target and measured should be established. Though many types of targets are desirable, in this work focus was made on the minimum recommended and most commonly used type, typically head.

Basically, there are two way of finding model parameter to achieve calibration method: (1) Manual trial and error calibration (2) Automated parameter estimation which is performed using software (Anderson and Woessner, 1992). While automated calibration using computer software has been available for decades, it is still common for calibration to be attempted by trial and error (Barnett et al., 2012). The model is run initially, using initial estimates of all model parameters, for the period of time during which historical data is available. Modeled heads and possibly fluxes are compared with observations, either numerically, graphically or spatially on a map.

The model calibration was done toward historical data in order to estimate model parameters and conditions that received from a good fit between observations of groundwater levels and simulated head calculated by the model. Parameters are adjusted within reasonable ranges in sequential forward runs of the model until the model produces an acceptable match.

### **5.2.4.2. Manual Trial and Error Calibration**

In this work, groundwater flow model was calibrated using manual trial-and-error method in modifying or adjusting initial estimates of aquifer properties (hydraulic conductivity) and recharge until the sequential model run match simulated head to calibration target. The general workflow for manual trial-and-error history matching is shown in (Figure 5.5).

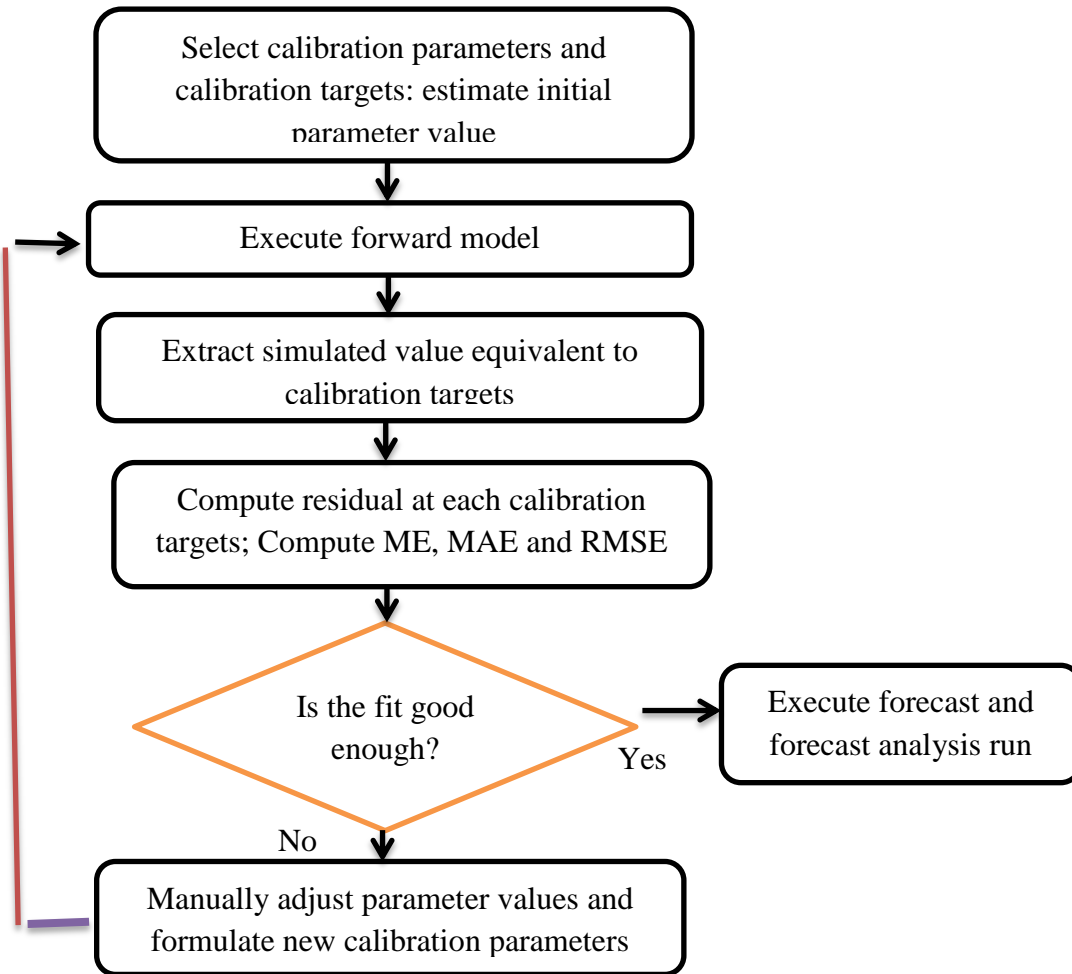


Figure 5.5: General Workflow for manual trial and error, the first phase of history matching a model intended for forecasting (adopted from: Anderson et al., 2015)

#### 5.2.4.3. Data Used for Calibration

The groundwater flow models calibration was done using measured groundwater level data. All of these wells are used for water supply and not designed as observation wells. Head information (water level data) was collected from pumping test reports where direct water level measurement was not possible. Totally, 121 water levels or heads were used for head observation during model calibration.

**5.2.4.4. Evaluation of Calibrated Model Result**

Qualitatively, calibration results are evaluated using visual examination of a scatter graph. A scatter graph (Figure 5.7) show all predicted heads on the vertical axis and corresponding measured heads on the horizontal axis. Ideally, the data points in the graph should fall along a straight line through the origin with slope.

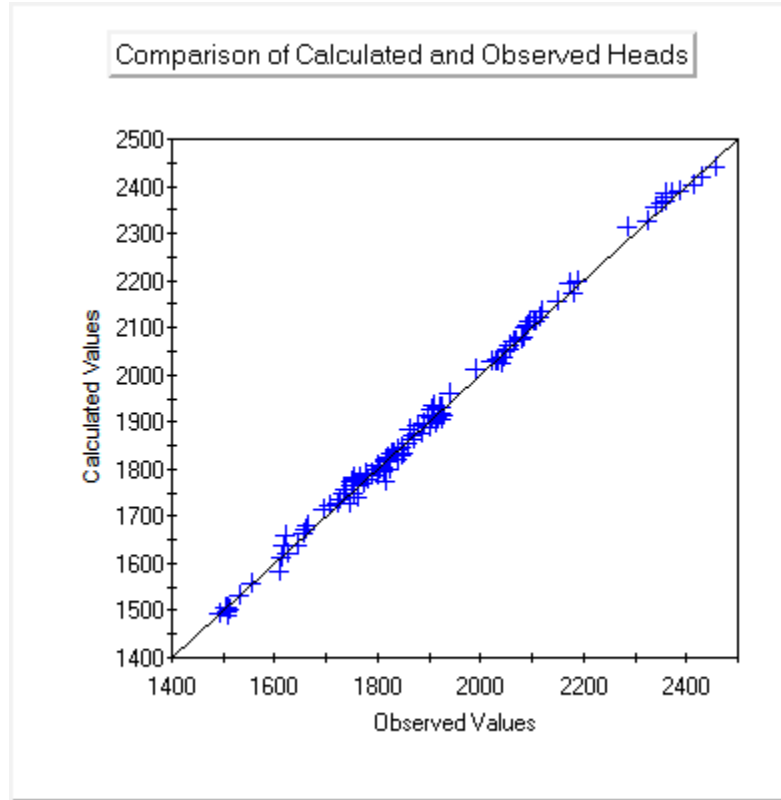


Figure 5.6: Scatter Plot of Head Distribution of Calibrated Model

In addition to visual representations of results, quantitative summary statistics was also calculated to measure the goodness of fit. Quantitative summary statistics implicate statistical lumped sum description of the average differences of residuals between simulated and measured heads in terms of mean error, mean absolute error and root mean square error.

1. The mean error (ME): is the mean difference of the residual errors (measured heads and simulated heads):

$$ME = \frac{1}{n} \sum_{i=1}^n (hm - hs)_i \tag{Equation 5.7}$$

2. The mean absolute error (MAE): is the mean of the absolute values of the differences between measured heads and simulated heads (residual).

$$MAE = \frac{1}{n} \sum_{i=1}^n |hm - hs|_i \quad \text{Equation 5.8}$$

3. The root mean squared error (RMSE): is the square root of the averages of the squared differences between measured heads and simulated heads (Average of the squared residuals.)

$$RMSE = \sqrt{\left[ \frac{1}{n} \sum_{i=1}^n (hm - hs)^2_i \right]} \quad \text{Equation 5.9}$$

RMSE is less robust to the effects of outlier residuals; thus, the RMSE is typically larger than the MAE.

Where

n is the number of targets.

hm is measured head, hs is calculated head and n is number of head measurements.

Table 5. Summary of calibration statistics

No	Statistical parameters	error, m
1	Mean error	-2.41875
2	Mean absolute error	10.86881
3	Root mean squared error	13.51742

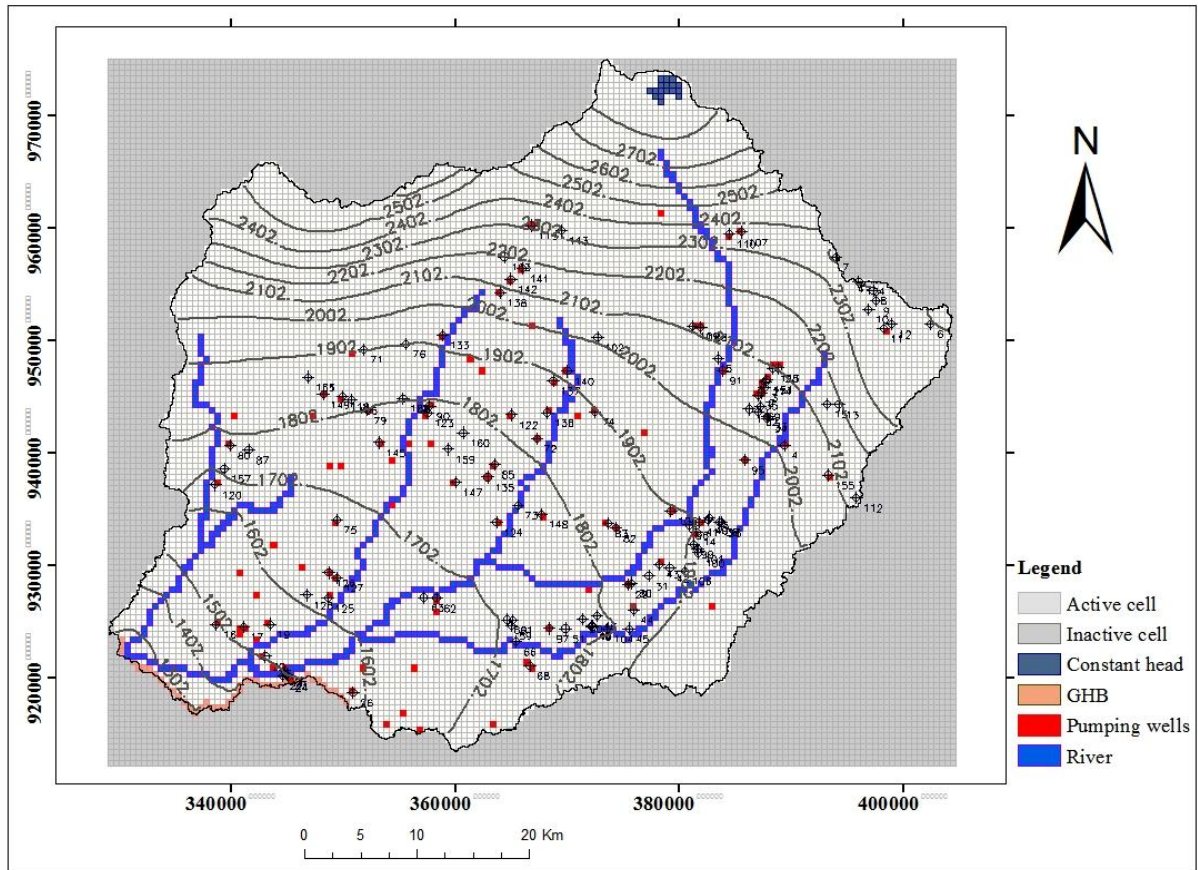


Figure 5.7: Simulated groundwater contour map

#### 5.2.4.5. Sensitivity Analysis

The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions which is performed by systematically changing the calibrated values of conditions (Anderson & Weossner, 1992).

According to Anderson et al. (2015) two broad sources of uncertainty to be considered: first, uncertainty associated with the model itself; and second, uncertainty associated with accurate specification of future conditions. The first source of uncertainty stems from assumptions used in the conceptual model, measurement error in observations used to calibrate the model, simplifications required by calibration, and simplification error resulting from defects in the parameterization of the model selected. The second source of uncertainty arises when forecasts need to estimate future stresses and properties. Examples of uncertain future parameters include future recharge rates, future pumping schedules, and locations of future sources and sinks, as well as related non hydrogeological factors.

Barnett et al. (2012) stated that, sensitivity analysis should be performed to compare model outputs with different sets of reasonable parameter estimates, both during the period of calibration (the past) and during predictions (in the future).

During manual trial-and-error calibration, sensitivity analysis involves changing model parameters by a small amount to establish how model predictions are affected by the change. In manual sensitivity analysis changing a single model parameter is required, re-running the model to obtain a new set of predicted heads and fluxes and observing the effect of the change, either by eye or numerically differentiating.

The calibrated values of hydraulic conductivity and recharge were varied by 20% and 40% (multiplier factors: 0.6, 0.8, 1.2 and 1.4). A total of eight model runs has been made by changing hydraulic conductivity and recharge by the specified percent and compared by respective absolute mean head changes from the calibrated value (Figure 5.8). In sensitivity analysis simulations, the model was observed that more sensitive to parameter changes in the northern part of the catchment compared to the southern. Figure 5.8 illustrates that the model sensitivity to both recharge and hydraulic conductivity.

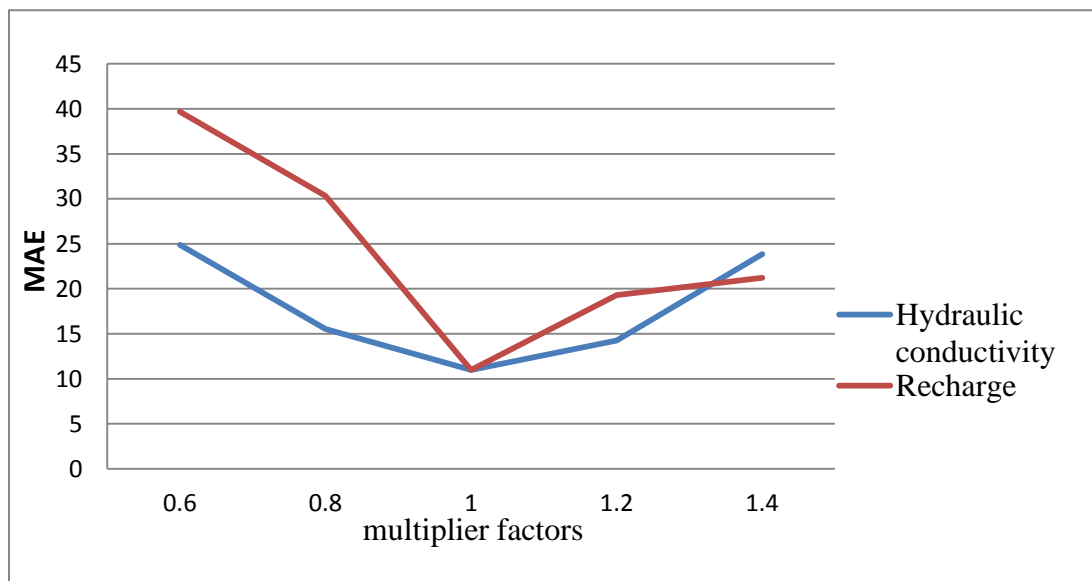


Figure 5.8: Plot of the result of sensitivity analysis test on heads

**5.2.5. Water Budget of the Model Domain**

The water budget refers to the quantification of the inflow to and outflow from parts or the entire model domain through the specified head boundaries. The inflow component includes direct recharge from precipitation, leakage from rivers and lateral inflow of groundwater. Outflows include base flow to rivers, well withdrawals, and lateral groundwater across the model boundary. Table 5.2 summarizes the steady-state water budget of the entire model domain.

The water budget of the model domain should show that total inflow equals total outflow. Typically, the code computes the water budget error as the difference between inflow and outflow. The water budget should be less than around 0.5% (ideally less than 0.1%; Konikow, 1978), but an error as high as 1% may be acceptable (Anderson et al., 2015).

Table 6. Water budget summary for a Steady state problem calculated by MODFLOW

Flow Term	Daily (m <sup>3</sup> /d)			Annually (m <sup>3</sup> /y)		
	IN	OUT	IN-OUT	IN	OUT	IN-OUT
Constant Head	3768.919	53.49833	3715.42	1375655	19526.89	1356128
Wells	0	16650.9	-16650.9	0	6077579	-6077579
Recharge	206634.1	0	206634.1	75421439	0	75421439
River Leakage	19371.27	203189.1	-183818	7070515	74164018	-67093500.7
Head Dep. Bounds	7300.735	17176.69	-9875.95	2664768	6269491	-3604723
Sum	237075	237070.2	4.828125	86532382	86530619	1762.266
Discrepancy [%]	0.00					

**5.2.5. Scenarios Modeling**

In scenario modeling, all initial parameters and hydrologic conditions from the base model are retained except for those the projection was carried as part of the forecast. The base model (calibrated model), modified for a set of future conditions, and represents a scenario or a projection of the future. It is executed as a forward run, a relatively small number of times (typically fewer than 20). Each run is executed with different assumed values which determined by the modeler for future conditions (Anderson et al., 2015).

### 5.2.5.1. Pumping Scenario Analysis

Ethiopian government has given special attention to clean drinking water supply for community. At the end the first Growth and Transformation Plan (GTP I) ended two years ago, the coverage of clean drinkable water supply was 82, 91 and 84 percent at rural, urban and country level respectively. This was through providing 15 liters of clean water per person in a day within the radius of 1.5 Kilometer at the rural level and 20 liters of clean water per person in a day within the radius of 0.5 Kilometer at urban areas. Even though the physical achievement is lower than the plan.

The second Growth and Transformation Plan (GTP II) was planned to put the nation at the level of the middle income countries and new standard was formulated for the clean drinking water supply coverage. According to the new standard, at the end of GTP II the rural clean drinking water coverage grows to 25 liters of clean water per person in a day within the radius of one kilometer at the rural level. Similarly, the urban clean water supply is planned to be 100 liters per person in a day at the first grade towns. As well, 80 liters, 60 liters, 50 liters and 40 liters at the second, third, fourth and fifth grade towns respectively (MoWR, 2015).

Based on this figure, there is the need of groundwater consumption high in the future.

Pumping scenarios were used to evaluate the response of the groundwater system under variable groundwater abstraction rates which may happen after a few years. The system response was compared with resulting changes in water level and groundwater outflow from the model domain. For scenarios analysis, production boreholes were assigned with different pumping rate.

Five stages of scenarios were modeled with increased abstraction rates under steady-state condition. In scenarios-model the abstraction rates were assumed to be increased by 25%, 50%, 75%, doubled & four times, based need of groundwater consumption. The average water table decline for increased groundwater withdrawal of 25%, 50%, 75%, doubling and four times is 1.58, 1.87, 2.33, 3.04 and 4.69 respectively (Fig 5.10). With increasing groundwater withdrawal by above rates, groundwater outflow to the river decline by the rate of 2.06%, 4.095%, 6.215%, 7.99% & 15.35% respectively. Change in discharge to General Head Boundary (GHB) is insignificant which only 0.56% with a maximum rate of withdrawal. In general, increasing the steady-state well discharges by above rates resulted in insignificant declines in groundwater

levels in most of the model domain. The overall of pumping scenarios executed and resulting changes in groundwater balance components summarized in table 7.

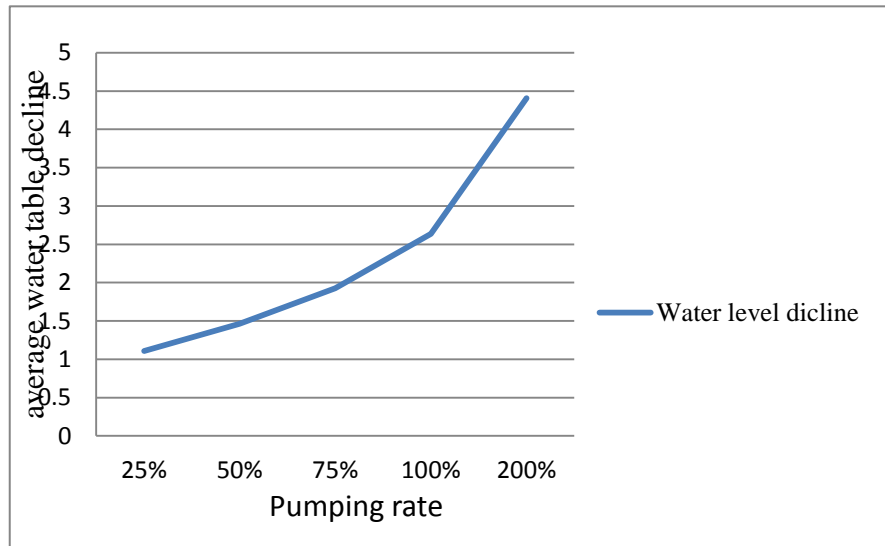


Figure 5.9: Response of aquifer to increased groundwater withdrawal

Table 7. The result of pumping scenario analysis

scenarios	Flow component	IN (m <sup>3</sup> /day)	OUT (m <sup>3</sup> /day)	Difference with respect to base model (Outflow)	Change in outflow with respect to the base model (%)
scenarios1 Increasing Pumping by 25%	Constant Head	3771.1431	53.456108	0.042222	0.078922
	Wells	0	20727.502	-4076.6	-25
	Recharge	206590.27	0		
	River Leakage	19280.477	198999.23	4189.87	2.062055
	Head Dep. Bounds	7300.8242	17157.863	18.827	0.109608
scenarios2 Increasing Pumping by 50 %	Constant Head	3771.3706	53.451614	0.046716	0.087322
	Wells	0	24991.104	-8340.2	-50.
	Recharge				
	River Leakage	19423.082	194867.44	8321.66	4.095525
	Head Dep. Bounds	7300.8364	17151.732	24.958	0.145302
scenarios3 Increasing Pumping by75 %	Constant Head	3771.7134	53.445362	0.052968	0.099009
	Wells	0	29510.303	-12859.4	-75
	Recharge				
	River Leakage	19629.959	190560.23	12628.87	6.215328
	Head Dep. Bounds	7300.8379	17147.055	29.635	0.17253
scenarios4 Increasing Pumping by 100 %	Constant Head	3774.1492	53.398251	0.100079	0.187069
	Wells	0	33410.305	-16759.4	-100
	Recharge	206590.27	0		
	River Leakage	19906.691	186960.91	16228.19	7.986742
	Head Dep. Bounds	7300.8926	17108.619	68.071	0.396299
scenarios5 Increasing Pumping by 200 %	Constant Head	3786.7114	53.171097	0.327233	0.61167
	Wells	0	48960.297	-32309.4	-200.
	Recharge	206590.27	0		
	River Leakage	20603.764	171991.81	31197.29	15.35382
	Head Dep. Bounds	7300.938	17082.865	93.825	0.546234

### 5.2.5.2. Effects of Altered Recharge Scenario

Less groundwater recharge leads to drop in groundwater table which can have a negative impact on ever increasing water demand and vegetation. The decreased of recharge to aquifers that may result from lower than normal precipitation (weather modification), land use land cover change and town expansion. It is real that changes in climatic conditions from time to time are affecting precipitation amount in the country adversely.

According to Anduale Shimeles and Jemal Seid (2013), under RCP8.5 scenario, mean warming in Ethiopia is likely to be in the range 1.46-2<sup>0</sup>C by 2030s and 2.68 – 3.8<sup>0</sup>C by 2080s. Similar study by USAID (2015) indicate that the temperature likely to be increase the future. While the rain fall projection are less reliable than temperature projections as it was reported in both study and Anduale Shimeles and Jemal Seid (2013) reported the change for short-term, medium term and long-term as 0.15,0.29 and 0.43mm/day respectively.

Upward trends in air temperature of + 0.03 °C year<sup>-1</sup> and downward trends in rainfall of -0.4 mm month<sup>-1</sup> year<sup>-1</sup> have been observed over Ethiopia’s southwestern region in the period 1948-2006. These trends are projected to continue to 2050 according to the Geophysical Fluid Dynamics Lab model using the A1B scenario (Jurya and Funk, 2013).

Depend on this circumstance, the rain fall input of SWAT have been changed to evaluate the impacts of variable rain fall on groundwater recharge. System responses to decreased groundwater recharge have been evaluated by using the calibrated model as base line.

Table 8. Impacts of variable rain fall on groundwater recharge

Change in rain fall	Recharge with respect to rain fall in mm/y	change in mm/year	Change of recharge in %
-20%	257.35	-57.95	-18.38
-10%	276.55	-38.75	-12.29
0	315.3	0	0.00
10%	366.91	51.61	16.37
20%	481.75	166.45	52.79

Decreasing to aquifer recharge has considerable change on water level and stream leakages as well on other water budget component. Generally, the responses of the system to increased and decreased recharge rates are summarized as table 8.

Table 9. The result of recharge scenario analysis

scenarios	Flow component	IN	OUT	change in outflow (m <sup>3</sup> /day)	Change in outflow with respect to the base model (%)
		(m <sup>3</sup> /day)	(m <sup>3</sup> /day)		
Decreasing Rain fall by 20% (decreasing recharge by 18.38%)	Constant Head	5006.8726	11.238231	-42.260099	-78.993305
	Wells	0	16650.9	0	0
	Recharge	172100.66	0	0	0
	River Leakage	21120.715	171755.38	-31433.72	-15.4701802
	Head Dep. Bounds	7300.8003	17121.24	-55.45	-0.32282122
Decreasing Rain fall by 10% (decreasing recharge by 12.29%)	Constant Head	4758.9229	19.683741	-33.814589	-63.2068123
	Wells	0	16650.9	0	0
	Recharge	179649.81	0	0	0
	River Leakage	20644.258	178557.23	-24631.87	-12.1226335
	Head Dep. Bounds	7300.7861	17133.049	-43.641	-0.25407107
Increasing Rain fall by 10% (Increasing recharge by 16.37%)	Constant Head	2503.5349	164.44395	110.94562	207.3814641
	Wells	0	16650.9	0	0
	Recharge	239890.31	0	0	0
	River Leakage	18116.506	233778.56	30589.46	15.05467567
	Head Dep. Bounds	7300.6733	17232.354	55.664	0.324067093
Increasing Rain fall By 20% (Increasing recharge by 52.79%)	Constant Head	284.82745	1.1471722	-52.3511578	-97.855686
	Wells	0	16650.9	0	0
	Recharge	316420.91	0	0	0
	River Leakage	16112.673	304971.31	101782.21	50.09235732
	Head Dep. Bounds	7300.543	17355.615	178.925	1.041673338

### **5.3. Model Limitation**

A ground-water model is a simplified approximation of the actual real world system. The accurateness of the ground-water model results is determined by on the accuracy of the input data. Due to the low quality of the existing data and limited data, the degree of uncertainty in the model was higher. Hydrologic and hydrogeologic input parameters used for 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 is hardly known. The assumption of homogeneity can also cause inaccuracies because the inherited heterogeneity of the earth materials. In general the model output should be interpreted and applied by considering the entire drawback.

## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

In this study, the numerical groundwater flow model was used to study regional groundwater flow and the response of the groundwater system to different scenarios. The study area boundary was delineated from 30m Shuttle Radar Terrain Mapping (SRTM) digital elevation model (DEM) using Arc SWAT software with ArcGIS interface.

Based on field data together with the pumping test data analysis, the volcanic aquifer is not an entirely unconfined type. Some part of the basin, particularly the waliso area shows Semi-confined and confined aquifer type. This is seemingly due to relatively thick clay (altered ash) and massive basalt in some areas, as it was verified from boreholes lithological logs.

The recharge rate of the study area was estimated using the semi-distributed hydrologic model Soil Water Assessment Tool (SWAT) which account for the spatial heterogeneity in climate, topography, land use and soil of the catchments. The long term annual recharge to shallow aquifer estimated by the model is 315mm/year. Water level data were collected from 121. Groundwater contours and flow directions were determined based on these observed heads. The general trend of groundwater flow direction was determined as it is from the north-east to south-west following topography, with some local variations. The spatial distribution of the hydraulic properties of the aquifer was classified based on the pumping test data as well as on the information about aquifer geology.

The area was represented by each cell size of 500m by 500m, arranged in 126 rows and 151 columns. A two dimensional model under steady state condition was developed to study the ground water flow system and the response of the system to different scenarios.

The model was calibrated using 121 observation points with simulated head. The calibration was done by adjusting hydraulic conductivity and recharge. Calibration result was evaluated using visual examination of a scatter graph and quantitative summary statistics. The model was calibrated to the mean error -2.43m; absolute mean error 10.82m and root mean squared error 13.47m. Model calibrations show good fit between observations groundwater levels and simulated heads.

The sensitivity of the main parameters of the model was identified during the calibration process. Based on the calibration process, the model is more sensitive in decreasing order change in recharge than hydraulic conductivity.

Scenario modeling executed by different groundwater abstraction rates and decreasing and increasing aquifer recharge as part of the forecast. The system response was compared with resulting changes in water level and groundwater outflow from the model domain. For pumping scenarios analysis, production boreholes were assigned with different pumping rate. Based on need of future water consumption, five stages of pumping scenarios model were run with increased abstraction rates under steady-state condition. In the scenarios-model, the abstraction rates have been increased by 25%, 50%, 75%, 100% & 200%. Increasing the steady-state well discharges by these rates resulted in insignificant declines in groundwater levels in most of the model domain.

In scenarios-model, the rain fall inputs of SWAT have been changed to evaluate the impacts of variable rain fall on groundwater recharge. System responses to decreased and increased groundwater recharge rate were evaluated by using heads of the calibrated model as the baseline and compared with resulting changes in water table elevation in the new scenario simulation. Decreasing and increasing of aquifer recharges has significant change in water level and fluxes.

The steady state simulated water budget of the entire model domain is 86532382m<sup>3</sup>/year inflows and 86530619m<sup>3</sup>/year out flow with 0.000% percent of error.

## 6.2. Recommendations

- Spatial and temporal variability of recharge and sensitivity to climate and land use land cover change has to be evaluated
- Model verification should be carried out with another set of data to improve the overall reliability and usability of the model. It is important to re-evaluate and update the model when new field data are collected
- The model could be represented with more than one layer to see three dimensional flows and evaluation their corresponding hydraulic parameters.
- Groundwater level and abstraction rates should be monitored at a set of monitoring wells that are properly distributed in the catchments. This helps for transient groundwater flow modeling.

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**ANNEX 1: THESIS ORIGINALITY TEST REPORT**

Name of Student	Abera Gonfa
ID. No	GSR/5847/09
Stream	Hydrogeology
Thesis Title	<i>Numerical Groundwater Flow Modeling of Walga-Darge Catchments</i>
Online site used for originality test	<a href="http://www.paperrater.com/plagiarism_checker">http://www.paperrater.com/plagiarism_checker</a>

	Particulars	Test I		Test II		Test III		Test IV		Test V		Average	
		Originality (%)	Plagiarism (%)	Originality (%)	Plagiarism (%)	Originality (%)	Plagiarism (%)	Originality (%)	Plagiarism (%)	Originality (%)	Plagiarism (%)	Originality (%)	Plagiarism (%)
1	Abstract	100%	0%									100%	0%
2	Chapter 1	100%	0%	100%	0%							100%	0%
3	Chapter 2	100%	0%									100%	0%
4	Chapter 3	100%	0%	100%	0%							100%	0%
5	Chapter 4	100%	0%	100%	0%							100%	0%
6	Chapter 5	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
	Chapter six	100%	0%									100%	0%
	Overall Thesis											100%	0%

	Name	Signature
Student	Abera Gonfa	
Advisor	Prof. Tenalem Ayenew	

**ANNEX II: Ground Water Withdrawal from Pumping Wells**

Site_Name	X	Y	Z	Well_ depth,m	SWL, m	Q(m <sup>3</sup> /D)
Woliso Prison	386183	943986	2032	108	0	201.6
Woliso	387305	945410	2056	100	0	230.4
Asgori-Gurara	381500	933000	1925	100	7	144
kulit/Kidanemihret	340966	924430	1564	130		136.8
Gefersa	355341	916638	1753	204		244.8
Ubbi	388820	947604	2097	148	5	201.6
Negash Lodge	387835	943260	2033	297	4.9	252
Negash Lodge	387802	943130	2028	300	5	252
Woliso-02	386986	945147	2050	133	0	201.6
Goru-Gurura	381713	933854	1904	100	7	129.6
Goru-Galiye Rogda	358319	926963	1671	195		86.4
Welkite(W-3)-Kelejeby	364905	923161	1694	152	12	158.4
Welkite(W-5)-Kelejeby	365433	923338	1696	200	35	216
Welkite(W-1)-Kelejeby	365427	923242	1697	103	3	223.2
Welkite(W-2)-Kelejeby	365447	922747	1708	152	54	208.8
Welkite(W-6)-Kelejeby	366319	921583	1742	160		122.4
Welkite-Felejety	366637	921104	1756	146	29	208.8
Muko Ujuba Kota	347532	943211	1819	175		158.4
Darian	378626	961413	2602	173		252
South-west Shoa-Kota	377000	942000	1987	174	14.70	230.4
Nono woreda,	340304	943271	1828	152	48	165.6
Goro	375734	926348	1785	360	14	223.2
Gindo	357700	944225	1835	360	23	324
Meti-walga	383826	947387	2058	265	0	230.4
Wolkite town	363415	915588	1801	280	98	273.6
galiye Rogida	358290	926080	1970	459	82	378
Meisa	370781	943250	1970	471	29.3	576
Woliso	385801	939409	1970	474	65	2592
Gurura	380825	933619	1886	138	0	252
Goro	382737	926288	1932	185		187.2
Goro	375821	929257	1815	250	9.8	237.6
Goro	373518	924344	1756	245	2.2	230.4
Wondimitu	385518	959705	2363	133	12.47	180
Dulele	384450	959524	2382	167	43	230.4
Kile	381160	951320	2108	101	5.05	201.6
Woliso	395770	936037	2117	135	0.5	270
Woliso	388317	947574	2089	133	0	216
Ameya	350776	948648	1899	135	29.8	230.4
Ameya	366782	960280	2301	172	27.41	180

Modeling Numerical Groundwater Flow Modeling of Walga-Darge Catchments

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Ameya	354182	939439	1725	150		172.8
Woliso#2TWS	387549	945858	2058	93	0	105.6
Kulit 2	341088	924567	1567	81	35	57.6
Kulit 1/Nacha Kulit	343035	921923	1555	92	48	76.8
Walga	344600	920184	1532	81	24	86.4
Walga	345006	920268	1534	82	27	86.4
Tawla/Soyama	354023	915772	1729	84		96
Goflele(Fenta)	356903	915385	1762	85		76.8
Webi borehole	387659	946376	2064	93	0	86.4
Goru	375409	928322	1854	80	7	81.6
Goro	368377	924410	1761	93	6.625	84
Chitu	381890	951238	2104	94	7.256	86.4
Chitu	381155	951326	2108	94	0.74	91.2
Got 8	342111	927489	1568	86		67.2
Got 2	340937	929536	1548	81		64.8
Got 4	356293	920917	1655	82		62.4
Got 2	351695	920724	1612	83		72
Obi Borehole	387748	946582	2081	83	0	76.8
Woliso	393227	938071	2090	85.5	5.5	81.6
Sarie	398182	951093	2373	62	14	36
Yaya Otona	338664	924779	1536	51	23	72
Kulit 2	340662	924050	1562	54		90
Nacha kulit	342102	923134	1520	58	42	108
Kulit/Abo sefer	343453	924775	1595	61	41	144
Kulit 1/Shola ber	343578	920886	1539	70		144
Walga	344752	920691	1540	69	36	36
Walga	345108	920062	1545	74	50	18
Abshege-Jeju	346814	919983	1585	74	50	36
Biddo (KHC)	350867	918698	1627	52	16	36
Goru-Weta	378206	930111	1874	50	5	54
Ameya-Kekewie	349638	939008	1800	54	10	36
Chaha kassaye(Atnafu)	351822	949233	1946	60	18	43.2
Lafto Tsega	367277	941299	1821	48	4	43.2
Ameya-Shonke	365592	935373	1759	68	9	57.6
	372467	943683	1346	72	15	36
S WS/ -Beticha cheleleka	349442	934074	1686	57	20	36
Ameya-Bereda	373172	928362	1788	66	17	36
Kereyu	352087	943847	1835	57	13	36
Ameya-Degago Jeto	339933	940705	1783	51	2	36
Dogema dembi-1	374345	933340	1845	61	5	36
Dogema-dembi-2	373599	933765	1843	61	12	36
Yesuf & Ya,a Gadi	363500	939000	1781	55	15	46.8

Modeling Numerical Groundwater Flow Modeling of Walga-Darge Catchments

Muka arba	363500	939000	1781	56	15	54
Wenchi, Haro	378500	945500	2158	56	21	54
Goro	379220	934882	1884.3	60	7	54
Chitu	381267	951278	2112	51	3	72
Walajo	346165	929691	1637	60	19	108
Ulaga jeft	343936	934937	1590	51	3	72
cheka	353415	949697	2012	60	7	108
Bosho	349949	945050	1820	60	0	108
Gimbi	348614	939121	1791	60	5	90
Asole	338567	937204	1665	60	42	36
Abado	361405	948560	1947	60	5	36
Kaba	365032	943441	1842	60	1	90
sekele	357506	943596	1807	54.96	20	54
Abuko	363666	933853	1743	50.38	10	36
Engiyo	348612	927098	1636	59	9	43.2
Metu	348703	929369	1640	59	23	36
Sodo sefer	349452	928915	1651	59.54	8	36
Moga	344004	931979	1592	59.54	22	36
Lita Giorgis	355451	936696	1703	58	11	54
Kulit	354512	935546	1694	59.54	10	36
Tirtira	358883	950544	1916	64.12	6	36
Kimbilo	358676	948198	1895	59.54	1	72
Ya	362871	937890	1757	64.12	2	72
Tono	368210	943622	1851	63.5	4	54
Lafto Meta	368724	946447	1906	59.54	4	54
Bino	364007	954317	2090	59.54	9	36
Kenchera	366719	951272	2032	59.54	7	54
Guraf mamud	370006	947316	1934	59.54	8	54
Batiso	366001	956441	2197	59.54	15	36
odo Kurse	364949	955514	2135	59.54	16	36
Bayima	362316	947329	1931	71	15	36
Badoye	353197	940964	1768	59.54	5	36
Korbasa	358004	940704	1749	59.54	22	36
Berama	360036	937410	1747	59.54	7	36
Chilalo	367685	934567	1767	59.54	14	36
Agamte	348210	945236	1851	68.25	25	36
Bislo	355529	940692	1750	60	26	36

**ANNEX III: Observe Vs. Simulated Water Level.**

OBS_nam	X	Y	Observed	calculated	Residual
1	386183	943936	2032	2029.401	2.599
2	387305	945410	2056	2054.803	1.197
3	387549	945858	2058	2063.146	-5.146
4	389339	940715	1991	2012.504	-21.504
5	383469	948467	2081	2078.734	2.266
6	402350	951544	2416	2400.927	15.073
7	393964	957477	2457	2442.465	14.535
8	397276	954511	2386	2390.392	-4.392
9	397540	953574	2362	2383.287	-21.287
10	396861	952816	2361	2367.656	-6.656
11	398182	951093	2359	2374.744	-15.744
12	398901	951499	2373	2385.102	-12.102
13	394200	944338	2173	2192.949	-19.949
14	381500	933000	1918	1909.035	8.965
15	393191	944399	2152	2155.178	-3.178
16	338664	924779	1513	1500.387	12.613
17	341088	924567	1532	1533.203	-1.203
18	343453	924775	1554	1558.046	-4.046
19	343035	921923	1507	1507.421	-0.421
20	344752	920691	1504	1505.948	-1.948
21	344600	920184	1508	1490.159	17.841
22	345006	920268	1507	1499.72	7.28
23	345108	920062	1495	1491.916	3.084
24	350867	918698	1611	1584.454	26.546
25	387659	946376	2064	2072.044	-8.044
26	388820	947604	2092	2105.751	-13.751
27	375409	928322	1847	1827.496	19.504
28	375733	928451	1850	1832.359	17.641
29	377246	929075	1857	1855.551	1.449
30	387025	943705	2035	2031.223	3.777
31	387835	943260	2028.1	2030.256	-2.156
32	387802	943130	2023	2028.524	-5.524
33	386986	945147	2050	2049.383	0.617
34	383711	933823	1919	1929.877	-10.877
35	383586	933863	1924	1929.528	-5.528
36	383538	933892	1923	1929.438	-6.438
37	382633	934291	1906	1925.667	-19.667
38	382560	934038	1908	1924.795	-16.795

39	381713	933854	1897	1913.774	-16.774
40	379119	929764	1864	1884.966	-20.966
41	378206	930111	1869	1873.103	-4.103
42	375881	926048	1800	1808.877	-8.877
43	375476	924377	1816	1818.673	-2.673
44	372612	925524	1804	1798.983	5.017
45	372198	924591	1776	1787.123	-11.123
46	372148	924659	1777	1788.622	-11.622
47	372178	924570	1776	1786.623	-10.623
48	371319	925254	1811	1793.969	17.031
49	364581	925183	1745	1728.464	16.536
50	365125	925132	1763	1739.383	23.617
51	358314	927117	1661	1670.816	-9.816
52	357207	927172	1658	1662.968	-4.968
53	365427	923242	1694	1714.155	-20.155
54	366637	921104	1727	1737.036	-10.036
55	387202	944167	2045	2038.201	6.799
56	351822	949233	1928	1913.664	14.336
57	367277	941299	1817	1817.488	-0.488
58	365592	935373	1750	1766.218	-16.218
59	372467	943683	1888	1897.881	-9.881
60	349442	934074	1666	1678.779	-12.779
61	355593	949734	1925	1904.113	20.887
62	352087	943847	1822	1800.2	21.8
63	339933	940705	1781	1779.994	1.006
64	374345	933340	1840	1840.86	-0.86
65	373599	933765	1831	1835.179	-4.179
66	363500	939000	1766	1780.921	-14.921
67	341561	940297	1750	1773.651	-23.651
68	357700	944225	1812	1796.407	15.593
69	383826	947387	2058	2063.089	-5.089
70	385801	939409	1941	1960.199	-19.199
71	380825	933619	1886	1877.32	8.68
72	368377	924410	1754.4	1749.951	4.424
73	381258	931912	1904	1909.224	-5.224
74	381668	931145	1920	1915.643	4.357
75	381598	931459	1910	1914.507	-4.507
76	372693	950317	2043	2024.737	18.263
77	373518	924344	1753.8	1781.415	-27.615
78	379220	934882	1877.3	1893.273	-15.973
79	380494	929522	1911.35	1898.226	13.124
80	385518	959705	2350.53	2366.216	-15.686

Modeling Numerical Groundwater Flow Modeling of Walga-Darge Catchments

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81	381890	951238	2096.744	2115.475	-18.731
82	381155	951326	2107.26	2111.811	-4.551
83	384450	959524	2339	2356.394	-17.394
84	381160	951320	2102.95	2111.73	-8.78
85	395770	936037	2116.5	2122.335	-5.835
86	388317	947574	2089	2099.513	-10.513
87	387657	946375	2069	2072.01	-3.01
88	366782	960280	2286.59	2311.355	-24.765
89	349949	945050	1820	1823.084	-3.084
90	365032	943441	1841	1819.295	21.705
91	357506	943596	1787	1791.02	-4.02
92	363666	933853	1733	1748.626	-15.626
93	348612	927098	1627	1619.976	7.024
94	348703	929369	1617	1638.656	-21.656
95	349452	928915	1643	1639.769	3.231
96	346724	927386	1613	1611.117	1.883
97	358883	950544	1910	1934.575	-24.575
98	362871	937890	1755	1771.824	-16.824
99	368210	943622	1847	1846.723	0.277
100	368724	946447	1902	1889.429	12.571
101	364007	954317	2081	2080.871	0.129
102	370006	947316	1926	1919.591	6.409
103	366001	956441	2182	2173.59	8.41
104	364949	955514	2119	2133.042	-14.042
105	369490	959830	2324	2325.499	-1.499
106	353197	940964	1763	1763.667	-0.667
107	360036	937410	1740	1757.917	-17.917
108	367685	934567	1753	1777.644	-24.644
109	348210	945236	1826	1832.896	-6.896
110	387748	946582	2081	2076.296	4.704
111	395975	955273	2429.35	2418.814	10.536
112	393227	938071	2084.5	2079.935	4.565
113	339374	938630	1708	1720.933	-12.933
114	355333	944878	1813	1804.138	8.862
115	359380	940371	1773	1771.568	1.432
116	360692	941831	1799	1785.987	13.013
117	346887	946784	1871	1864.188	6.812
118	364361	957506	2189	2196.863	-7.863
119	346887	946784	1871	1864.188	6.812
120	350696	944734	1822	1816.754	5.246
121	355333	944878	1813	1804.138	8.862

ANNEX IV : Well Lithological Logs adapted from well completion report

