



**ADDIS ABABA UNIVERSITY**  
**ETHIOPIAN INSTITUTE OF**  
**WATER RESOURCES**



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**SCHOOL OF GRADUATE STUDIES**

**MSc. RESEARCH THESIS ON “SUSTAINABILITY OF  
GROUNDWATER USE USING INTEGRATED METHODS: THE CASE  
OF ATEBALA CATCHMENT: UPPER AWASH SUB-BASIN”**

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**MSc RESEARCH THESIS SUBMITTED**

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**ADDIS ABABA**

## **Declaration**

I hereby declare that this thesis entitled “**(SUSTAINABILITY OF GROUNDWATER USE USING INTEGRATED METHODS: THE CASE OF ATEBALA CATCHMENT: UPPER AWASH SUB-BASIN)**” was composed by myself, with the guidance of my advisor, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted, in whole or in part, for any other degree or professional qualification. Parts of this work have been published in [state previous publication].

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## Certificate

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“(SUSTAINABILITY OF GROUNDWATER USE USING INTEGRATED  
METHODS: THE CASE OF ATEBALA CATCHMENT: UPPER AWASH  
SUB-BASIN)” and submitted in fulfillment of the requirements for the Degree of  
Master of Science in Water Resources Engineering and Management  
Specialization in Groundwater Management, complies with the regulations of the  
University and meets the accepted standards with respect to originality and  
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## **List of Abbreviation**

<b>a.m.s.l</b>	-	above mean sea level
<b>DD</b>	-	Draw down
<b>DEM</b>	-	Digital elevation model
<b>EC</b>	-	Electrical Conductivity
<b>EIGS</b>	-	Ethiopian Institute of Geological Survey
<b>EMA</b>	-	Ethiopian Mapping Authority
<b>GHB</b>	-	General Head Boundary
<b>ITCZ</b>	-	Inter Tropical Convergence Zone
<b>km</b>	-	kilometer
<b>l/s</b>	-	liter per second
<b>LBA</b>	-	Lower basalt aquifer
<b>m<sup>3</sup>/s</b>	-	cubic meters per second
<b>MCM</b>	-	Million Cubic Meters
<b>mm</b>	-	millimeter
<b>MMC</b>	-	Million m <sup>3</sup>
<b>MoWR</b>	-	Ministry of Water Resources
<b>NMSA</b>	-	National Meteorological Services Agency
<b>SWL</b>	-	Static water level
<b>STTW</b>	-	Sebeta Tefki Test Wells
<b>TDS</b>	-	Total Dissolved Solids
<b>UBA</b>	-	Upper Basalt aquifer
<b>WHO</b>	-	World Health Organization
<b>WWDSE</b>	-	Water Works Design and Supervision Enterprise

## **Abstract**

*Atebala River catchment is part of Upper Awash Sub-Basin, it is geologically dominated by Addis Ababa Ignimbrite, specifically in the west and southern parts of the study area. In the study area there are lots of industries which own water boreholes in their compound. In this research detailed hydrogeological investigation is undertaken to understand the groundwater resources of the catchment. To create an ideal picture for the major hydrogeological setting of the field situation of the study area, the study developed a conceptual model which maintain the mathematical representation by identifying the available major system, the possible boundaries and aquifer characteristic which results an input data base, cross section and simplified map for the modeling. The study will recommend to enhance the groundwater potential by identification of recharge and evapotranspiration; by using SWAT model and the result is taken as an input data for the numerical model. Numerical modeling is being simulated using the USGS three-dimensional finite difference groundwater flow model MODFLOW to quantify the water resource availability of the complex, dynamic groundwater/surface water systems and to take account of the environmental impact of abstraction. The calibration technique that the model used in this study is Manual trial and error calibration technique. From the model result the general groundwater flow direction is towards the Atebala River from all directions. It also assures that the groundwater withdrawal from the water boreholes of the catchment do not reach at the over abstraction rate, however the modeler has tried for the simulation of two scenarios with the abstraction of the groundwater and the influence of fluctuation of Evapotranspiration. Generally, Atebala river catchment has good groundwater potential for domestic, irrigation and industrial use. But if the well withdrawal and evapotranspiration of Atebala river catchment is increases, then the catchment has needed serious integrated monitoring and control mechanism to sustainably preserve the groundwater resource of the catchment.*

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## **1. INTRODUCTION**

### **1.1. Background**

Water is one of the most significant natural resource for all living things in the globe. In many parts of the world the available water resource is under stress due to growing demands with increasing population. It is the most basic resource affecting municipal, agricultural and economic activity. Any development is related either directly or indirectly with water utilization. Water is also existing below the surface of the earth that many of human being depends on for continuity of life.

According to the Economists prestigious journal research, 33 countries will face sever water shortages by 2040 due to poor water resources management in the agricultural and industrial sectors [\\_\(Andrew Maddocks et.al., 2015\)\\_](#) The water which exists below deep in the surface of the earth is called Groundwater. It is now a days the most precious natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply [\\_\(Kemper and Karine, 2004\)\\_](#) Groundwater is generally economical to develop compared to other sources; aquifers are naturally protected from contamination; and groundwater offer reliability of supply and a shield against drought [\\_\(Kebede, 2013\)\\_](#) It has been estimated that between one third and one half a billion people in Sub-Saharan Africa use protected or unprotected groundwater for their daily water supply [\\_\(Carter & Bevan, 2008\)](#). The ability to meet challenges for increased demand and propose justifying strategies will require intensive studies looking into the way that population growth and associated land use change and water demands influence the local, regional and global water cycle.

Ethiopia, however has vast amount of water resources, is frequently affected by recurrent drought, and as a result many people are not food secured. These problems, to some extent, are related to the absence of knowledge of the potential in a clear manner, underutilization of the existing water resources and resource management besides to the irregular nature of the rainfall in most parts of the country. Population growth and land use changes have resulted in significant impacts on surface water and groundwater resources. Population growth, developing huge industrial zones and land use changes have led to unsustainable groundwater resource use as well as soil deterioration through erosion, salinization, and of course pollution.

Groundwater is one of the great resources of Ethiopia and various studies have confirmed that most parts of the country have ample groundwater potential but not distributed uniformly in space and time. The occurrence of groundwater is mainly influenced by the geology, geomorphology, tectonics and climate of the country. The recharge from the rainfall of highlands is major source of groundwater in Ethiopia, the rainfall varies between 250mm in the lowlands to 2800mm on the southwestern plateau ([Alemayehu, 2006](#)).

To sustain the current economic development that the country had planned, proper development and utilization of groundwater needs detailed hydrogeological assessment and investigation. This detailed hydrogeological investigation is needed to understand the groundwater resources of every basin for sustainable management of the resource. To know the hydrogeological condition, it is crucial to apply a combination of geophysical survey, drilling and field testing to define the aquifers, groundwater flow systems and aquifer characteristics, at least in the most important basins that can be utilized for large-scale development of irrigation, industrial and water supply systems.

However, the country should work on the impacts and managing mechanisms of over abstraction on areas where densely concentrated boreholes exist, which leads to sustainable groundwater development. In earlier times there is evidence that the very well-being of the traditional Borena community in Southern Oromia region is strongly linked to groundwater resources management [\(Kebede, 2013\)](#). Nevertheless, in this era there should be adequate attention for utilization, development and management of groundwater; and this requires detailed hydrogeological investigation and assessment.

The current study area, Atebala River Catchment, is part of the Upper Awash Basin and its vicinity to the capital city of the country, Addis Ababa, makes the area preferable for establishment of large number of different types of industries especially bottled water companies. These industries utilize fresh water for various purposes. For this reason, many of them have their own water well in their compound. In addition to this there is dynamic population growth, this scenario leads to a huge demand of water for domestic purposes. In order to fulfil this industrial and community water demand, so many water wells are being drilled and will be constructed in this catchment. Hence this research is undertaken to investigate how those multiple water boreholes stress the groundwater potential of the area and accordingly propose a guideline to manage the groundwater potential of the catchment.

## **1.2. Problem Statement**

The Atebala River Catchment includes Alemgena and Sebeta towns which are the most industrial areas in the country. Due to this and the closeness to the capital Addis Ababa, the population is growing rapidly. Water demand on the catchment increases time to time and this fact leads to the need of additional water from drilled water boreholes.

In this catchment there are multiple active water wells and there is limited awareness about proper planning of groundwater resources development as well as sustainable utilization. However, this increasing demand and improper utilization may have led to degradation of the resource, one of this is over abstraction of groundwater. Over pumping of groundwater from water wells may cause long term environmental impacts and it will affect the hydrogeologic system of the area. There are no previous studies which investigate the problem and propose a management method for the sustainable groundwater utilization in the study area.

Therefore, it is important to investigate the present recharge and discharge rates, then predict the long-term impacts based on current improper utilization. In addition, it is essential to propose the optimum management method to sustainably manage groundwater usage in Atebala River Catchment.

This research targets to study if there is over abstraction in this catchment because of those multiple existing boreholes. In Atebala River Catchment currently there are more than 70 existing water wells, most of them are owned by private industries. The catchment also has a lack of sustainable management system on the use of groundwater, in the long run this situation may lead to aquifer depletion. These impacts call for the design, development and implementation of climate change resilient integrated water resource management strategy at catchment level. And to sustain the groundwater use of the catchment, it needs to balance the recharge and discharge pumping rates and implement the best groundwater monitoring and management mechanisms related with abstraction of water from the existing and newly constructed water wells.

Hence this research is proposed to develop awareness of the different actors utilizing the water resource and various concerned stakeholders about the dynamics of the groundwater and how to address sustainable utilization of the groundwater potential of the catchment.

### **1.3. General and Specific Objectives of the Research**

#### **1.3.1 General objective**

The main objective of the research is to manage the groundwater use of Atebala River Catchment by calculating the water balance based on the annual water recharge and discharge components.

### **1.3.2 Specific objectives**

The specific objectives of the study are

- To assess the existing groundwater, use in Atebala River catchment,
- To identify the most vulnerable component of the hydrological system and to outline best methodology for sustainable development of the groundwater resource.

### **1.4. Research Questions**

This research is conducted to investigate and fill the gaps of some undefined problem occurrence regarding to over pumping specifically on Atebala River Catchment. The main research questions in this investigation are:

- Is there sustainable groundwater use in Atebala River Catchment?
- Which component of the hydrogeological system is more vulnerable?
- What are the appropriate methods that can be used to manage, sustain and develop the groundwater resource of this catchment?

### **1.5. Significance of the Study**

The study is planned to investigate how those multiple existing water wells stress the groundwater resource of the area and to show that this activity may have an impact on the groundwater table and in general hydrogeological system of the study area. Therefor to recommend a strategic guideline to sustainably manage and monitor the groundwater usage of the catchment.

## **1.6. Scope of the Study**

This research aims to understand the groundwater table fluctuation which may appear due to the withdrawal of water from those existing wells comparing with the recharge quantity. The study tries to scientifically evaluate how the abstraction influence the aquifers and tries to implicate the future impacts by building scenarios through numerical modeling.

## **2. LITERATURE REVIEW**

In the upper awash basin and its surrounding areas, a number of geological and hydrogeological investigations and studies have been conducted in previous times. Among these previously conducted geological and hydrogeological investigations and studies in the upper Awash basin and its surroundings which are relevant for this research are reviewed and summarized.

In 2009 Andarge Ytibarek investigated the hydrogeological framework of a complex fractured volcanic aquifer system in the Upper Awash River basin and find out the basin has complex flow pattern; the upper and lower aquifers have the same recharge origin and he outlined the interaction between surface water and groundwater\_(Andarge, 2009). Andarge Ytibarek also has carried out a study on the estimating transmissivity using empirical and geo-statistical methods in the volcanic aquifers of upper Awash River basin, and he explains that transmissivity and specific capacity values are spread over several orders of magnitude, revealing the strong heterogeneity of the volcanic aquifer\_(Yitbarek, 2013).

Mesele in his research called Groundwater dynamics and aquifer characterization of the shallow aquifers of Becho and Koka area, explains that Becho area medium field saturated hydraulic conductivity values have come from due to the presence of alluvial deposits during the wet season, which covers the most upper parts of the soils. This study indicates the groundwater classification in Becho area and the shallow groundwater has been classified as excellent and good. In both areas, the stable isotopes signature of the Hand dug well water characterized by depleted isotopic signature. From the result of isotopic signature, the recharge for depleted hand dug well water is from the precipitation. Nevertheless, the research lacks scientific information about deeper hydrogeological and aquifer system\_(Mesele, 2017).

Mekdes Nigatie's unpublished MSc Thesis, Addis Ababa University, a stud conducted on the title of characterization of aquifers and hydrochemistry in volcanic terrain of central Ethiopia. Her classification on the basis of hydrogeological characteristics of lithological unit described high productive porous aquifers and aquiclude or minor aquifers with limited groundwater resources\_(Nigatie, 2012).

According to Behailu's study on inter-basin groundwater transfer and multiple approach recharge estimation of the upper Awash Aquifer system, Journal of Geoscience and Environment Protection. It was found that recharge estimated for the upper Awash River basin ranges from 51.5mm/y to 157mm/y, and the estimated mean annual recharge from base flow separation over the upper Awash River basin is 91.25mm (Berehanu et.al., 2017)

Nuramo in his research the mean annual recharge of the Becho area using the water balance method was found to be 319.5mm and using base flow separation excel spread sheet program it was found to be 81.4mm. He used trend analysis of long term and recent hydro-meteorological variables for the study area was conducted to detect possible effects of climate changes and human activities in the area. Based on recent trend analysis, his study indicates that except the Awash River at Bello the other rivers in the study area show decreasing trends. But this study does not deeply investigate the effects of water boreholes on these areas [\(Nuramo, 2016\)](#).

In the journal called Inter-Basin Groundwater Transfer and Multiple Approach Recharge Estimation of the Upper Awash Aquifer System [\(Berehanu et.al., 2017\)](#), the upper Awash basin get a recharge from Middle Blue Nile basin, which is almost 37% of the total annual recharge to the Upper Awash basin makes from part of the Middle Blue Nile basin, it is an important recharge zone for the Upper Awash groundwater. The researchers use methods like Water Balance, Chloride Mass Balance and HYDRUS 1D infiltration model for recharge estimation. Base Flow Separation (BFS) methods, using both River Analysis Package Software Version 3.0.3 and Excel-based Time Plot program are also used as an alternative for recharge estimation.

Tilahun in his research called Groundwater Dynamics in the Left Bank Catchments of the Middle Blue Nile and the Upper Awash River Basins, Central Ethiopia: he finds there is an indication of inter-basin groundwater flow from the Blue Nile to the Upper Awash basin and it has been obtained at a regional scale, which is attributed to the interplay between regional faults [\(Azagegn, 2014\)](#).

In Brittan the Environment Agency Area hydrogeologists provide estimates of the impacts of groundwater abstraction pressures as part of the abstraction licensing process. The agency's hydrogeologists proved that the over abstraction causes: depletion on rivers, drawdown beneath boreholes and wetlands, estimating change in groundwater flow to & from wetlands as a result of groundwater abstraction. The most complex reasonable numerical model predicts that the flow in the Candover Stream is depleted by about 15% of the abstraction rate. However, in the real aquifer system, the effect of groundwater abstraction (the drawdown) continues to spread until it prevents an amount of water equal to the abstraction rate leaving the aquifer (Survey, 2008).

(SRK Consulting et.al., 2003) In South Africa the National Groundwater Quality Monitoring Program launch a model called **Groundwater Resource Assessment Phase II (GRA II)** which is used for estimation of groundwater allocation scenarios and it provides an introduction to the world of groundwater quantification on local and regional levels. GRA II is designed to model a distinct hydrological or hydro-lithological unit and to provide estimate of the status of the groundwater resource and what volume might be abstracted without damaging local surface aquatic ecosystems over the long term. The result includes several valuable datasets, maps and will provide input to various levels of planning and management of water resource once reviewed and proved.

(Asfaw, 2016) Unpublished MSc Thesis Addis Ababa University, made study on groundwater potential evaluation and use trends in upper Awash Basin. According to his investigation the amount of land irrigated using shallow groundwater and the corresponding number of shallow groundwater wells used to irrigate is increasing with time.

(WWDSE, 2008) Water works design and supervision enterprise worked on evaluation of water resources of the Adaa' and Becho plains groundwater basin for irrigation development project. On the report Becho plain has massive ground water potential for irrigation, but their evaluation lacks suggestion about the groundwater potential for the use of industrial purpose and the sustainability management.

MAR (Managed Aquifer Recharge) is the overall term for a variety of methods of artificially recharging and improving water in aquifers. As (Demisse, 2014 ) mention it in her research, MAR plays an important role by given that an opportunity for restoration of stressed groundwater resources. This technology is focused for ensuing recovery and conservational benefit of water recharge to aquifers. MAR technology selection for suitable sites and option of method will depend on the hydrogeology, topography and land use of the area. The technology is widely used in many countries to development water storage.

\_(Wogari, 2006) In his research the current water resource potential of the Holeta catchment for domestic, agricultural, and industrial is evidently massive. However, the long-term sustainable use of this resource requires an integrated effort of all concerned stakeholders of the catchment and its surroundings as to how to use and protect the soil- water- forest system in the catchment as it is very decisive in the destiny of the future generation. The study lacks detail clarification about the management methods for sustainably use the groundwater potential of the catchment.

\_(Yilikal, 2019) In his unpublished project document developed for the UNDP in title ‘surface water and groundwater monitoring strategy and integrated water resource monitoring guideline for the 6 woredas and 2 town administrations’, has evaluated the groundwater resource of Sebeta woreda using water balance method. Based on his estimation the groundwater recharge is  $133,036,783.50\text{m}^3/\text{y}$ , well withdrawal is  $30,768,660.00\text{m}^3/\text{y}$  and base flow from time plot method is  $14,726,414.60\text{m}^3/\text{y}$ .

This result shows that about 23% of the groundwater recharge from precipitation is discharged through existing wells annually in Sebeta area. He also proposed 10 existing water wells and three gauging stations at Awash River to be used as fixed groundwater and surface water monitoring sites in order to periodically monitor the groundwater and surface water resources of the area and to check water quality trends in time. The project document also outlined, in the case of Sebeta Hawass woreda the plain near Wochecha Mountain is suffering from water logging caused by the flood every year. The newly constructed rail road project has also aggravated the flood problem by accumulating the water from the highland and blocking the natural flow. These problems in addition to the high withdrawal rate of groundwater from abstraction wells calls for the development of integrated water resource management strategy. To this end surface water and groundwater monitoring strategy and integrated water resource management guideline have also been developed and incorporated in the project document.

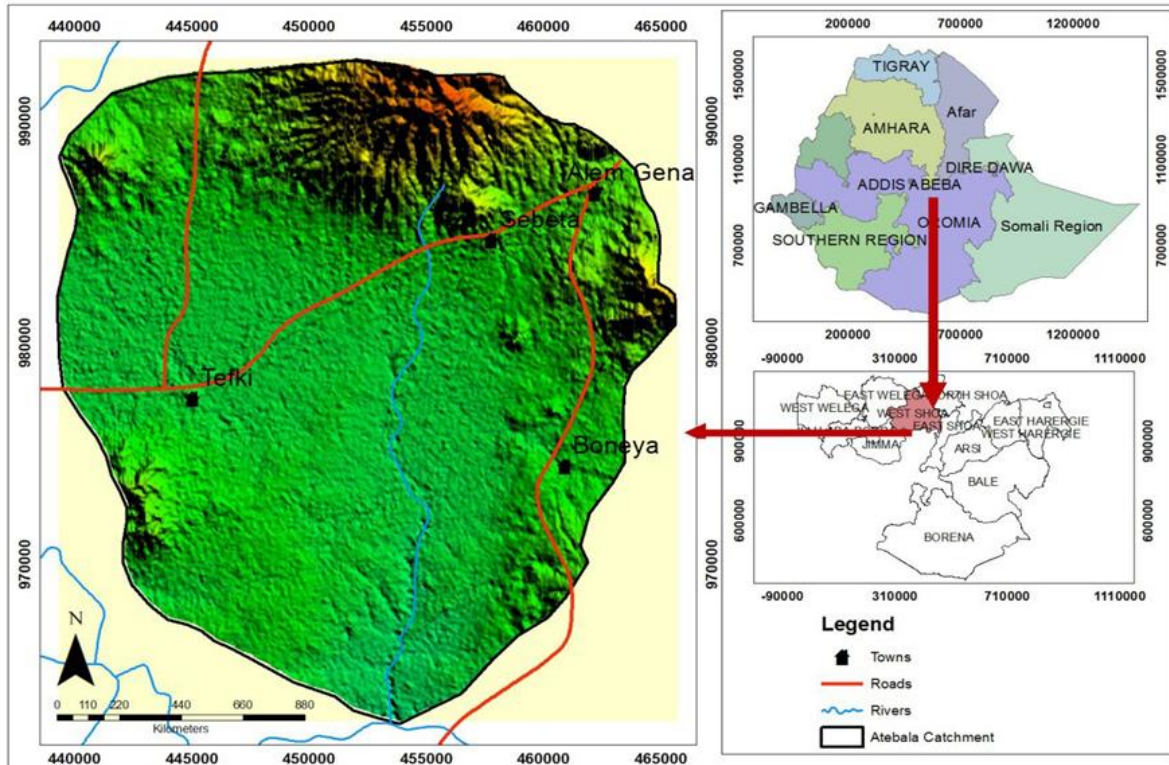
### **3. METHODOLOGY**

#### **3.1 General Description of the Study Area**

The proposed study area is situated in Oromia Regional State, Ethiopia. Atebala River catchment is found West of Addis Ababa and it is a part of upper Awash River Basin. The study area is located about 25km far from Addis Ababa on the way to Jimma road. Starting from Sebeta town in the North which is between Wechecha and Furi mountains up to the joint of Atebela and Awash rivers, from the West the area includes few portions of Becho plain which is from around Tefki town and to the East Boneya town.

Three streams that flow from north Sebeta and Dima and from east Boneya streams together create Atebela river catchment and it then flows to south to finally join Awash River. The major volcanic centers and ridges which the catchment includes are Wechecha and Furi mountains. Part of Wechecha Mountain is located in the Northern bound of the catchment and it remains a surface water divide of the catchment. A part of mount Furi also divides the Atebala catchment from other catchment in the North-East direction.

According to these the study area is named **Atebala** catchment and it is located between 439700 to 465692 east and 963012 to 992948 north, UTM, Adindan datum, zone 37 and the maximum elevation is about 3100m (a.s.l) at Wechecha mountain and around 2000m (a.s.l) at the joint of Atebala and Awash River. But most of the catchment has laid on average of 2060m above mean sea level. The catchment covers a total area of 766.06sq.km, and it is shown below in **Figure: 3.1**.



**Figure 3.1: Location Map of Atebala River Catchment**

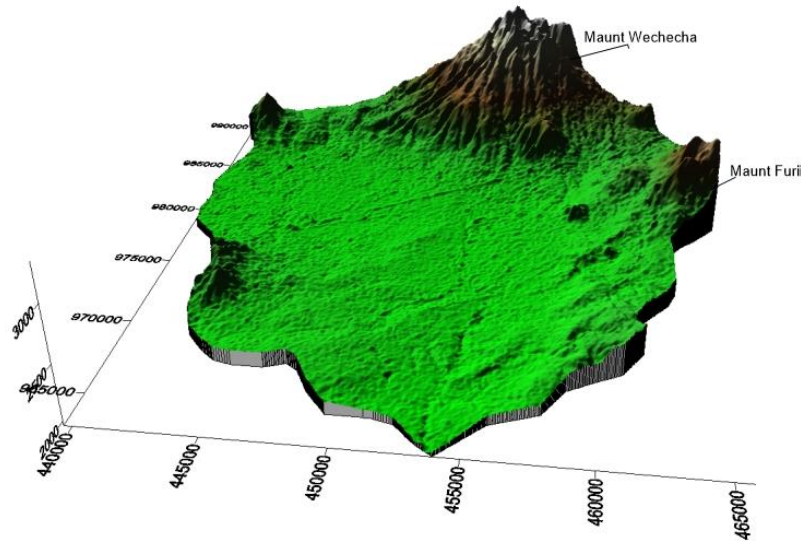
### 3.2 Topography of the Area

The formation and development of the Main Ethiopian Rift Valley system during Miocene caused the formation of the north-western and south-eastern Ethiopian plateaus to the west and east respectively, and separated by the rift valley itself. Upper Awash basin in general has a controlling dominance by a series of volcanic mountains appearing as the watershed divide and exceptional acidic volcanic narrow hilltops are also common characteristics to be considered and known by dividing into categories the upper Awash Basin behave as local divides.

Atebala catchment is restricted in the North by the Wechecha Mountain and in the East by mount Furi which are volcanic ridges. The present topographic setting of the study area is the result of volcano-tectonic activity that forms the plateau and the rift. Later erosion and river dissection have contributed to the existing rugged landform. Two major types of landforms generally characterize the study area: volcanic ridges and hills surrounding the basin at its NE and north western, with flat landforms in central, and southern part.

The Atebala catchment area is bordered in the north by Wechecha Mountain which has an elevation of about 3400 a.m.s.l, in the east there is mount Furi and the area covers some part of Becho plan in the west

while in the south the Atebela river joins Awash River. The western part of the study area is a flat seasonally flooded plain with small scrubs and trees.



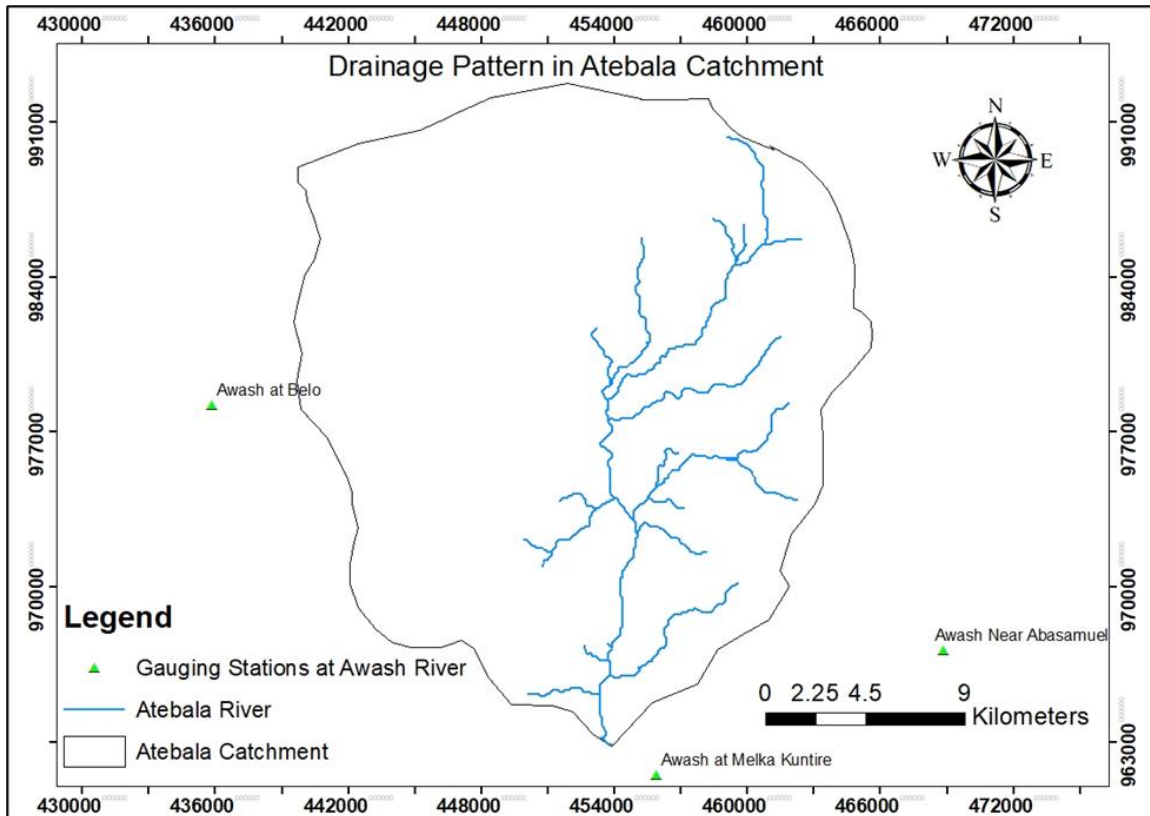
**Figure 3.2: Topography of the Study Area**

### 3.3 Drainage Pattern

The drainage pattern of upper Awash River basin and its tributaries generally form dendritic drainage pattern, and it flows in a NW to SE general direction (Andarge, 2009).

However, in the Atebala catchment the drainage pattern heading from North to South direction. The main river in this catchment is Atebala River which is one of the tributaries of Awash River in the Upper Awash basin. Atebala River is the joint of Sebeta River which rise at the bottom of Wechecha Mountain and Dima River.

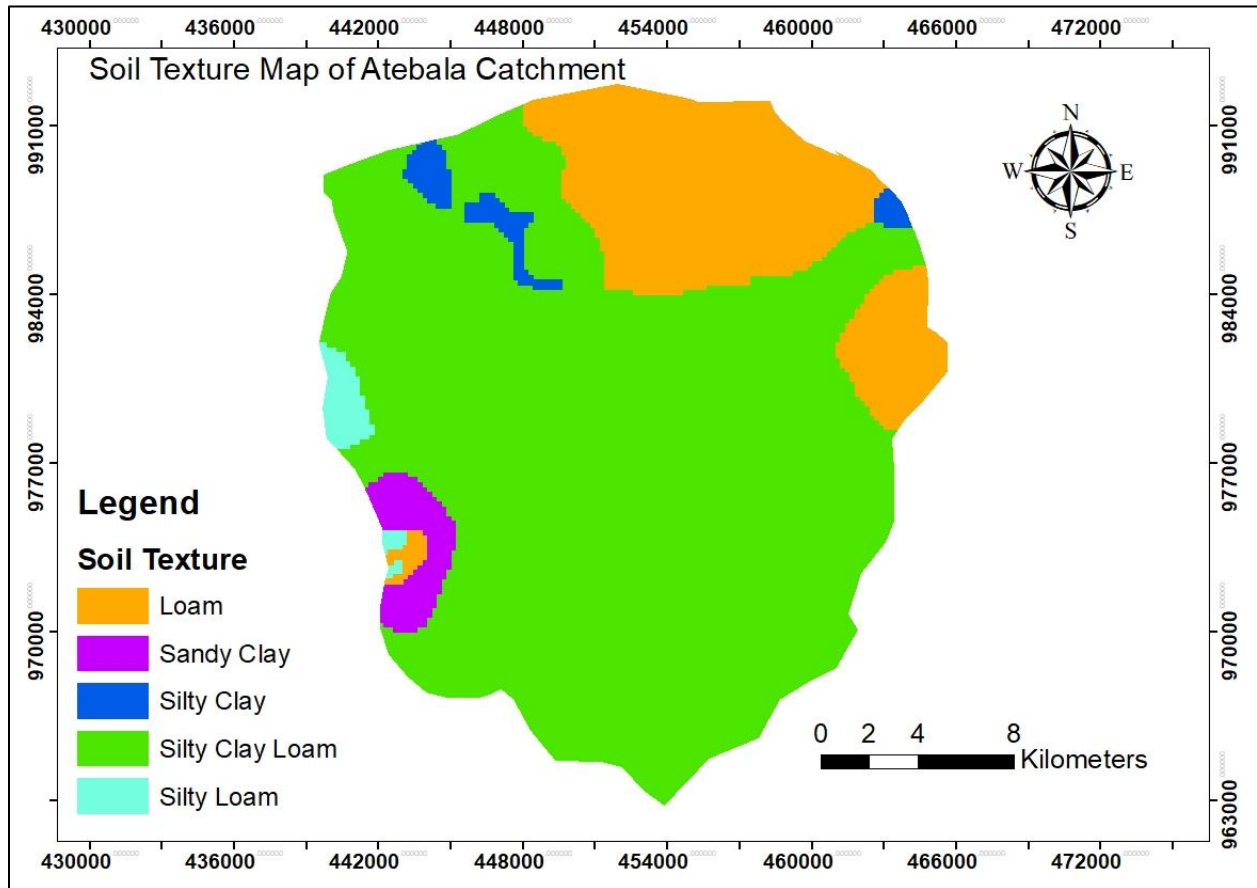
Since there is no gauging station at Atebala River which is a tributary to Awash River the hydrological data from Melkakuntire gauging station is used to represent the monthly flow of the river by using area ratio method which obtained dividing the total area of the ungagged catchment by total area of the gaged catchment and then multiplying all the monthly flow values of the gaged station data with the areal ratio.



**Figure 3.3: Drainage Pattern and gauging stations**

### 3.4 Soil and Land Use of the Area

According to [\(WWDSE, 2008\)](#) the identified soil texture units of the study area are described as follows: The dominant soil type in Atebala area is Silty Clay Loam. There are also Loam, Silty Loam, Silty Clay and Sandy Clay with small area coverage. The Silty Clay Loam in the area is black clay that is dominated by the montmorillonite clay mineral. This mineral expands when wet and contracts when dry, causing cracks at the surface in the dry season.



**Figure 3.4: Soil Texture map of the study area (Modified after FAO)**

The land use land cover of the catchment has been considered for this research as it has great influence in the recharge calculation and estimation of evapotranspiration. Land can be put to different uses based on the suitability of its different physical land resources, demand, climate, location, etc. The existing land use patterns in the catchment have been broadly divided into six groups: Cultivation, Grass Land, Plantation, Natural Forest, Seasonal Wetlands, and Urban areas.

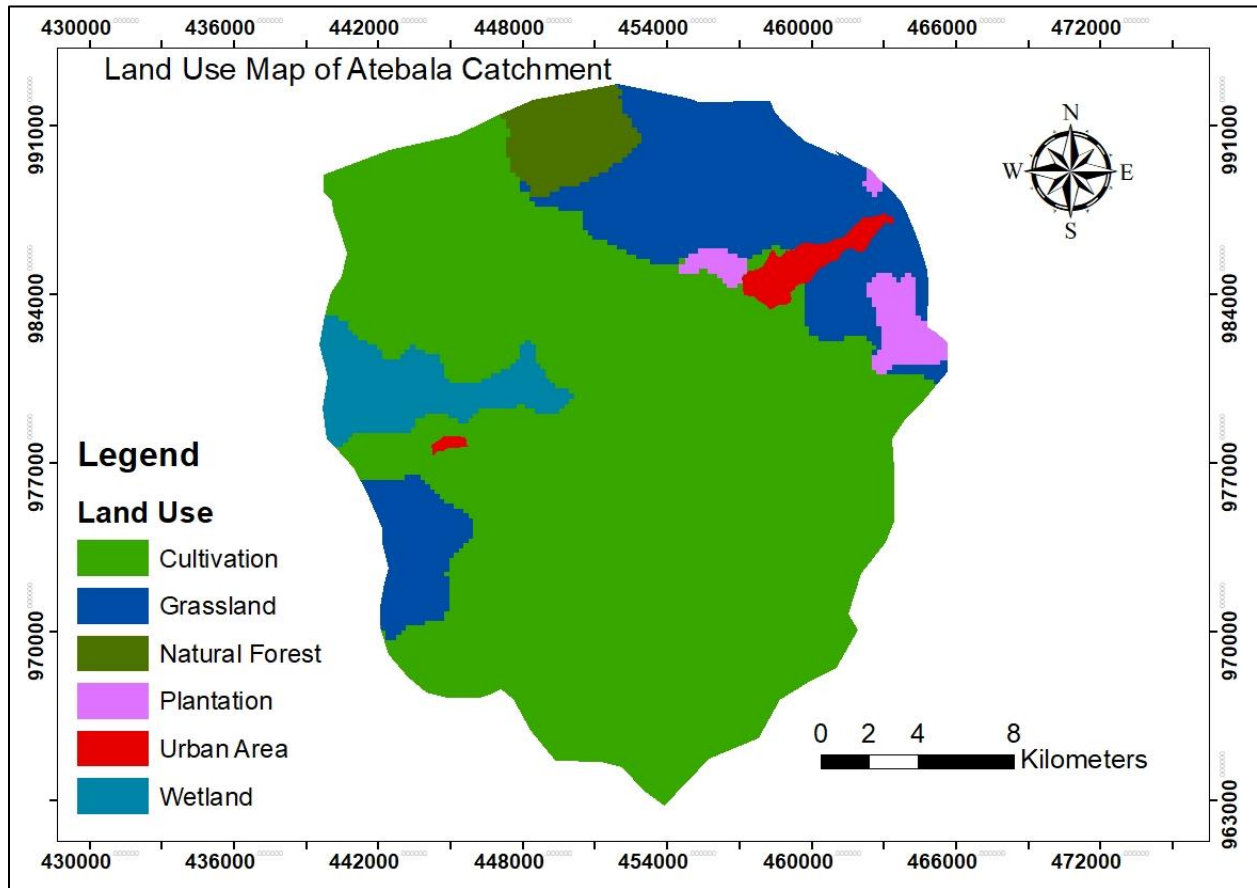


Figure 3.5: Land Use Map of the Study Area (Modified after FAO)

### 3.5 Hydro-Meteorological Setting

Climate comprises the average of atmospheric pressure, temperature, humidity, wind, rainfall and consisting of many other meteorological elements over a long portion of time in a specified area. The climatic condition and the rainfall pattern of Atebala catchment is similar with most of the upper Awash Basin areas. The main rainy seasons are occurring from July to September (locally known as **Kirmet**), the rest of the year is mainly dry (locally known as **Begga**) except small rains during March to May (locally known as **Belg**), June is a transition month between the Kirmet and Belg. The temperature condition of Atebala catchment is also similar with most of the upper Awash basin catchments, the mean monthly temperature is about 17.64°C (WWDSE, 2008).

#### 3.5.1 Precipitation

The capacity of rainfall in Ethiopia is influenced by the position where the opposing north-east and south-east trade winds come together from distinct directions, so called the Inter-Tropical Convergent Zone (ITCZ). Seasonal slight difference of precipitation is of great significant aspect of hydrology for the cause it is a decisive factor for the river flow, groundwater dynamics and groundwater recharge.

In the study area two rainy seasons have been experienced. The main rainy season often extends from June through end of September and the small rainy season from end of March to May, the rest of the months are generally dry. The mean annual rainfall varies from over 998.69mm per year in the high elevated highlands to below 722.13 mm per year in the lower areas.

*Table 3.1: Location of Metrological Stations in Atibala Catchment*

S/N	Data Recorded Meteorological Station	X	Y	Elevation	Recorded Year	Mean Annual Rainfall
1	Sebeta	459323.00	987043.78	2240.00	1995 - 2019	998.69
2	Tefki	443807.72	977112.69	2063.00	1995 – 2019	883.34
3	Boneya	461179.00	974616.00	2130.00	1995 - 2019	722.13

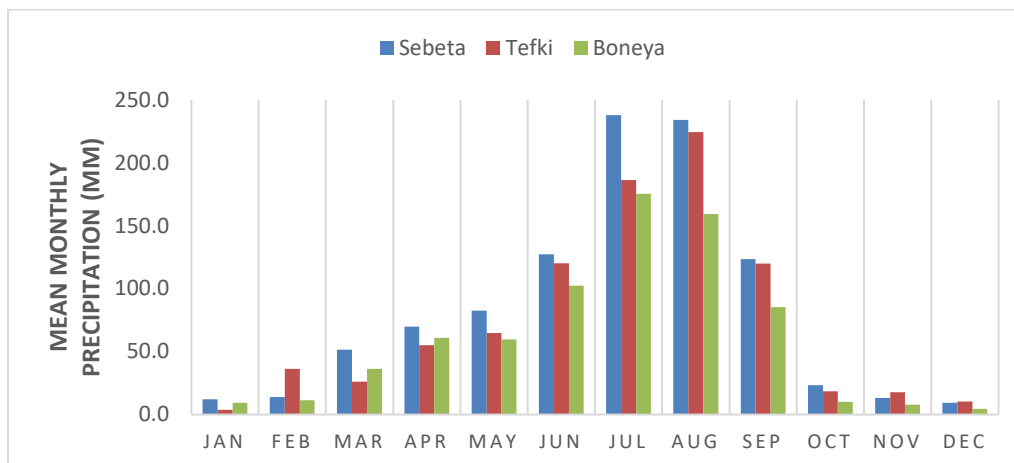


Figure 3.6: Mean Monthly Precipitation of Metrological Stations in Atibala Catchment

### 3.5.2 Spatial Distribution of Rainfall

The areal pattern of the seasonality of rainfall in the study area determined by analyzing long term mean monthly rainfall data for three stations in and around the basin. Precipitation is the most commonly measured meteorological data. In this study, from 1995 to 2019 monthly total rainfall records of three stations are used to analyze monthly mean rainfall, mean annual rainfall, rainfall coefficient and areal depth of precipitation. The mean monthly and annual mean rainfall as recorded by National Meteorological Services Agency (NMSA) at the stations is listed in the following table: 3.2.

Table 3.2: Mean Monthly Rainfall in the Three Stations.

Met. Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Mean Annual Precipitation, mm
Sebata	12.19	13.92	51.44	69.92	82.54	127.34	237.86	234.12	123.56	23.28	13.07	9.44	<b>998.69</b>
Tefki	3.72	36.38	26.15	55.12	64.87	120.17	186.18	224.30	119.90	18.52	17.60	10.43	<b>883.34</b>
Boneya	9.30	11.26	36.31	60.90	59.75	102.43	175.31	159.30	85.25	10.05	7.79	4.49	<b>722.13</b>

In order to effectively represent point rainfall data for the area under investigation, the Isohytal method is employed. The mean annual precipitation of the area is 868.05 mm per year.

$$R = \sum_{i=1}^n \frac{a_i r_i}{A} \quad \text{Equation 3.1}$$

Where R: areal rainfall

$a_i$ : area between adjacent isohyets

$r_i$ : the corresponding mean rainfall

A: total area

**Table 1.3: Mean Annual Weighted Precipitation of Atebala Catchment**

Station	Enclosed area (km <sup>2</sup> )	Weighted area (%)	Mean annual precipitation (mm)	Annual weighted PPT (mm)
P1	159.64	28.34%	<b>722.13</b>	<b>204.65</b>
P2	116.31	20.65%	<b>998.69</b>	<b>206.23</b>
P3	287.36	51.01%	<b>883.34</b>	<b>450.6</b>
<b>Total</b>	<b>563.31</b>	<b>100.00%</b>	<b>868.05</b>	<b>861.48</b>

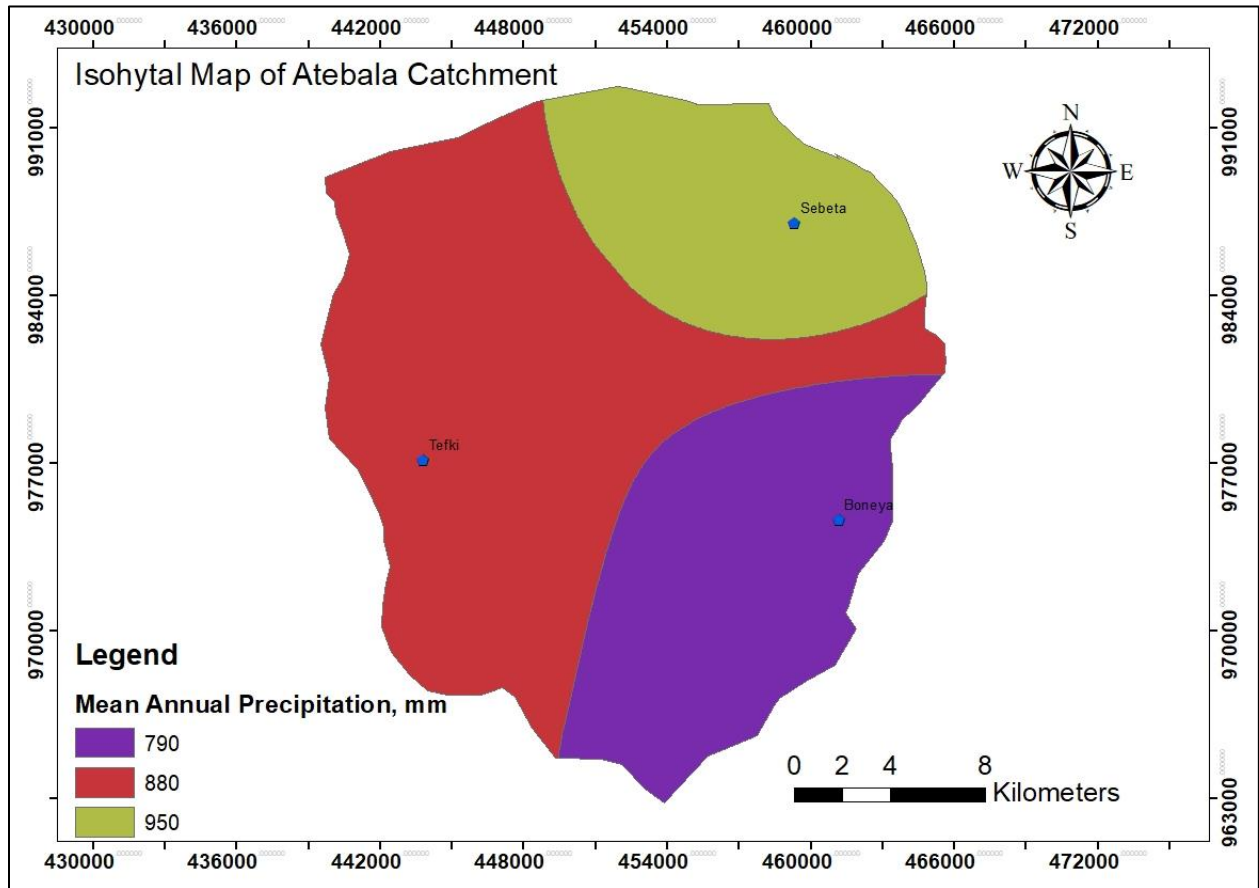


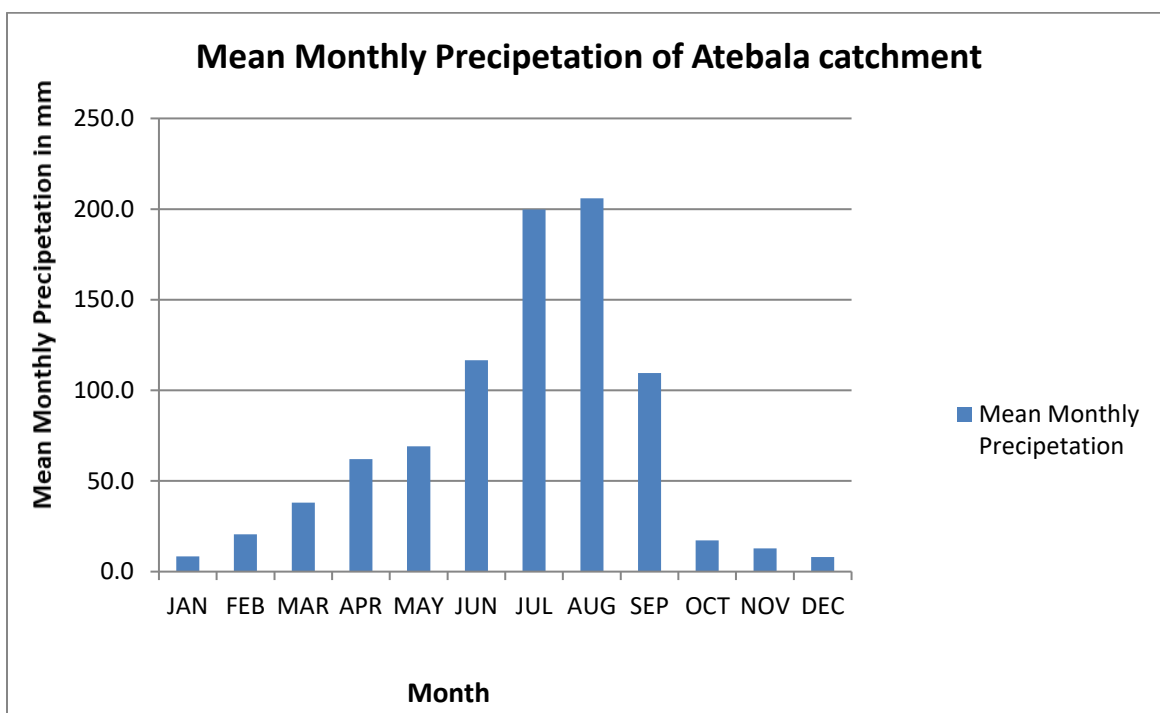
Figure 3.7: Isohytal Map of Atebala Catchment

### 3.5.3 Temporal Distribution of Rainfall

The temporal distribution of rainfall in the study area is great with maximum rainfall recorded in the month of August 205.9mm/m and the minimum monthly rainfall is observed in the month of December 8.1mm/m. Based on the meteorological data analysis of the available long-term data the mean annual rainfall is general decreasing especially in the last three years in all the three stations.

**Table: 3.4. Mean Monthly Precipitation of Atebala Catchment**

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean Monthly Precipitation, mm	8.4	20.5	38.0	62.0	69.1	116.6	199.8	205.9	109.6	17.3	12.8	8.1



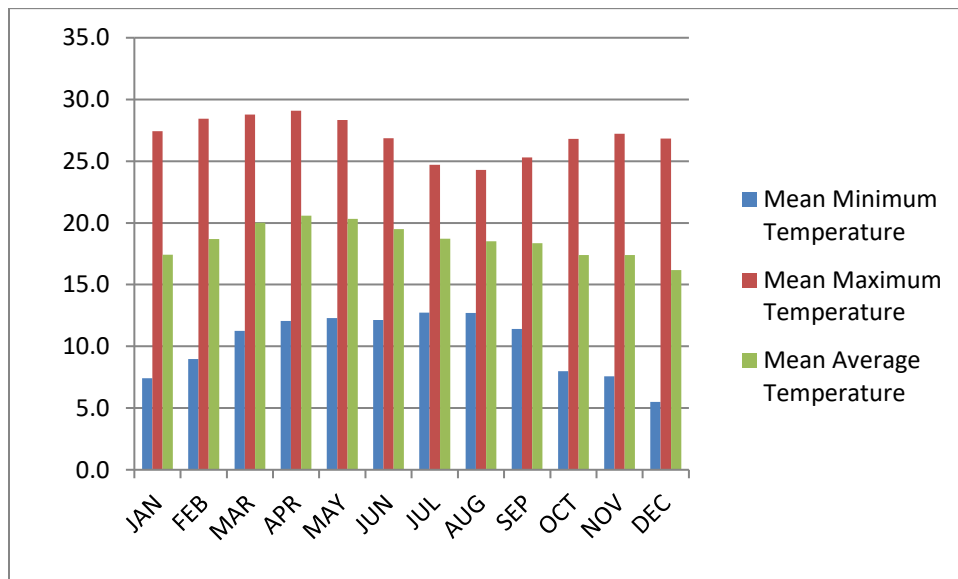
**Figure 3.8: Temporal Distribution of Rainfall in Atebala Catchment**

### 3.5.4 Temperature

Based on the analysis of long-term meteorological data analysis the mean minimum temperature of the study area is 9.7°C, the mean maximum temperature is 25.5°C and the mean average temperature is 17.6°C.

**Table: 3.5. Mean Monthly Temperature of Atebala Catchment**

Temperature in Degree Celsius	MONTHS											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean Minimum	7.88	9.07	10.58	11.50	11.42	11.21	11.48	11.48	10.49	8.15	7.27	6.38
Mean Maximum	26.35	27.41	27.55	27.35	27.00	25.27	22.93	22.55	23.58	25.22	25.73	25.54
Mean Average	17.12	18.24	19.07	19.42	19.21	18.24	17.21	17.02	17.04	16.69	16.50	15.96



**Figure 3.9: Mean Monthly Temperature in Atebala Catchment**

### 3.5.5 Relative Humidity

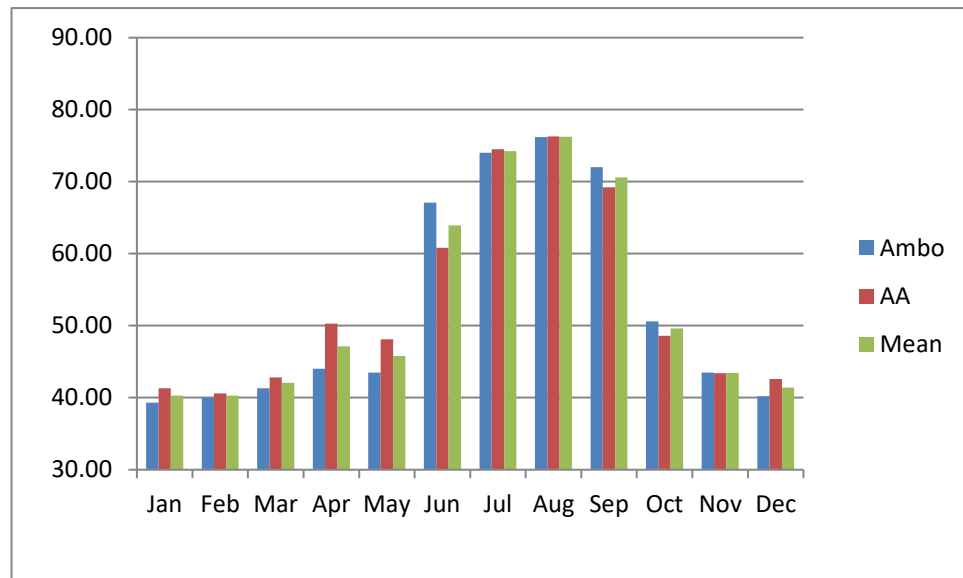
Relative humidity is the relative measure of the extent of moisture in the air to the amount required to saturate the air at the identical temperature. The relative humidity of the air is mostly contingent on temperature and rain fall. According to [\(Shaw, 1985\)](#) relative humidity is the relative measure of the amount of moisture in the air to the amount needed to saturate the air at the same temperature and represents as a percentage.

The relative humidity for an air mass is the percent ratio of the grams of water per cubic meter of air to the capacity of air to hold maximum amount of air, for the temperature of air mass [\(Fetter, 1999\)](#). It expresses the degree of saturation of the air as a ratio of the actual ( $e_d$ ) to the saturation ( $e_s(T)$ ) vapor pressure at the same temperature (T):

$$RH = 100e_d/e_s$$

Where, RH: relative humidity

$e_d$ : actual vapor pressure and  $e_s$ : saturation vapor pressure

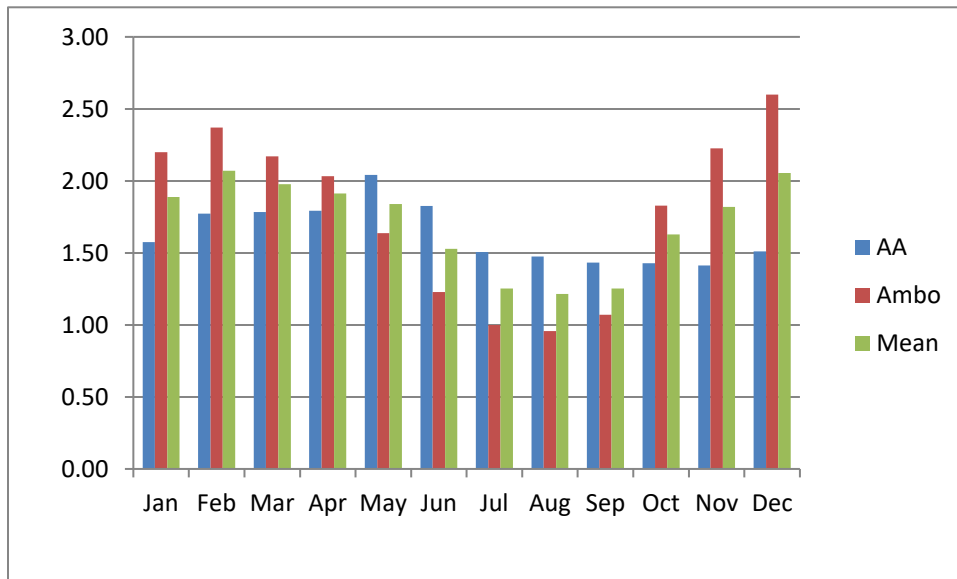


**Figure 3.10: Mean Monthly Relative Humidity in Atebala Catchment**

### 3.5.6 Wind Speed

Presence of atmospheric turbulence can greatly increase the rate of evaporation by removing vapor from evaporating surfaces and giving space for fresh air capable of holding additional vapor in the atmosphere. Four stations located in the study area have records of wind speed at 2m above the ground surface.

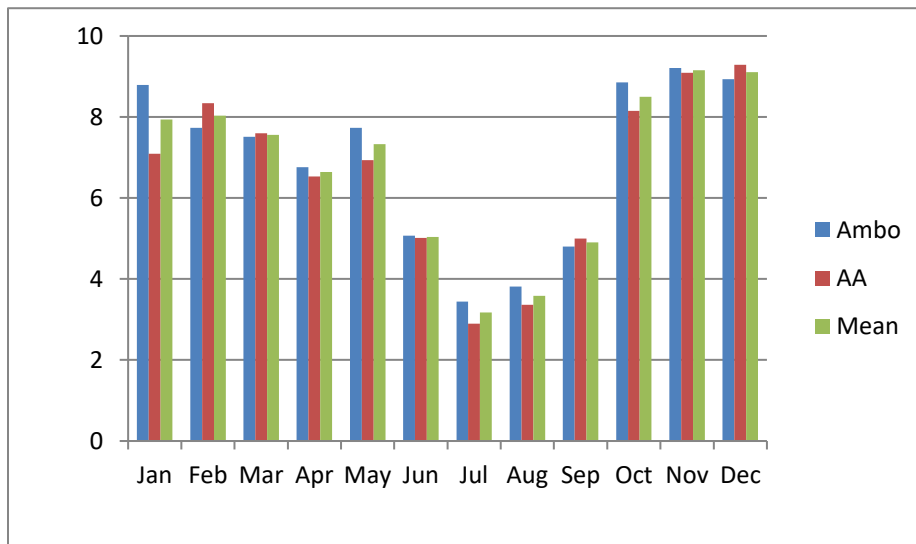
One of the major factors of evaporation is wind speed, the action of decreasing of wind speed resulting in non-removal of saturated vapor that make a difference to evaporation rate. Wind speed data in the study area is analyzed from the Ambo and Addis Ababa meteorological Station.



*Figure 3.11: Mean Monthly Wind Speed in Atebala Catchment*

### 3.5.7 Sunshine Hour

Since the evaporation requires continues supply of energy which is derived mainly from solar radiation, the radiation will be a factor of considerable importance. In the study area Sunshine hour is not gaged but Addis Ababa and Ambo is close to the study area this therefore it represents and it is used for analysis. The maximum sunshine hour is recorded in the months of October, November and December and minimum values in the months of July and August.



*Figure 3.12: Mean Monthly Sunshine Hour in Atebala Catchment*

### **3.5.8 Estimation of Evapotranspiration**

Evapotranspiration refers to the loss of water to the atmosphere through evaporation from all earth's surfaces; this includes evaporation from free water surfaces, soil, and artificial manmade surfaces and transpiration from plants [\(Houghton, 1985\)](#). The rate of occurrence of evapotranspiration at any particular place is governed by different conditions containing as part of the whole obtained energy are connected to solar radiation and, humidity, air temperature, wind speed above the surface, water serviceability, land cover features such as vegetation, and soil characteristics [\(Bonan, 2002\)](#). Evapotranspiration cannot be measured directly. The Pan Evaporation data can be used to determine lake evaporation, apart from transpiration and evaporation of intercepted rain on vegetation are unknown variables. There are two principal standards to quantify evapotranspiration indirectly. But because of absence of pan evaporation data, empirical formulas that use distinct meteorological data are used to determine mathematically potential evapotranspiration and actual evapotranspiration.

It is customary to divide evapotranspiration in to free water (or lake) evaporation and evapotranspiration from plants and soil. Although the deriving climatic forces behind the two processes are the same, evapotranspiration from soil and plants is more complex. This is due to the fact that the nature of evaporating surface of soil and plants is influenced by various physiological and aerodynamic factors as well as the availability of water.

As stated by [\(Brutsaert, 1982\)](#) PET is the quantity of water that was evaporated under an optimal set of circumstances, among unlimited supply of water. In other words, it would be the water needed for evaporation and transpiration given the local environmental significant influence. One of the greatest significant factors that establish water requirement is solar radiation as energy supplied increases the pressing requirement for water.

### 3.5.9 Potential Evapotranspiration

The potential evapotranspiration of the study area is calculated using Thornthwaite method. Thornthwaite's method is based up on the assumption that potential evaporation was dependent only up on meteorological conditions and ignored the effect of vegetation index and maturity. However, the method devised by Thornthwaite is still useful. The necessary factors to input are: mean monthly air temperature, latitude, and a month. Latitude and month yield average monthly sunshine. Accordingly, the land surface annual potential evapotranspiration of the study area based on Thorn Thwaite method is 795.83mm/y.

$$PET_m = 16N_m \left( \frac{10t}{I} \right) a \text{ mm} \quad \text{Equation 3.1}$$

Where; **m**: months

**PET<sub>m</sub>**: monthly Potential evapotranspiration,

**N<sub>m</sub>**: monthly adjusted factor depending on latitude and season,

**t**: mean monthly temperature,

**I**: annual heat index obtained by adding monthly heat index (*i<sub>m</sub>*) of 12 months.

$$i_m = (t/5)^{1.5}$$

$$a = 6.7 \cdot 10^{-7} I^3 - 7.7 \cdot 10^{-5} I^2 + 1.8 \cdot 10^{-2} I + 0.49$$

**Table 3.6: Potential Evapotranspiration of Atebala Catchment**

Element	Month												Annual
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
<b>T<sub>m</sub> (°C)</b>	17.11	18.24	19.06	19.42	19.21	18.23	17.20	17.01	17.03	16.68	16.49	15.96	
<b>N</b>	11.60	11.80	12.00	12.30	12.60	12.70	12.60	12.40	12.10	11.80	11.60	11.50	
<b>N<sub>m</sub></b>	0.967	0.983	1.00	1.025	1.05	1.058	1.050	1.033	1.008	0.983	0.967	0.958	
<b>Im</b>	3.422	3.648	3.812	3.884	3.842	3.646	3.440	3.402	3.406	3.336	3.298	3.192	
<b>I</b>	79.614												
<b>A</b>	1.773												
<b>PET<sub>m</sub></b>	60.05	68.42	75.23	79.71	80.09	73.57	65.84	63.53	62.12	58.39	56.25	52.63	795.83

### 3.5.10 Actual Evapotranspiration

The actual evapotranspiration of the study area is calculated using Thornthwaite and Mather standard soil water balance model based on the soil, vegetation cover, precipitation and potential evapotranspiration as main inputs. Based on the analysis the actual evapotranspiration of the area is 663.34mm/y. That is 373,666,055.40m<sup>3</sup> of water is lost by evapotranspiration from the catchment per year.

$$AET = PET \text{ if } P_m > PET_m,$$

Otherwise;

$$AET_m = P_m - DSm \quad \text{Equation 3.2}$$

Where; *AET* is actual evapotranspiration, *PET* is potential evapotranspiration, *P* is aerial precipitation, *DS<sub>m</sub>* are soil moisture during the month m-1 and m respectively.

$$S_m = W \exp \left[ -\frac{Lam}{W} \right] \quad \text{Equation 3.3}$$

Where; *S<sub>m</sub>*: Soil moisture during the month M (mm),

*L<sub>m</sub>*: Accumulated potential water loss at month M (mm),

*W*: Available water capacity of the root zone (mm).

**Table 3.7: Actual Evapotranspiration of Atebala Catchment**

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
P <sub>m</sub>	8.40	20.52	37.96	61.98	69.05	116.64	199.78	205.91	109.57	17.284	12.82	8.12	868.05
PET <sub>m</sub>	60.05	68.42	75.22	79.71	80.09	73.57	65.84	63.53	62.12	58.39	56.25	52.62	795.81
P <sub>m</sub> -PET <sub>m</sub>	-51.65	-47.90	-37.26	-17.73	-11.04	43.07	133.94	142.38	47.45	-41.11	-43.42	-44.50	
Acc.Pot.Wl(Lam)	-180.69	-228.59	-265.85	-283.58	-294.61					-41.11	-84.53	-129.04	
S <sub>m</sub>	88.83	70.71	59.21	54.42	51.63	210	210	210	210	172.66	140.41	113.59	
DS <sub>m</sub>	-24.77	-18.12	-11.49	-4.79	-2.79	0	0	0	0	-37.33	-32.25	-26.81	
AET <sub>m</sub>	33.17	38.64	49.46	66.77	71.84	73.57	65.84	63.53	62.12	58.39	45.08	34.93	663.34
AWCR(W)	210												

### 3.6 Runoff

#### 3.6.1 Mean Monthly and Annual Flows

The major river in the study area is the Awash River with many tributaries. The length of the Awash River that passes near the boundary of the catchment is 64.73 kilometers. There are three gauging stations around the study area that are designed to collect river flow data. The gauging stations are sited at Belo, Melka Kuntire and near Reservoir Abasamuel. The available data collected from 2000 to 2015 GC from Ministry of Water, Irrigation and Energy Hydrology and Water Quality Directorate are used for analysis of surface run off and base flow. The 2016 GC data misses the record of July to December and there is no record for years of 2017 and 2018 GC. The mean annual flow of the Awash River based on the long-term flow data obtained from Melkakuntire gauging station is 228.39mm.

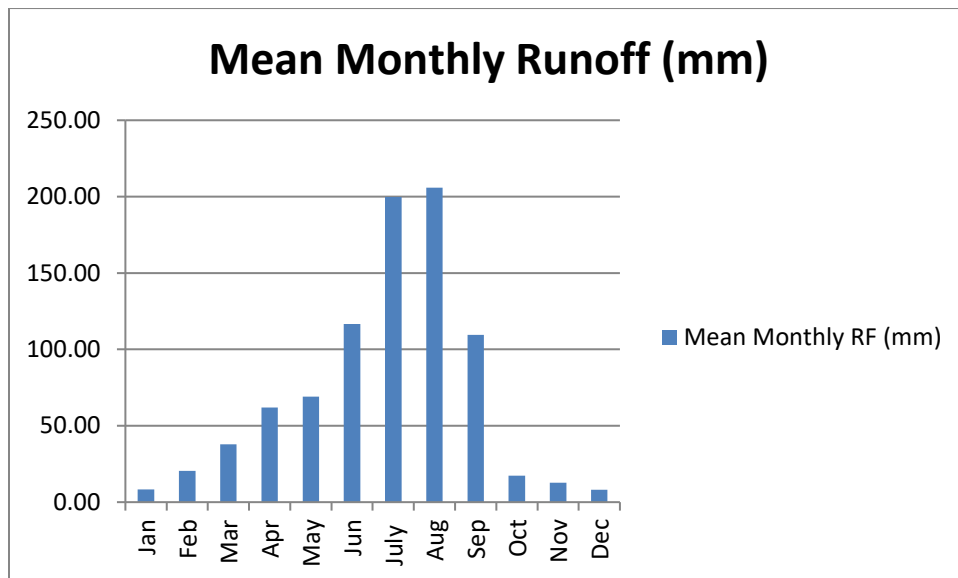


Figure 3.13: Mean Monthly Discharge of Awash River (Data from Melkakuntire Gauging Station)

### 3.6.2 Hydrograph Separation

The hydrograph analysis is done based on the available data from the gauging stations around the study area using geometric method. Based on the area ratio analysis method which is obtained by dividing the area of ungagged station with total area of the gaged station and multiplying the result with measured values of the station. Then, the total mean annual runoff in the study area is 28.87mm/y (16,263,471.43m<sup>3</sup>/y), the surface runoff is 18.05mm/y (10,168,524.74m<sup>3</sup>/y) and the base flow is 10.82mm/y (6,094,946.70m<sup>3</sup>/y).

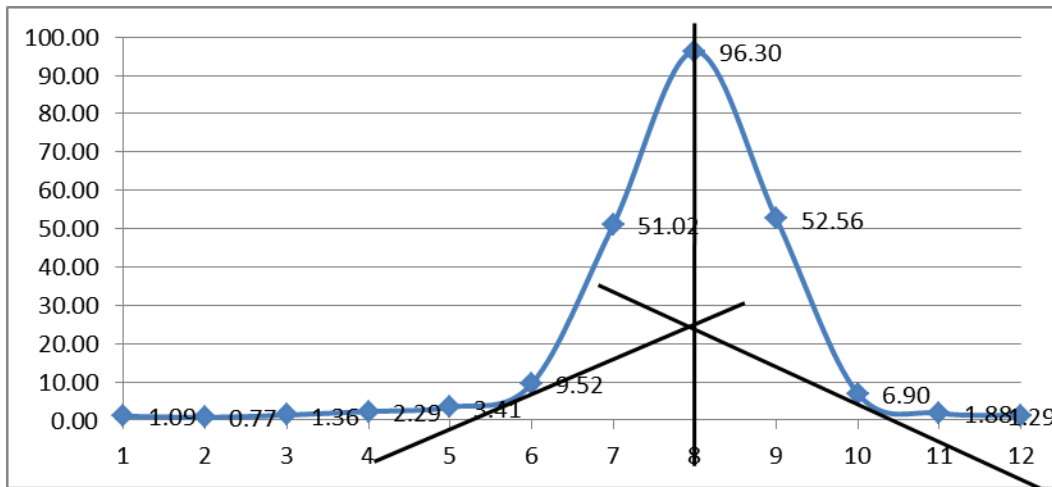


Figure 3.14: Hydrograph Separation of Awash River

Table 3.8: Base Flow Separation of Awash River

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Measured Runoff, mm	1.09	0.77	1.36	2.29	3.41	9.52	51.02	96.30	52.56	6.90	1.88	1.29	228.39
Base Flow, mm	1.09	0.77	1.36	2.29	3.41	8.50	18.00	25.00	16.00	6.00	1.88	1.29	85.59
Surface Runoff, mm	0.00	0.00	0.00	0.00	0.00	1.02	33.02	71.30	36.56	0.90	0.00	0.00	142.80

**Table 3.9: Base flow separation for the study area based on area ratio**

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Measured Runoff, mm	0.14	0.10	0.17	0.29	0.43	1.20	6.45	12.17	6.64	0.87	0.24	0.16	28.87
Base Flow, mm	0.14	0.10	0.17	0.29	0.43	1.07	2.28	3.16	2.02	0.76	0.24	0.16	10.82
Surface Runoff, mm	0.00	0.00	0.00	0.00	0.00	0.13	4.17	9.01	4.62	0.11	0.00	0.00	18.05

### **3.7 Geology and Hydrogeology**

#### **3.7.1 Regional Geology**

In Ethiopia, the existing geological settings are a result of two major post-Paleozoic events which were followed by important phases of volcanic activity. The first tectonic event which occurred in late Mesozoic-Early Tertiary period produced the Afro Arabian Dome. The volcanic activity gave rise to the extrusion of the Trap Series succession of plateau volcanism that is assumed to be the up-doming (Mohr P. , 1972). The second tectonic event caused in rift development and related volcanic phenomenon during late Tertiary-Quaternary period.

Ethiopia can be divided in to four main physiographic regions, generally known as the western plateau, southeastern plateau, the main rift and the afar depression. The Ethiopian plateau is underlain at depth by Precambrian rocks of the Afro-Arabian Shield. The Precambrian basement is enclosed for the most part by glacial and marine sediments of Permian to Paleogene period and Tertiary volcanic rocks with related sediments (WWDSE, 2008).

The formation of the Ethiopian Rift during the Miocene separated the eastern and western highlands. The Upper Awash basin is exclusively confined within the north-central plateau and the adjacent escarpment and rift. The adjacent central plateau is drained due west by the Blue Nile River drainage system and due north-east by the Awash River drainage system.

The Precambrian basement upon which all the younger formations were deposited contains the oldest rocks in the country, with ages of over 600 million years. The Precambrian contains a wide variety of sedimentary, volcanic and intrusive rocks which have been metamorphosed to varying degrees. At the end of Precambrian times uplift occurred, which was followed by a long period of erosion. Any sediments which were deposited during the Paleozoic interval, which lasted some 375 million years, have been largely removed by erosion, except for shales and deposits partly of glacial origin laid down in northern Ethiopia towards the end of this period.

Subsidence occurred in the Mesozoic, which began some 225 million years ago, and a shallow sea spread initially over the Ogaden and then extended farther north and west as the land continued to subside. Sand, now sandstone, was deposited on the old land surface. Deposition of mudstone and limestone followed as the depth of water increased. Extensive fracturing occurred early in the Cenozoic, the earliest rocks of which are dated at 65 million years [\(Kazmin, 1975\)](#). Faulting was accompanied by widespread volcanic activity and the two processes, which are partly related, have largely determined the form of the landscape in the western half of Ethiopia and in the Afar Depression. The outpouring of vast quantities of basaltic lava over the western half of the country was accompanied by, and alternated with, the eruption of large amounts of ash and coarser fragmental material, forming the Trap Series. Several shield volcanoes, also consisting of alkali basalts and fragmental material, then developed around the eastern edge of the Lake Tana depression and Bale area. More recent volcanism is associated with the development of the Rift Valley, activity being concentrated within this structure and along the edge of the adjoining plateau. Volcanism has persisted into the present time in the Afar region within small eruptive centers. The composition of the lavas produced ranges from basalt to siliceous types.

The youngest sediments are of Quaternary age. These include conglomerate, sand clay and reef limestone which accumulated in the Afar Depression and the northern end of the main Rift Valley. Sediments which accumulated in the former lakes occur in the south end of the Afar, in the main Rift Valley, and in the Omo valley. Undifferentiated Quaternary sediments and superficial deposits occur intermittently along the Sudanese and Kenyan borders [\(Kazmin, 1975\)](#). To greater extent recent volcanism make conceptual relationship with the advancement of the Rift Valley, a condition being focused within this structure and along the edge of the adjacent plateau. A volcanic phenomenon has extended firmly into the recent time in the Afar area within regular eruptive centers. The constituents of the lavas stimulated to alter composition ranges from basalt to siliceous category. Of all sediments the youngest depositions are of Quaternary age. These comprise sand, clay, conglomerate and reef limestone, which gather together in the northern end of the Main Ethiopian Rift Valley and Afar Depression [\(Kazmin, 1975\)](#).

The conceptual connection between fissure volcanic conditions gave rise to the force out of the Trap Series succession (plateau volcanism) which is considered to be the up-doming [\(Mohr, 1967\)](#). The regional geologic setting of Upper Awash Basin is place in a particular position to distinct rock units having a separate time of formation. A set of this Mesozoic Sedimentary succession, Tertiary and Quaternary age groups of acidic and basic volcanic rocks and Quaternary Lacustrine and alluvial deposits constitute the regional geologic arrangement of the study area.

### 3.7.2 Local Geology

Atebala river catchment is included in Becho sub-basin which is a part of upper Awash Basin. The study area is geologically dominated by Addis Ababa Ignimbrite, specifically in the west and southern parts of the study area. In southern part, the thickness of this unit reaches up to 200m. In the western part it is covered with 5-7m thick residual soil developed from the same rock [\(WWDSE, 2008\)](#). Addis Ababa Ignimbrite is composed of welded Tuff (Ignimbrite) and non-welded Pyroclastic fall (ash and tuff). The age of this unit is 5.11-3.26 Ma [\(Morton et al., 1979\)](#).

There is central volcanic of Wechecha and Furi ridges [\(Mesele, 2017\)](#), this scattered volcanic mountains are trachytic. There are minor alluvial deposits and Entoto-Becho rhyolite around the western margin of the study area.

Akaki basalt also exist at the eastern end of the catchment which is around Boneya town. It is coarse grained, porphyritic, highly vesicular basalt and in places the vesicles are filled by secondary minerals. It consists of scoria and spatter cones with associated lava flows. The age of the Akaki basalt is 2.9-2.0 Ma [\(Chernet et al., 1998; Morton et al., 1979\)](#).

The other outcrop which exists in the study area is Tarmaber Basalt, this unit is overlain by thick Central Volcanic and Addis Ababa Ignimbrite. Especially the thickness of the younger Ignimbrite which revealed from deep water well lithological logs is around 280 meters [\(WWDSE, 2008\)](#). Tarmaber Basalt is not exposed on the surface of the earth in the study area. This unit is mainly scoraceous lava flows and at places it is columnar basalt as pockets within the scoraceous units. It is highly weathered, fractured and pinkish to grayish in color (Justin Visentin et.al., 1974).

The western and northwestern plateau area of Upper Awash, around the watershed divide of the Awash and Blue Nile River basins is mainly covered with Tarmaber Basalts. In the rift valley part of the study area, this unit is downthrown by the regional east-west trending Ambo Fault and overlain by thick (282m) younger ignimbrite as revealed from deep water well logs of Legadadi and Melkakunture localities [\(WWDSE, 2008\)](#). In the north and central part of the area around Addis Abba, Akaki and Dukem localities, three major rock unit's outcrops; Addis Ababa and Akaki Basalts and Addis Ababa Ignimbrites. Addis Ababa basalt is characterized by fine to coarse grained texture and in most cases, it is relatively thin (20m) lava flow overlying the Ignimbrite [\(Chernet et al., 1998; Morton et al., 1979\)](#). The Addis Ababa Ignimbrite outcrops in most part of the plain area around Addis Ababa and in the western part (Becho plain). Akaki

basalt outcrops in Akaki and Dukem areas. The thickness of this unit around Akaki is 202m (exploration drilling data).

The eastern and south eastern parts of the area are covered with Chefedonsa volcanic rock units that consist of fall deposits (ash, tuff and pumice) and poorly welded ignimbrites of rhyolitic composition. At places in the Dukem and Mojo area they are covered with lacustrine deposits. The age of this unit is 2.24 to 1.71 Ma (Morton et al., 1979).

The southern part of the study area around Debrezeit and Mojo is covered with lacustrine deposits with the exception of Entoto which is dominantly rhyolitic. The acidic volcanic ridges act as watershed boundaries between the Omo-Gibe and Awash River, in the south and south western part and with that of the Blue Nile in the north. The rhyolite picks in the Becho plain and the trachytic domes like Ziquala and Bedegebaba form isolated cones forming local groundwater divides within the watershed. Figure 3.14 shows simplified geological map of the Atebala river catchment.

### 3.7.3 Geologic Structures

Upper Awash River basin is exclusively confined within the north central plateau and the adjacent escarpment and rift (Yitbarek, 2013). The basin is located at the intersection of two regional structures, that is to say the NNE-SSW trending MER (Main Ethiopian Rift) and the East-West trending Addis Ababa-Nekemt volcanic lineament (Andarge, 2009). According to Andarge Yitbarek, 2009 the volcanic rocks of the upper awash basin have subjected to large area faulting often shows a general direction of NE – SW, E-W and at places NW-SE also the majority of the linear features along the general direction of the rift. In Atebala river catchment there is a main fault structure that is heading from North to South. This NS fault system is the recent fault system which serves as a conduit for young volcanic. This fault system lease nearly parallel to the Atebala river which drain from North to South direction in the study area.

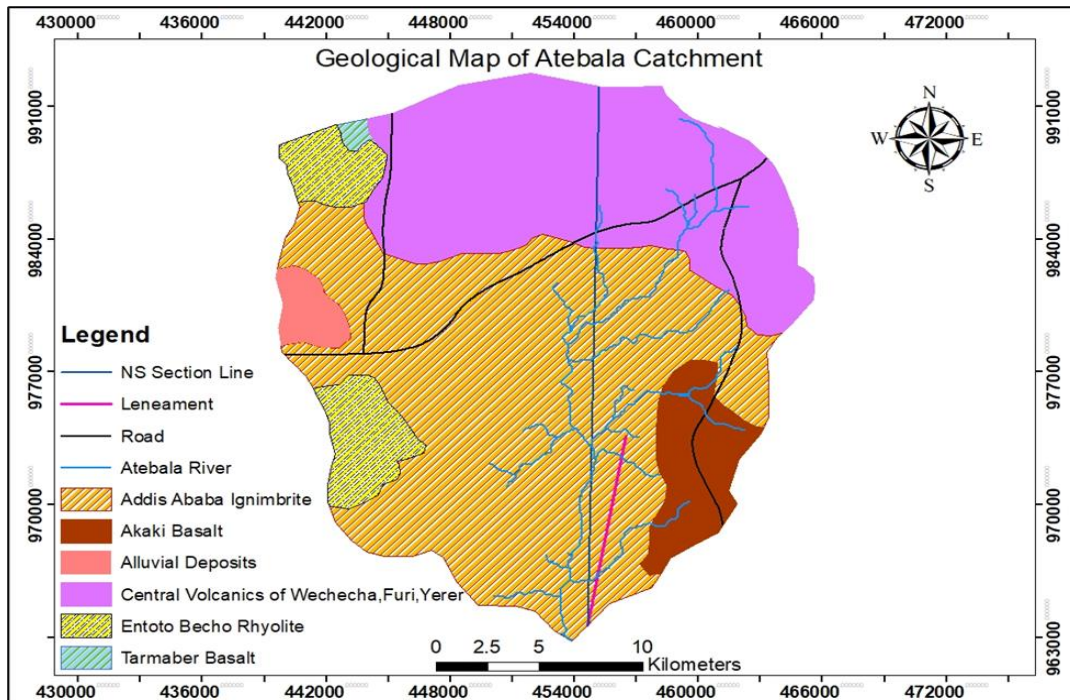
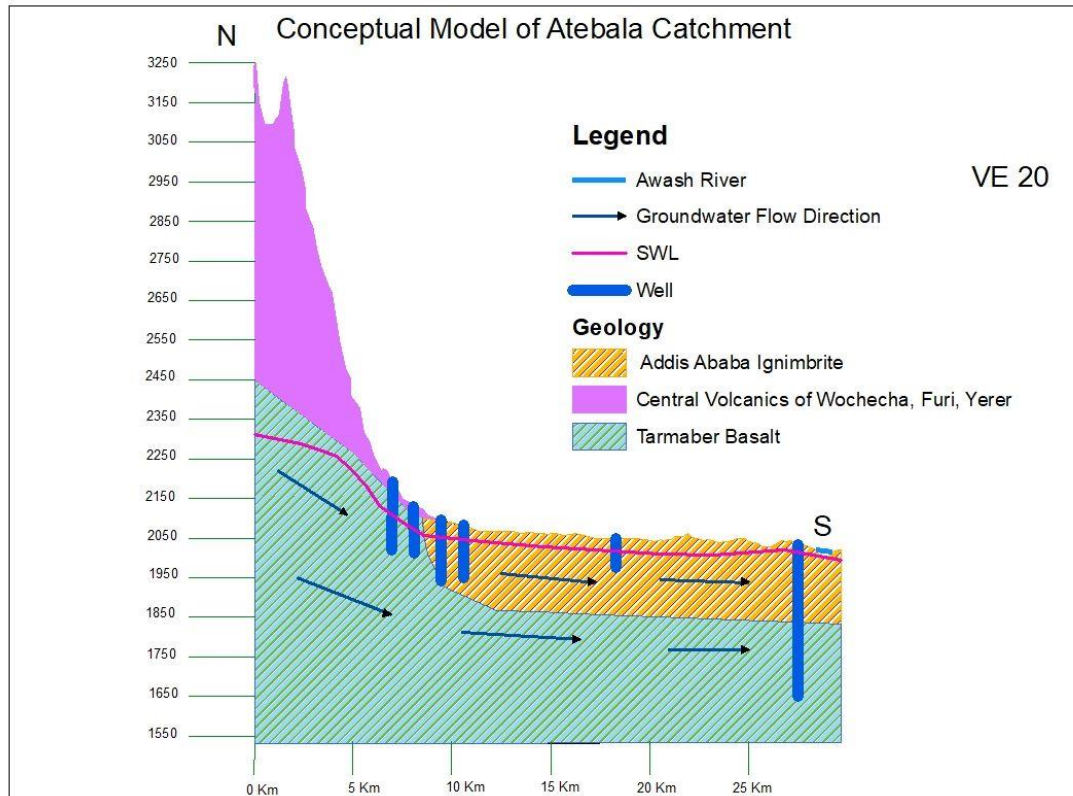


Figure 3.15: Geological Map



**Figure 3.16: NS Geological Section of the Study Area**

### 3.7.4 Hydrogeology

The groundwater in Upper Awash basin can be divided broadly into two aquifer categories; The first category includes aquifers associated to Quaternary alluvial and lacustrine deposits and the second broad categories belongs to the basaltic geological formation and again subdivided in to upper and lower basaltic aquifers according to their permeability characteristics [\(Andarge, 2009\)](#).

The Upper basaltic aquifer is composed of quaternary of Weliso-Ambo basalts, Akaki basalts: scoria and spatter cones, and Tertiary-Neogene’s basalt of Addis Ababa basalts. This aquifer has wide distribution and forms confined and unconfined aquifer system. The groundwater level depth regionally increases from north-south direction. At the northern part the groundwater of the aquifer is shallow (less than 5 meters) and at the central part it is between from 5 to 20 meters’ depth and at the south is increases more than 50 meters’ depth. The lower basaltic aquifer unit is composed of lower Tertiary Tarmaber and Amba Aiba basalts, dominantly scoraceous. [\(WWDSE, 2008\)](#).

There are also regionally upper and lower aquicludes which separates the upper and lower volcanic aquifer in Becho area. The upper regional aquiclude includes Chefe Donsa Pyroclastics, and Addis Ababa ignimbrites. The lower regional aquicludes includes Ashange basalt and Blue Nile basalt (WWDSE, 2008).

Based on the hydrogeological map modified for this study the aquifer system of the Atebala catchment is classified as highly productive, moderately productive and low productive aquifers. The highland area in the north dominated by the central volcanics of Wochecha, Furi, Yerer and Entoto Becho Rhyolite formation exposed in some part of the west of the study area have low groundwater potential. The central, southern, eastern and most of the western parts of the area in which Addis Ababa Ignimbrite and Akaki Basalt units dominate and the Tarmaber Basalt exposed in small portion in the north are classified as moderately productive aquifer systems. While the alluvial deposit in the west has high groundwater potential. Generally, the Atebala River Catchment has good groundwater reserve with great potential for developmental activities.

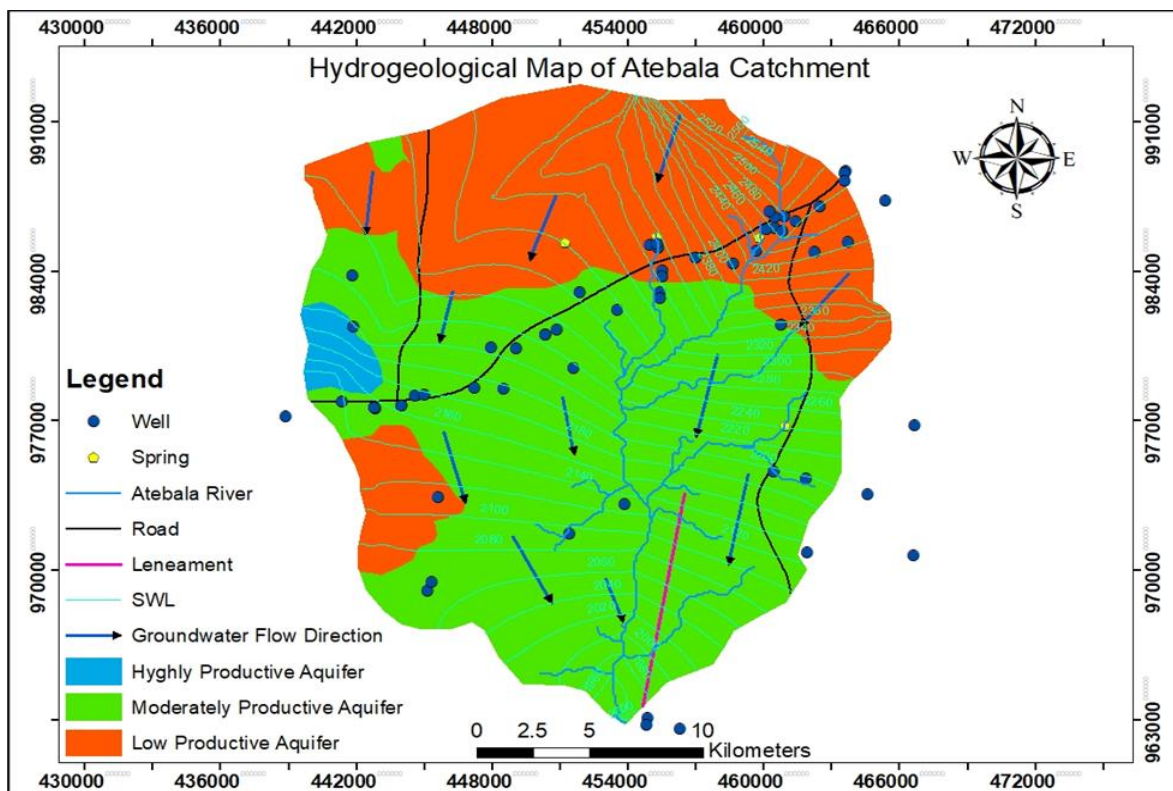


Figure 3.17: Hydrogeological Map

### **3.7.5 Water Quality**

In the shallow aquifers of the rift floor the presence of lacustrine sediments imparts high salinity to the ground waters. The low TDS waters are characterized by Ca-Mg-HCO<sub>3</sub> chemistry while the high TDS waters are dominated by Na and Cl and SO<sub>4</sub> content becomes important anions. Generally, the TDS, HCO<sub>3</sub>, Na and Cl content increases in groundwater as one moves towards the rift. Groundwater of the upper Awash Basin have fairly dilute chemistry with TDS ranging between 100 mg/L and 1000 mg/L. These kinds of water are safe for drinking and irrigation applications. The waters are dominated by Ca, Mg and Na cations and HCO<sub>3</sub> anions.

Pollution due to anthropogenic activity is observed in shallow wells in Atebala catchment and shallow unprotected groundwater points in the rift floor aquifers. Some groundwater wells show fluoride content exceeding the WHO standard limits. The knowledge on the sources of fluoride is now commonplace. Wells and thermal waters associated with acid volcanic rocks contain the highest Fluoride content. Apart from high Nitrate pollution and Fluoride content in some wells the groundwaters of the Atebala catchment area of suitable quality for irrigation, industry and domestic water supply.

Based on the water quality data analyzed using Aquachem software the major water type of the study area is Ca-Mg-HCO<sub>3</sub>, Ca-Na-HCO<sub>3</sub>, Ca-HCO<sub>3</sub>, Ca-Mg-Na-HCO<sub>3</sub> and in some wells Na-Ca-HCO<sub>3</sub> and Na-Ca-HCO<sub>3</sub>-Cl water types are observed. And all parameters are within the permissible range of WHO and MoWIE standards except high Fluoride content is observed in some of the deep wells. Therefore, the groundwater resource available in the area is generally good for domestic, irrigation and industrial use (WWDSE, 2018).

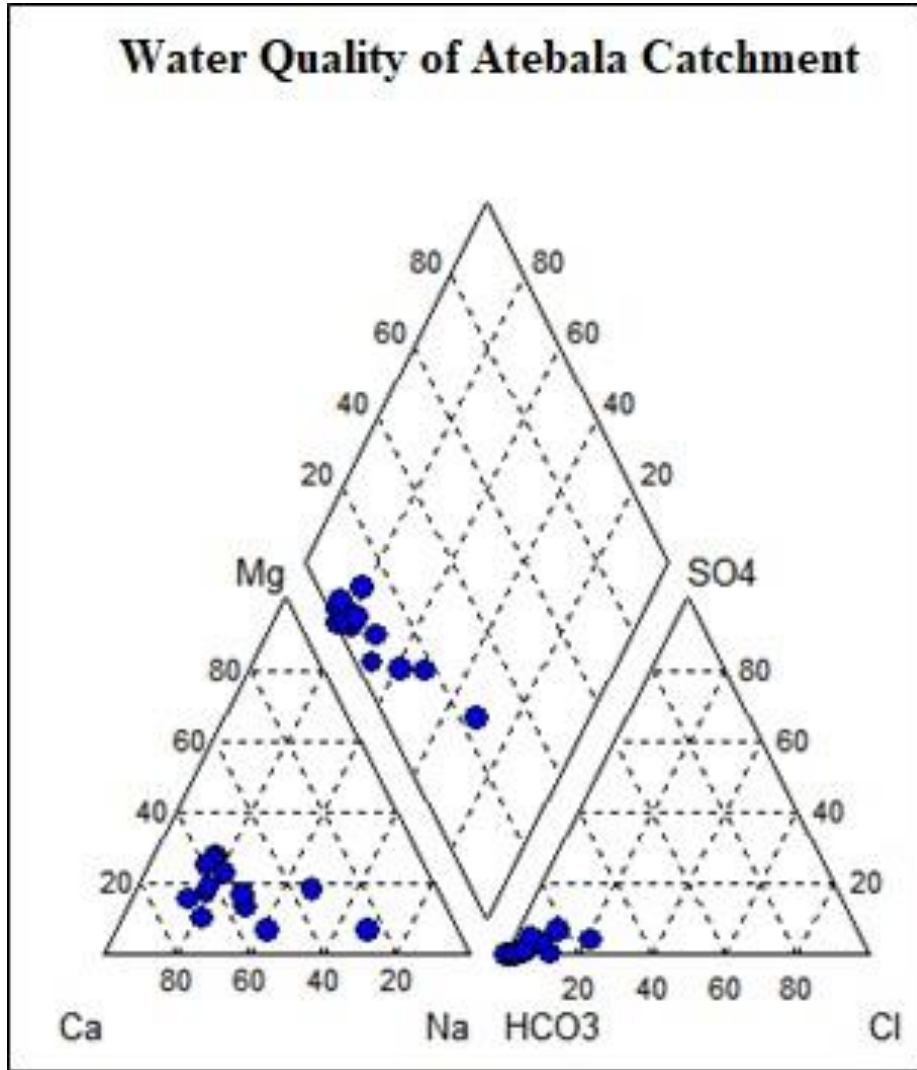


Figure 3.18: Water Quality analysis result of the study Area (Piper Plot)<sub>(WWDSE, 2018)</sub>.

### 3.8 Required Data and Data Collection

The most important typical data required for this research work are listed in Table 3.10 below, and have been collected in this research from field measurements but also from existing meteorological stations, maps, and representative Agencies.

**Table 3.10: Data sets and sources**

Parameter	Description	Location	Period	Resolution	Source
Discharge	River flow gauging:	3 stations:	2001-2018	-	MoWIE
Surface water levels	Using pressure transducer;	At selected stations	2020	20 min interval	Field measurement
Groundwater level	Once off measurements at surveyed wells	wells	2020	Scattered points throughout the catchment	Well construction report
Precipitation	Meteorological station	sebeta	1995-2019	Daily	Ethiopian metrological agency
Precipitation	Meteorological station	tefki	1995-2019	Daily	Ethiopian metrological agency
Precipitation	Meteorological station	boneya	1995-2019	Daily	Ethiopian metrological agency
Temperature, wind, relative humidity, solar radiation	Meteorological station	Tefki, boneya, sebeta	1995-2019	Daily	Ethiopian metrological agency
Topographic map (DEM)	Raster format	Whole catchment	-	raster 15 x 15m	USGS

Riverbed longitudinal profile	Topographical elevation meas.	Along the main streams	-	a point meas. every 300 m	Field meas.
River cross-sections	Topographical elevation meas.	3 locations for measuring river discharge	-	a point meas.	Field meas.
Hydraulic conductivity (K)	Obtained from pumping test analyses	Whole catchment	2019	wells	Well construction report.
Land use maps	Landsat and Sentinel imagery	Whole catchment	2016	-	MoWIE
Soil map	Vector format	Whole catchment		Polygon map	FAO

### 3.9 Materials used in the study

The following materials and software were used in the research.

- ✓ The 1: 50,000 scale topographic map of the study area
- ✓ Digital elevation model /DEM/ 15m resolution.
- ✓ Geological map of the area at available scale and hydrogeological map of Ethiopia.
- ✓ Various computer software /ArcSWAT-10.7, MODFLOW-2000, ArcGIS-10.7, Global mapper-12, Sufer-11, Strater, Excel Spreadsheet.../
- ✓ GPS,
- ✓ Previous research works, study reports, reference books, and journals

### **3.10 Model Development and Input Data**

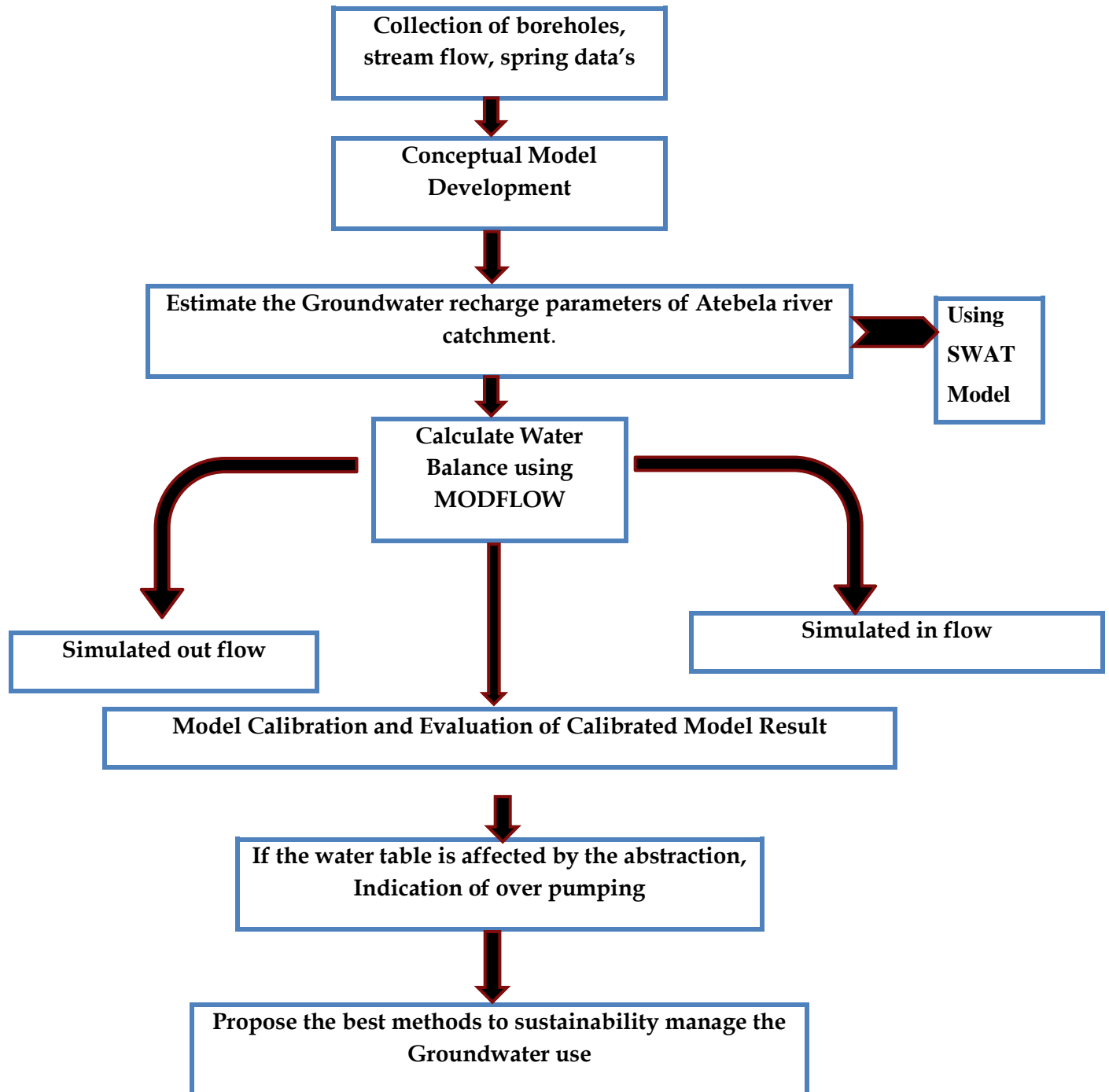
#### **3.10.1 General simulation work flow**

The simulation involves the analysis and synthesis of the available data with a help of various software such as ArcGIS, Global Mapper, Surfer, Excel, etc... and feed the inputs to **SWAT** model to estimate the basic hydrogeological parameters like recharge, evapotranspiration and river discharge which are basic inputs to **MODFLOW**.

For this study, the SWAT2012 model is used as a parameter estimation tool. SWAT is a large area watershed model in which computation is based on HRUs and sub basin scales. The HRU is the smallest structured element of the delineated watershed comprising a unique combination of soil, LULC, and landscape features in a sub basin. Fixing the optimal number of HRUs is an important step to optimize the model size without losing important information. The SWAT model has multiple HRU definition options, but dominant LULC, soil, and slope option and multiple HRU options are the most extensively employed methods the watersheds were delineated using a 15m resolution digital elevation model (DEM) and divided into 8 sub basins. Then, by combining slope classes, soil, and LULC data, 17 HRUs were created using zero threshold value (multiple HRU option). Wind speed, precipitation, humidity, maximum–minimum temperature data were imported and written. The SWAT model simulation was performed for 18 years (2001–2018). The first two of the simulations were a warmup period—the model does not give output for these years.

The outputs of the **SWAT** model are used as an input to the numerical mathematical code of **MODFLOW** software that consider the physical condition of the study area to be represented with governing equation. This part of the work embarks the modeling protocol like conceptual model development, selection of appropriate computer code, defining model geometry and boundary, assigning the hydrogeological parameters, running the model and model calibration.

### 3.11 Conceptual Framework of the Research Study



## **4. CONCEPTUAL MODEL DEVELOPMENT**

### **4.1 General overview**

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

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

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

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

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

The development of this conceptual model takes in to account the fact stated above and followed the major steps of defining hydrostratigraphic units, analyzing water budget components and defining flow system as of [\(Mary P. Anderson and William W. Woessner, 2002\)](#), procedure of building conceptual model.

The conceptual model of the catchment, the region under study, consider every previous verified investigation, hydro-meteorological data, borehole data and literature review with judgment of the modeler.

## 4.2 Hydro-stratigraphic units

The general hydrogeological set up of the sub-basin is governed by the lithological stratigraphy of the area and tectonic. The recharge condition, groundwater flow and aquifer parameters in the Atebala catchment is highly governed by the general bedding of the sedimentary formation underlying the volcanic unit, the tectonic condition and the hydraulic properties of the different volcanic units that outcrops in the catchment.

The total average estimated recharge of the upper and lower basalt aquifer of Ada'a-Becho plains groundwater system is about 965Mm<sup>3</sup>/year or 2,643,835m<sup>3</sup>/day [\(WWDSE, 2008\)](#). The estimation is made by different methods, water balance method, chloride method and Darcy Approach method. The average water level gradient is very gently in Becho plain groundwater basin not greater than 0.002 while in Ada'a plain groundwater basin is 0.004. In Becho plain it was penetrated two aquifers by drilling of about 300 meters i.e., upper and lower basaltic aquifer, while the lower aquifer is confined and the upper is confined and unconfined. In Ada'a plain only one aquifer is identified by about 300 meters of drilling, the aquifer is unconfined and regional. From the available well data and water quality monitoring the Ada'a plain aquifer is regional (both the upper and lower aquifer forms one aquifer system) after Dukem and Melka Kunture to the south [\(WWDSE, 2018\)](#).

In Atebala catchment, there are two hydro-stratigraphic units, which are classified as upper basalt and lower basalt units.

### 4.2.1 Lower basalt

This volcanic rock unit is comprised of lower Tertiary Tarmaber basalts, dominantly scoriaceous. According to [\(Andarge, 2009\)](#) the exploratory wells drilled in Becho, Holeta, Melka Kunture, and Legadadi areas penetrated this lower basaltic aquifer under thick impermeable ignimbrites (up to 225m). The water level significantly rises from its first striking depth (220m rise at Asgori well). The Static water level of most deep wells in the Atebala river catchment, differs from artesian condition to a depth of 67.5 meters' lower level than the ground surface.

### 4.2.2 Upper basalt

This rock unit is comprised of Quaternary flows of Wolliso-Ambo basalts, Akaki basalts, scoria and spatter cones, and Tertiary-Neogene basalts of Addis Ababa region as a sub-basin level. In Atebala catchment, the upper basalt aquifer has of great distribution in the region and in the north eastern part and found overlain by ignimbrites and tuffs in west and southern region of the catchment. It forms confined and unconfined aquifer system, locally destroyed by trachytic and rhyolitic volcanic centers and ridges. The static water level in this aquifer is highly variable and at places artesian conditions to a maximum of 150 meters below ground surface.

### 4.2.3 Quaternary alluvial

These are recent deposits found at the bank of Awash river and in some parts of the southern part of Atebala catchment.

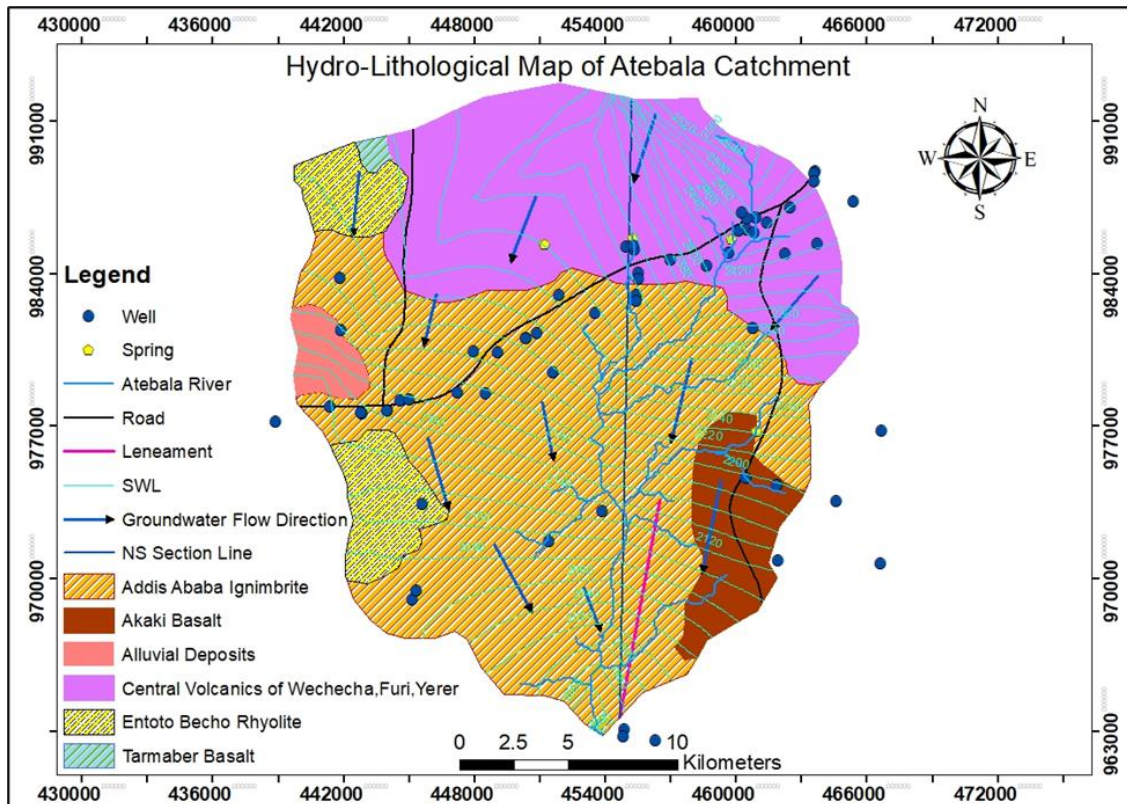


Figure 4.1: Hydro-lithological Map of the Study Area

## 4.3 Conceptualized flow system

### 4.3.1 Aquifer type

The drilling at Becho plain showed that the lower aquifer is confined. For example, at Asgori water strike at 255 meters and the water level raised to 4.2m, at Melka Kunture water strike at 192 meters artesian and at Tjei water strike at 300 meter and water level raised to 9.40 meters. These results showed the confinement of this aquifer varies from 190 meters to 290 meters. The large part of the plain groundwater depth (Piezometric level) varies from artesian to 10 meters deep, especially in the northern, central and southeastern part of the plain. In general, the Piezometric level of the lower aquifer is shallow less than 30

meters. Specifically, in areas delineated for irrigation, piezometric water level of lower aquifer is less than 10 meters.

Water level of boreholes that penetrated the lower aquifer of Becho plain is less than 10 meter and in most case it is artesian. However, water level of boreholes that penetrated upper basalt is relatively deep. This shows that the upper basalt aquifer is unconfined.

Therefore, the model considers unconfined and confined aquifer systems in the catchment since the upper basalt aquifer is unconfined and the lower basalt aquifer is confined.

### **4.3.2 Conceptual groundwater flow system of the catchment**

The conceptual model of the catchment is developed based on the major aquifer system of the area. The Atebala catchment comprises of two major aquifer systems and aquiclude separating the upper and lower aquifers.

Therefore, the two major aquifer units, i.e., the Upper Basalt and Lower Basalt aquifers are considered for modeling in this thesis.

#### ***4.3.2.1 Upper basalt aquifer***

The upper basalt aquifer is composed of weathered, fractured and massive basalt, thickness less than 50 meters, recharged locally and in the larger part of the plain it is confined. The yield of boreholes in this aquifer highly depends on the intensity of fracturing and faulting. Along faults the yield is highly significant while the massive basalt has low yield. The transmissivity is highly variable and, in most cases, it is less than 50m<sup>2</sup>/day the Electrical conductivity of the aquifer varies from less than 250  $\mu$ S/cm to 900  $\mu$ S/cm. The groundwater level depth increases from north-south direction. At the northern part the groundwater of the aquifer is shallow (less than 5 meters) and at the central part it varies from 5 to 20 meters deep and to the south depth increases progressively to more than 50 meters deep). The groundwater potential of this aquifer is not significant as compared to the lower basalt aquifer; however, this aquifer can be exploited for the water supply of the rural towns and rural settlements by moderate wells depth of up to 150 meters (WWDSE, 2018).

#### ***4.3.2.2 Lower basalt aquifer***

The drilling at Becho plain in the lower basalt aquifer showed that the aquifer is composed of scoraceous basalt and scoria. The water level at the southern part is above the surface of the earth and in the central part less than 5 meters. The transmissivity of the aquifer from three mapping wells (AM4- Melak Kunture), (AM-3-Asgori) and also production wells at the central and the southern part of the plain respectively showed the transmissivity is very high and greater than 1000 m<sup>2</sup>/day.

It is estimated that more than 1/3 of Abay plateau recharge is flowing to the rift Valley along Becho plain lower basalt aquifer which amount about 321 Mm<sup>3</sup>/year and the thickness of the lower basaltic scoraceous and fractured aquifer is more than 100 meters. For estimation of the exploitable groundwater resources of Becho plain the thickness of the aquifer is considered to be 100 meters and the storage coefficient of the aquifer to be about 0.15. The deepest water well which constructed in the Atebala catchment has the length of 482m depth (BPW-01910). [\\_\(WWDSE, 2018\)](#).

### 4.3.2.3 Localized and regional aquiclude

Tertiary Entoto-Becho rhyolites, Central Volcanics of Wechecha, Furi and Yerer possesses low permeability, not including along weathered and fractured regions and act as local aquiclude by dividing into categories the upper basaltic aquifer. Welded ignimbrite and Addis Ababa ignimbrites of low productivity along the weathered and fractured regions and/or impermeable in different circumstances, act as aquicludes by separating the upper and lower basaltic aquifers (WWDSE, 2018).

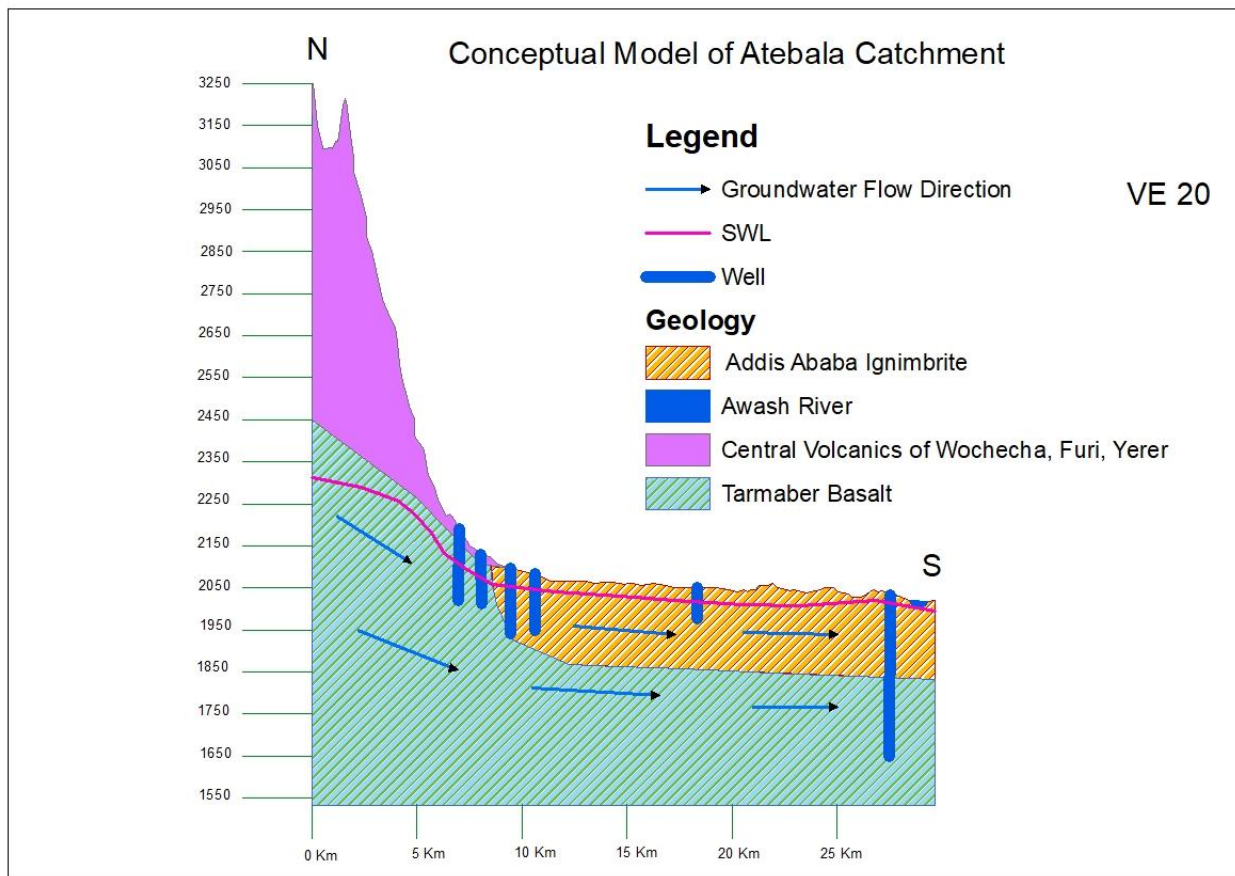


Figure 4.2: Conceptual Model of Atebala Catchment

### **4.3.3 Model thickness**

Over 38 deep wells and shallow wells data, DEM and geological and hydrogeological maps modified for this project were used to prepare the conceptual model of the study area using AutoCAD, Global Mapper, Excel and ArcGIS software in order to visualize the hydro-stratigraphy and thickness of each aquifer in the catchment.

Great effort and time have been put to visualize the catchment properly and prepare a more realistic conceptual model. During this effort it was possible to identify the depth of the two major aquifer systems. In order to delineate the contact of the upper and lower basalt formations the lithologic log of the wells was analyzed carefully in view of the regional characteristics of the two basalt units.

The output was cross-referenced with literatures and previous studies conducted by various scholars and companies. The maximum depth obtained during the analysis of well logs is 482 meters. Based on the analysis of lithologic logs of wells the average thickness of the upper basalt aquifer is 200 meters and the average thickness of the lower basalt unit is 300 meters. Of course, the depth of the lower aquifer extends beyond this depth but based on the analysis the weathering and fracturing decreases below 300 meters. Therefore, a thickness of 200 meters for the upper layer and 300 meters for the lower layer which are designated as layer 1 and layer 2 in mudflow is considered in this model. The total thickness of the model is 500 meters and a greater depth is used in the highland areas in the north of the catchment in order to characterize the hydrogeological setting of the study area.

**Table: 4.1. Lithologic and hydrologic characteristics units of Ada'a – Becho plains ground water system (WWDSE, 2018).**

Hydro-geologic Unit	Unit Label	Range of thickness (estimated average thickness in meters)	Lithologic and hydrologic characteristics
Localized aquiclude (barriers)	LA	Most probably volcanic centers	Quaternary Bede Gebaba volcanic unit: Rhyolitic to minor trachytic lavas and pumice and Ziquala trachytes and Tertriary Entoto-Becho Rhyolites and Central Volcanic of Wechecha, Furi, Yerer: prophyritic trachytic lavas. They have very low permeability, except along weathered and fractured zones. They act as local barriers.
Alluvial Aquifers	(Qal + Qld)	5 to 80 [40]	Unconfined aquifer consisting of coarse sediments. The static water level varies from 7 to 39 meters deep. The static water level is shallower at the Debre Zeit lake areas and becomes deeper to Mojo area. The specific capacity of bore holes varies from 950 to 90000m <sup>3</sup> /day/m. The water quality is generally fresh and the electrical conductivity varies from 444 - 841 μS/cm and total dissolved solids from 220 to 750 mg/l. The unit occurs geological units of alluvial and lacustrine sediments (Qal +Qld) of Debre Zeit area. Highly permeable and forms one aquifer system with the upper basalt aquifer in the area.

Upper Aquifers	Basalt	UBA	50 to 300 [100]	In most part of Ada'a-Becho groundwater system it is unconfined except at some part of Becho plain, where it is slightly confined. The geological formation is highly variable from place to place i.e. massive basalts, scoraceous basalt and scoria. The basalts when it is faulted and fractured the yield of bore holes increases. The static water level varies from place to place from 5 to 20 meters. The transmissivity of this aquifer is less than 50m <sup>2</sup> /day. At Ada'a plain both the upper and lower basalts aquifer forms single aquifer? Transmissivity reaches more than 10,000 m <sup>2</sup> /day
Upper Confining unit		UC	60 to 150 [120]	Chefe Donsa Pyroclastics, Nazaret unit (Welded ignimbrites) and Addis Ababa ignimbrites of low productive along the weathered and fractured zone. Acts as a regional aquiclude which separates the upper and lower volcanic aquifer in Becho plain
Lower aquifer	basalt	LBA	greater than 300 m	Lower Basalt aquifer (LBA) is composed of tertiary Tarmaber basalt composed of dominantly scoraceous basalt and Amba Aiba basalt. Static water level varies from artesian condition to a depth of 67.5 meters. Regional aquifer transmissivity 100 -1700 m <sup>2</sup> /day. Highly permeable.
Lower Confining unit		LCU	170 to 460 [250]	Ashange basalt and Blue Nile basalt of old basalt and columnar massive basalt practically impervious except at local area due to secondary fracturing. Due to the massive and hard condition it was difficult to drill in Blue Nile basalt. These formation acts as an aquiclude between the Mesozoic sedimentary formation and lower basalt aquifer

#### **4.4 Hydraulic conductivity**

Hydraulic conductivity is the most essential aquifer parameter that determines the flow system of a model. It is a measure of the ability of fluid to move through aquifer media. It is dependent on the properties of both porous media and the fluid. It is obtained through pumping test data analysis, laboratory analysis and literature review. In this model, it is obtained from the pumping test data analysis of 27 wells that are drilled in and around the study area.

The spatial distribution of the hydraulic conductivity of the catchment is the most crucial input of the model. The initial hydraulic conductivity parameter is assigned from pumping test data analysis of wells in view of the hydrogeological properties of the major aquifer systems in the study area. The initial hydraulic conductivity map used as an input is gradually refined and updated through the calibration process.

The hydraulic conductivity of an aquifer has a directional value and in this model as the model area is conceptualized as isotropic and two layer unconfined and confined aquifer, the vertical flow is calculated in relation to the horizontal hydraulic conductivity value which has the same value in the x and y direction.

#### 4.4.1 Hydraulic conductivity of the upper basalt aquifer

The existing wells that penetrate only the upper basalt aquifer are used for analysis of the hydraulic conductivity of the first layer. As it is clearly seen in the table below the yield of the wells depend not only on the hydraulic conductivity of the formation but it is also dependant on the aquifer thickness. Hence the discharge depends largely on the transmissivity of the formation.

*Table: 4.2. Hydraulic conductivity of the wells that only penetrate the upper aquifer*

Longitude	Latitude	Elevation	Well ID	Well depth(m)	Discharge( $m^3/d$ )	Hydraulic Conductivity (m/d)	Transmissivity ( $m^2/d$ )
461930	970844	2204	AdBh0198	183	198.72	4.27	170.80
463635	988675	2296	AdBh0247	83	328.32	6.10	61.00
455450	983014	2110	AdBh0249	120	570.24	1.75	34.92
455426	982736	2105	AdBh0250	150	462.24	1.40	35.12
444624	978143	2074	AdBh0255	65.4	64.80	1.88	18.78
442842	977555	2067	AdBh0300	100	293.76	1.84	23.96
463599	988583	2283	AdBh0328	130	345.60	4.25	101.90
463600	988200	2280	AdBh0527A	64	259.20	2.55	50.99
455000	985200	2238	AdBh0723	126	302.40	0.67	10.72
455300	985250	2198	AdBh0889	101	384.48	1.52	25.92
455550	983750	2138	AdBh0891	181	345.60	0.55	16.64
444000	977700	2068	AdBh0892	100	34.56	0.03	0.43
460850	985850	2251	AdBh0895	106	561.60	10.03	240.69
460500	986500	2296	AdBh0896	100	786.24	3.11	55.89
460121	985966	2254	AdBh0981	120	576.29	8.69	173.76

457030	984617	2218	AdBh1037	140	432.00	1.12	28.02
462260	984901	2284	AdBh1103	180	576.29	1.16	58.00
460295	986769	2314	AdBh1152	158	1468.80	1.06	53.00
<b>Average</b>					<b>443.95</b>	<b>2.89</b>	<b>64.47</b>

#### 4.4.2 Hydraulic conductivity of the lower basalt aquifer

In order to define the hydraulic conductivity of this layer wells that penetrate the lower basalt aquifer are used. The depth of most of the wells was increased since the water obtained from the upper basalt aquifer was not enough for the desired purpose. Ofcourse some deep wells were drilled as test well to study the hydraulic properties of the lower aquifer unit. But during drilling of these test wells the yield of the upper aquifer was found to be low [\(WWDSE, 2018\)](#). Tehrefore the pumping test analysis result of these deep wells can represent the hydraulic conductivity of this layer. Bisides this research is used a simple method to nearly identifie and compare the avarage hydroulic conductivity values of the lower basaltic aquifer by subtracting the avarage haydroulic conductivity value of the upper aquifer from the avarage hydroulic conductivity value of the lower one.

Based on the analysis of these wells the hydraulic conductivity is found to be the governing factor for the discharge of the wells. The average hydraulic conductivity of this layer is found to be much greater than that of the upper layer. In some wells both the hydraulic conductivity and transmissivity values are much more greater. This is due to the fact that these wells are situated in the more fractured horizon of the formation. This is clearly seen from the yield of these wells which is greater than the other wells.

**Table: 4.3. Hydraulic conductivity of the wells that penetrate the lower aquifer**

Longitude	Latitude	Elevation	Well ID	Well depth(m)	Discharge( m <sup>3</sup> /d)	Hydraulic Conductivity (m/d)	Transmissivity (m <sup>2</sup> /d)
448502	978502	2067	BHT-19	440	2505.60	0.62	62.00
438871	977181	2253	STTW1	443	3542.40	0.37	37.20
447224	978514	2241	STTW2	440	1728.00	0.87	86.90
449082	980399	2267	STTW3	440	1123.20	0.36	36.20
450359	981037	2059	AMW14	280	1641.60	0.51	40.50
450887	981258	2079	BPW-018-10	436	5011.20	5.05	505.00
451632	979475	2070	BPW-01910	482	2160.00	1.82	182.00
454868	963109	2006	BPW-012-10	352	5443.20	20.80	2080.00
456314	962592	2014	AMW4	290	3074.86	31.30	1690.00
<b>Average</b>					<b>2914.45</b>	<b>6.86</b>	<b>524.42</b>

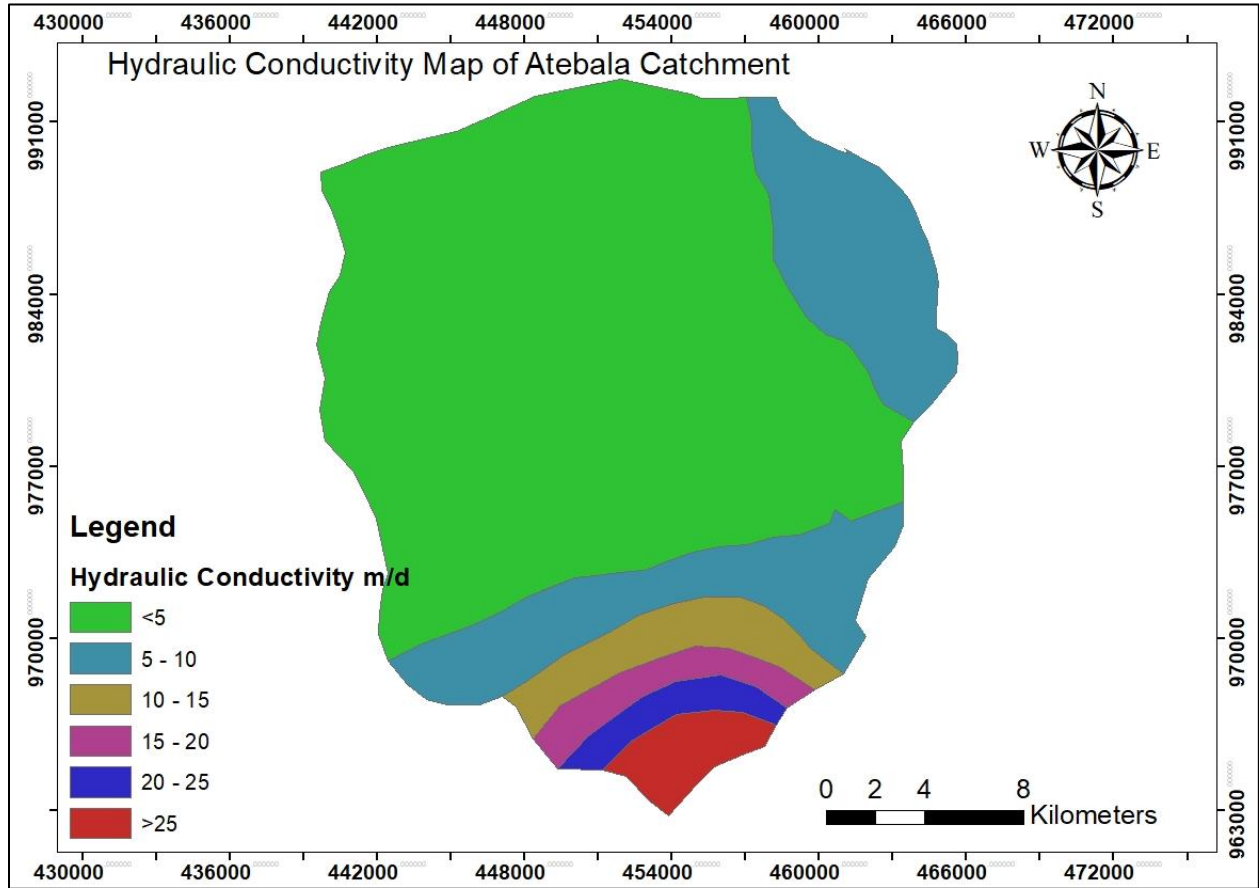


Figure 4.3: Hydraulic Conductivity Map of the Study Area

#### **4.5 Aquifer system boundary**

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

The boundary of aquifer system determines the relation of the model system with its adjacent environment. The catchment model of the aquifer system is bounded at the top by the water table, laterally by the central volcanic ridge to the North, East and West considered as no flow which is defined as no recharge and not conductive. It is bounded by Awash River to the South which is considered as General Head Boundary since it interacts with the aquifer system. The base of the model is assumed as no flow by the dying of the fractures as depth increased; massive bed rock emerges at an average depth of 500 meter.

The model system is conceptualized that the groundwater outflow is to Awash River. Most studies confirm the convergence of the groundwater flow to the river. In fact, no earth material is completely impervious to water. Many earth materials, however, have very low hydraulic conductivities and thus contribute relatively small amount of water to adjacent permeable groundwater systems.

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

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

The model under the study considers the central volcanic ridge surface water divide as the no flow boundary and at the same time due to the decreasing of the conductivity down the depth of the aquifer makes the bottom of the model a no flow boundary.

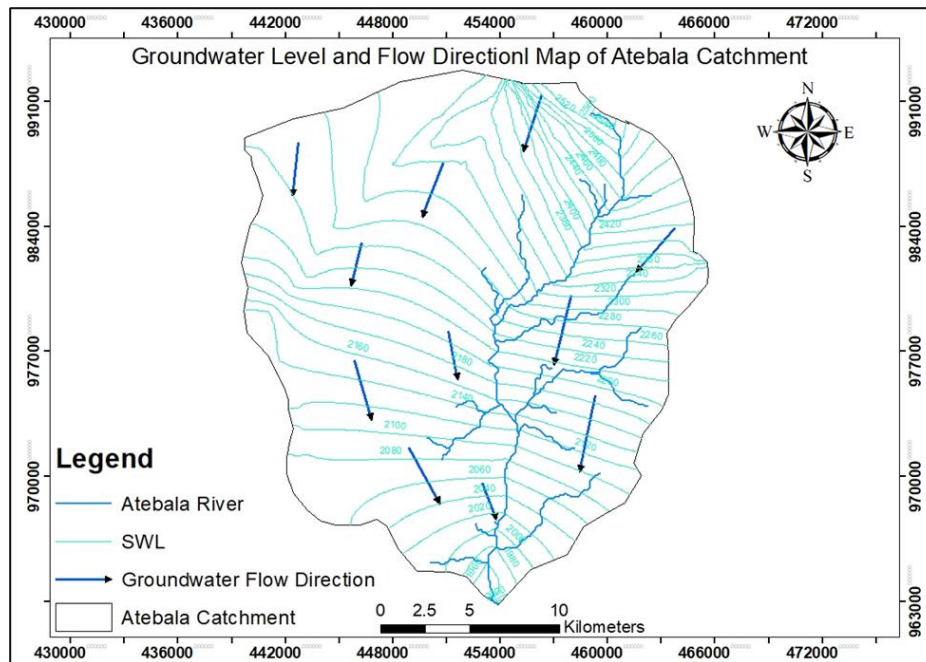
#### **4.6 Groundwater level and movement**

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

The balance between groundwater recharge and discharge controls groundwater level and storage in a manner analogous to how deposits and withdrawals control savings in a bank account.

Groundwater level contour stand for the same water level head of the aquifer system. It helps to understand the general trend of the groundwater flow as the groundwater flow from high head to lower head with perpendicular direction to the contour line. In this study, the water level contour is developed by using static water levels of 38 deep wells taken during construction time and water level of perennial rivers taken at different points where there is no well data. There is no groundwater level monitoring system and easy access to measure the water level for most wells since they are not provided with observation pipes.

The depth of the water level ranges from 2040m to 2320m a.m.s.l and a tendency to converge toward the Awash River to the south direction.



**Figure 4.4: Groundwater level and Flow Direction Map of the study area**

## 4.7 Parameter estimation using SWAT model

### 4.7.1 General

The Soil and Water Assessment Tool (SWAT) is a physically-based continuous-event hydrologic model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. For simulation, a watershed is subdivided into a number of homogenous sub-basins (hydrologic response units or HRUs) having unique soil and land use properties. The input information for each sub-basin is grouped into categories of weather; unique areas of land cover, soil, and management

within the sub-basin; ponds/reservoirs; groundwater; and the main channel or reach, draining the sub-basin. The loading and movement of runoff, sediment, nutrient and pesticide loadings to the main channel in each sub-basin is simulated considering the effect of several physical processes that influence the hydrology.

For this project **ArcSWAT** is used to conduct the SWAT model and retrieve outputs for the mudflow model. **ArcSWAT** extension of ArcGIS 10 creates an ArcMap project file that contains links to your retrieved data and incorporates all customized GIS functions into your ArcMap project file. The project file contains a customized ArcMap Graphical User Interface (GUI) including menus, buttons, and tools (Srinivason, *SWAT Introductory Manual*, 2012).

The automatic watershed delineation tool is used to demarcate the watershed and divide the study area into various sub-watersheds or HRUs. The major parameters like land use, soil, slope, rainfall, and temperature data were prepared and feed to the data base. Then the **SWAT** model was run and calibrated by using available measured river flow data. Finally, the recharge, evapotranspiration and river flow data are extracted as an output. The outputs of the **SWAT** model are utilized as an input for the **MODFLOW** model.

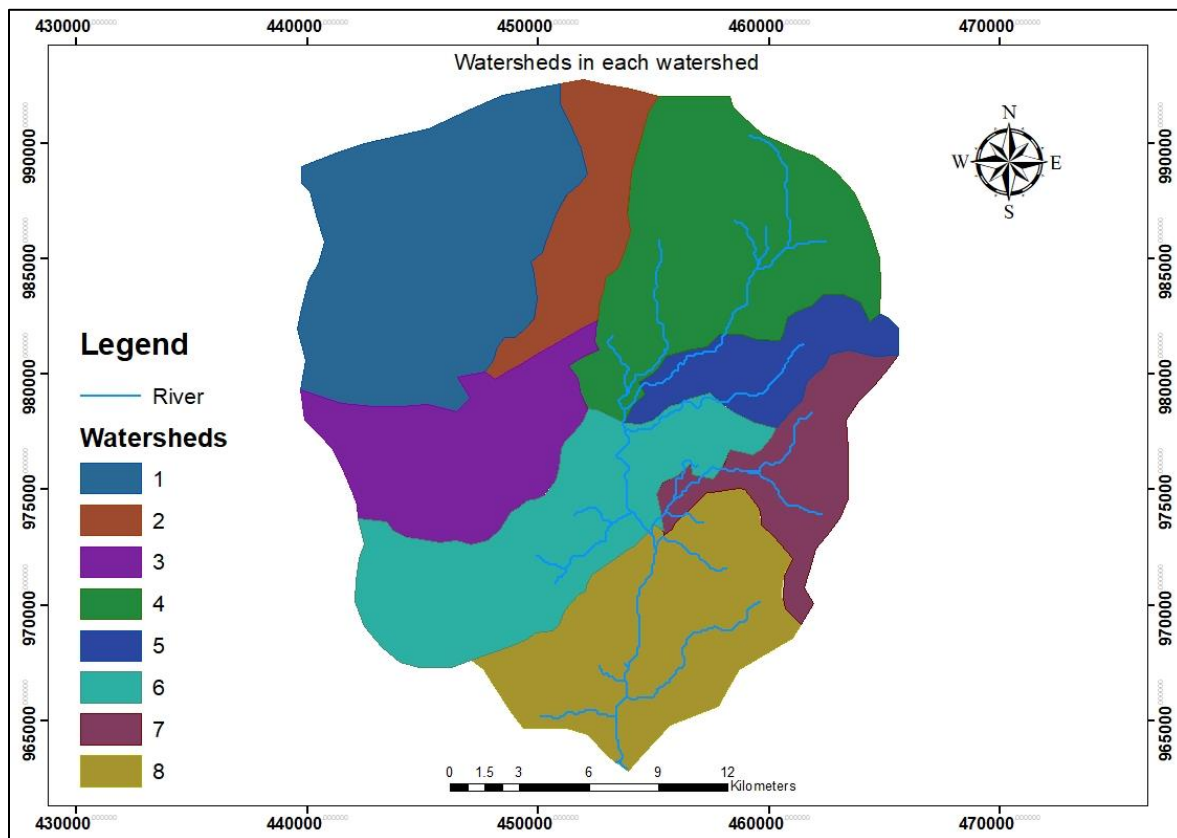


Figure 4.5: Watersheds of the study area

#### **4.7.2 Recharge**

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

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

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

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

In this research the recharge is estimated by **ArcSWAT** model and the result is expressed as cubic meter per second. The output from **ArcSWAT** model is used as an input to **Modflow** recharge package.

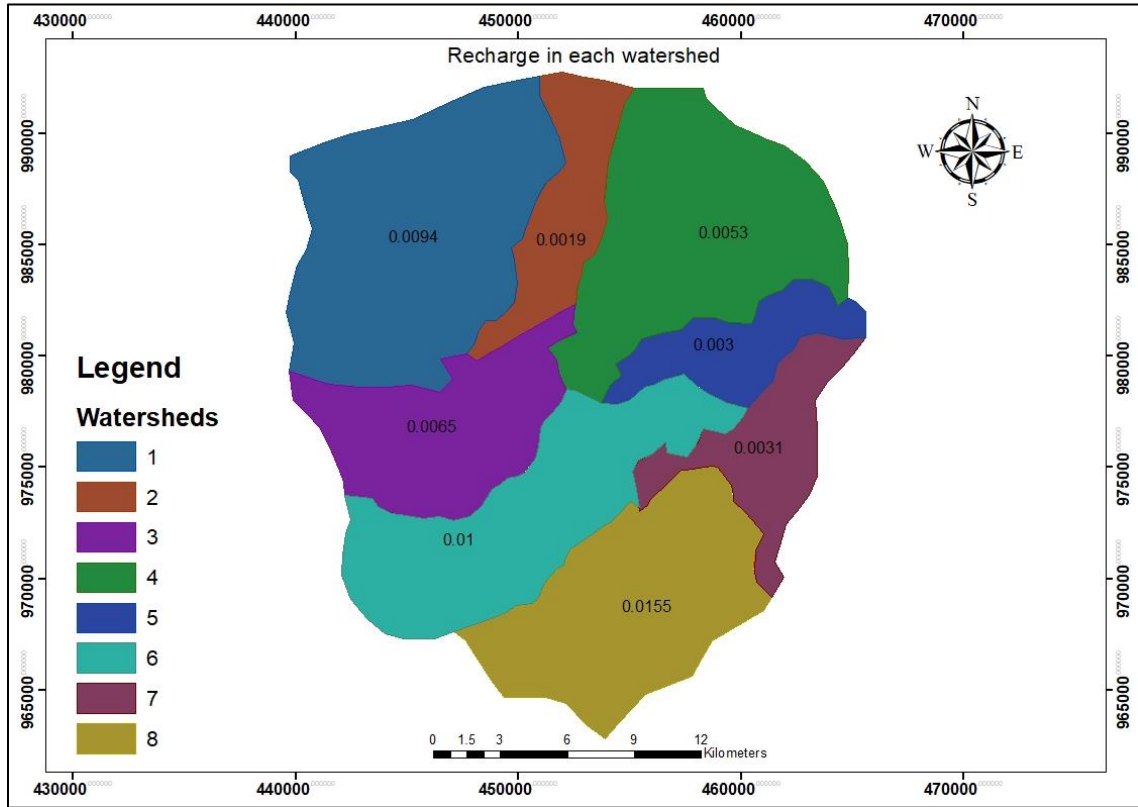


Figure 4.6: Recharge Estimated for each watershed of the study area using SWAT Model

### 4.7.3 Evapotranspiration

The actual evapotranspiration is estimated for each watershed of the study area using ArcSWAT simulation and the output is used as an input in MODFLOW model evapotranspiration package. The AET result is expressed as cubic meter per second.

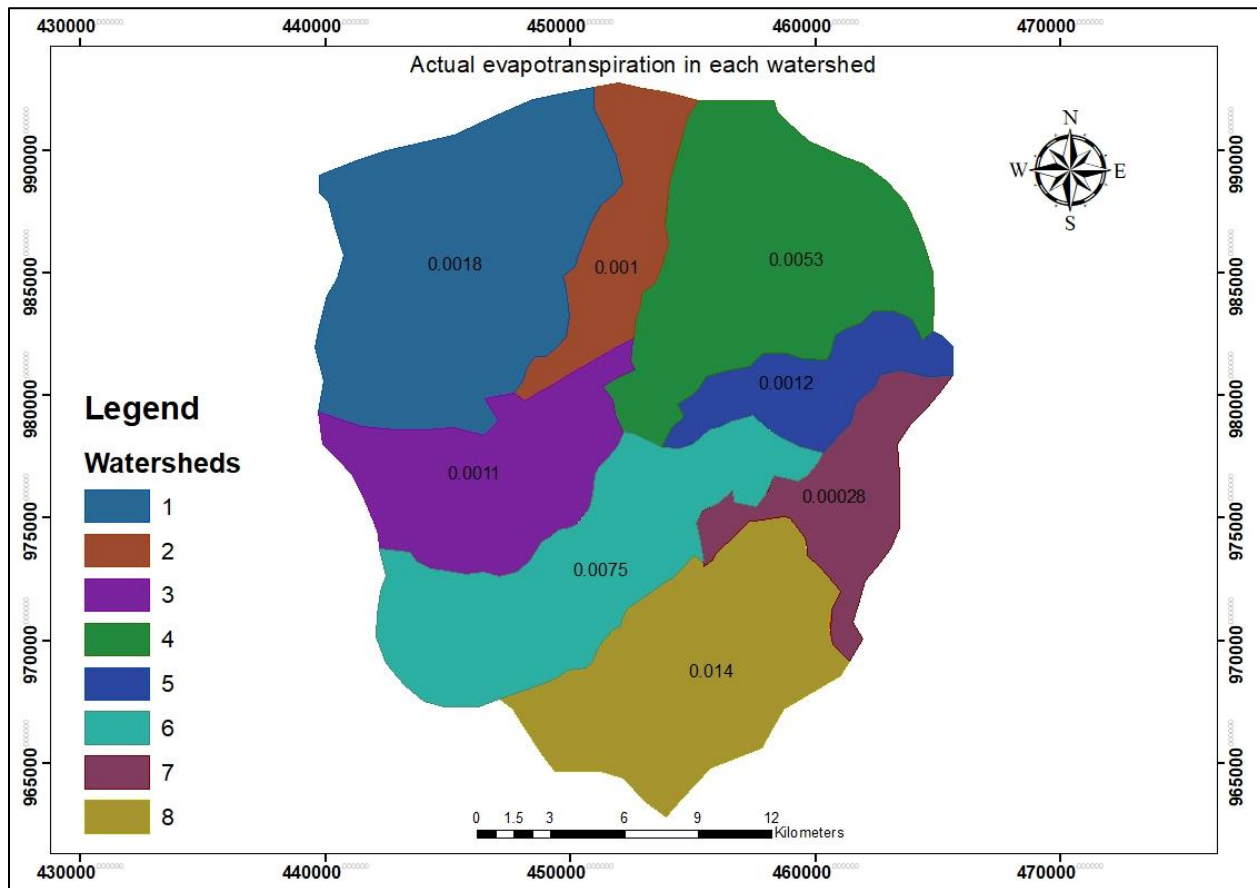
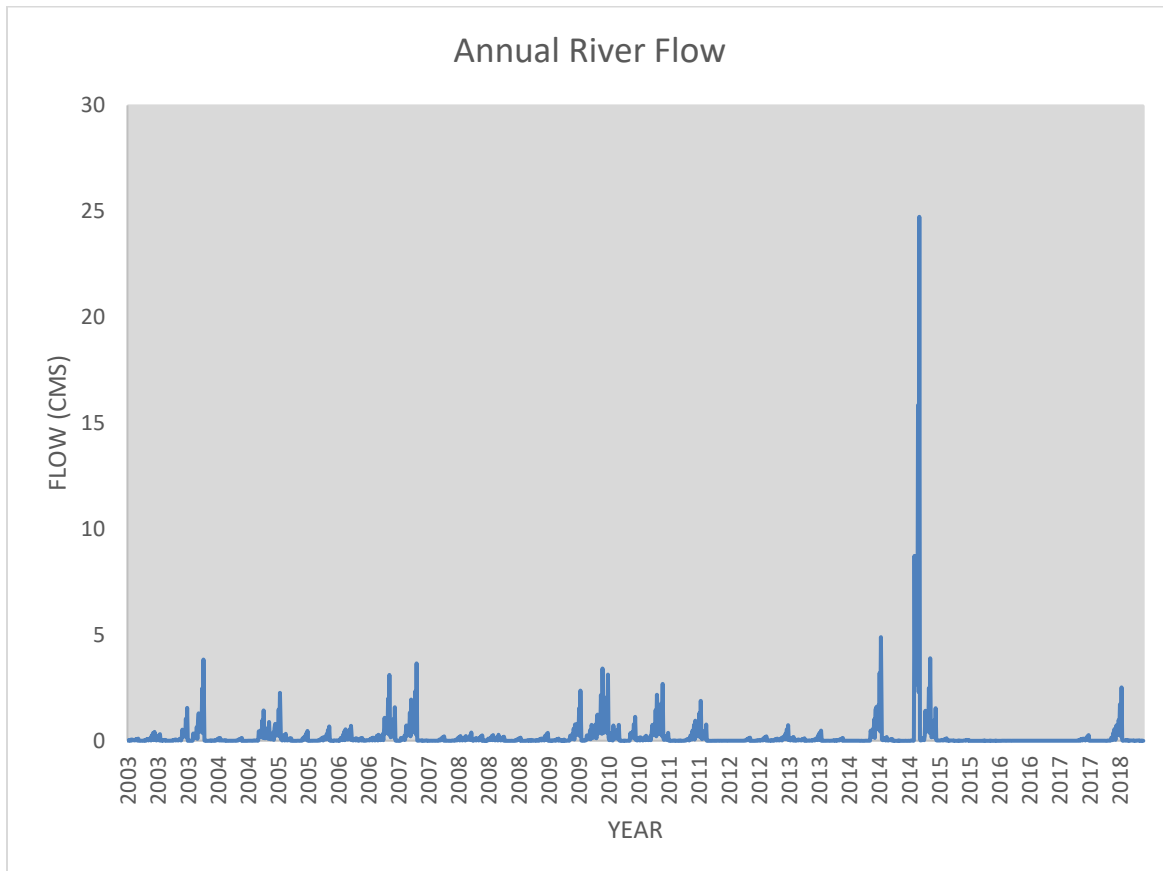


Figure 4.7: Estimated Evapotranspiration for each watershed of the study area using SWAT Model

#### 4.7.4 River parameter estimation

In evapotranspiration of the catchment, the water is supposed to leave the aquifer system from shallow water level at which the solar energy is able to reach or accessed with deep rooted plants.

The annual river flow for a long period of time is calculated by the ArcSWAT model. The simulated river flow of Atebala catchment is shown in the figure below.



**Figure 4.8: Simulated River flow in the study area using SWAT**

## **4.8 Groundwater discharge**

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

The abstraction of wells, recharge from springs, base flow to surface water body and evapotranspiration are considered in the model.

### **4.8.1 Spring discharge**

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

In the region under study, there are a number of small springs with discharge less than 5l/s which is almost insignificant discharge and a very few prominent springs with large discharge.

### **4.8.2 Well withdrawal**

Groundwater use in the catchment is for domestic water supply consumption for the town and villages and it is also used for industrial purposes.

The common practice to abstract the groundwater is with hand dug well by hand pump, shallow well and deep boreholes with motorized pump. The model considers the hand dug wells, shallow wells and motorized deep borehole. The current actual yield of the wells is used in this model.

### **4.8.3 Base flow**

The base flow represents the interaction of the aquifer system with the streams with a concept of groundwater will maintain the flow of streams during dry season.

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

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

## 5. NUMERICAL MODELING

### 5.1 General overview

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

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

Groundwater flow of the Atebala River catchment aquifer system is simulated using the USGS three-dimensional finite difference groundwater flow model **MODFLOW** [\\_\(Michael G. McDonald and Arlen W. Harbaugh , 1988\).](#) It uses version of MODFLOW2000 which is a modified version of MODFLOW interfaced with groundwater vista-3 that facilitates input and output parameters to define model input, the calculation of parameter sensitivities and the modification of parameter values to match observed heads, flows transport using the observation, sensitivity and parameter estimation processes described by [\\_\(Mc. Hill, et.al, 2000\).](#)

The MODFLOW employs a numerical modeling with widely used, tested and verified model which simulate each hydrologic feature independently with its modules grouped package. It is deterministic model approach which assume the stage or response of aquifer is predetermined by the help of physical laws

governing the groundwater flow. Unlike the analytical model which solves one equation of groundwater flow at a time, provide solution for the entire flow of the study area at the same time.

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

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

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

## 5.2 Governing equation

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

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

Where:

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

h: is hydraulic head, in meters;

W: is a volumetric flux per unit volume and represents sources or sinks or both of water, such as well discharge, recharge and water removal from the aquifer by drains, per day; ( $LT^{01}$ )

Ss: is the specific storage of the porous materials, per meter; ( $L^{01}$ )

t: is time, in days (T)

To model the study area, Upper Awash River Basin Atebala River Catchment aquifer system the above governing equation has been adjusted according to the prevailing field condition. Since the conceptualized model is steady state unconfined/confined aquifer and a two layer with possible flow in the Z direction, the equation can be simplified and rewritten in to the following equation. This equation assumes flow system view point that allows both vertical and horizontal component of flow throughout the system and there by allows treatment of flow in two dimensional profiles (Anderson, M.P. and Woessner, W.W. , 1992).

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) = +(-)R \quad \text{Equation 5.2}$$

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

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

### **5.3 Spatial discretization**

In the numerical modeling, the continuous problem domain is replaced by discretized model consist of an array of nodes and associated finite difference cell (Block) [\(Anderson, M.P. and Woessner, W.W. , 1992\)](#). The nodal grid forms the frame work of the numerical model. There are two types of finite difference grids, block-centered grid and the mesh centered grid. The difference between them lies mainly in the way in which the flux boundaries are handled. In the block centered approach flux boundaries always are located at the edge of the block. In mesh centered grid, the boundary coincides with the nod. In most computer codes, including MODFLOW the finite difference mathematics for boundaries are more easily treated with the block centered approach.

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

The surface area of the region under investigation and the size of cell determines the number of cells required. The region under investigation covers a total area 766.06sq.km and the model are discretized with a uniform cell size of 250m by 250m. The model size is large but meets the objective to understand the regional groundwater flow system. It is also considered a uniform cell size to ease the computation, the accuracy of the model and better convergence of the model simulation. The model extent is defined with 25.75km width and 29.75km height.

The origin of the Model spread from the lower left corner of the grid with geographic coordinate of UTM 37N 439654.5973E and 962866.6843N. The model makes up an array of a cell with 120 rows and 104 columns. The model used a total number of 12,257 cells in two layers of which only 9,013 cells are active and effective to compute the hydraulic head. The remaining 3,244 cells are inactive and no computation will be carried out in this part of the model.

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

#### **5.4 Top of the layer**

Top layer is the top elevation of the aquifer under consideration. The top layer of the unconfined aquifer is adopted from the land surface (topography). In this model, the aquifer was assumed to be two layer unconfined/confined aquifer system. Generally, the top layer elevation was considered to be the surface elevation of the area. The nodal values of ground surface elevation were interpolated from DEM data. The interpolation was done at the resolution of 12.5m X 12.5m and then loaded in to the MODFLOW top elevation array.

The model upper boundary is open to the flux of the recharge and evapotranspiration and assumed to be the water level of the unconfined upper aquifer system.

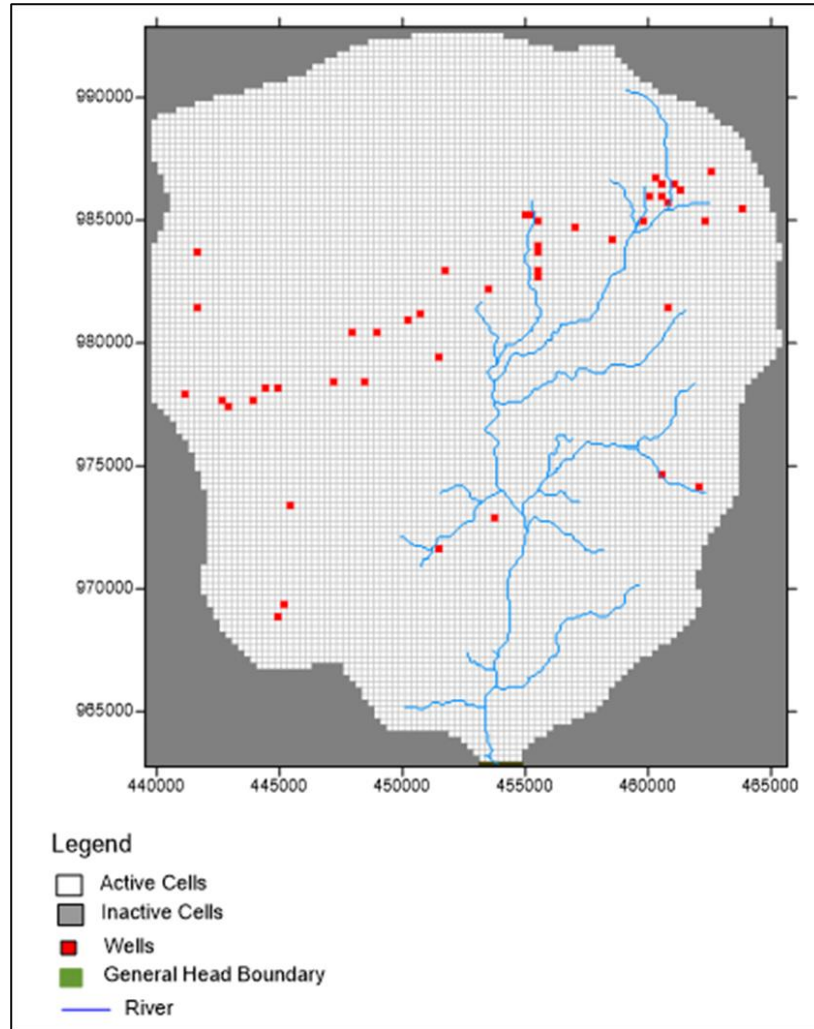
### **5.5 Bottom of the layer**

The bottom of the layer in association to the top layer determines the thickness of the aquifer. In this model, the bottom of the first layer is determined with a consideration of 200m depth from the ground elevation and it is considered as the top of the second layer and the bottom of the second layer is obtained by deducting a depth of 300 meters from the bottom of the first layer. The bottom of the layer is developed with a help of SURFER-10 by deducting a total of 500m up to 700m in elevated areas from the top layer grid data. In fact, there is a deficient in information to delineate the basin aquifer thickness; however, it assumed the aquifer forming fracture decrease with depth and die after an average depth of 500m as confirmed from borehole data analysis in this paper. This also has been imported to the modeling the same manner as the top layer with grid format and the data was distributed in zoning spatially with geographical reference.

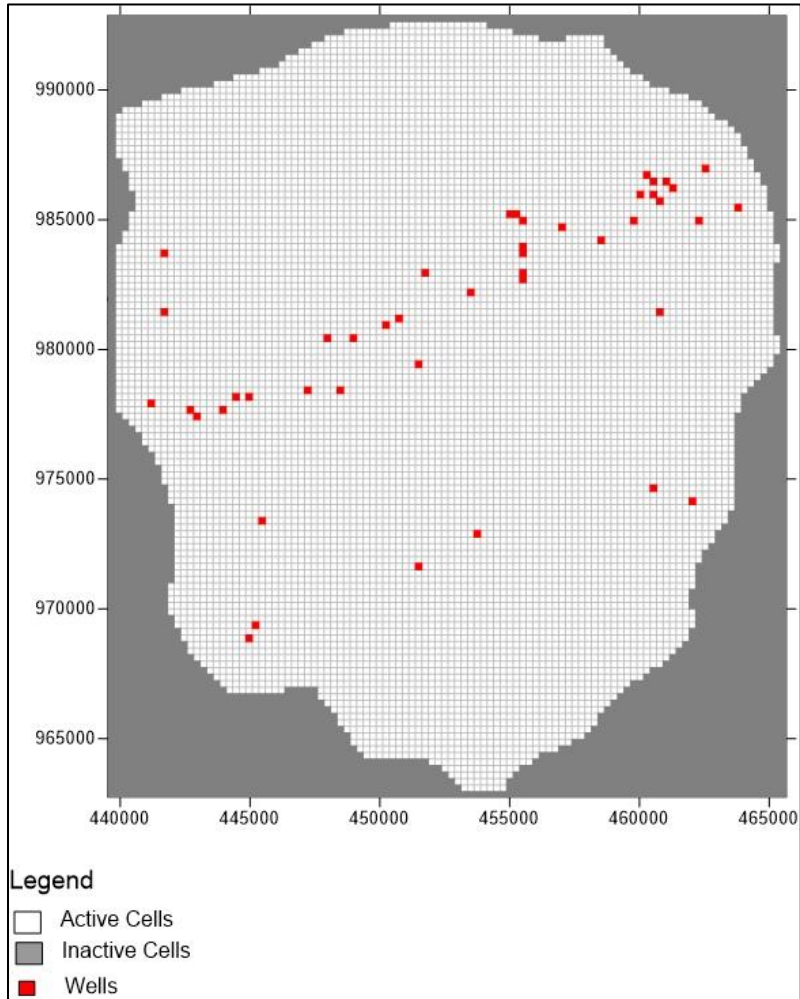
The lower boundary with impermeable bed of massive volcanic rock with a dying effect of the opening as depth of the formation increased and simulated with no flow boundary.

### **5.6 Boundary condition**

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



*Figure 5.1: Boundary condition in layer one*



*Figure 5.2: Boundary condition in layer two*

### 5.6.1 Geographical boundary

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

Geographically, the Atebala River Catchment is surrounded with a relatively low hydraulic conductivity volcanic ridge. And also, topographically dip and converge toward the Awash River in the south direction.

The same convergence is observed in the static water level map too. This is for the case of the lateral boundary of the aquifer system with adjacent catchments. It is simulated with no flow boundary for all side of the catchment. The hydraulic conductivity map prepared for this model also shows increased values towards the river to the south and this could increase the interaction of surface water with the groundwater system of the study area. The hydrograph separation also indicates the interaction of the Awash River with the aquifer system.

### 5.6.2 Hydrological process boundary

This boundary condition is a mathematical model that determines how and where the groundwater in and out of the aquifer system. The boundary specifies the dependent variable or the derivative of the dependent variable at boundary problem domain [\(Anderson, M.P. and Woessner, W.W. , 1992\)](#). This boundary condition falls into one of five categories: specified head or Dirichlet, specified flux or Neumann, mixed or Cauchy boundary condition, free surface boundary, and seepage face [\(Franke, et.al, 1987\)](#).

GV interface modeling supports the use of the first three types, specified head, specified flux, and mixed type boundary conditions. Specified head boundary cells are called constant head cells. Specified flux boundary cells are represented using no flow, wells, or recharge. The latter flux is actually defined as a parameter. Mixed type boundary conditions are called rivers, drains, general head boundaries, streams, or evapotranspiration. The latter is treated like recharge as property for its aerial distribution. The Atebala River Catchment modeling uses the specified flux for no flow boundary, wells or recharge and mixed type boundary for the river, general head boundary and evapotranspiration.

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

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

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

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

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

In this model, the southern part of the study area boundary coincides with Awash River. As a result, its boundary has been specified head and such nodes are assigned by -1 value to entries of I-BOUND array in MODFLOW. Thus, water surface elevation of 2004m, where the Atebala River joins the Awash River was given as initial heads to cells representing such constant head nodes.

#### ***5.6.2.1 Mixed-type boundary***

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

$$Q = C(H_b - H_m) \quad \text{Equation 5.3}$$

Where:  $Q$  = flux into or out of boundary cell ( $L^3/T$ ),

$H_b$  = boundary head (L),

$H_m$  = head computed by model (L), and

$C$  = boundary conductance ( $L^2/T$ ).

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

$$C = K_b \frac{A}{B} \quad \text{Equation 5.4}$$

Where:  $K_b$  = hydraulic conductivity of the boundary material (L/T),

$A$  = area of the boundary ( $L^2$ ), and

$B$  = thickness or width of boundary (L).

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

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

### 5.6.2.2 River boundary

The major perennial streams are the most essential river boundary in the sub-basin that holds the surface water and aquifer system interaction. It is believed that Atebala River and its major tributaries sustain their dry period of flow with the contribution of the groundwater as base flow. These streams are also expected to feed the groundwater during the wet period when the stage of the river exceeds the adjacent aquifer system head.

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

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

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

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

$H_{RIV}$ : Head in the river

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

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

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

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

Where; K: Hydraulic conductivity of the river bed

L: Length of the river reaches

W: Width of the river reaches

M: Thickness of the river bed

In order to fulfill mathematical model that govern the interaction of the surface water and aquifer, the physical characteristics range used for each major river is summarized below. The values for the width of the river are obtained from measured values by using Google earth image of the river and delineating the river banks. Head of the river is collected from DEM data and the river bed thickness is estimated by considering the sediment load history of the river. And lower values are given at the initial points of the river based on the geology of the area and the relatively steep slope. At the lower parts of the river where the river width is wider and the flow is less steady there is a chance of thicker river bed and it is confirmed during the field visit. The results of this analysis were used as an input in the first layer of the model since the rivers lay on layer one. The river data obtained from SWAT model output is also used to calibrate the input data.

**Table: 5.1. Major stream model input summary**

No	Major stream	Conductivity (M/D)	Bed Thickness (m)	Head of the river (m)	Width (m)
1	Atebala River	5 - 25	0.1 - 0.5	2004- 2670	10-15

### **5.6.2.3 Specific flux boundary**

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

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

The recharge rate and evapotranspiration rate are applied in layer one of the model but the well discharge is considered in both layers since most of the wells penetrate the two aquifers. And the share of the well abstraction for the two layers is calculated based on the ratio of the hydraulic conductivity and aquifer thickness of the two layers for wells that penetrate the two aquifer systems.

On the other hand, specific flux across which zero flow is considered as no flow boundary. Accordingly, as specified by the conceptual model the no flow boundary surround the model peripheries.

### **5.7 Initial condition**

Initial condition refers to the head distribution everywhere in the system at the beginning of the simulation ([Mary P. Anderson and William W. Woessner, 2002](#)). Initial heads are known as Starting Heads in the MODFLOW manual and are given the variable name HEAD. These heads are written in the BASIC Package to start the simulation. In this model, the preliminary water table (static water level) map developed is used as an initial condition and imported as grid surfer file format.

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

## **5.8 Model properties**

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

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

The very essential parameter in the aquifer system is the hydraulic conductivity that defines the flow rate of the groundwater in the aquifer system. The model imports the spatial and an attribute of hydraulic conductivity map described in the conceptual model. The model used a range of conductivity 0.36m/d to 30m/d all other properties are also imported with both spatial and attribute data to form the properties database of the model.

Recharge is a specific flux boundary which is independent of the head in the cell but GV3 consider it as a property for spatially distributed all over the model area. The recharge stated used on the conceptual model is also used as an input to model parameter.

In order to remind the input data of the recharge with spatial distribution of the area the result found from recharge estimation by using water balance method is calibrated based on the **SWAT** model output and used as an input in this model. The recharge is implemented with recharge package of **MODFLOW** 2000. As it is a boundary property, the recharge has a mathematical code that assume the volumetric rate of flow in to cell described with multiplication of the recharge rate by the horizontal area of the cell.

## 6. MODEL CALIBRATION AND SENSITIVITY ANALYSIS

### 6.1. General overview

Calibration of a flow model refers to a demonstration that the model is capable of producing field measured heads and flows which are calibration values (Anderson, M.P. and Woessner, W.W. , 1992). It is accomplished by finding the set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field measured value with in prescribed range of error. Calibration is carried out to demonstrate that the calibrated model can reproduce measured heads or fluxes, and groundwater flow modeling is usually intended to produce a model that can accurately simulate future conditions for area where no head data are available. To make good projection and to understand system dynamics, model calibration was done to acceptable error range by considering realities in the area. Field measured values can be measurements of head, concentration, drawdown or groundwater flow (flux).

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

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

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

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

## 6.2. Calibration method

### 6.2.1. SWAT Model Calibration and Validation Performance

The SWAT model was calibrated for discharge against values from a gauging station located in the outlet of the modelling area. Calibration was performed on a time step 18 years (2001–2018), with a 2 -year warm-up period.

Automatic calibration was carried out with SWAT-CUP (v. 5.1.6.) using the Sequential Uncertainty Fitting Algorithm (SUFI2; Abbas pour 2015). Then, model performance was evaluated through statistical metrics, including the coefficient of determination (R<sup>2</sup>), the Nash-Sutcliffe efficiency coefficient (NSE), percent bias (PBIAS) and the root mean square error (RMSE).

Nine parameters—selected from the initial simulation of the model for 500 times—were optimized. The parameters are groundwater (GWQMN, REVAPMN, and GW\_REVAP), soil water (SOL\_AWC), lateral flow (HRU\_SLP, OV\_N, ESCO and SLSUBBSN), surface runoff (CN2). The same parameter settings were used for all the three watersheds. The descriptions and minimum–maximum value limits are summarized in Table below.

**Table 6.1: Selected SWAT model calibration parameters' descriptions and value ranges.**

#	Basic Information Par Name	Value		
		Method	Min	Max
1	<b>CN2</b>	Ⓕ Relative	35	85
2	<b>SOL_AWC</b>	Ⓕ Relative	0	0.6
3	<b>OV_N</b>	Ⓖ Replace	0.01	30
4	<b>ESCO</b>	Ⓖ Replace	0	1
5	<b>HRU_SLP</b>	Ⓖ Replace	0	0.6
6	<b>SLSUBBSN</b>	Ⓖ Replace	10	50
7	<b>GWQMN</b>	Ⓖ Replace	0	5000
8	<b>GW_REVAP</b>	Ⓖ Replace	0.1	0.22
9	<b>REVAPMN</b>	Ⓖ Replace	0	0.2

The calibration of the model is performed in the following way. The SWAT automatic calibrations were undertaken to adjust the key parameters of the model separately. The accuracies of the outputs were weighted by observed data using model performance evaluation criteria.

The statistical model performance indicators comparisons are presented in Table below. NSE and PBIAS values prove the performance of the model is “very good” for the outlets, the R2 is “satisfactory” based on the scales given by (Moriassi et al., 2012).

*Table 6.2: Statistical model performance indicators for SWAT models*

Model	Subbasin outlet	R2	PBIAS	NSE
SWAT	8	0.25	24.5	0.62

### 6.2.2. MODFLOW Calibration

There are basically two ways of finding model parameters to achieve calibration; manual trial and error adjustment of parameters and automated parameter estimation. Manual trial and error calibration were the first technique to be used and still the technique is preferred by most practitioners (Anderson, M.P. and Woessner, W.W. , 1992). In trial-and-error calibration, parameter values are initially assigned to each nod in the grid. During calibration, parameter values are adjusted in sequential model runs to match simulated heads and flows to the calibration targets.

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

The model calibration accounts the matching of the 38 observation points with simulated head with a permissible residual head of  $\pm 5.38\text{m}$ . It is almost with tolerable difference with respect to the gradient, the objective to understand the groundwater flow pattern and the diversity of hydraulic nature of volcanic aquifer.

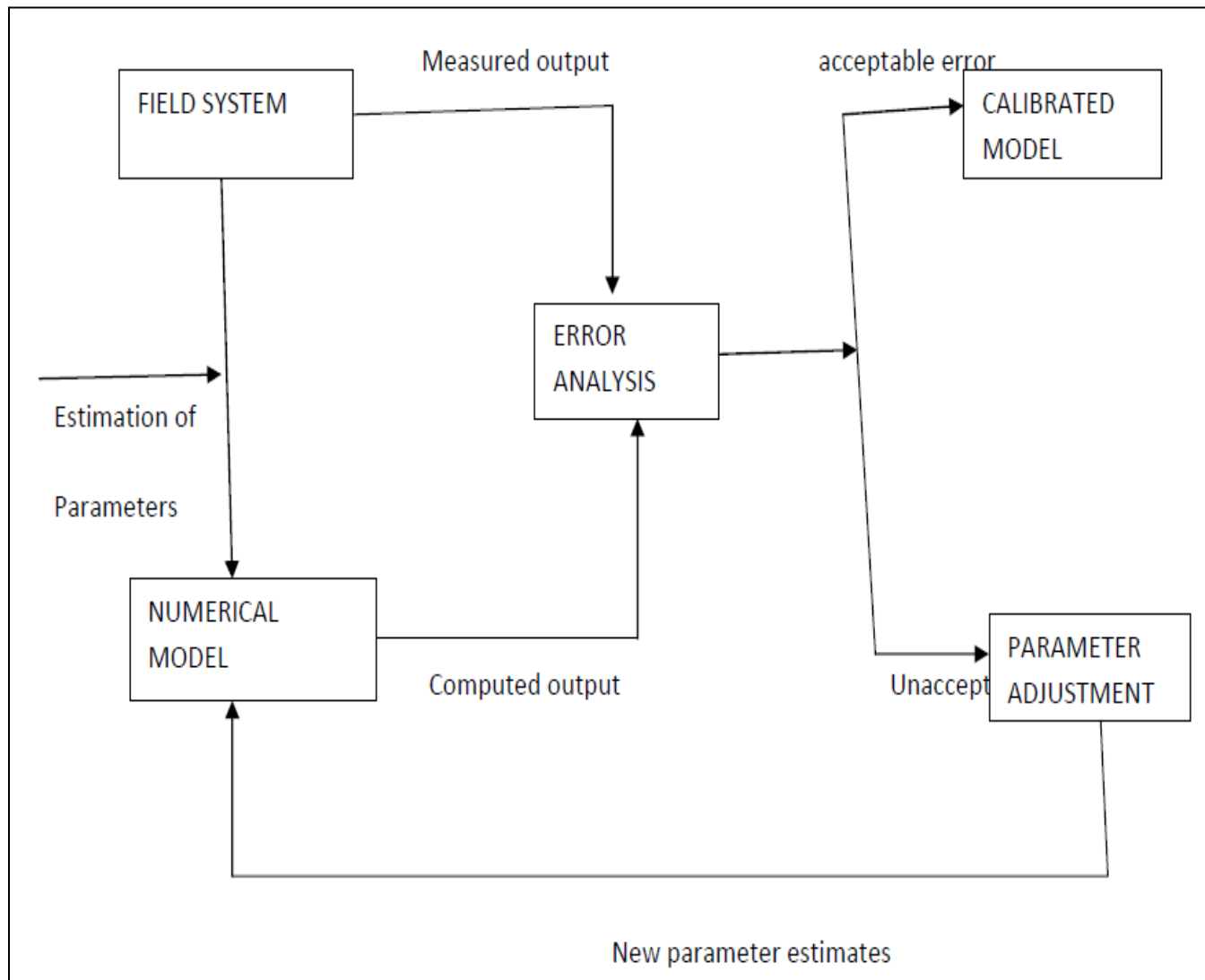


Figure 6.1: Trial-and-error calibration procedure (Anderson, M.P. and Woessner, W.W. , 1992)

### 6.2.3. Calibration target

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

The majority of the observation of water level is taken from different part of the catchment during 2015-2019 borehole construction times. The model uses 38 calibration targets distributed within the catchment which were drilled recently. The model tolerates the possible error introduced by the different time measurement of the heads, head derivation from static water level map produced from well data.

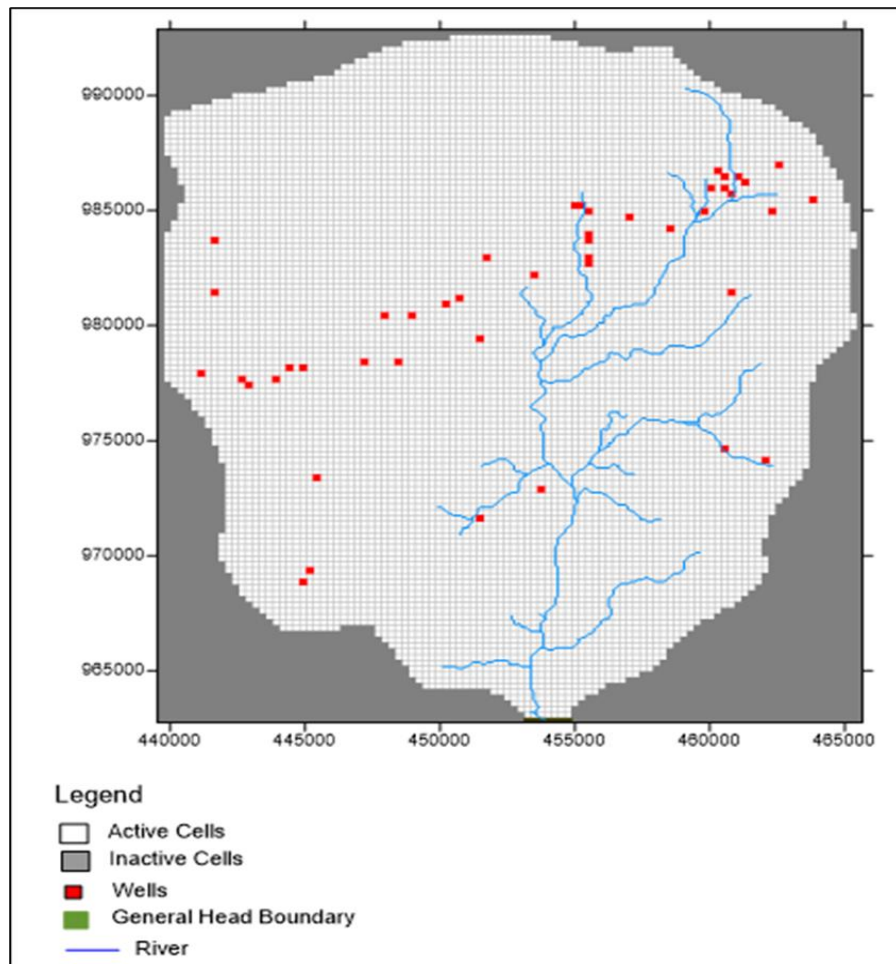


Figure 6.2: The Spatial distribution of target wells of the model

### **6.3. Evaluation of calibrated model result**

The result of the calibration is evaluated both quantitatively and qualitatively. Now a day, there is no standard protocol for evaluating the calibration process. This model tries to use the protocol suggestion to evaluate the calibration. These include matching of contour map of measured and simulated head, calibration statistics and scatter plot used to evaluate the calibrated result [\(Mary P. Anderson and William W. Woessner, 2002\)](#).

#### **6.3.1. Contour map comparison**

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

Atebala River Catchment modeling could be categorized as local studies and matching simulated and measured map trend is very essential to calibrate the model. Accordingly, the model simulated contour of the hydraulic head is approached to match the measured contour.

The simulated head follows the trend and hydraulic gradient of the measured one. However, it will be very difficult to achieve identical simulated and measured contour in the context of volcanic aquifer with inherited nature of head difference in small distance and poor groundwater data management of the catchment. The simulated head is found to follow almost the same trend as of the observed groundwater table contour.

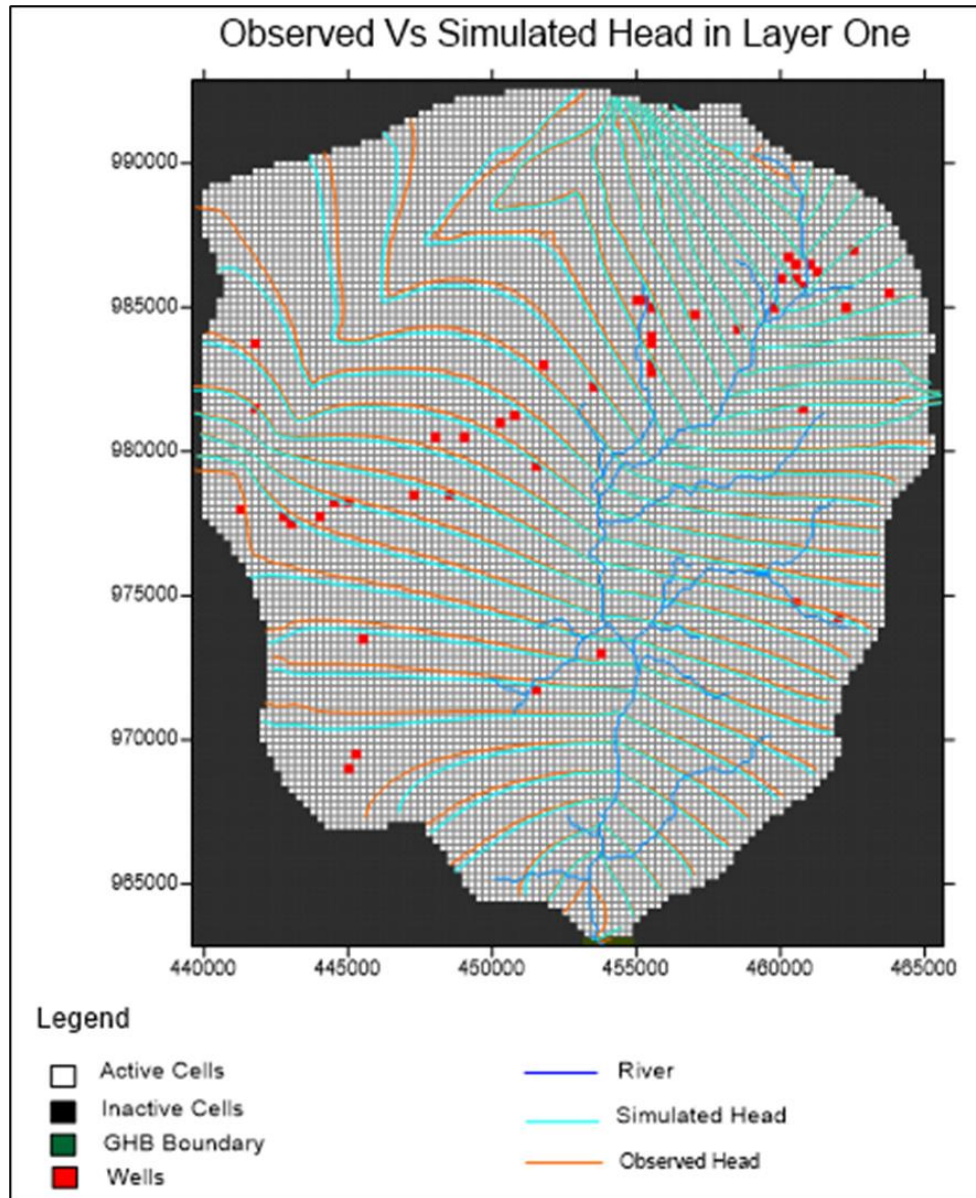


Figure 6.3: Map of observed Vs simulated hydraulic head in layer one

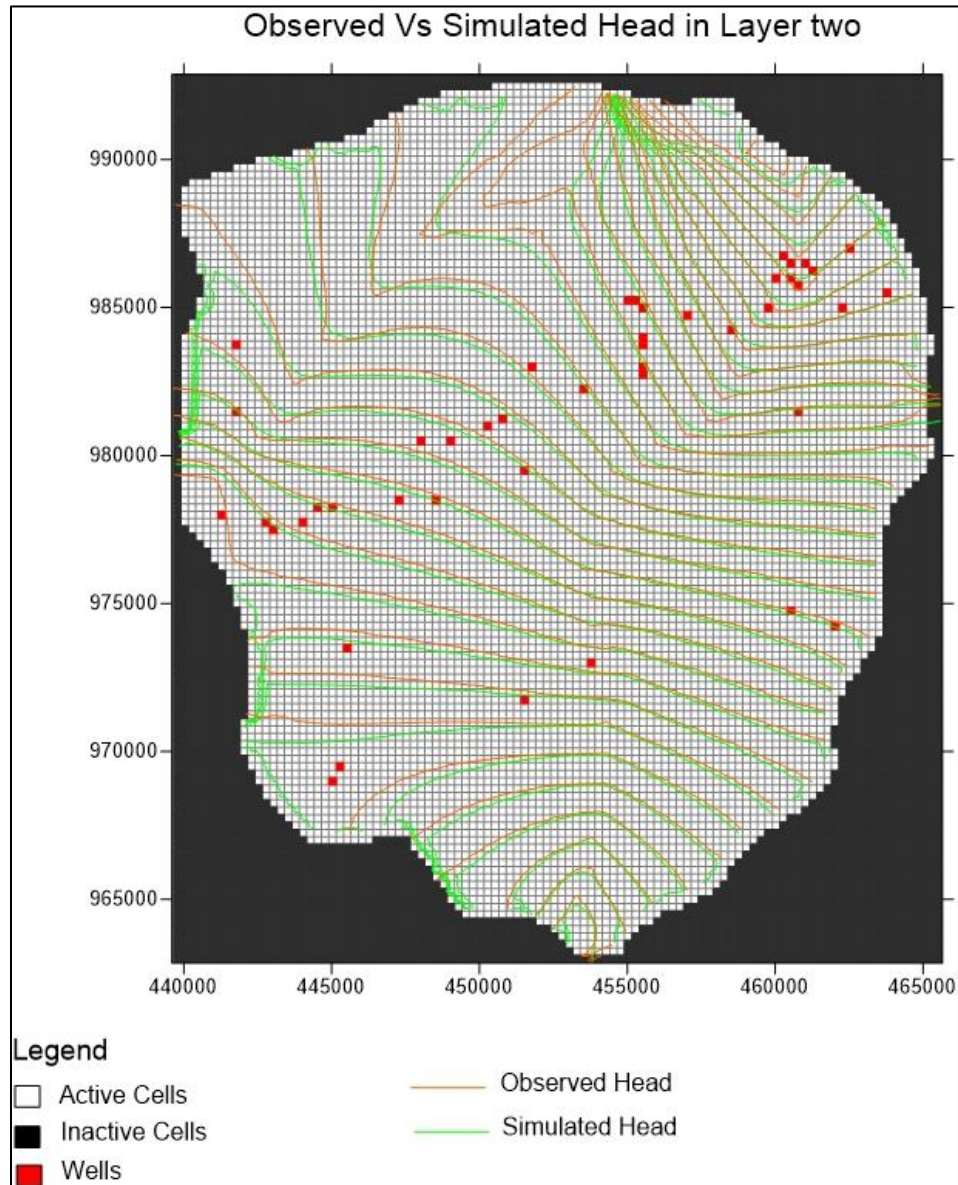


Figure 6.4: Map of observed Vs simulated hydraulic head in layer two

### **6.3.2. Calibration statistics**

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

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

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

- Sum of squared residuals
- Residual mean
- Absolute residual mean

The sum of squared residuals is meaningless by itself but is useful to plot on sensitivity curves or when judging several different simulations. The sum of squared residuals is used by inverse models in the automated calibration process. In this model, the mean of the square residual is **2.91**.

The residual mean is computed by dividing the sum of residuals by the number of residuals. Because both positive and negative residuals are used in the calculation, this value should be close to zero for a good calibration. In other words, the positive and negative errors should balance each other. The model of the region under investigation has a residual mean of **-1.04** that is not too far for local modeling and is too close for good calibrated model.

The absolute residual mean, on the other hand, is calculated using the absolute value of the error (only positive values) and is a measure of the average error in the model. The residual standard deviation is a measure of the overall spread of residuals. The model results an absolute residual mean of **2.34** which is close a fine calibration for the fulfillment of objective of the model.

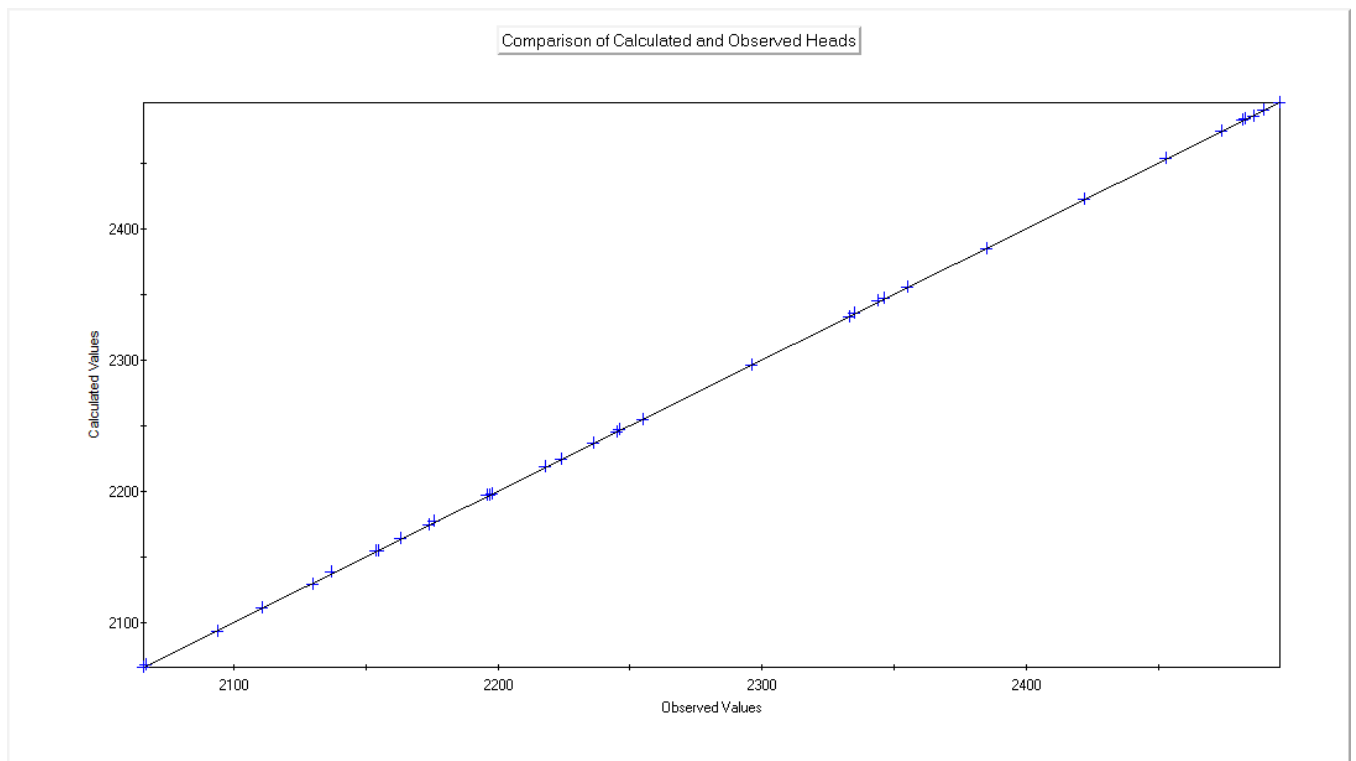
*Table: 6.3. Comparison of calculated and observed head values*

Head Observation	Observed Head (O)	Calculated Head (C)	O-C	/O-C/	/O-C/2
AA168	2154	2157.18	-3.18	3.18	10.1124
AA169	2163	2160.9	2.1	2.1	4.41
AA92	2246	2249.39	-3.39	3.39	11.4921
AdBh0196	2358	2356.57	1.43	1.43	2.0449
AdBh0197	2197	2195.41	1.59	1.59	2.5281
AdBh0249	2335	2339.8	-4.8	4.8	23.04
AdBh0250	2333	2332.47	0.53	0.53	0.2809
AdBh0254	2097	2095.55	1.45	1.45	2.1025
AdBh0255	2174	2173.17	0.83	0.83	0.6889
AdBh0256	2111	2114.98	-3.98	3.98	15.8404
AdBh0300	2155	2152.67	2.33	2.33	5.4289
AdBh0301	2154	2159.18	-5.18	5.18	26.8324
AdBh0323	2224	2222.99	1.01	1.01	1.0201
AdBh0324	2483	2481.57	1.43	1.43	2.0449
AdBh0325	2453	2452.63	0.37	0.37	0.1369
AdBh0326	2496	2495.56	0.44	0.44	0.1936
AdBh0410	2245	2244.81	0.19	0.19	0.0361
AdBh0628	2482	2481.51	0.49	0.49	0.2401
AdBh0725	2176	2179.9	-3.9	3.9	15.21
AdBh0739	2198	2200.49	-2.49	2.49	6.2001
AdBh0890	2349	2348.03	0.97	0.97	0.9409
AdBh0891	2348	2346.07	1.93	1.93	3.7249
AdBh0892	2163	2169.9	-6.9	6.9	47.61
AdBh0895	2486	2485.98	0.02	0.02	0.0004
AdBh0896	2491	2495.34	-4.34	4.34	18.8356
AdBh0981	2474	2473.94	0.06	0.06	0.0036
AdBh1037	2385	2389.43	-4.43	4.43	19.6249
AdBh1044	2422	2427.75	-5.75	5.75	33.0625
BHT-19	2196	2192.9	3.1	3.1	9.61
AMW14	2246	2245.39	0.61	0.61	0.3721
AdBh0259	2296	2299.13	-3.13	3.13	9.7969
BPW-018-10	2257	2256.62	0.38	0.38	0.1444
BPW-01910	2236	2238.65	-2.65	2.65	7.0225
AdBh0408	2137	2139.58	-2.58	2.58	6.6564
AdBh0253	2134	2132.13	1.87	1.87	3.4969
AdBh0258	2072	2070.46	1.54	1.54	2.3716
AdBh0257	2067	2070.38	-3.38	3.38	11.4244
AdBh0409	2218	2222.22	-4.22	4.22	17.8084
			<b>-1.04</b>	<b>2.34</b>	<b>8.48</b>
			<b>ME</b>	<b>MAE</b>	<b>2.91</b>
					<b>RMS</b>

## 6.4. Plotting calibration results

### 6.4.1. Scatter plots

Two types of plots are used in assessing the quality of calibration simulations. The first is the scatter plot where observed target values (measurements) are plotted versus the values computed by the model. In an ideal calibration, the points will fall on a straight line with a 45-degree slope; i.e., the computed value equals the measured value. The degree of scatter about this theoretical line is a measure of overall calibration quality. In this modeling, it is most difficult to match the theoretical line of the plot, but follows a straight line with  $\pm 5.38\text{m}$ .



**Figure 6.5: Observed Vs Computed target value chart**

### 6.4.2. Post residual on contour map

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

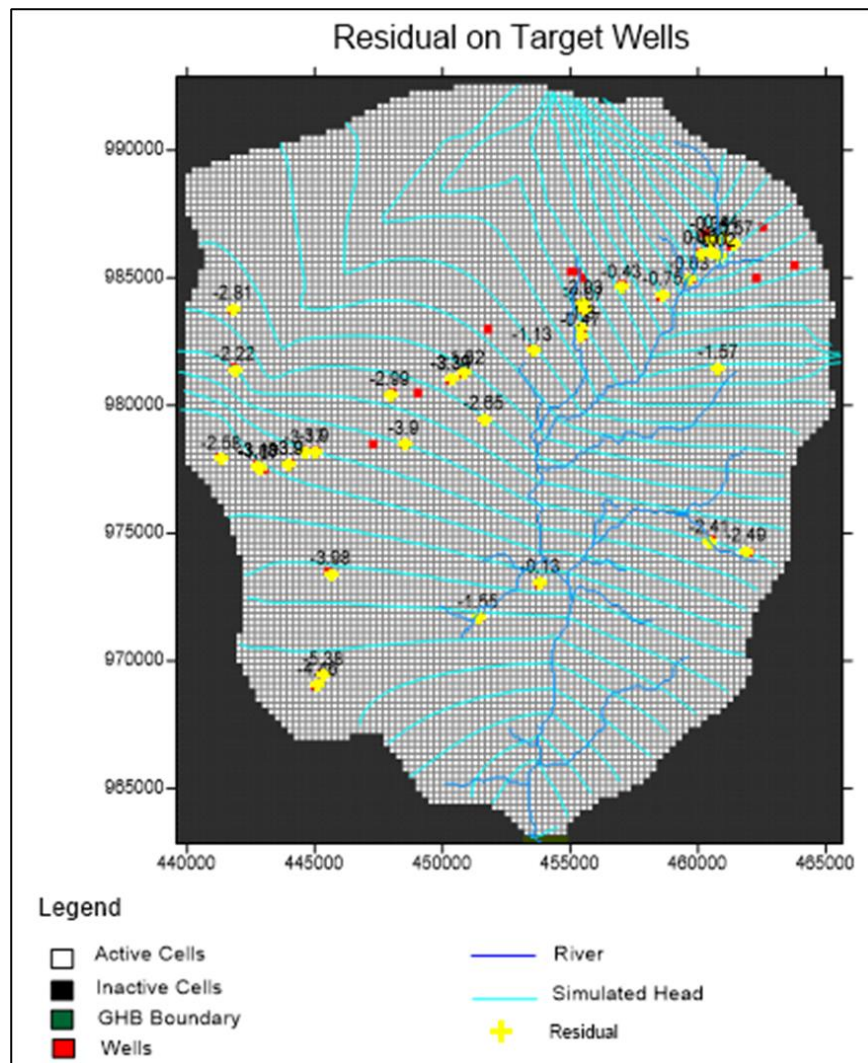


Figure 6.6: Post residual on target wells of the model

### **6.5. Model sensitivity analysis**

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

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

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

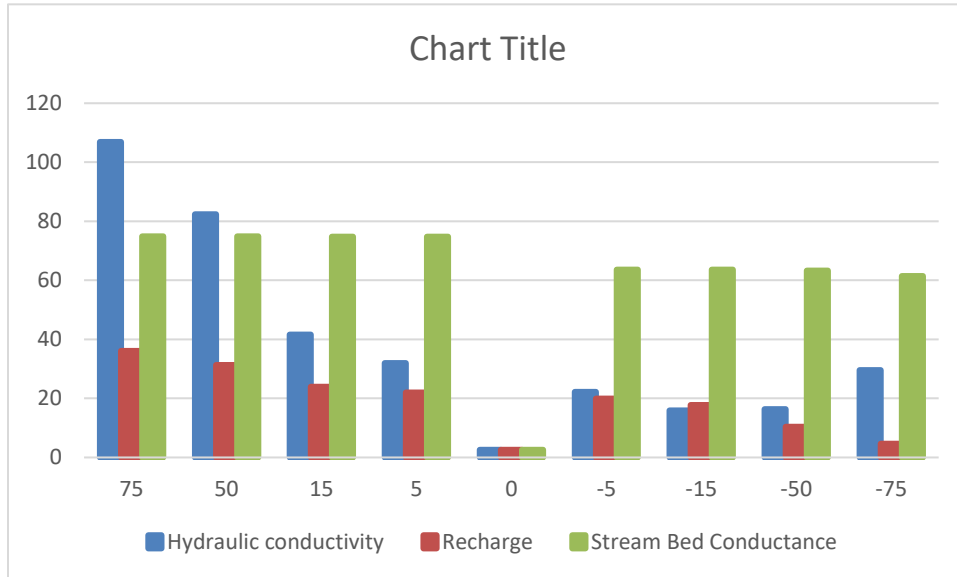
The calibration process to some extent shows the major sensitive parameter of the model and how the model response to fulfill the calibration criteria. Based on the calibration process, it is found that the model is very sensitive to change in hydraulic conductivity and recharge rate change. The other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

The sensitivity of the model to hydraulic conductivity, recharge and stream bed conductance was determined by increasing and decreasing the calibrated model result by 5%, 15%, 50 and 75%. The sensitivity analysis was done by running the model twenty-four times with the proposed changes of parameters.

The Atebala River Catchment show high sensitivity to hydraulic conductivity and recharge. The sensitivity of the model to less change of the parameters is lower and the higher sensitivity is observed for greater changes in the parameters. The calibrated model is much sensitive to change in hydraulic conductivity, recharge and river bed conductance.

**Table: 6.4. Result of sensitivity analysis test on water levels**

Change in parameters in %	ME, MAE and RMS Values for the Parameters								
	Hydraulic conductivity			Recharge			Stream Bed Conductance		
	ME	MAE	RMS	ME	MAE	RMS	ME	MAE	RMS
+75%	86.66	86.66	106.89	-31.65	31.65	36.05	-62.30	62.34	74.85
+50%	64.61	64.61	82.38	-27.55	27.55	31.32	-62.30	62.34	74.85
+15%	30.25	29.69	41.6	-21.18	21.18	23.98	-62.26	62.31	74.82
+5%	22.80	22.97	31.98	-19.44	19.44	21.97	-62.25	62.30	74.81
0%	-2.12	2.15	2.57	-2.12	2.15	2.57	-2.12	2.15	2.57
-5%	15.27	15.45	22.25	-17.65	17.65	19.92	-51.17	51.17	63.62
-15%	10.65	10.79	15.95	-15.82	15.82	17.82	-51.15	51.15	63.6
-50%	3.67	11.93	16.4	-9.18	9.18	10.35	-50.94	50.94	63.35
-75%	10.60	21.48	29.62	-4.02	4.02	4.65	-49.94	49.94	61.5



**Figure 6.7: Plot of the result of sensitivity analysis test on heads**

## **7. MODEL RESULT AND DISCUSSION**

### **7.1. General overview**

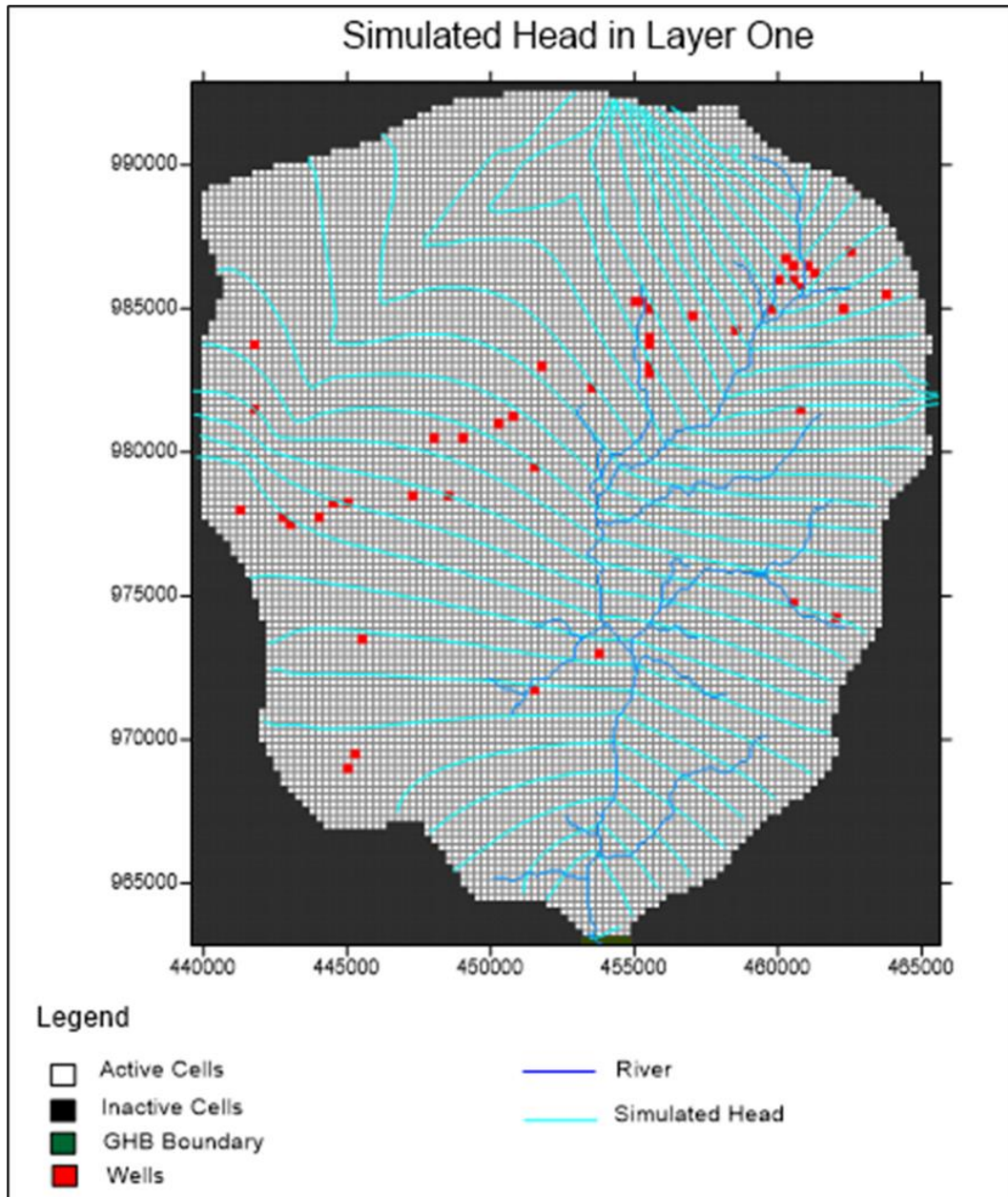
The final result of the model is a calibrated steady state groundwater flow model with simulated head of groundwater surface. The model can be manipulated and simulated with user define interest. The primary result is to satisfy the theme of the paper stated on the objective. The whole effort was to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

### **7.2. Simulated groundwater flow**

The **MODFLOW** calculates the hydraulic head distribution of the groundwater surface. The simulated head distribution shows the groundwater surface follow the topographical contour and flow directions also coincide with surface water catchments flow. The hydraulic head of the two layers is examined and the contour maps of the heads are presented.

The hydraulic head is characterized with very steep hydraulic gradient on the mountain area in the north and with a relative an intermediate gradient higher on the west part than the East. The hydraulic gradient is getting low toward lower part of the catchment where a relative high conductivity is observed towards Awash River in the south.

The general groundwater flow direction is towards the Atebala River from all directions. The simulated groundwater flow in the catchment coincides with the surface water flow direction. The flow in the two layers also similar and it is from the north to the south direction as it is seen in the simulated hydraulic head maps.



*Figure 7.1: Spatial distribution of simulated head in layer one*

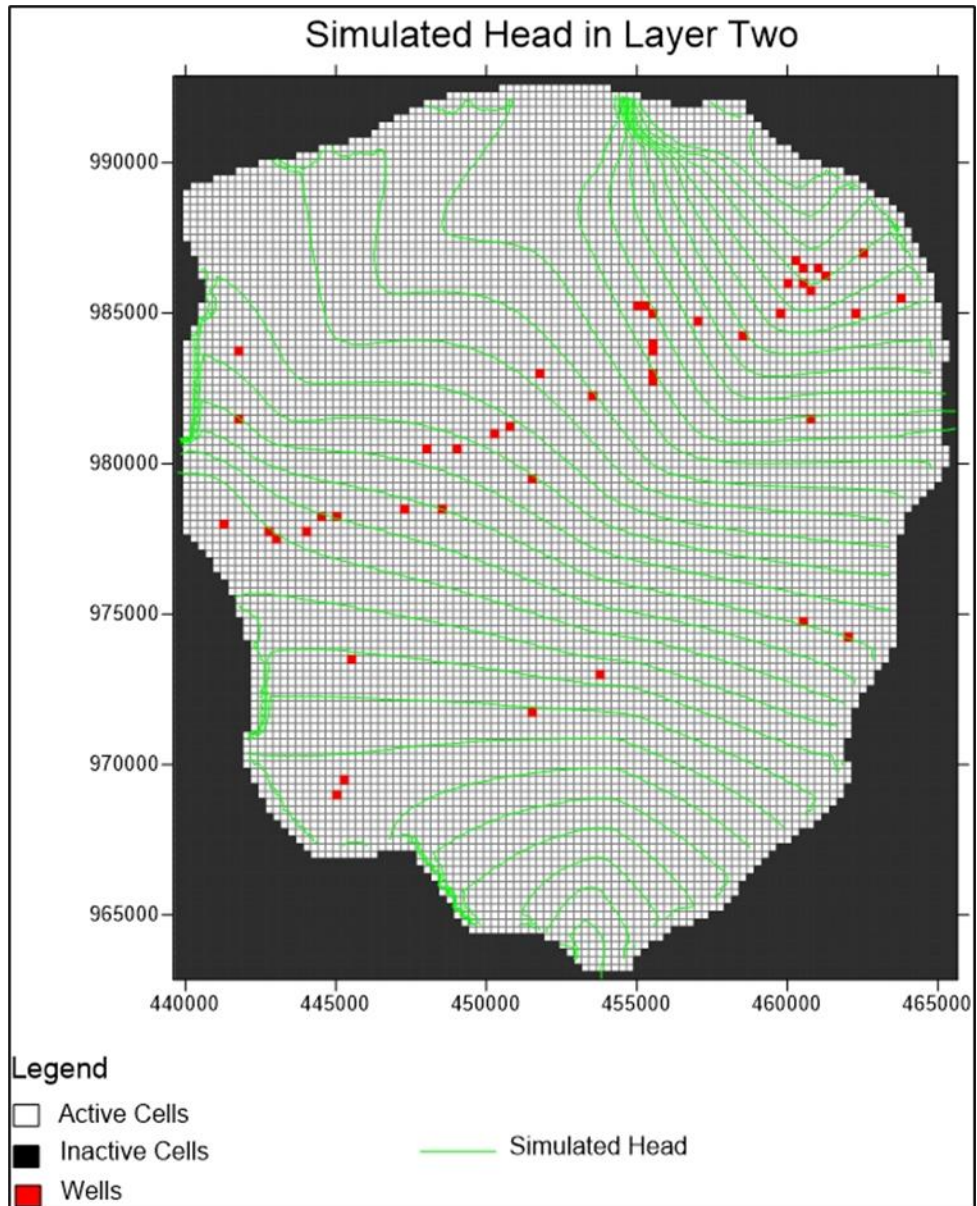


Figure 7.2: Spatial distribution of simulated head in layer two

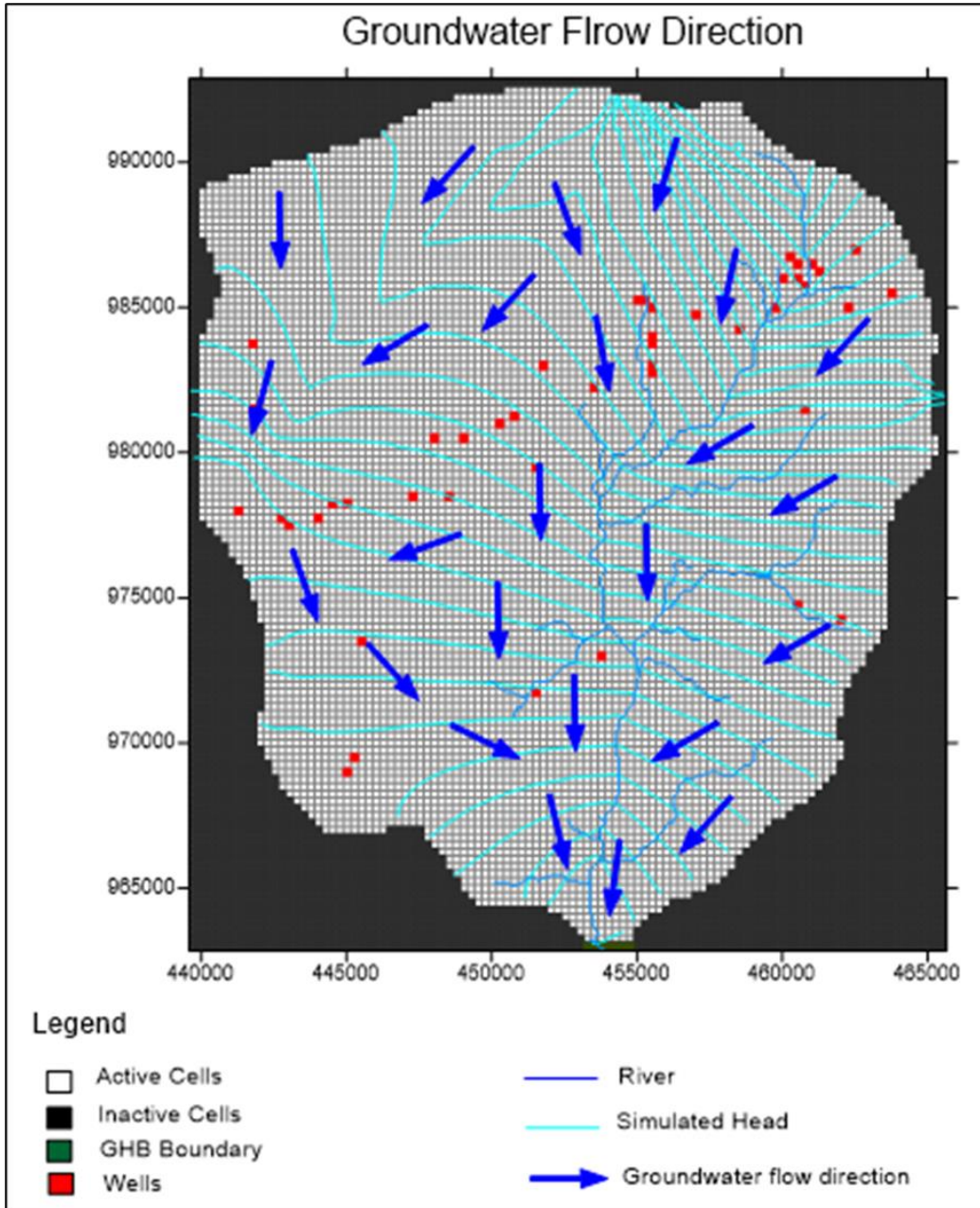


Figure 7.3: Atebala river catchment groundwater flow vector direction

### 7.3. Simulated catchment water budget

The water budget of the Atebala River Catchment is computed using numerical groundwater flow modeling technique. And the simulated inflow is a total of 1,801,374,999.39m<sup>3</sup>/y which is almost equal to the simulated outflow of 1,800,439,911.91m<sup>3</sup>/y with a total difference of 935,087.48m<sup>3</sup>/y which is 0.05% of error.

The river leakage of the simulated model holds 60.72% of the total inflow and 80.66% of the total outflow. This shows that the groundwater and surface water interaction is very high in the catchment and the Atebala River system gets much of its recharge from the groundwater system to sustain its flow in the dry season as base flow. The simulated evapotranspiration in the catchment holds 18.76% of the outflow. The well discharge accounts for only 0.57% of the total outflow. The Awash River which is simulated as GHB on the entrance point of the Atebala River contributes 12.01% of the total inflow. The impact of the precipitation recharge in the groundwater system of the catchment is good with 27% share out of the total inflow. The high groundwater and surface water interaction observed in this model is due to the fact that the model area has high hydraulic conductivity and the river bed conductance is also significant.

*Table: 7.1. Simulated water budget of Atebala river catchment*

No	Water Balance Component	Annual	
		Inflow (m <sup>3</sup> /y)	Outflow (m <sup>3</sup> /y)
I	Precipitation Recharge	491,169,937.50	
II	Pumping well		10,190,475.00
III	River inflow	1,093,787,365.65	
IV	River outflow		1,452,211,464.08
V	General Head Boundary	216,417,696.24	
VI	ET		338,037,972.83
	Total	1,801,374,999.39	1,800,439,911.91
	Percentage Error	0.05	

In this model layer one has the highest share to the inflow since it receives most of the recharge from precipitation and the river package is simulated only for this layer. Its increased contribution to the out flow is attributed to the general head boundary, river and evapotranspiration packages that are only considered in layer one.

The total water budget of the catchment is calculated by adding the result of each parameter and subtracting the internal and horizontal exchanges which are presented in the output only to show the interaction of the two layers.

**Table: 7.2. Simulated water budget of Atebala river catchment in layer one**

No	Water Budget Component	Annual	
		Inflow (m <sup>3</sup> /y)	Outflow (m <sup>3</sup> /y)
I	GHB	84,740,746.68	
II	Horizontal Exchange	145,228,729.00	12,899,116.04
III	Exchange (Lower)	1,002,320,291.85	978,880,117.43
IV	Recharge	458,571,375.00	
V	River Leakage	1,093,787,365.65	1,452,211,464.08
VI	Well		3,287,250.00
VII	ET		336,435,438.46
	Total	2,784,648,508.18	2,783,713,386.00
	Percentage Error	0.03	

**Table: 7.3. Simulated water budget of Atebala river catchment in layer two**

No	Water Budget Component	Annual	
		Inflow (m <sup>3</sup> /y)	Inflow (m <sup>3</sup> /y)
I	GHB		
II	Exchange (Upper)	978,880,117.43	1,002,320,291.85
III	Horizontal Exchange	21,459,618.72	21,468,524.61
IV	Recharge	30,352,275.00	
V	River Leakage		
VI	Well		6,903,225.00
VII	ET		
	Total	1,030,692,011.14	1,030,692,041.46
	Percentage Error	0.00	

## **7.5. Scenario analysis**

The calibrated flow model helps as a tool to evaluate the response of the aquifer system to different stress. The modeler has tried for the simulation of two scenarios with the abstraction of the groundwater and the influence of fluctuation of Evapotranspiration.

This part of model analysis has ability to predict the response of the system to change in the future events. It has become clear that the Atebala River catchment groundwater resource is being used for domestic, industrial and irrigation projects. Therefore, it is important to see the water level fluctuation to increased groundwater withdrawal.

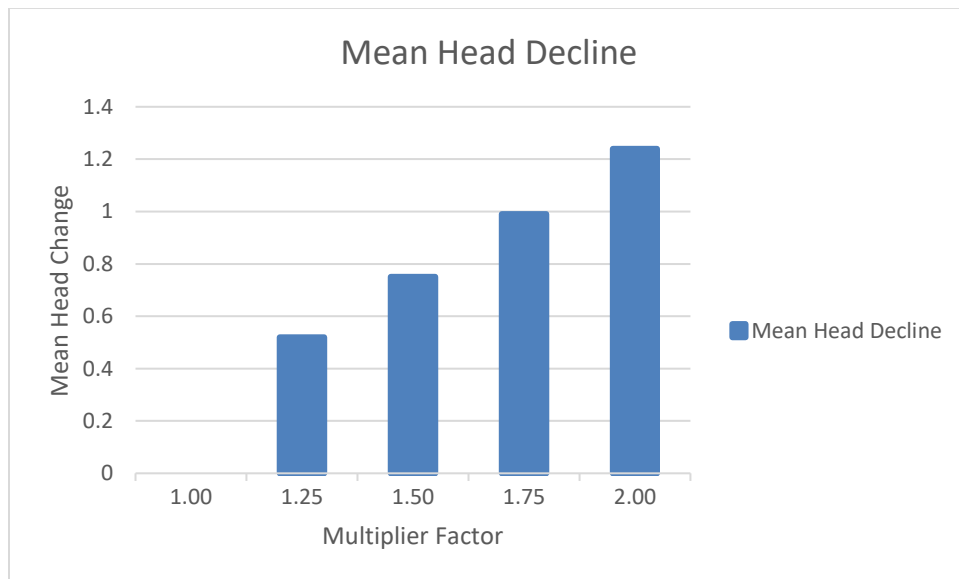
### **7.5.1. Effects of increased well withdrawal**

The steady state withdrawal rates were increased by 25%, 50%, 75% and 100% to study the response of the system in this scenario. These increased are equivalent to withdrawing 60,000.00, 72,000.00, 84,000.00 and 96,000.00m<sup>3</sup>/d over the whole catchment respectively and the increased withdrawal rate distributed among the existing wells. Model simulated results of stream base flow and water table elevations in the scenarios were compared with the model calculated steady state results, and the difference showed the response of the system to the assumed scenarios.

The calibrated model shows change for further increment of well withdrawal rate and the water level has decreased significantly with every increased discharge of water from the wells. Further increment of groundwater withdrawal has also an effect on other model parameters like the discharge of water from the aquifer system to the River, GH boundaries and evapotranspiration. The increment of the groundwater withdrawal has slight impact on the Awash River that is represented by the GHB in this model. The main parameter which is affected by the increment of well withdrawal is the river leakage out flow from the groundwater system.

**Table: 7.4. Groundwater withdrawal effect on water level**

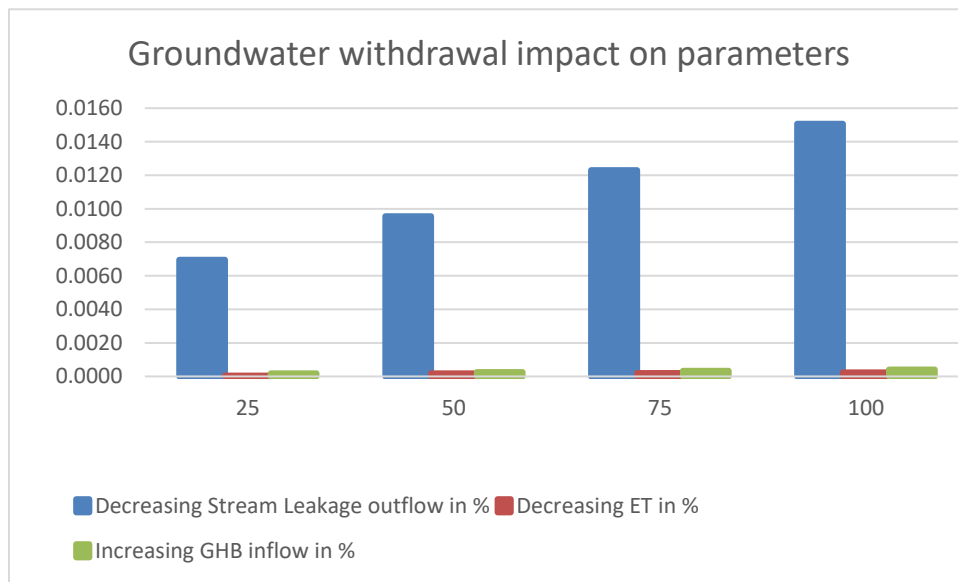
Run	Multiplier	Decreasing Groundwater Level (m)		
		Mean	Minimum	Maximum
1	1	0.00	0.00	0.00
2	1.25	0.52	0.088	0.836
3	1.50	0.75	0.145	1.089
4	1.75	0.99	0.376	1.343
5	2.00	1.24	0.265	1.627



**Figure 7.4: Groundwater withdrawal impact chart on the Atebala river catchment**

**Table: 7.5. Groundwater withdrawal effect on other parameters**

Increased in groundwater withdrawal from	Decreasing Stream Leakage outflow in %	Decreasing ET in %	Increasing GHB inflow in %
25	0.0070	0.0001	0.0002
50	0.0096	0.0002	0.0003
75	0.0123	0.0002	0.0003
100	0.0151	0.0002	0.0004



**Figure 7.5: Groundwater withdrawal impact chart on other parameters**

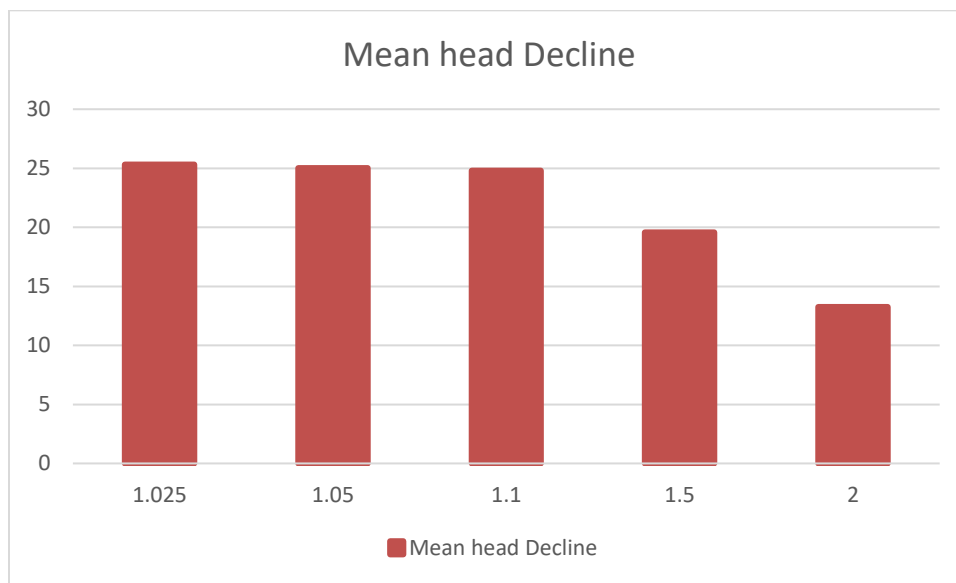
Therefore, additional groundwater pumping would most likely result in decline of groundwater level and reductions in natural discharge based on intensity of pumping. These observed changes simply represented local effects of the proposed groundwater withdrawals. The head decline in this case is small relative to the steady state withdrawal rate and the natural discharges were not altered highly. But further withdrawal of groundwater by pumping wells should be managed properly.

### 7.5.3. Effect of increased evapotranspiration

The second scenario analysis considers increased evapotranspiration. Evapotranspiration is increasing in the study area due to urbanization, industrialization and intensive irrigation practice. To study the impact of this scenario the calibrated evapotranspiration is increased by 2.5%, 5%, 10%, 50% and 100%.

*Table: 7.6. Effect of raised evapotranspiration on water level*

Run	Multiplier	Decreasing Groundwater Level (m)		
		Mean	Minimum	Maximum
1	1	0.00	0.00	0.00
2	1.025	1.02	0.8	1.24
3	1.05	1.24	0.92	1.56
4	1.10	1.68	1.33	2.03
5	1.5	2.72	2.32	3.12
6	2	4.15	3.67	4.63



*Figure 7.6: Raised Evapotranspiration impact chart on water level*

As observed from the five runs of the calibrated model by increasing evapotranspiration rate the mean decline in head is found to be higher for up to 10% increment. Although further increment in evapotranspiration causes the head decline to decrease significantly the head change is still great. Since the potential evapotranspiration is higher in the study area mitigation measures shall be devised in order to decrease the evapotranspiration rate.

### **7.6. Model limitation**

The accuracy of groundwater model result depends on the accuracy of the input data. The groundwater flow model for this study was constructed with available site-specific hydrologic data to determine groundwater reserve and flow direction.

The database management of the hydro-geologic parameters of the study area is poor and with scarce essential parameter. Therefore, the user of the model should consider the deficiency of the data that encountered during the modelling.

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

The resolution of any numerical model is limited by the level of discretization used to create the model. The level of discretization used in the Atebala River catchment modelling is too coarse for studying effects at a local scale, but the discretization is adequate for studying groundwater withdrawal effects at the intermediate scale.

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

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

## **7.7. Groundwater management**

### **7.7.1. Groundwater management based on model result**

The main purpose of the numerical groundwater flow modeling conducted for Atibala River Catchment is to support the Water Resources Management and Planning for sustainable use of the water resource in the catchment.

Groundwater is a key component of water resources management and planning in developed basins. It is generally in constant interaction with the surface flow system and acts as a buffer in replenishing the depleted surface water resources as well as meeting the unmet portion of water demand after surface water resources are utilized.

Catchment wise monitoring strategies are the keys for proper management of the groundwater resources. Prior to management practice the available resource has to be quantified and monitored regularly to see seasonal and annual changes in the hydrological system of the study area. In this paper the annual water budget has been calculated using numerical groundwater flow modelling and the main parameters of the hydrological system have been estimated.

Based on the analysis of the calibrated model result the hydraulic conductivity, river bed conductance and recharge have been found to be the most sensitive parameters. The scenario analysis has also showed that further increase in the groundwater abstraction rate by wells has significant impact on the water resource of Atebala River catchment. The evapotranspiration is also increasing in the study area due to deforestation and climate change. Further increase in evapotranspiration on the calibrated model has showed significant mean head decline. In addition, increased irrigation practices, urbanization and industrialization are also responsible for depleting the quality and quantity of surface water and groundwater resources in the study area. The model result also shows that the surface water and groundwater interaction in the catchment is high. This calls for integrated surface water and groundwater management approach at catchment level.

The water quality analysis conducted in this research based on available data shows that all the parameters are within the permissible range of WHO and MoWIE standards except high Fluoride content is observed in some of the deep wells. In this regard the surface water and groundwater quality of the catchment should be checked frequently for sustainable development of the water resource.

Therefore, integrated water resource management is curtailing for the sustainable utilization of the groundwater resource. In order to utilize the available water resource properly it is vital to implement the existing monitoring and management strategies and design and develop catchment wise integrated water resource monitoring and management strategies and guidelines for the sustainable utilization of the water resource.

The model is run at steady state condition in order to estimate the groundwater reserve and to see the most sensitive parameters in the catchment. Therefore, transient models are recommended to further quantify the impact of each parameter on the model at different time series and to analyze the stress on the model.

### **7.7.2. Existing groundwater management practice**

There are some production wells fitted with piezometers designed for groundwater monitoring in the study area. There are also some gauging stations at Awash River for surface water monitoring. In 2019 GC a comprehensive surface water and groundwater monitoring strategy and integrated water resources management guideline has been developed for Sebeta Hawass woreda in which the study area is situated by the United Nations Development Program (UNDP) and this project document is being implemented (Yilikal, 2019). Besides these attempts and the national water use strategy developed for the country there are no monitoring and management strategies designed for the Atebala River Catchment at watershed level and the groundwater management practice is poor in the study area.

### **7.7.3. Integrated Surface Water and Groundwater Management at Catchment Level**

Water resources management and planning in a basin are generally further complicated by the changing climate, competing interests among farmers, cities and environmental requirements, as well as a regulatory environment that tries to balance flood control with water supply availability while honoring water rights (Jyrkama, 2007; Karamouz et.al., 2004). Additionally, maintaining the surface and subsurface water quality at or above a level that is suitable for agriculture, human consumption, and the environment tends to be an integral water resources planning component in many basins (Swartjes, 1999). Groundwater management and planning are generally affected by all these factors and a proper management plan must address many of these issues.

In order to perform a comprehensive groundwater resources analysis and planning study, it is generally necessary to use more than one type of model and simulate not just the groundwater flow dynamics but also the entire hydrologic system, reservoir operations, agricultural water demands, etc. Additionally, these models must effectively and dynamically exchange information (i.e., they must be linked to each other) since each model will depend on some information another model produces.

In this regard in this research SWAT model was used to analyze the surface water condition in Atebala River Catchment and to estimate river flow, recharge and evapotranspiration. The outputs of the SWAT model were utilized in the Modflow model as input parameters.

In order to evaluate the estimated parameters continuous and reliable data are necessary. To solve this there is a need to develop fixed groundwater monitoring system (to see the change in the static water level and to monitor the quality of the groundwater) and to plant gauging station at Atibala River to better understand the surface water condition in the catchment. The data obtained from the monitoring stations can be utilized to further enhance the model and to estimate the input and output parameters of the water budget component more accurately.

Therefore, integrated surface water and groundwater management approach is necessary for the sustainable utilization of the surface water and groundwater resource of the Atebala River Catchment.

In principle water is a flow resource, a scarce one, and also exposed to negative externalities, proper management of surface water, groundwater and of groundwater related activities are crucial to the implementation of successful and sustainable processes of water development and conservation. For this reason there should be a thiooretical guideline to strategically develop and manage the groundwater potential of the catchment.

#### ***7.7.3.1. General principle***

The management of a surface water and groundwater basin implies a program of development and utilization of surface and subsurface water for some stated purpose, usually of a social or economic nature. In general, the desired goal is to obtain the maximum quantity of water to meet predetermined quality requirements at least cost.

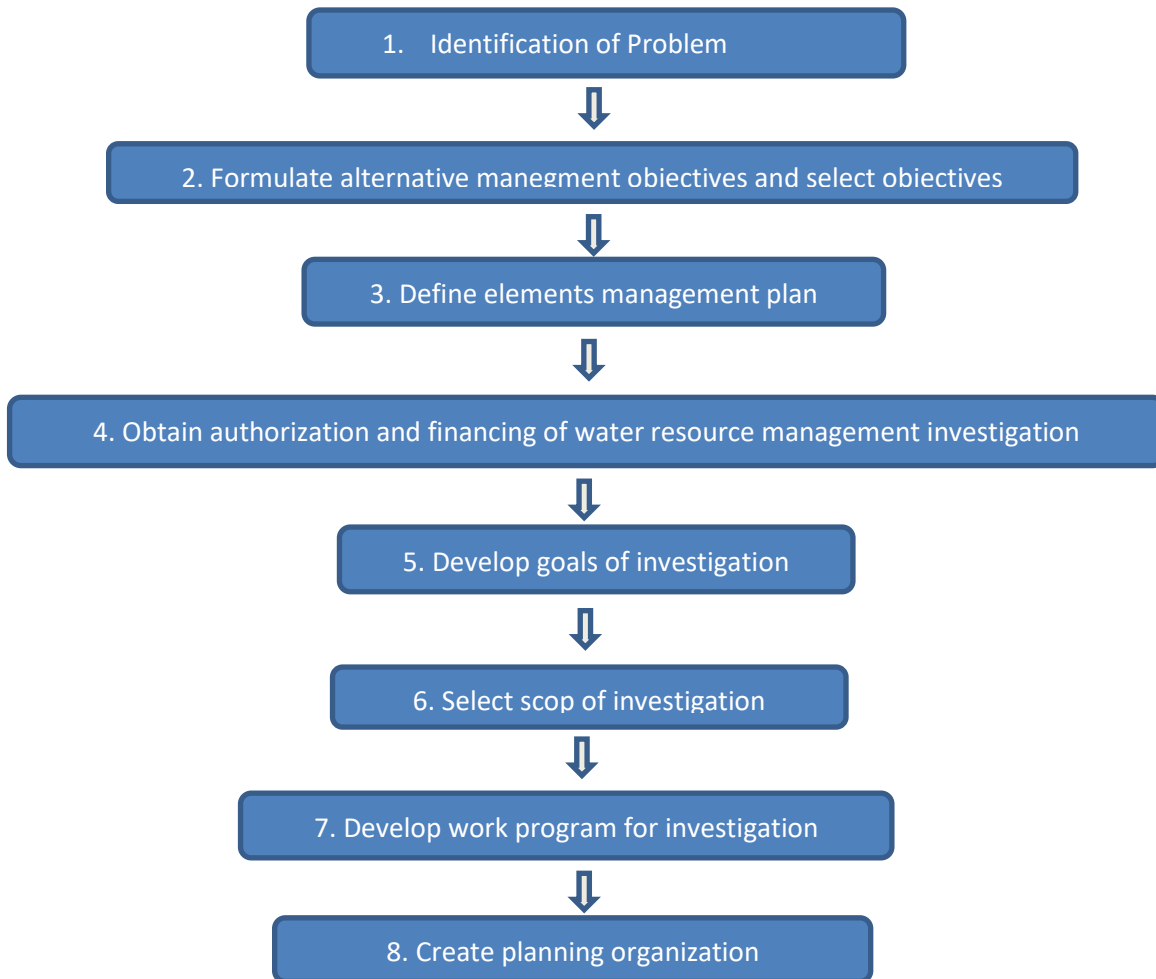
Integrated Water Resources Management (IWRM) is defined by the Global Water Partnership (GWP) as “a process, which promotes the coordinated development and management of water, land, and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” [\(Anil Agarwal and Marian Delos Angeles, 2000\)](#).

*Table.7.7: Type of data required for groundwater management*

TYPE OF DATA	BASELINE DATA (from archives)	TIME-VARIANT DATA (from field stations)
Groundwater Occurrence and Aquifer Properties	Water well records (hydrogeological log, instantaneous groundwater level and quality). Well and aquifer pumping tests.	Groundwater level monitoring. Groundwater quality monitoring.
Groundwater Use	Water well pump installation Water-use inventories Population registers and forecasts Energy consumption for irrigation	Water well abstraction monitoring (direct or indirect) Well water level variations
Supporting Information	Climatic data Land-use inventories	River flow gauging Meteorological observations Satellite land-use surveys

### 7.7.3.2. Guiding principles for groundwater management

In order to develop groundwater management strategies at catchment level it is important to revise the national water use strategy development for the country and other existing management guidelines. At this stage it is recommended to follow the sequence of activities presented below to design and develop groundwater management strategies and guidelines for Atebala River Catchment.



*Figure 7.7: Sequence of activities preceding start of a groundwater management investigations  
(Todd, 1980)*

❖ **Identification of Problem**

Problems generally include the following: lowering water levels; water logging; subsidence; seawater intrusion through offshore outcrops and from excavation of harbors and canals; water quality degradation as a result of an improperly constructed and destroyed wells; percolation of wastewaters, increasing salinity from adverse salt balance, and other water quality problems.

❖ **Formulate alternative management objectives and select objective**

The general and specific objectives for water resource management plan will be identified and properly addressed.

The objectives may include water service at least cost; basin versus region, social, legal and economic constraints; aquifer management as part of the total water supply and disposal system.

❖ **Define elements management plan**

The management plan shall be defined at this stage. And it will address issues like pumping locations and schedule; artificial recharge locations and schedule; boundary conditions; legal structure; monitoring; organizational and financial.

❖ **Obtain authorization and financing of water resources management investigation**

Prior to groundwater management investigation for water resource management strategy and guideline preparation the necessary authorization and finance shall be obtained from the mandated government body.

❖ **Develop goals for investigation**

Prepare report discussing alternative management plans, including nonstructural alternatives, and recommend a single plan. It is recognized that implementation of a suitable plan is ultimate goal.

❖ **Select scope of investigation**

Determine study area, study schedule, and level of study-preliminary examination, reconnaissance, or feasibility.

❖ **Develop work program for investigation**

Identify what must be accomplished to achieve planning goals, with emphasis on need for historic basic data, continued data collection, and elements development planning techniques, include diagrams showing work elements, sequence and schedule.

❖ **Create planning organization**

Governance and institutional arrangements for water resources development and management are organized at three levels – the federal level which establishes policy and sets standards; the basin level where resources are managed; and the local level where services are managed.

The planning organization shall also include engineers, economists, hydro-geologists, attorneys and others experts from responsible governmental and non-governmental offices and institutions for the successful completion of the desired document.

## **8. CONCLUSION AND RECOMMENDATION**

### **8.1 Conclusion**

The main aquifer systems in the study area are the Upper basalt and Lower basalt units. The main aquifer is found at depth with greater discharge. The main recharge areas for the Atebala catchment are the surrounding mountains in the north (has a good vegetation cover) and part of plain area around eastern part of the study area are the main discharge areas.

The water budget of the study area shows that the interaction of the surface water and groundwater is remarkable. But generally further investigation is required to accurately state the interaction of the Awash River and its tributaries with the aquifer system.

Generally, the Atebala river catchment has good groundwater potential for domestic, irrigation and industrial use. The water quality is also in the acceptable range of the WHO and Ethiopian national standards for drinking, agricultural and industrial uses.

The main source of water supply for domestic, irrigation and industrial use in the study area is groundwater. To satisfy the growing need for potable water both in rural and urban towns many boreholes and hand dug wells are being drilled. Many springs are also being developed. Therefore, the groundwater potential of the study area should be assessed using different hydrogeological techniques for the proper utilization of the resource and to evaluate the management options. The impact of the currently growing irrigation practice and industrialization should also be evaluated to minimize its influence on the groundwater resource and its overall effect on the catchment.

Results of analysis of existing data and detail hydrogeological investigations carried out on Atebala river catchment led to the following conclusion.

There are two main aquifers in Atebala river catchment (Upper and Lower Basaltic aquifer)

The surficial clay and alluvial deposit, pyroclastic and silicic rocks that separate the upper and lower aquifer is confining layer. The lower basalt is deep seated below 300 m known as lower aquifer and it is confined.

The general groundwater movement is from northern to southern direction.

The total dissolved solids and chemical contents of the chemical analysis results of water samples collected from the wells drilled in the study area are within WHO's recommended standard for domestic uses.

Estimated Recharge for the study area is 154.46 mm/year.

The groundwater withdrawal from pumped deep and shallow wells and the total evapotranspiration in the catchment is not significant in current conditions when compared with the natural recharge.

If the well withdrawal and evapotranspiration of Atebala river catchment is increases (as mentioned in the above with different scenarios), the catchment has needed serious integrated monitoring and control mechanism to sustainably preserve the groundwater resource of the catchment.

## **8.2 Recommendation**

Groundwater monitoring strategies should be designed and implemented in order to assess the groundwater level fluctuation and water quality trends in Atebala river catchment.

Integrated surface water and groundwater management guidelines shall be developed in order to satisfy the growing water demand in the catchment without depleting the groundwater resource of the area.

Water use plans shall be prepared and priorities shall be set for each developmental project that requires the use of groundwater from the catchment.

The groundwater resource should be evaluated continuously to assess the temporal and spatial distribution of the resource.

Environmental impact assessments should be conducted for each project in the catchment in order to mitigate the adverse impact of developmental activities and to protect recharge and discharge areas from degradation.

Prepare a pumping control mechanism by local governmental administrative offices on private companies which are highly uses the groundwater in Atebal river catchment for their functionality. Such as bottled water companies.

Frame a specific pumping rate limits on privet companies which uses a groundwater for their products and prepare taxation system or policy on the companies that pumps more groundwater that states by the local governmental office.

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