ADDIS ABABA UNIVERSITY
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SCHOOL OF GRADUATE STUDIES

NUMERICAL GROUNDWATER FLOW MODELING FOR SUSTAINABLE GROUNDWATER RESOURCE DEVELOPMENT: THE CASE OF SIBILU RIVER CATCHMENT ABAY BASIN

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Numerical Groundwater Flow Modeling for Sustainable Groundwater Resource Development: The Case of Sibilu River Catchment Abay Basin

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Addis Ababa University
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Dedicated To

My Father with Love and Gratitude

“Who encouraged me to Knowledge”!

ABSTRACT

Groundwater plays an important role in Ethiopia as a significant source of water for domestic, bottling, industrial and /or agriculture uses. In rural areas, which cover more than 85% of the population of Ethiopia, development and utilization of groundwater is most common.

When the groundwater is used for irrigation, industry and domestic purposes, it is necessary to maintain the groundwater reservoir in state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the wet and dry seasons. To do so detail groundwater study, monitoring and quantification through different analysis methods like numerical modeling is a crucial and this study focuses on the numerical groundwater modeling of Sibilu River catchment under the steady state flow conditions. The catchment drains about 650 km^2 land areas and covered by alluvial deposit and different types of volcanic geological formation.

The surface hydrologic dynamic was modeled by using ArcSWAT integrated with ArcGIS. The area was classified into 1215 HRUs, to simulate the groundwater recharge distribution, evapotranspiration and interactions between Stream network and Aquifers in each Hydrologic Response Units. Accordingly, the recharge and ET distribution of the area were 292.2 and 253.01 mm per annum. As estimated with Base flow separation and CMB method in the validation process the recharge were 318.8 and 304.9 mm/year which is indicating the good agreement between the models with slight differences and the source of the recharge in the catchment were found to occur from direct precipitation and riverbed infiltration.

Furthermore, Processing Modflow pro (version Pm 5) has been used to simulate the subsurface dynamism of groundwater of the area. The area discritized by 32,185 finite-difference Block Centered rectangular cells (205 rows, 157 column, 200m*200m cell size) and 350 m thick single upper layer and then in and out flow system of groundwater has been modeled.

Zoned horizontal hydraulic conductivity has been used through the trial-and-error method to calibrate the model using the observed and simulated hydraulic heads. The water budget of the catchment reached at equilibrium conditions and annually about 181 and 20.3 million cubic meters of water flowing into the Aquifer system of Sibilu catchment from Precipitation Recharge and River leakage respectively. Similarly, a total of 201.25 million cubic meters of water is flowing out of the Aquifer system of the study area through head dependent boundary (0.91 MCM), Wells abstraction (5.6MCM), Drains (5.47 MCM) ,ET (164 MCM) and leakage of groundwater to the river course (25.1 MCM) in a period of a year. Discharging of groundwater from the Aquifer system is occurred through unregulated Well abstraction, spring discharges, ET and groundwater outflow to the stream. Intensive well abstraction for Water bottling, different industrial uses, Agro processing, commercials, irrigation, hotels and domestic water supplies are the main groundwater abstraction means in the Sibilu Catchments due to an anthropogenic activities.

Under increasing abstraction and reducing recharge rates scenarios to see the impact of future potential stresses on the groundwater resources, the result shows that there is a significant groundwater level drop (on average by 31.3 meters for 50% abstraction rate increment and 19.31 meters for 10% recharge reduction) and there is a decrease in base flows to the Sibilu River, evapotranspiration flux from the area and Groundwater outflow through head dependent boundary. However, except under recharge reduction with 10% scenario the River leakage to the Aquifer system is increasing positively.

Key Words: Abay, Sibilu catchment, Central Ethiopia, Groundwater, Numerical, Modeling

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ACRONYMS

AAWSA	Addis Ababa Water and Sewerage
AAO	Addis Ababa University Observatory
AET	Actual Evapotranspiration
BFS	Base Flow Separation
CMB	Chloride Mass Balance
DEM	Digital Elevation model
DHRU	Disaggregated Hydrologic Response Units
DWL	Dynamic Water Table
EGR	Exploitable groundwater resource
ETH	Ethiopia
GDP	Gross domestic product
GHB	General head boundary
GSE	Geological Survey of Ethiopia
GW	Groundwater
GWDM	Groundwater development and management
HRU	Hydrologic Response Units
IN	Inflow
Lulc	Land use land cover
MCM	Million Cubic Meter
m.a.s.l.	meters above sea level
MMR	Mean Monthly Rainfall
OUT	Out flow
RH	Relative Humidity
SWL	Static Water Level
TGWA	Total Groundwater Abstraction
WWDSE	Water Works Design Supervision Enterprise
Vs	Versus
VI	Vulnerability indicator

1. INTRODUCTION

1.1. General Background

Groundwater plays an important role in Ethiopia as a significant source of water for domestic, bottling, industrial and /or agriculture uses. In rural areas, which cover more than 85% of the population of Ethiopia, development and utilization of groundwater is most common (Tamiru, 2006). The rural communities are using Groundwater to satisfy their demand because of its several inherent qualities; widespread and continuous availability, excellent natural quality and draught reliability, but the majorities are limited to use shallow Wells, Dug wells and unprotected springs. In recent past the use of the deep groundwater from boreholes for agriculture is almost non –existent (Tamiru, 2006).

Currently parallel to population growth, urbanization, industrialization and development advances, the food demand of people and the water demand of all sectors are increasing quickly. Agricultural yield and productivity need to be increased to provide a sustainable development and food security of the increasing population and the Government of Ethiopia is trying to utilize the groundwater resource in a better way than past trend for irrigation purpose at different location of the country including the Sibilu Catchment (Case of Horticulture/flower farming). When the groundwater is used for irrigation, industry and domestic purposes, it is necessary to maintain the groundwater reservoir in state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the wet and dry seasons. Though groundwater is a strategic resource due to its usually high quality and availability, the resource is degrading in the long term by over pumping and Climate variability (Mengistu, et al., 2021). Moreover, groundwater development all over the world often lacks development sustainability as evidenced by falling water tables, drying wetlands and general deterioration of water quality. As groundwater cannot be renewed artificially on a large scale, studying through modeling to enable a better sustainable management of this resource is vital. Sustainable groundwater development and management is to ensure quantity, quality, safety and sustainability of groundwater, which is used as a strategic source for life (for drinking and other sanitary purposes), economic development (agriculture, industry) and an important component of ecosystem (UNESCO, 2007).

Now a day as the easily exploitable shallow ground water already been taped, deep groundwater in the complex aquifers is becoming the main target for water supply of all purposes which needs complex investigations and assessment to locate the resource and its management. To do so modeling becomes scientifically more important in data scarce areas rather than manual for a wise managed development of ground water resource. Typically, the numeric modeling, which is used in the analysis of this research, has advantageous on understanding the entire flow system of the aquifer and to quantify the water budget of the upper most layer of Sibilu catchment using SWAT and MODFLOW analysis system. Modeling is an excellent way to organize and synthesize field data, and the future water management will be more trustful while analyzed on calibrated mathematical simulation model at the basin scale that more rigorously describing for the inherent variability in the material properties recharge rates, and ground water with drawls of the study area.

The application of SWAT for hydrological surface dynamics and MODFLOW modeling system for subsurface groundwater analysis in this research enables of simulating a spatiotemporal distribution of groundwater recharge rates, aquifer evapotranspiration, and groundwater levels. It also enables to understand an interaction between the saturated aquifer and stream networks of Sibilu river catchment together with the impact of future potential stresses.

Thus, it is believed that this research plays an important role toward the sustainable development and use of water resources in the Sibilu catchment.

1.2. Statements of the Problem

Under the reconnaissance study of Water III project in 1984 which was undertaken by AESL for all potential water supply sources located within a radius of 50 km distance from Addis Ababa alongside with the expansion and rehabilitation activities on the existing surface water resources and treatment plants: the Sibilu and Gerbi dam developments have been identified as the principal potential surface water sources in the adjacent reaches of the Abay basin for supplying Addis Ababa city and environs (AAWSA, 2005).These surface water sources are highly interconnected with the groundwater of the catchment and according to (Bereket F. , 2015) study, even the wetland of Sibilu catchment are originated mainly from groundwater during the dry season. Thus, the long season flow of the Sibilu River to the proposed dam reservoir could probably be a base flow of this river and this will impose its stress on the groundwater of the catchment.

At present more pressure is coming to the groundwater resources of the catchment in a form of commercial farming (flower farming), in time increasing consumption due to increment of Sululta, Mizan and Chancho town's population with surrounding villages, expansion of groundwater consuming and demanding industries and bottling. In addition, AAWSA, exploring the groundwater of Sibilu catchment associated with drilling of test wells and, proposed surface water of Sibilu and Gerbi rivers together with Sibilu catchment groundwater, as one of the possible future water supply of Addis Ababa and the surrounding area (Bereket B. , 2006). Despite its high value and future importance, the whole Sibilu catchment has not been well studied through numerical modeling.

As there is no sufficient information for the annual ground water recharge, total groundwater withdrawals through different means, interactions between ground and surface water of the catchment and an entire clear groundwater flow situation of the Sibilu catchment at the basin scale, it is vital to assess and evaluate the current groundwater rate of recharge, groundwater evapotransparation, extraction, its flow dynamism and the impacts of the potential future stresses on groundwater flow and head through numerical groundwater modeling approach. Finally, this helps to contribute its part to insure the sustainable groundwater development of the area under the existing consumption and ongoing conditions.

Therefore, this research is numerically model the groundwater flow system of Sibilu catchment and come up with appropriate recommendations and findings.

1.3. Objective of the study

1.3.1. Main Objective

The primary objective of this study is to numerically model the ground water flow system of the Sibilu catchment, under steady state condition, using SWAT and MODFLOW analysis techniques for sustainable groundwater development of Sibilu River Catchment and finally, to come up with better recommendations based on research findings

1.3.2. Specific Objective

The specific objectives include:

- ☐ To Develop the conceptual model of Sibilu Catchment
- ☐ To simulate the hydraulic head and groundwater flow system of the study area
- ☐ To develop steady state scenario
- ☐ To approximate the Ground and Surface water interaction

1.4. Research Questions

To attain the Specific and principal objectives of the research the following questions has to be answered:

- How the simplified hydrogeology and hydrology of Sibilu catchment does conceptually appears?
- How are, the hydraulic head and the spatiotemporal distribution of groundwater flow occurs in Sibilu river catchment?
- What would be the response of groundwater flow component and hydraulic head for scenarios increase in Groundwater abstraction and decrease in recharge rates?
- Is there the Surface and Groundwater exchange in the study area?

1.5. Significance of the Study

The finding of this study offers detailed understanding of the characteristics of the aquifer parameters, the rate of the groundwater recharge, responses of stresses for different scenarios and the groundwater distribution and flow simulation of top aquifer. If the groundwater flow system is modeled as much as possible, managing the resource development will be easier and a bit help decision makers to make relatively precise decisions regarding the groundwater resource of the Sibilu River catchment. From detailed study of this research: Governmental, none- governmental and private organizations which are involved in agricultural practices, groundwater development and bottling, investors who desire to invest in agricultural activities using groundwater resource of the area will have a clear understanding about the available exploitable amount of groundwater and groundwater flow circumstances in the top Aquifer layer of the catchment. It allows improving the rational utilization of ground water resources and able to plan the development activities align to the identified available resource. And in this manner the study is contributing to a development.

The primary and secondary data that have been collected and analyzed in this study will help as a secondary information for the future different regional to detailed scale groundwater studies of the catchment and its periphery, and moreover contribute its part in base flow enhancement, hydro ecosystem/wetland restoration of the catchment.

1.6. Scope of the study

This study covers the numerical groundwater flow simulation of a top aquifer layer, under steady state conditions in the Sibilu River catchment by using SWAT, MODFLOW, ArcGIS and other related softwares to understand the groundwater flow system of the catchment. It also includes the development of steady state scenarios in increasing abstraction and decreasing the recharge rates to observe the impacts of the potential future stresses on groundwater flow and head. This study surly enhances the sustainable groundwater Development and Management conditions of the catchment, for different purposes. It is a simplification of the “real world” ground-water flow system of the catchment.

2. LITERATURE REVIEW

Entirely there are a limited previously conducted written works in the study area at the Sibilu river catchment scale. However, still there are considerable literatures those were previously studied in the catchment largely focusing at the Sululta Town and Nestle _Abyssinia water bottling JV Company. The Government line offices also carried out some local studies for the purpose of site selections of borehole, spring development, and hand dug well constructions.

2.1. Hydrogeological Studies

Hydrogeologically AAWSA & AESL (1984) carried out reconnaissance survey and identified Sibilu catchment as regional water resources potential for Addis Ababa water supply under project study II, while Seureca, (1991) conducted the feasibility study of Sibilu and Gerbi river dams together with the preliminary design.

(Debebe, 2005), Classify the water bearing formations of the catchment in to three hydrostatic units based on the aquifer characteristics. Accordingly the area covers the central part along the stream fracture lines with transmisivity greater than 27.4 m2/day and yield ranges from 2 to 4 l/sec was classified to high productive zone, while acidic lava flows of Entoto ridge with transmissivity values ranges from 1.12 to 4.49 m^2/day & aquifer yields in the ranges of 0.5 to 1 l/sec was also mapped as low productive/permeable zone and the remaining areas with transmissivity 4.49 to 27.4 m2/day was identified as a moderate permeable/productive zone. The resistivity survey which carried out during this study in the catchment showed the depth of ground water goes to a depth of 120 meters and the identified predominant aquifer was weathered and/or fractured basaltic lava flow. Under this study groundwater potential of the catchment was identified as more localized along fractured and weathered part of the rocks.

(Trufat, 2001), did a Geotechnical and engineering geological investigation of Sibilu catchment and showed that the geotechnical and engineering geological characteristics of Soils/rocks exposed at dam site, reservoir and catchment area as mostly a suitable for the proposed surface water damming.

(WWDSE, 2008) Carried out the Ade'a Becho Plain hydrogeological and water resource study including Sibilu catchment.

(Bereket F. , 2015) had conducted the valuable works in identifing the origin of the Sibilu catchment wetlands those are observed here and there in the catchment using ^{222}Rn and δ^2H and

$\delta^{18}O$ Isotope methods. Accordingly, the wetlands are originated from both surface and groundwater, but mainly from the groundwater.

(Tilahun, 2014), Studied the Groundwater Dynamics in the Left Bank Catchments of the Middle Blue Nile and the Upper Awash River Basins which are covering: Jema, Muger, Guder and upper Awash River basins. By this investigation, unique groundwater flow pattern that indicates inter basin groundwater flow from the Blue Nile to the Upper Awash basin has been obtained at a regional scale, and estimate the horizontal annual groundwater inflow of 152 Mm^3 to the Upper Awash groundwater basin which was obtained from the regional groundwater flow model, and those findings, authenticate the inter basin groundwater flow conceptualized from litho-structural and hydrodynamic characterization.

(Behilu et al., 2021), included the Sibilu area as planned surface water reservoir during Impact of Natural and Anthropogenic Stresses on Surface and Groundwater Supply Sources of the Upper Awash Sub-Basin, Central Ethiopia study.

Previously Geological Survey of Ethiopia, (2010) carried out the hydrogeological mapping of Addis Ababa Map Sheet (NC 37-10) in 1:250,000 scale and covers parts of Oromia National Regional State, Amhara National Regional State and Addis Ababa city administration and even if it is a small scale, this Map Sheet incorporates the Sibilu catchment. In this work the hydrogeological units of the area classified into different productivity zones.

Metaferia Consulting Engineering PLC conducting a geotechnical Investigation at Sibilu Dam Water Supply project commencing from 2018, and still borehole drilling and laboratory investigations are ongoing.

2.2. Groundwater modeling

However, regarding numerical groundwater modeling the existing of previously studied literatures are almost none (Bereket F. , 2015). On the other hand, there are a number of numerically modeled areas and researches elsewhere in the country either far or adjacent to the current study area.

3. METHODS OF THE STUDY

This research work has been carried out by qualitative/Descriptive and quantitative methods and entirely the method could be classified in to three major categories. The first category illustrates the secondary data collection and organization. This phase is followed by field investigation and primary field data collection phase. The final stage of the study will be the data integration, analysis, interpretation and result generation phase to identify the groundwater flow system by using ArcGIS routine, SWAT and MODFLOW modeling softwares. Finally the steady state scenarios has been developed based on the calibrated Groundwater flow model results The overall procedures that were followed in this research are presented in figure 1 below.

3.1. Data Collection

During data collection phase different relevant data types have been collected from different sources. This includes:

- Weather data from Ethiopian Meteorological agency or from Climate Forecast System Reanalysis (CFSR) web site.
- Existing boreholes with Well drilling completion history, hand dug wells, Cold Springs, Geophysical survey data: Vertical Electrical Sounding data, Water quality and population data of the study area were collected from, AAWSA, Oromia Special zone water Bureau, Sululta and Chancho city Administration water offices and local private organizations (Water bottling, Drilling companies and Consultancy firms)
- Previous groundwater related studies from universities and research institutes
- Geological, hydrological, hydrogeological investigations and maps from geological Survey of Ethiopia and WWDSE

Soil map, land use land cover maps and DEM were collected from Ministry of Agriculture, while river flow data were collected from Ministry of Water, irrigation and Energy. In addition to these, to fill the data gap and strengthen/refine the data quality and an appropriate coverage of representative data acquiring distribution, primary data including inventory of some wells, River package data (river channel length, width and riverbed material thickness), discharge of some springs and hydrogeological conditions have been assessed in details, through field survey.

Different instruments like Deeper to measure groundwater level, Tape meter (50 m), Ec meter to measure the Total dissolved Solids of water, one litter size plastic bottles to collect water samples from different sources for hydrochemical analysis and GPS to locate Water points were used during field data collections.

3.2. Data Analysis

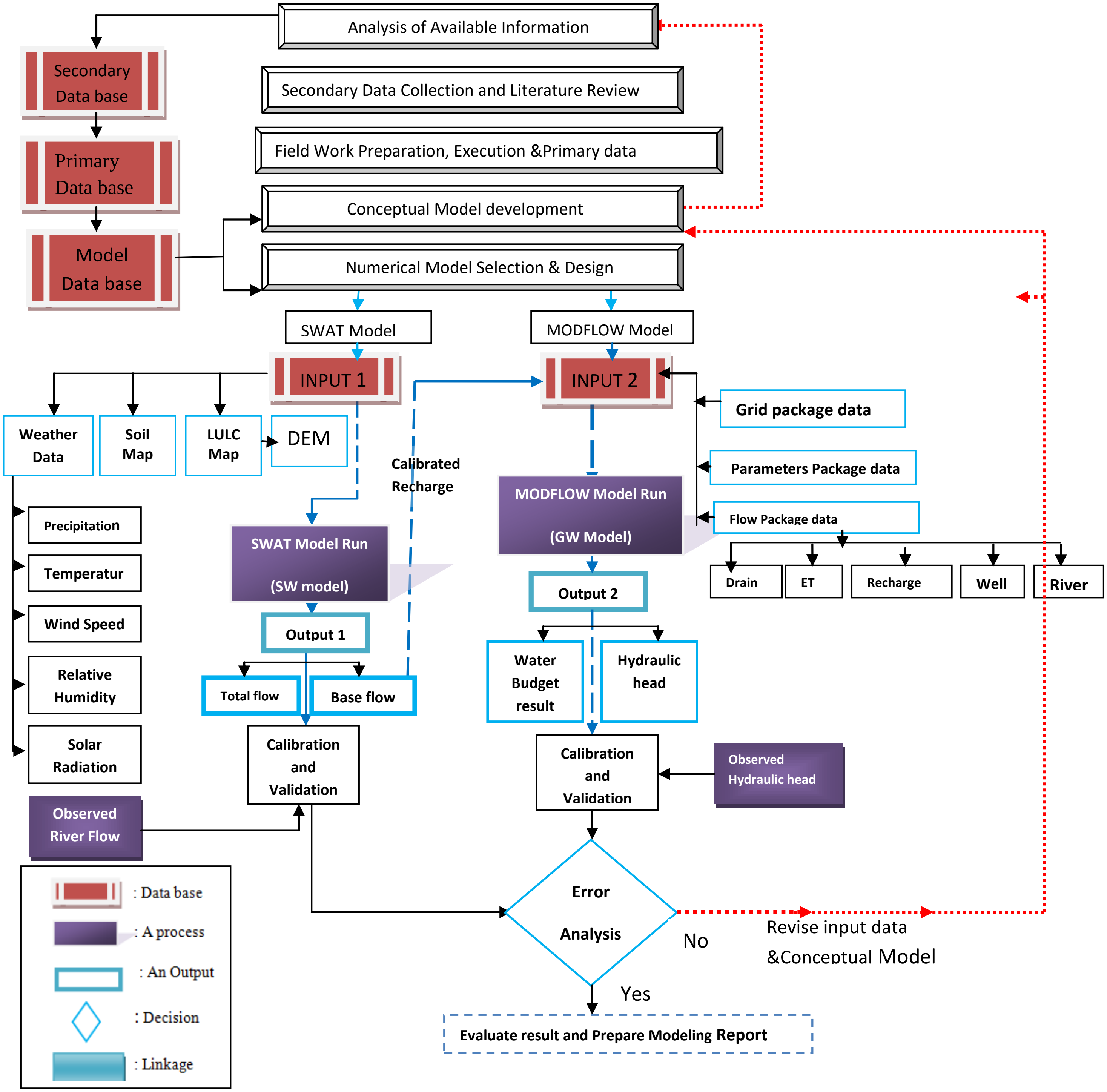
After the field work, data compilation, analysis and interpretation were conducted to construct a steady-state groundwater flow models and calibration of the models.

After building the database required for the model, the next step is developing a conceptual model using a geological formation, geological structural Map, Hydrogeological information (in and out flow components), Topographic Contour maps, well log and VES data. Those all data were analyzed to determine the aquifer thickness, total model layer thickness, number of model layers, water point distribution and groundwater flow direction.

Next to conceptualization of the catchment, groundwater recharge and ET were estimated by using SWAT model, Chloride Mass Balance and Base flow separation methods. SWAT model uses Soil map, Topographic slop/DEM and land use land cover info jointly with their associated lookup tables in an appropriate format to develop or classify the area in to an Hydrologic Response Units (HRUs) and Sub basins together with catchment delineation and Reach development. Additionally, by using the weather data (precipitation, max and min temperature, Wind speed, Relative humidity and solar radiation) in a daily basis as an input for SWAT Model, it simulates the groundwater recharge distribution and Evapotranspiration in each Hydrologic Response Units/Sub basins. SWAT model calibrated and validated with monthly observed flow of Sibilu River in order to optimize the output simulated flows nearly to the real natural one and the model performance or calibration process evaluated with statistical error evaluation indices (ME, AME and RMSE) and scattered plot graph.

Then the calibrated SWAT output i.e recharge and ET were employed to the MODFLOW as input to model the groundwater.

Aquifer thicknesses and hydraulic property (Transmisivity, conductivity, hydraulic head and etc) maps of an aquifer were processed by interpolating point well data to the entire study area and exported to ASCII files through ArcGIS tools to use as an input files for MODFLOW. Then finally, the Modflow modeling was developed including set boundary conditions, layer parameters, Well packages, River packages and discretization of the model area. MODFLOW calibrated with observed hydraulic heads by varying the hydraulic conductivity of the area in manual tray and error methods until the simulated head nearly much with the observed hydraulic heads and re-run the model to find the entire calibrated water budget of the catchment. See the framework of the method below in Fig.1.



By:Astatike .K

Figure 1. Conceptual frame work of the study

Then, after calibrating the model results, the population and demand for water had been projected to 15 years a head to see the impact of future potential effect for increasing abstraction and decreasing the recharge rate scenarios on the groundwater head, and Groundwater movement.

Table 1 Necessary data type that to be analyzed under MODFLOW system

No	MODFLOW Packages	Necessary data for the Packages	Remark
1	Grid Packages	Mesh size, Layer type (confined or unconfined), Cell Status/Ibound (boundary conditions), Elevation of Top and bottom layers	
2	Parameters Package	Time, initial hydraulic head, Horizontal hydraulic conductivity, Effective porosity	
3	Flow Packages		
3.1	Drains	Drain hydraulic conductance (m^2/d), Drain Elevation and location	
3.2	Evapotranspiration	Daily ET	
	Recharge	Daily Recharge	
3.3	Well	Water Well location and abstraction rate	Location in terms of rows, column and layer (i,,j& K)
3.4	Rivers	River hydraulic conductance, head in the river, and elevation of river bed bottom	
3.5	GHB	Hydraulic conductivity in the cell(k), Boundary length perpendicular to the flow direction (L), Distance from the GHB to the model boundary, Aquifer thickness in the cell (W) & GHB Elevation	

4. DESCRIPTION OF THE STUDY AREA

4.1. Location

Sibilu River is a perennial river draining a catchment area of about 64,955 hectares/ 650 km^2 at upper catchment of Muger basin. It is found in the northwestern plateau of Ethiopia, situated in Oromia regional State, Special zone, District of Sululta (Figure 2). Geographically, it is bounded by 9^{o}5'8.23''and 9^{o}27'26.7'' North latitude and 38^o 33'28.453'' and 38^o 49'55.207'' East longitude within zone of 37-northern hemisphere and far about 27 km from Addis Ababa.

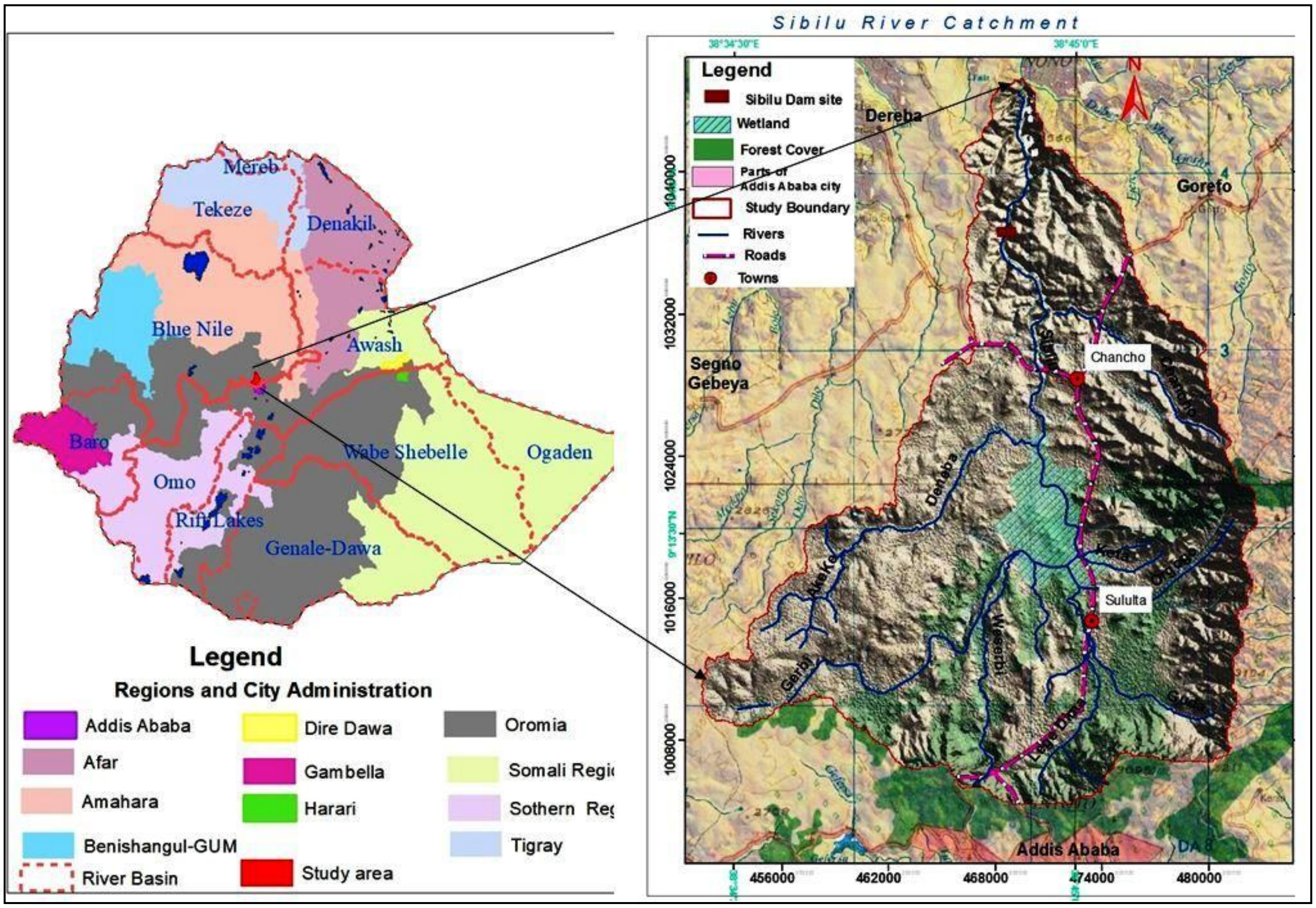
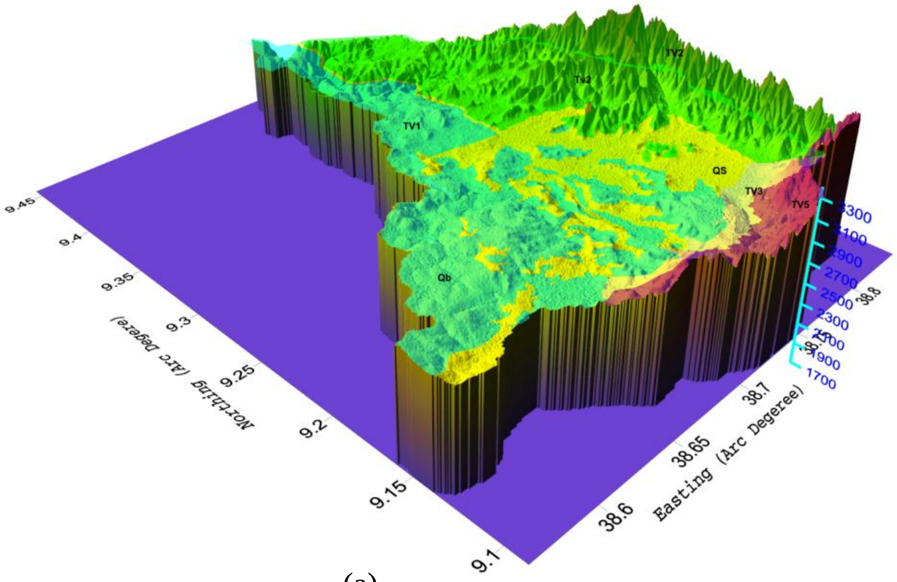


Figure 2.Location map of Sibilu River Cachment

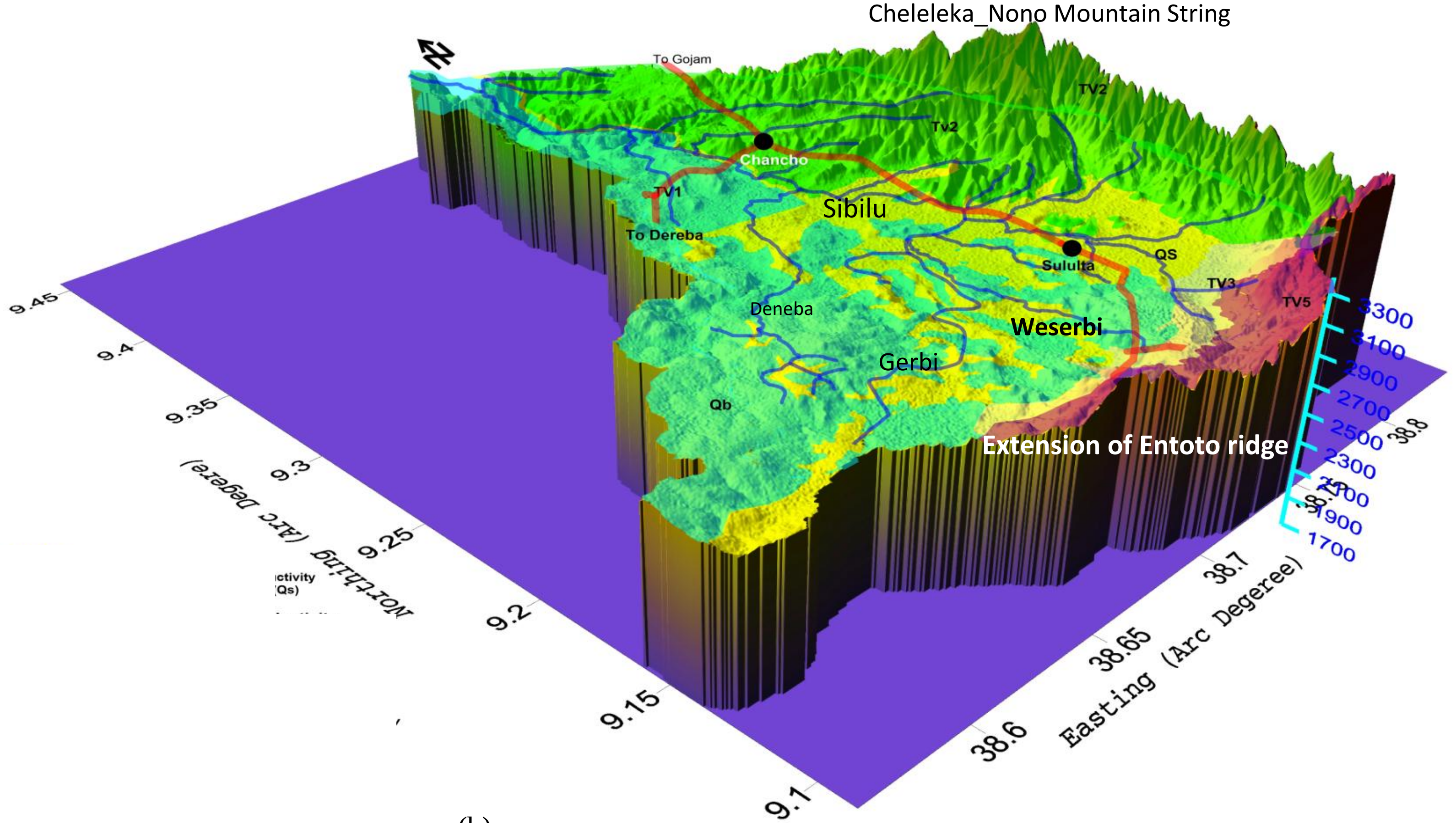
4.2. Physiographic features and Drainage

The study area is physiographically belonging to the northwestern plateau of Ethiopia, which is resulted from the development of Main Ethiopian Rift system during Miocene (Bereket F. , 2015). The area is predominantly composed by two distinct geomorphologic features, these are flat lands and hill domes, but also small part of the area comprises undulating terrain and river gorges. It is in the Blue Nile River drainage basin which is very close to the Entoto Mountain chain, a regional water divide between Awash and the Blue Nile River basin. Sibilu River catchment drains towards the northwest crossing the central flat plain and bounded by Cheleleka_Nono mountain chain in the east, Entoto in the south and undulating terrain with River gorges in the northwest.

The elevation of the area ranges from 1420 m.a.s.l at the downstream of Sibilu River to 3400 m.a.s.l. at the picks of Cheleleka Mountain (Figure 3), where a number of streams are originated and flow towards the northwest and west parts of the study area. The northwest and west flowing rivers are merge together near Chancho Town to form a broad and deep dissected gorges and farther down too where totally Joins the Muger River canyon. The River Sibilu which is the major stream in the project area originates from Laga Dima, Guda, Orgogo, Weserbi, Gerbi, Deneba and Chancho intermittent streams/tributaries in the project area. See fig 3 (a) and (b).



(a)



(b)

Figure 3 (a) and (b). 3-D Physiographic features and drainage pattern of the study area

4.3. Climatic conditions

As any parts of Ethiopia, the climatic condition of the area is the result of altitude and seasonal migration of Inter Tropical convergence Zone (ITCZ) (Tamiru, 2006). Based on the factors, the Ethiopian climatic zones are defined by five traditional climatic zones (EMA, 1988).”Kur” (Alpine), ranges from 3000 m and above; “Dega” (temperate), 2000 m to about 3000 m;”Weyna dega” (Sub tropical), 1550 m to about 2300 m, “Kola” (Tropical) ,800 m to about 2300 m; and “Bereha” (Desert), less than 800 m above mean sea level. Except the Tropical and Desert climatic conditions the study area experiences the rest three climatic conditions in its different parts based on the Rain fall distribution and existing altitudes. See figure 8 for spatial distribution rain fall in the catchment.

The study area is characterized by two different rain fall patterns which is called a bimodal (two peaks)(Graph 1).The main wet season locally named Keremet, extends from June to September while the minor rainy season which is locally called Belge, contribute the moisture to the region from mid February to mid April. See the details about weather and hydrologgical conditions under section 7.2 which are analyzed for SWAT input purposes.

4.4. Geological and Hydrogeological Settings

4.4.1. Geology

4.4.1.1. Regional Geology

Regionally the oldest rock in the country, which forms the basement, is of Precambrian age. Overlaying this basement formation the Mesozoic Sedimentary succession and/or Cenozoic Volcanic rocks occurs, except where the basement rocks are directly overlain by Paleozoic Sedimentary rocks (like Edaga Arbi glacial), quaternary deposit or simply exposed to the surface.

The largest part of the country (about 32%) is covered by volcanic rocks of different ages and types. One can categories these volcanic rocks based on various criteria such as age (tertiary and Quaternary Volcanic) and taking the rift formation/occurrence as a reference (pre rift/Trap series and post rift/Aden Series volcanic).Trap series represent the oldest volcanic rocks in Ethiopia compared to the Aden series volcanic occurrences.

The major uplifting followed by cracking of Horn of Africa gave rise to the formation of Trap series and consists of mainly flood basalt with some trachytes and rhyolites, especially on its upper part. Trap series is hardly distinguishable from the Aden volcanic series based on the peterographic analysis, Mohor, (1971) and somehow based on morphological distribution. Accordingly, the Trap series predates the rift faulting and usually occupies a great height of the Ethiopian plateau, whereas the Aden volcanic series are associated with Well –preserved volcanic cones or lava flows Mohor, (1971).The Trap series which forms the northwest and southeast plateau reaching its maximum development in the central Ethiopia attaining a thickness of up to 3 km (Mengesha et al., 1996) and generally the central Ethiopia ,including current study area the regional geological occurrences are described in the table below from the youngest to the oldest units.

Table 2. Summary of Geological formations that surrounding the study area as a regional view

No	Geological Units of Central Ethiopia	Age (Era)
1	Quaternary plateau basalts of central Ethiopia and Quaternary supper facial deposits (Qb &Qs)	Quaternary
2	Wechecha-Yere-Furi ignimbrite/trachyte & tarchy basalt (Tv6)	Tertiary
3	(Entoto mixed rock) Entoto rhyolite, trachyte and ignimbrite (Tv5)	
4	lower ignimbrite (Tv3)	
5	Tarmaber basalt (Tv2)	
6	Aiba basalt (Tv1)	
7	Upper sandstone (Deberelibanose sandstone)	Mesozoic
8	Muger mudstone formation	
9	Antalo limestone	
10	Gypsum (Gohatsion formation)	
11	Lower sandstone(Adigrat sandstone)	
12	Paleozoic sandstone	Paleozoic
13	Meta-gabro Granite	Precambrian
14	Biotite hornblende gneiss	
15	Biotite gneiss	

4.4.1.2. Site Specific Geological Characteristics

Locally the central part is characterized by typical flat plain and covered by Quaternary elluvial soil (QS) and Quaternary volcanic rocks (Qb).The Entoto Mountain is covered by Entoto mixed rocks (Rhyolite and trachyte (Tv5)) while Cheleleka_Nono mountain chain is covered by Scoracious Tarmaber volcanic formations (Tv2) (Fig. 4).

Quaternary superficial deposits (QS): This unit comprises mainly the eluvial wind deposit and small amount of alluvial deposit along Sibilu river valley. It is mainly covering the central part of the area and on average it is 9 meter thick.

Plate 1. Elluvial superficial deposit at eastern part of Sululta Town

Quaternary plateau basalts of central Ethiopia (Qb): This unit is exposed in southwestern part of the study area. It is characterized by grey color on fresh outcrop and reddish brown while weathered. In most case it outcrops in boulder form and vesicles filled by clay and/or Calcium Carbonate secondary materials as observed during assessment.

Plate 2. Bolder forming Vesicular Quaternary Basalt of the study area

Entoto Rhyolite and Trachyte (Tv5): The Entoto mixed rocks are found in the southern part of the study area. This unit constitutes ryholite, trachyte and massive ignimbrite. This lithologic unit is highly affected by joints trending E-W. It forms high mountain chain called 'Entoto' trending E-W (Assiged, 2007).

Plate 3. Trachyte formation and alpine vegetation of Entoto Mountain string

Lower Ignimbrite (Tv3): This unit is exposed in southern part of the study area underlying the Entoto mixed formation. It consists of interlayer of ignimbrite, ash and tuff. It is grey and black color and shows columnar jointing having medium to fine grained.

Tarmaber Megzeze basalt) (Tv2): This basalt is exposed in eastern parts of Sibilu river catchment. It mainly forms gentle slope plateau lands resulted from fissural eruption. In some localities it forms an extensive ridges and mountains (such as Cheleka Mountains) and as observed it is underlay unconformably the lower ignimbrite. It exhibits fine to very coarse grained, aphanitic to porphyritic and sometimes very coarse grained phorphyritic basalt and mainly vesicular basalt. The rock shows high degree of weathering and fracturing.

Aiba Basalt (Tv1): This unit is exposed in northwestern part of the study area, including in river valleys and canyons. It mainly forms steep slope cliffs and sometimes gentle slope.

This basalt has a dark grey color on fresh outcrops. Up on weathering, it has dark-brown, gray and reddish-brown color. In general, this basalt is characterized by well-developed columnar joints with hexagonal faces, and cliff forming. See figure 4 and plates below.

The natural and weather modified natures of the geological formation in the study area are playing significant roles to make the formations better, in Groundwater holding and transmission capability.

Plate 4. Columnar jointed and fractured brown and dark Aiba basalt (Hiko locality)

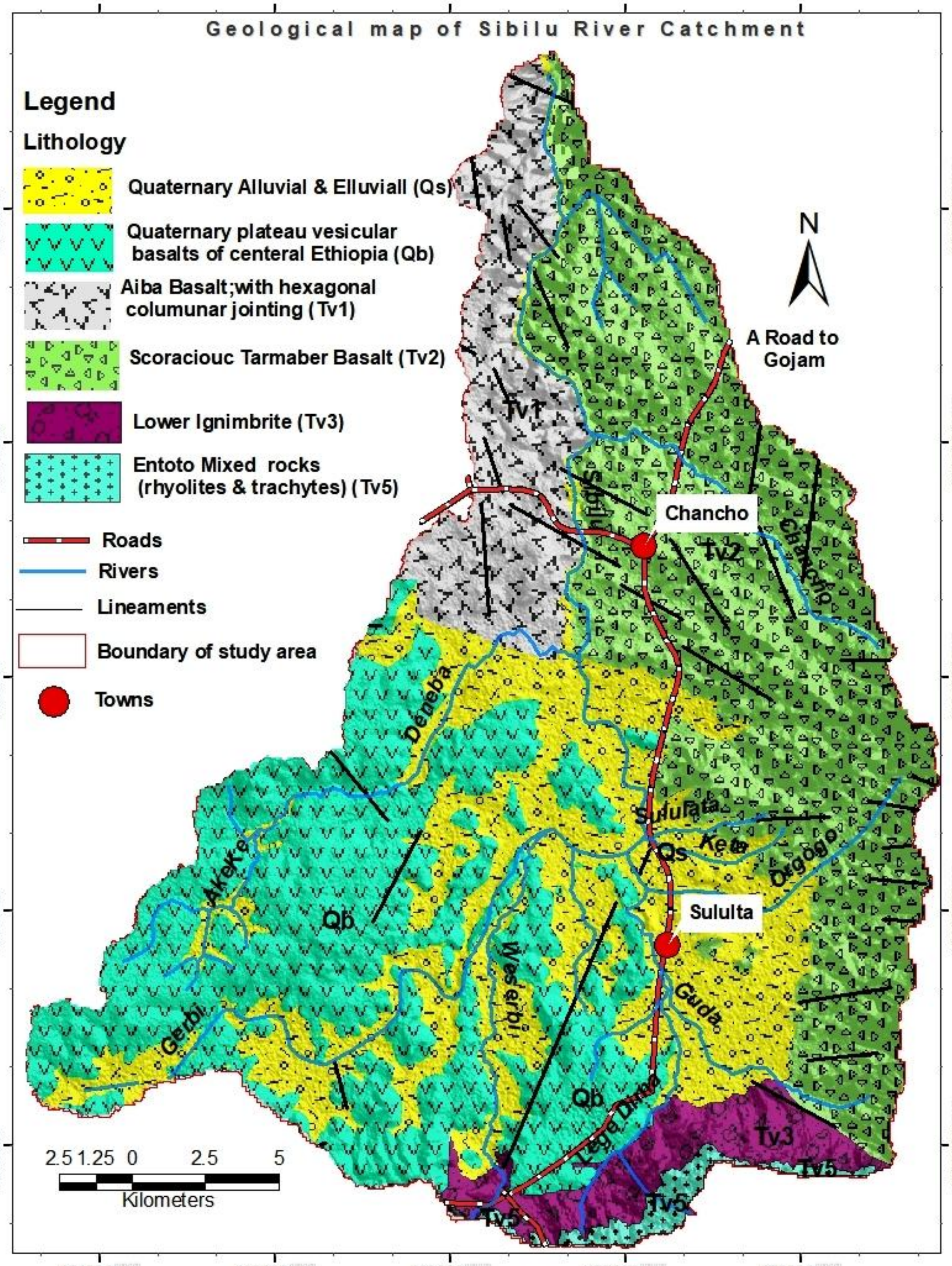


Figure 4. Geological formation of the study area (Modified after GSE, 2009)

4.4.2. Hydrogeology

4.4.2.1. Hydrogeological characteristics and Aquifer System

Aquifer properties and groundwater flow patterns have been characterized using hydraulic properties of rocks from geological formations and well tests. As cited by (Tilahun, 2014) both primary and secondary porosities of rocks play significant role in groundwater occurrence, localization and flow, particularly in hard rock terrains (Todd D.K., 1976). As mentioned above under geological explanation session Volcanic rocks mainly basalts of different nature, trachytes, rhyolites and Ignimbrite are the dominant rocks that outcrops in the study area. From hydrogeological point of view the existing geological formations are classified in to five hydrogeological units, these are:

- Shallow porous Aquifer with moderate productivity developed on Alluvial and Elluvail Sediment (Qs).
- Fissured Aquifer with moderate to high productivity developed on Scoracious Tarmaber Basalt (Tv2).
- Fissured Aquifer with moderate Productivity developed on Tertiary Aiba and Quaternary Basalt (Tv1 and Qb).
- Fissured Aquifer with low to moderate productivity developed on lower Ignimbrite (Tv3).
- Aquitared developed on Entoto rhyolite and trachyte (Tv5) (Figure 5).

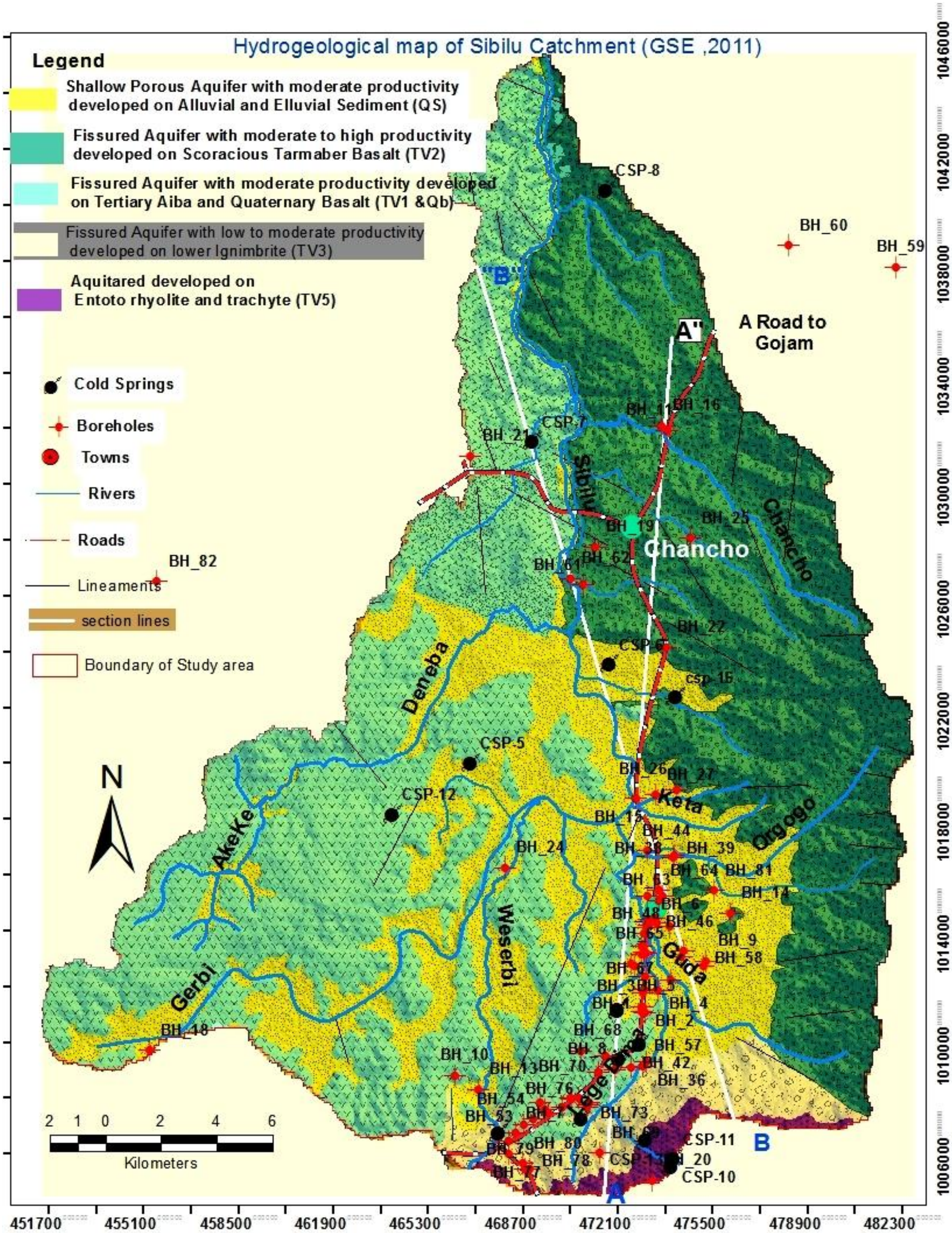


Figure 5. Hydrogeological map of Sibilu Catchment

4.4.2.2. Groundwater occurrence and flow

The moderate to high productive Fissured Scoracious Tarmaber volcanic aquifer and Moderate Productive fissured volcanic Aquifer (developed on Aiba and Quaternary vesicular basalt) are the main and dominant Aquifers of the study area while Shallow porous Aquifer with moderate productivity developed on Alluvial and Elluvail Sediment (Qs) is a superficial and thin deposits. Thus, it has an insignificant role on the main groundwater movement and occurrence in the catchment except possessing soil water which is mostly developed in the form of Hand Dug wells. The groundwater of the area is discharging through Hand dug wells, Boreholes, cold springs and base flow to the stream beds as observed during field assessment (plate 2).

Plate 5. Boreholes (BH 15 &13), Cold Spring and, One of Hand dug well developed on Shallow porous Quaternary Elluvial

As evidenced from different well logs also the low permeable, slightly weathered and fractured rock is separating a series of highly weathered and/or fractured aquifers makes the system to consider it as Semi confined/leaky Aquifer system. The observed hydraulic head distribution in the catchment also shows the hydraulic head gradient is towards NW of the study area and the wells in the area yield from 0.3 to 27 l/s in different localities.

According to (Tilahun, 2014) the groundwater of Sululta area is modern aged water as evaluated with carbon dating and this indicates that the relatively shallow groundwater i.e up to 350 meters deep is not traveling from far distance while the deepest one may flow to the adjacent basin.

Table 3. ^{14}C activity and groundwater ages in years (Source: Tilahun Azagegn, 2014)

ID	Locality	T^0C	pH	Alk	a^{14} C (pmc)	**δ^{13}C (%)**	Conv.age	Age from Pearson
BHT001	Legedadi	28	8.10	225.46	15.80	-10.05	15505	12910
BHT002	Muketuri	19	7.30	188.44	90.20	-11.96	1072	Modern
BHT003	Akaki	22	7.86	345.90	66.00	-8.79	3708	178
BHT004	Jemo BH24	22	7.84	197.64	59.80	-9.57	4510	1571
BHT005	Ginchi	21	8.23	384.30	66.60	-7.76	3650	Modern
BHT006	Meleka Kuture	31	7.71	319.47	49.00	-10.10	6148	3588
BHT007	CMC	22	7.98	209.80	74.90	-8.08	2674	Modern
BHT008	**Sululta**	**18**	**7.30**	**85.05**	**80.9**	**-9.65**	**2010**	**Modern**
BHT009	Derba	19	7.50	183.00	49.10	-9.06	6148	2828
BHT010	Salayish	22	8.02	274.50	24.90	-9.21	11759	8552
BHT1011	Inchini	17	7.10	143.30	90.90	-12.00	1008	Modern

5. GROUNDWATER MODELING OF SIBILU CATCHMENT

5.1. General overview

Groundwater flow modeling is a mathematical representation of groundwater flow through an aquifer which simulates and predicts aquifer condition. It is a simplified representation of the complex natural world (Wang and Anderson, 1982). The science of groundwater modeling includes basic modeling theory and numerical solution methods and enables to understand the basic groundwater flow systems and characteristics of the past, present and future forecasting.

Entirely Groundwater modeling process possesses 6 to 8 working stages to simulate the groundwater flow system of the target area (Fig. 6).

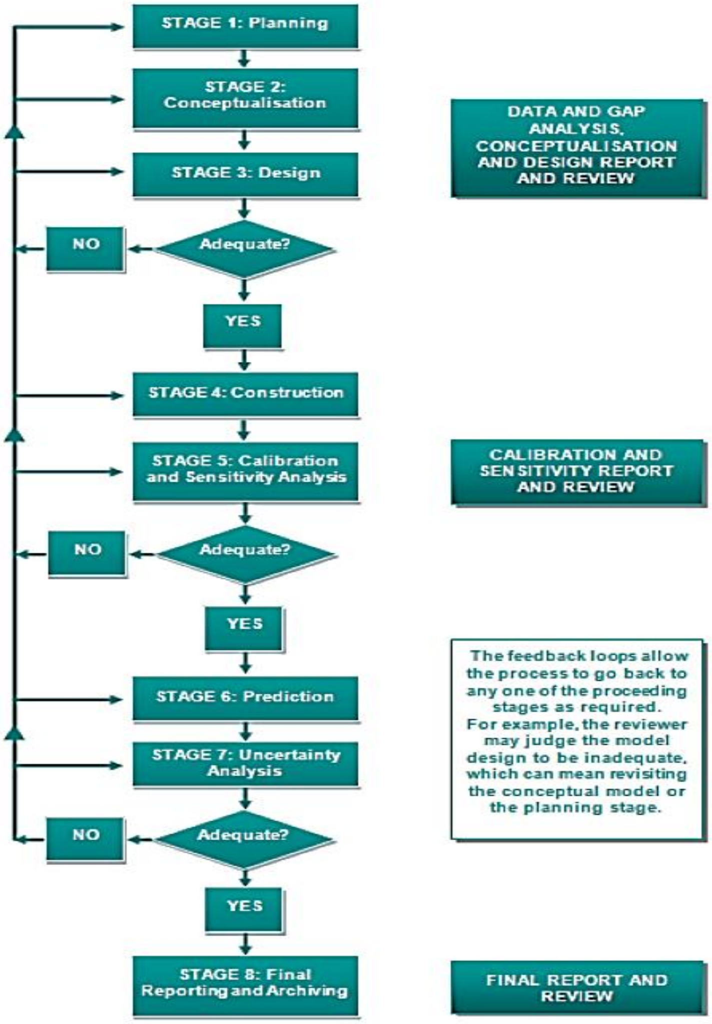


Figure 6.Groundwater modeling process (Australian Groundwater modeling guidelines, 2012)

5.2. Conceptual model Development

A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross-section (Anderson M.P and Woessener, 1992). The development of a conceptual model depends on the amount of data available, the model scale, the purpose of the model and the simplicity or complexity of the area under study. After building the database required for the model, the next step is developing a conceptual model and this is the crucial part of the modeling process.

The conceptual model development of Sibilu water shed system is arrived at from detailed studies and investigations of geology, hydrogeology, borehole lithology and water level in the wells (Table 4).

Table 4. Parameters considered in conceptualization of the system (Aquaterra ,consultant, 2000)

Features	Description	Comment
Boundaries	Location and type of boundaries for the area to be modeled	Boundary types include specified flow, specified head/initial head, and head dependent flow
Geological framework	Geological units with hydro-stratigraphic units, model layers, and hydro-geomorphological zone.	Geological units with similar aquifer properties combined in to one hydrogeological unit or model layer and a single geological unit may be subdivided into different aquifer units or many layers
Hydrological framework &stress	Recharge and Discharge mechanisms/processes and dominant aquifer flow mechanisms	Defining of Aquifer media type (porous and fractured medium). Surface-groundwater interaction process
Human_ induced factors	Anthropogenic influences on the system	Pumping out, drainage etc

Except degree of weathering and fracturing the penetrated basaltic formation in the area is more or less hydrogeologically similar and considered as a single, semi-confined Aquifer and this weathered and fractured basaltic hydrogeological unit is tilted towards the northwestern part of the study area, and as well, the groundwater of the area is found to be occurred in this unit.

As evidenced from lithological logs of drilled test wells (BH_15&BH_16), weathered, fractured and vesicular hydrogological unit is continue alternatively to the depth of 880 meters, however most of the wells in Sibilu Catchment drilled in between 200 to 400 meters deep and the total model layer thickness adjusted to 350 meters depend on the availability of necessary data to run the model. The static water level in the area ranging from artesian to 81.25 m deep and recharged vertically only from direct precipitation.

Using the above all information, the conceptual model along the probable groundwater flow direction (Section AA' and BB") have been developed and shown in the subsequent section (Fig 7a&7b) which describes how water enters, flows through and leaves the aquifer system.

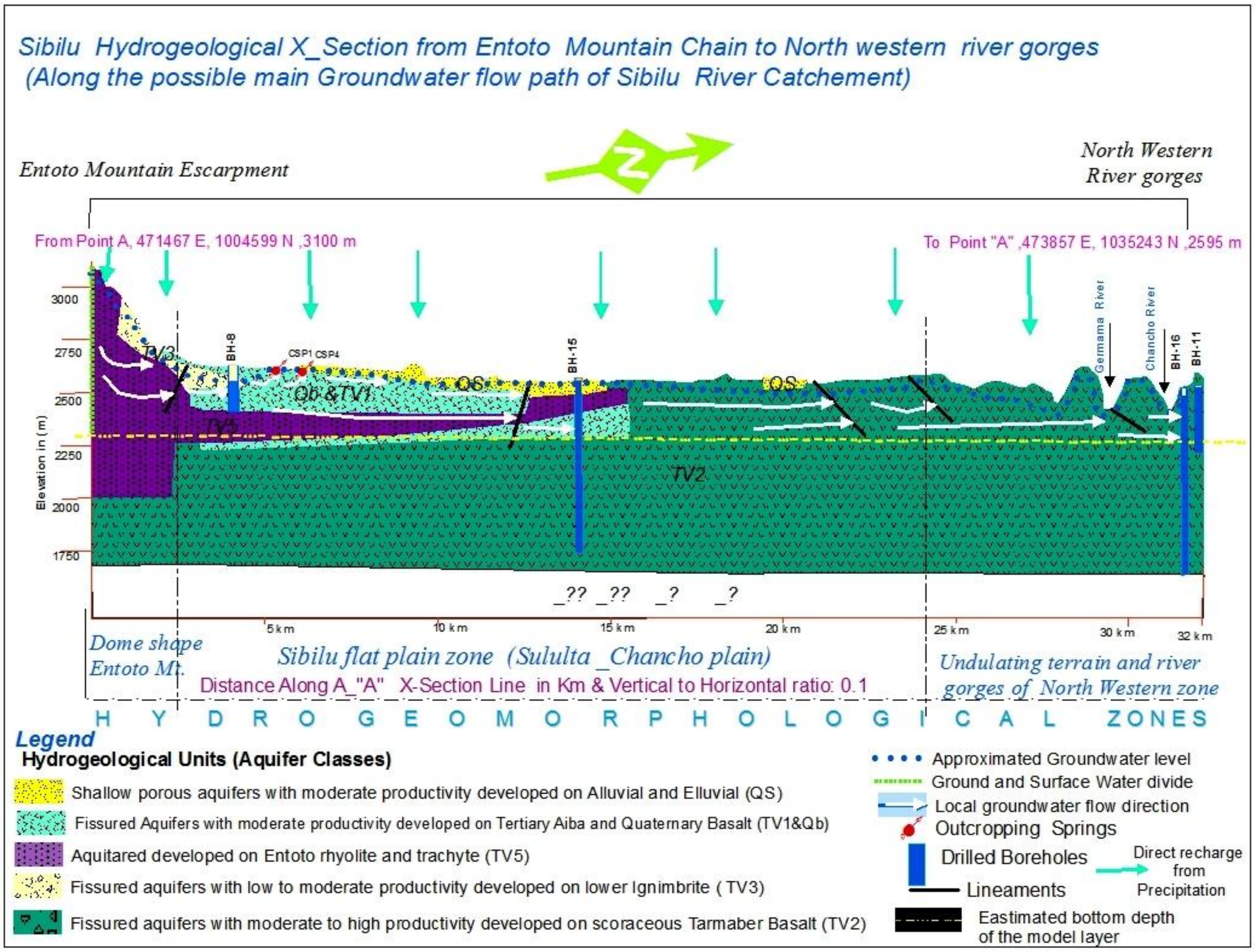


Figure 7a. Conceptual model of Sibilu catchment developed on 2D Hydrogeological cross-section AA'

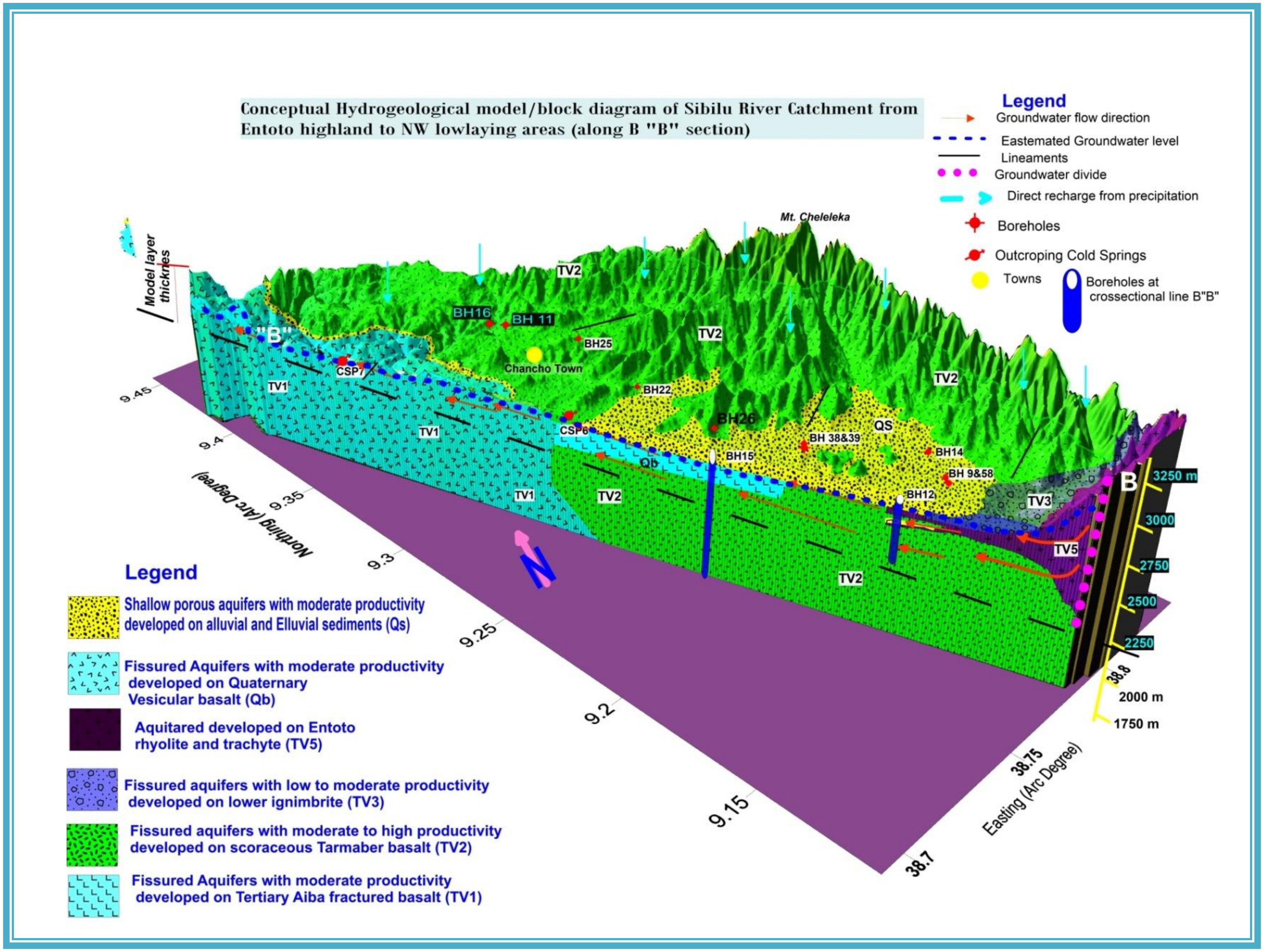


Figure 7b. Conceptual model of Sibilu catchment developed on 3D Hydrogeological cross-section BB”

5.3. General Assumption and Limitations

The study generally covers the numerical groundwater flow Simulation of a topmost aquifer layer, under steady state conditions of Sibilu Catchment to understand the groundwater flow system and to enables acceptable and sustainable groundwater Development and Management conditions of the catchment, for different purposes.

The model of the study area is a simplification of the "real world" ground-water system, which is the case of all groundwater-flow models and has corresponding limitations in model precision and how the model can be used. For example, the MODFLOW model cell lateral discretization is a rectangular 200 meter by 200 meter while a vertical discretization is forced to a single semi-confined layer. As a result of this discretization, the conditions within the node, such as groundwater level and flow, are reduced to one average value for the entire node. Therefore, the model is not suitable for analysis of site-specific problems or issue.

The other limitation is the delimitations (assumptions which are accepted as a true by a researcher) to simplify the complex hydrogeological and hydrological natural system in the catchment. These are:

- System condition has been assumed to be the steady-state and one-time groundwater level measurements is assumed to represent constant conditions i.e the overall mass balance of the catchment considered as it is in equilibrium condition and etc, whether naturally it might not.

- The ground water flow through fractures, faults, and solution openings of the geological formations of the catchment is also assumed to be as it occurs in porous media in which it obeys the Darcy's law (Getachew, 2005).

- Horizontal hydraulic conductivity is assumed to be isotropic within a model cell.

- Vertical flow is assumed to be negligible, since a single layer Aquifer system is considered and the bottom Basaltic Aquifer also assumed as it is impervious layer.

5.4. Governing Flow Equation

Groundwater flow modeling of Sibilu Water shed applies different governing equations to deliver the necessary model output results. Entirely the model uses water balance, differential and statistical mathematical equations.

The following main formulas are applied in the research for different specific conditions:

Equation 1 is the general water balance equation which is used for water balance component estimations.

GW inflow- GW outflow=Change in storage **(1)**

The SWAT uses the water balance equation (2) to simulate the hydrological processes and to determine water balance components of the area.

$$SWt = SW0 + \sum_{i=1}^{t}(\mathrm{P\ day} - \mathrm{R\ surf} - \mathrm{ET} - \mathrm{Wseep} - \mathrm{Qgw}) \qquad \textbf{(2)}$$

Where: SW_t is the final soil water content, SW_o is the initial soil water content, t is the time in days, P_{day} is the amount of precipitation on day i, R_{surf} is the amount of surface runoff on day i, ET is the amount of evapotranspiration on day i, W_{seep} is the amount of percolation and by pass flow exiting in the soil profile bottom on day i, and Q_{gw} is the amount of return flow on day i.

The other one is the flow modeling equations which are the general governing equation (differential equation), proposed by ((Harbaugh et al., 1988) and representing three-dimensional Transient (3&4) and groundwater flow for heterogeneous and anisotropic conditions:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_S \frac{\partial h}{\partial t} - R^* \qquad \textbf{(3)}$$

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h \frac{\partial h}{\partial y}\right) = Sy \frac{\partial h}{\partial t} - R^* \qquad \textbf{(4)}$$

Kx, Ky, and Kz are values of hydraulic conductivity in the x, y and z directions along Cartesian coordinate axes, which are assumed to align with principal directions of hydraulic conductivity K (LT^{-1}), and h is representing hydraulic head (L), R^* is a volumetric flux per unit volume and represents sinks and/or sources of water (T^{-1}), Ss is the specific storage of the porous material (L^{-1}), and t, is time (T). Equation (3 and 4) describes the distribution of hydraulic head and flow throughout confined and unconfined aquifers respectively. However, in considering the assumption of the conceptualized model as steady state semi confined aquifer and single layer with no possible flow in Z direction, the above equation is modified and is given by:

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h \frac{\partial h}{\partial y}\right) + R = 0 \qquad \textbf{\textit{(5)}}$$

Equation 5 shows steady state condition when there is no change in the head with time, therefore, the part of the right-hand side of equation (4) becomes zero. The horizontal hydraulic conductivity along rows (Kx) and along column (Ky) are also assumed to have the same vale at any given location/cell and it is logical to replace them by a single value *K* to describe the horizontal hydraulic conductivity. Therefore, the flow equation that can be representing the Sibilu Catchment can be re-written as:

$$\frac{\partial}{\partial x}\left(K\ h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\ h \frac{\partial h}{\partial y}\right) = + - R* \qquad \textbf{\textit{(6)}}$$

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

To see and improve the model precision (to evaluate the model error) the following statistical equations has been employed:

$$\mathbf{ME} = \frac{\mathbf{1}}{\mathbf{n}}\sum_{i=1}^{\mathrm{n}}(\mathbf{h}_{\mathrm{m}} - \mathbf{h}_{\mathrm{s}})_{\mathrm{i}} \qquad \textbf{\textit{(7)}}$$

To find the mean error (ME), this is the mean difference between measured heads (hm) and simulated heads (hs).

$$RMSE = [\frac{1}{n}\sum_{i=1}^{n}|\ (h_m - h_s)_i 2\ |]0.5 \qquad (8)$$

The root mean square error (RMSE) is the standard deviation of the average of the squared differences in measured and simulated heads and shows whether the calibration criteria set prior to or during calibration has been met or not.

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |(h_m - h_s)|_i \tag{9}$$

The Mean Absolute Error (MAE) is the mean of the absolute value of the differences in the measured (h_m) and model simulated (h_s)results.

5.5. Modeling Approach

In Groundwater modeling of Sibilu River shed ArcSWAT (Version 2012.10_5.21) installed on ArcGIS 10.5 and Processing Modflow pro (version Pm 5) models were employed.

By using, Soil data, land use land cover map and Topographic slop/DEM: the SWAT model developed the Hydrologic Response Units and additionally using the hydro_ climatic data as an input to SWAT the groundwater recharge distribution, evapotranspiration and interactions between Stream network and Aquifers in each Hydrologic Response Units have been estimated by SWAT tools.

Calculations in SWAT are performed for each HRU and then scaled up to the sub-basin outlet by considering the percent area of the HRU within the sub-basin. Entirely the land phase of the water balance calculated by SWAT per HRU was analyzed in mm of water as shown in Equation 2.

Then the Modflow modeling was developed including set boundary conditions, layer parameters, discretization of the model area and estimate the groundwater outflow in the form of springs, wells, leakage to streams and inflows in different mechanisms. In order to use a finite difference approximation, a grid is superimposed over the DEM of the research area, and aquifer hydraulic parameters necessary to solve the Groundwater flow equation are averaged over the area of cell (the smallest volumetric units over which the hydraulic properties are assumed constant) and assigned at a node at the center of the block. The finite-difference method is used to compute the average head value and flows in all model cells.

Finally, the ground and surface water interaction and the entire water budget of the Sibilu river catchment were estimated.

5.6. Geographic Extension of Model area

From the developed conceptual model and assumed boundary conditions, the aquifers aerial extension of Sibilu river catchment is irregular and non-uniform (Fig 14). The maximum model area extent along rows (Top_ bottom) is 41 km while along Column (East _West) is 31.3 km. It covers the limits of the general flow system of the Sibilu River watershed and to the northwest extended up to the upper catchment of the Muger River gorges.

Except a few portions of the Northwestern part which is an outlet and considered as a general head boundary; the northern, southern, eastern and western parts of the watershed boundaries of the catchment are taken as a no-flow boundary.

Excluding the superficial thin Quaternary sediment which covers the central part of the catchment, the main aquifer system is weathered, fractured and sometimes vesiculated basaltic formation and depth wise extended at least up to 850 meters, as observed from the facts gathered from very deeply drilled test wells. But 350 meter thick-layer of volcanic aquifer has been modeled depend up on the availability of sufficient necessary model data.

5.7. SWAT Model Development

5.7.1. General overview of SWAT

SWAT (The Soil and Water Assessment Tool) model is a method for estimating spatially distributed, long-term average groundwater recharge developed by the U.S. Department of Agriculture's, Agricultural Research Service (USDA-ARS) (Arnold and Fohrer, 2005). It uses long-term average climatic data together with elevation, land use/land cover and soil map of an area to simulate average spatial patterns of surface runoff, Potential and actual evapotranspiration and groundwater recharge in the area. This model is fully integrated or embedded in the Arc GIS (version 10.5) as a raster model.

It is a physically based, basin-scale; continuous-time watershed model and mainly emphasizing surface dynamics. In addition to delineating the watershed, SWAT works by taking gauged or ungauged single watershed, and disaggregated it into multiple sub-basins which are then further separated into multiple unique combinations of land use, soil, and slope polygons known as Hydrologic Response Units (HRUs) (Fig 11a) and flow estimations in SWAT model are performed per each HRU and then scaled up to the sub-basin and/or basin outlet.

5.7.2. SWAT input Data

The SWAT model begins with climate information (daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, wind speed) and grid maps (DEM, Soil and land use _ land cover) in appropriate file formats.

About 4 meteorological stations which can represent the study area were selected and all necessary data (Table 5) were collected from Ethiopian meteorological Agency and analyzed for all metrological parameters.

Table 5. Meteorological stations location, year of records and data availability

No	**Station**	**Year**		**Location**		P	T		**RH**	**Ws**	**Solar Radi.**	**SSH**	**Remark**
		From	To	UTME	UTMN		MAX	MIN					
1	Fiche	1997	2019	470750	1079630	√	√	√	√	√		√	RH:2010_2019 SSH:2006_2019
2	AAU Observatory	1997	2019	472248	996952.4	√	√	√	√	√		√	SSH:2006_2019
3	Chancho	1997	2019	472546	1030240	√	√	√					
4	Entoto	1997	2019	469377.2	1004114	√	√	√					

√ - symbol refers availability of data

5.7.2.1. Weather Data

Precipitation

The variation in the seasonal distribution of rainfall in Ethiopia can be attributed by the reference to the position of the inter-Tropical Zone (ITCZ), the relationship of between upper and lower air circulation, the effects of Topography and the role of local Convection currents and the amount of rainfall (Daniel .G, 1977)

According to Daniel (1977) classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region there are seven rainy months from March to September and small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August (Graph 1).

To calculate aerial depth of precipitation of the study area, point measurements from 4 meteorological stations (Table 5) with complete data found in each station were averaged by using arithmetic mean method (Annex I) and the mean minimum, maximum and average annual precipitation of Sibilu Catchment is estimated to be 960.6, 1501.6 and 1217.34 mm respectively.

Table 6. Mean Rain fall depth at representative gauge Stations

Station	X	Y	Z	Mean daily Precipitation (mm/day)	Mean Monthly Precipitation (mm/Month)	Mean Yearly Precipitation (mm/year)	Min (mm/year)	Max (mm/year)
Chanacho	472546	1030240	2650	3.39	104.4	1248.739	1057.65	1484.225
Fiche	470750.2	1079630	2900	3.11	95.4	1145	881.7	1349.3
Entoto	469377.2	1004114	2800	3.46	106	1272.8	973.7	1720.75
AAU Observatory	472248.1	996952.4	2400	3.28	100	1202.8	929.4	1452
Mean of four Stations						1217.34	960.61	1501.57

Spatially the precipitation distribution in the area is varying and decreasing towards the rugged and relatively low laying areas of the upper Catchment of Muger River (Fig. 8).

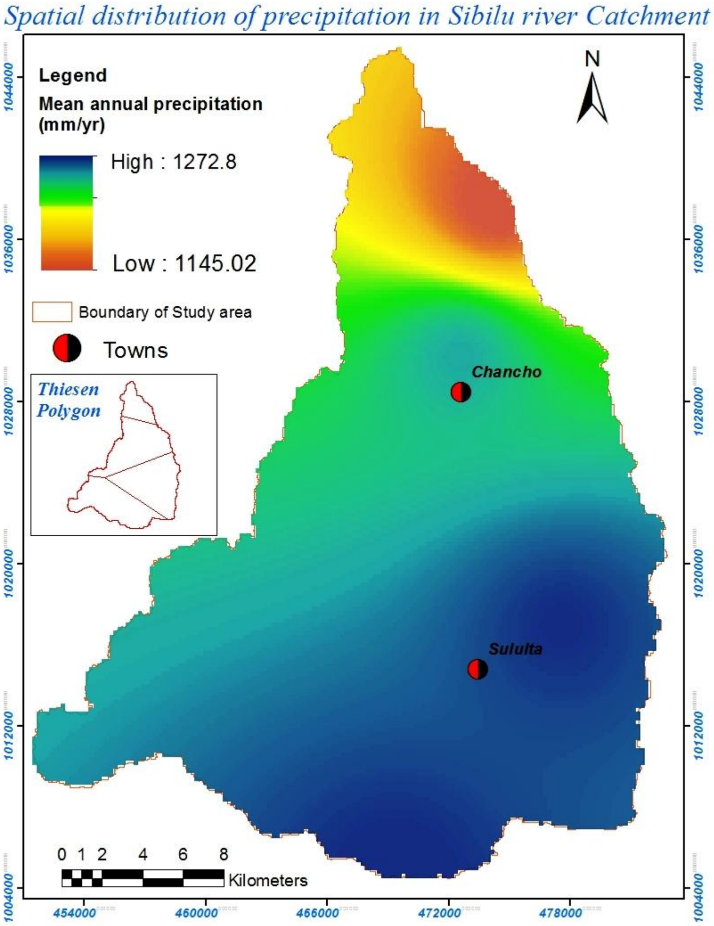
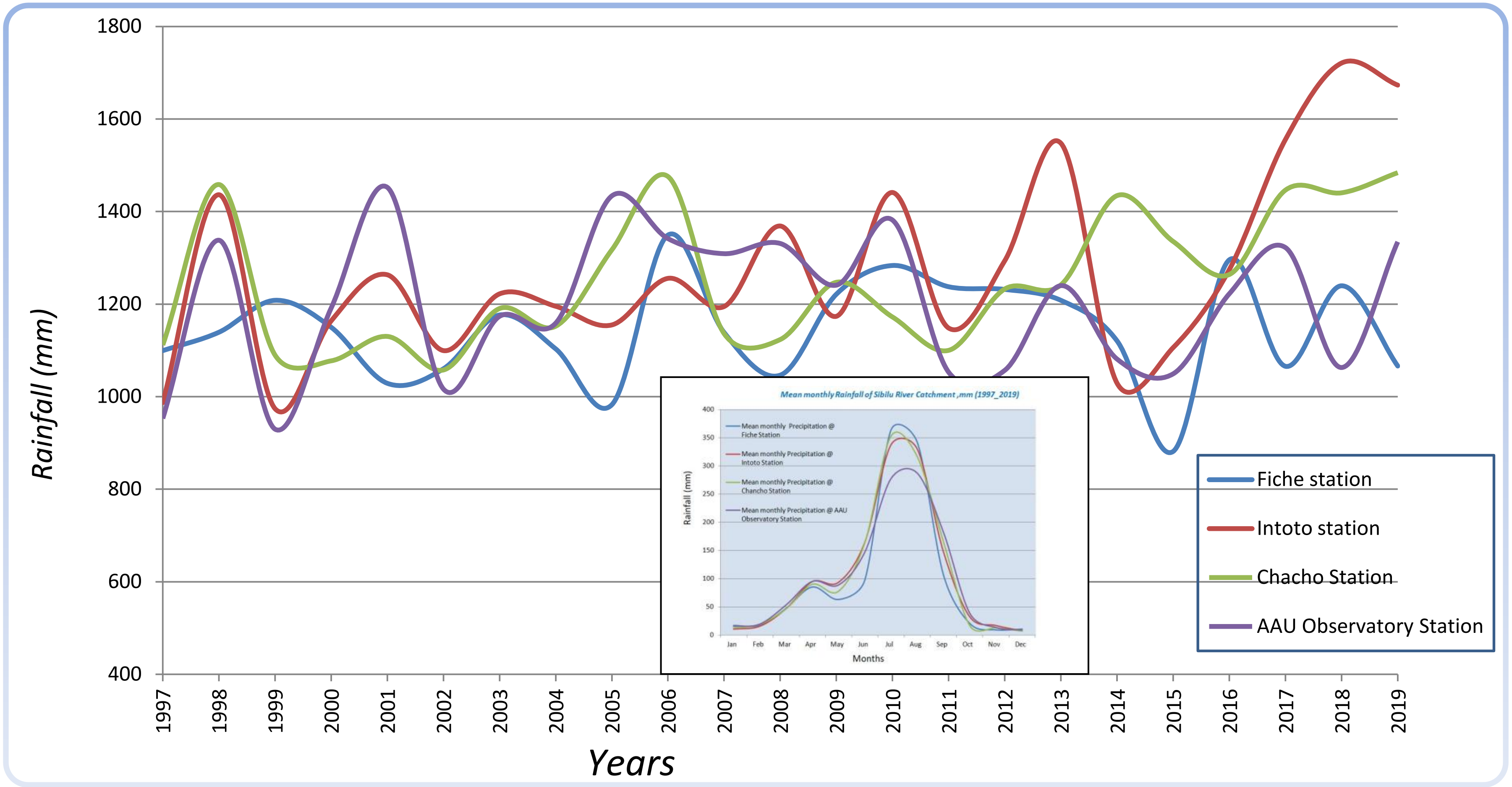

Spatial distribution of precipitation in Sibilu river Catchment

Figure 8. Spatial rainfall distribution

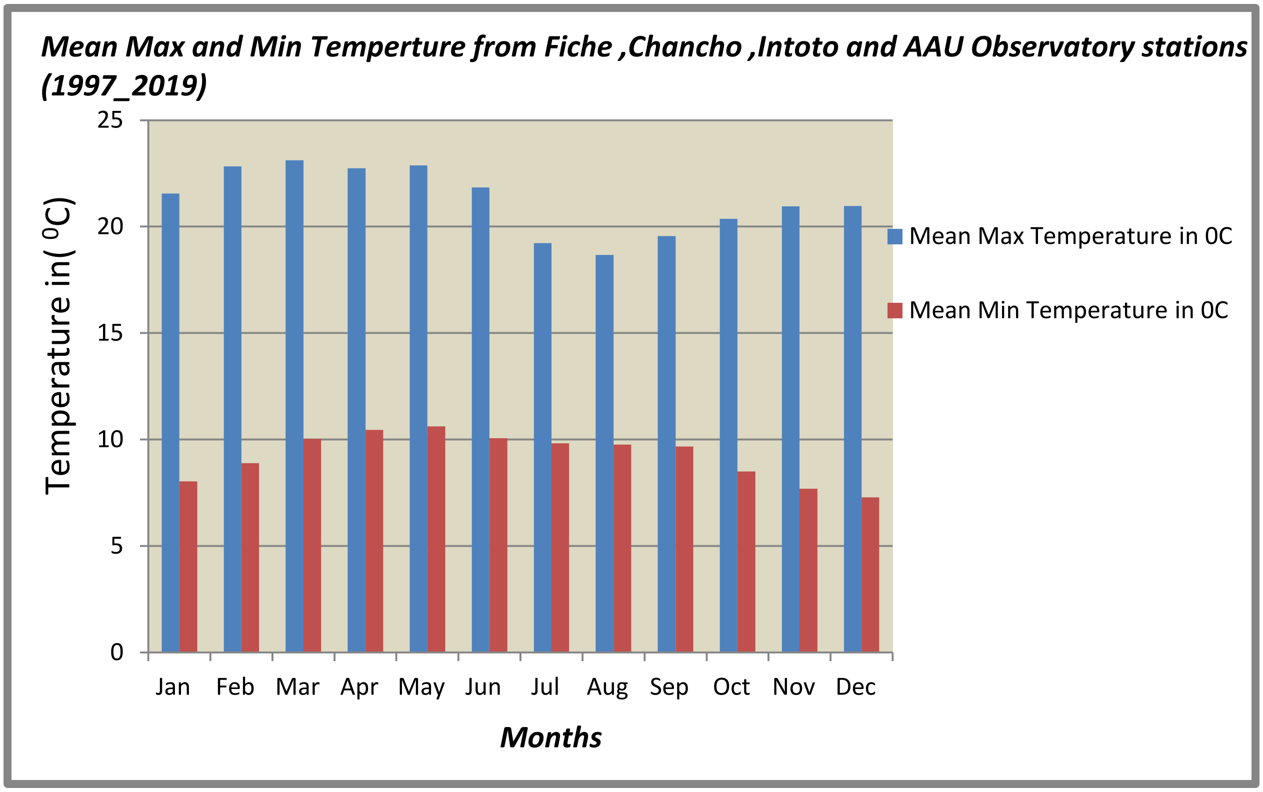


Graph 1. Temporal variation of annual and Monthly Rainfall about the mean

Temperature

Temperature is one of the most important parameters to be considered in hydro-meteorological characterization and recharge estimation, daily minimum and maximum records were used for analysis. To get representative monthly and annual means, point measurements with complete data were averaged. As analyzed from observed point data temperature ranges between 6^{0}C mean monthly minimum at Fiche station to extreme 23.9 ^{0}C mean monthly maximum at AAU Observatory station.

In general, November and December months are relatively the coldest months, while February and March are the warmest months (Graph 2).



Graph 2. Mean monthly Min and Max Temperature of Study area

Relative Humidity

Relative humidity is the ratio of the amount of water vapor actually present in the air to the greatest amount possible at the same temperature. At any given temperature, air can hold a maximum amount of moisture; the saturation humidity and this is directly proportional to the air temperature. It is a dimensionless quantity and is commonly given as a percentage (Shaw M. E, 1994). The relative humidity expresses the degree of saturation of the air. Monthly and annual means of humidity in area were taken from available point data and shown below (Table 7).

Table 7. Mean Monthly Relative Humidity of the study area (%)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Fiche	68.3	55.9	57.4	58.7	68.2	64.1	73	81	82.1	58.9	76.9	66.4	67.6
AAU Observatory	48	44.6	48.9	52.9	53.3	64.9	73.4	75.4	68.6	53	48.9	47.8	56.7

However for SWAT input, daily Relative Humidity in decimal form were used and for stations those have no data (Chancho &Entoto) were automatically simulated based on the available point data of Fiche and AAU Observatory.

Wind Speed

Rate of evaporation and evapotranspiration has a direct relation to and is strongly affected by wind speed. According to Shaw, (2005) the movement of the air and moisture transfer is directly proportional to wind speed and turbulence. From available point data Monthly and annual means of wind speed in the area were compiled as shown below (Tale 8).

Table 8. Mean monthly and annual wind speed (m/s)

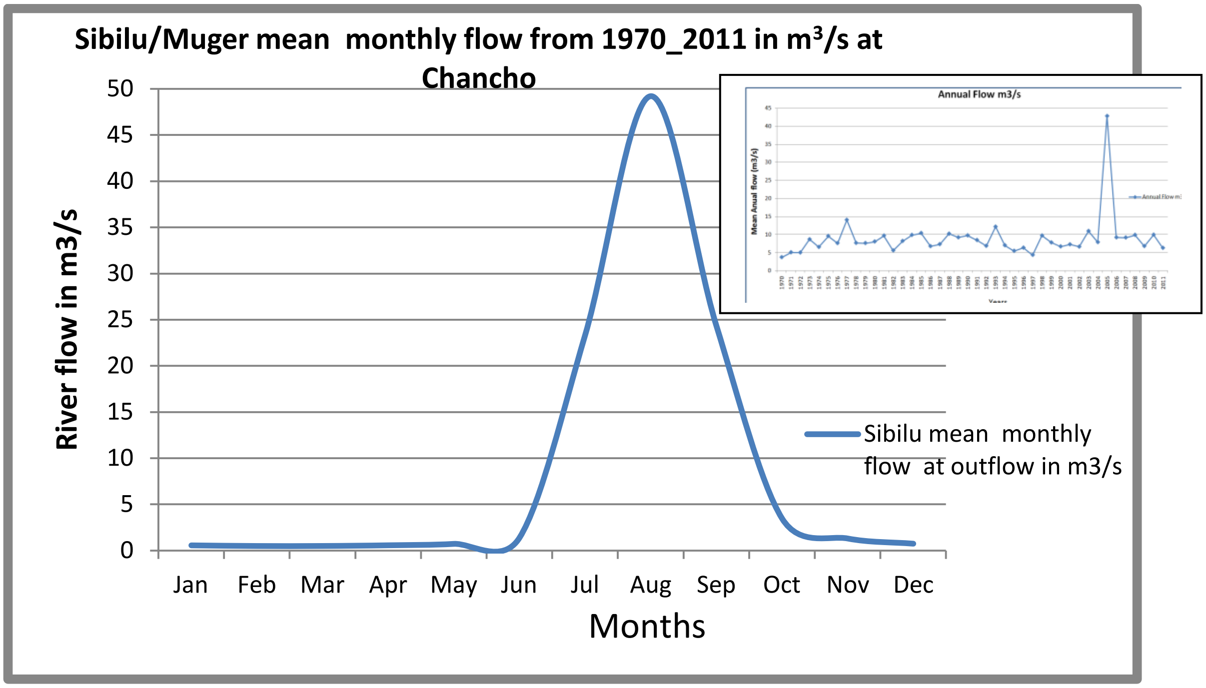
Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Fiche	0.89	1.09	1.13	1.2	1.39	1.15	0.86	0.78	0.84	0.88	0.81	0.895	0.988
AAU Observatory	0.64	0.75	0.71	0.66	0.61	0.48	0.37	0.34	0.43	0.64	0.69	0.65	0.58

Daily wind speed data from 1997_2018 and 1997_2019 years at Fiche and AAU Observatory stations respectively processed with appropriate ASCII files were used for SWAT input while solar radiation of the study area was simulated.

5.7.2.2. Hydrological Data

Sibilu River is Originated from about 3200 m.a.s.l at Entoto mountain chain, southern part of the study area and drops about 1450 m.a.s.l in the river length of 48 km from its origin to its confluence with Muger River. It is a perennial River draining a catchment area of about 64,955 hectares and from the left side Weserbi, Gerbi, Dakeye and Deneba Rivers are the main to feed the Sibilu River while Lega guda, Shunke, Bori, Roba, Garmama and Chancho rivers are the right tributaries of this River.

According to the stream flow data recorded at Chancho station (Muger at Chancho) (1970 – 2011), average annual runoff volume of the river is 279.8 MCM and parallels to the increment of precipitation the flow of the River start rising at June, reaches the peak at August and start slowdown from September (Graph.3). Generally, this observed River flows were used finally to Calibrate and validates the SWAT output.



Graph 3. Mean Monthly flow of Sibilu River

5.7.2.3. Soil, Land use land cover and Slope of the area

Soil

Soil data is one of the major input data for the SWAT model and the Modified FAO, 2016 soil map of the study area was obtained from Ethiopian Ministry of Agriculture.

By using Arc-GIS routine five major soil groups were retrieved for Sibilu catchment from this FAO_UNESCO Soil classification of Ethiopia (Fig. 9) and prepared in an appropriate ASCII format to use as an input of SWAT.

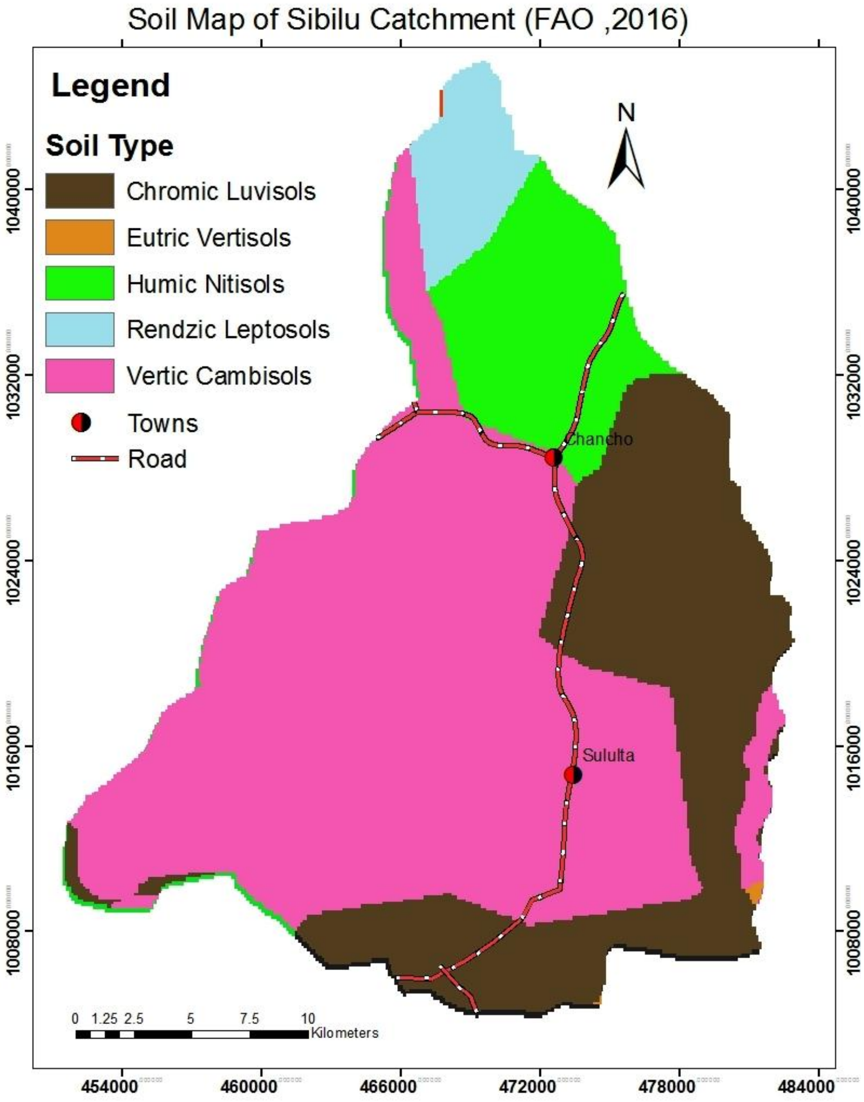


Figure 9. Soil Classification Map of Sibilu River Catchment

Table 9. Soil types, symbols and their areal extents in the study area

ID	SYMBOL	SOIL TYPE	SOIL NAME	CODE	AREA IN HAC.	AREA IN %
1	LVX	CHROMIC LUVISOLS	CHLUVISOLS	ET038	19264.2	27.76
2	CMV	VERTIC CAMBISOLS	VTCAMBISOLS	ET018	39183.3	56.47
3	VRE	EUTRIC VERTISOLS	EUVERTISOLS	ET056	48.35	0.07
4	LPK	RENDZIC LEPTOSOLS	RNLEPTOSOLS	ET032	3085.9	4.45
5	NTU	HUMIC NITISOLS	HUNITISOLS	ET044	7804.13	11.25

Land Use Land Cover

Land use land cover map of Sibilu Catchment was obtained from high spatial resolution Sentinel-2 satellite Image. The land cover of the catchment is controlled with topographical, climatic and ecological conditions and considerably influencing the hydrological properties of the watersheds. It is one of the main input data of the SWAT model to describe the Hydrological Response Units (HRUs) of the watersheds.

The SWAT model has predefined four-letter codes for each land use category and these codes were used to link the land use map of the study area to SWAT land use databases after preparing in lookup table of ASCII format.

The major land use and cover is categorized as forest, grassland, intensively cultivated Agricultural land, marshland, shrub land, Barren and urban land areas covering in various percent of areal coverage (Table 10).

Table 10. Land Use land cover classification of the study area for SWAT input

No	**Land use / Land cover**	SWAT Code	Areal coverage %
1	Agricultural Land-Generic	AGRL	84.2
2	Range-Grasses	RNGE	9.8
3	Range-Brush	RNGB	0.34
4	Forest-Mixed	FRST	4.8
5	Wetlands-Mixed	WETL	0.03
6	Barren	BARR	0.02
7	Building area	URBN	0.88

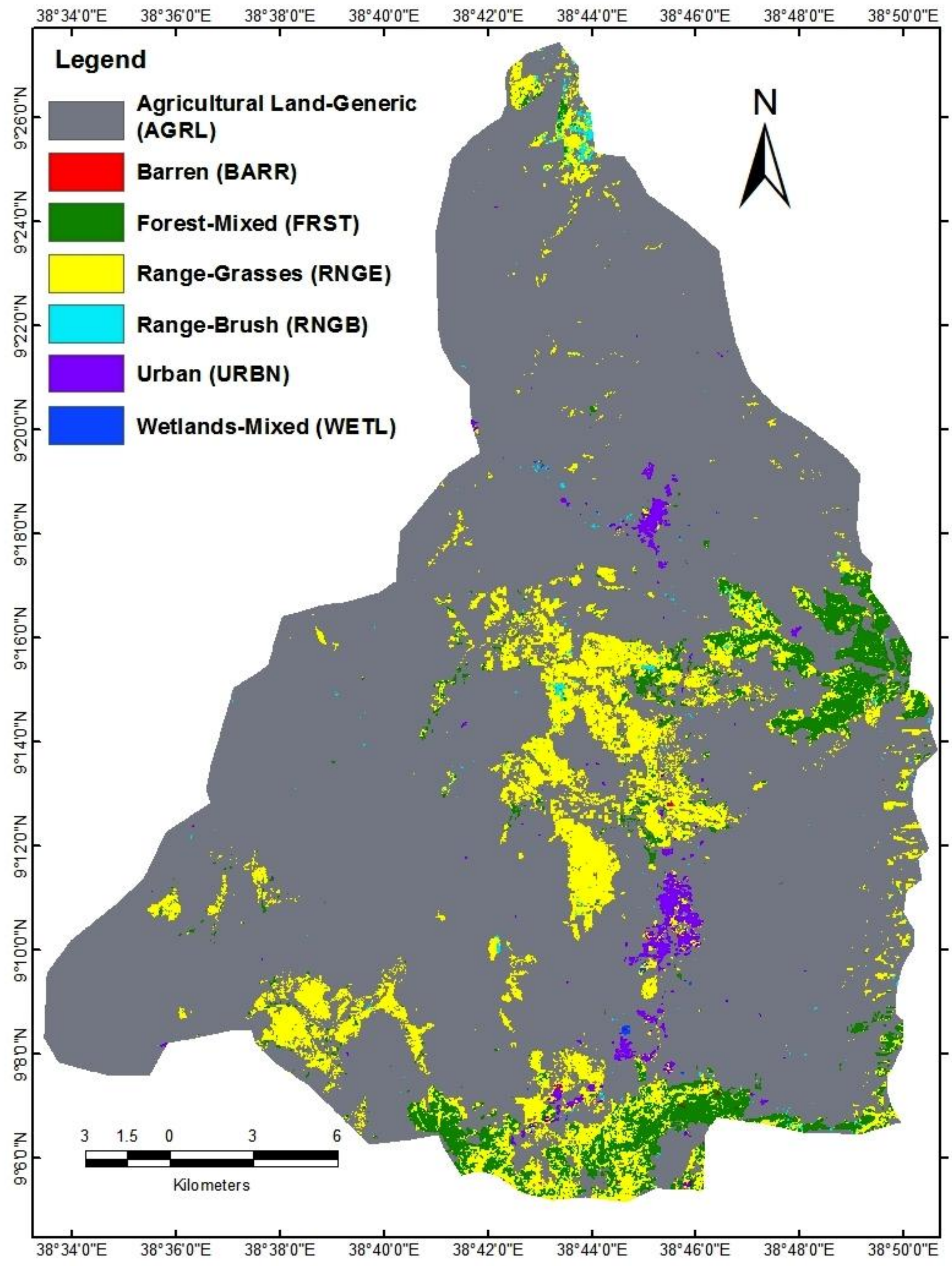


Figure 10. Land use land cover map of Sibilu Catchment (Sentinel_2)

Slope

In addition to Soil and/or land use/cover parameters of the study area, variation in surface roughness is considerably influencing the hydrologic Response Units (HRUs) and Hydrologic dynamism of the watershed. Accordingly, 5 classes of slope in different slope ranges were identified in the catchment and used for SWAT input in the form of Grid raster map (Fig 11).

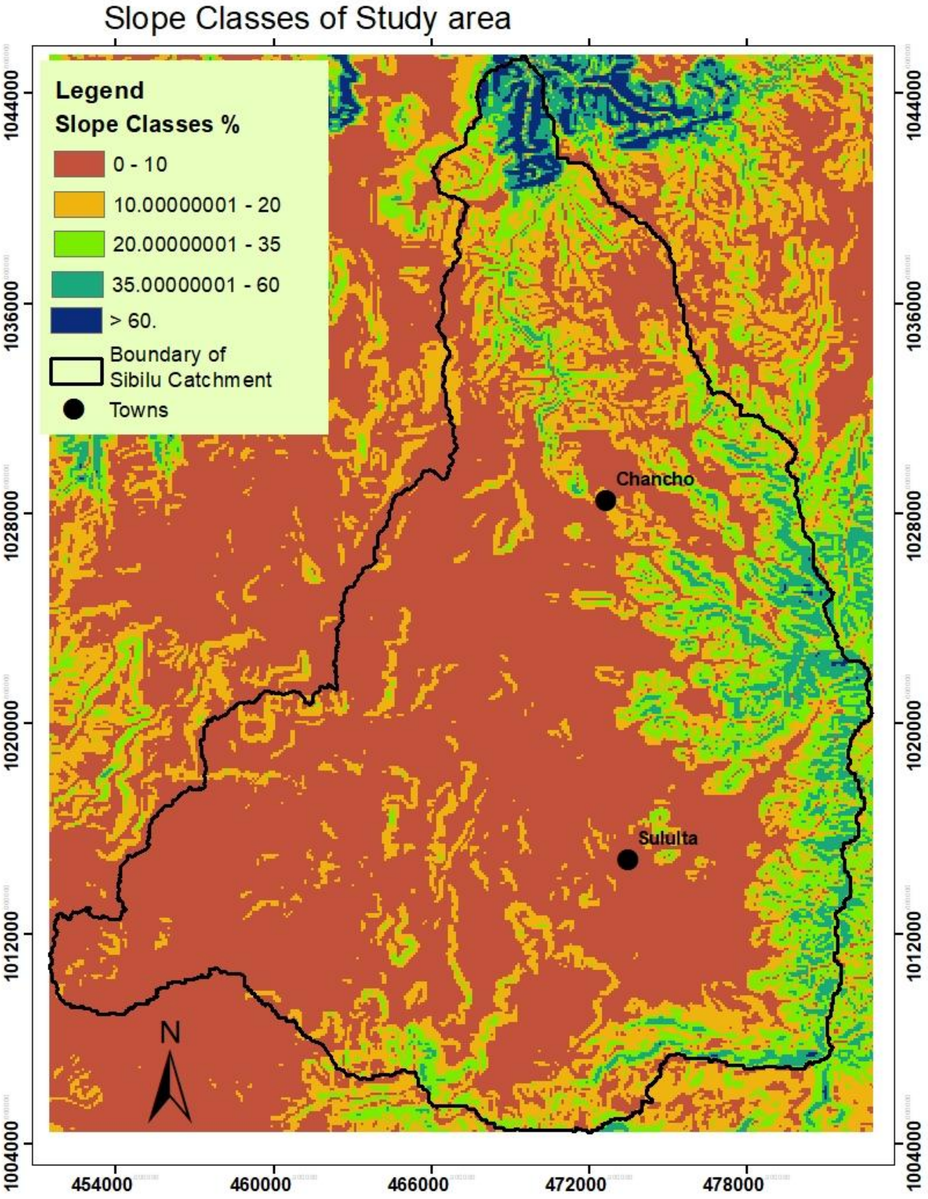
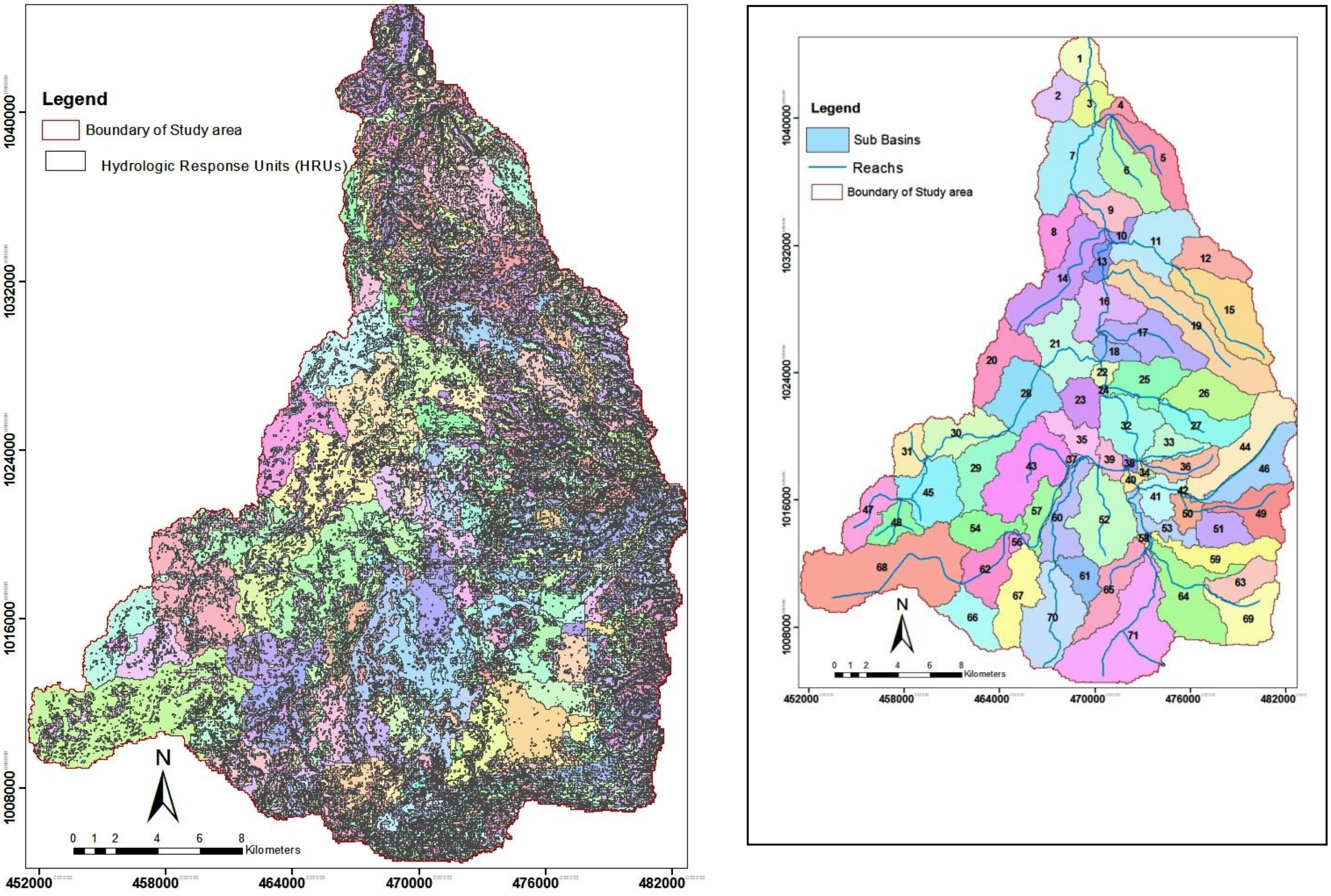


Figure 11. Slope Classes of Sibilu watershed (Developed from DEM)

5.7.3. SWAT out put

5.7.3.1. HRUs

Generally Arc-SWAT produces a number of simulated out puts just based on the interest of the modeler, however in Sibilu case Arc-SWAT assists in delineating the watershed ,sub basins , HRUs ,Reaches and sub basin outlet points. Totally the Sibilu watershed discretized to 1215 HRUs and 71 Sub basins (Fig.12 a and b) to make easy and increase the precision of estimated flows (Recharge, ET, Surface runoff etc) based on site specific characteristics of Soil type, land use covering and surface roughness. Each HRU has a unique land use, slope and soil combinations while the numbers of the HRUs are vary within the sub-watersheds.



(b)

(a)

Figure 12. (a) Hydrologic Response Units (HRUs) and (b) Sub Basin distribution of Study area

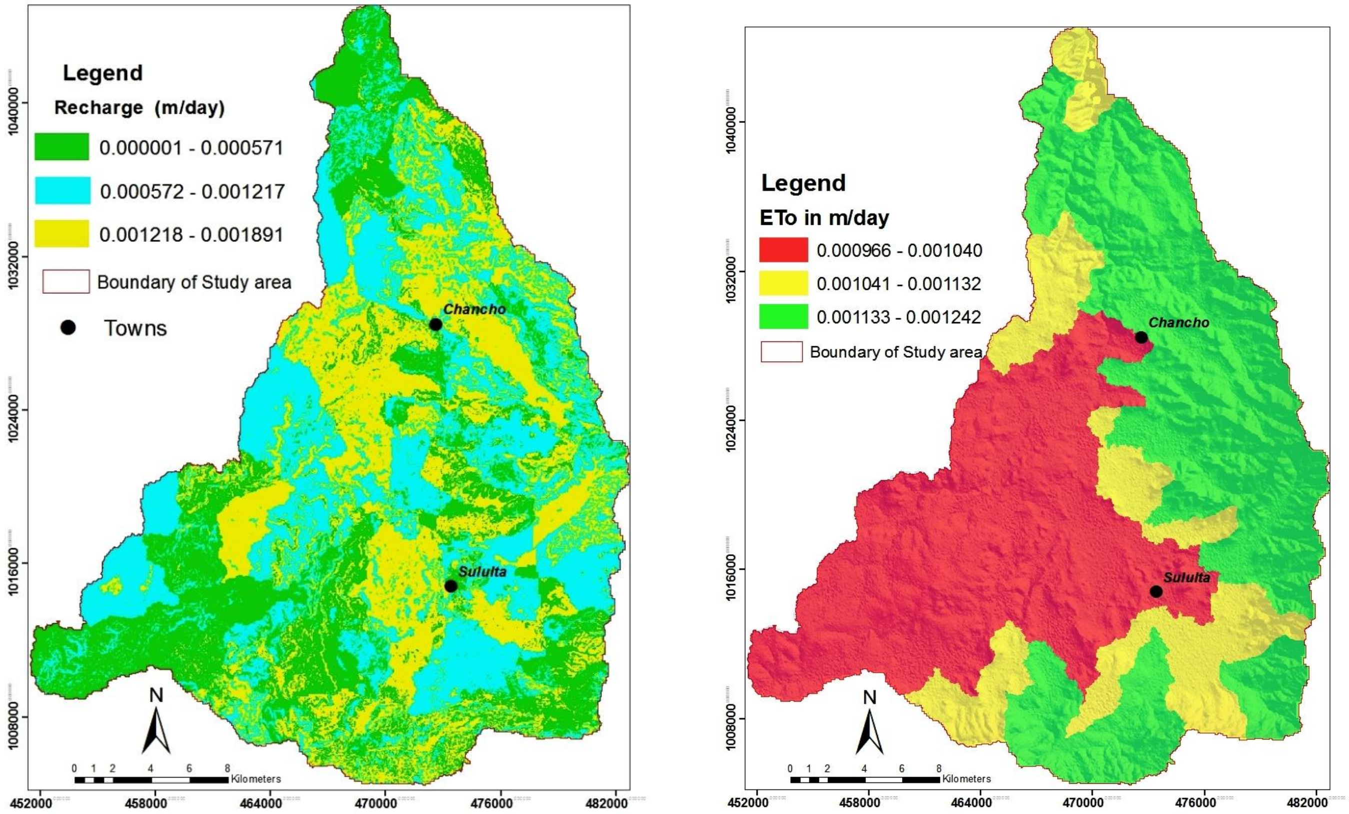
5.7.3.2. Recharge

Recharge is the most important factor in evaluating the regional Aquifer system and considerably difficult to quantify (Wood W.W and Sanford W.E.W, 1995). It is the volume of the water that joins the saturated zone of the aquifer and a term used to describe many of the processes involved in the addition of water to the saturated zone (Wilson, 1978).

Natural Groundwater recharge to the saturated aquifer may occur from vertical percolation of precipitation and loss of surface water bodies after important rains in the upper part of the catchment. Recharge could also be direct, indirect or localized based on the source and mechanism by which water reaches the water table.

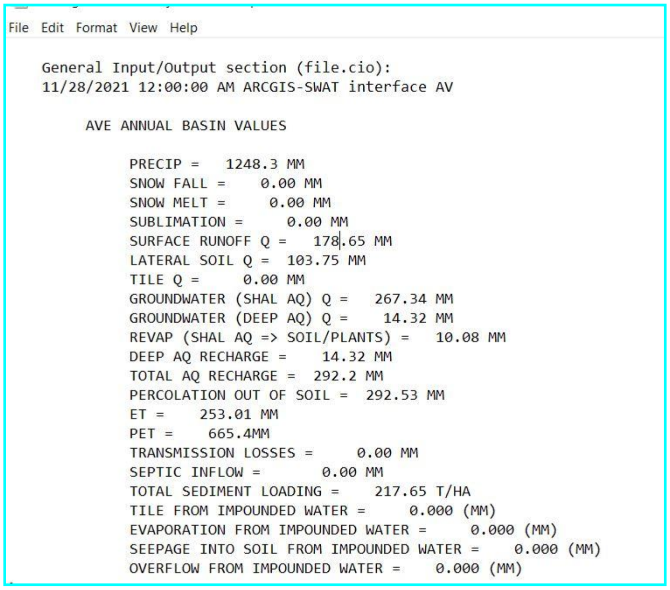
The assigned direct recharge input from precipitation was assumed to be spatially variable due to variability of Soil type, land use/cover and slope, and also assumed to take place in all areas (Fig 13) with different depths. Most recharge to the groundwater occurs only during the wet season and the rainfall distribution in the study area is bimodal (Belg and Kiremet season).Thus, the daily mean recharge of study area is fairly distributed from these season days to the other months having a negligible recharge.

In SWAT, the base flow in the shallow and deep groundwater contribution to the river discharge and can reasonably be taken to be the groundwater recharge to the shallow and deep aquifer. The annual groundwater recharge of the model area to the shallow and deep aquifer is 267.34 and 14.32 mm/year respectively. The spatial distribution of recharge per HRU is indicated below as analyzed by SWAT tools.



(a) (b)

Figure 13. SWAT output rate of Recharge (a) and ETo (b) distribution per HRUs and Sub basins respectively



```
General Input/Output section (file.cio):
11/28/2021 12:00:00 AM ARCGIS-SWAT interface AV

     AVE ANNUAL BASIN VALUES

          PRECIP =   1248.3 MM
          SNOW FALL =    0.00 MM
          SNOW MELT =     0.00 MM
          SUBLIMATION =     0.00 MM
          SURFACE RUNOFF Q =   178.65 MM
          LATERAL SOIL Q =  103.75 MM
          TILE Q =     0.00 MM
          GROUNDWATER (SHAL AQ) Q =   267.34 MM
          GROUNDWATER (DEEP AQ) Q =    14.32 MM
          REVAP (SHAL AQ => SOIL/PLANTS) =   10.08 MM
          DEEP AQ RECHARGE =    14.32 MM
          TOTAL AQ RECHARGE =  292.2 MM
          PERCOLATION OUT OF SOIL =  292.53 MM
          ET =    253.01 MM
          PET =    665.4MM
          TRANSMISSION LOSSES =     0.00 MM
          SEPTIC INFLOW =       0.00 MM
          TOTAL SEDIMENT LOADING =    217.65 T/HA
          TILE FROM IMPOUNDED WATER =     0.000 (MM)
          EVAPORATION FROM IMPOUNDED WATER =     0.000 (MM)
          SEEPAGE INTO SOIL FROM IMPOUNDED WATER =    0.000 (MM)
          OVERFLOW FROM IMPOUNDED WATER =    0.000 (MM)
```

Figure 13. (c) SWAT Simulated Basin values

5.7.4. SWAT Calibration and Validation

Calibration is crucial for optimization parameters or to make the model parameters as good as possible to reduce the uncertainty in the model outputs. It is fitting the SWAT model outputs that are not uncertain to a relative degree of certain. Model uncertainty may appears from different sources of uncertainties such as driving variables like rainfall, conceptual model, parameters sensitive to the area, measured data and model procedures (SWWAT_CUP 2012, user manual). on the other hand the calibration of model with multiple parameter is a difficult task and determining which parameters have to be calibrated is a time taking and conducting a sensitivity analysis is important in this case to identify and rank the parameters those have a significant impact on the specific model outputs of interest (Van Griensven et al., 2006). Accordingly, among 7 earlier tried parameters 5 sensitive parameters that mostly affect the stream flow of Sibilu have been selected (Table 12). Finally the SWAT output calibrated by using SWAT_CUP and a Sequential Uncertainty Fitting, version 2 (SUFI2) calibration methods. During SWAT calibration and validations, the Sibilu River flow from 1970 to 2011 years at the gage near to the outlet has been employed and the details are shown in the following Table 11.

Table 11. Entire Calibration input data and factors to SWAT-CUP to calibrate SWAT out puts

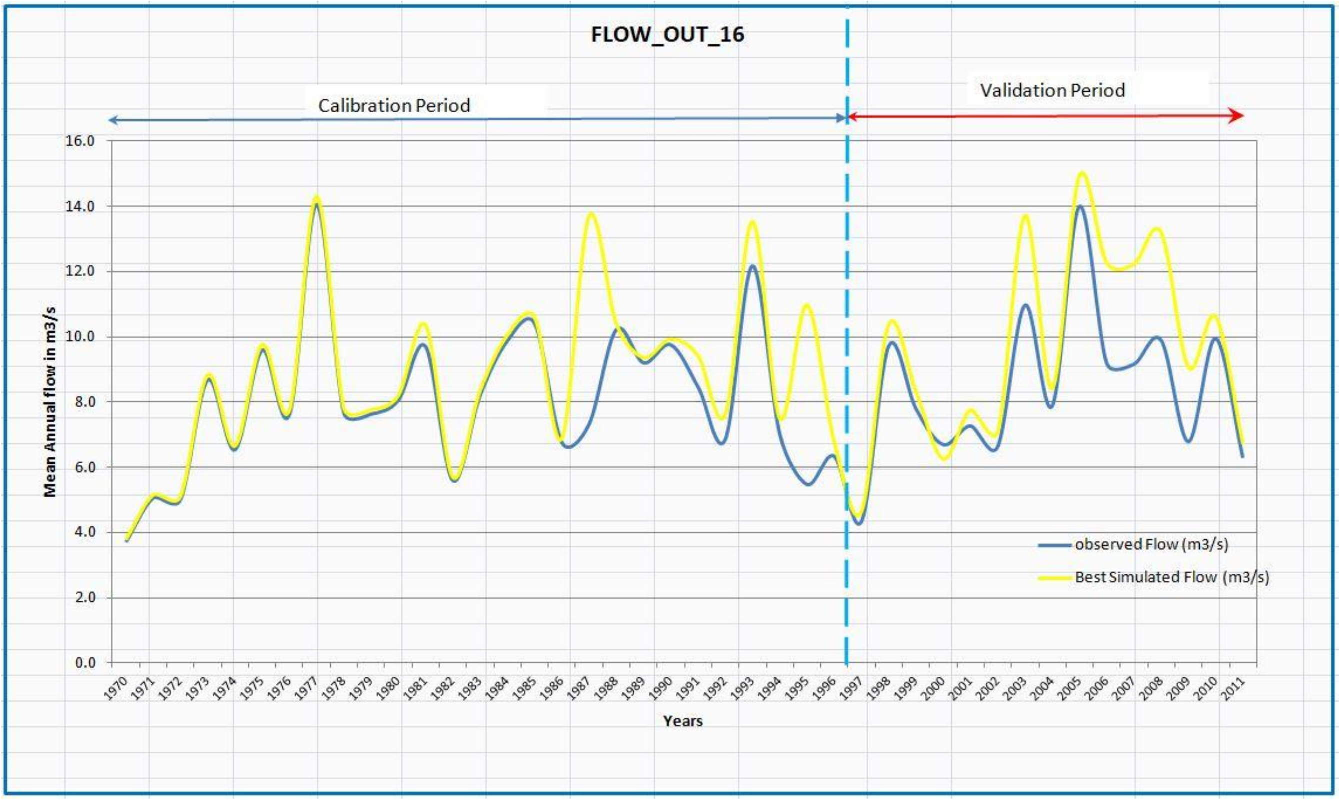
No	Factors required by SWAT_CUP	Descriptions	Remark
1	The name of the variable and the sub basin number	FLOW_OUT_16	River flow out is a variable while Sub basin 16 is a point of flow out
2	Beginning year of Simulation (File Cio)	1968	Including Warm up period
3	Warm up period	2	No of years (1968 &1969)
4	Number of years Simulated, (File.Cio)	29	Including Warm up period
5	Beginning year of Simulation not including the warm up period	1970	
6	End year of Simulation	1996	Excluding the validation year (1997_2011)
7	Number of variables	1	Only Monthly/yearly Flow data in m3/s
8	Number of Simulation	20	Only one best Simulation Selected
9	Number of HRU	1215	Total number of HRUs developed in the study area to estimate flows
10	Number of Sub basin	71	Total No of sub basin in the project
11	Number of Parameters	5	No of parameters that to be estimated and sensitive to the study area
12	Number of data Points	324	No of mean monthly measured flows (1970 to 1996)
13	Used Objective function type (behavioral parameters)	R^2 and NS	R^2 , coefficient of determination (0_1) & NS ,Nash-Sutcliffe simulation efficiency ($-\infty$ to $+1$) are used to evaluate model error (performance)

Table 12. List of Parameters with calibration values

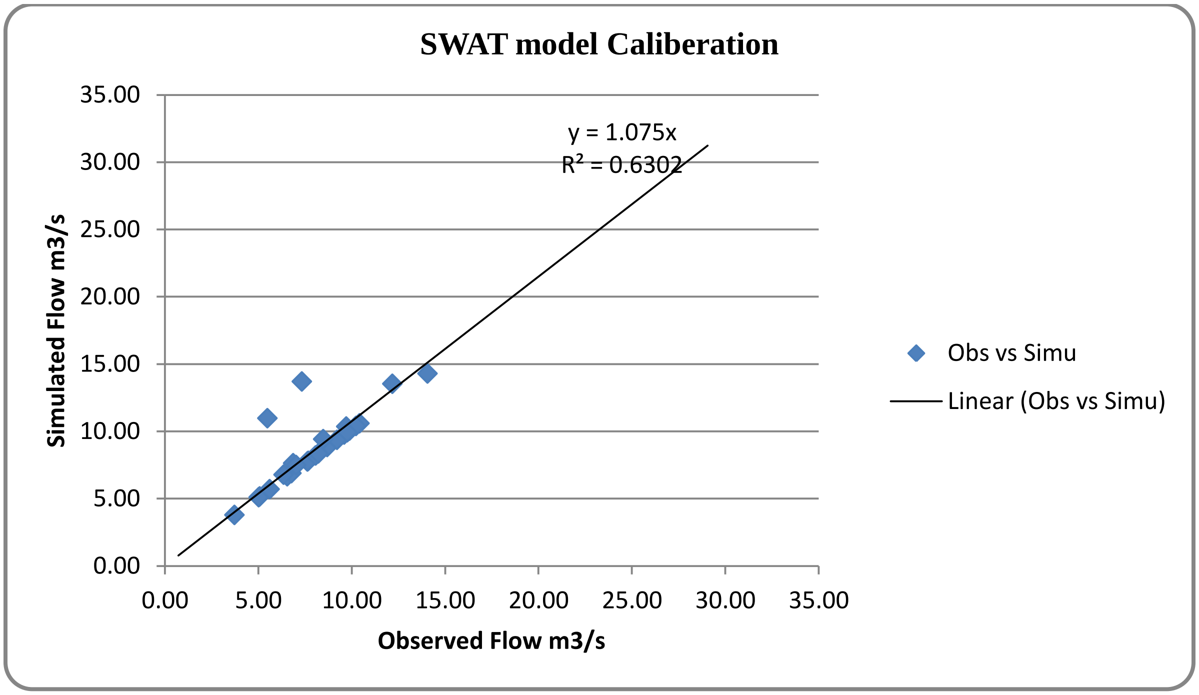
Parameters	*Description*	*Category*	*Absolute SWAT value (min & max ranges)*	*Calibrated new Results*
CN2	SCS runoff curve number (%)	Specification of Management Parameters	35-98	62.3
ALPHA_BF	Base flow alpha factor (days)	Specification of GW Parameters	0_1	0.05
GW_DELAY	Ground water delay (days)	>>	0_500	31
GW_REVAP	Groundwater “revap” coefficient	>>	0.02-0.2	0.02
RCHRG_DP	Deep aquifer percolation fraction	>>	0_1	0.1

NB: Threshold depth of water in the shallow aquifer required for return flow (GWQMN, mm) and Base flow alpha factor for bank storage (ALPHA_BNK.rte) are the factors that are relatively possess insignificant influence in controlling the stream flow in the Sibilu catchment.

After some sensitivity flow parameters were adjusted by manual calibration procedure, the calibration process continued through continuous tray and error within the allowable ranges for parameters above until the simulated flow as close as possible to observed stream flow. The result of calibrated river flow graph is shown below and the result of calibration for yearly flow showed that there is a good agreement between the observed and simulated average yearly flows with coefficient of determination (R2) of 0.6302 and as Nash-Sutcliffe simulation efficiency (ENS) of 0.42.

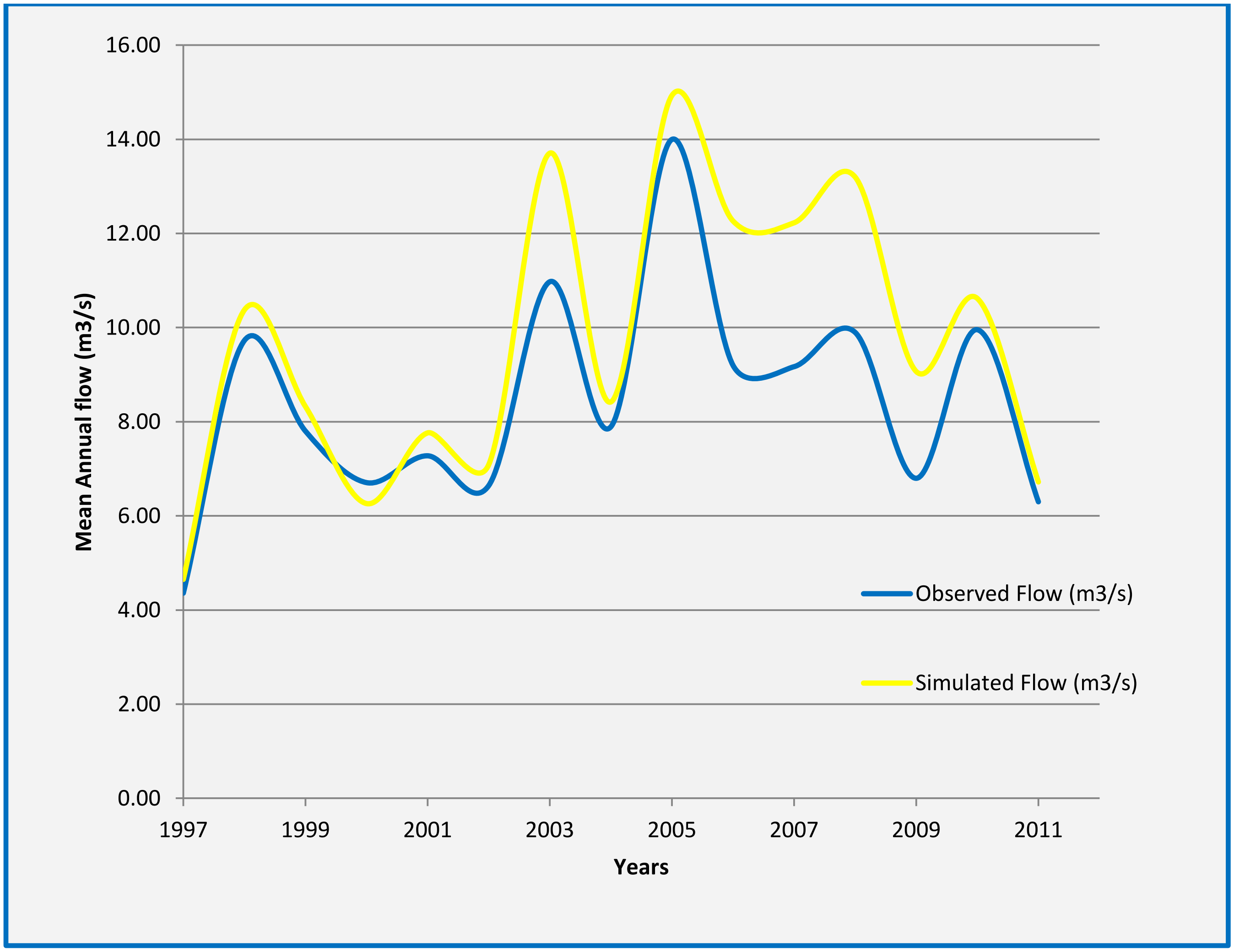


Graph 4. Calibration and validation results



Graph 5.Scattered plot for simulated Vs observed Flow (Calibration Period)

The Sibilu river flow periods from Muger at Chancho gage station is divide in to two parts for calibration and validation near at a 2/3 rd of total data points where the mean and variance of the observed data of the calibration and validation periods are either equal or very close to each other. Thus, based on this principle the year from 1997 to 2011 (15 years) were selected for validation purposes without further adjustment of the calibrated parameters. The validation result for yearly flow is shown in the figures below and the simulation for validation also showed good agreement between the simulated and observed yearly flow with the R^2 value of 0.86 and this again shows the model simulation result is valid.



Graph 6. Validation result for average annual stream flow (1997 to 2011)

5.8. MODFLOW model development

Numerical models are used when complex boundary conditions exist or where the value of parameters varies within the model (Zheng C. and Bennett, 1995). Numerical modeling is constructed for Sibilu watershed by using Processing Modflow Pro (Version 8.0.15). Processing Modflow Pro is an enhanced version of Modflow which allows the user to define a groundwater model using a conceptual model approach. It is a three-dimensional, saturated, physically based, finite-difference groundwater flow model. This grid-based subsurface flow model combines a simple mass balance with Darcy's law to simulate steady-state groundwater conditions. Through the applications of various packages in MODFLOW, Groundwater discharge, Recharge, water table, vadose zone percolation, Aquifer _stream interactions and some other more can be simulated.

It offers a variety of boundary conditions, including specified head, areal recharge, evapotranspiration, drains, Rivers, and Streams. Aquifer units may be confined, unconfined, or treated as convertible between confined and unconfined states. The three-dimensional capabilities and flexibility in boundary conditions offered by MODFLOW are necessary to simulate groundwater flow in the Sibilu River catchment due to the relatively complex Topography, geology, and boundary conditions of the model domain. The groundwater flow model in the study area was set up as a one-layered, local, Steady-state and convertible between confined/unconfined conditions, to simulate groundwater flow of the aquifer, and thereby compute the dispersion of water table elevations and groundwater fluxes to manage the groundwater system in the basin.

5.8.1. Spatial discritization and Extent of the Model grid

In MODFLOW an aquifer system replaced by a discritized domain called grid which is consisting of an array of nodes at which hydraulic heads are calculated and associated in finite difference blocks/cells. Grid size depends on hydraulic gradient, degree of aquifer heterogeneity, size of the model area, level of detail required and availability of data. Selecting the size of the nodal spacing is a critical step in grid design (Anderson M.P and Woessener, 1992). Accordingly, the model domain of Sibilu Catchment spans approximately 41 km in the north-south direction and 31.3 km in the east-west direction and the model domain has been discritized by 157 columns, 205 rows, and a single vertical layer with 32,185 total numbers of cells. Each cell has a uniform grid size of 200 m by 200 m. The northwest reference corner of the model grid

(X_o, Yo) is located at UTM: 451456.5 Easting and 1045409.4 Northing. The irregular shape of the study area boundary treated with quadrangular finite difference model approach and this increase the number of inactive cell and reduces the number of active cell in the model (Fig.16).

5.8.2. Model Structure

As discussed in the conceptual model development section 5.2, the model domain is defined based on the surface topography and local physical boundaries. The main basaltic aquifer system within the model area is complex and cannot be separated and it is assumed that they are hydraulically connected. The low permeable, slightly weathered and fractured rock is separating a series of highly weathered and/or fractured aquifers as evidenced from different well logs (Fig 15) and how ever they do not have sufficient extent to justify as a multilayer representation of the reservoir.

As clearly indicated on the log section from 858 and 882 m deep Sululta and Chancho test wells below, an alternative different degree of fractured and weathered basalt/volcanic layer with few paleosol between 2550 and 2200 m elevation in Sululta Well (right) and between 2500 and 2230 m elevation in Chancho test well (left) is tilting towards the North (Chancho test Well) while the layer below 2250 m elevation depth, is dipping towards the south (upper Awash basin).Thus the layer which is dipping to the north is estimated to be 350 m thick and this study focuses on this top most layer due to fairly available data.

Therefore, because of above reasons, a single layer structure is adopted for the model and the horizontal variation being accommodated by the variable hydraulic properties while a vertical variability is neglected, since a single model layer considered.

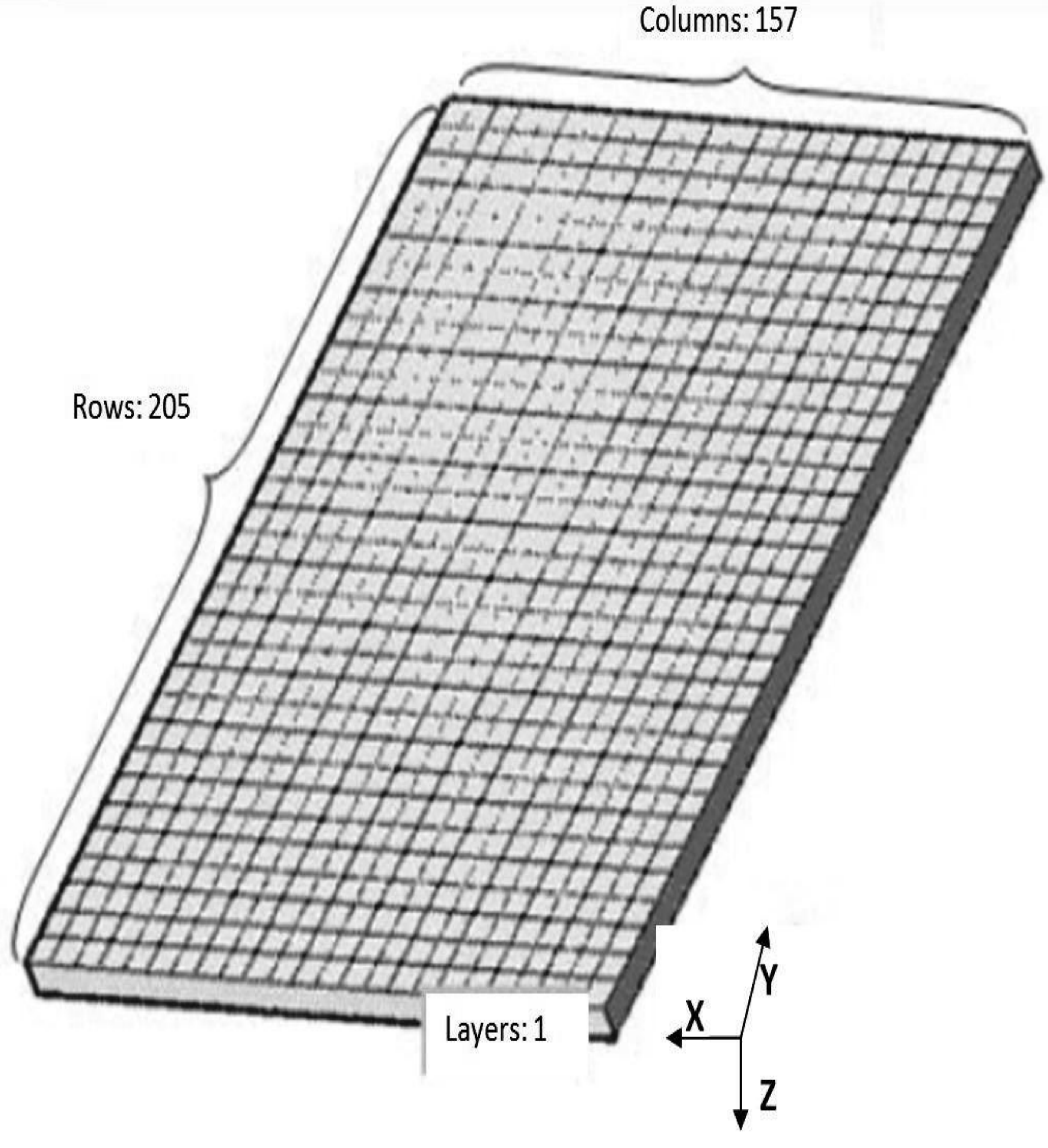


Figure 14. 3D Discritization of the model domain

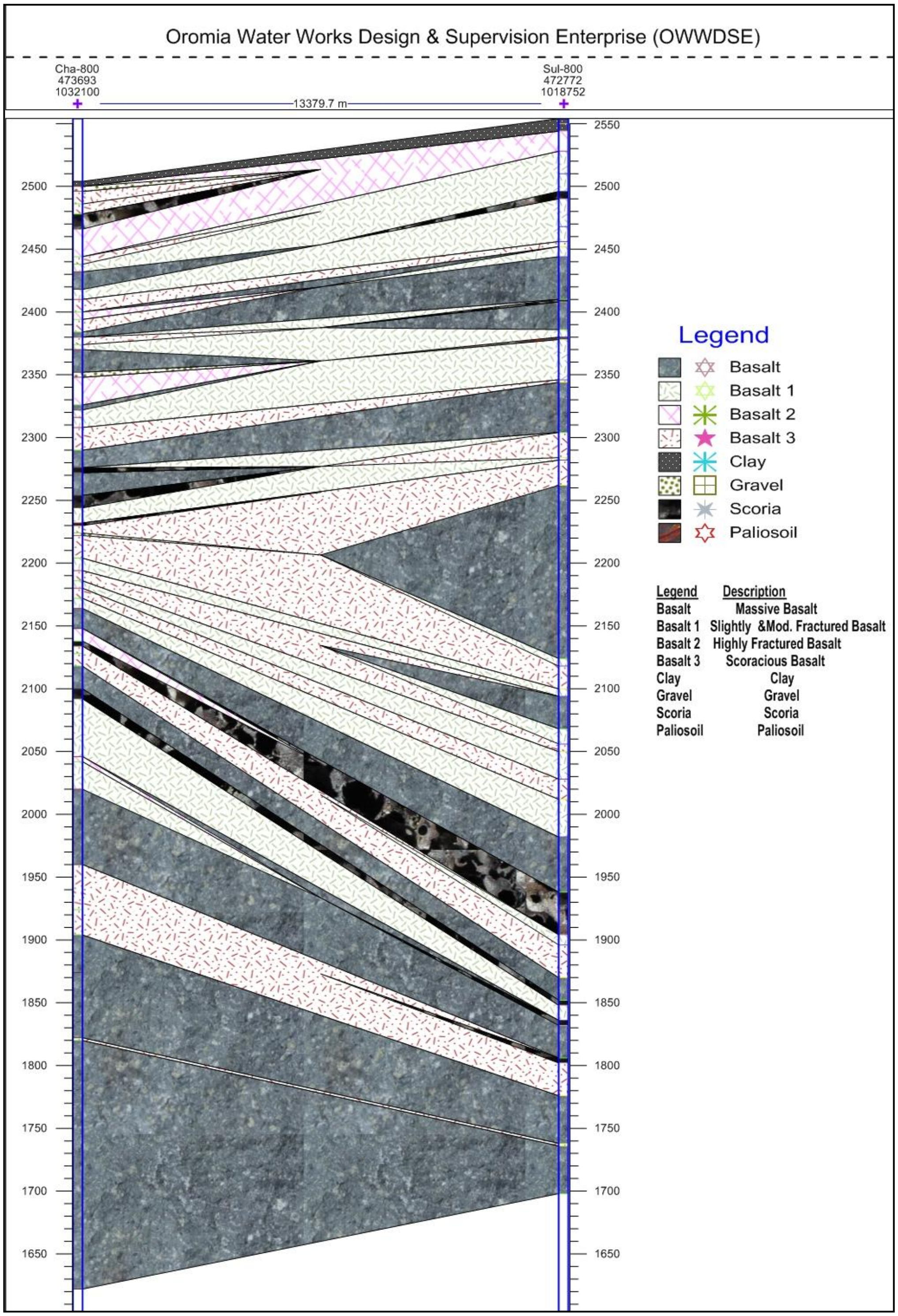


Figure 15. Well log section of Cancho and Sululta test wells (13379.7 m far apart)

(Source: OWWDSE, Sululta & Chancho Deep Test Well Drilling Accomplishment Report, July 2015)

5.8.3. Physical Parameters of the system

During Groundwater development, the model hast to generally possess values specified initially for all necessary parameters. The Spatial input variables are Boundary condition, initial hydraulic head, horizontal and vertical hydraulic conductivities, Transmisivity, horizontal anisotropy, Effective porosity, Aquifer geometry and different stresses. Thus, values are assigned by interpolating available point data to each active grid cells based on its location within the study boundary as initial inputs.

5.8.3.1. Model Boundary Condition

According to Anderson and Woessner, (1992), boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. Setting the boundary of the model domain is the critical step in the modeling process and controls the water entrance and exit point of the model system.

Three types of boundary conditions were considered to define the groundwater flow system in the Sebilu river catchment: no-flow boundaries, specified-flux boundaries and head-dependent flux boundaries (GHB). Geologic or hydrologic barriers to groundwater flow were simulated using no-flow boundaries. The contact between the nearly impermeable bedrock is an example of a no-flow boundary. Known or estimated hydrologic fluxes, such as recharge, Drains and well abstraction/discharge, are represented using specified-flux boundaries. A head-dependent flux boundary is one across which ground water moves at a rate proportional to the hydraulic-head gradient between the boundary and the groundwater system.

Broadly there are boundaries: 1. which related to the geographic extent of the regional aquifer system, such as contacts with effectively impermeable bed rock units of Entoto rhyolite and 2. Boundaries within the model extent related to hydrologic processes or features, such as stream systems, local slope and local impermeable hydrogeologic units such as Cheleleka_Nono Mountain covering Basaltic formation.

The ground water Divide of the Sibilu catchment assumed to be coinciding with the topographic divide and the basin is regarded as a closed one with no flow across the boundaries except outflow through small section in the northern boundary (Fig 16). There are however, a few ephemeral surface streams, which take off the groundwater effluence across the northern boundary of the area, during the Wet season. The aquifer has been assumed to be a single layer aquifer (Topmost) having a vertical recharge (top boundary). The bottom of the aquifer is assumed to be impermeable bedrock while the Southern, Eastern, Western and Northern boundaries are no flow boundary condition.

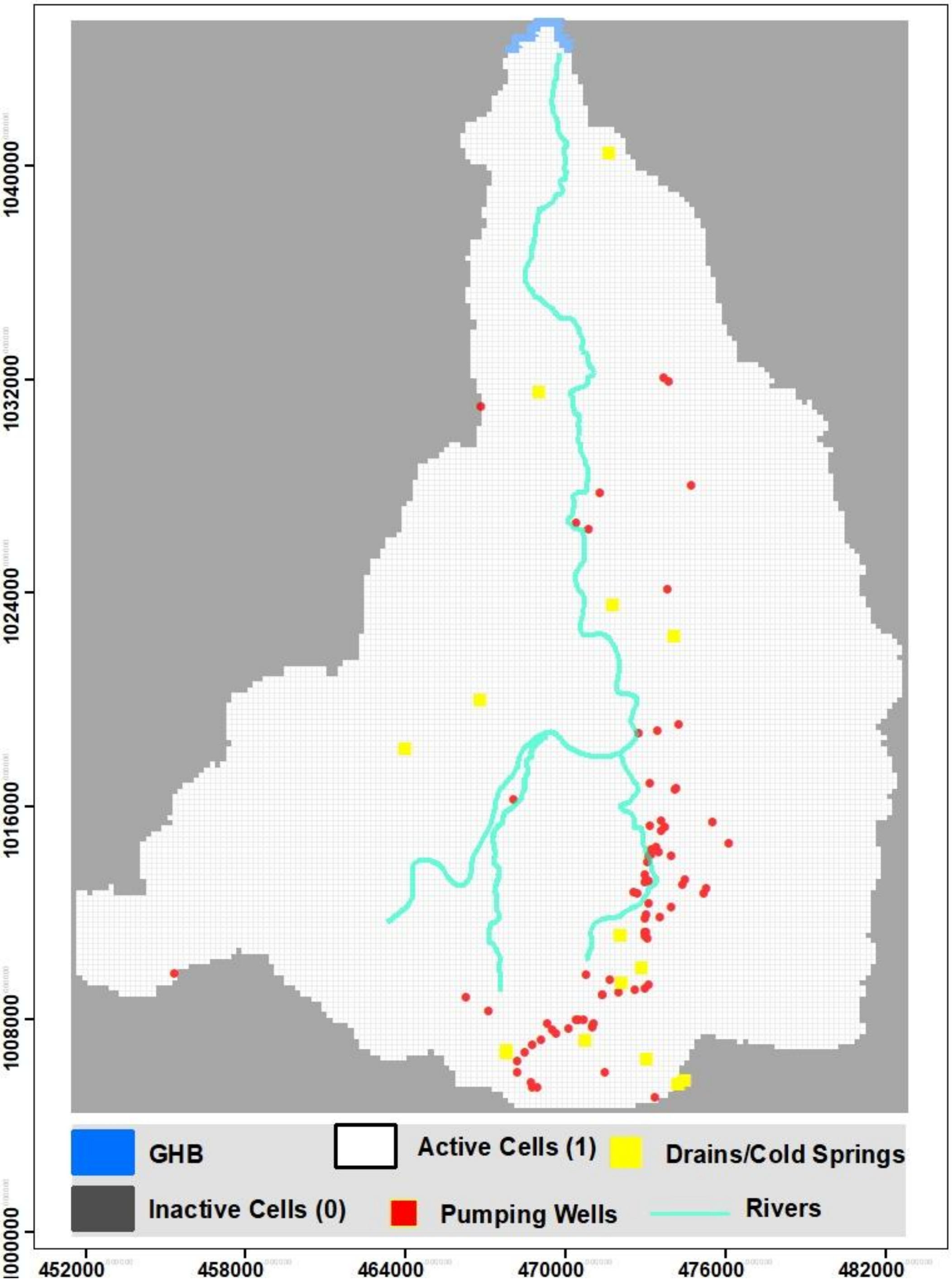
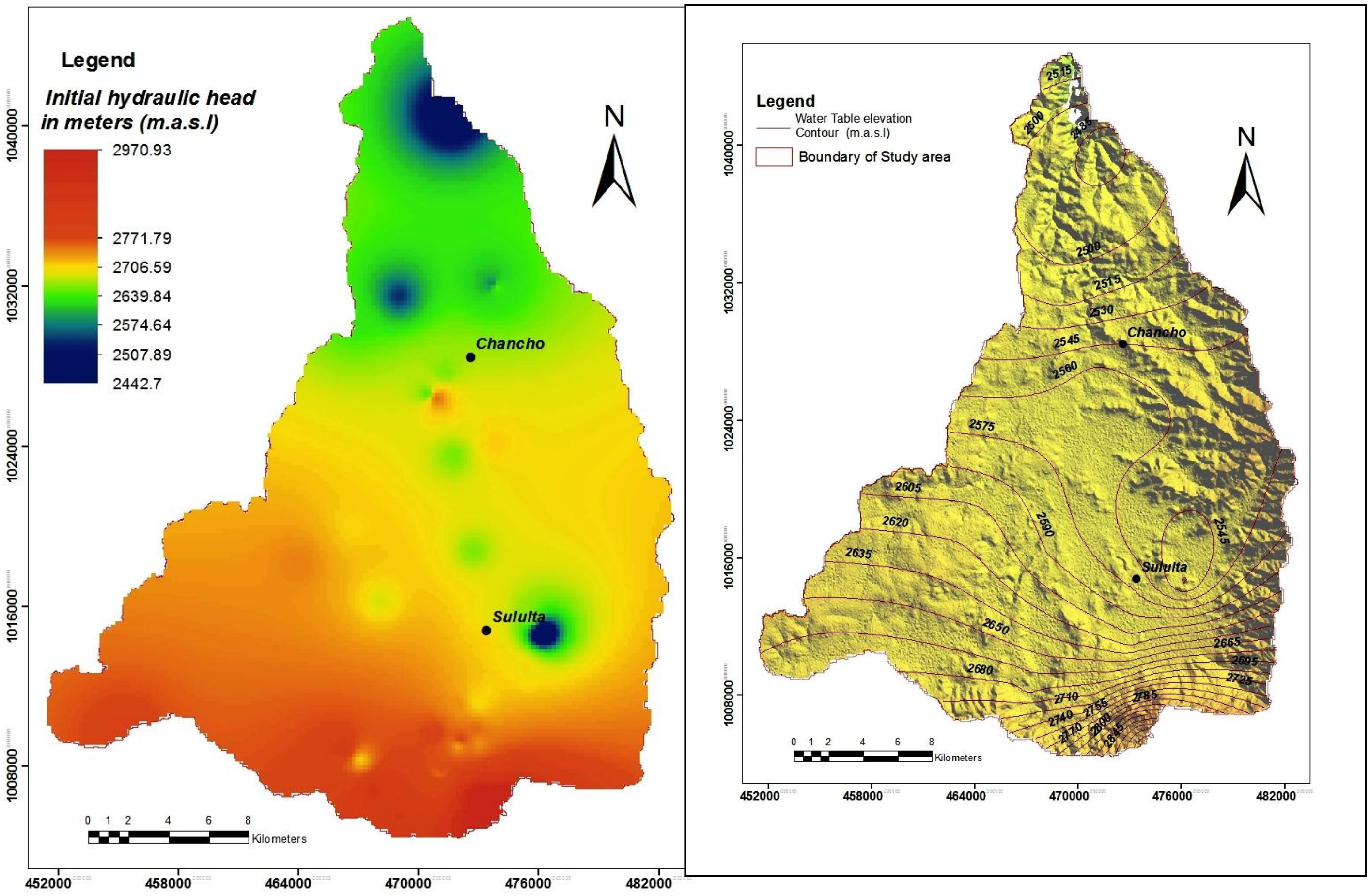


Figure 16. Model grid design, boundary conditions and Well distribution

5.8.3.2. Initial hydraulic head

MODFLOW requires initial hydraulic heads at the beginning of a flow simulation. Initial hydraulic heads at constant head cells are used as specified head values of those cells and remain constant throughout the flow simulation. The ground elevation at each model cell/Wells location point are extracted from ASTER DEM of the area, and then depth to static water level values those were obtained from the well database in the area are subtracted from each DEMs obtained. These obtained/calculated hydraulic head distribution was interpolated within the model to obtain the initial hydraulic heads for the entire model first using ArcGIS routine with kriging method and imported to ASCII-matrix file at the beginning of the model run and each cell in the model was assigned its head value.



(a) (b)

Figure 17. Initial Hydraulic head (a) and Groundwater table contour (b)

5.8.3.3. Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer material to transmit water which in turn controls the rate at which groundwater will flow under a given hydraulic gradient and it is a measure of the water transmitting properties of aquifer material. Hydraulic Conductivity is one of the important parameters to control the rate of groundwater movement in the saturated zone both vertically and horizontally.

Vertical hydraulic Conductivity or vertical leakance is not considered in the Sibilu case, since the PMWIN Pro calculate the vertical leakance by using vertical leakance between the layers i and i+1 to find the value of i^{th} layer. For a single layer model like the one currently dealt with, MODFLOW assumes that the Model layer is underlain by impermeable material and no flow takes place in it.

The Horizontal hydraulic conductivity (along Rows and Column) of the study area was estimated from pumping test data of boreholes drilled in the study area and interpolated to the entire active cell areas by using ArcGIS routine and finally export it to ASCII format to use in the appropriate MODFLOW package.

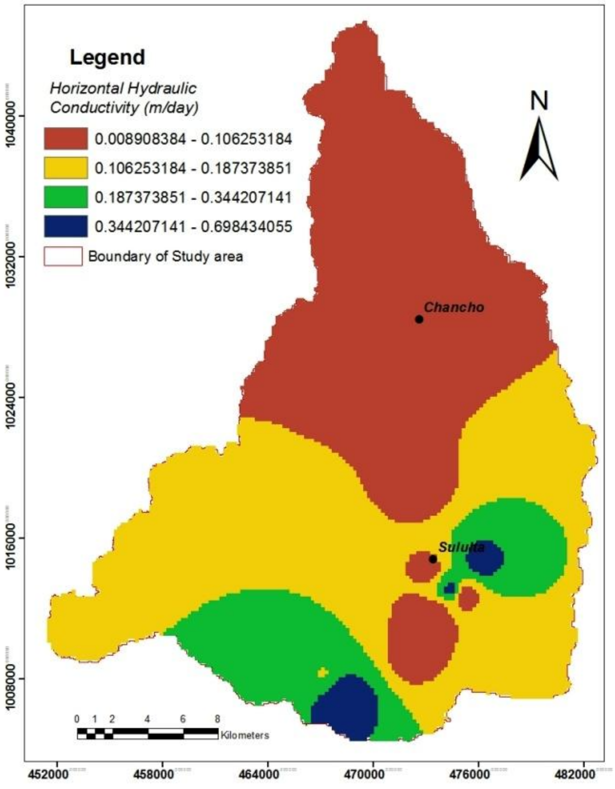


Figure 18. Initial hydraulic Conductivity of the study area as input source

5.8.3.4. Transmisivity

Transmissivity is the rate/frequency at which water of an existing density and viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. For the wells those possess Specific Capacity data only, Transmissivity values were calculated by Logan's 1964 approximation method from the obtained specific capacity by the following relationship.

T=1.22*Sc, where T=Transmissivity (m2/day) and Sc =Specific capacity (m2/day)

For some of the Wells in the study area transmissivity has been calculated from pumping test data and the result revels that it ranges between 0.4 m^2 to 95.4 m2 per a day. After interpolating to the entire active cell area from point well data, it exported to ASCII file to use it in the MODFLOW processing.

5.8.3.5. Effective Porosity

Total porosity is the ratio of Volume of voids (pore spaces) to the total volume of certain rock mass while Effective porosity is the sum of the interconnected pore space which is excluding isolated pores and pore volume occupied by water adsorbed on clay minerals or other grains (JP Gibb, 1984). Sometimes when effective porosity is high it will becomes equal to total porosity .Although a steady state flow simulation model does not require effective porosity parameter, it is necessary for the computation travel times and contaminant transport processes and determination of effective porosity also requires core analysis (humidity-dried or oven-dried) which is beyond the scope of this study.

According to (Tesfaye A. E and Asmelash. A, 2016), the porosity of Entoto rhyolite is 6%, Ignimbrite 9.13%, Welded Tuff 17.38%, Weathered and fractured basalt 30% and 35% for Sediment deposit in and around Addis Ababa.

For the vast majority of rocks in the study area, effective porosity considered as it is equal to total porosity, because most of them are composed of non –clay minerals coarser than silt and at the same time they are affected by weathering and fracturing activities (Fig.19).

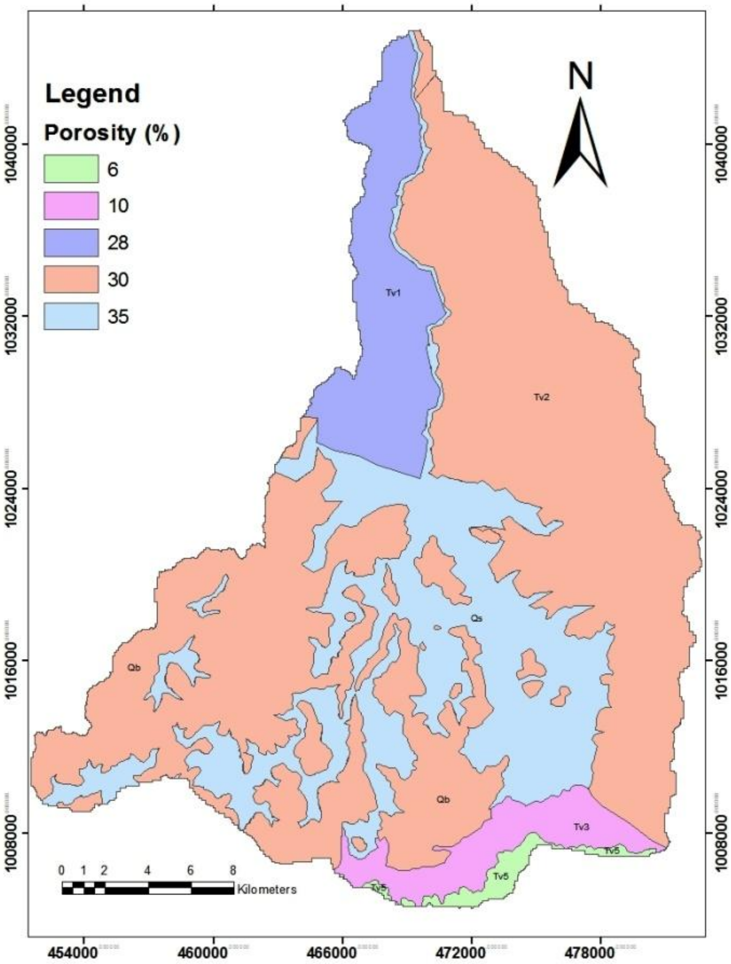


Figure 19. Porosity distribution of geological materials in Sibilu Catchment

5.8.3.6. Aquifer geometry and thickness

From conceptual model and assumed boundary conditions the aquifers aerially extend in the non-uniform manner (see section 8.3). The Spatial variability of Aquifer thickness, Aquifer top and bottom elevations are controlling the geometry of an Aquifer.

Aquifer thickness

The Aquifer thickness of the catchment was obtained from the length of Screen casing and log data of different Wells those sunk in the Sibilu watershed .These obtained point data interpolated to the entire catchment area and then after, exported to ASCII file by GIS tools to use in the MODFLOW processing.

The saturated aquifer ranges from 15 m to a maximum of 241 m as determined from different water Wells with different total depths (Fig.20).

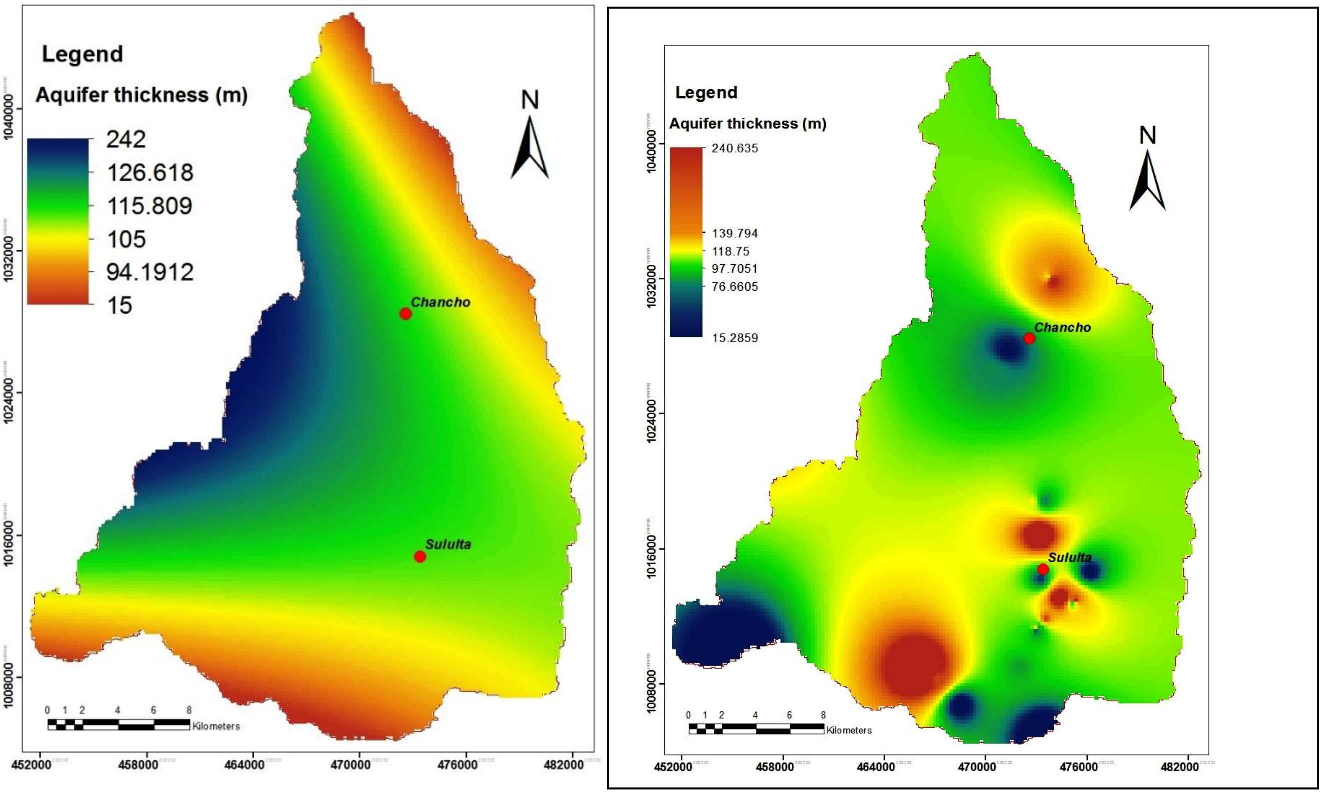


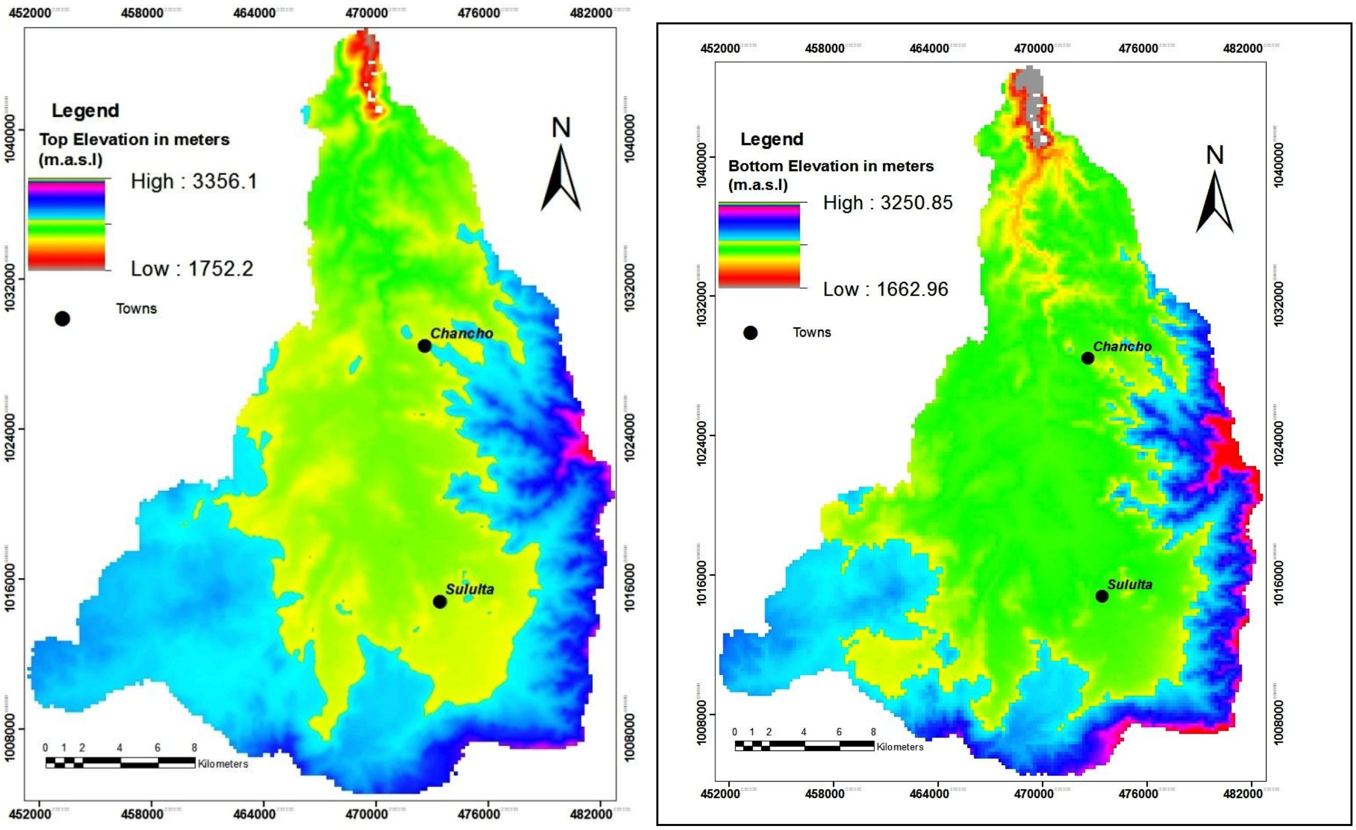
Figure 20. Aquifer thickness map (kriging & IDW)

Top of Aquifer

The top of the aquifer layer is assumed to be the ground elevation and drawn from the 30 m by 30 m resolution ASTER digital elevation model. The DEM data is processed to generate grid file to be in a format compatible to the Processing Modflow and imported to the model with elevation referenced according to its geographic position. Accordingly, the top surface elevation of an Aquifer ranges from 1752.2 m to 3356.1 m mean above sea level (Fig. 21).

Bottom of an Aquifer

During model development assigning the bottom elevation is a difficult task as the aquifer thickens is variable. As mentioned in section 6.4.6 the aquifer thickness in the Sibilu river catchment varies from few meters to several meters (more than 240 meters) in different parts of the study area except along the Entoto-Cheleleka-Nono chain of mountain with high elevation. In order to avoid drying of cells during simulations elevated zones were given relatively higher thickness at the cells. The bottom Aquifer elevation simply obtained by subtracting the Aquifer thickness from Top elevation by using the GIS Spatial analysis tool (minus) and finally modified a bit in few areas during model calibration process. The top and bottom elevation of the study area is shown in Figure.21.



(a) (b)

Figure 21. Top (a) and Bottom (b) elevation of an Aquifer

5.8.3.7. River packages

The major perennial streams are another important boundary condition which facilitates the movement of groundwater to and from perennial rivers. The flux of water between the groundwater system and rivers is generally dependent on the hydraulic head in the groundwater system and is simulated as a head-dependent flux boundary. It allows water to flow from the aquifer to the source reservoir, thereby removing water from the model by seepage to gaining stream reaches. Water can also flow out of the stream into the aquifer. Thus, a losing reach of stream could recharge the aquifer with more water. In order to simulate the interaction of the surface and groundwater the model used the river package to simulate the flow between an aquifer and an overlying or under lying source of reservoir but usually River. In Sibilu catchment case the perennial Sibilu, Weserbi and Gerbi Rivers are used to simulate the flow between River and in contact Aquifer system (Fig.16).

Table 13. Major stream model input summary (After Makin et al., 1976)

No	Main Rivers	**1.Bed Thickness (m)**	**2.Head of the River (m)**	**3. Width of the river in the grid Cell (m)**	**4. Length of the river in grid cell (m)**	**Conductivity (m^2/day)**
1	Sibilu	0.15_0.51	1731_2655	9.96_62.8	36_647	0.01_0.2
2	Weserbi	0.12_0.30	2559_2581	7.3_15.3	94_676.4	0.06_0.23
3	Gerbi	0.17_0.25	2559_2641	11.2_20.6	74_201	0.12_0.2

Note: CD= (L*W*Kr)/M

Where CD is River Bed Conductance in m^2/d, M is an average river bed material thickness in m

W is average width of the river in the grid cell (m), L is the length of the river in a grid cell (m)

Kr is the hydraulic Conductivity of materials under the stream in the grid cell (m/d)

5.8.4. Stresses

Groundwater stress measures the Groundwater in the Aquifer system response to sinks and sources. Precipitation is the main and only sources to recharge the ground water of the area while well withdrawals, Natural Spring discharge, sub river Groundwater outflows and Actual Evapotranspiration process are the main groundwater discharge/sink mechanisms in the Sibiulu River catchment.

5.8.4.1. Recharge

Recharge estimated by SWAT

The recharge of the area is applied through the recharge package of MODFLOW and estimated by SWAT tools (see section 5.7.3.2 for details of recharge rate).

Recharge estimated by previous Studies

In previous Studies there are a few attempts to estimate the recharge in the Sibilu river catchment. In earlier time (Debebe, 2005) estimated the recharge rate of the study area to be 342 mm/yr using a semi distributed water balance method while recently (Bereket F. , 2015) estimated a base flow as a minimum recharge rate that to be 174.5 mm/yr by Base flow separation method during his Origin of Sibilu wetland identification study using ^{222}Rn, δ2H and δ18O Isotope method.

Recharge estimated by chloride Mass Balance method

Chloride mass Balance (CMB) method is one of the recharge estimation methods, which is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface (Yongxin & Beekman, 2003). This method is used to estimate the average areal groundwater recharge to the Sibilu catchment by taking the following main assumptions in to account:

- Chloride Ion is not leached from the Aquifer formation
- Chloride Ion behaves conservatively under steady state condition (no sources and sinks for chloride ion)
- The only source of chloride in the area is rain fall and recharge to the Aquifer of the study area is assumed only from direct precipitation.

This Assumption only accepted when there is no addition from fertilizers or permanent removal by crop harvesting or transfer by grazing animals ((Obakeng, 2000).

According to Singh, (2007) representative chloride input data of precipitation should be weighted over a long enough period of time i.e a minimum 1 to 6 months. Accordingly, weighted chloride value of Muger basin (0.88 mg/l) and Akakai Catchment (0.8 mg/l) that are measured by (Tilahun, 2014) and (Alema, 2009) is used respectively to estimate the recharge of Sibilu River catchment.

As the sample is collected in the main rainy season July and August, Seasonality of chloride concentrations in precipitation is not also taken into account in calculating groundwater recharge through the chloride mass balance and impacts of rainfall in other months is also considered to be negligible.

For Groundwater Chloride Concentration of study area, it is determined from a total of 48 water samples, 27 Deep wells, 7 Hand dug wells and 14 cold springs. The mean, minimum and max chloride concentration in the groundwater of the area is 12.7, 0.85 and 165.2 mg/l respectively. (Erikson .E, 1985), stated that the average groundwater chloride content has to be calculated as harmonic mean of chloride concentration and hold in the following formula:

$$Cl_{gwhm} = \frac{N_{sample}}{\sum_{i=1}^{n} \frac{1}{Cl_{gw}}} \qquad (9)$$

Where Cl_{gw} is the individual chloride concentration of samples in *mg/l*

N_{sample} is the total number of measured samples based on the collected groundwater samples *(*Annex III).

As cited by (Taye, 2016) applying the law of mass conservation the freight of non-reactive chloride input equals to the chloride output (Singh, 2007).

$$Cl_{input} = Cl_{output}$$

$$P * Cl_{p} = R_{gw} * Cl_{gwhm}$$

$$R_{gw} = \frac{\left(Cl_{p} * P\right)}{Cl_{gwhm}}$$

Where, P is average annual rainfall in the area, 1217.34 mm/year

Cl_{p} is average Chloride concentration in rainwater sample, 0.88 mg/l

Cl_{gwhm} is harmonized mean concentration of groundwater samples, 3.1941 mg/l

- R_{gw} is average depth of recharge rate to the groundwater table, mm/year
- N_{sample} is the total number of measured samples, 48 samples

Substituting the above parameters in to the mass conservation equation, groundwater recharge that estimated by using chloride mass balance method is 335.4 mm/year. When an average Chloride concentration in a rainwater sample of adjacent Akakai Catchment (0.8 mg/l) is applied, the estimated groundwater recharge in the area would be 304.9 mm/year or 24.8 % of the annual average rainfall in the basin and a total of 198.2 MCM/year (Annex III) which is very close to the recharge rate estimated by SWAT tool.

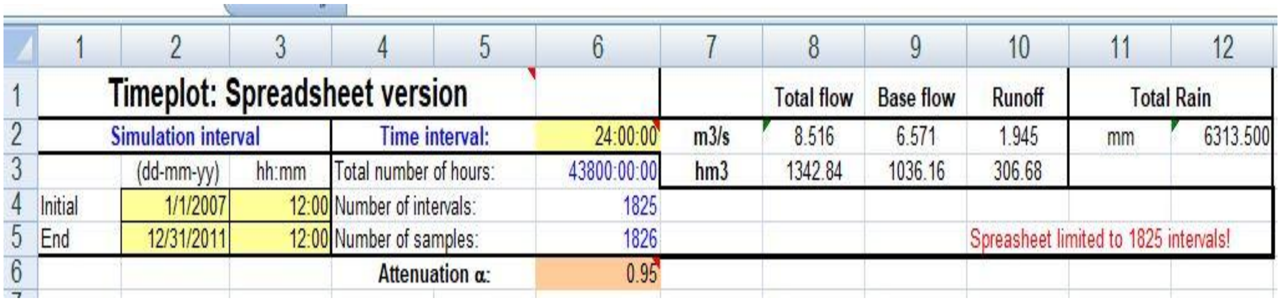
As discussed by (Yongxin and Beekman, 2003) during the recharge estimation using CMB method the important concern area includes the uncertainty in the measured chloride content of precipitation and precipitation amount. The largest uncertainty associated with CMB method recharge estimation, comes from the determination of chloride concentration in the rain fall precisely while the difficulty of measuring the highly variable rainfall amount accurately also contribute its part to the uncertainty of recharge estimation by such method. The absence of long-term rainfall quality data and Groundwater sampling density together with analysis accuracy also might be the source of uncertainty during CMB recharge estimation approach.

Recharge estimated by Base flow Separation method

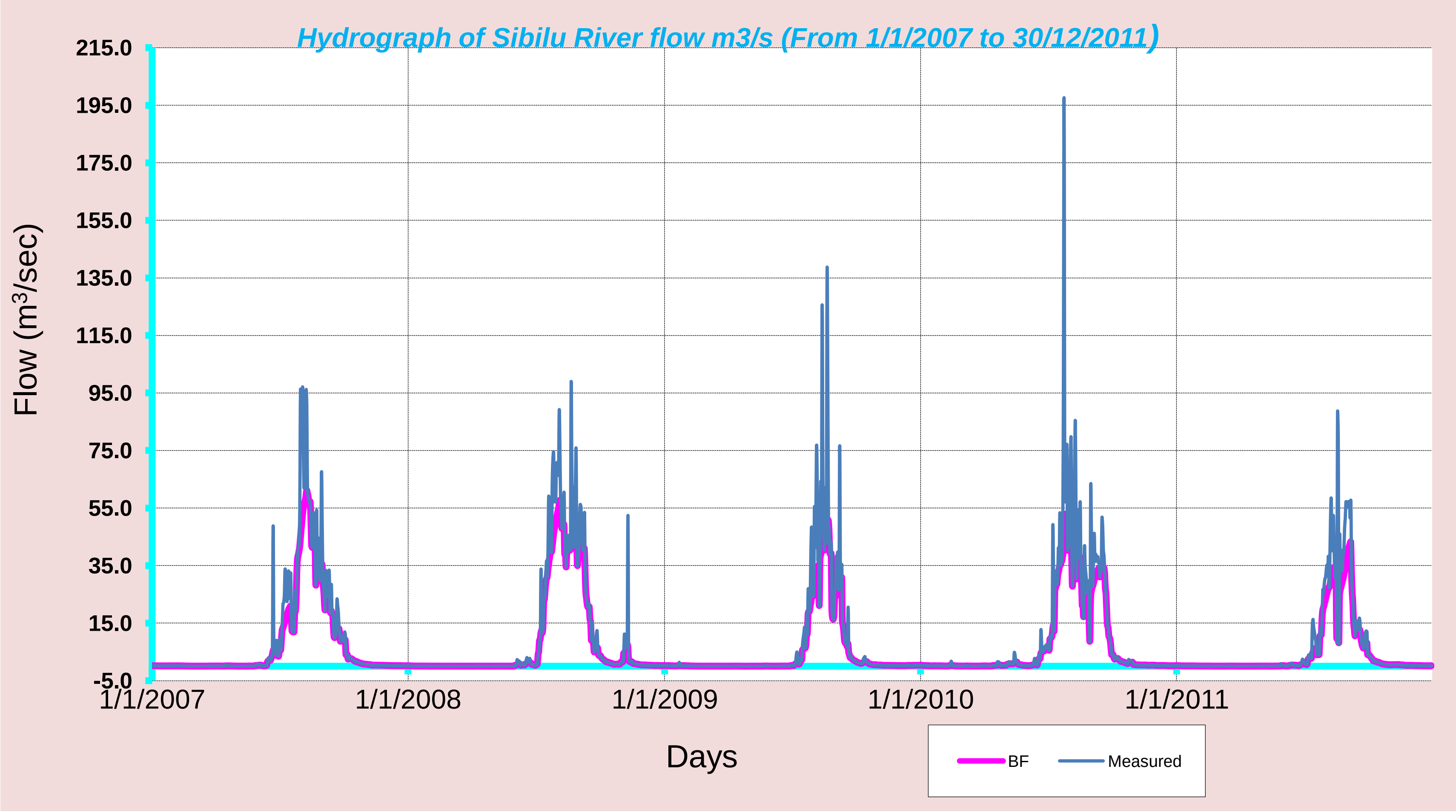
Base flow Separation from hydrograph, deals mainly with classifying the stream flow records in to quick runoff and base flow components. From several base flow separation methods Timeplot: Spreadsheet version has been used in this case and Sibilu river flow data from 2007 to 2011 years at the river gage station mentioned as Muger at Chancho, together with precipitation data from Addis Ababa University Observatory station of the same year have been utilized to estimate the recharge of Sibilu catchment.

In this estimation Gabriel Parodi attenuation coefficient (α) of 0.95 (the bigger the coefficient, the stronger the runoff and the lesser the base flow) has been applied and a recharge rate of (6.571 m^3/s) 318.8 mm/year has been determined. See the details in the subsequent Table and hydrograph.

Table 14. Parameters of Time Plot for Recharge estimation



	1	2	3	4	5	6	7	8	9	10	11	12
1	**Timeplot: Spreadsheet version**							**Total flow**	**Base flow**	**Runoff**	**Total Rain**	
2	Simulation interval			Time interval:		24:00:00	**m3/s**	8.516	6.571	1.945	mm	6313.500
3		(dd-mm-yy)	hh:mm	Total number of hours:		43800:00:00	**hm3**	1342.84	1036.16	306.68		
4	Initial	1/1/2007	12:00	Number of intervals:		1825						
5	End	12/31/2011	12:00	Number of samples:		1826				Spreasheet limited to 1825 intervals!		
6				**Attenuation α:**		0.95						



Graph 7. Base flow Simulation from Total flow in Sibilu River Catchment (Gage station: Muger @ Chancho)

5.8.4.2. Discharge

As observed during assessment, ground water discharge is carried out through unregulated Well abstraction, spring discharges, Evapotranspiration and groundwater outflow to the stream. Intensive well abstraction for Water bottling, different industrial uses, Agro processing, commercials, irrigation, hotels and domestic water supplies are the main groundwater abstraction means in the Sibilu Catchments as a result of anthropogenic activities.

Abysinia, Selam, Cheers, Arki and Gift water bottling companies are currently exploiting the groundwater in the Sibilu catchment for bottling while Oromia Steel and pipe factory for steel and pipe production, China _African Tannery for lather processing, Allied Chemicals for agrochemical production, Tamaz food complex for floor production and Textile factory for textile processing are using the groundwater of the area which is considered in general as Industrial uses.

Elemtu Integrated Milk Industry Sh. Co, Selalle Diary and Dr. Hilu Werku are exploiting groundwater for milk production and agro processing. Different Flower Framings, local vegetable cultivation and apple seedlings in the catchment are using the well water for irrigation purposes while Sululta Town, Chancho Town, Mizan town and surrounding Village communities are exploiting the groundwater of the catchment for domestic water supplies and hotel services (Annex II). Disregarding some of water wells with non data availability, as estimated during field assessment totally 16,270.58 and 1,948.32 m3/day from deep Wells and cold springs respectively are discharging out from groundwater system of the area for different purposes and used as in put data for MODFLOW Well packages.

Table 15. Well abstraction rate and their location that applied to the model (layer 1)

Bore hole ID	*Rows (i)*	*Column (j)*	*Stress rate (m3/d)*	*Local Name*	*Remarks*
BH_1	172	108	-70.848	Abysynia Factory /inside	
BH_2	171	108	-322.56	Abysynia Factory /inside	
BH_3	171	108	-65.664	Abysynia Factory /outside	
BH_4	169	111	-397.44	Abysynia Factory /outside	
BH_5	171	108	-149.76	Abysynia Factory /inside	
BH_6	157	109	-26.928	Issac Abdulahi Noc fuel station	
BH_7	194	86	-505.44	Belaya Industrials PLC	
BH_8	183	103	-259.2	Elemtu Integrated Milk Industry Sh. Co	
BH_9	163	120	-777.6	Sululta Town (Omo doroba)	
BH_10	184	75	-1584	Weserbi (10 kilo)	
BH_11	68	113	-86.4	Chancho (mapping Well)	
BH_12	162	115	-1094.4	Sululta o1 (G/Arbe)	
BH_13	186	79	-2138.4	Sululta/kara ta'aa (laga kawe 2nd)	
BH_14	155	124	-586.08	Suluta 01/Goro Arba	
BH_15	134	107	0	Sululta (Wereso)	Test Well
BH_16	67	112	0	Chancho/Gutu Ilamo	Test Well
BH_17	188	97	-14.4	Sululta Depo (Sunshine Petroleum Depot)	
BH_18	179	20	-8.064	Gudu	
BH_19	89	100	-56.16	Chancho	
BH_20	202	110	-864	Entoto Mariam	
BH_21	73	78	-86.4	Rob Gebeya	
BH_22	107	113	-86.4	Korke Robe	
BH_23	172	109	0	Sululta	Data not Available
BH_24	147	84	0	Shegole Meda	Data not Available
BH_25	87	117	0	Arbi Akako/Chancho	Data not Available
BH_26	132	115	0	Wereso/keto (Goliye)	Data not Available
BH_27	133	111	0	Wereso/keto (Goliye)	Data not Available
BH_28	156	111	0	Selasie/Sululta 01	Data not Available
BH_29	157	113	0	Selasie/Sululta 01	Data not Available
BH_30	161	116	0	Degefa Bula/Wale lube babu	Data not Available
BH_31	164	107	0	Kajima Sululta	Data not Available
BH_32	152	112	-307.8	Red Cross (sululta 01)	
BH_33	151	109	-171	Bilao (Sululta 01)	
BH_34	189	90	-164.16	Atlete Mender (k/wasarbi)	
BH_35	167	113	-432	Fereja Eth & Chancho Flower	
BH_36	181	109	-86.4	Kefle Bulo Apple Farm	
BH_37	164	106	-691.2	JJ Kothari Flowering Farm	
BH_38	145	114	-38.88	Allied Chemicals 1	
BH_39	144	114	-38.88	Allied Chemicals 2	

Bore hole ID	Rows (i)	Column (j)	Stress rate (m3/d)	Local Name	Remarks
BH_40	157	109	-43.2	Dr. Hailu Worku	
BH_41	169	108	-12.96	Tamaz food complex	
BH_42	182	106	-43.2	Oromia Steel Pipe Mill Factory	
BH_43	183	100	-86.4	Selale Diary	
BH_44	143	109	-1036.8	China Africa Tannery	
BH_45	188	96	-86.4	Textile (?)	
BH_46	155	110	-7.2	Dr Feseha	
BH_47	156	109	-7.2	Palace Hotel	
BH_48	158	109	-7.2	Bolina Boru Hotel	
BH_49	161	108	-7.2	Solomon Hotel	
BH_50	161	109	-7.2	Dire Sululta Hotel	
BH_51	162	109	-7.2	Hanymoon Hotel	
BH_52	195	84	-7.2	Yaya Athletics Village	
BH_53	193	87	-7.2	Kenenisa Resort	
BH_54	191	89	-14.4	Nile Petroleum	
BH_55	190	91	-7.2	Tsena Lodge	
BH_56	180	102	-4.32	Shufune	
BH_57	182	108	-7.2	Federal Dog Training Center (Fengi ,Kaso weserbi guto)	
BH_58	164	119	-597.6	Sululta /Wale	
BH_59	39	154	-403.2	Hambiso/Chancho	Outside of the catchment
BH_60	35	135	-144	Moye Gajo/Chancho	
BH_61	96	98	-144	Laga Tame/Chancho	
BH_62	95	95	-149.76	Chnacho/Buba keb.	
BH_63	152	111	-5	Hirut Agonafer/sullta	
BH_64	151	111	-60	Mokonin & Tsige	
BH_65	162	108	-85	Getachew Garage	
BH_66	166	109	-30	ARM Factory	
BH_67	168	108	-50	Ethiopia Hotel	
BH_68	179	97	-20	Abayas Trading	
BH_69	198	101	-80	Zewudu Tadesse	
BH_70	183	100	-85	Berhanu Ragassa	
BH_71	189	98	-576	Gift Water _1	
BH_72	189	99	-103.68	Gift Water _2	
BH_73	189	99	-288	Gift Water _3	
BH_74	188	95	-90	Daksen Village	
BH_75	189	94	-140	Indris Teshome	
BH_76	190	91	-50	Kasu Negash	
BH_77	198	84	-40	Hunde Resort	
BH_78	200	88	-540	Tadesse Debelle 1	
BH_79	201	87	-230.4	Tadesse Debelle 2	
BH_80	200	87	-201.6	Weserbi Real State	
BH_81	151	121	-194.4	Doroba /sululta	
BH_82	95	21	-151.2	Segno gebeya	Outside of the catchment

Table 16. Abstraction rates from cold springs and Drain hydraulic conductance applied to the model with drain package

ID	Rows (i)	Column (j)	Stress rate (m3/d)	hydraulic head in a drain cell (m)	Elevation of the Drain (m)	Drain Hydraulic conductance (m2/d)	Locality
CSP-1	181	104	172.8	2667.63	2666	106.01	Shefune
CSP-2	194	82	146.88	2718.09	2717	134.75	10_killo (Aser kilo)
CSP-3	194	82	103.68	2718.09	2717	95.12	Guto elamo
CSP-4	172	104	60.48	2620.37	2619	44.15	Bokisa
CSP-5	128	77	120.96	2588.02	2587	118.59	Gulele_Gebreal
CSP-6	110	102	51.84	2565.2	2550	3.41	_
CSP-7	70	88	64.8	2506.04	2472	1.90	Werkito/EkoBabo
CSP-8	25	102	43.2	2480.5	2430	0.86	Boku Abo, Boku ureta
CSP-9	192	97	172.8	2724	2683	4.21	Qimbrie, Weserbi
CSP-10	200	114	17.28	2988.5	2826	0.11	Entoto mariam, Kebele 20
CSP-11	199	116	181.44	2977	2825	1.19	Entotomariam, Kebele 20
CSP-12	137	63	95.04	2612.8	2612	118.80	Burka Gibsa, Hawaso
CSP-13	195	109	25.92	2905.7	2830	0.34	Chefe Entoto
CSP-14	178	108	259.2	2653	2651.5	172.80	Sululta Ashewa
CSP-15	172	104	302.4	2620.37	2619	220.73	_
CSP-16	116	114	129.6	2560.3	2559	99.69	Doro Erbata Spring

5.8.5 Modflow Model Calibration and Validation

5.8.5.1. General

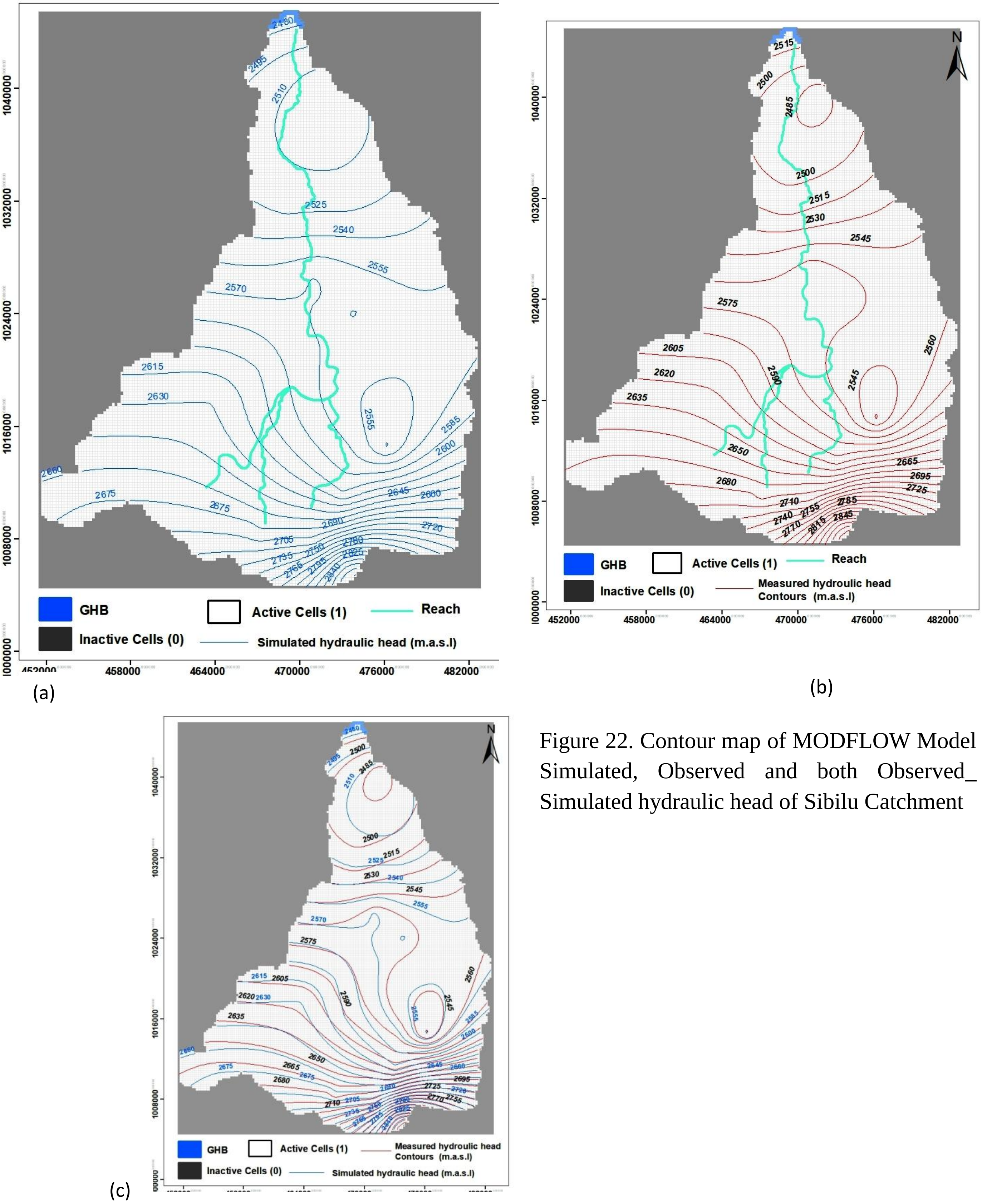
Steady state Groundwater flow model calibration process involved adjusting of parameters, Boundary Conditions and/or stresses (sinks) within an expected range till the difference between models predicted and observed state variables attains good much. In order to provide some assurance to the Model derived results, the model should be calibrated prior to use as predictive tool and to be a good representative of the real world the difference between the simulated/Modeled and observed state variables has to be small as possible. This procedure requires the calibration target which is referred to as goodness of fit criterion (Rientjes T.H.M, 2007).The error in the calibration process is determined by various aspects such as accuracy of measurements, complexity of the system being modeled and the applied model resolution (Alema, 2009). Within this challenges adjusting the calibration criterion is a tedious and routine task.

5.8.5.2. Calibration Target

Prior to Starting calibration process in modeling the selection of calibration target is crucial and hydraulic heads obtained from Groundwater level measurement during well completion pump testing were used as calibration values. The calibration target was to much the simulated hydraulic head with observed values that recorded in different years as the Wells that used in calibration processes were drilled in various years by varying suitable hydraulic conductivity values. In case of the study area most of the measured hydraulic heads data are might associated with a slight errors due to: the static water level measurements were taken very soon after well completion and absence of monitoring wells to collect precise water level data.

5.8.5.3. Calibration Techniques and Results

Basically, there are two ways of calibration and parameter estimation: 1.Manual trial and error calibration and 2. Automated parameter estimation (Anderson M.P and Woessener, 1992).In this case manual trial and error technique was applied with varying the hydraulic conductivity values and comparing the observed and simulated hydraulic heads of 52 water points. If the modeler posses prior information and has a considerable knowledge about the study area the calibration would be a bit easy and the most effective calibration mechanism for the adjustment of the hydraulic conductivity parameter in the model was to initially delineate fewer conductivity zones and then gradually increase the number of zones based on the geology and hydrogeological units in the area. After repeating trials, a satisfactory simulation result of hydraulic head has been obtained and the calibration result shown in the form of graphs, map and tables below.



(a)

(b)

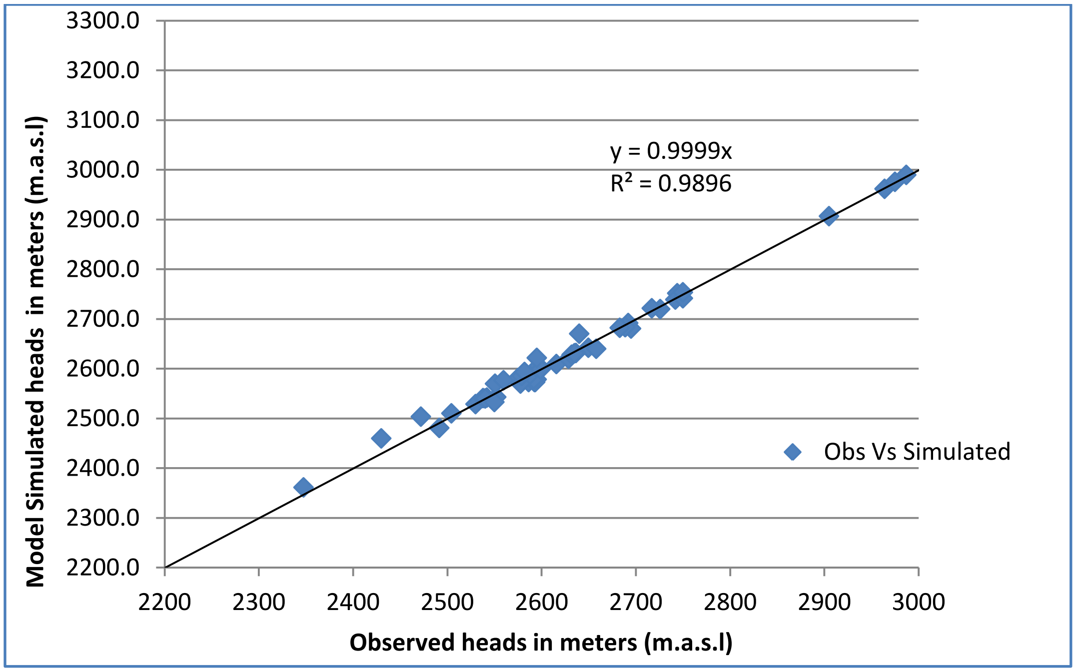
(c)

Figure 22. Contour map of MODFLOW Model Simulated, Observed and both Observed_ Simulated hydraulic head of Sibilu Catchment

5.8.5.4. Model Calibration process evaluation

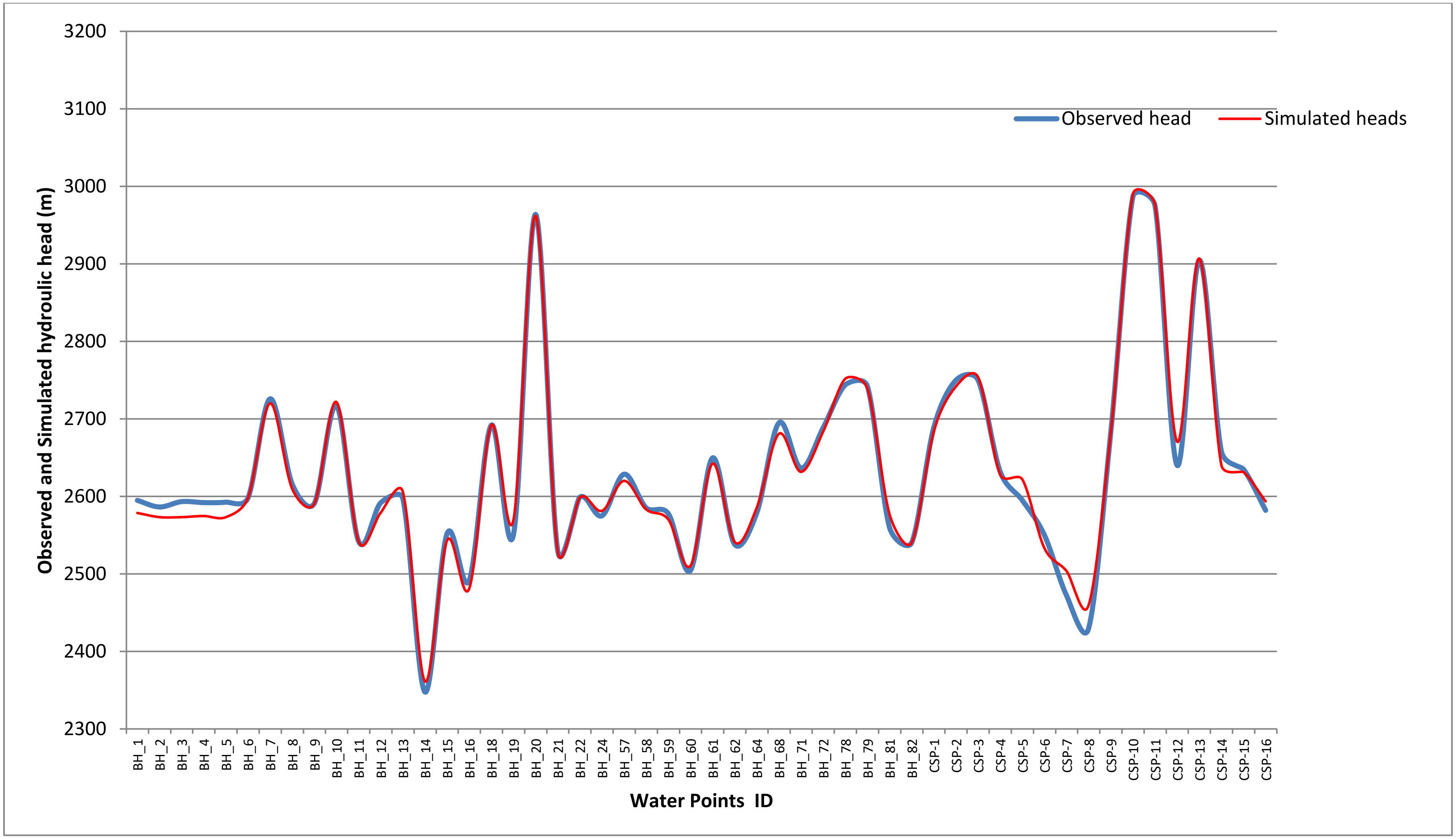
During Model calibration the calibration process has to be evaluated with graphical techniques, quantitative Statistical methods or both, to indicate the acceptable quality of calibration procedure or to measure the performance of the model.

Accordingly, Map (section 5.8.5.3) and graphical comparisons together with error evaluation indices (ME, RMSE and MAE) have been employed to evaluate the performance measures of the calibration in the case of this research and described as follows.



Graph 8. Observed and simulated hydraulic head

From the scatter plot graph of above the observations Vs simulated value points those lie on the straight trend line shows the exact fit between the observed and simulated heads while the points that are scattered above the straight trend line indicates that, the simulated head values are a bit higher than the observed ones and the points those scattered below the trend line shows the simulated head values are slightly lower than the observed heads. The coefficient of determination (R^2) also describes the degree of co-linearity between observed and simulated head results and ranges from 0 to 1, with values near to 1 indicating less error variance and typically values greater than 0.5 are considered. Overall it shows the head differences are normally distributed and the fit is quite good.



Graph 9. Comparison of Observed and Simulated hydraulic head distribution plotted on a one graph

As mentioned above the other Model calibration processes evaluation method used, are the most commonly used error indices such as Mean Error (ME), Absolute Mean Error (AME) and Root Mean Square Error (RMSE) based on their governing equations mentioned under equation 7, 8 and 9 of section 5.4. See the Annex IV and Table 17 for the details calculations of the error indices and water point distribution used for hydraulic head simulation.

Table 17. Observed and simulated heads in meters

BH Id	**Obs. head (hm)**	**Simu. head (hs)**	**hm-hs**	**|hm-hs|**	**(hm-hs)^2**	**((hm-hs)^2 /n)**
BH_1	2594.87	2578.68	16.19	16.19	262.148	7.282
BH_2	2586.36	2573.29	13.08	13.08	170.956	4.749
BH_3	2593.29	2590.00	3.29	3.29	10.824	0.301
BH_4	2592.00	2574.75	17.25	17.25	297.632	8.268
BH_5	2592.56	2573.29	19.28	19.28	371.526	10.320
BH_6	2597.95	2598.20	-0.25	0.25	0.065	0.002
BH_7	2725.90	2720.09	5.81	5.81	33.710	0.936
BH_8	2615.75	2609.60	6.15	6.15	37.835	1.051
BH_9	2591.00	2590.78	0.22	0.22	0.050	0.001
BH_10	2717.00	2721.76	-4.76	4.76	22.620	0.628
BH_11	2542.00	2542.00	0.00	0.00	0.000	0.000
BH_12	2591.80	2579.06	12.75	12.75	162.435	4.512
BH_13	2597.10	2605.86	-8.76	8.76	76.773	2.133
BH_14	2347.52	2361.44	-13.92	13.92	193.850	5.385
BH_15	2552.00	2543.21	8.80	8.80	77.352	2.149
BH_16	2491.50	2489.00	2.50	2.50	6.250	0.174
BH_18	2692.00	2692.00	0.00	0.00	0.000	0.000
BH_19	2550.70	2570.00	-19.30	19.30	372.490	10.347
BH_20	2964.00	2962.00	2.00	2.00	4.000	0.111
BH_21	2530.00	2529.00	1.00	1.00	1.000	0.028
BH_22	2599.00	2598.69	0.31	0.31	0.096	0.003
BH_24	2575.00	2581.42	-6.42	6.42	41.165	1.143
BH_57	2628.68	2620.12	8.56	8.56	73.239	2.034
BH_58	2585.15	2583.37	1.79	1.79	3.186	0.089
BH_59	2577.70	2570.26	7.44	7.44	55.339	1.537
BH_60	2504.40	2510.39	-5.99	5.99	35.868	0.996
BH_61	2649.70	2642.35	7.35	7.35	54.022	1.501
BH_62	2538.00	2541.05	-3.05	3.05	9.284	0.258
BH_64	2579.00	2585.73	-6.73	6.73	45.253	1.257
BH_68	2695.00	2690.00	5.00	5.00	25.000	0.694
BH_71	2636.50	2631.78	4.72	4.72	22.297	0.619
BH_72	2688.73	2683.75	4.98	4.98	24.790	0.689
BH_78	2744.00	2751.96	-7.96	7.96	63.346	1.760
BH_79	2742.00	2739.24	2.76	2.76	7.607	0.211
BH_81	2559.70	2576.93	-17.23	17.23	296.735	8.243
BH_82	2540.25	2540.30	-0.05	0.05	0.003	0.000
			ME=1.6	AME=6.8		RMSE=8.9

Table 18. Summary of Statistical evaluation for Calibration

<table>
<tr><th>No</th><th>Description</th><th>SWAT model Calibration & Validation</th><th>MODFLOW model Calibration & Validation</th></tr>
<tr><td>1</td><td>Calibration Target</td><td>Observed Sibilu yearly River Flow (1970_1996), 27 years for calibration, 1997_2011, 15 years for Validation</td><td>To much the simulated hydraulic head with observed values (goodness of fit)</td></tr>
<tr><td>2</td><td>Calibration Techniques</td><td>Using SWAT_CUP and a Sequential Uncertainty Fitting, version 2 (SUFI2) calibration methods</td><td>In this case, repeating manual trial and error technique was applied with varying the hydraulic conductivity values till a satisfactory simulation result of hydraulic head has been obtained</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Model Calibration process evaluation</td><td>■ coefficient of determination (R2) of 0.6302 and
■ Nash-Sutcliffe simulation efficiency (ENS) of 0.42</td><td rowspan="2">■ Map and graphical comparisons, R^2 =0.98
■ Error evaluation indices (ME, RMSE and MAE) have been employed to evaluate the performance measures of the calibration
<table>
<tr><th colspan="4">Evaluation of Calibration</th></tr>
<tr><td>Error measured (m)</td><td>ME</td><td>AME</td><td>RMSE</td></tr>
<tr><td>Value 1</td><td>1.6</td><td>6.8</td><td>8.9</td></tr>
<tr><td>Value 2</td><td>0.1</td><td>9</td><td>12</td></tr>
</table></td></tr>
<tr><td>For validation, R2 value is 0.86 and this again shows the model simulation result is valid.</td></tr>
<tr><td>4</td><td>Calibration results</td><td>Piper graph, Simulated Vs observed River flow</td><td>Maps, Graphs, and Statistical error evaluation indices</td></tr>
</table>

NB: Value 1, resulted when 36 water points are used, & Value 2 resulted when 52 water samples are used (n=36 or 52, see Annex IV)

6. RESULT AND DISCUSSION

6.1. Hydrogeology

Geology of the Sibilu catchment contains fracturing and vesicles which enhance the water holding and transmission capacity. Hydrogeologically the area covered by porous Aquifer of quaternary sediment and fractured with vesicular Aquifers of basaltic formation. The whole hydrogeologic domain classified in to: low to moderate productive (Tv3), Moderate productive (Tv1, Qb &Qs) and moderate to high productive (Tv2) Aquifer system.

As known Topographic aspect, gradient of ground water and structural trend of the area influence and guide the local and regional flow directions of ground water. By using mainly, the calibrated simulated hydraulic head of the Sibilu catchment the general groundwater flow direction are determined to be to the northwest and northern part of the study area just in considering the perpendicular lines to the simulated potentiometeric surfaces from high gradient towards low gradient (Fig.23).

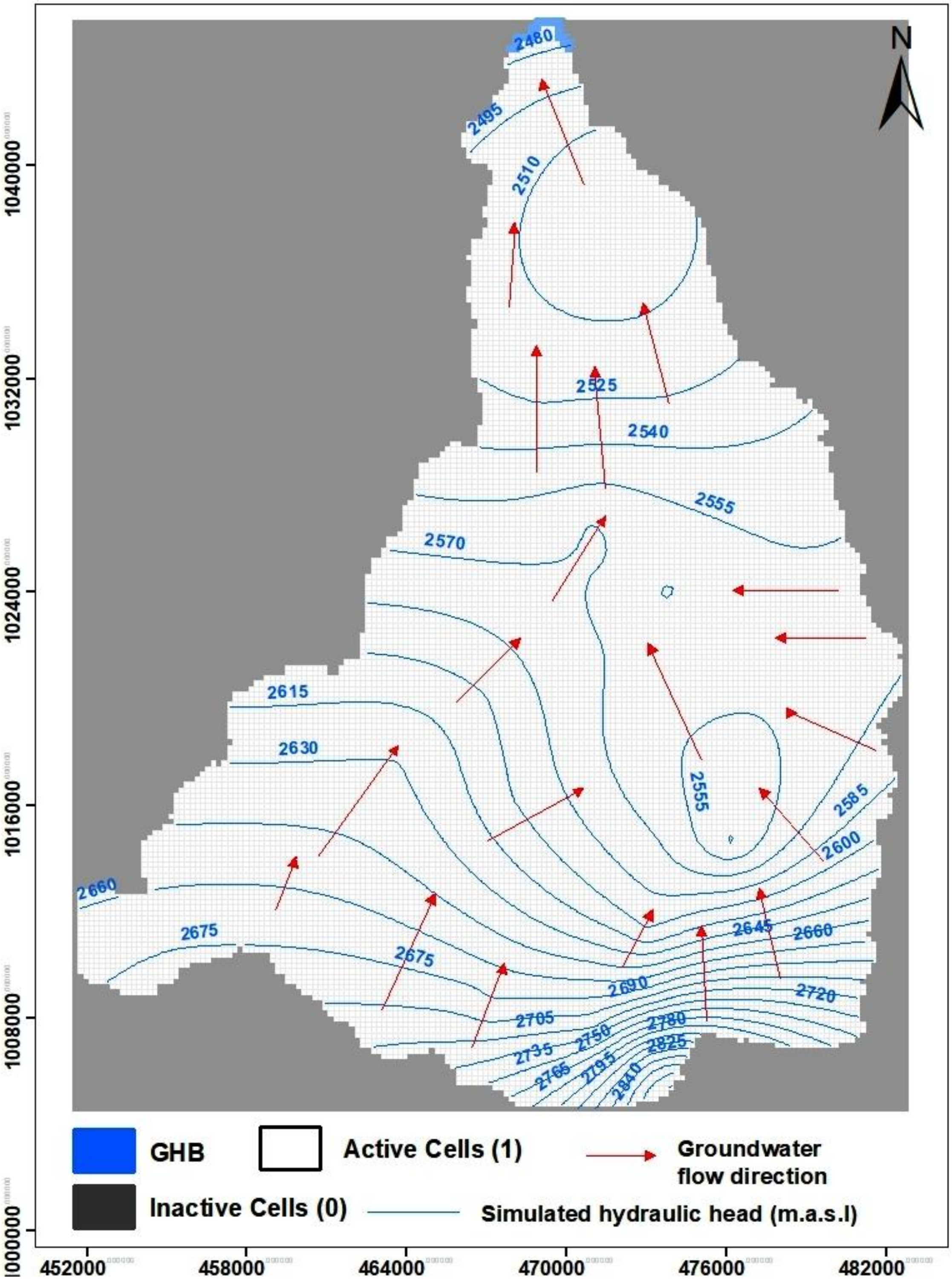


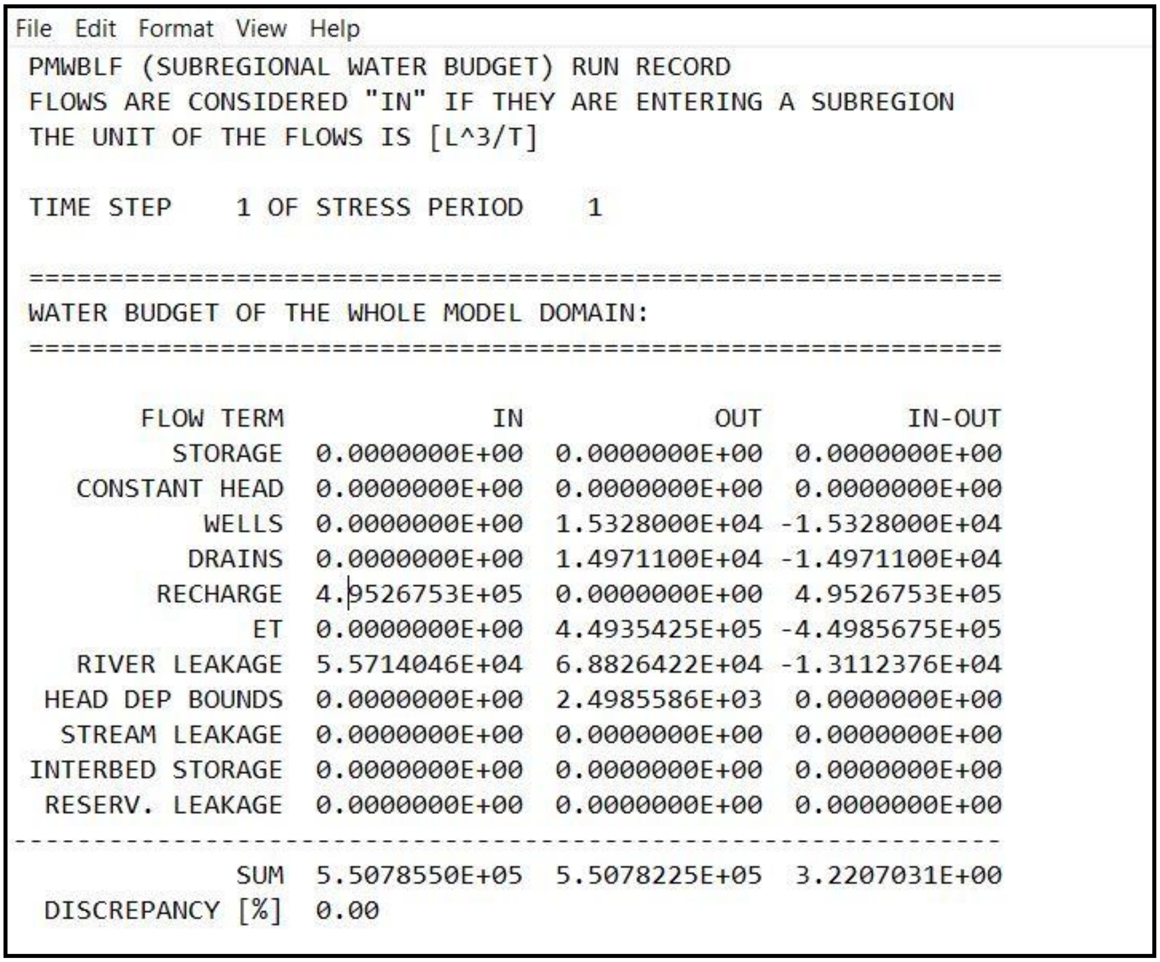
Figure 23. Groundwater flow direction of Sibilu catchment

6.2. The steady State model derived Groundwater Budget

MODFLOW simulate the hydraulic head distribution of the study area which latter calibrated by varying the hydraulic conductivity results in a tray and error mechanisms. The simulated head distribution shows that the groundwater flow is from southern and eastern parts of the study area towards the northwestern river gorges. The groundwater level is relatively steep slope at the south and western part and flat in the central Sululta plain of the Catchment.

Using calibrated model, the water budget of the whole domain has been estimated with a 0% discrepancy that is due to a better recharge estimation and comprises the inflow and outflow components to and out of the groundwater system of the catchment. The simulated inflow component includes direct recharge from precipitation and inflow from the river leakage. While the simulated outflows carried out through Wells, as ET, Drains/Springs, river leakage and head dependent boundary components (Table 19).

Table 19. Daily Simulated Water Budget of Sibilu River Catchment (650 km^2) in m^3/day



```
 PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
 FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
 THE UNIT OF THE FLOWS IS [L^3/T]

 TIME STEP    1 OF STRESS PERIOD    1

 =============================================================
 WATER BUDGET OF THE WHOLE MODEL DOMAIN:
 =============================================================


        FLOW TERM             IN            OUT         IN-OUT
          STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
    CONSTANT HEAD  0.0000000E+00  0.0000000E+00  0.0000000E+00
            WELLS  0.0000000E+00  1.5328000E+04 -1.5328000E+04
           DRAINS  0.0000000E+00  1.4971100E+04 -1.4971100E+04
         RECHARGE  4.9526753E+05  0.0000000E+00  4.9526753E+05
               ET  0.0000000E+00  4.4935425E+05 -4.4985675E+05
    RIVER LEAKAGE  5.5714046E+04  6.8826422E+04 -1.3112376E+04
  HEAD DEP BOUNDS  0.0000000E+00  2.4985586E+03  0.0000000E+00
   STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
--------------------------------------------------------------
              SUM  5.5078550E+05  5.5078225E+05  3.2207031E+00
  DISCREPANCY [%]  0.00
```

Generally, from the table above, annually about 181 and 20.3 million cubic meters of water flowing in to the aquifer system of Sibilu catchment from Precipitation Recharge and River leakage respectively and totally it would be 201.3 MCM per annum excluding the model error amount 3.22 m^3/day. Similarly, a total of 201.08 million cubic meters of water is flowing out of the aquifer system of the study area through head dependent boundary (0.91 MCM), Wells abstraction (5.6MCM), Drains (5.47 MCM), ET (164 MCM) and leakage of groundwater to the river course (25.1 MCM) in a period of year.

Regarding Surface _Groundwater interaction, the interface between the two water domains is clearly seen in calibrated model simulation result of above summary table 19. The perennial Sibilu river losses about $5.57*10^{4}$ cubic meters of water in a day to feed the Aquifer reservoir, while intern Aquifer system leaks about $6.88*10^{4}$ cubic meters of groundwater in a day to the river channels along its way. This indicates that the Sibilu River is a gaining River.

6.3 The steady state Model Scenario

The calibrated model was used to predict the impacts of the projected changes in groundwater abstraction and recharge or to simulate the potential effect of alternative water management plans on the groundwater head, and Groundwater movement (groundwater _surface waters interaction) under steady state conditions. It can also be used as a tool to evaluate and compare the responses of an aquifer system to potential future stresses. Scenario analyses made for 1) increase in abstraction for different uses and 2) decrease in recharge.

In fact it should be noted that the results of the scenarios depend on future land use, population growth, weather conditions, hydrologic stresses etc, and may not be used as a predictive tool to generate absolute amounts in the future, but used primarily to test the groundwater level response. In general, the results of the scenarios depend on the validity of the assumptions behind the scenarios and errors introduced due to limitations associated with the model expected to affect the results of the scenarios and should be taken into considerations during interpretation and application of results.

The population growth rate (r) is among the factors, which are predominantly used to facilitate the computation of the future water demand. The future population in a project area has been computed using the following formula.

$P_n = P_O (1 + r / l00)^{n}$

Where: P_n = population after n years

P_O = present population, and

r = annual growth rate (%)

n=the number of year

Table 20. Population of Sululta Woreda

Category	Estimating numbers	Percent
Children<1-year age group	3,011	2.02
Children<5-year age group	15,364	10.33
<15 years age group	44,520	29.94
15-59 years age group	44,446	29.89
Women in reproductive age group (15-49)	20,694	13.92
Estimated pregnancies	3,245	2.18
Non- pregnant women	17,421	11.72
Estimated total population	148,701	

Source: Sululta Woreda Health Office, 2016

The boundary of Sibilu River catchment covers 70% (454.6 km 2) of Suluta Woreda, 20% (128.7 km 2) of Welmera Woreda, 8.8% (57.7 km 2) of Mulo Woreda and 1.2% (8.6 km 2) of Northern parts of Addis Ababa. For Simplicity the water demand projection was carried out by using the domestic, Irrigation, industry, commercial and institutional consumption of water in the Sululta Woreda as it covers 70% of the catchment. Livestock watering in all rural parts of the area is mainly from surface waters. However, a few peoples in Mizan, Suluta and Chancho Towns, use groundwater for their domestic animals watering as observed during field assessment and this water demand was not accounted for in the water demand projection.

During the final detail design of Sululta Town water supply system study by Laliftu General Development Consulting PLC in 2015 the anticipated water demand of Sululta and surrounding was estimated on average as 90 L/cap/day at current year including losses and this figure applied for the whole catchment area to project the water demand of the study area. The commercial, industrial and institutional water consumption and demand of the Sululta area was also estimated to be a 10 and 5 % of domestic water consumption (Laliftu, 2015).

Once the predicted future population is determined, it can be multiplied by the anticipated population to be served and individual consumption to determine the future demand (Table 21)

Table 21. Summarized and projected water demand

No	**Description**	**unit**	**Years**					**Remark**
			2016	2021	2026	2031	2036	2007 Population and Housing Census of Ethiopia
1	Population Growth rate	%	Base year	4.2	4	3.8	3.6	
2	Projected Population	Numbers	148,701	182,664	222,238	267,797	319,599	Current abstraction rate in 2021 from Well and drains is: 18,218.90 m3/d
3	Assumed Coverage	%		100	100	100	100	
4	Domestic Water Demand	m ^{3}/d		16439.74	20001.46	24101.74	28763.87	
5	Non Domestic Water Demand							
5.1	Industrial Demand (5%)	m ^{3}/d		821.99	1000.07	1205.09	1438.19	
5.2	Commercial Demand (10%)	m ^{3}/d		1643.97	2000.15	2410.17	2876.39	
5.3	Institutional Demand (5%)	m ^{3}/d		821.99	1000.072	1205.09	1438.19	
	Livestock Demand	m ^{3}/d		0	0	0	0	Not considered
5.4	Irrigation Demand	M3/d	1486	1486	1486	1486	1486	
	Total water demand	m ^{3}/d		21213.69	25487.75	30408.09	36002.64	
Demand increment by %		%		14.12	28.5	40.08	49.4	

Source for population growth rate: The 2007 Population and Housing Census of Ethiopia: Statistical Report for Oromia Region; Part V: Population size of Kebeles.

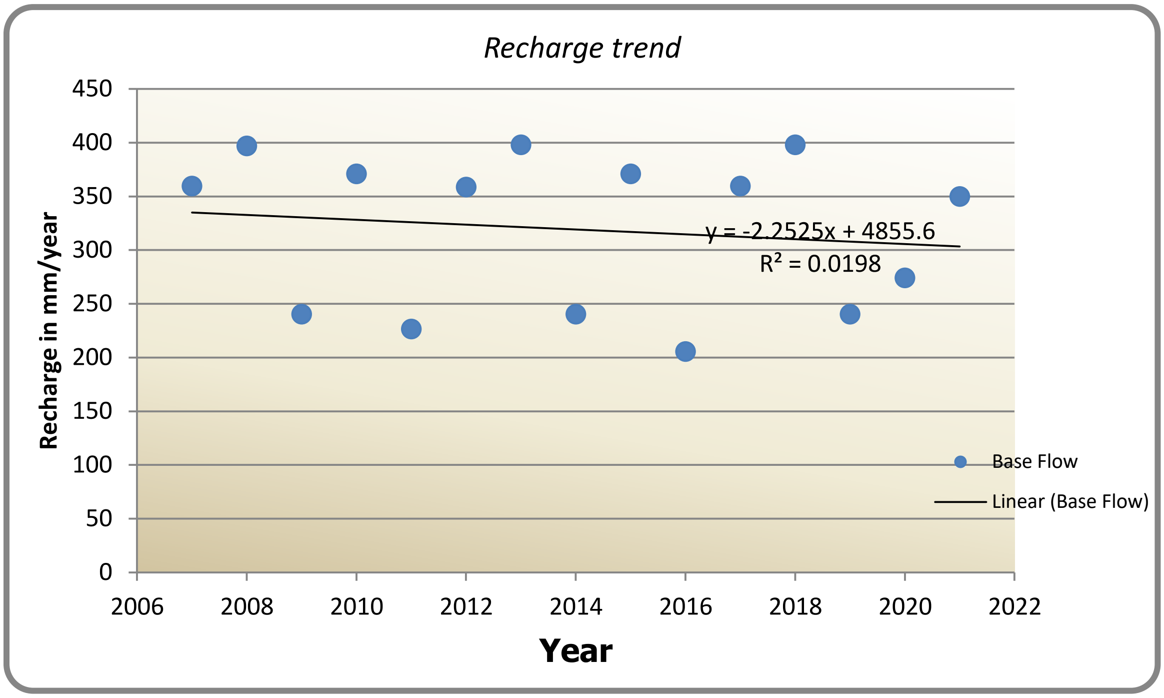
In the table above the population in the area was projected for 15 years (2036) and the water demand was estimated based on the water demand per capita of 90 Litters/day. The result showed that the total water demand will increase by at least 50 % of the present (2021) abstraction rate, and this value is used for increase abstraction scenario analysis. Due to resettlement, migration to the town and expansion of industries in Sululta area the estimated water demand may not feet the actual demand value and it will be escalated. The water demand per capita will also expected to increase from the present value and the current water abstraction as well shows an unmet demand by 14.12 percent.

Recharge Trend Condition

The precipitation in the study area (Graph 1) shows high fluctuations and variability. In general, the annual total precipitation in Ethiopia shows a decreasing trend for the keremet season while Belge rain fall totals do not show a significant trend over period of 1973-2002 (Sefu et al., 2005).The current study area also is not out of this reality and this decreasing precipitation trend together with Climatic condition and land use changes in the study area are expected to cause recharge reduction.

The base flow component of the Sibilu River flow (2007-20121) was separated based on recursive filter method using TIMESPLOT: Spreadsheet version, by using 95 % attenuation coefficient (α). Then, recharge deduced from precipitation data.

Plotting these separated recharge values against base flow years and the recharge trend has been determined by using the trend line equation of this graph (Graph 10).



Graph 10. Recharge trend for the study area

The above graph revealed that there is a decreasing trend of recharge and although the coefficient of determination (R^2) is low due to cyclical variability of Base Flow in different years (Annex VIII).

Scenario one

Based on the above projected water demands of the area (Table 21), the first scenario was developed by increasing the abstraction rate by 30, 40 and 50 percents of the current well abstraction. The increase in abstraction distributed equally to all pumping wells, which were used during model calibration.

From, the simulated scenarios the decline in groundwater level, base flow, and ET fluxes were observed under all developed scenarios. On the other hand, the case one scenario showed a mean groundwater level decline of 10.5, 15.7 and 31.3 m from the calibrated value for 30, 40 and 50 percent increase in abstraction respectively (Table 22). The outflow fluxes as base flows to streams, ET flux and groundwater outflow through head dependent boundary decreased when compared to the calibrated values as increasing the abstraction rate by such percents. Leakages from streams to the aquifer system increased in different percentage amount from the calibrated values (Table 23 & Annex VII). Thus, these indicate that there will be a water use conflict in the future and more stress to the groundwater unless implementing proper management and monitoring plan.

Scenario two

A recharge reduction of about 10.3 % was predicted for the coming 15 years based on the trend line equation. Hence, the calibrated model was tested in scenario two by a 10 % decrease in groundwater recharge from the calibrated value based on the future recharge trend circumstance that has been analyzed from the existing Base Flow condition, while a 20 % decreasing in groundwater recharge is an hypothetical assumption just to see the effect of the recharge reduced by that much percent on some flow components and Groundwater head.

Entirely, except the similarity of decline in groundwater level with scenario one, the outflow fluxes as base flows to streams, ET flux and groundwater outflow through head dependent boundary decreased when compared to the calibrated values and scenario one, as decreasing the recharge rate by 10 and 20%. Leakages from streams to the aquifer system also decreased from the calibrated values as recharge rate decreased with 10 % (Table 23 & Annex VII).

Table 22. Drawdown for different scenarios from the calibrated heads

Increase in abstraction %	Drawdown (m)			Decrease in Recharge %	Drawdown (m)		
	Min	Max	Mean		Min	Max	Mean
30	0.11	46.62	10.5	10	4.3	42.8	19.31
40	0.185	67.99	15.69	20	6.03	131.10	47.91
50	0.27	131.5	31.3				

Table 23. Response/change to flow components for different scenarios from the calibrated flows (IN: inflow, OUT: outflow)

Flow Term	**Flow Change by Percent (%) when abstraction rate increased with 30%**		**Flow Change by Percent (%) when abstraction rate increased with 40%**		**Flow Change by Percent (%) when abstraction rate increased with 50%**		**Flow Change by Percent (%) when Recharge rate Decreased by 10%**		**Flow Change by Percent (%) when Recharge rate Decreased by 20%**	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
ET		-0.17		-0.31		-0.49		-57.57		-57.57
RIVER LEAKAGE	4.3	-2.19	5.6	-3.27	7.1	-4.10	-23.8	-45.15	39.5	-45.15
GHB		-29.54		-30.31		-30.91		-61.49		-61.49

Due to lack of well monitoring data the mean seasonal groundwater level fluctuation is unknown to compare with the scenarios result. However, the groundwater level drops under both scenarios is a significant and unless mitigation measures applied the water table decline may lead to move the groundwater head below the total depth of some shallow boreholes, hand-dug wells, and the depth of pump positions. It may also cause the negative effects on the existence of Wetlands that occurs here and there in the Sibilu River Catchment.

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

Groundwater plays an important role in Ethiopia as a significant source of water for domestic, bottling, industrial and /or agricultural uses. Recently, Ethiopia trying to utilize the groundwater resource in a better way than past trend for irrigation purpose at different location of the country including the Sibilu Catchment (Case of Horticulture/flower farming). When the groundwater is used for irrigation, industry and domestic purposes, it is necessary to maintain the groundwater reservoir in state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the wet and dry seasons.

At present more pressure is coming to the groundwater resources of the Sibilu catchment in a form of commercial farming (flower farming), in time increasing consumption due to increment of Sululta and Chancho town's population with surrounding villages, expansion of groundwater consuming and demanding industries and bottling. In addition, AAWSA exploring the groundwater of Sibilu catchment associated with drilling of test wells and, proposed surface water of Sibilu and Gerbi rivers, as one of the possible future water supply of Addis Ababa and the surrounding area. Despite its high value and future importance, the whole Sibilu catchment has not been well studied through numerical modeling and this study tray to contribute its part in that regards. The main objective of the study is to numerically model the steady state condition ground water flow system of the Sibilu catchment, using a SWAT, MODFLOW and ArcGIS analysis technique and this area is located at about 27 km of north of Addis Ababa. It drains 650 km ^{2} catchment areas and geologically covered with Alluvial_Elluvaials with Quaternary basalt at the central flat plain, Scoracious Tarmaber megezez formation (Tv2) and fractured Aiba tertiary basalt (Tv1), lower Ignimbrites (Tv3) and Entoto mixed formation (Tv5) those are exposed here and there at different localities.

In terms of hydraulic properties hydrogeological units of the area is porous media and fractured media, but due to wide availability both in horizontal and lateral extension the fractured basaltic domain is the dominant Aquifer system of the study area. Except degree of weathering and fracturing the penetrated basaltic formation in the area is more or less hydrogeologically similar and considered as a single, semi-confined Aquifer and this weathered and fractured basaltic hydrogeological unit is tilted towards the northwestern part of the study area and as well, the groundwater of the area is found to be occurred in this unit. Based on these observations the conceptual model of the Sibilu catchment developed with a total model layer thickness of 350 meters with groundwater in and out flow mechanisms. The static water level of the area ranges from artesian to 81.25 meters deep.

The area classified in to three hydogeomorphological zones: Dome shaped Entoto Mt., Sibilu flat plain, undulating terrain and River gorges of the northwestern part zones.

Following the conceptual model development, the SWAT model has been developed to estimate the groundwater recharge distribution from direct precipitations, evapotranspiration and interactions between Stream network and Aquifers in each Hydrologic Response Units. Accordingly, SWAT tools divided the area in to 1215 HRUs and estimated the flow components per each HRUs. In considering the land use land cover, Soil type, slope and all-weather data the SWAT tool estimate the annual basin recharge of the area as 292.2 mm while base flow separation and CMB method estimated recharge rates, are 318.8 mm and 304.9 mm per annum respectively.

Intern Modflow discritized the catchment area into 205 rows and 157 columns which are a total of 32,185 Block Centered rectangular cells and among those all, 22 cells are GHB, 15,873 cells are in active cells (0) or no flow boundary and 16,290 cells are Active cells (1). Based on those dicritized cells the MODFLOW model simulated the entire out and in flow of groundwater.

Annually, about 181 and 20.3 million cubic meters of water flows into the Aquifer system of Sibilu catchment from Precipitation Recharge and River leakage respectively while a total of 201.08 million cubic meters of water is flowing out of the Aquifer system of the study area through head dependent boundary (0.91 MCM), Wells abstraction (5.6 MCM), Drains (5.47 MCM), ET (164 MCM) and leakage of groundwater to the river course (25.1 MCM) in a period of a year.

Discharging of groundwater from the Aquifer system is occurred through unregulated Well abstraction, spring discharges, and groundwater outflow to the stream. Intensive Well abstraction for water bottling, different industrial uses, Agro processing, commercials, irrigation, hotels and domestic water supplies are the main groundwater abstraction means in the Sibilu Catchment due to anthropogenic interference.

The Aquifer system and the stream network of the catchment also exchanging a considerable amount of water, but in more the groundwater of the study area feeds the perennial Sibilu River course and this makes the Sibilu River to be a gaining river.

Among the developed scenario one i.e increase in abstraction rate with 50 % resulted in a significant groundwater level drop ranges from 0.27 to 131.5 meters and mean 31.3 meters. From the developed scenario two i.e reducing the recharge rate with 10 % (the probable future scenario) also resulted in a significant groundwater draw down ranges from 4.3 to 42.8 and mean 19.31 meters. The obtained result shows that, the water table decline may lead to move the groundwater head below the total depth of shallow boreholes, hand-dug wells, and the depth of pump positions. It may also cause the negative effects on the existence of Wetlands and discharge of springs of the area.

Under both scenarios, reduction in base flows to the Sibilu River, evapotranspiration flux from the area and Groundwater outflow through head dependent boundary are observed. However, except under recharge reduction with 10% scenario the River leakage to the Aquifer system is increasing.

7.2. Recommendation

From the entire study results the following issues are recommended:

- Further work is required to define the boundary of multilayer Aquifers and to collect additional time dependent data and run the transient state modeling
- Currently Region, Zones, Districts, City Admin, NGOs, Private business companies and Water bottling companies are studied and develop the groundwater of the Sibilu Catchment through their own ways separately just focusing on their own issue and the water supply satisfaction, but not the risk. Thus, there should be stronger organizational entity that permits the groundwater exploitation and implement the proper groundwater management strategy to insure the sustainability of the groundwater resources of the area.
- Most of Deep Boreholes in the study area concentrated at the south central part of the catchment, centering the Sululta Town and even some of the Wells are falls within the same grid cells, in this case their cone of depression may overlap and cause land subsidence in between them. Therefore, Distance drawdown and group pumping tests shall be conducted by concerned body to determine aquifer storativity and effect of one well over the other.
- As the Sululta, Mizan and Chancho towns are growing quickly, the groundwater well field area has to be studied and delineated for future groundwater exploitation and this has to be planed when the city master plan design revised.

- The upper catchment of the Sibilu river catchment in general, Entoto, cheleleka_Nono mountain chain in particular has to be protected and covered with vegetations to enhance the base flow or recharge of the aquifer system of the area and to reduce the water loss due to ETo.
- The Boreholes those drilled in the study area for details study and testing has to be operational and serve for the community in the catchment, as they were drilled with the expenses of the country.
- It is better to have more and evenly distributed modern/ automatic meteorological and river gagging stations in the study area watershed to get more reliable picture of the area and model results.

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ANNEXES

Annex I. Mean Daily precipitation at Fiche, Entoto, Chancho and AAU observatory gage stations

Daily mean Precipitation at Fiche station mm/d , in a Months (1997_2019)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	1.40	0.00	2.32	1.50	0.94	4.99	11.22	8.93	1.70	2.02	0.67	0.06
1998	0.36	0.68	1.58	1.79	1.48	2.93	8.61	12.38	6.04	1.31	0.01	0.00
1999	1.37	0.00	0.12	0.41	0.70	2.14	13.63	16.00	1.93	2.58	0.22	0.03
2000	0.00	0.00	0.77	2.94	1.15	2.08	14.28	12.32	3.06	0.35	0.28	0.14
2001	0.06	0.37	3.20	0.76	2.13	4.53	12.93	6.93	1.86	0.05	0.13	0.50
2002	1.34	0.60	4.48	1.40	0.76	2.34	7.45	10.10	4.71	0.00	0.00	1.37
2003	0.75	1.83	1.64	3.75	0.07	4.06	11.61	10.03	4.14	0.09	0.06	0.48
2004	0.03	0.40	1.79	4.12	0.88	5.05	9.57	9.65	3.98	0.46	0.12	0.00
2005	1.58	0.04	2.35	2.30	2.63	2.55	9.21	6.85	3.98	0.35	0.15	0.00
2006	2.49	1.06	2.25	2.77	1.47	2.51	15.69	11.54	3.20	0.26	0.20	0.46
2007	0.69	1.66	0.77	1.37	1.89	4.01	12.11	10.15	4.19	0.28	0.08	0.00
2008	0.06	0.03	0.00	1.01	2.03	2.23	9.45	13.38	3.27	0.62	1.95	0.00
2009	0.54	0.10	1.28	1.76	0.53	1.58	14.94	14.20	2.66	2.03	0.00	0.00
2010	0.37	1.16	2.30	2.43	3.64	2.15	14.49	10.86	2.87	0.05	0.54	0.92
2011	0.50	0.00	1.78	1.50	3.10	4.52	7.95	13.61	5.97	0.00	1.42	0.00
2012	0.70	0.00	0.73	2.53	0.94	3.75	13.23	13.19	4.55	0.10	0.00	0.38
2013	0.00	0.00	0.33	1.07	1.01	5.19	14.19	12.75	3.33	1.81	0.07	0.00
2014	0.12	0.85	2.00	2.60	1.64	1.32	12.29	11.05	3.64	0.57	0.03	0.36
2015	0.01	0.11	0.67	0.16	2.29	3.89	7.22	7.45	3.40	1.17	0.19	2.14
2016	0.00	1.10	1.02	1.92	6.12	4.84	14.30	9.49	3.34	0.07	0.00	0.00
2017	0.00	1.15	1.19	0.34	4.16	1.06	11.45	10.44	4.23	0.01	0.11	0.00
2018		1.46	1.10	1.13	5.14	4.10	12.65	11.54	2.28	0.65	1.46	0.00
2019	0.00	1.24	1.10	1.13	1.86	3.33	12.80	10.49	3.28	0.24	0.52	0.00
mean in a months (mm/d)	0.56	0.60	1.51	1.77	2.02	3.27	11.79	11.01	3.55	0.66	0.36	0.30

Mean daily precipitation at Entoto mm/d (1997_1997)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	0.6839	0.0000	0.6000	2.5767	0.8839	2.5733	8.2677	7.7677	2.9767	2.8484	3.0000	0.0065
1998	0.8161	0.9036	1.4581	1.5667	4.8226	4.9733	11.9032	12.1387	6.8267	1.4355	0.0000	0.0000
1999	0.5097	0.2250	1.1258	0.8467	1.1935	4.2567	9.1323	9.0419	3.5000	1.8710	0.0067	0.0000
2000	0.0000	0.0000	0.1677	3.6000	2.9484	3.6900	9.8000	11.5839	4.4267	0.5548	1.1167	0.0548
2001	0.6645	0.1964	4.7581	0.9933	4.5710	5.4767	9.2129	10.3677	3.0833	1.6903	0.0000	0.0581
2002	0.5774	1.8000	2.8645	2.2467	1.5871	4.6233	9.4548	8.4806	3.0700	0.3452	0.0000	0.9032
2003	0.1677	1.7036	1.8419	3.9100	0.4484	6.2667	11.9613	8.0290	4.7033	0.0000	0.2100	0.8258
2004	0.9290	1.0793	1.5065	4.1533	0.4452	5.5333	8.7710	10.7968	4.1600	1.6032	0.0367	0.0516
2005	0.2677	0.4071	1.3806	3.2867	4.6419	3.5467	7.8000	10.9452	4.4800	0.6323	0.2733	0.0000
2006	0.0290	0.6821	3.0258	2.2167	2.5516	4.3833	11.9710	10.0484	4.2900	1.1645	0.0200	0.5323
2007	1.2452	0.5786	1.1742	1.7367	3.4323	8.2233	8.7774	10.4065	2.9000	0.5290	0.0000	0.0000
2008	0.0000	0.3207	0.0484	2.4933	1.4613	4.7500	12.8806	11.5968	6.3533	1.6161	3.1700	0.0161
2009	0.3516	0.1179	0.5129	1.3367	0.9097	4.0900	9.8290	10.5258	5.1400	2.9452	0.2467	2.2065
2010	0.3065	2.6214	2.5613	2.3733	3.4806	7.8400	12.5419	9.3097	5.7733	0.0581	0.0000	0.3839
2011	0.0000	0.0000	1.6226	1.7233	3.1032	4.7733	8.7452	11.8065	3.7867	0.0000	1.4500	0.3968
2012	0.0000	0.0000	0.6290	2.6500	2.4871	4.4400	11.7097	11.8161	8.0900	0.1355	0.0100	0.2516
2013	0.3935	0.0000	1.9290	4.2933	2.6484	5.4867	11.7516	14.9097	6.6033	2.0742	0.3567	0.0065
2014	0.0000	0.5750	1.3484	1.0233	2.6000	2.7233	10.4387	9.1194	4.3867	0.8226	0.4667	0.0129
2015	0.0000	0.1643	0.0000	0.2200	3.8645	5.2700	11.7516	10.3968	2.8767	0.4548	0.9867	0.0032
2016	0.6258	0.4103	2.1000	3.4667	5.2581	5.9133	9.7032	9.7194	3.7867	0.4806	0.0900	0.0097
2017	0.0000	0.4571	1.0968	1.4133	5.4355	2.6333	15.1065	11.8581	11.0933	1.5871	0.0333	0.0000
2018	0.3129	0.4337	1.5984	2.4400	5.3468	14.9633	14.6161	12.2323	2.2233	0.9677	1.0767	0.0000
2019	0.0000	0.2000	1.3476	1.9267	5.3911	9.7300	14.4968	12.0452	8.6300	0.3419	0.5550	0.0000
Mean in a Months (mm/d)	0.3426	0.5598	1.5086	2.2823	3.0223	5.4852	10.8966	10.6496	4.9200	1.0504	0.5698	0.2487

Addis Ababa Observatory mean precipitation mm/d (1997_2019)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	1.26	0.00	0.79	1.71	1.24	3.47	8.79	6.27	3.79	2.01	1.68	0.05
1998	1.78	0.73	1.58	1.62	4.97	4.15	9.21	8.39	7.12	4.09	0.00	0.00
1999	0.09	0.01	0.93	0.54	0.77	3.99	9.26	9.85	2.95	2.43	0.00	0.00
2000	0.00	0.00	0.57	1.66	3.55	4.82	7.90	9.88	8.35	1.50	0.70	0.00
2001	0.00	0.44	6.80	0.83	5.42	7.21	13.81	7.95	4.39	0.44	0.00	0.00
2002	0.47	0.75	2.91	1.88	2.04	5.75	8.29	6.96	3.63	0.01	0.00	0.53
2003	0.34	1.90	2.02	3.31	0.65	5.06	9.41	7.53	6.44	0.03	0.05	1.77
2004	0.80	0.70	1.60	4.66	0.97	4.73	7.69	8.79	5.47	2.48	0.00	0.00
2005	0.41	1.48	1.84	2.68	5.36	4.31	5.99	7.94	10.17	5.42	0.15	0.00
2006	0.02	0.40	4.29	2.63	2.41	5.00	11.49	7.86	7.97	1.74	0.01	0.26
2007	1.65	0.68	1.93	2.46	3.87	5.83	8.45	12.30	4.92	0.80	0.00	0.00
2008	0.00	0.45	0.00	1.65	3.04	2.96	8.94	11.64	8.56	2.85	2.65	0.74
2009	0.69	0.10	0.92	2.69	1.90	2.75	11.29	12.53	3.76	1.48	0.15	2.10
2010	0.08	2.85	1.79	3.26	2.40	9.04	10.13	6.64	7.93	0.06	0.86	0.48
2011	0.45	0.47	1.43	0.76	2.13	6.07	5.84	10.99	4.87	0.00	1.41	0.00
2012	0.00	0.00	0.51	2.46	1.62	2.31	10.46	9.61	7.18	0.07	0.00	0.32
2013	0.14	0.00	1.56	3.08	2.74	5.11	7.59	11.39	6.77	1.88	0.74	0.00
2014	0.05	1.69	1.98	0.87	3.02	2.22	7.09	8.46	8.82	1.13	0.06	0.00
2015	0.00	0.00	0.91	0.52	3.64	7.38	7.00	10.00	4.96	0.00	0.26	0.00
2016	1.93	0.42	1.55	4.56	4.28	6.24	5.90	9.67	4.73	0.50	0.12	0.06
2017	0.00	0.74	1.18	1.12	4.84	2.15	9.37	10.64	12.87	0.33	0.00	0.00
2018	0.00	1.15	0.61	2.06	2.32	6.11	10.16	9.16	1.66	1.57	0.50	0.00
2019	0.00	0.33	1.18	5.83	3.80	5.31	10.95	6.61	7.40	1.62	0.67	0.00
Mean in a Months (mm/d)	0.44	0.66	1.69	2.30	2.91	4.87	8.91	9.18	6.29	1.41	0.43	0.27

Precipitation in mm/day at Chancho Station (1997_2019)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	1.76	0.014	1.984	1.757	1.771	4.077	12.284	7.423	1.87	1.603	1.573	0.058
1998	1.71	1.164	0.694	1.44	4.623	5.34	13.29	10.723	6.13	2.432	0.03	0
1999	0.50	0	1.152	0.777	1.271	2.18	12.219	10.542	4.543	2.158	0	0.55
2000	0.00	0	0.284	3.423	1.055	3.417	8.006	10.216	4.593	1.374	1.897	0.919
2001	0.40	0.461	4.352	1.327	4.016	5.277	10.723	8.929	1.27	0	0	0
2002	1.24	1.764	4.323	1.87	1.565	10.527	23.226	16.113	2.05	0.113	0	1.261
2003	1.86	1.75	2.55	6.897	0.145	10.503	25.106	26.913	19.38	0	0.117	0.9
2004	2.20	0	0.877	2.66	0.7	23.143	37.252	25.119	12.017	3.729	0	0.432
2005	0.17	2.55	0	1.29	2.471	6.547	8.503	10.084	11.7	0.048	0	0
2006	2.55	0	1.29	2.471	6.547	8.503	10.084	11.7	0.048	0	0	0
2007	0.00	1.29	2.471	6.547	8.503	10.084	11.7	0.048	0	0	0	0.371
2008	0.00	0	0	1.47	4.316	11.667	14.374	2.271	0	0.935	1.687	0
2009	1.08	0.854	1.287	0.077	0.2		15.848	21.077	13.713	2.787	0	2.01
2010	0.54	2.421	1.845	3.653	3.2	9.82	12.016	10.752	9.057	0	0.12	0.539
2011	0.52	0.118	0.935	1.347	2.506	3.82	13.623	16.99	10.163	22.084	0	0
2012	0.00	0	0.223	2.91	1.539	3.277	20.087	18.252	13.833	0	0	0
2013	0.00	0	0.774	2.87	0.097	8.8	11.077	8.829	7.847	0.2	0.197	0
2014	0.08	0	2.084	1.363	2.032	0.277	9.271	19.355	12.227	0.042	0	0
2015	0.00	0	0.403	0.263	5.781	6.6	11.574	24.277	1.837	0.539	0.557	0.29
2016	0.46	0	2.226	5.76	7.665	11.617	19.987	24.277	8.223	0.265	0.613	0
2017	0.00	0	0.032	0.553	2.735	3.48	19.016	14.523	6.67	0	0	0
2018	0.00	0	0.032	0.553	2.735	3.48	19.016	14.523	3.063	0	0.377	0.432
2019	0.00	0	0.032	0	2	5.827	14.952	14.523	8.497		0.377	0
Mean in a Months (mm/d)	0.655	0.539	1.299	2.229	2.933	7.194	15.36	14.24	6.901	1.741	0.328	0.3374

Annex II. Purpose and abstraction rate of water point in the study area

No	Bore hole ID	Local Name	X	Y	Z	Discharge (l/s)	Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
1	BH_1	Abysynia Factory /in	472997	1011121	2627.87	1.23	16	0.666666667	70.848	Bottling
2	BH_2	Abysynia Factory /in	473051	1011283	2615.36	5.6	16	0.666666667	322.56	Bottling
3	BH_3	Abysynia Factory /out	472992	1011287	2617.29	1.14	16	0.666666667	65.664	Bottling
4	BH_4	Abysynia Factory /out	473559	1011841	2611	6.9	16	0.666666667	397.44	Bottling
5	BH_71	Gift Water _1	471032	1007698	2686	10	16	0.666666667	576	Bottling
6	BH_72	Gift Water _2	471060	1007766	2690	1.8	16	0.666666667	103.68	Bottling
7	BH_73	Gift Water _3	471100	1007850	2681	5	16	0.666666667	288	Bottling
8	BH_78	Tadesse Debelle _1	468993	1005478	2754	7.5	20	0.833333333	540	Bottling
9	BH_79	Tadesse Debelle _2	468798	1005449	2752	3.2	20	0.833333333	230.4	Bottling
Count	9								**2594.592**	Total
No	Bore hole ID	Local Name	X	Y	Z	Discharge (l/s)	Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
10	BH_9	Sululta Town (01 ,Omo doroba)	475292	1012922	2615	18	12	0.5	777.6	Supply
11	BH_10	Weserbi (10 kilo)	466306	1008828	2738	20	22	0.916666667	1584	Supply
12	BH_11	Chancho (mapping Well)	473911	1031930	2543	2	12	0.5	86.4	Supply
13	BH_12	Sululta o1 (G/Arbe)	474421	1013070	2610	15.2	20	0.833333333	1094.4	Supply
14	BH_13	Sululta/kara ta'aa (laga kawe 2nd)	467125	1008326	2617	27	22	0.916666667	2138.4	Supply
15	BH_14	Suluta 01/Goro Arba	476170	1014624	2375.82	8.14	20	0.833333333	586.08	Supply
16	BH_18	Gudu	455345	1009722	2710	0.28	8	0.333333333	8.064	Supply
17	BH_19	Chancho	471304	1027754	2561	1.3	12	0.5	56.16	Supply
18	BH_20	Entoto Mariam	473376	1005065	2974	20	12	0.5	864	Supply
19	BH_21	Rob Gebeya	466862	1031004	2585	2	12	0.5	86.4	Supply
20	BH_22	Korke Robe	473871	1024156	2605	2	12	0.5	86.4	Supply
21	BH_23	Sululta	473104	1011068	2622				0	Supply
22	BH_24	Shegole Meda	468100	1016250	2578				0	Supply
23	BH_25	Arbi Akako/Chancho	474740	1028068	2629	_	?		0	Supply
24	BH_26	Wereso/keto (Goliye)	474261	1019062	2566	_	?		0	Supply
25	BH_27	Wereso/keto (Goliye)	473501	1018863	2549	_	?		0	Supply
26	BH_28	Selasie/Sululta 01	473520	1014292	2593	_	12	0.5	0	Supply
27	BH_29	Selasie/Sululta 01	474005	1014163	2596	_	12	0.5	0	Supply
28	BH_32	Red Cross (sululta 01)	473758	1015231	2591	4.5	19	0.791666667	307.8	Supply
29	BH_33	Bilao (Sululta o1)	473182	1015259	2577.37	2.5	19	0.791666667	171	Supply
30	BH_34	Atlete Mender (k/wasarbi)	469335	1007837	2730.71	2.4	19	0.791666667	164.16	Supply
31	BH_58	Sululta /Wale	475210	1012720	2610	8.3	20	0.833333333	597.6	Supply
32	BH_59	Hambiso/Chancho	482081	1037780	2577	14	8	0.333333333	403.2	Supply
33	BH_60	Moye Gajo/Chan	478260	1038550	2503	5	8	0.333333333	144	Supply
34	BH_61	Laga Tame/Chan	470913	1026393	2660	5	8	0.333333333	144	Supply
35	BH_62	Chnacho/Buba keb.	470446	1026620	2538	5.2	8	0.333333333	149.76	Supply
36	BH_67	Ethiopia Hotel	473054	1011920	2603	3.5	4	0.166666667	50.4	Supply
37	BH_77	Hunde Resort	468207	1006015	2750	2.8	4	0.166666667	40.32	Supply
38	BH_80	Weserbi Real State	468720	1005654	2767	7	8	0.333333333	201.6	Supply
39	BH_81	Doroba /sululta	475567	1015435	2586	6	9	0.375	194.4	Supply
40	BH_82	Segno gebeya	455620	1026514	2610	2.1	20	0.833333333	151.2	Supply
Count	31								10087.34	Total

No	Bore hole ID	Local Name	X	Y	Z	Discharge (l/s)	Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
41	BH_5	Abysynia Factory /in	473000	1011282	2621	2.6	16	0.667	149.76	industrial use
42	BH_7	Belaya Industrials PLC	468486	1006756	2772	11.7	12	0.5	505.44	industrial use
43	BH_8	Elemtu Integrated Milk Industry Sh. Co	472027	1009035	2697	6	12	0.5	259.2	industrial use
44	BH_38	Allied Chemicals (BH_1)	474123	1016624	2573.34	0.9	12	0.5	38.88	industrial use
45	BH_39	Allied Chemicals (BH_2)	474177	1016690	2574.81	0.9	12	0.5	38.88	industrial use
46	BH_40	Dr. Hailu Worku	473160	1014133	2596.8	1	12	0.5	43.2	industrial use
47	BH_41	Tamaz food complex	473020	1011782	2608.09	0.3	12	0.5	12.96	industrial use
48	BH_42	Oromia Steel Pipe Mill Factory	472621	1009120	2632.11	1	12	0.5	43.2	industrial use
49	BH_43	Selale Diary	471434	1008936	2714.58	2	12	0.5	86.4	industrial use
50	BH_44	China Africa Tannery	473188	1016856	2561.05	16	18	0.75	1036.8	industrial use
51	BH_45	Textile (?)	470503	1007986	2727.98	2	12	0.5	86.4	industrial use
52	BH_66	ARM Factory	473134	1012347	2604	0.7	12	0.5	30.24	
53	BH_76	Kasu Negash	469524	1007602	2740	1.5	9		50	industrial use
Count	13								2381.36	Total

No	Bore hole ID	Local Name	X	Y	Z	Discharge (l/s)	Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
54	BH_6	Issac Abdulahi Noc fuel station	473252	1014205	2601	1.87	4	0.166666667	26.928	commercial
55	BH_17	Sululta Depo (Sunshine Petroleum Depot)	470714	1008000	2724	1	4	0.166666667	14.4	commercial
56	BH_30	Degefa Bula/Wale lube babu	474513	1013274	2608	_	4	0.166666667	0	commercial
57	BH_46	Dr Feseha	473447	1014467	2596.66	0.5	4	0.166666667	7.2	commercial
58	BH_47	Palace Hotel	473226	1014393	2597.29	0.5	4	0.166666667	7.2	commercial
59	BH_48	Bolina Boru Hotel	473081	1013890	2604.26	0.5	4	0.166666667	7.2	commercial
60	BH_49	Solomon Hotel	472996	1013432	2609.87	0.5	4	0.166666667	7.2	commercial
61	BH_50	Dire Sululta Hotel	473077	1013256	2610.97	0.5	4	0.166666667	7.2	commercial
62	BH_51	Hanymoon Hotel	473146	1013204	2612.96	0.5	4	0.166666667	7.2	commercial
63	BH_52	Yaya Athletics Village	468210	1006467	2755.87	0.5	4	0.166666667	7.2	commercial
64	BH_53	Kenenisa Resort	468766	1007046	2767	0.5	4	0.166666667	7.2	commercial
65	BH_54	Nile Petroleum	469103	1007255	2757.68	1 or 6	4	0.166666667	14.4	commercial
66	BH_55	Tsena Lodge	469654	1007457	2753.53	0.5	4	0.166666667	7.2	commercial
67	BH_56	Well	471702	1009505	2706.99	0.3	4	0.166666667	4.32	commercial
68	BH_57	Federal Dog Training Center (Fengi ,Kaso weserbi guto)	473021	1009146	2627.68	0.5	4	0.166666667	7.2	commercial
69	BH_63	Hirut Agonafer/sul	473627	1015082	2596	0.6	2.3	0.095833333	5	commercial
70	BH_64	Mokonin & Tsige	473625	1015444	2585	3	5.5	0.229166667	60	commercial
71	BH_65	Getachew Garage	473002	1013161	2605	5	4.7	0.195833333	85	commercial
72	BH_68	Abayas Trading	470810	1009695	2704	1.4	4	0.166666667	20	commercial
73	BH_69	Zewudu Tadesse	471496	1006043	2718	5.6	4	0.166666667	80	commercial
74	BH_70	Berhanu Ragassa	471433	1008935	2717	5.9	4	0.166666667	85	commercial
75	BH_74	Daksen Village	470427	1007993	2724	3	8.3	0.345833333	90	commercial
76	BH_75	Indris Teshome	470160	1007676	2732	5	8	0.333333333	140	commercial
Count	23								**697.048**	Total

No	Bore hole ID	Local Name	X	Y	Z	Discharge (L/s)	Water abstraction Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
77	BH_31	Kajima Sululta	472722	1012748	2605	_	24	1	0	Irrigation/Flower
78	BH_35	Fereja Eth & Chancho Flower	474018	1012230	2605.2	5	24	1	432	Irrigation/Flower
79	BH_36	Kefle Bulo Apple Farm	473157	1009306	2627.5	1	24	1	86.4	Irrigation /Apple
80	BH_37	JJ Kothari Flowering Farm	472609	1012803	2598.89	8	24	1	691.2	Irrigation/Flower /
Count	4								**1209.6**	Total
No	Bore hole ID	Local Name	X	Y	Z	Discharge (L/s)	Water abstraction Pumping rate (hrs/day)	Water abst. Distributed over 24 hrs	m3/day	Purpose/Usage
81	BH_15	Sululta (Wereso)	472772	1018752	2554	2.3			0	test Well
82	BH_16	Chancho/Gutu Ilamo	473693	1032100	2504	1.6			0	test Well
Count	2								0	Total

Annex III. Chloride concentration of Groundwater

No	**ID**	**Lab No**	**Name**	**Cl$^-$ (mg/l)**	X	Y	Z
1	BH_1	BH1Abysinia	BH1Abysinia	9.2	472997	1011121	2627.87
2	BH_2	BH2Abysinia	BH2Abysinia	10.95	473051	1011283	2615.36
3	BH_4	BH4Abysinia	BH4Abysinia	9.99			2611
4	BH_5	BH5Abysinia	BH5Abysinia	5.57	473000	1011282	2621
5	BH_6	Belaya Industrials PLC	Belaya Industrials PLC	2.06	468486	1006756	2772
6	BH_7	Elemtu	Elemtu Integrated Milk Industry Sh. Co	10.01	472027	1009035	2697
7	BH_8	Issac Abdulahi	Issac Abdulahi Noc fuel station	29.76	473252	1014205	2601
8	BH_10	Weserbi	Weserebi	3.64	466306	1008828	
9	BH_11	69	Chancho mapping	1.9	473911	1031930	2543
10	BH_12		Sululta mapping well	25.8	474421	1013070	2610
11	BH_13	Sululta BW-2	Sululta/kara ta'aa (laga kawe 2nd)	6.13	467125	1008326	2617
12	BH_14		Goro Arba	19.99	476170	1014624	2375.82
13	BH_15	MBH001	Sululta (Wereso)	15.33	472772	1018752	2554
14	BH_16	MBH002	Chancho/Gutu Ilamo	14.43	473693	1032100	2504
15	BH_17	S25	Sululta Depo (Sunshine Petroleum Depot) (AdBh0448)	1.99	470714	1008000	2724
16	BH_19	70	Chancho town	1.9	471304	1027754	2561
17	BH_26	6697	Arbi Akako/Chancho	6	474740	1028068	2629
18	BH-27	53	Wererso_malima	0.85	473501	1018863	2549
19	BH_31	2866	Kajima Sululta	2	472722	1012748	2605
20	BH_32	S34	Atlete Mender	1	469335	1007837	2730.71
21	BH_33	2865	Bilo (Sululta o1)	14	473270	1015465	2577.37
22	BH_34	Red Cross	Red Cross	27.99	473758	1015231	2591
23	BH_44	S28	China Africa Tannery	35.99	473188	1016856	2561.05

No	**ID**	**Lab No**	**Name**	**Cl^- (mg/l)**	X	Y	Z
24	BH_50	S13	Dire Sululta Hotel	4.99	473077	1013256	2610.97
25	BH_58		Walle Borhole	17.02	475210	1012720	2610
26	BH		Kera Borhole	37.99			
27	BH		Cheers Borhole	3.99			
28	SHW		Bureka Shembeko (SHW)	9.99			
29	DW		Bertukan Hotel (DW)	16			
30	DW-2	54	Elamu_roba	1.84	473851	1021092	2605
31	DW-3	55	Elamu_roba	4.75	473800	1022831	2570
32	DW-5	56	Elamu_roba	0.92	474087	1022690	2577
33	DW-6	57	Robe_gebeya	165.20	466460	1032320	2610
34	DW-7	58	Ejara/WeresoMalima	7.30	470874	1020368	2565
35	CSP-1	46	Shefune	6.66	472130	1009336	2689
36	CSP-2	47	10_killo	39.49	467807	1006732	2750
37	CSP-3	48	Gutoelamo	2.76	467807	1006732	2750
38	CSP-5	49	Bokekisa	3.47	472073	1011135	2632
39	CSP-7	50	Gulele_Gebreal	3.19	466821	1019985	2595
40	CSP-8	51		2.55	471779	1023515	2550
41	CSP-10	52	Werkito/EkoBabo	3.19	469038	1031497	2472
42	Spring	S12	_	0.99	472078	1011124	2634.92
43	CSP-16	6681	Boku Abo	3	471668	1040491	2430
44	CSP-22	6685	Entoto mariam	4	474208	1005540	2987
45	CSP-26	6688	Burka Gibisa	1	463999	1018139	2640
46	CSP-28	6690	Chefe Entoto	1	473059	1006482	2905
47	CSP		Ulandhula Spring	9			
48	CSP		Weserbi Spring	1.99			

Annex IV. Model Calibration evaluation indices result, Observed and simulated heads

BH Id	Obs. Head (hm)	Simu. head (hs)	hm-hs	|hm-hs|	$(hm\text{-}hs)^2$	Sqrt $((hm\text{-}hs)^2/n)$
BH_1	2594.87	2578.68	16.19	16.19	262.148	5.041
BH_2	2586.36	2573.29	13.08	13.08	170.956	3.288
BH_3	2593.29	2573.29	20.01	20.01	400.200	7.696
BH_4	2592.00	2574.75	17.25	17.25	297.632	5.724
BH_5	2592.56	2573.29	19.28	19.28	371.526	7.145
BH_6	2597.95	2598.20	-0.25	0.25	0.065	0.001
BH_7	2725.90	2720.09	5.81	5.81	33.710	0.648
BH_8	2615.75	2609.60	6.15	6.15	37.835	0.728
BH_9	2591.00	2590.78	0.22	0.22	0.050	0.001
BH_10	2717.00	2721.76	-4.76	4.76	22.620	0.435
BH_11	2542.00	2542.00	0.00	0.00	0.000	0.000
BH_12	2591.80	2579.06	12.75	12.75	162.435	3.124
BH_13	2597.10	2605.86	-8.76	8.76	76.773	1.476
BH_14	2347.52	2361.44	-13.92	13.92	193.850	3.728
BH_15	2552.00	2543.21	8.80	8.80	77.352	1.488
BH_16	2491.50	2481.10	10.40	10.40	108.222	2.081
BH_18	2692.00	2692.00	0.00	0.00	0.000	0.000
BH_19	2550.70	2570.00	-19.30	19.30	372.490	7.163
BH_20	2964.00	2962.00	2.00	2.00	4.000	0.077
BH_21	2530.00	2529.00	1.00	1.00	1.000	0.019
BH_22	2599.00	2598.69	0.31	0.31	0.096	0.002
BH_24	2575.00	2581.42	-6.42	6.42	41.165	0.792
BH_57	2628.68	2620.12	8.56	8.56	73.239	1.408
BH_58	2585.15	2583.37	1.79	1.79	3.186	0.061
BH_59	2577.70	2570.26	7.44	7.44	55.339	1.064
BH_60	2504.40	2510.39	-5.99	5.99	35.868	0.690
BH_61	2649.70	2642.35	7.35	7.35	54.022	1.039
BH_62	2538.00	2541.05	-3.05	3.05	9.284	0.179
BH_64	2579.00	2585.73	-6.73	6.73	45.253	0.870
BH_68	2695.00	2680.91	14.09	14.09	198.472	3.817
BH_71	2636.50	2631.78	4.72	4.72	22.297	0.429
BH_72	2688.73	2683.75	4.98	4.98	24.790	0.477
BH_78	2744.00	2751.96	-7.96	7.96	63.346	1.218
BH_79	2742.00	2739.24	2.76	2.76	7.607	0.146
BH_81	2559.70	2576.93	-17.23	17.23	296.735	5.706
BH_82	2540.25	2540.30	-0.05	0.05	0.003	0.000
CSP-1	2689	2684.09	4.91	4.91	24.128	0.464
CSP-2	2750	2741.87	8.13	8.13	66.113	1.271
CSP-3	2750	2753.87	-3.87	3.87	14.969	0.288
CSP-4	2632	2628.33	3.67	3.67	13.498	0.260
CSP-5	2595	2621.96	-26.96	26.96	727.057	13.982
CSP-6	2550	2533.16	16.84	16.84	283.451	5.451

CSP-7	2472	2503.75	-31.75	31.75	1008.253	19.389
CSP-8	2430	2460.00	-30.00	30.00	900.000	17.308
CSP-9	2683	2682.48	0.52	0.52	0.275	0.005
CSP-10	2987	2990.00	-3.00	3.00	9.000	0.173
CSP-11	2975	2976.00	-1.00	1.00	1.000	0.019
CSP-12	2640	2670.61	-30.61	30.61	936.911	18.018
CSP-13	2905	2907.00	-2.00	2.00	4.000	0.077
CSP-14	2658	2640.26	17.74	17.74	314.672	6.051
CSP-15	2634.92	2631.33	3.59	3.59	12.917	0.248
CSP-16	2582	2593.63	-11.63	11.63	135.187	2.600
			ME=0.1	AME=9		RMSE=12

Annex V. Mean Monthly flow of Sibilu (Muger at Chancho in m^3/s 1970_2011)

No	Month	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
1	Jan	0.2230	0.22	0.134194	0.134	0.126	0.086	0.147	0.342	1.9530	0.355	0.177	0.131	0.302	0.222
2	Feb	0.2340	0.126	0.0665	0.067	0.098	0.066	0.078	0.8665	1.6550	0.318	0.126	0.122	0.208	0.236
3	Mar	0.6580	0.162	0.063516	0.064	0.131	0.065	0.108	0.104	1.7380	0.17	0.156	0.248	0.156	0.184
4	Apr	0.3870	0.257	0.069267	0.069	0.182	0.189	0.136	0.124	1.4850	0.205	0.138	0.395	0.314	0.234
5	May	0.1680	0.265	0.114484	0.114	0.107	0.086	0.219	0.175	1.4580	0.331	0.116	0.234	0.33	0.837
6	Jun	0.2390	0.699	0.620433	0.62	0.568	1.012	0.588	1.19	1.4230	0.442	0.3	0.14	0.268	1.123
7	Jul	3.4090	13.966	13.96574	13.706	25.097	35.86	29.429	47.179	16.2160	31.853	21.893	23.589	6.115	10.207
8	Aug	23.2007	29.405	29.40465	50.939	33.812	47.48	41.74	53.085	29.1940	31.68595	51.461	52.695	41.329	55.409
9	Sep	13.3568	12.658	12.65807	33.361	16.231	26.874	17.584	30.788	29.213	23.28	20.365	34.265	14.755	26.319
10	Oct	2.0033	2.173	2.173484	4.492	1.761	2.869	0.923	16.367	6.8410	2.35	1.517	3.89	2.475	2.9
11	Nov	0.4825	0.623	0.622767	0.465	0.321	0.399	0.393	13.695	0.5820	0.438	0.334	0.49	0.627	0.603
12	Dec	0.2996	0.323	0.322806	0.209	0.137	0.181	0.185	4.772	0.3430	0.264	0.204	0.278	0.382	0.291
Annual Mean in m3/s		3.7217	5.0731	5.0180	8.6867	6.5476	9.5973	7.6275	14.0573	7.6751	7.6410	8.0656	9.7064	5.6051	8.2138

No	Month	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1	Jan	0.21	0.174	0.174	0.2	0.211	0.249	0.231	0.222	0.241	0.203	0.234	0.161	0.17	0.109
2	Feb	0.132	0.139	0.179	0.16	0.256	0.278	0.319	0.428	0.239	0.169	0.113	0.194	0.198	0.066
3	Mar	0.133	0.083	0.227	0.437	0.196	0.194	0.242	0.474	0.138	0.113	0.14	0.154	0.229	0.057
4	Apr	0.115	0.143	0.274	1.028	0.193	0.377	0.474	0.197	0.161	0.362	0.191	0.378	0.286	0.113
5	May	0.151	0.324	0.212	0.952	0.145	0.188	0.216	0.14	0.193	0.471	0.161	0.329	0.258	0.064
6	Jun	3.601	0.236	0.538	3.578	0.255	0.247	0.279	0.49	0.313	1.248	0.905	0.36	0.298	0.187
7	Jul	43.97	20.196	20.341	23.172	21.742	23.111	13.123	15.513	9.41	30.436	19.615	14.558	20.394	12.261
8	Aug	41.923	68.753	36.203	39.546	58.305	61.369	64.847	58.735	44.95	63.747	39.307	36.127	42.967	28.643
9	Sep	26.417	32.76843	20.659	15.771	35.775	21.306	33.467	23.068	23.494	42.929	20.5	11.633	10.072	9.451
10	Oct	1.067	1.498	1.776	2.323	4.684	2.348	2.981	1.675	2.446	5.32	2.28	1.277	0.912	0.775
11	Nov	0.569	0.444	0.423	0.491	0.629	0.517	0.598	0.429	0.51	0.759	0.533	0.387	0.271	0.394
12	Dec	0.326	0.239	0.271	0.294	0.325	0.349	0.361	0.308	0.28	0.351	0.3	0.268	0.164	0.189
Annual Mean in m3/s		9.8845	10.4165	6.7731	7.3293	10.2263	9.2111	9.7615	8.4733	6.8646	12.1757	7.0233	5.4855	6.3516	4.3591

No	Month	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	Jan	0.199	0.181	0.13	0.159	0.164	0.124	0.103	13.61	0.13	0.166	0.099	0.258	0.213	0.159
2	Feb	0.101	0.055	0.05	0.078	0.081	0.061	0.058	11.686	0.106	0.132	0.051	0.09	0.25	0.074
3	Mar	0.079	0.072	0.032	0.177	0.109	0.076	0.033	11.914	0.481	0.075	0.039	0.046	0.114	0.07
4	Apr	0.071	0.052	0.068	0.134	0.107	0.145	0.22	12.943	0.411	0.134	0.047	0.048	0.377	0.056
5	May	0.199	0.057	0.134	0.326	0.069	0.076	0.093	18.8	0.261	0.141	0.05	0.065	1.009	0.14
6	Jun	0.707	0.292	0.219	3.41	0.186	0.581	0.441	20.16	0.751	4.211	1.135	0.091	3.112	0.559
7	Jul	24.711	12.669	9.785	26.84094	20.452	38.253	18.387	93.248	33.215	26.135	34.711	11.161	40.703	9.115
8	Aug	55.92	57.182	51.527	39.4771	44.302	49.946	53.318	169.608	46.203	56.508	53.654	50.784	40.803	41.203
9	Sep	25.667	18.353	14.928	15.174	13.238	38.221	19.66	100.375	26.043	19.068	23.083	17.247	30.141	21.903
10	Oct	7.958	3.912	2.795	1.057	0.433	3.755	1.701	28.634	2.036	2.811	1.427	1.174	2.044	1.608
11	Nov	0.829	0.564	0.56	0.317	0.385	0.297	0.4258	17.5	0.503	0.448	4.168	0.319	0.457	0.487
12	Dec	0.286	0.229	0.265	0.183	0.201	0.168	0.286167	15.168	0.252	0.223	0.328	0.318	0.251	0.228
Annual Mean in m3/s		9.7273	7.8015	6.7078	7.2778	6.6439	10.9753	7.8938	42.8038	9.1993	9.1710	9.8993	6.8001	9.9562	6.3002

Annex VI. Well inventory of the study area

Bore hole ID	Local Name	X	Y	Z	Well depth (m)	SWL (m)	Well Type	Discharge (l/s)	Draw Down (m)
BH_1	Abysynia Factory /in	472997	1011121	2627.87	147	33/31.1	Open	1.23	70.5
BH_2	Abysynia Factory /in	473051	1011283	2615.36	85	29/26.9	Open	5.6	30.3
BH_3	Abysynia Factory /out	472992	1011287	2617.29	244	24/28.4	Open	1.14	57
BH_4	Abysynia Factory /out	473559	1011841	2611	233	19	Open	6.9	76.44
BH_5	Abysynia Factory /in	473000	1011282	2621	250	28.44	Open	2.6	154.7
BH_6	Issac Abdulahi Noc fuel station	473252	1014205	2601	95	3.05		1.87	52.95
BH_7	Belaya Industrials PLC	468486	1006756	2772	171	46.1		11.7	20
BH_8	Elemtu Integrated Milk	472027	1009035	2697	250	81.25		6	100
BH_9	Sululta Town (01 ,Omo doroba)	475292	1012922	2615	274	24		18	102.9
BH_10	Weserbi (10 kilo)	466306	1008828	2738	460	21		20	70.1
BH_11	Chancho (mapping Well)	473911	1031930	2543	324	1.00	Cased	2	158.05
BH_12	Sululta o1 (G/Arbe)	474421	1013070	2610	304	18.20	Cased	15.2	48.91
BH_13	Sululta/kara ta'aa (laga kawe 2nd)	467125	1008326	2617	470	19.9	Cased	27	107.6
BH_14	Suluta 01/Goro Arba	476170	1014624	2375.82	137	28.3	Cased	8.14	18.78
BH_15	Sululta (Wereso)	472772	1018752	2554	858	2	Cased	2.3	68.7
BH_16	Chancho/Gutu Ilamo	473693	1032100	2504	882	12.5	Cased	1.6	93.39
BH_17	Sululta Depo (Sunshine Petroleum	470714	1008000	2724			Cased	1	
BH_18	Gudu	455345	1009722	2710	20	18.00	Open	0.28	
BH_19	Chancho	471304	1027754	2561	65	10.30	Cased	1.3	
BH_20	Entoto Mariam	473376	1005065	2974	15	10.00	Open	20	
BH_21	Rob Gebeya	466862	1031004	2585	117	55.00	Cased	2	
BH_22	Korke Robe	473871	1024156	2605	15	6.00	Cased	2	5
BH_23	Sululta	473104	1011068	2622			Cased		
BH_24	Shegole Meda	468100	1016250	2578	193	3.00			
BH_25	Arbi Akako/Chancho	474740	1028068	2629	_	_	_	_	_
BH_26	Wereso/keto (Goliye)	474261	1019062	2566	_	_	_	_	_
BH_27	Wereso/keto (Goliye)	473501	1018863	2549	202	_	_	_	_
BH_28	Selasie/Sululta 01	473520	1014292	2593	_	_	_	_	_
BH_29	Selasie/Sululta 01	474005	1014163	2596	_	_	_	_	_
BH_30	Degefa Bula/Wale lube babu	474513	1013274	2608	_	_	_	_	_
BH_31	Kajima Sululta	472722	1012748	2605	100	_	_	_	_
BH_32	Red Cross (sululta 01)	473758	1015231	2591	180			4.5	
BH_33	Bilao (Sululta o1)	473182	1015259	2577.37	45			2.5	
BH_34	Atlete Mender (k/wasarbi)	469335	1007837	2730.71	96			2.4	
BH_35	Fereja Eth & Chancho Flower	474018	1012230	2605.2	60			5	
BH_36	Kefle Bulo Apple Farm	473157	1009306	2627.5	120			1	
BH_37	JJ Kothari Flowering Farm	472609	1012803	2598.89	80			8	
BH_38	Allied Chemicals (BH_1)	474123	1016624	2573.34	80			0.9	
BH_39	Allied Chemicals (BH_2)	474177	1016690	2574.81	80			0.9	
BH_40	Dr. Hailu Worku	473160	1014133	2596.8	60			1	
BH_41	Tamaz food complex	473020	1011782	2608.09	98			0.3	

Bore hole ID	Local Name	X	Y	Z	Well depth (m)	SWL (m)	Well Type	Discharge (l/s)	Draw Down (m)
BH_42	Oromia Steel Pipe Mill Factory	472621	1009120	2632.11	304			1	
BH_43	Selale Diary	471434	1008936	2714.58	-			2	
BH_44	China Africa Tannery	473188	1016856	2561.05	320			16	
BH_45	Textile (?)	470503	1007986	2727.98	_			2	
BH_46	Dr Feseha	473447	1014467	2596.66	-			0.5	
BH_47	Palace Hotel	473226	1014393	2597.29	102			0.5	
BH_48	Bolina Boru Hotel	473081	1013890	2604.26	-			0.5	
BH_49	Solomon Hotel	472996	1013432	2609.87	-			0.5	
BH_50	Dire Sululta Hotel	473077	1013256	2610.97	80			0.5	
BH_51	Hanymoon Hotel	473146	1013204	2612.96	70			0.5	53
BH_52	Yaya Athletics Village	468210	1006467	2755.87	-			0.5	
BH_53	Kenenisa Resort	468766	1007046	2767	-			0.5	
BH_54	Nile Petroleum	469103	1007255	2757.68	112			1 or 6	78.2
BH_55	Tsena Lodge	469654	1007457	2753.53	-			0.5	
BH_56	Well	471702	1009505	2706.99	60			0.3	
BH_57	Federal Dog Training Center (Fengi ,Kaso	473021	1009146	2627.68	238	Artesian		0.5	
BH_58	Sululta /Wale	475210	1012720	2610	275	24.85	Cased	8.3	39.63
BH_59	Hambiso/Chancho	482081	1037780	2577	202	ve 0.7 (artesi.)		14	45.45
BH_60	Moye Gajo/Chan	478260	1038550	2503	270	ve1.4(artesi.)		5	160.6
BH_61	Laga Tame/Chan	470913	1026393.2	2660	226	10.3		5	58.55
BH_62	Chnacho/Buba keb.	470446	1026620	2538	272	Artesian (0)		5.2	224
BH_63	Hirut Agonafer/sul	473627	1015082	2596	70	_	_	0.6	52
BH_64	Mokonin & Tsige	473625	1015444	2585	88.35	6		3	
BH_65	Getachew Garage	473002	1013161	2605	70	_		5	51.45
BH_66	ARM Factory	473134	1012347	2604	265			0.7	221
BH_67	Ethiopia Hotel	473054	1011920	2603	102			3.5	68
BH_68	Abayas Trading	470810	1009695	2704	90	9		1.4	
BH_69	Zewudu Tadesse	471496	1006043	2718	100			5.6	72
BH_70	Berhanu Ragassa	471433	1008935	2717	145			5.9	97.5
BH_71	Gift Water _1	471032	1007698	2686	323	49.5		10	228
BH_72	Gift Water _2	471060	1007766	2690	150	1.27		1.8	108
BH_73	Gift Water _3	471100	1007850	2681	180	_		5	
BH_74	Daksen Village	470427	1007993	2724	100			3	52
BH_75	Indris Teshome	470160	1007676	2732	120			5	
BH_76	Kasu Negash	469524	1007602	2740	64			1.5	
BH_77	Hunde Resort	468207	1006015	2750	152			2.8	
BH_78	Tadesse Debelle _1	468993	1005478	2754	150	10		7.5	
BH_79	Tadesse Debelle _2	468798	1005449	2752	90	10		3.2	
BH_80	Weserbi Real State	468720	1005654	2767	150			7	
BH_81	Doroba /sululta	475567	1015435	2586	398	26.3		6	
BH_82	Segno gebeya	455620	1026514	2610	273	69.75		2.1	99.99

Annex VII. The response/change to Flows components for different Scenarios from the calibrated Flows values

Flow terms	Calibrated IN &OUT Flow (m^3/d)		Simulated Flow when abstraction rate increased by 30%		Change in IN Flow (m^3/d)	Change in OUT Flow	Flow Change by %	Remark
			IN (m^3/d)	OUT (m^3/d)				
WELLS	0.00E+00	1.53E+04		1.99E+04			30	
DRAINS	0.00E+00	1.50E+04		1.49E+04			constant	
RECHARGE	4.95E+05	0.00E+00	4.94E+05		-8.40E+02		-0.17	
ET	0.00E+00	4.49E+05		4.49E+05		-7.69E+02	-0.17	Decreased by 0.17 %
RIVER LEAKAGE	5.57E+04	6.88E+04	5.81E+04	6.73E+04	2.38E+03	-1.51E+03	4.3, -2.19	Out flow to the River decreased by 2.1 % while in flow from the river increased by 4.3%
HEAD DEP BOUNDS	0.00E+00	2498.559	0.00E+00	1760.545	0.00E+00	-7.38E+02	-29.54	Out flow through GHB decreased by 29.5%
Flow terms	Calibrated IN &OUT Flow		Simulated Flow when abstraction rate increased by 40%		Change in IN Flow (m^3/d)	Change in OUT Flow	Flow Change by %	Remark
			IN (m^3/d)	OUT (m^3/d)				
WELLS	0.00E+00	1.53E+04		2.14E+04			40	
DRAINS	0.00E+00	1.50E+04		1.49E+04			constant	
RECHARGE	4.95E+05	0.00E+00	4.94E+05		-1.49E+03		-0.3	
ET	0.00E+00	4.49E+05		4.48E+05		-1.39E+03	-0.31	Decreased by 0.31 %
RIVER LEAKAGE	5.57E+04	6.88E+04	5.88E+04	6.66E+04	3.10E+03	-2.25E+03	5.6, -3.27	Out flow to the River decreased by 3.1 % while in flow from the river increased by 5.6%
HEAD DEP BOUNDS	0.00E+00	2498.559	0.00E+00	1741.183	0.00E+00	-7.57E+02	-30.31	Out flow through GHB decreased by 30.3%
Flow terms	Calibrated IN &OUT Flow (m^3/d)		Simulated Flow when abstraction rate increased by 50%		Change in IN Flow (m^3/d)	Change in OUT Flow	Flow Change by %	Remark
			IN (m^3/d)	OUT (m^3/d)				
WELLS	0.00E+00	1.53E+04		2.30E+04			50	
DRAINS	0.00E+00	1.50E+04		1.49E+04			constant	
RECHARGE	4.95E+05	0.00E+00	4.93E+05		-2.12E+03		-0.43	
ET	0.00E+00	4.49E+05		4.47E+05		-2.19E+03	-0.49	Decreased by 0.49 %
RIVER LEAKAGE	5.57E+04	6.88E+04	5.96E+04	6.60E+04	3.93E+03	-2.82E+03	7.1, -4.1	Out flow to the River decreased by 4.1% while in flow from the river increased by 7.1%
HEAD DEP BOUNDS	0.00E+00	2498.559	0.00E+00	1.73E+03	0.00E+00	-7.72E+02	-30.91	Out flow through GHB decreased by 30.9 %
Flow terms	Calibrated IN &OUT Flow (m^3/d)		Simulated Flow when Recharge rate Decreased by 10%		Change in IN Flow (m^3/d)	Change in OUT Flow	Flow Change by %	Remark
			IN (m^3/d)	OUT (m^3/d)				
ET	0.00E+00			1.91E+05		-2.59E+05	-57.57	Decreased by 57.6 %
RIVER LEAKAGE	5.57E+04	6.88E+04	4.25E+04	3.78E+04	-1.33E+04	-3.11E+04	23.8, -45.15	Out flow to the River decreased by 45.2% while in flow from the river decreased by 23.8 %
HEAD DEP BOUNDS	0.00E+00	2498.559	0.00E+00	9.62E+02	0.00E+00	-1.54E+03	-61.49	Out flow through GHB decreased by 61.5 %
Flow terms	Calibrated IN &OUT Flow m3/d		Simulated Flow when Recharge rate Decreased by 20%		Change in IN Flow (m^3/d)	Change in OUT Flow (m^3/d)	Flow Change by %	Remark
			IN (m^3/d)	OUT (m3/d)				
ET	0.00E+00	4.49E+05		2.79E+05		-1.70E+05	-37.84	Decreased by 38 %
RIVER LEAKAGE	5.57E+04	6.88E+04	7.77E+04	3.57E+04	2.20E+04	-3.31E+04	39.5, -48.09	Out flow to the River decreased by 48 % while in flow from the river increased by 38.5 %
HEAD DEP BOUNDS	0.00E+00	2498.559		9.34E+02	0.00E+00	-1.56E+03	-62.60	Out flow through GHB decreased by 61.5 %

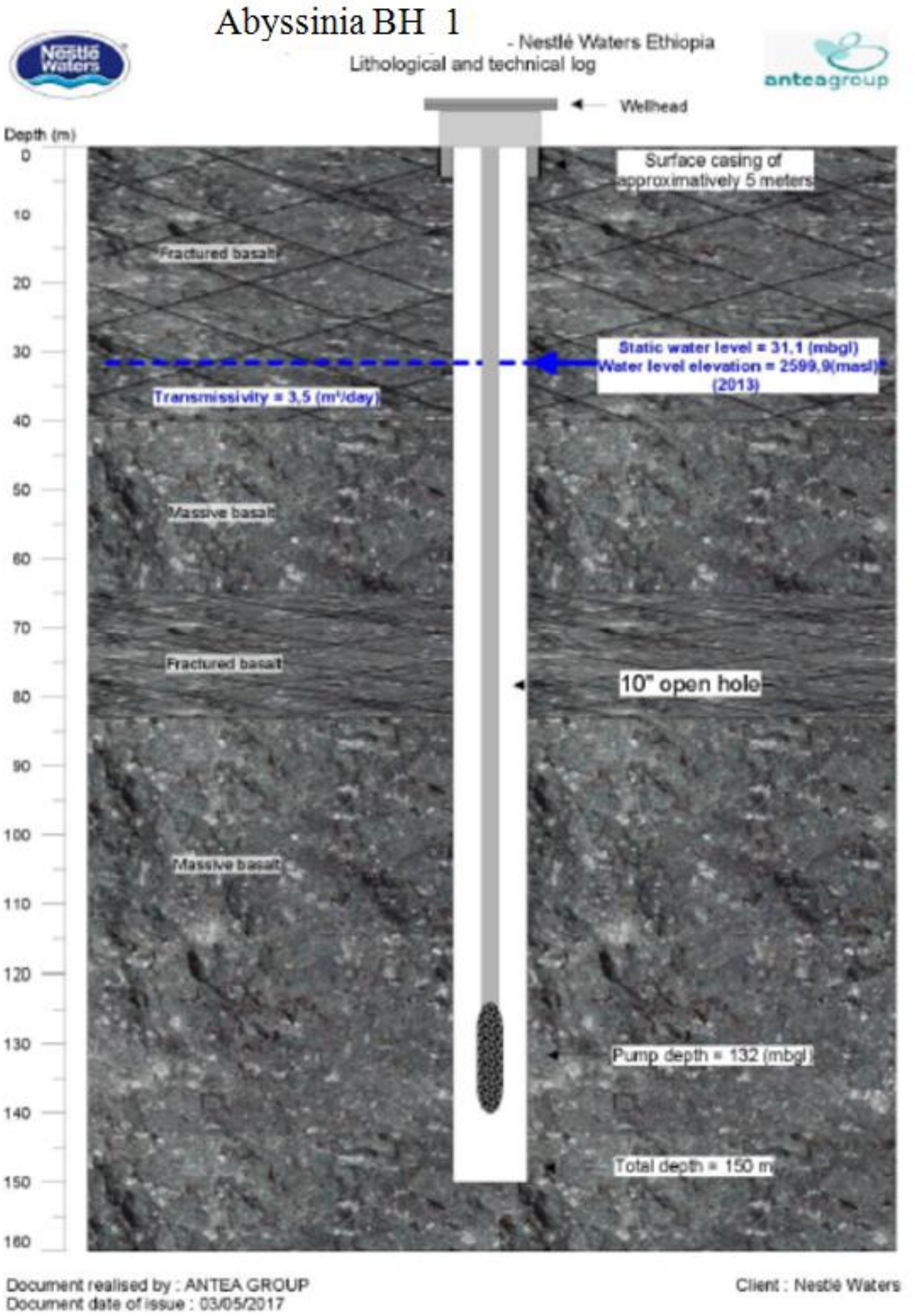
Annex VIII. The Recharge trend for the coming 15 years Calculated from 2007_2021 Base Flow data

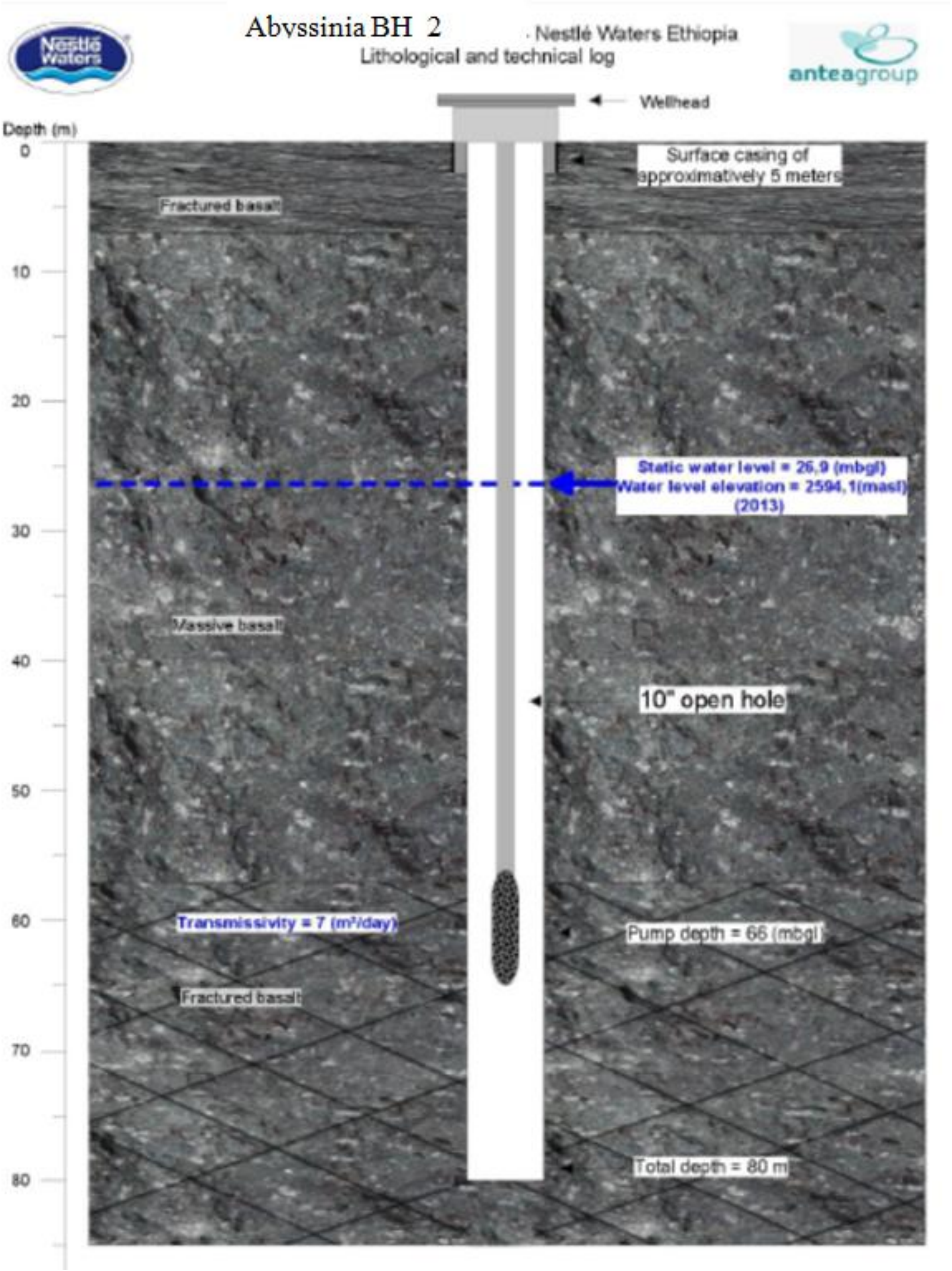
year	Average Base Flow m^3/s	Estimated Recharge in mm/year	Estimated Recharge in mm/year by using Y=-2.2539x+4858.8 equation	Projected year	Annual Change of recharge by %
2007	7.41	359.69	335.22	2022	0.67
2008	8.18	397.06	332.97	2023	0.68
2009	4.95	240.34	330.71	2024	0.68
2010	7.64	371.06	328.46	2025	0.69
2011	4.67	226.53	326.21	2026	0.69
2012	7.39	358.73	323.95	2027	0.70
2013	8.20	398.12	321.70	2028	0.70
2014	4.95	240.34	319.45	2029	0.71
2015	7.64	371.06	317.19	2030	0.71
2016	4.23	205.56	314.94	2031	0.72
2017	7.41	359.69	312.68	2032	0.72
2018	8.20	398.12	310.43	2033	0.73
2019	4.95	240.33	308.18	2034	0.73
2020	5.65	274.17	305.92	2035	0.7368
2021	7.21	349.98	303.67	2036	0.80
		319.39	319.45 mean		10.3 Total

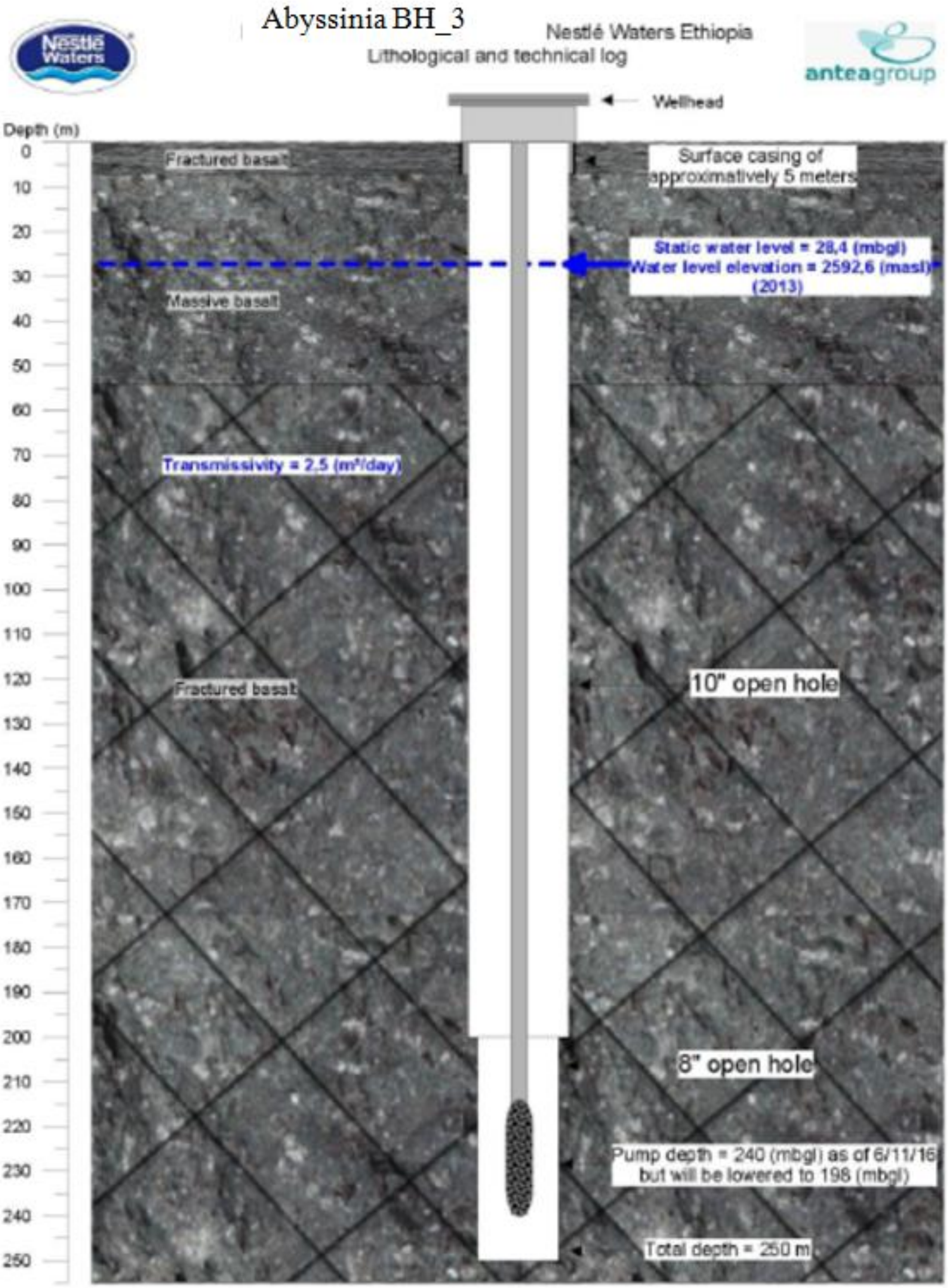
Annex IX .Head dependent Boundary nodes imposed to the Sibilu River Catchment

No	i	j	k	Average hydraulic conductivity (K) in the cell (m/d)	Aquifer thickness in the cell (W) in meters	Conductance (m2/d)	GHB Elevation
1	1	88	1	0.0892	87	41.018	2531.38
2	1	89	1	0.0892	87	41.018	2531.38
3	1	90	1	0.0892	87	41.018	2531.38
4	1	91	1	0.0892	87	41.018	2531.38
5	1	92	1	0.0892	87	41.018	2531.38
6	2	87	1	0.0891	90.94	39.212	2531.62
7	2	88	1	0.0891	90.94	39.212	2531.62
8	2	92	1	0.0888	87.78	40.465	2529.45
9	3	87	1	0.0891	92.7	38.453	2533.62
10	3	92	1	0.0882	87.47	40.335	2526.34
11	4	84	1	0.0893	96.52	37.014	2534.85
12	4	85	1	0.0889	95.48	37.250	2533.43
13	4	86	1	0.0889	94.44	37.660	2532.02
14	4	87	1	0.0887	93.4	37.995	2530.62
15	4	92	1	0.0878	88.2	39.805	2524.14
16	4	93	1	0.0876	87.2	40.178	2523.03
17	5	84	1	0.0889	98.22	36.219	2533.41
18	5	93	1	0.0871	87.89	39.660	2520.63
19	5	94	1	0.0870	86.85	40.048	2519.50
20	6	83	1	0.0888	98.88	35.909	2533.56
21	6	84	1	0.0886	97.85	36.199	2531.94
22	6	94	1	0.0865	87.58	39.505	2516.87

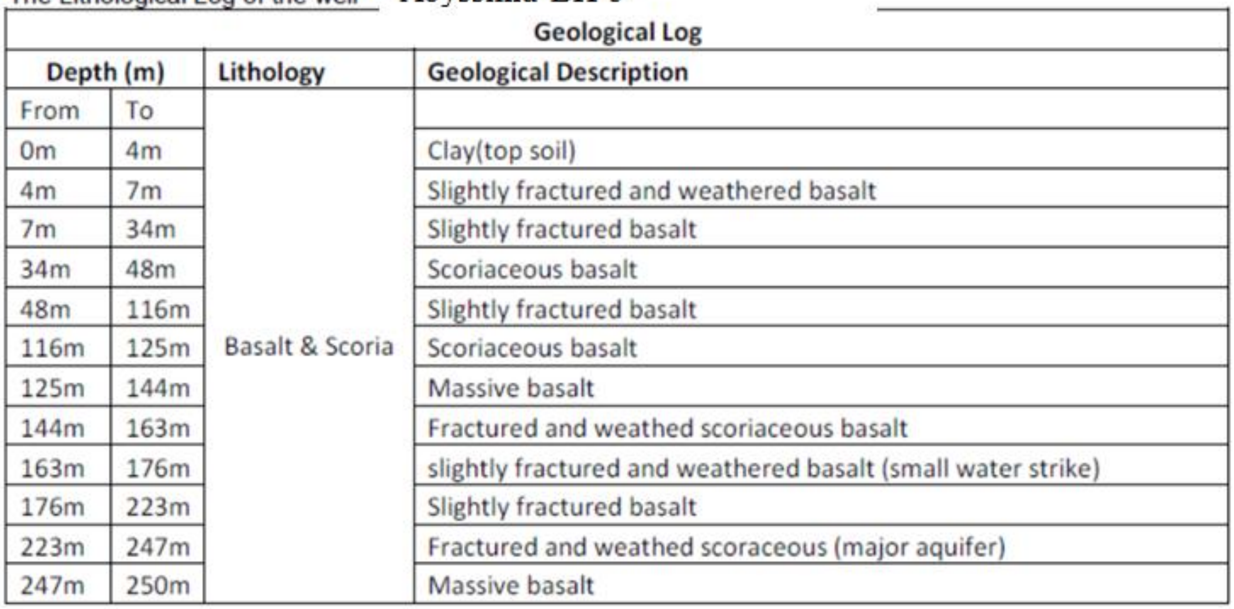
Annex X. Lithological Log and Casing arrangement of some Wells




Abyssinia BH 2
Nestlé Waters Ethiopia
Lithological and technical log
anteagroup
Wellhead
Depth (m)
0
10
20
30
40
50
60
70
80
Surface casing of approximatively 5 meters
Fractured basalt
Static water level = 26,9 (mbgl)
Water level elevation = 2594,1(masl)
(2013)
Massive basalt
10" open hole
Transmissivity = 7 (m²/day)
Pump depth = 66 (mbgl)
Fractured basalt
Total depth = 80 m

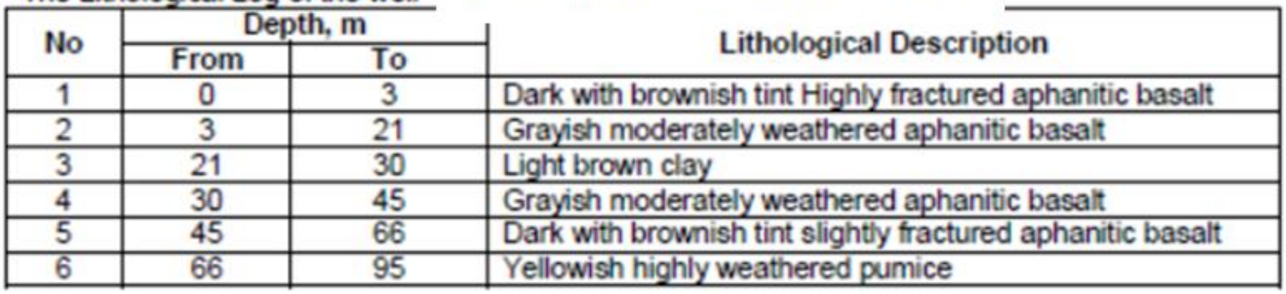

Abyssinia BH_3
Nestlé Waters Ethiopia
Lithological and technical log
Nestlé Waters
anteagroup
Wellhead
Depth (m)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
Fractured basalt
Surface casing of approximatively 5 meters
Static water level = 28,4 (mbgl)
Water level elevation = 2592,6 (masl)
(2013)
Massive basalt
Transmissivity = 2,5 (m²/day)
Fractured basalt
10" open hole
8" open hole
Pump depth = 240 (mbgl) as of 6/11/16 but will be lowered to 198 (mbgl)
Total depth = 250 m

The Lithological Log of the well Abyssinia BH-5



Geological Log			
Depth (m)		Lithology	Geological Description
From	To		
0m	4m	Basalt & Scoria	Clay(top soil)
4m	7m		Slightly fractured and weathered basalt
7m	34m		Slightly fractured basalt
34m	48m		Scoriaceous basalt
48m	116m		Slightly fractured basalt
116m	125m		Scoriaceous basalt
125m	144m		Massive basalt
144m	163m		Fractured and weathed scoriaceous basalt
163m	176m		slightly fractured and weathered basalt (small water strike)
176m	223m		Slightly fractured basalt
223m	247m		Fractured and weathed scoraceous (major aquifer)
247m	250m		Massive basalt

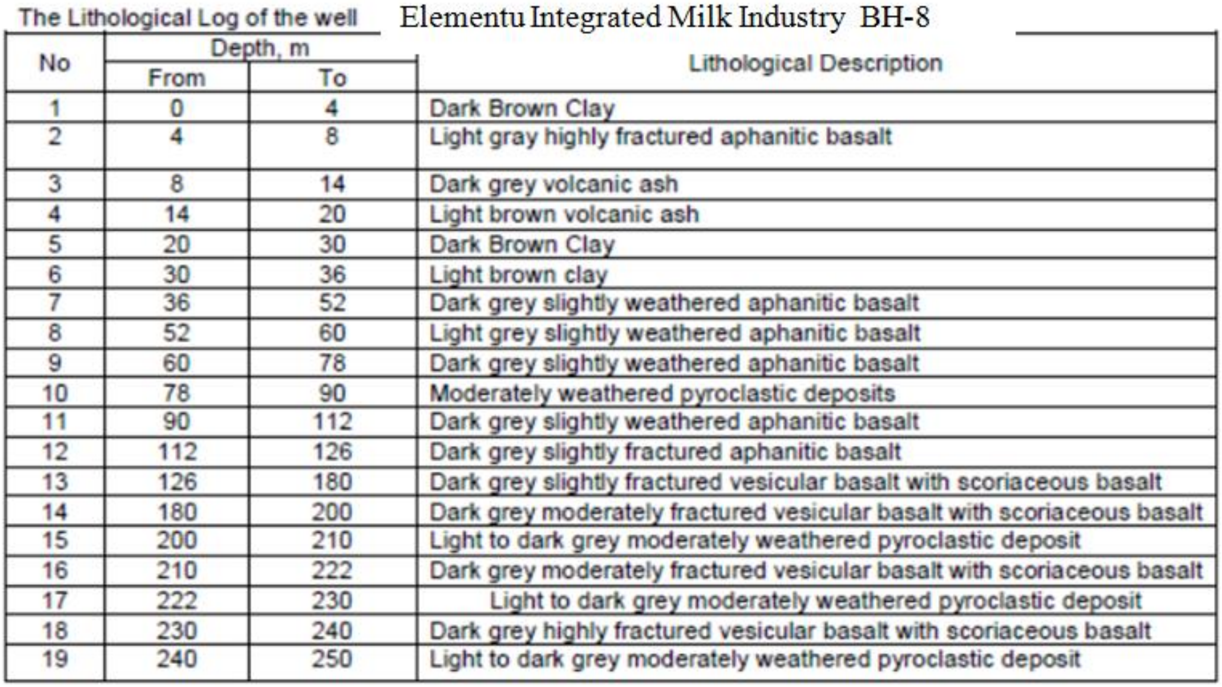
The Lithological Log of the well Isac Abdulahi NOC fuel station BH_6



No	Depth, m		Lithological Description
	From	To	
1	0	3	Dark with brownish tint Highly fractured aphanitic basalt
2	3	21	Grayish moderately weathered aphanitic basalt
3	21	30	Light brown clay
4	30	45	Grayish moderately weathered aphanitic basalt
5	45	66	Dark with brownish tint slightly fractured aphanitic basalt
6	66	95	Yellowish highly weathered pumice

The Lithological Log of the well Belay Industrial PLC BH-7

No	Depth, m		Lithological Description
	From	To	
1	0	18	Light brown silty clay
2	18	42	Dark brown silty clay
3	42	54	Light grey volcanic ash
4	54	66	Light grey ignimbrite
5	66	78	Dark moderately fractured basalt
6	78	84	Dark brown clay
7	84	99	Light brown clay
8	99	123	Light grey volcanic ash
9	123	150	Dark brown clay
10	150	171	Dark brown highly weathered and fractured basalt

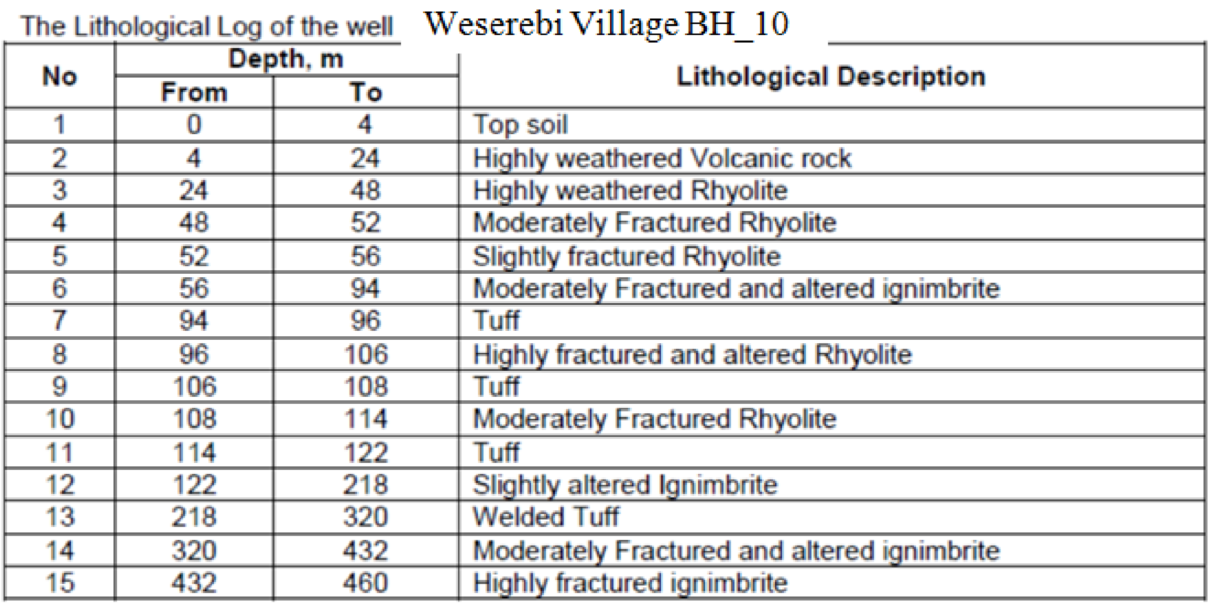


The Lithological Log of the well Elementu Integrated Milk Industry BH-8

No	Depth, m		Lithological Description
	From	To	
1	0	4	Dark Brown Clay
2	4	8	Light gray highly fractured aphanitic basalt
3	8	14	Dark grey volcanic ash
4	14	20	Light brown volcanic ash
5	20	30	Dark Brown Clay
6	30	36	Light brown clay
7	36	52	Dark grey slightly weathered aphanitic basalt
8	52	60	Light grey slightly weathered aphanitic basalt
9	60	78	Dark grey slightly weathered aphanitic basalt
10	78	90	Moderately weathered pyroclastic deposits
11	90	112	Dark grey slightly weathered aphanitic basalt
12	112	126	Dark grey slightly fractured aphanitic basalt
13	126	180	Dark grey slightly fractured vesicular basalt with scoriaceous basalt
14	180	200	Dark grey moderately fractured vesicular basalt with scoriaceous basalt
15	200	210	Light to dark grey moderately weathered pyroclastic deposit
16	210	222	Dark grey moderately fractured vesicular basalt with scoriaceous basalt
17	222	230	Light to dark grey moderately weathered pyroclastic deposit
18	230	240	Dark grey highly fractured vesicular basalt with scoriaceous basalt
19	240	250	Light to dark grey moderately weathered pyroclastic deposit

The Lithological Log of the well Sululta Town BH 9

No.	Lithological Description	Depth interval, m	
		From	To
1	Top Soil (black cotton soil)	0	8
2	Decomposed basalt (highly weathered basalt)	8	14
3	Clay	14	40
4	Slightly Weathered Basalt	40	52
5	Massive Basalt	52	56
6	Moderately Weathered slightly fracturing Basalt	56	68
7	highly Weathered rhyolite	68	74
8	Moderately Weathered scoraceous Basalt	74	78
9	Slightly Weathered scoraceous Basalt	78	80
10	Moderately Weathered and moderately fracturing Basalt	80	82
11	Highly Weathered scoraceous basalt	82	86
12	Moderately Weathered and slightly fracturing Basalt	86	90
13	Moderately Weathered and slightly fracturing scoraceous Basalt	90	94
14	Moderately Weathered and slightly fracturing Basalt	94	102
15	Slightly weathered Scoraceous Basalt	102	114
16	Moderately Weathered and slightly fracturing scoraceous Basalt	114	124
17	slightly weathered scoraceous Basalt	124	148
18	Moderately Weathered Basalt	148	152
19	Moderately Weathered and highly fracturing Basalt	152	162
20	Moderately Weathered and moderately fracturing Basalt	162	168
21	Moderately Weathered and highly fracturing Basalt	168	172
22	Moderately Weathered and slightly fracturing Basalt	172	176
23	highly Weathered and highly fracturing Basalt	176	180
24	Moderately Weathered and moderately fracturing Basalt	180	198
25	Moderately Weathered (Rounded) Basalt	198	208
26	Slightly Weathered Basalt	208	214
27	highly Weathered and highly fracturing Basalt	214	224
28	Moderately Weathered scoraceous Basalt	224	232
29	Decomposed scoraceous Basalt	232	238
30	Moderately Weathered scoraceous Basalt	238	244
31	Slightly Weathered and moderately fracturing Basalt	244	246
32	Slightly Weathered Basalt	246	250
33	Decomposed Basalt	250	256
34	Moderately Weathered and slightly fracturing Basalt	256	266
35	Slightly Weathered Basalt	266	274



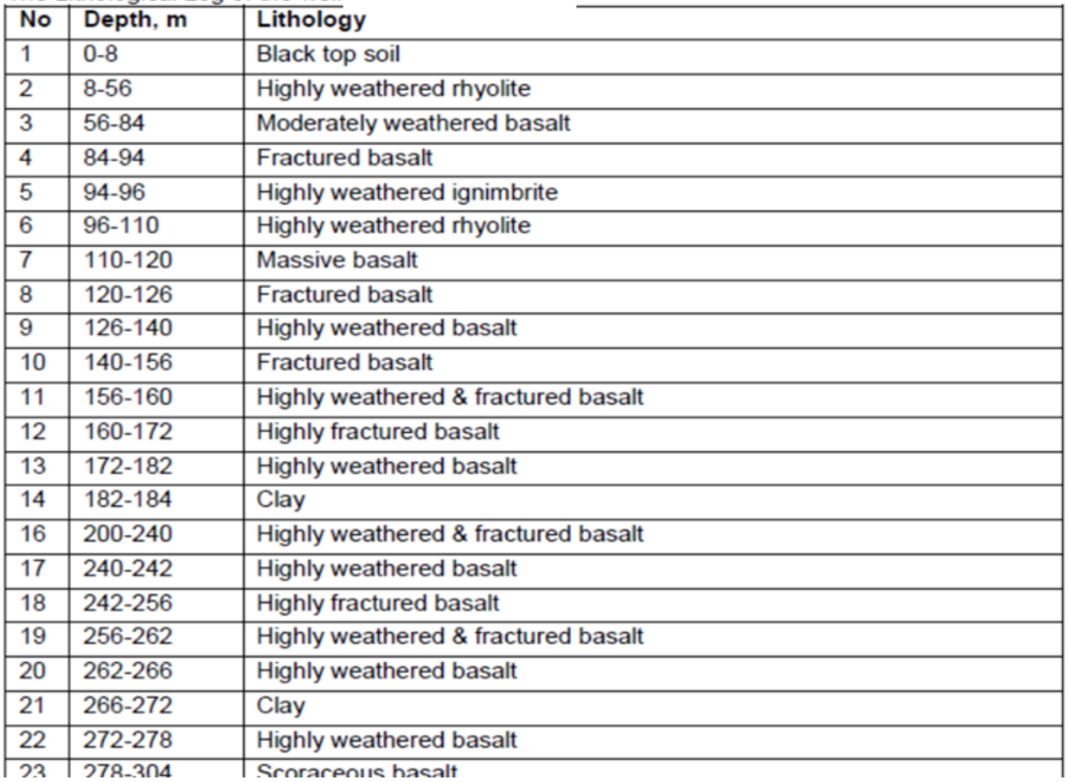
The Lithological Log of the well Weserebi Village BH_10

No	Depth, m		Lithological Description
	From	To	
1	0	4	Top soil
2	4	24	Highly weathered Volcanic rock
3	24	48	Highly weathered Rhyolite
4	48	52	Moderately Fractured Rhyolite
5	52	56	Slightly fractured Rhyolite
6	56	94	Moderately Fractured and altered ignimbrite
7	94	96	Tuff
8	96	106	Highly fractured and altered Rhyolite
9	106	108	Tuff
10	108	114	Moderately Fractured Rhyolite
11	114	122	Tuff
12	122	218	Slightly altered Ignimbrite
13	218	320	Welded Tuff
14	320	432	Moderately Fractured and altered ignimbrite
15	432	460	Highly fractured ignimbrite

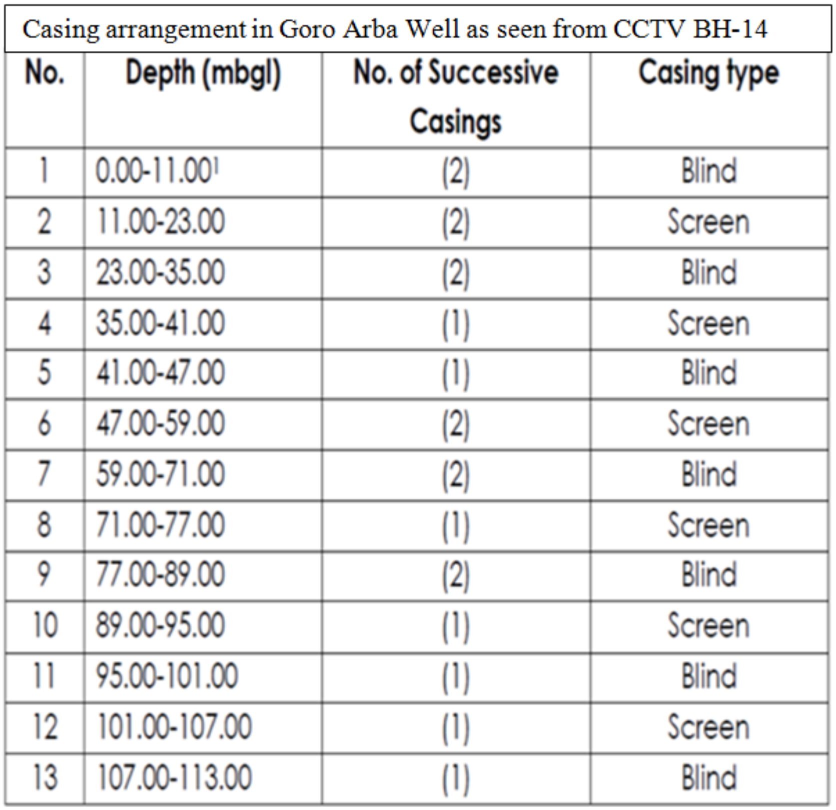
1. TCK46-Chancho mapping well (BH_11)

No	*Depth, m*	*Lithologic description*
1	*0-38*	*Black top soil*
2	*38-44*	*Slightly weathered scoraceous basalt*
3	*44-146*	*Highly weathered scoria 102*
4	*146-164*	*Highly weathered basalt 18*
5	*164-176*	*Massive basalt*
6	*176-186*	*Fractured basalt*
7	*186-188*	*Highly weathered scoria 2*
8	*188-210*	*Massive basalt*
9	*210-220*	*Highly weathered scoria 10*
10	*220-230*	*Highly weathered basalt 10*
11	*230-240*	*Moderately weathered scoria 10*
12	*240-264*	*Massive basalt*
13	*264-268*	*Highly weathered scoria 4*
14	*268-280*	*Massive basalt*
15	*280-290*	*Highly weathered scoraceous basalt 10*
16	*290-300*	*Scoraceous basalt*
17	*300-308*	*Fractured basalt*
18	*308-312*	*Massive basalt*
19	*312-320*	*Moderately weathered scoria 8*
20	*320-324*	*Massive basalt*

The Lithological Log of the well G/Arbe BH-12

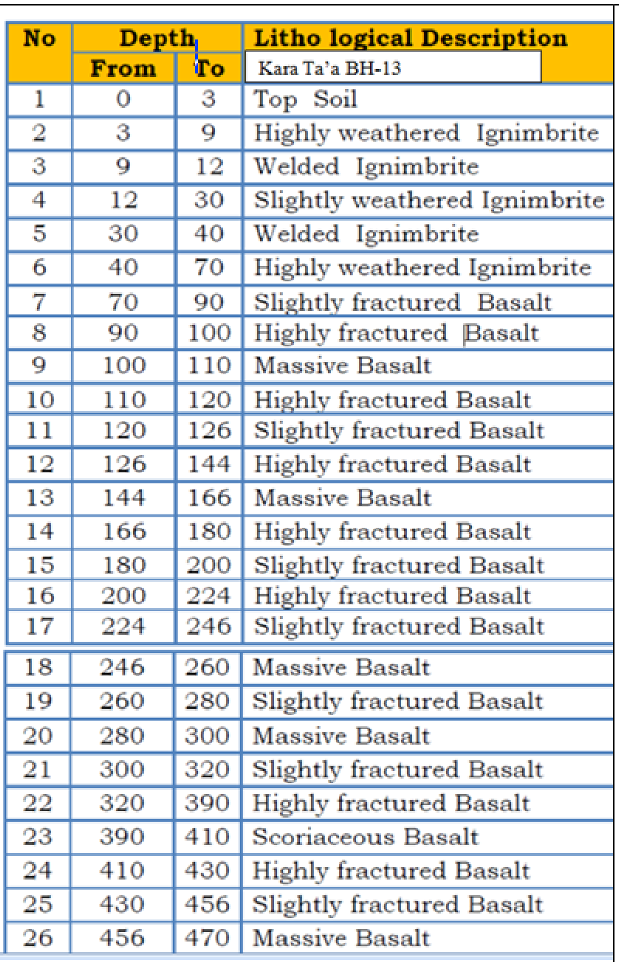


No	Depth, m	Lithology
1	0-8	Black top soil
2	8-56	Highly weathered rhyolite
3	56-84	Moderately weathered basalt
4	84-94	Fractured basalt
5	94-96	Highly weathered ignimbrite
6	96-110	Highly weathered rhyolite
7	110-120	Massive basalt
8	120-126	Fractured basalt
9	126-140	Highly weathered basalt
10	140-156	Fractured basalt
11	156-160	Highly weathered & fractured basalt
12	160-172	Highly fractured basalt
13	172-182	Highly weathered basalt
14	182-184	Clay
16	200-240	Highly weathered & fractured basalt
17	240-242	Highly weathered basalt
18	242-256	Highly fractured basalt
19	256-262	Highly weathered & fractured basalt
20	262-266	Highly weathered basalt
21	266-272	Clay
22	272-278	Highly weathered basalt
23	278-304	Scoraceous basalt

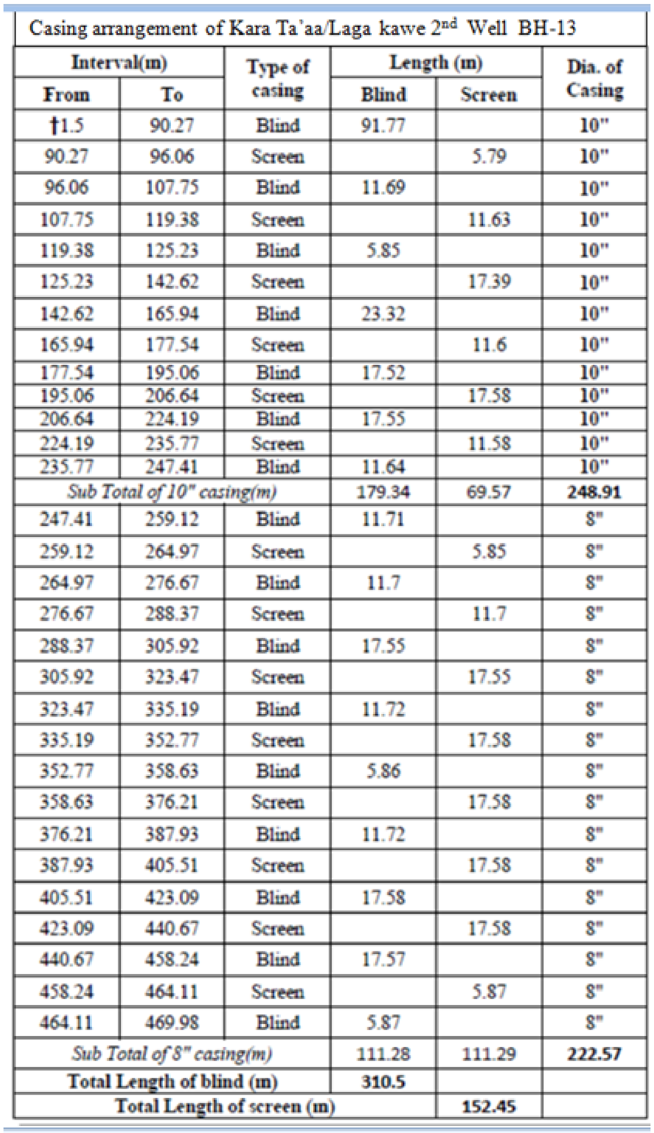


Casing arrangement in Goro Arba Well as seen from CCTV BH-14

No.	Depth (mbgl)	No. of Successive Casings	Casing type
1	0.00-11.00[1]	(2)	Blind
2	11.00-23.00	(2)	Screen
3	23.00-35.00	(2)	Blind
4	35.00-41.00	(1)	Screen
5	41.00-47.00	(1)	Blind
6	47.00-59.00	(2)	Screen
7	59.00-71.00	(2)	Blind
8	71.00-77.00	(1)	Screen
9	77.00-89.00	(2)	Blind
10	89.00-95.00	(1)	Screen
11	95.00-101.00	(1)	Blind
12	101.00-107.00	(1)	Screen
13	107.00-113.00	(1)	Blind



No	Depth		Litho logical Description
	From	To	Kara Ta'a BH-13
1	0	3	Top Soil
2	3	9	Highly weathered Ignimbrite
3	9	12	Welded Ignimbrite
4	12	30	Slightly weathered Ignimbrite
5	30	40	Welded Ignimbrite
6	40	70	Highly weathered Ignimbrite
7	70	90	Slightly fractured Basalt
8	90	100	Highly fractured Basalt
9	100	110	Massive Basalt
10	110	120	Highly fractured Basalt
11	120	126	Slightly fractured Basalt
12	126	144	Highly fractured Basalt
13	144	166	Massive Basalt
14	166	180	Highly fractured Basalt
15	180	200	Slightly fractured Basalt
16	200	224	Highly fractured Basalt
17	224	246	Slightly fractured Basalt
18	246	260	Massive Basalt
19	260	280	Slightly fractured Basalt
20	280	300	Massive Basalt
21	300	320	Slightly fractured Basalt
22	320	390	Highly fractured Basalt
23	390	410	Scoriaceous Basalt
24	410	430	Highly fractured Basalt
25	430	456	Slightly fractured Basalt
26	456	470	Massive Basalt



Casing arrangement of Kara Ta'aa/Laga kawe 2^{nd} Well BH-13

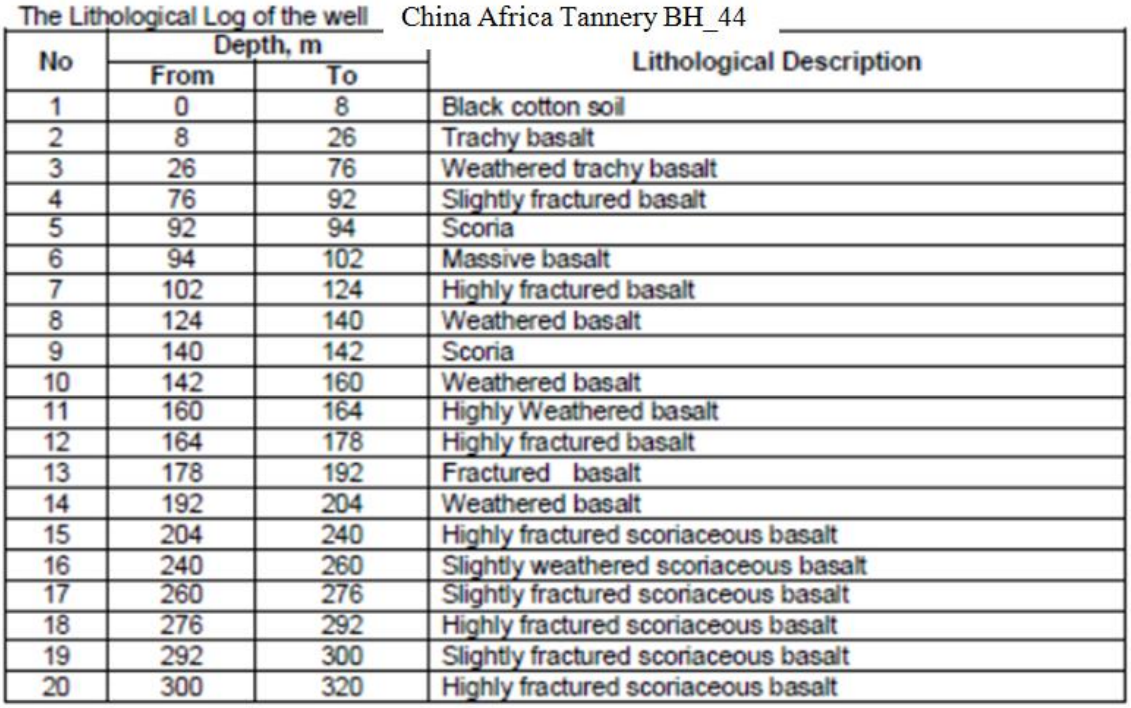
Interval(m)		Type of casing	Length (m)		Dia. of Casing
From	To		Blind	Screen	
†1.5	90.27	Blind	91.77		10"
90.27	96.06	Screen		5.79	10"
96.06	107.75	Blind	11.69		10"
107.75	119.38	Screen		11.63	10"
119.38	125.23	Blind	5.85		10"
125.23	142.62	Screen		17.39	10"
142.62	165.94	Blind	23.32		10"
165.94	177.54	Screen		11.6	10"
177.54	195.06	Blind	17.52		10"
195.06	206.64	Screen		17.58	10"
206.64	224.19	Blind	17.55		10"
224.19	235.77	Screen		11.58	10"
235.77	247.41	Blind	11.64		10"
Sub Total of 10" casing(m)			179.34	69.57	**248.91**
247.41	259.12	Blind	11.71		8"
259.12	264.97	Screen		5.85	8"
264.97	276.67	Blind	11.7		8"
276.67	288.37	Screen		11.7	8"
288.37	305.92	Blind	17.55		8"
305.92	323.47	Screen		17.55	8"
323.47	335.19	Blind	11.72		8"
335.19	352.77	Screen		17.58	8"
352.77	358.63	Blind	5.86		8"
358.63	376.21	Screen		17.58	8"
376.21	387.93	Blind	11.72		8"
387.93	405.51	Screen		17.58	8"
405.51	423.09	Blind	17.58		8"
423.09	440.67	Screen		17.58	8"
440.67	458.24	Blind	17.57		8"
458.24	464.11	Screen		5.87	8"
464.11	469.98	Blind	5.87		8"
Sub Total of 8" casing(m)			111.28	111.29	**222.57**
Total Length of blind (m)			**310.5**		
Total Length of screen (m)				**152.45**	

Depth Ranges		Lithologic Description Sululta test Well (BH_15)
From	To	
0	4	verity clay soil
4	10	silt soil
10	26	Water bearing weathered trachite basalt
26	44	Slightly fractured basalt.
44	58	Moderately fractured basalt
58	64	Scoria
64	86	Moderately fractured basalt
86	98	Slightly fractured basalt.
98	102	Moderately fractured scoria
102	110	Slightly fractured basalt.
110	144	Massive basalt
144	146	Scoria
146	168	Massive basalt
168	174	Slightly fractured basalt.
174	176	Paliosoil
176	208	Slightly fractured basalt.
208	210	Scoracious basalt
210	250	massive basalt
250	270	Slightly fractured scoracious basalt
270	272	Slightly fractured basalt.
272	292	Slightly fractured scoracious basalt
292	430	Massive basalt
430	436	Slightly fractured basalt.
436	454	Scoricious basalt
454	460	Moderately fractured basalt
460	486	Massive basalt
486	498	Slightly to moderately fractured basalt
498	504	Slightly fractured scoracious basalt
504	526	Slightly fractured basalt
526	542	Slightly fractured scoracious basalt
542	572	Moderately fractured to slightly fractured basalt
572	616	Massive to slightly fractured basalt
616	650	Scoria
650	658	Slightly fractured water bearing basalt
658	684	Scoracious basalt
684	702	Massive basalt
702	706	Scoria
706	718	Slightly fractured basalt
718	722	Scoria
722	748	Massive basalt
748	752	Scoria
752	778	Scoracious basalt
778	816	Massive basalt
816	818	Scoracious basalt
818	858	Massive basalt

From (m)	To (m)	Length (m)	Diameter (inch)	Type
0	102.8	102.8	10	Blind
102.8	108.58	5.78	10	Screen
108.58	120.08	11.5	10	Blind
120.08	125.86	5.78	10	Screen
125.86	172.09	46.23	10	Blind
172.09	177.89	5.8	10	Screen
177.89	189.46	11.57	10	Blind
189.46	201.08	11.62	10	Screen
201.08	206.82	5.74	10	Blind
206.82	218.4	11.58	10	Screen
218.4	230	11.6	10	Blind
230	235.8	5.8	10	Screen
235.8	243.4	7.6	10	Blind
243.4	249.81	6.41	10	Screen
249.81	253.81	4	8	Blind
253.81	259.52	5.71	8	Blind
259.52	277.19	17.67	8	Screen
277.19	282.94	5.75	8	Blind
282.94	294.66	11.72	8	Screen
294.66	306.66	12	8	Blind
306.66	318.2	11.54	8	Screen
318.2	324.02	5.82	8	Blind
324.02	329.78	5.76	8	Screen
329.78	335.47	5.69	8	Blind
335.47	341.49	6.02	8	Screen
341.49	353.49	12	8	Blind
353.49	365.21	11.72	8	Screen
365.21	382.89	17.68	8	Blind
382.89	394.62	11.73	8	Screen
394.62	406.62	12	8	Blind
406.62	412.44	5.82	8	Screen
412.44	424.44	12	8	Blind
424.44	430.3	5.86	8	Screen
430.3	436.05	5.75	8	Blind
436.05	447.74	11.69	8	Screen
447.74	453.49	5.75	8	Blind
453.49	459.36	5.87	8	Screen
459.36	465.19	5.83	8	Blind
465.19	470.9	5.71	8	Screen
470.9	476.59	5.69	8	Blind
476.59	482.67	6.08	8	Screen
482.67	488.4	5.73	8	Blind
488.4	494.04	5.64	8	Screen
494.04	500.09	6.05	8	Blind
500.09	529.98	29.89	6	Blind
529.98	535.92	5.94	6	Screen
535.92	547.97	12.05	6	Blind
547.97	553.88	5.91	6	Screen
553.88	559.98	6.1	6	Blind
559.98	565.94	5.96	6	Screen
565.94	613.82	47.88	6	Blind
613.82	619.78	5.96	6	Screen
619.78	625.69	5.91	6	Blind
625.69	637.7	12.01	6	Screen
637.7	643.63	5.93	6	Blind
643.63	649.68	6.05	6	Screen
649.68	655.63	5.95	6	Blind
655.63	661.55	5.92	6	Screen
661.55	667.58	6.03	6	Blind
667.58	679.45	11.87	6	Screen
679.45	697.45	18	6	Blind
697.45	703.5	6.05	6	Screen
703.5	715.41	11.91	6	Blind
715.41	721.46	6.05	6	Screen
721.46	745.43	23.97	6	Blind
745.43	751.34	5.91	6	Screen
751.34	757.39	6.05	6	Blind
757.39	763.39	6	6	Screen
763.39	769.31	5.92	6	Blind
769.31	775.35	6.04	6	Screen
775.35	811.21	35.86	6	Blind
811.21	817.17	5.96	6	Screen
817.17	847.9	30.73	6	Blind

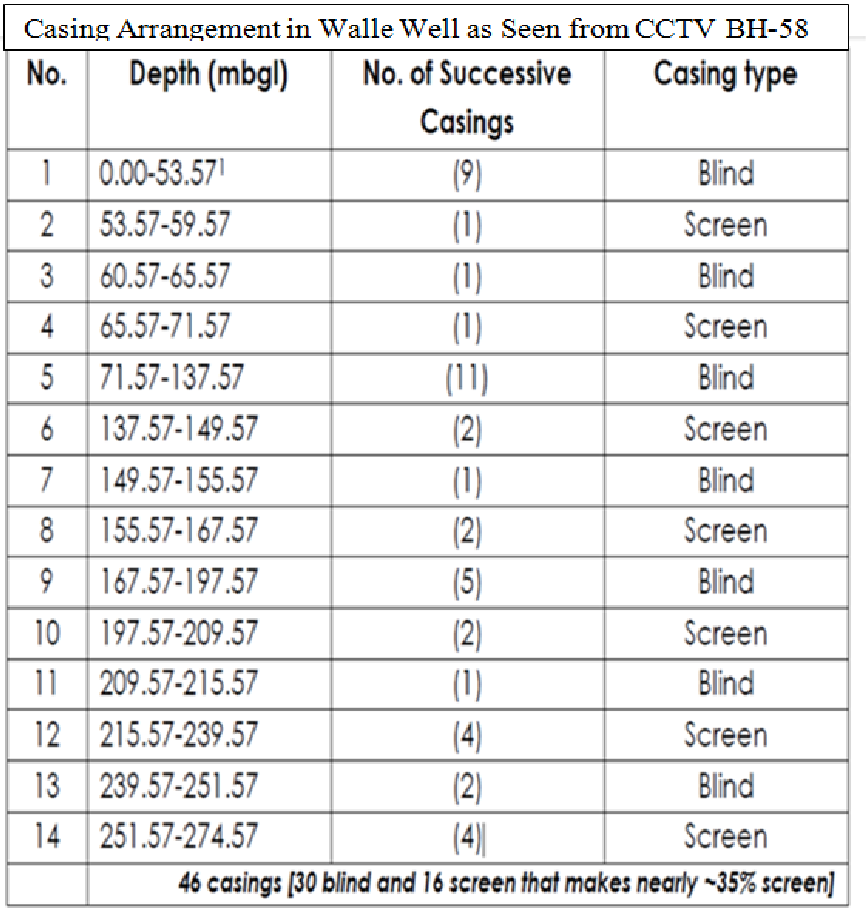
Depth Ranges		Lithologic Description of Chancho test well (BH-16)
From	To	
0	4	Top Soil (Black cotton soil)
4	8	River Gravel
8	18	Weathered Scoracious Basalt
18	26	Scoracious Basalt
26	38	Scoria
38	60	Highly To Moderately Fractured Basalt
60	66	Scoriacious Fractured Basalt
66	72	Slightly Fractured Basalt
72	86	Massive Basalt
86	94	Slightly Fractured Basalt
94	104	Scoriacious Basalt
104	110	Fractured Basalt
110	120	Scoriacious Basalt
120	124	Massive Basalt
124	130	Scoriacious Basalt
130	134	Slightly Fractured Basalt
134	152	Massive Basalt
152	156	River Gravel With Basalt
156	178	Highly Fractured Basalt
178	182	Massive Basalt
182	188	Slightly Fractured Basalt
188	196	Moderately Fractured Basalt
196	214	Highly Fractured Scoriacious Basalt
214	228	Massive Basalt
228	232	Pure Scoria
232	250	Massive Basalt
250	260	Scoria
260	272	Slightly Fractured Basalt
272	274	Scoria
274	280	Highly Fractured Scoriacious Basalt
280	282	Gravel With Fractured Basalt
282	300	Moderately Fractured Scoriaciou Basalt
300	310	Moderately Fractured Basalt
310	318	Moderately Fractured Scoriacious Basalt
318	324	Moderately Fractured Basalt
324	332	Moderately Fractured Scoriaciou Basalt
332	340	Moderately Fractured Basalt
340	356	Massive Basalt
356	366	Fractured Basalt
366	370	Scoria
370	376	Slightly Fractured Scoriacious Basalt
376	386	Scoriaciou Basalt
386	404	Massive Basalt
404	412	Scoria(Water Bearing)
412	458	Slightly Fractured Basalt
458	462	Fractured Basalt
462	484	Very Slightly Fractured Basalt
484	544	Massive Basalt To Very Slightly Fractured Basalt
544	580	Scoriaciou Basalt With Some Calcite Filling
580	600	Slightly Fractured Scoriacious Basalt
600	630	Massive Basalt
630	682	Massive To Slightly Fractured Basalt
682	684	Scoriaciou Basalt
684	882	Massive Basalt To Very Slightly Fractured Basalt

Depth Ranges (m)		*Diameter (“)*	*length (m)*	*Type*
From	*To*			
1	123.52	10	124.52	Blind
123.52	129.52	10	6	Screen
129.52	141.56	10	12.04	Blind
141.56	147.67	10	6.11	Screen
147.67	153.68	10	6.01	Blind
153.68	165.76	10	12.08	Screen
165.76	177.76	10	12	Blind
177.76	189.89	10	12.13	Screen
189.89	195.94	10	6.05	Blind
195.94	207.99	10	12.05	Screen
207.99	220.02	10	12.03	Blind
220.02	226.04	10	6.02	Screen
226.04	244.6	10	18.56	Blind
244.6	256.73	10	12.13	Screen
256.73	272.69	10	15.96	Blind
272.69	272.71	8	0.02	Blind
272.71	278.73	8	6.02	Screen
278.73	284.8	8	6.07	Blind
284.8	296.87	8	12.07	Screen
296.87	302.92	8	6.05	Blind
302.92	308.92	8	6	Screen
308.92	315	8	6.08	Blind
315	326.86	8	11.86	Screen
326.86	338.93	8	12.07	Blind
338.93	344.89	8	5.96	Screen
344.89	356.96	8	12.07	Blind
356.96	368.81	8	11.85	Screen
368.81	374.86	8	6.05	Blind
374.86	380.92	8	6.06	Screen
380.92	386.81	8	5.89	Blind
386.81	392.94	8	6.13	Screen
392.94	398.88	8	5.94	Blind
398.88	404.78	8	5.9	Screen
404.78	410.82	8	6.04	Blind
410.82	416.83	8	6.01	Screen
416.83	422.73	8	5.9	Blind
422.73	428.82	8	6.09	Screen
428.82	434.75	8	5.93	Blind
434.75	440.68	8	5.93	Screen
440.68	446.74	8	6.06	Blind
446.74	452.74	8	6	Screen
452.74	464.68	8	11.94	Blind
464.68	476.68	8	12	Screen
476.68	482.76	8	6.08	Blind
482.76	488.83	8	6.07	Screen
488.83	494.83	8	6	Blind
494.83	500.92	8	6.09	Screen
500.92	506.65	8	5.73	Blind
506.65	512.5	6	5.85	Blind
512.5	518.53	6	6.03	Screen
518.53	542.49	6	23.96	Blind
542.49	554.55	6	12.06	Screen
554.55	566.56	6	12.01	Blind
566.56	578.56	6	12	Screen
578.56	584.61	6	6.05	Blind
584.61	590.61	6	6	Screen
590.61	632.61	6	42	Blind
632.61	638.68	6	6.07	Screen
638.68	650.63	6	11.95	Blind
650.63	656.69	6	6.06	Screen
656.69	668.64	6	11.95	Blind
668.64	680.73	6	12.09	Screen
680.73	704.68	6	23.95	Blind
704.68	710.75	6	6.07	Screen
710.75	728.75	6	18	Blind
728.75	734.75	6	6	Screen
734.75	740.7	6	5.95	Blind
740.7	752.81	6	12.11	Screen
752.81	776.8	6	23.99	Blind
776.8	782.86	6	6.06	Screen
782.86	806.92	6	24.06	Blind
806.92	812.85	6	5.93	Screen
812.85	818.95	6	6.1	Blind
818.95	824.99	6	6.04	Screen
824.99	861.01	6	36.02	Blind
861.01	866.94	6	5.93	Screen
866.94	882	6	15.06	Blind



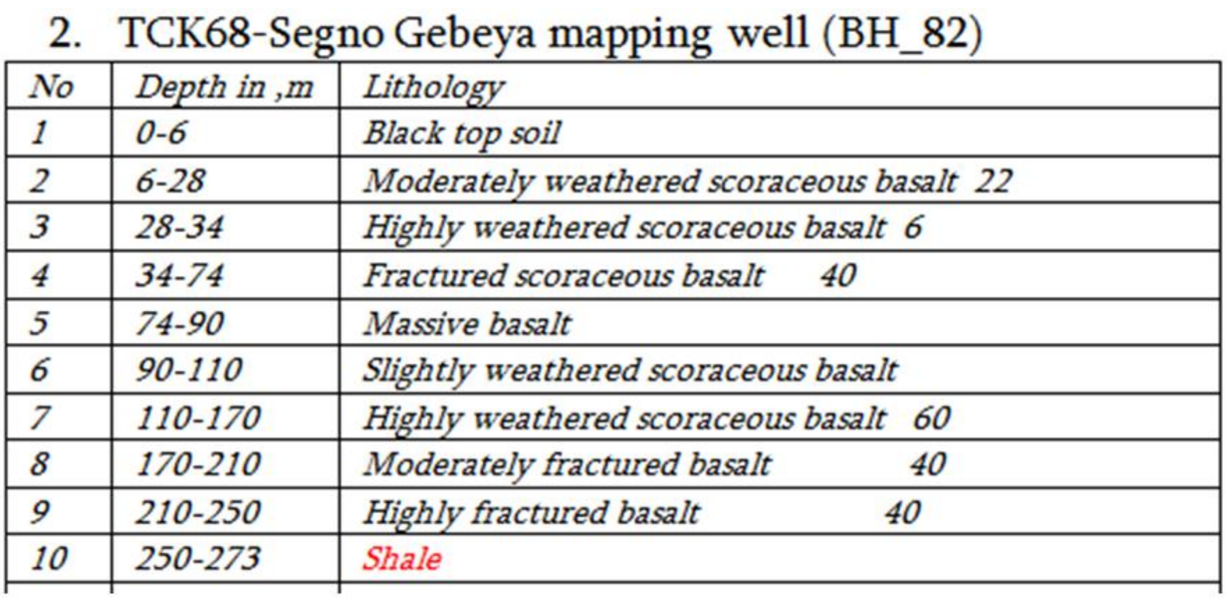
The Lithological Log of the well China Africa Tannery BH_44

No	Depth, m		Lithological Description
	From	To	
1	0	8	Black cotton soil
2	8	26	Trachy basalt
3	26	76	Weathered trachy basalt
4	76	92	Slightly fractured basalt
5	92	94	Scoria
6	94	102	Massive basalt
7	102	124	Highly fractured basalt
8	124	140	Weathered basalt
9	140	142	Scoria
10	142	160	Weathered basalt
11	160	164	Highly Weathered basalt
12	164	178	Highly fractured basalt
13	178	192	Fractured basalt
14	192	204	Weathered basalt
15	204	240	Highly fractured scoriaceous basalt
16	240	260	Slightly weathered scoriaceous basalt
17	260	276	Slightly fractured scoriaceous basalt
18	276	292	Highly fractured scoriaceous basalt
19	292	300	Slightly fractured scoriaceous basalt
20	300	320	Highly fractured scoriaceous basalt



Casing Arrangement in Walle Well as Seen from CCTV BH-58

No.	Depth (mbgl)	No. of Successive Casings	Casing type
1	0.00-53.57[1]	(9)	Blind
2	53.57-59.57	(1)	Screen
3	60.57-65.57	(1)	Blind
4	65.57-71.57	(1)	Screen
5	71.57-137.57	(11)	Blind
6	137.57-149.57	(2)	Screen
7	149.57-155.57	(1)	Blind
8	155.57-167.57	(2)	Screen
9	167.57-197.57	(5)	Blind
10	197.57-209.57	(2)	Screen
11	209.57-215.57	(1)	Blind
12	215.57-239.57	(4)	Screen
13	239.57-251.57	(2)	Blind
14	251.57-274.57	(4)	Screen
	46 casings [30 blind and 16 screen that makes nearly ~35% screen]		



2. TCK68-Segno Gebeya mapping well (BH_82)

No	Depth in ,m	Lithology
1	0-6	Black top soil
2	6-28	Moderately weathered scoraceous basalt 22
3	28-34	Highly weathered scoraceous basalt 6
4	34-74	Fractured scoraceous basalt 40
5	74-90	Massive basalt
6	90-110	Slightly weathered scoraceous basalt
7	110-170	Highly weathered scoraceous basalt 60
8	170-210	Moderately fractured basalt 40
9	210-250	Highly fractured basalt 40
10	250-273	Shale