ADDIS ABABA UNIVERSITY

College of Natural and Computational Science

School of Earth sciences

Steady State Groundwater Flow Modelling of the Sunuta Catchment (Western Afar Region): Special Emphasis on Effect of Groundwater Pumping for Irrigation

A Thesis

Submitted to

School of Graduate Studies of Addis Ababa University

In Partial Fulfillment of the Requirements for the Degree of Masters of Science (Hydrogeology)

Mulatu Tarekegn

Addis Ababa, Ethiopia

July, 2020

Steady State Groundwater Flow Modelling of the Sunuta Catchment (Western Afar Region): Special Emphasis on Effect of Groundwater Pumping for Irrigation

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Statement of the Author

By my signature below, I declare and confirm that this thesis is my own work. I have followed all ethical and technical principles of research in the preparation, data collection, data analysis and compilation of this thesis. Any scholarly article that is included in the thesis has been given acknowledgment through reference.

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This thesis has been submitted for examination with my approval as University Advisor

Name: Dr. Dessie Nedaw

Signature: _____________

Date: _________________

Addis Ababa University
School of Graduate Studies

This is to certify that the thesis prepared by Mulatu Tarekegn, entitled: **Steady State Groundwater Flow Modelling of the Sunuta Catchment (Western Afar Region): Special Emphasis on Effect of Groundwater Pumping for Irrigation** and submitted in partial fulfillment of the requirements for the Degree of Master of Science (Hydrogeology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

The study area is situated in the lower Awash basin, with in zone four of Afar National Regional State and Northern Wollo zone of Amhara Regional state. Sunuta plain is located about 690km Northeast of Addis Ababa. The total study catchment area is 1870km^2 of which 1476 km^2 belongs to Sunuta plain (rift floor/ lowlands) and 394 km^2 belongs to the mountainous area (rift escarpments and highlands). In sunuta catchment there are more than 69 boreholes drilled so far for groundwater-based irrigation and water supply purpose. Currently the groundwater abstraction rate is 26,047.80m^3/day. However, in the study area there is no significant research conducted so far to know the groundwater resources. The main objective of the research is steady state numerical groundwater modeling of sunuta catchment to evaluate the impact of current and projected pumping on the groundwater system. Groundwater recharge in the study area is estimated using WetSpass modeling method. The estimated recharge result was 61.1mm/year. The mathematical code Processing MODFLOW Pm8 software is applied in the study area for steady state conditions. The model is horizontally discretized with regular grid spacing of 300m by 300m having 147 rows and 283 columns and one layer having 250m thickness. The layer type is confined/unconfined transmissivity variable. Model calibration is carried out by manual trial and error adjustments of the parameters until the value of simulated and observed result is within the acceptable error. The simulated recharge of the model domain is 50.2mm/year which is close to the estimated recharge using WetSpass model and lateral groundwater flow within certain cross-sectional area using Darcy's approach methods. The current abstraction rate of the area is 26,047.80m^3/day which accounts 10.1% of the simulated recharge. And pumping scenario for steady state model are scenario- one (69 boreholes are operated simultaneously) and scenario-two (91 wells are operated simultaneously) indicate respective groundwater abstraction of 92,039.04 m^3/day and 128,759.04 m^3/day. This resulted in an average groundwater level decline of about 27m and 41m respectively.

Keywords: Sunuta catchment, recharge, abstraction, groundwater modeling

Acknowledgment

I would like to extend my great appreciation to my advisor Dr. Dessie Nedaw who gave me guidance, encouragement and constructive comments that helped me to complete my thesis. My deepest gratitude goes to Professor Tenalem Ayenew kind support and encouragements during my research work.

I also need to acknowledge Addis Ababa University, School of Earth sciences and my instructors who supported me in gaining very important knowledge about the subject matter and related fields.

I would like to extend my gratitude to Afar Design and Supervision Works Enterprise my employer that helped me by gave me an opportunity to study my Msc program. Especially the enterprise General Manager Mr. Ahimed Husen. And also, all of the staff.

I gratefully acknowledge Nabro Geo Solution Consult General Manager Mr. Kebede Fekede for his guidance, encouragement, constructive advice and help.

Institutes from where data have been taken are deeply acknowledged; Afar Water Works Construction Enterprise, Ethiopian National Meteorological Service Agency (ENMSA), Ministry of Agriculture SDG project office.

I also need to acknowledge individuals for their special help during data collection and Groundwater modelling such as Mr. Ephrem Tadesse (PhD candidate), Mr. Mengeste Mathewos Sunuta project manager, Mr. Eskinder Debru, Tesfu Kiros, Simegnew Tadeg and Paulos Wondimneh.

Finally, I offer my deepest gratitude and appreciations to my family and friends for their support and love throughout my life.

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Acronyms

AET	Actual evapotranspiration
PET	potential evapotranspiration
AVG	Average
DD	Drawdown
DEM	Digital Elevation Model
DWL	Dynamic Water Level
GSE	Geological Survey of Ethiopia
ETo	Potential Evapotranspiration
GIS	Geographic Information System
GPS	Global Positioning System
HK	Hydraulic conductivity
Hm	Measured head
Hs	Simulated head
l/sec	Liter per second
M	Meter
M a.m.s.l	Meter above mean sea level
MAE	Mean absolute error
ME	Mean error
MCM	Million Cubic Meters
MM	Millimeter
RMSE	Root mean square error
SDG	Sustainable Development Goal
SQRT	Square root
SWL	Static Water Level
T	Transmissivity

Chapter One

1. Introduction

1.1 Backgrounds

Groundwater is a precious resource, especially in the arid regions like Afar, where there is a limited supply of surface water and groundwater. Growing populations coupled with expansion of groundwater-based irrigation have increased the demands on this limited supply of water.

In developing a sustainable ground water frame work the principles followed are conservation of groundwater resources, protection of groundwater quality and consideration of environmental impacts. (Aleen R. K. and Hasan A.,2014**)**

Approaches of sustainable development and integrated groundwater resources management must be developed and implemented to guarantee the right use of the limited water resources for future generation. Groundwater resource management of an aquifer system involves developing a quantitative understanding of the flow processes that operate within the aquifer.

The best tool available to formulate technically sound ground water resources management is usually a ground water model. Groundwater models have been used as interpretation tools for investigating groundwater system dynamics, assessment tools for evaluating recharge and quantifying sustainable yield (Anderson and Woessner, 2002)

The study area mainly focuses on Sunuta catchment located in Afar rift floor and rift escarpments, in western Afar region of Northeastern Ethiopia. The catchment is found in arid and semi-arid climatic conditions and have medium and variable annual rainfall. There are existing inventoried 69 boreholes drilled in the catchment for groundwater-based irrigation and water supply purpose. From the existing borehole, 50 boreholes are drilled for irrigation purpose and the rest 19 boreholes are drilled for water supply purposes. However, there is no any attention given to groundwater resource management

The research focuses on steady state numerical groundwater flow modeling of Sunuta catchment. Especial emphasis on effect of groundwater pumping for irrigation. Therefore, clear understanding of the response of the aquifer is crucial for better management of groundwater resources

1.2 Statement of the problem

In sunuta catchment there are a number of wells which is drilled for groundwater-based irrigation and water supply purposes. Currently the irrigation projects are on progress. Previously, there is one research conducted on characteristics and Productivity of the Sediments and Volcanic rocks aquifers in Sunuta catchment, Northeast Ethiopia. The research characterizes the main aquifer, aquifer types, hydraulic parameters distribution. However, in the study area there is no significant research conducted so far to know the resources of the groundwater. Moreover, in the catchment groundwater resources are developed for the groundwater-based irrigation, the resources of the groundwater in the catchment should be studied well.

In order to better understand the groundwater system, aquifer properties, groundwater flow systems and predict the future groundwater level under different pumping scenarios and give a recommendation on groundwater resource development at the study area, steady state groundwater flow modeling needs to be applied in sunuta catchment.

1.3 Objectives of the research

1.3.1 General objectives

The main objective of the research is steady state numerical groundwater modeling of sunuta catchment to evaluate the impact of current and projected pumping on the groundwater system.

1.3.2 Specific objectives

- To quantify the recharge of the study area and discharge of groundwater from the study area
- To give a recommendation on groundwater resource development in the study area

1.4 Research questions

What is the recharge and abstraction of groundwater in the study area?

How is the groundwater contour of the study area?

What is the groundwater level of boreholes under different well operation scenarios?

1.5 Literature review

In developing a sustainable ground water frame work the principles followed are conservation of groundwater resources, protection of groundwater quality and consideration of environmental impacts. **(Aleen R. K. and Hasan A.,2014).**

Agriculture, Industry and domestic activities use enormous of water which results in the over-pumping and leading to continuous decline of groundwater level. **(Getahun Wendmkun Adane., 2014).**

The starting point of every groundwater modeling application is to identify the purpose of the model. The most common purpose is to forecast the effects of some future action or hydrologic condition. **(Anderson and Woessner, 2002).**

Reilly and Harbaugh (2004) cited on Anderson and Woessener,2002 identify five broad categories of problems for groundwater modeling: basic understanding of groundwater systems; estimation of aquifer properties; understanding the present; understanding the past; and forecasting the future.

Before Numerical groundwater modeling, conceptual model should develop first which is an input for the model. The main components of a conceptual model include a field-based groundwater budget, boundaries, hydrostratigraphy and estimates of hydrogeological parameters. **(Anderson and Woessner, 2002).**

Boundaries include hydraulic features such as groundwater and surface water divides and physical features such as bodies of surface water and impermeable rock. Boundaries are identified from potentiometric level/ water level, topographic variation, and geologic maps of the region and site. **(Anderson and Woessener, 2002).**

The calibrated model is used to forecast groundwater flow pattern, the interaction of groundwater and surface water, and the effect of pumping on the well field under different scenarios. **(Tenalem Ayenew et al., 2008).**

The input model data, the size of the space and time discretization and the numerical method used to solve the model equation are the main to have accurate numerical models **(Aleen R. K. & Hasan A.,2014).**

Regional hydrogeological, hydro geophysical, hydrogeochemical and isotope hydrology of Chifra-Eliwuha area, Afar, Ethiopia **(GSE, 2015).**

The report dealt on sediments in north and west of Ewa locality and along Ewa river is dominated by sand size material with lesser amount of clay content having high amount of groundwater storage. In contrary to the high storativity, the aquifer has limited thickness to provide ample amount of groundwater for deep wells. The lithological logs of few deep boreholes fully penetrating the unconsolidated material indicates that the availability of basalt aquifer with high permeability. In Sunuta well field, the yield of boreholes ranges from 35 to 80 l/s and transmissivity from 350-560 m^2/d. The area between Ewa and Sunuta aquifers are drain by Ewa river where their tributaries come from the highlands of Sirinka.
Evaluation of the groundwater resources of the Teru area groundwater basin (**WWDSE, 2011)**

The report dealt that the ground water recharge is very small or there is no recharge from the rainfall. Therefore, the recharge of the area is combined from the perennial springs, seasonal springs and rivers. This can be confirmed from the fact that rivers flowing to this catchment and disappearing after some kilometers from the escarpment. The estimated discharge of Ewa river at the foot of the escarpment which is disappearing after some kilometers to ground water is 300 l/s (in December).

Groundwater potential assessment and water quality investigation in Hara basin, North Wollo Amhara regional state, Ethiopia **(Bereket Dina.,2018).**

The researcher estimates the groundwater recharge using water balance method. Due to absence of river gauge, the researcher uses GIS based rational method to calculate runoff. This method considers the slope, land use and soil type. The results obtained from the research is 51.4 mm/year.

The areal coverage of Kobo and Raya valleys are 2369 km^2 and 1439 km^2 and the annual average groundwater recharge of Raya and Kobo valley was estimated to be 84 million cubic meters and 122.9 million cubic meters respectively. (**Nata Tadesse et al., 2015)**

1.6 Methodology and Materials used

In order to achieve the objectives stated above, appropriate methods and materials was used

1.6.1 Procedures and Methodology

The main procedures or activities can be classified in to three main parts such as: - pre-field, field and post-field works

a. Pre-field work

Collecting and organizing appropriate secondary data from different government and non-government organizations such as Afar design and supervision works enterprise, Afar water works construction enterprise, Ethiopian construction design and supervision works corporation, Meteorological agency and individuals and reviewing previous studies. Delineation of the study area and literature review of groundwater modelling is included in this stage.

b. Field work

This stage was used in order to get primary data from the study area. Collecting primary data such as taking reading of borehole locations and elevation using GPS, measuring groundwater level using deep meter, EC and PH measurements using EC meter and PH meter, measuring river width, river stage and river bed thickness and determination of physical boundaries of the model domain

c. Post-field work

In this stage the activities were conducted for data processing, analyzing and interpretation

The conceptual model will be developed which consists of a description of the groundwater flow system including associated surface water bodies, as well as hydro stratigraphic units and system boundaries, field data are assembled and the hydrogeologic system is described; water budget will be estimated using WetSpass method, Darcy approach and if necessary, from previous works.

After conceptual model development, choice of the mathematical model consisting of a governing equation, boundary conditions. Following this, the model will be designed to translate the conceptual model into a numerical groundwater flow model by designing the grid/mesh, setting boundaries, assigning values of aquifer parameters, and hydrologic stresses. Then arguably calibrating the model to establish the legitimacy of the conceptual and numerical models. At the end to use the calibrated model or a set of acceptably calibrated models to forecast the response of the system to future events.

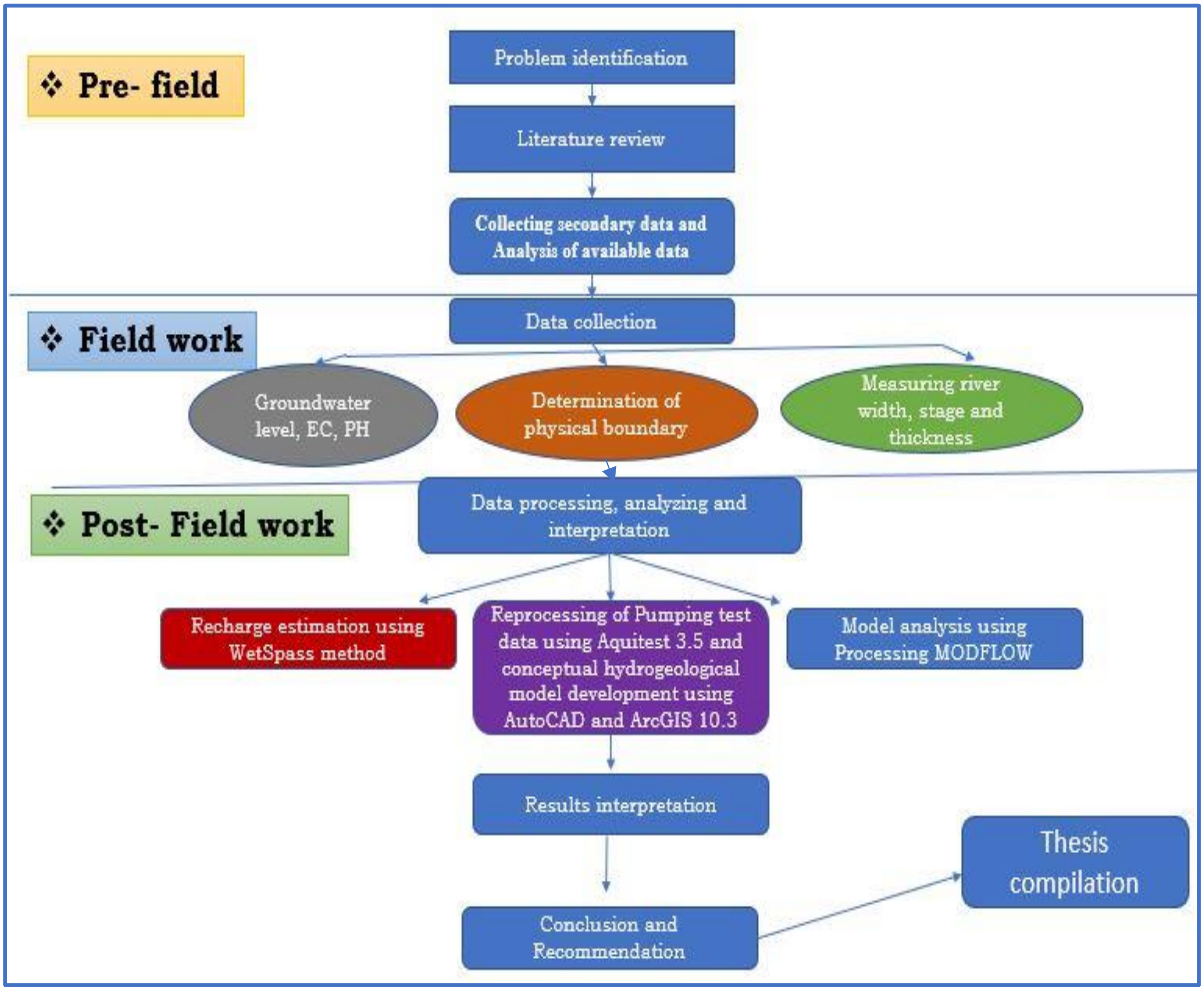

Figure 1.1:- Procedural activities flow chart

1.6.2 Materials and software's used

Materials

- GPS: For capturing and searching of location of points of interest.
- Digital Camera: For capturing images of exposures, water points, well fields etc.
- Deep meter: For measuring static water level of borehole.
- Meter: For measuring average width of river at selected points.
- Maps: topographic, geological, hydrogeological
- Satellite images and 30m by 30m DEM data

Software's

- **Aquitest 3.5**: For re-analysis of pumping test data that will be used as inputs for modeling process, such as hydraulic conductivity, transmissivity, specific capacity.
- **Global Mapper v.15**: For preprocessing satellite images, clipping DEM data for the area of interest to facilitate exporting to ARCGIS for further processing.
- **ARGIS 10.3/Archydro/ tools**: To produce several maps such as location map, soil map, hydraulic conductivity map, water level or potentiometric contour maps, geological maps, hydro geological maps and delineation of catchment, computation of different characteristics of the basin
- **AutoCAD 2007**: - to construct a hydrogeological cross section
- **Processing MODFLOW**: For groundwater modeling simulation for varying scenarios.
- **Surfer**: To produce surface, vector and shaded relief maps

1.7 Significance of the research

The primary significance of the research is the people of Afar region specially sunuta woreda community and its surrounding and Ministry of Agriculture who performs the irrigation projects in the area. At the final stage of this research it will indicate the groundwater flow system and the available groundwater resources in the catchment. The habitation in the catchment will be beneficiaries for utilization and the concerned officials will get good information about the groundwater system in the catchment. The researchers who are interested in the area will also have good understanding about the groundwater flow system and aquifer system. Organizations that are going to involve research works in the catchment will have adequate figures about the catchment. It can also serve as an initial model for other researchers, who possibly will study the area in the future.

Chapter Two

2. Description of the Study area

2.1 Location

The study area is situated in the lower Awash basin, with in zone four of Afar National Regional State and Northern Wollo zone of Amhara Regional state. Sunuta plain is located about 690km Northeast of Addis Ababa. The main asphalt road from Addis Ababa to Mille- Chifra town is about 620km and the remaining about 50km up to Sunuta plain is dry weather road. The study area is bounded between the geographic coordinates of 39^o 36’ to 40^o 23’ E and 11^o 38’ to 12^o 02’N.**(Figure 2.1)**

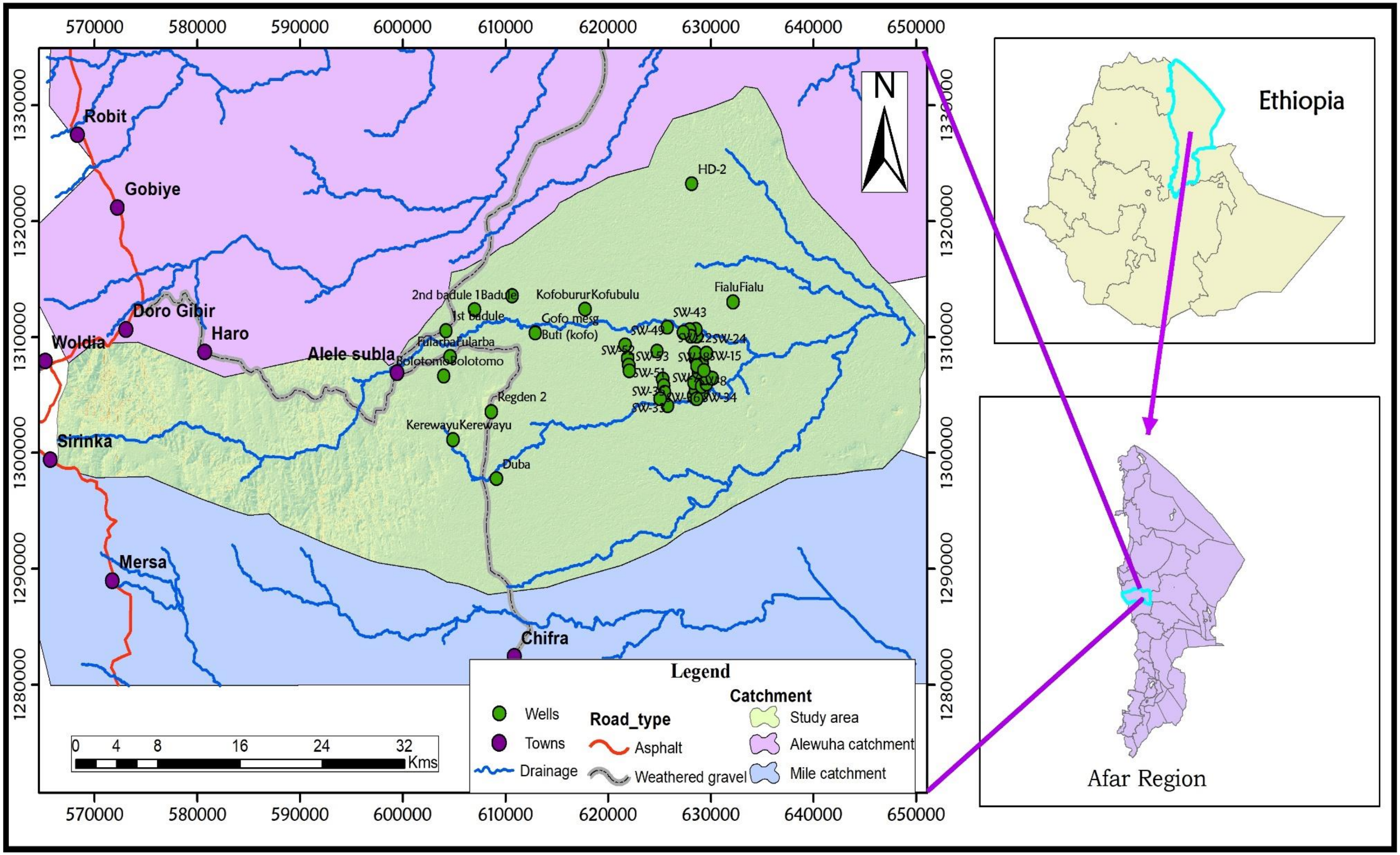

Figure 2.1: - Location Map of the study area

2.2 Geomorphology of the catchment

The morphology of the study area is the result of geologic structure, tectonic evolution and erosion processes, which gradually causes undulating terrain. Consequently, morphological parameters are changed and they give us indications of a hydrological balance (Gianneli, 2009 cited on **Marios C. Kirlas,2015**)

The total study catchment area is 1870km^2 of which 1476 km^2 belongs to Sunuta plain (rift floor/ lowlands) and 394 km^2 belongs to the mountainous area (rift escarpments and highlands). The altitude ranges between 2539masl at the highlands of Sirinka to 734masl in the sunuta plain of the rift floor. The study area is bounded by the Ethiopian plateau and rift escarpment (western escarpment) across the western side and by Danakil depression in the North and East. The surface geology of the Sunuta plain consists of alluvial deposits ranging from clay to pebbles grain size and volcanic rocks which covers the rift escarpments, transition zone and forming some ridges within the plain.

The drainage system is mainly controlled by topography and geological structures. Each river in the study area has numerous small tributaries joining at different angles to the higher order streams that can be characterized as dendritic drainage system. **(Figure 2.2).**

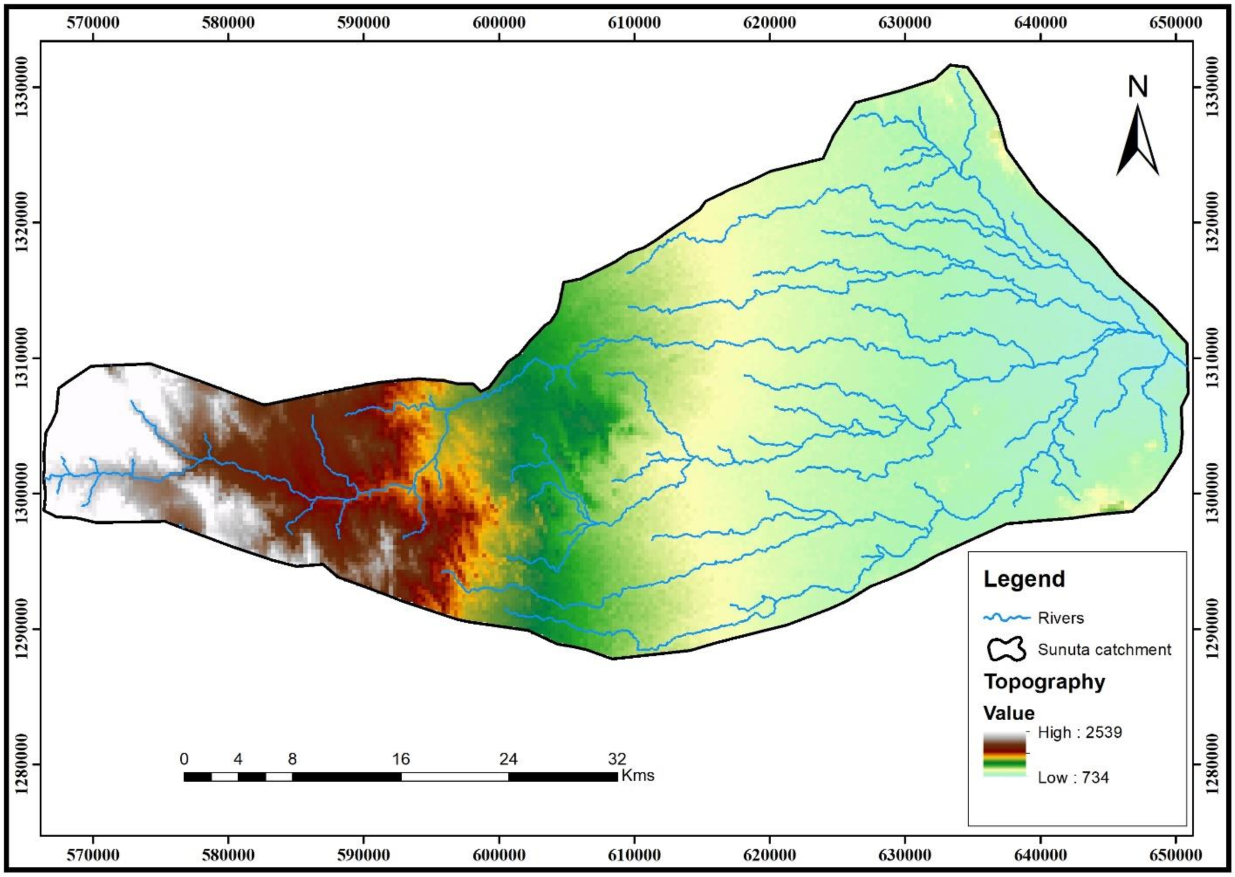

Figure 2.2: - Drainage pattern and elevation of the study area

2.3 Climate

The study area encompasses different climate zones from Cool temperate (Dega) to Warm Temperate (Kola) climatic zone with the mean annual rainfall ranging 1083-389 mm; maximum at Sirinka and minimum at Awura stations respectively. **(Figure 2.1).**

Table 2-1:- Climatic classification of Ethiopia (Tamiru Alemayehu, 2006)

Altitude (m.a.s.l)	Mean annual temperature (^{0}C)	Description	Local name
3,300 and above	10 or less	cool	*Kur*
2,300 - 3,300	10 - 15	cool temperate	*Dega*
1,500 - 2,300	15 - 20	temperate	*Woina Dega*
500 - 1,500	20 - 25	warm temperate	*Kola*
below 500	25 and above	hot	*Bereha*

The main feature of rainfall in the area is seasonal, poor distribution and variable from year to year. Rainfall distribution in the catchment is bimodal, followed by the long and short rainy season that occurs in July-September and March and April respectively. The rest of the months are generally low to dry. The mean monthly temperatures in Sununta catchment vary from 22.4^{o}C in December to about 28.1^{o}C in June. The study area also has a monthly maximum and minimum sunshine of 10 hour in December and January and 6 hours in July respectively.

Detail account of the different climatic elements is given on chapter three that deals with model input.

2.4 Soil texture

Soil texture is a soil property that describes the relative proportion of sand, silt and clay particles and indicate the general nature of soil physical properties (Brady and Well, 2002 cited on Belete Birhanu et al., 2013). The soil texture map is modified from GIS-based hydrological zones and soil geo-database of Ethiopia. (Belete Berhanu et al.,2013). **(Figure 2.3)**

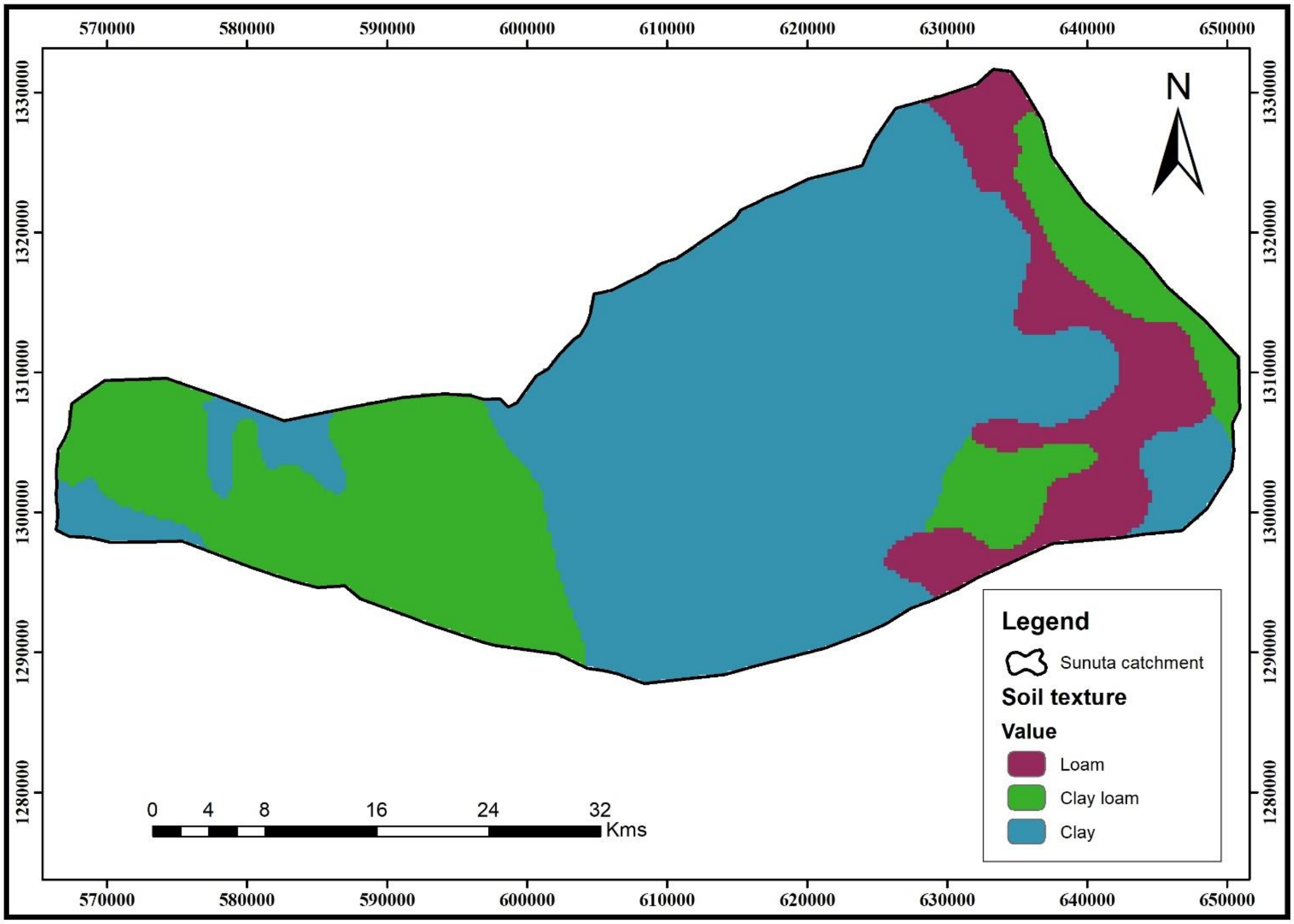

Figure 2.3: -Soil textural map GIS-based hydrological zones and soil geo-database of Ethiopia

2.5 Land use and cover

Land use is essential in the hydrological and groundwater studies since it is a prominent factor influencing the recharge. The Land use identified in the study area was grassland, cropland, shrubs cover areas and bare areas. The first three were the dominant land uses in the catchment. **(Figure 2.4)**

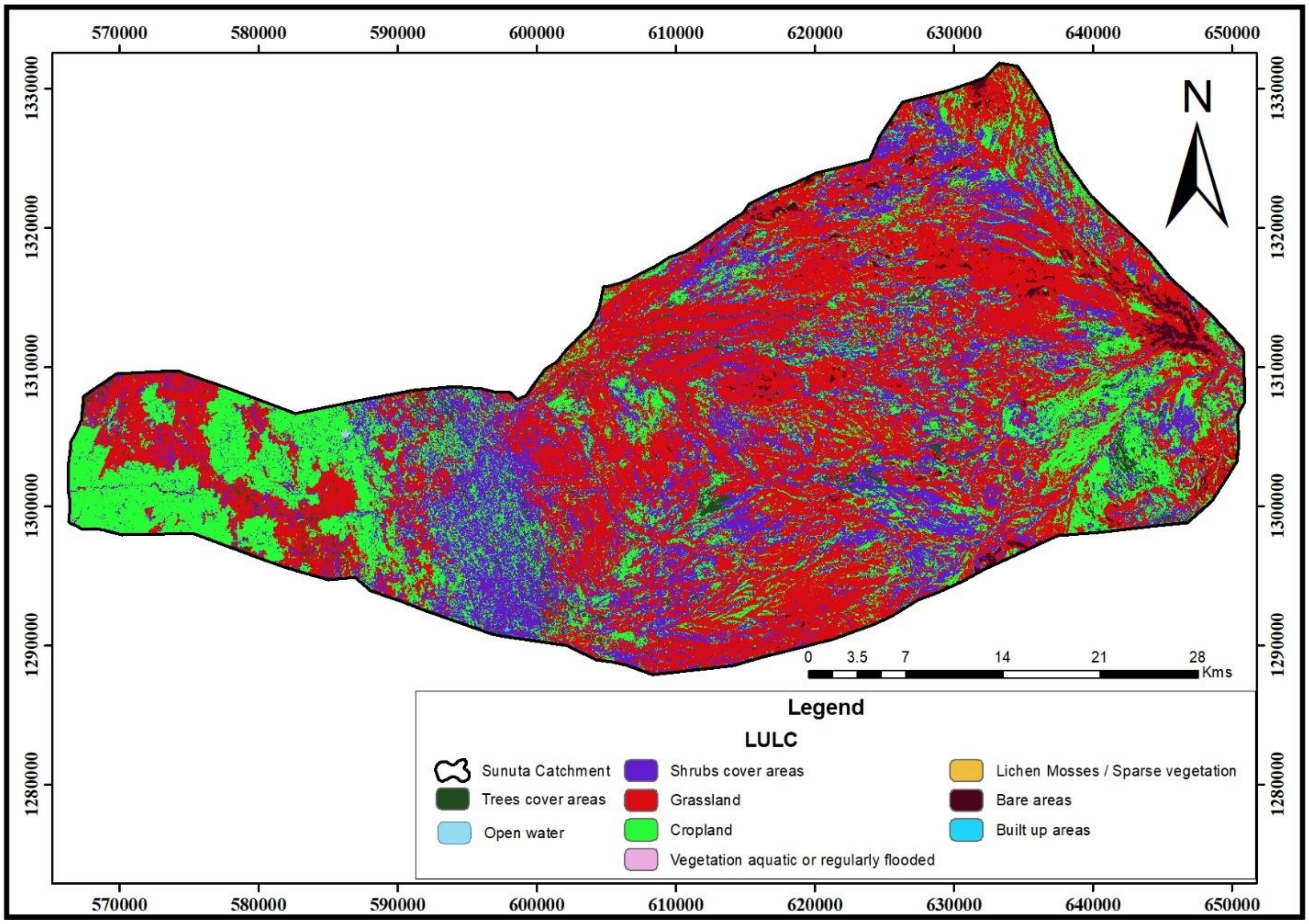

Figure 2.4:-Land use and Landcover map

2.6 Regional Geology

The Afar Depression is a part of lowland plains split by fault blocks and dotted with shield volcanoes. It's bordered to the west by the Ethiopian Plateau and escarpment, to the northeast by the Danakil block, to the southeast by the Ali-Sabieh block and to the south by the Somalian Plateau and escarpment. **(UNICEF-UNESCO,2013).**

The oldest basement rocks of the Afar region is a series of volcanic, meta-igneous and meta-sedimentary rocks found at the edge of the Afar Depression, which form part of the Arabian-Nubian Shield. They were accreted when east and west Gondwana collided during the Pan African orogeny in the late Proterozoic, creating a series of north-south to ENE-WSW trending structures and northwest-southeast trending shear zones (e.g. Vail, 1985; Stern 94; Abdelsalem & Stern 96 cited on **UNICEF-UNESCO,2013)**.

The most extensive volcanic sequence covering about two thirds of the Afar Depression is the Pliocene-Pleistocene Afar stratoid series. Individual basalt flows are between 1 and 6m thick and the whole Series is up to 1500m thick. It lies non-conformably on the Dalha Series indicating a period of erosion and lowered magmatic activity between the two series (Varet, 1978).

2.7 Hydrogeology

2.7.1 General

The occurrence of groundwater is mainly influenced by the geology, geomorphology, tectonics and climate of the country. The variability of these factors in Ethiopia strongly influences the quantity and quality of the groundwater in different parts of the country. **(Tamiru Alemayehu,2006).**

The western Afar Margin forms the water divide between the eastern Awash river basin and the western Abay and Tekeze basins. West to east flowing tributaries of the Awash River starts from this geomorphologic feature **(GSE, 2016).**

2.7.2 Hydrogeology of Sunuta catchment

Sunuta Catchment is located south of Alewuha catchment that starts from 2539 m a.m.s.l high land area of Merto and Wetek area mountainous ranges. Sirinka perennial streams merge at about 2 km north east of sirinka town and drains to the east. The stream cuts at Werelalo and Chira- ber ridges drains Sirinka and Weydo plain through deeply dissected gorge and finally flows to Afar Region Uwa river. Uwa stream is a tributary of Awash River Basin. Similar to other adjacent streams. The stream transport large volume of sediments comprising boulders, cobles, pebbles, sand, silt and clays from high land area and deposits mainly at Sirinka and Weydo and Sunuta plain. There are Guagur Sibilka and Wembede area along the stream downstream of Sirinka & Weydo plain and south of Hara closed sub-basin that looks prospective for groundwater circulation and storage but because of highly rugged terrain and limited recharge area, high yield well could not be expected there.

The groundwater source for the sunuta catchments are recharged through perennial streams, runoff during rainy season, groundwater inflow from upper highlands of Sirinka, Hara and from direct rainfall. The groundwater from the catchment is discharged through base flow (groundwater outflow) and well abstraction for irrigation and water supply purpose.

In the sunuta catchment there are 69 inventoried deep and shallow wells which has used by the community for water supply and irrigation purpose.

The wells are drilled by different organization (Afar water resources bureau, Ministry of Agriculture and Ministry of water, Energy and Electricity) for different purposes such as water supply, irrigation and test wells. Most of the wells are found on sunuta plain which is drilled for irrigation purpose. The depth of the borehole's ranges from 80 to 450m. The water level ranges from 5.81m to 79.54m deep. All wells found in Sunuta plain have a static water level of deeper than 40m.

The test well (SWTW1) drilled around Sirinka town to the depth 242 m has 72 m alluvial deposits thickness and the underlain basalt is fractured to be potential aquifer. The test well has 52.7m SWL and 19.5 lit/sec yield with 71 m drawdown in 72 hours pumping.

2.7.3 Aquifer Properties

The study area is characterized by highly rugged topography in the highlands and Afar rift escarpments which is dominantly covered by volcanic rocks, and the rift floor of the sunuta plain are covered by unconsolidated sediments and small ridges of volcanic rocks within the plain. The western parts of the study area also have alluvial sediments in Sirinka, and Woydo area underlying by basaltic rock, which is the major water bearing formation in this part of the sub-basin **(Gobeze Begashaw and Tafesse NT, 2017)**

Hydrogeologically, the geologic formation of the study area is categorized into three different parts: - intergranular porosity and permeability of sediments, weathered and fractured volcanic rocks and extensive aquifer with intergranular porosity and permeability and aquifer with fracture porosity and permeability **(Gobeze Begashaw and Tafesse NT, 2017).**

According to the borehole lithological logging profiles **(Figure 4.10;11;12)**, the thickness of the Quaternary deposits, varies from 40 m in the Western part of the plain to 200 m in the central part of the plain. Moreover, the thickness of the alluvial deposits is increasing from the western part to the eastern part of the plain of the study area. High thickness is found at central part of the Sunuta plain. The alluvial deposit also found interbedded with the volcanic rocks. Numerous lava flows overlap and the flows are separated by alluvial deposits. The alluvial deposits and volcanic rocks thickness distribution of the catchment is shown in **(Figure 4.10;11;12)**.

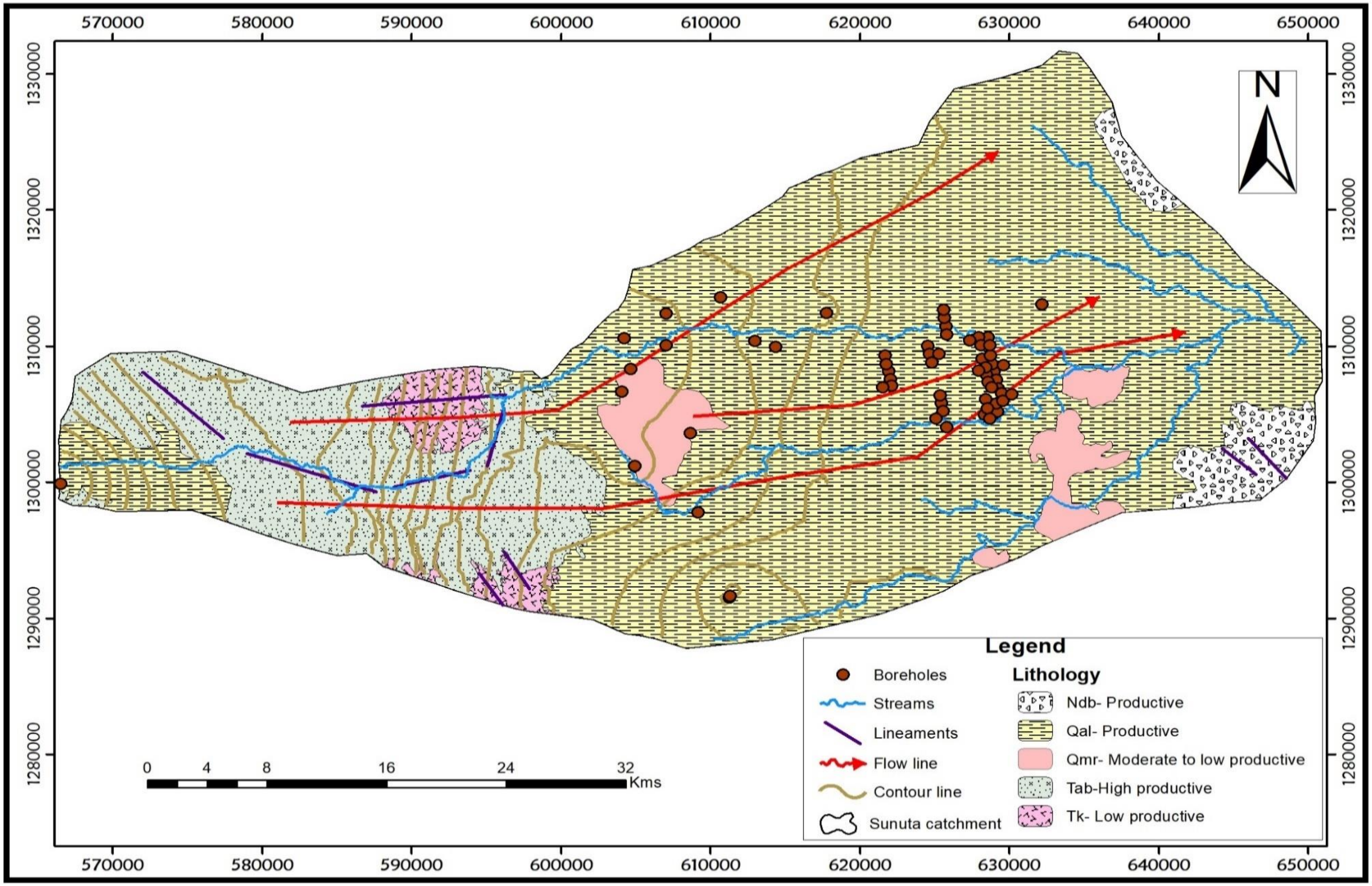

Figure 2.5: -Hydrogeological map of the study area

2.7.4 Hydraulic properties

Transmissivity

The transmissivity is a measure of how much water can be transmitted horizontally, such as to a pumping well. An aquifer may consist of *n* - soil layers (Discoll, 1986). The transmissivity for horizontal flow (T) of the soil layer with a saturated thickness (D) and horizontal hydraulic conductivity (k) is the equation T= Kb

Transmissivity is directly proportional to horizontal hydraulic conductivity (k) and thickness (D). Expressing (k) in m/day and (D) in m, the transmissivity (T) is found in units m2/day. (**MARIOS C KIRLAS, 2015)**

The Existing pumping test data of 25 wells were obtained from Afar Water Works Construction Enterprise. The raw data of pumping test (constant and recovery test) are re analyzed using Aquitest 3.5 software. The analysis of the pumping test result of the wells represent the whole catchment.

The hydraulic conductivity and transmissivity distribution of the area ranges between 4-53m/day and 43.7- 4824m^2/day respectively. the highest value (2799-4824m^2/day) is found at south eastern part of the study area which covers small part in the study area. The hydraulic conductivity and Transmissivity map are shown on chapter four in model input parameters. (Figure 4.13;14)

2.7.5 Water Uses

In the study area (especially in Sunuta plain) the water is used for irrigation and domestic purpose. The current total abstraction rate of the boreholes is 44987.78 m^3/day. from this 35,640.02 m^3/day is used for irrigation purpose and 9,347.76 m^3/day is used for water supply purposes.

2.7.6 Hydro geochemistry

According to previous borehole hydrogeochemical analysis, Sunuta catchment has a good water quality which is within the WHO standard for Agricultural and domestic uses.

The Electrical conductivity (EC) and Total dissolved solids (TDS) value of the study area ranges between 959 µs/cm to 1295 µs/cm and 425mg/l to 863mg/l respectively. The average value of EC and TDS of the area are 959 µs/cm and 662mg/l respectively. **(Figure 2:6; 2:7)**

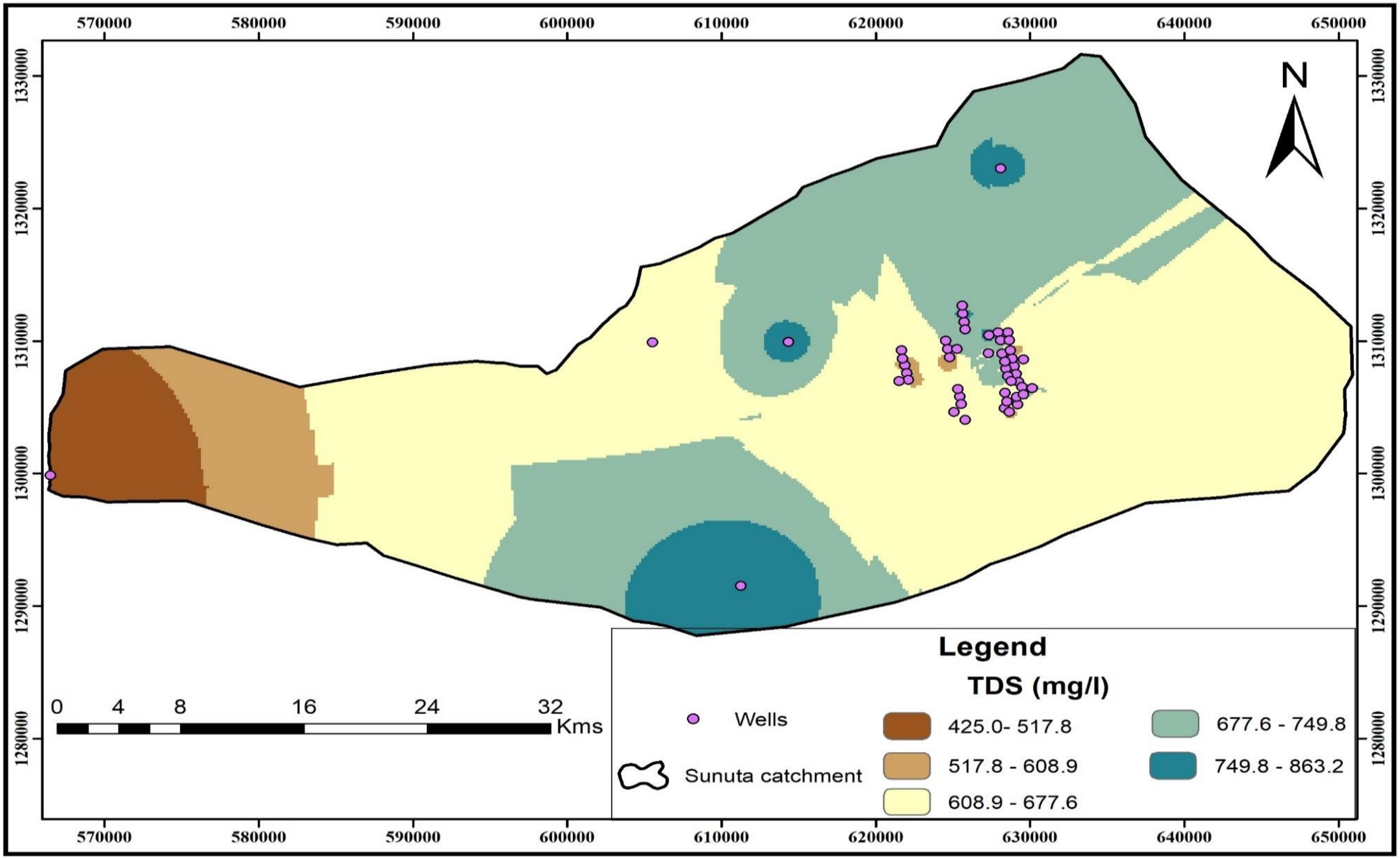

Figure 2.6: - TDS distribution map

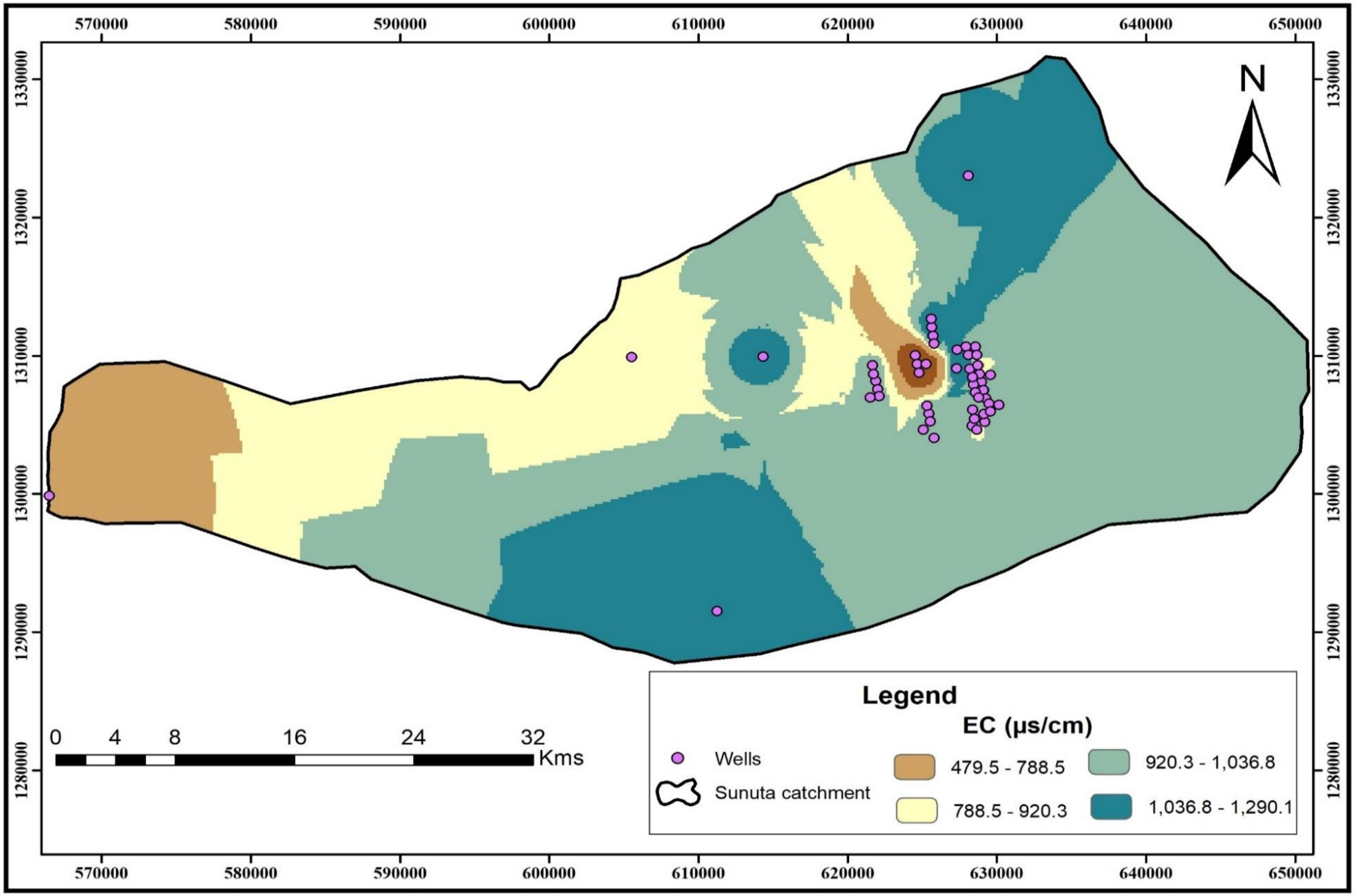

Figure 2.7: - EC distribution map

Chapter Three

3. Geology and Structures

3.1 Stratigraphic Outline of the Afar Depression

Stratigraphic outline of the Afar depression is described as follows cited on UNICEF-UNESCO,2013

Precambrian Basement Rocks

The Pre-Cambrian to late Palaeozoic basement rocks cover the Atsbi horst and the lower parts of the Danakil horst, both horsts bounding the northern Afar depression. from west and east, respectively. The dominant rock units are phyllite rocks of the Tsaliet metavolcanics unit comprising of phyllites partly intercalated with limestones and dolomites (**Pc**); light coloured quartizitic phyllites (**Pq**); greenish, partly conglomeratic phyllites and schists (**Ps**), and largely undifferentiated phyllites (**Pp**).

Mesozoic Sedimentary Formations

The Mesozoic Sedimentary Formations (Adigrat Sandstone, Antalo Limestone, Agula Shale and Ambaradam Formations) are dominantly exposed on the western margins of the Afar depression (the Tigrai plateau) and higher parts of the Danakil horst.

Tertiary Volcanic Units

The Afar depression is dominantly covered by post-Tertiary volcanic sequences (Pliocene-Pleistocene). However, the western margin of the Afar depression exposes some units of the Ashenge and Aiba Basalts (***E2as/ai***), which are alkaline and transitional basaltic flows and associated tuffs (Eocene-Oligocene), and flood basalts with rare basic tuffs (Oligocene), respectively.

Pliocene – Pleistocene Volcanic Units

The Afar Stratoid Series (4-1 Ma) covers two thirds of the Afar depression. Dominant parts of central and southern Afar are covered by these extensive, up to 1500 m thick sequence, with individual basalt flows ranging in thickness between 1 and 6 m.

Pliocene Sedimentary Units

The Danakil depression on either side of the Erta'Ale volcanic range and the Dallol depression, close to the eastern foot of the Atsbi horst and western foot of the Danakil horst, is underlain by relatively thick sedimentary rocks collectively known as the "Danakil Formation". These units are incised and exposed by numerous transversal (E-W and W-E) streams and wadis.

Quaternary Sedimentary Units

Overlying the Pliocene sedimentary units or directly over the volcanic units, numerous beds of Quaternary sediments are exposed in the Danakil depression and in the wide structural grabens and plains of central and southern Afar. The two older units, "Zariga Formation" and "Afrera Formation", are exclusively exposed in the northern part of the Danakil depression overlying the Pliocene sediments, while the recent Quaternary deposits are widely distributed in the whole Afar depression. (**UNICEF-UNESCO,2013)**

Regional structures

The Afar Depression is separated from the Ethiopian Plateau by the Ethiopian Escarpment, N–S trending marginal basins and hilly terrain of faulted blocks forming the western margin of the Afar Depression

The western margin was formed by down-warping of the Afar Depression and subsequent faulting and rift-ward tilting of faulted blocks (Zanettin and Justin-Visentin, 1975 cited on ….

The faulted blocks are rift-ward tilted and eroded by dense drainage networks that resulted in the development of a terrain dominated by remnant hogback-like structures.

Elevation drops from 3000–2500 m at the ridgeline of the Ethiopian Escarpment to 800–100 m in the Afar Depression lowlands (Mohr, 1983). Marginal basins are developed at the foot of the Ethiopian Escarpment.

3.2 Local Geology

Ashange basalt

It is one of tertiary volcanic units which are alkaline and transitional basaltic flows and associated tuffs (Eocene-Oligocene). It covers the Afar marginal rift escarpments. The units are exposed at the western part of the study area

Rhyolite

The Rhyolite /silicic centers/ are exposed in different parts of the study area forming ridges and domes. The rhyolite at all localities have characterized by high degree of deformation exhibiting faults, folds, fractures, joints and foliations. Its color varies from dark brown to pink alternatively depending on the degree of weathering. Compositionally it contains quartz, feldspar, plagioclase, and muscovite that could be easily seen by hand specimen

Fluvial deposits

It has a grain size of clay, silt, sand and gravel of fluvial or lacustrine origin. The fluvial sediments are very widely distributed in the study area with variable thickness, and cover most of the low-lying plains and structural grabens of Sunuta plain

Dalha formation

It has a basalt intercalated with rhyolite and ignimbrite composition. The formation is exposed in the eastern part of the study area. **(Figure 3.1).**

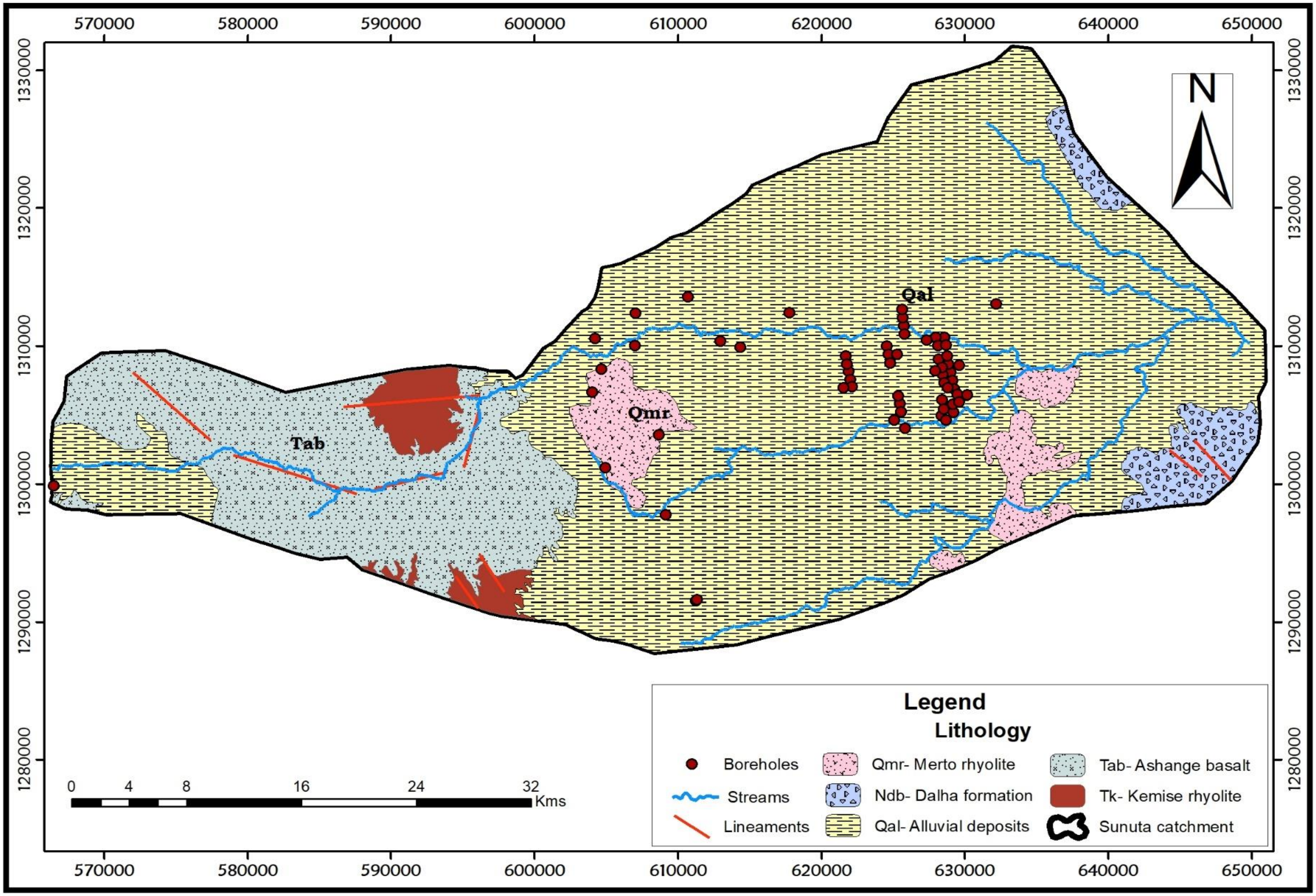

Figure 3.1: -Geological map of the study area

3.3 Geological structures

The geological structures in the study area are two related structural features: - The afar rift escarpments and the depression that is formed by down-warping of the Afar Depression and subsequent faulting and rift-ward tilting of faulted blocks. The structures are exposed mostly on the rift escarpments. The major structures of the study area are fractures, joints, lineaments and faults.

The length of fractures, lineaments and faults varies from 2-6 km with different trends. Their major trends of these structures are N-S, E-W, NW-SE and NE-SW. The dominant trend in the western parts (around Sirinka) of the study area is NNW-SSE direction. (Gobeze Begashaw and Tafesse NT, 2017).

Chapter Four

4. Model input Parameters and Conceptual Model development

4.1 Introduction

Before Numerical groundwater modeling, conceptual model should develop first. The main components of a conceptual model include boundaries, hydrostratigraphy and estimates of hydrogeological parameters, general directions of groundwater flow and sources and sinks of water and a field-based groundwater budget. (Anderson and Woessner, 2002).

4.2 Groundwater Recharge estimation

Ground-water recharge is a fundamental component in the water balance of any catchment. However, because it is nearly impossible to measure the recharge directly, numerous methods, ranging widely in complexity and cost, have been used to estimate recharge (Lerner and others, 1990; Scanlon and others, 2002 cited on **Saiful Islam et al., 2016**).

Selection of appropriate method depends on available data, local geographic and topographic conditions, spatial and temporal scale required and reliability of results obtained by different methods (**Saiful Islam et al., 2016).**

The assessment of spatial and temporal distribution of groundwater recharge is required as an input to develop the groundwater flow model in the study area for more accurate simulations of different management scenarios. (**Ali Salem et al., 2019).**

The methods selected to estimate the recharge of the Sunuta catchment was WetSpass model method and to know the lateral groundwater flow within certain cross-sectional area was Darcy's approach method.

4.2.1 WetSpass Modeling

WetSpass modeling is GIS integrated model for water balance evaluation which has the ability to simulate spatially distributed recharge, surface runoff, and evapotranspiration for seasonally averaged conditions. The models provide the output in the form of spatially distributed recharge, runoff and actual evapotranspiration raster maps. It requires the basic input data prepared in grid-maps using the ARCGIS tool. It comprises monthly climatological data (rainfall, potential evapotranspiration, temperature, windspeed), distributed land use, soil texture map, groundwater depth, topography, elevation and slope. (Khodayar Abdollahi et.al, 2017).

4.2.1.1 WetSpass Modeling inputs

Meteorological data analysis

a) Rainfall

Rainfall records of eight stations were selected to describe the rainfall regime of the sunuta catchment. Sirinka, Hara and Woldia stations are found in western highlands. Wa'ama, Chifra, Awra, Kelewan stations are found in rift floor and aligned in North-South direction of the study area. Mile station is found to the east of the study area. Except Sirinka, Hara and Ewa station all of the stations are found outside the study area. Twenty-five years rainfall records starting from 1991-2015 were collected to have adequate data for analysis purpose.

Table 4-1:-Mean monthly rainfall distribution in mm from (1991-2015) years

Stations	Month (mm)												Annual (mm/year)
	1	2	3	4	5	6	7	8	9	10	11	12	
Hara	19.8	22.3	54.9	59.4	61.5	17.4	169.0	262.3	88.9	44.8	20.5	14.3	835.0
Mile (AVA)	5.4	9.5	32.3	45.6	11.4	4.6	63.7	105.5	25.7	14.9	1.6	7.0	327.1
Kelewan	14.7	0.0	81.1	24.3	2.1	14.2	197.7	154.1	88.2	17.2	26.2	0.0	619.6
Sirinka	33.0	34.9	81.6	102.8	55.7	30.2	240.8	277.2	91.9	58.4	40.3	35.9	1082.7
Waama	6.4	13.6	7.8	30.8	21.5	7.3	106.7	237.5	49.9	4.6	0.0	1.1	487.3
Woldia	11.3	13.5	69.3	105.9	48.1	26.0	216.5	282.6	110.7	50.6	20.1	16.1	970.8
Awura	0.0	0.0	2.5	61.2	48.0	1.8	9.9	78.6	25.0	21.8	10.8	21.9	281.6
Chifra	21.2	8.8	34.2	51.7	35.1	42.1	103.1	119.7	22.3	19.1	7.0	0.0	463.9

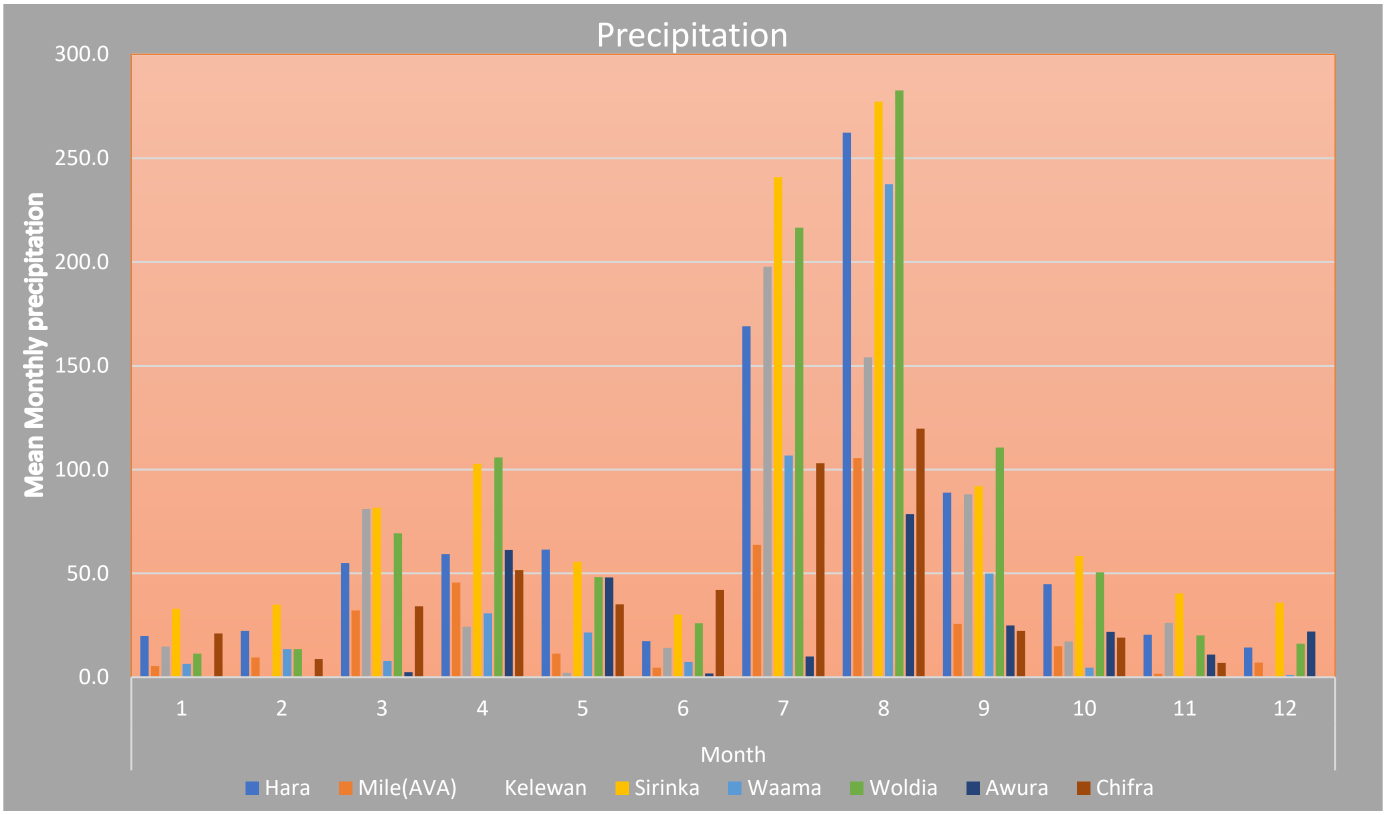

Figure 4.1:- Mean monthly rainfall of the stations in mm/month

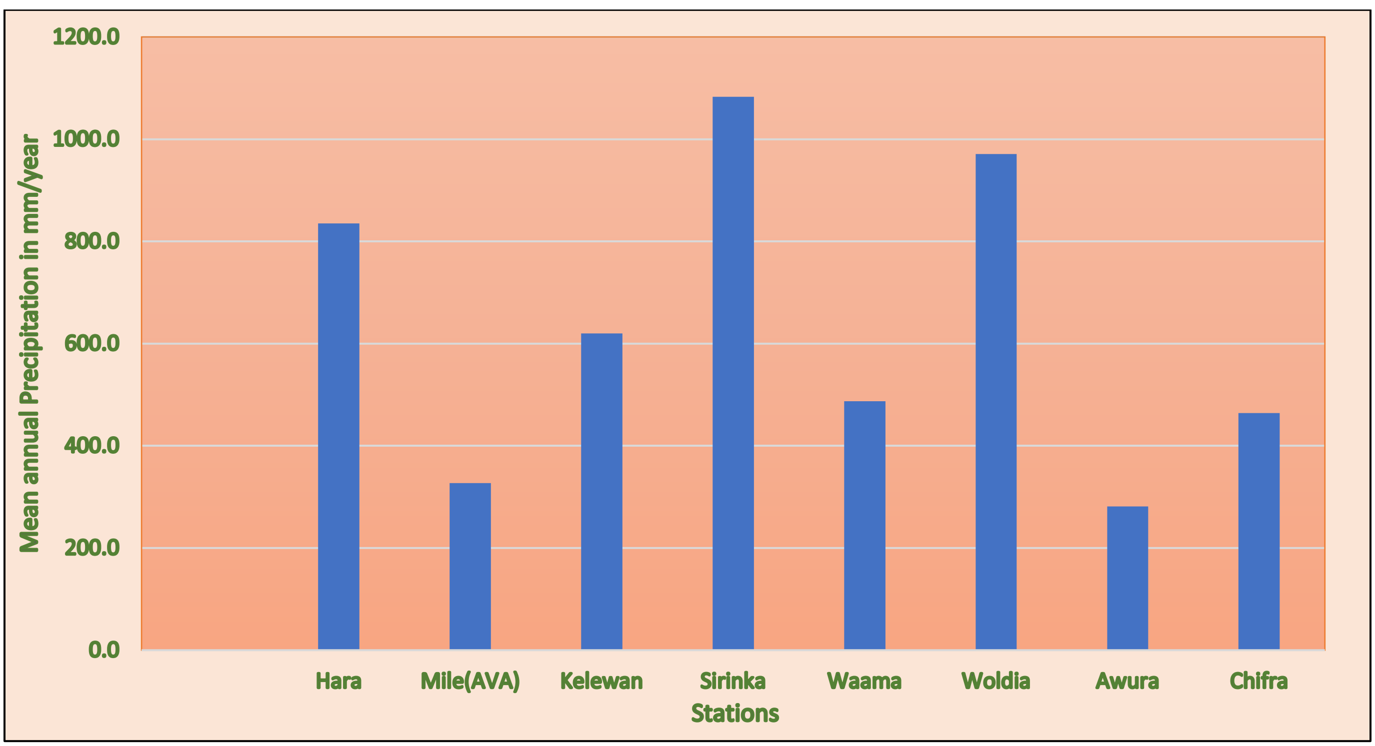

Figure 4.2:- Mean annual rainfalls of the stations in mm/year

b) Temperature

Four stations are selected to analyze the temperature. Mean Minimum temperature of the four stations was 17.3^{0}c and mean maximum temperature was 27.8^{0}c.

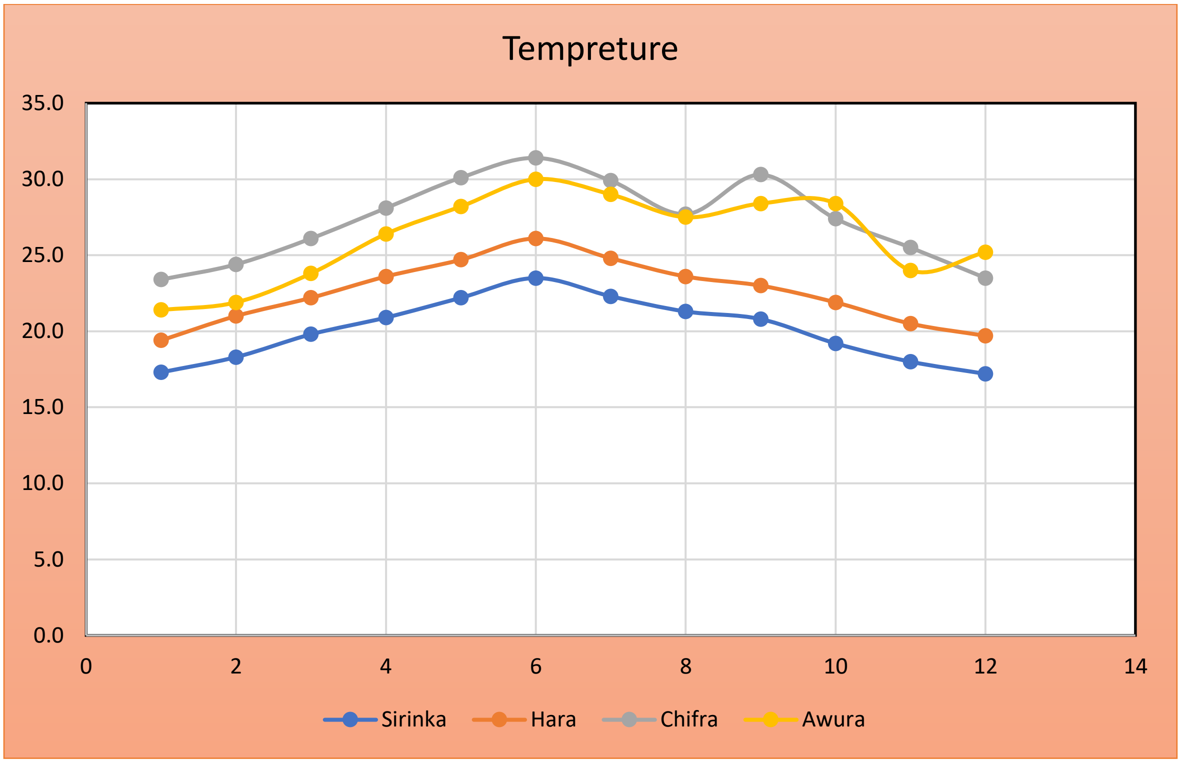

Figure 4.3:- Mean monthly temperature (°C) of Sirinka, Hara, Chifra and Awura stations

c) Wind Speed

Wind direction refers to the direction from which the wind is blowing. It is expressed by its direction and velocity. At Sirinka station maximum and minimum recorded value is 1.5 and 0.9m/s respectively and at Chifra station maximum and minimum recorded value is 1.3 and 2.7m/s respectively

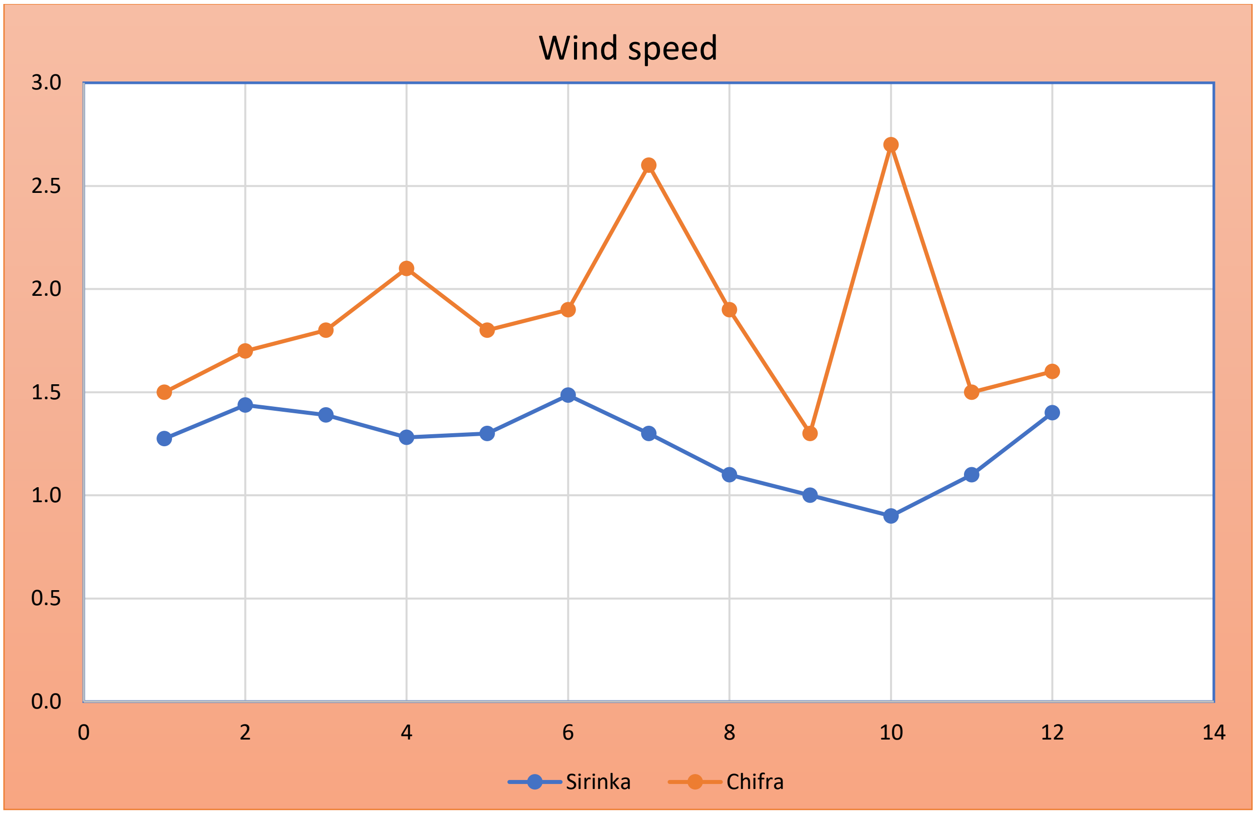

Figure 4.4:- Monthly windspeed of Sirinka and Chifra stations

d) Potential Evapotranspiration (PET)

Evapotranspiration is the process in which water is returned back to the atmosphere by a combination of evaporation and transpiration. Potential evapotranspiration is the water loss that will occur under given climatic condition without deficiency of water supply whereas actual evapotranspiration is the amount of water that actually returns to the atmosphere depending on the availability of water. For this study, **Thorenthwaite** equation is used to estimate potential evapotranspiration from gathered weather data. Thornthwaite take into consideration the average monthly temperature and the thermal index.

Accordingly, the formula used to calculate potential evapotranspiration are: -

$$Et = 1.6b\left[\frac{10T_a}{I}\right]^a$$

Where

- Et = Potential evapotranspiration in cm/month
- Ta = Mean monthly air temperature in (^{0}C)
- I = annual heat index
- b. latitude correction

$$I = \sum_{i=1}^{12}\left[\frac{Ta_i}{5}\right]^{1.514}$$

$$a = 0.49 + 0.0179I - 0.0000771I^2 + 0.000000675I^3$$

Table 4-2:-Monthly potential evapotranspiration calculated using Thornthwaite method

Stations	Element	Month												Annual (mm/year)
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
Sirinka	PET (cm)	5.2	5.9	7.2	8.3	9.7	11.1	9.8	8.8	8.2	6.7	5.7	5.1	
	PET (mm)	51.8	59.3	71.9	83.4	97.0	110.9	98.0	87.8	81.6	66.5	56.5	50.7	915.5
Hara	PET (cm)	5.8	7.2	8.5	10.3	11.9	13.9	12.0	10.4	9.5	8.1	6.7	5.9	
	PET (mm)	57.6	71.9	85.1	103.2	118.8	138.8	120.2	104.3	95.3	81.2	66.7	59.3	1102.5
Chifra	PET (cm)	7.6	9.2	12.3	17.1	23.1	27.7	22.5	16.3	22.9	14.8	10.8	7.7	
	PET (mm)	76.0	91.7	123.1	171.2	230.8	276.6	224.9	163.3	229.4	148.1	108.2	76.9	1920.2
Awura	PET (cm)	5.9	6.5	9.0	13.6	17.7	22.5	19.7	16.0	17.5	17.0	9.0	10.6	
	PET (mm)	59.0	65.2	90.5	136.4	177.3	224.6	196.7	160.0	175.4	169.9	89.7	105.8	1650.5

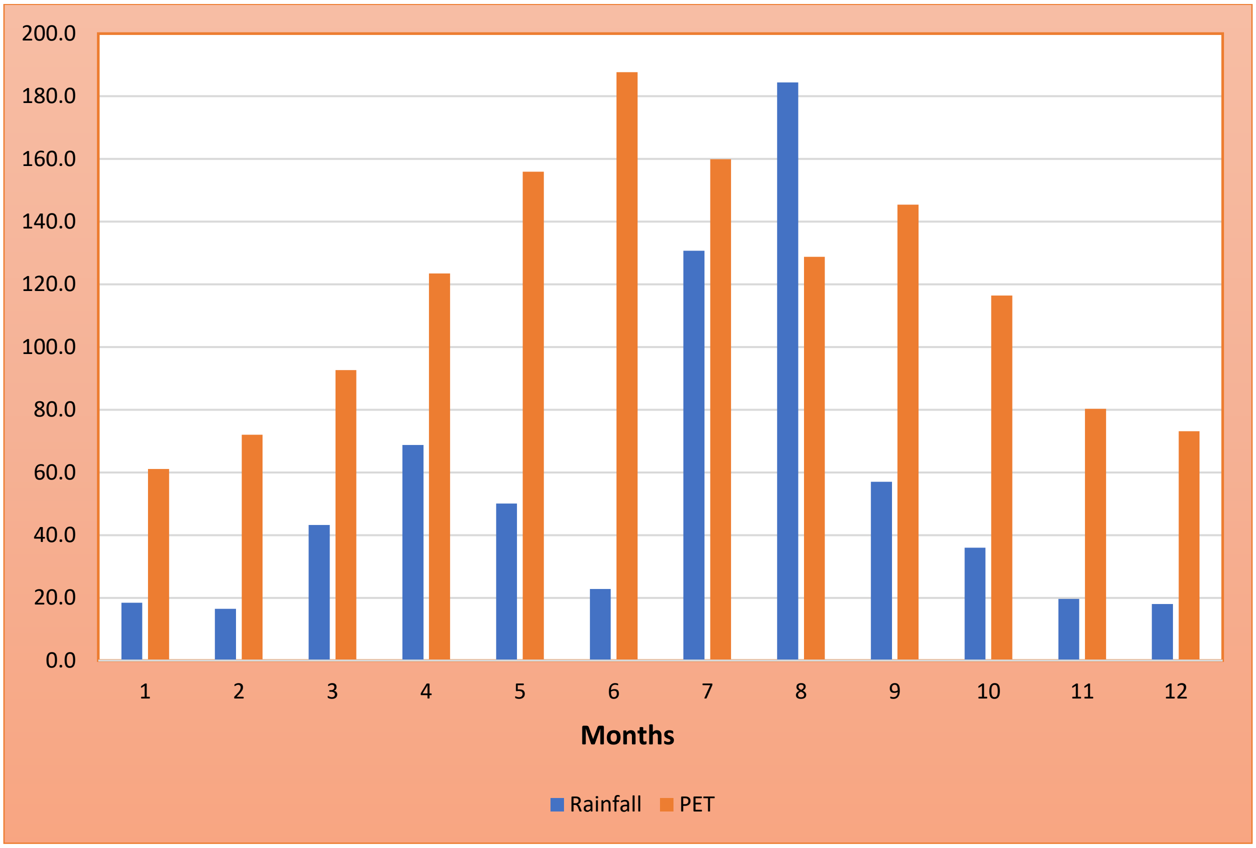

Figure 4.5:- Comparison between mean Monthly Rainfall and potential evapotranspiration

e) Elevation

The elevation of the study area ranges from 2539m at the highlands and western escarpments to 734m at the rift floor of Afar depression. Most of the study area elevation falls below 1000m and it have flat and gentle slope. The elevation map is prepared and exported in ASCII format to make readable to the WetSpass model. **(Figure 4.6)**

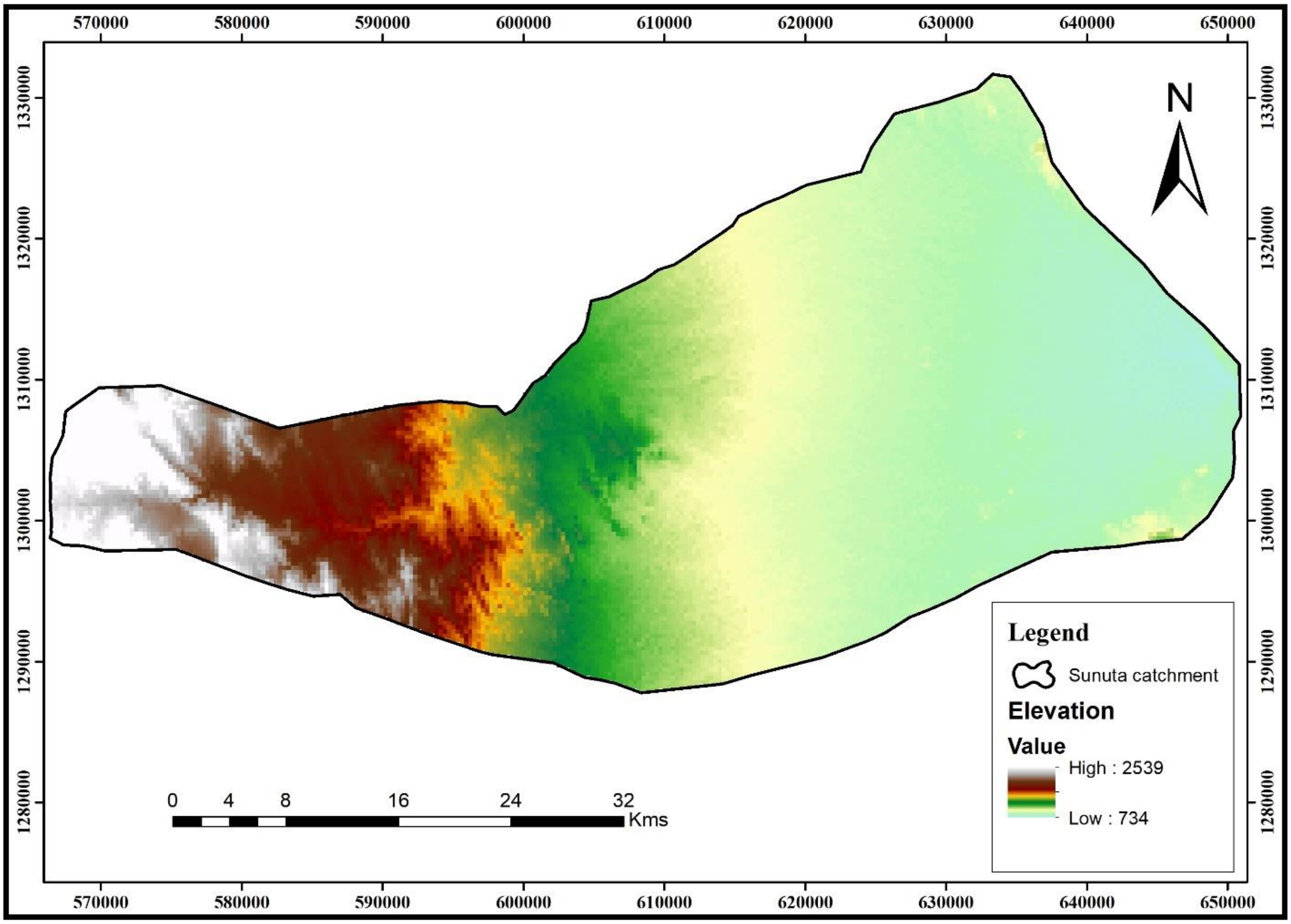

Figure 4.6:- Elevation map of the study area

f) Slope

Slope offers information about the catchment topography. Rains that fall in steep mountainous areas will reach the primary river in the drainage basin faster than flat or slightly sloping areas. The maximum slope of the study area is **34.7^0** and the minimum slope is **0^0** and the mean is **2.4^0.** Most of the study areas is flat and it covers the rift floor **.** The flat plain and very gently sloping (slope ranging from $0\text{-}2^0$) covers 72% of the total study area..**Figure 4.7**

g) Soil texture

The soil texture distribution in the study area is subdivided into three basic texture such as clay, clay loam and loam. The dominant soil texture coverage in the study area from high to low is clay, clay loam and loam . It covers 60%, 28.5% and 11.5% respectively. The clay texture covers most of the sunuta plain and clay loam covers most of the western escarpments.**Figure 4.7**

h) Landuse

Land use is one of the input parameters for the WetSpass model to estimate the recharge of the study area. The land use data is obtained from Satellite image (Sentinel,2016) and modified based on the field observation. The Land use identified in the study area was grassland, cropland, shrubs cover areas and bare areas. The first three were the dominant land uses in the catchment. The map is prepared and exported in ASCII format and applied to the WetSpass model. **Figure 4.7.**

i) Depth to groundwater level

Depth to groundwater level map is one of the input parameters for WetSpass model to estimate the recharge of the study area. It is one of the vital hydraulic parameters that should be collected during inventory of both office and field survey. The static water levels are obtained from existing inventoried wells construction completion reports of archives of different organizations. However, for model calibration purpose the water level is measured directly from non-pumping borehole and boreholes having operational observation pipe that allows insertion of deep meter.

Based on the inventoried boreholes water level data, depth to groundwater map is prepared and exported in ASCII format and applied to WetSpass model. **Figure 4.7**

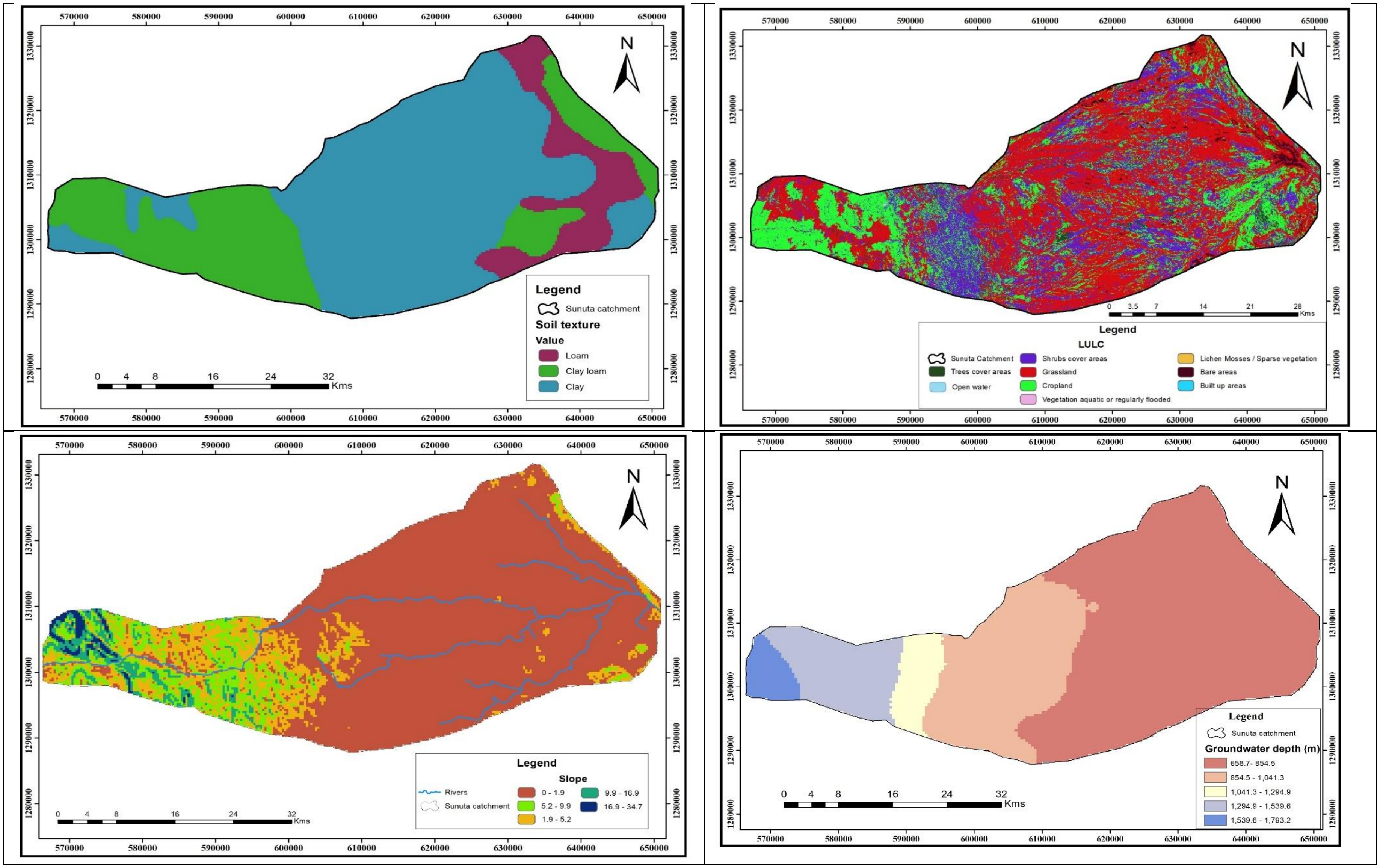

Figure 4.7: - Spatial distribution of Soil, land use/cover, Slope and groundwater level

4.2.1.2 WetSpass Modeling outputs

Actual Evapotranspiration

The model calculates evapotranspiration per grid cell by summing up actual evapotranspiration from the vegetated area, open water, bare soil and impervious surface area fractions. The estimated annual Actual evapotranspiration of the study area is 675mm/year which accounts 58.9% of the total annual average precipitation. **(Figure 4.8)**

Surface runoff

The surface runoff of the study area shows variation with land-use, soil type, slope, topography variation, precipitation and the other meteorological parameters. The estimated annual Actual evapotranspiration of the study area is 194.6mm/year which accounts 30.5% of the total annual average precipitation. **(Figure 4.8)**

Groundwater recharge

Groundwater recharge is a hydrological process by which infiltrated water from precipitation moves downward into the saturated zone of an aquifer and replenishes groundwater ((Wu et al. 1996) cited on Khodayar Abdollahi et.al, 2017). The estimated annual groundwater recharge of the study area is 61.1mm/year which accounts 9.6% of the total annual average precipitation. **(Figure 4.8)**

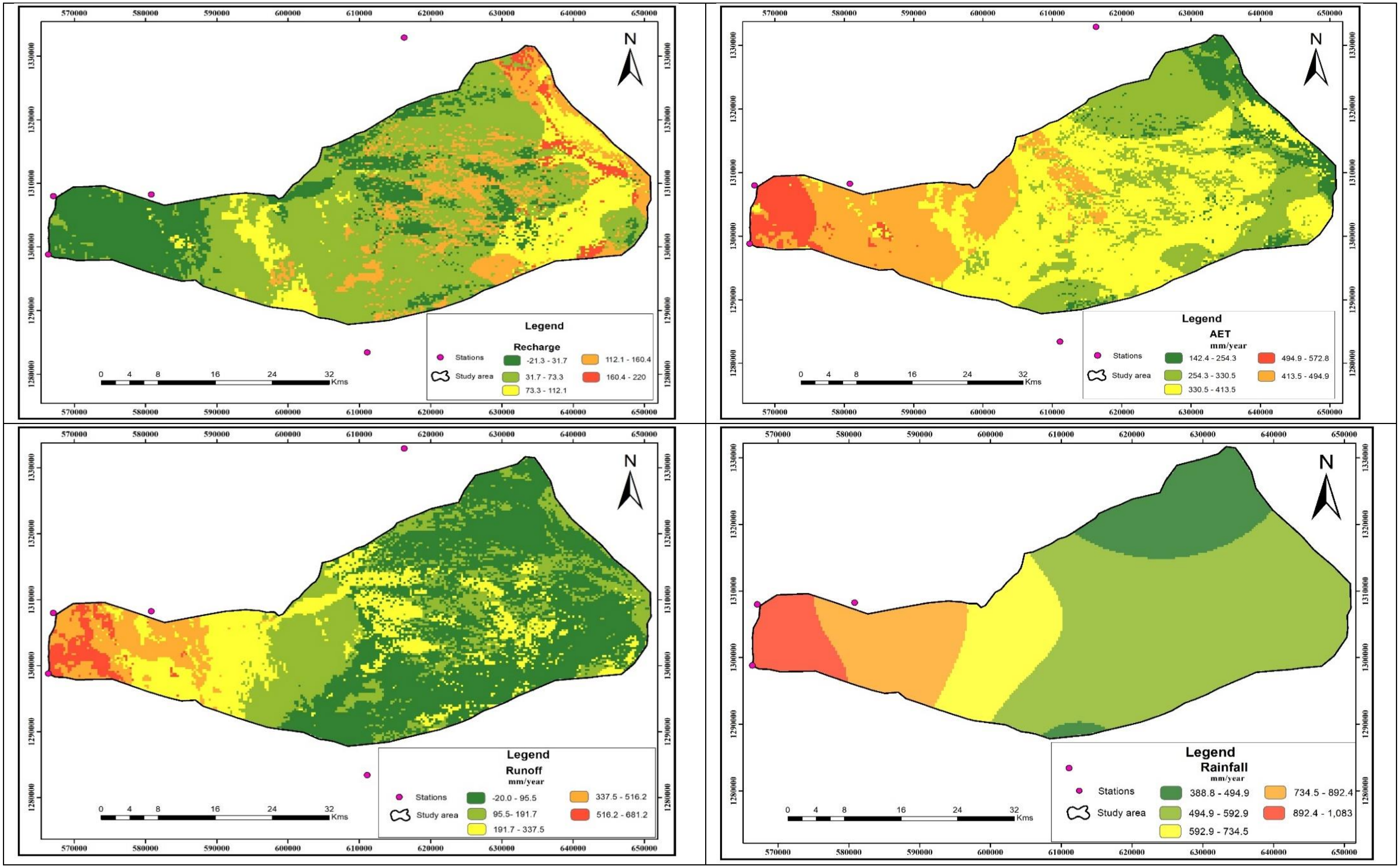

Figure 4.8:- Spatial distribution of simulated mean annual water balance component and spatial average annual rainfall distribution

Table 4-3:-Comparison between WetSpass model result and rainfall data

Time Step	AET (mm/year)	Runoff (mm/year)	Recharge (mm/year)
1	7.2	2.7	1.7
2	5.6	1.7	1.9
3	27.6	8.1	4.9
4	40.8	9.8	6.4
5	24.1	5.6	9.1
6	7.0	2.2	10.3
7	83.1	53.0	6.7
8	108.6	87.9	1.2
9	40.7	10.7	9.5
10	14.0	9.3	5.5
11	8.3	3.0	2.7
12	8.4	0.6	1.2
Total	**375.3**	**194.6**	**61.1**
WetSpass model output= 631.0 mm/year			
Rainfall input to the Model= 637.3mm/year			
AET= 58.9%			
Runoff = 30.5%			
Recharge= 9.6%			
Error= 0.98%			

Comparison of groundwater recharge estimated result using WetSpass model with groundwater recharge determined by different authors are determined as follows: -

Table 4-4:- Comparison of current estimated recharge with the previous researcher on nearby catchment

S. No	Researchers	Year	Estimated recharge(mm/year)	Applied methods	Study area
1	Bereket	2018	51.44	WBM	Hara basin
2	Nata Tadesse et al.	2015	58.3	WBM	Raya valley
			51.8	WBM	Kobo
3	This Study	2020	61.1	WetSpass model	Sunuta catchment

4.2.2 Darcy's Approach method

Darcy's law states that discharges in an aquifer system can be calculated if both the head gradients and hydraulic conductivities are known. The method has been applied in many studies under arid and semiarid conditions (**Saiful Islam et al., 2016).**

If flow under field conditions is steady and driven by gravity alone, then, according to Darcy's Law, downward percolation rate will be numerically equal to the hydraulic conductivity of the material at the measured in-situ water content. The major advantage is that all quantities involved on the Darcy's equation are measurable. A major limitation is that the hydraulic conductivity of a soil and rock is poorly known due to heterogeneity and variation with saturation (**Gabriel I. O. and Donatus M. O., 2010).**

The dynamic groundwater resources of subsurface seepage from the volcanic aquifer of the western escarpment and plateau and alluvial deposits in Sunuta plain are estimated by the method. The lateral groundwater flow in certain cross-sectional area are estimated using Darcy's law in the saturated zone according to the following equation:

$$Q = T * I * L * 365$$

Where**, Q** - Average annual groundwater recharge in Mm^3

I - Hydraulic gradient

T - Transmissivity in m^2/day

L - Width of flow at right angle to the direction of flows in meters

Calculating the weighted average parameters of transmissivity and flow gradient values from transmissivity maps and hydraulic head maps respectively. And applying the above formula for the Sunuta catchment at the rift escarpment and rift floor. The estimated value from Darcy's approach method is tabulated below

Table 4-5:- Darcy approach discharge estimation of Sunuta catchment

Location	**Flow width (m)**	**Flow length (m)**	**Difference in hydraulic head along the flow line(m)**	**Hydraulic gradient**	**Average transmissivity (m2/day)**	**Discharge in m³/year**
Rift escarpments	14015	35000	828	0.024	435	52,642,622
Rift floor	30158	49000	193	0.004	1028	44,570,730
Total (Volumetric)						**97,213,352.00**

The total mean annual lateral groundwater flow in certain cross-sectional area of the Sunuta catchment is estimated to be about **266,337.95m^3/day or 97.2 MCM/year.**

4.3 Hydrogeological properties and Hydro stratigraphy

Hydrostratigraphic unit consists of contiguous geological material having similar hydraulic properties (Seaber, 1988) cited on Anderson and woessener, 2002. Several geologic formations may be combined into a single hydrostratigraphic unit or a geologic formation may be subdivided into aquifers and confining beds. (Anderson and wossener, 2002)

Based on field visit and existing boreholes lithological log description and borehole geophysical log, in the study area there are two geological units identified. They are alluvial deposits ranging in grain size from clay to gravel and Volcanic rocks (basalts and rhyolite). However, they are hydraulically connected and average hydraulic parameter is considered. Due to this it is considered as one hydrosratigraphic unit.

The groundwater flows from the western rift escarpments to the rift floor of Sunuta plain. And has high groundwater potential in the plain.

Appropriate existing wells data enables as to develop a hydrogeological, groundwater flow direction maps and to construct hydrogeological cross section. **(Figure 4.9)**

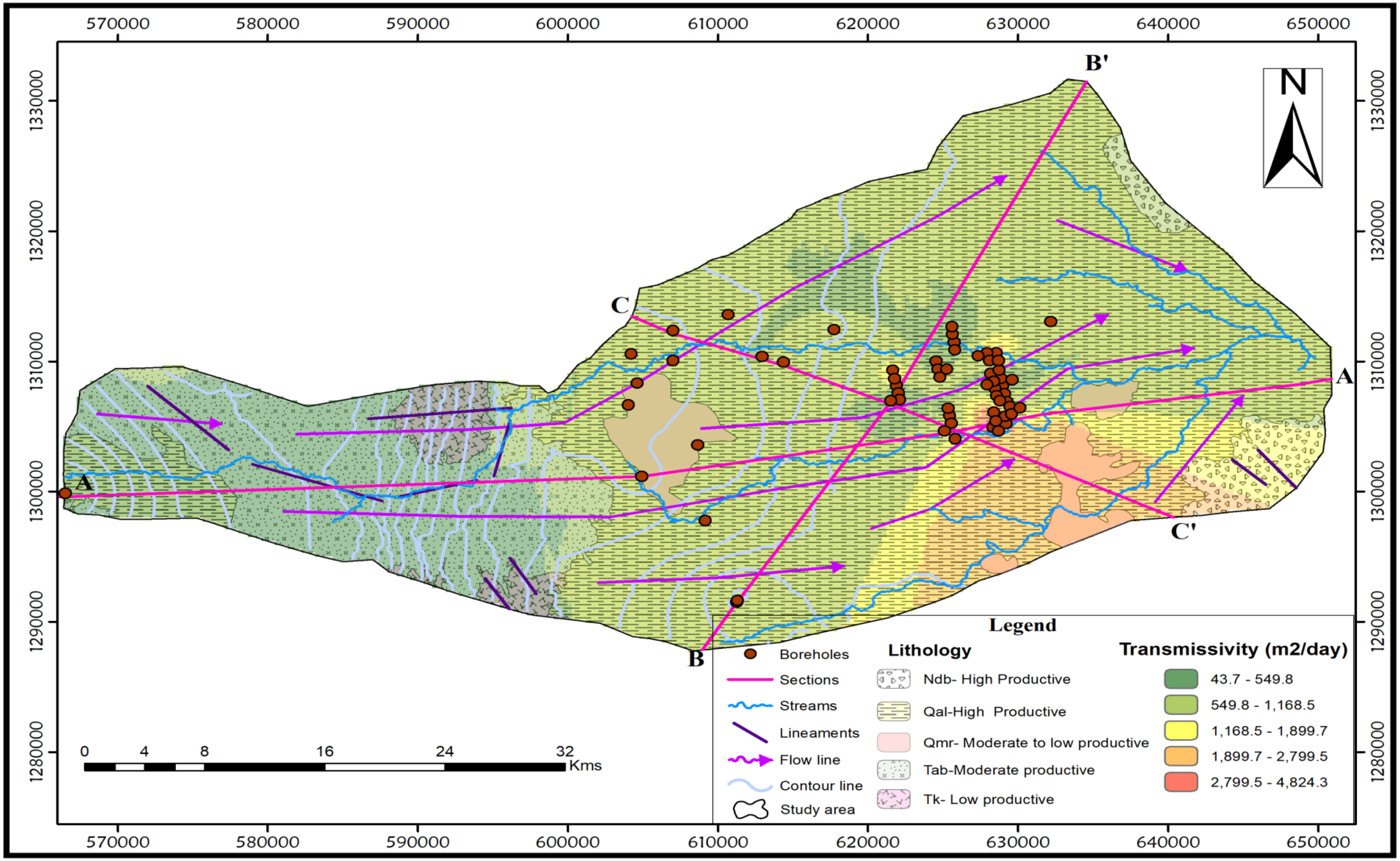

Figure 4.9: - Schematic hydrogeological map of the study area

Hydrostratigraphic units

To understand and determine the three-dimensional view of the groundwater system, the hydrogeological cross section is constructed along the groundwater flow direction and perpendicular to the groundwater flow direction. One cross section is constructed from West to east along the groundwater flow path and the other two are constructed from North to south and SW to NE direction across the groundwater flow path to visualize the lithological distribution and it thickness variation within the study area. **(Figure 4.10; 4.11; 4.12)**

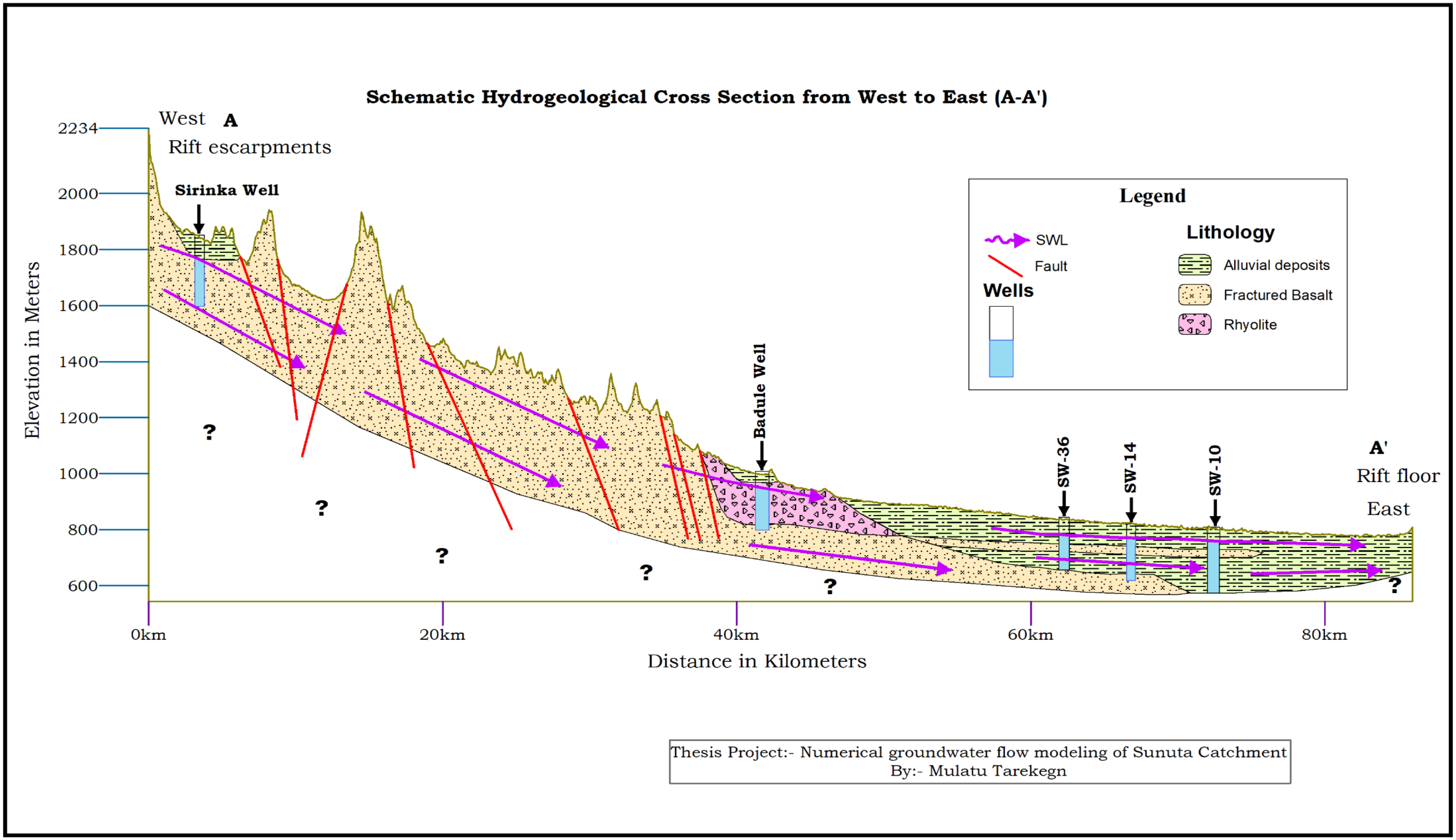

Figure 4.10: - Schematic Hydrogeological cross section from West to East

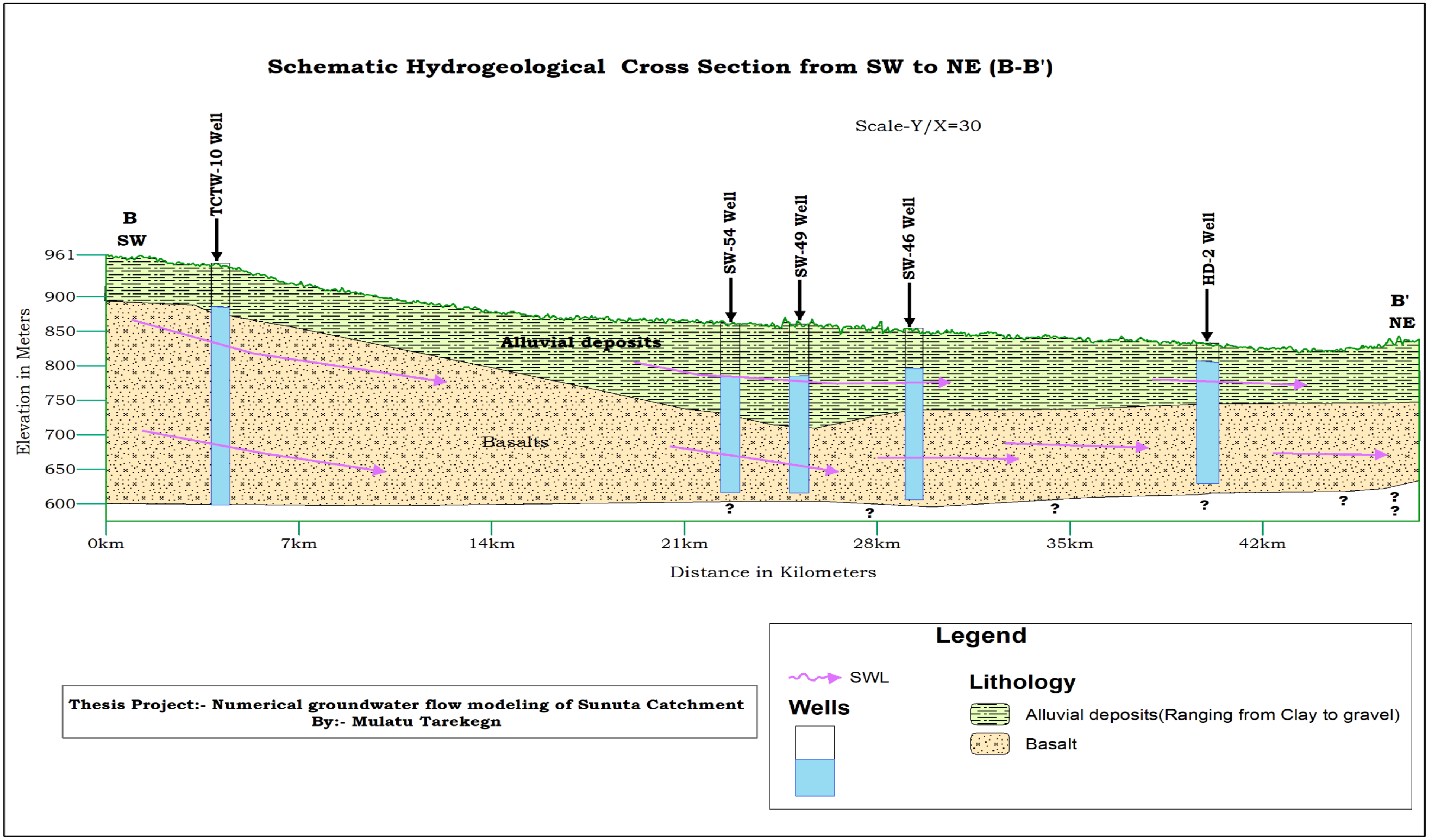

Figure 4.11: - Schematic Hydrogeological cross section from SW to NE

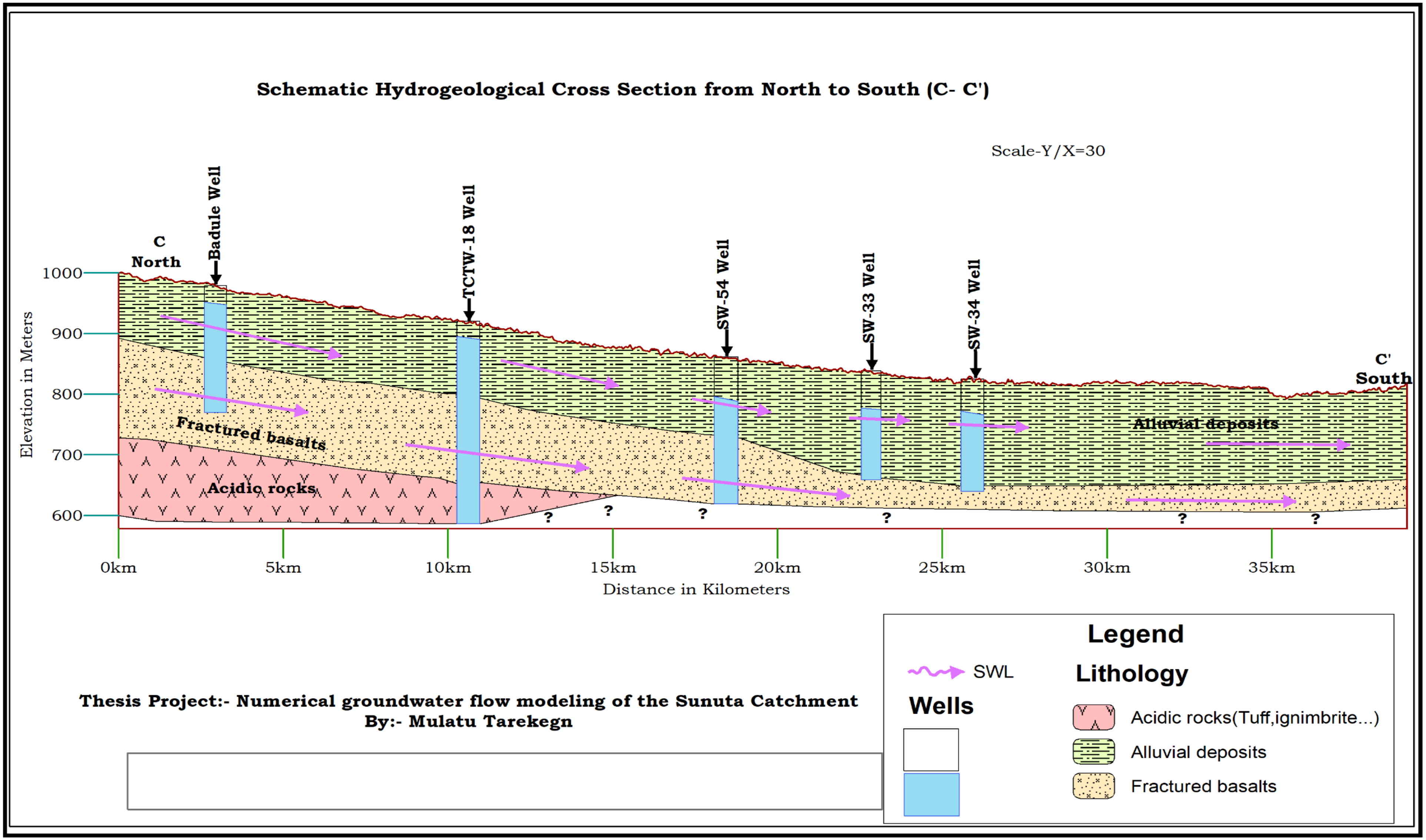

Figure 4.12: - Schematic Hydrogeological cross section from North to South

4.4 Reprocessing Pumping test data

Pumping test is a scientific approach where the groundwater storage and movement are expressed on terms of the physical and hydraulic properties of the aquifer system. Aquifers are groundwater reservoir where the lateral continuity and vertical boundaries are often not well defined. Since direct observation of groundwater movement is impossible, mathematical analysis offers a convenient and reliable way to predict what happens to water in the ground. It is therefore, imperative to derive simple mathematical expressions for describing the flow region of water in the subsurface. Groundwater declining due to pumping can be defined with different well flow equations which are developed for steady state and unsteady state flows for various types of aquifers and boundary conditions. Together with the basic assumptions and conditions for steady and unsteady state flows, the equations are presented in their final mathematical form for practical application.

Generally, all the analytical methods assumed the aquifer is homogenous and isotropic, groundwater flow is horizontal and Darcy's law is valid, discharged at constant rate, fully penetrating well of very small diameter and geologic formations are horizontal and have infinite horizontal extent. (G.P. Kruseman, 1994).

One of the specific objectives of the study is to reprocessing existing wells pumping test data which is useful to know the catchment hydraulic parameters such as Transmissivity, Hydraulic conductivity, which later used as one of the model input parameters.

The Existing pumping test data of 25 wells were obtained from Afar Water Works Construction Enterprise. The raw data of constant and recovery test are reanalyzed using Aquitest 3.5 software. The analysis of the pumping test result of the wells represent the whole catchment.

The hydraulic conductivity and transmissivity distribution of the area ranges between 4-53m/day and 43.7- 4824m^2/day respectively. the highest value (2799-4824m^2/day) is found at south eastern part of the study area which covers small part in the study area. The hydraulic conductivity map is prepared and exported in ASCII format and applied to each active cell in the model domain. **(Figure 4.13; 4.14)**

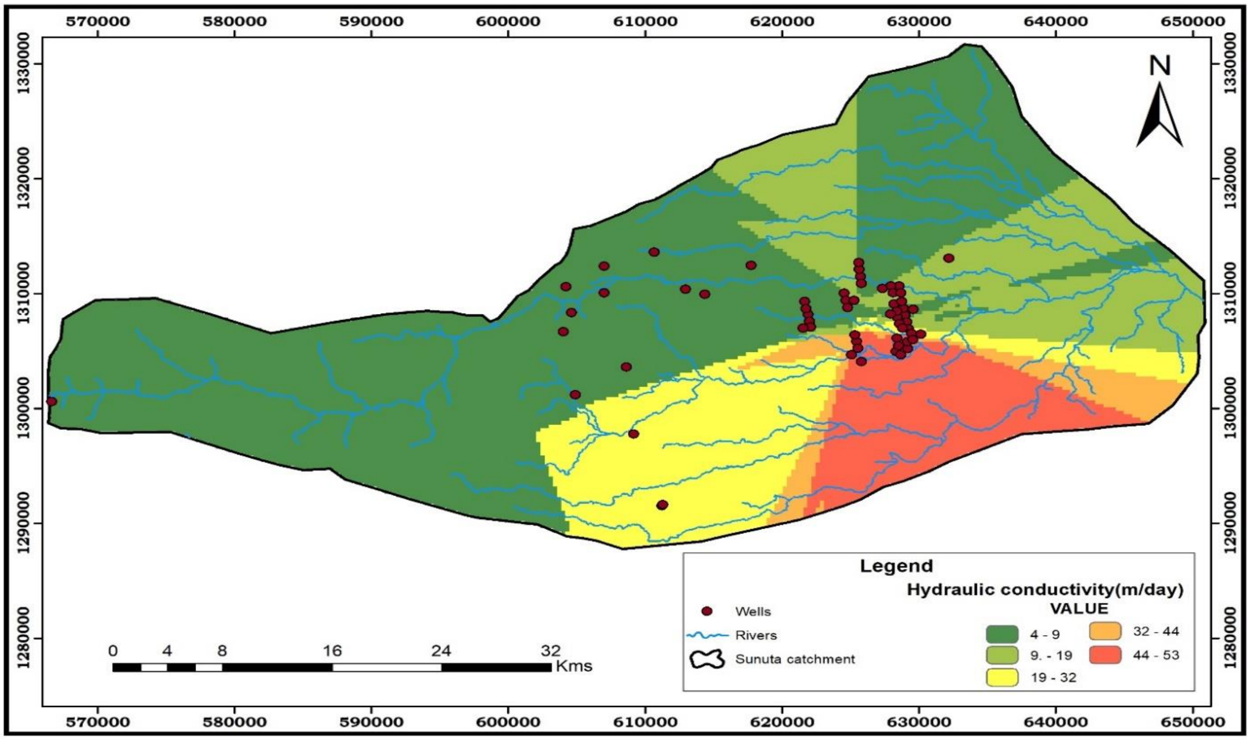

Figure 4.13: - Hydraulic conductivity distribution map

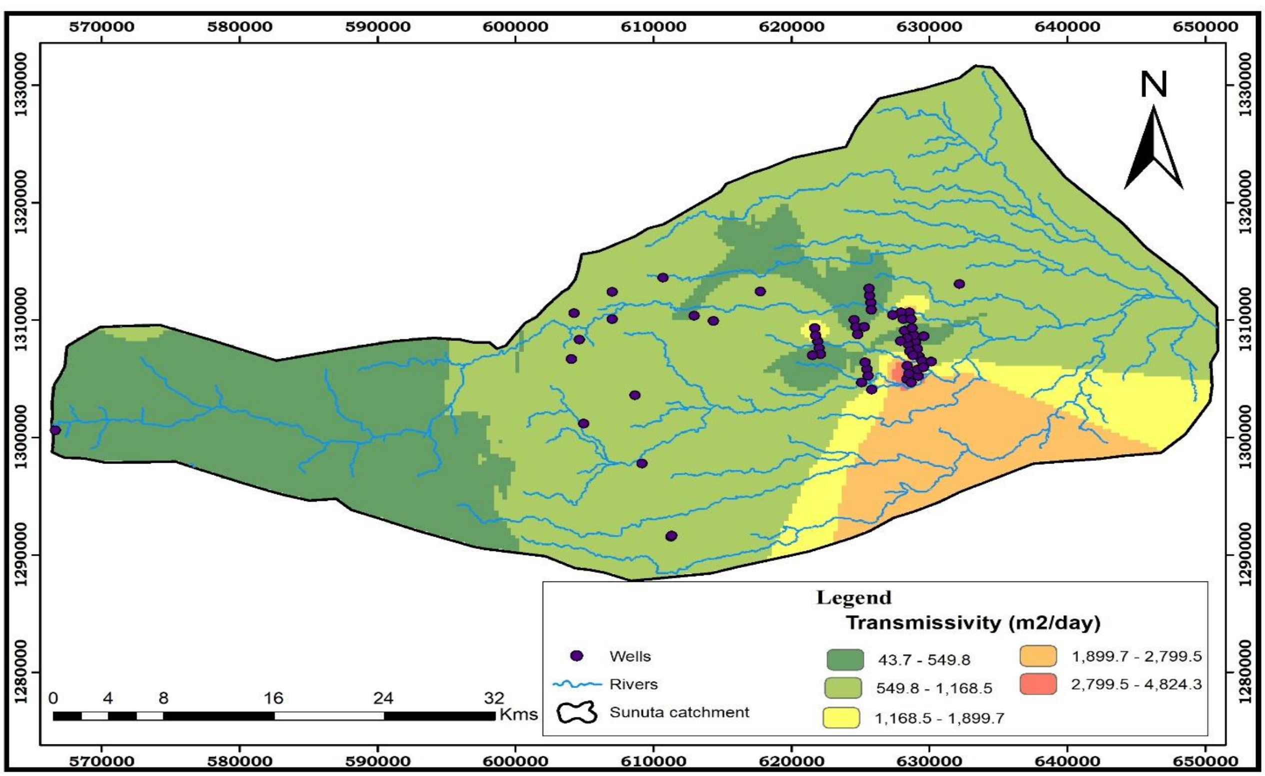

Figure 4.14: - Transmissivity distribution map

4.5 Model Boundaries

Boundaries include hydraulic features such as groundwater and surface water divides and physical features such as bodies of surface water and impermeable rock. Boundaries are identified from potentiometric level/ water level, topographic variation, and geologic maps of the region and site. (Anderson and wossener, 2002)

In the study area the boundaries are identified and delineated based on surface water divides through delineating water shed and groundwater divides by analyzing the water level in the study area and surroundings.

Based on the above reason the lateral boundaries of the model areas are mostly no flow. However, at a highly fractured areas there is a head dependent flow boundary. The location of head-dependent flux boundary for the study area is assumed at the localities of the fracture zones of the surrounding ridges along river channels and valley channels.

4.6 Groundwater Discharge

Groundwater in the study area are discharged naturally through perennial rivers and springs and artificially through boreholes. Uwa big river which is perennial throughout the year flows across the sunuta catchment and further flows and join Logia river and at the end it fed Afambo Lake at the place where Awash river ends.

The groundwater also abstracted for irrigation use, community water supply purpose and for test wells. In the study area there are 69 deep boreholes drilled for irrigation and domestic uses. Out of 69 drilled deep boreholes, 30 boreholes are used for current abstraction. The current abstraction rate for the irrigation and domestic uses are 20,291.40 m^3/day and 5,756.40 m^3/day respectively. Total current abstraction rate of Sunuta Catchment study area is 26,047.80 m^3/day. Total planned abstraction rate for irrigation and domestic uses are 92,039.04 m^3/day. **(Table 4.6)**

Table 4-6:- Current groundwater abstraction rate of the study area

Well ID	Easting	Northing	Elevation (m)	Abstraction (l/Sec)	Current Abstraction (m^3/day)
SW-19	628985	1308094	824	56	1998
SW-23	628445	1307923	826	53	1908
SW-16	629117	1307514	825	56	1998
SW-20	628859	1308685	823	38	1368
SW-21	628184	1309065	827	56	1998
SW-17	628578	1307344	827	52	1872
SW-24	629597	1308598	820	52	1872
SW-15	629256	1306899	823	53	1908
SW-22	628392	1308445	827	62	2237.4
SW-25	628745	1309301	819	58	2088
SW-52	622018	1307576	857	29	1044
SWTW1	566480	1299859		20	720
Badule#1	607011	1310053		28	1008
Merto#1	627929	1308203		23	810
Badule#2	605536	1309896		27	957.6
Merto#2	627309	1309076		28	993.6
Kofoburur	617757	1312420	885	3	86.4
Fialu	632178	1313057	805	3	86.4
2 Badule	607015	1312377	980	4	115.2
1st badule	604222	1310570	1013	5	144
Jara	607624	1289396	983	3	86.4
Gofo mesg	612950	1310367	920	3	86.4
2 Badule	607015	1312377	980	3	86.4
ewa22	610679	1313591	938	3	86.4
Bolotomo	604031	1306661	1042	3	86.4
Fularba	604630	1308330	1013	2	57.6
1st badule	604222	1310570	1013	3	86.4
Fialu	632187	1313051	806	3	86.4
Regden 2	608643	1303577	928	3	86.4
Kerewayu	604920	1301166	983	3	86.4
Irrigation uses					**20,291.40**
Domestic uses					**5,756.40**
Total					**26,047.80**

Chapter Five

5. Numerical Groundwater Flow Modeling

5.1 Introduction

Groundwater models are a simplified representation of a reality. If properly constructed it is a valuable predictive tool for management of groundwater resources. the validity of the predictions will depend on how well the model approximates field conditions. To have good approximation a good field data is essential.

The groundwater flow models can be described by differential equation which is derived from two basic principles of physics. One of the basic principles is conservation of mass which states that water is not created and nor destroyed and the other principle is Darcy's law which states that groundwater flows from high to low potential energy. (Anderson and woessener, 1992)

5.2 Governing equation for groundwater flow

The governing mathematical equation of groundwater flow model assumes that flow of a single-phase fluid (water) at constant density in a continuous porous medium under Darcy's law

5.3 Numerical models

The model uses an approximate form of the governing equation to calculate head at selected locations. Most commonly used numerical methods in groundwater modeling are finite-difference (FD) method and the finite-element (FE) method. The most widely used code for solving groundwater flow problems is the finite difference (FD) code MODFLOW developed by the U.S. Geological Survey (USGS). **(Anderson and Wossener,2002).** In this study Processing MODFLOW is used to Model the groundwater system of sunuta catchment to evaluate different scenarios envisaged based on the current and projected development interventions. The steady-state groundwater flow is simulated based on the following governing differential equation under two- dimensional aerial view (Anderson and Wossner, 2002).

$$\frac{\partial}{\partial X}\left(K_x \frac{\partial h}{\partial X}\right)+\frac{\partial}{\partial Y}\left(K_y \frac{\partial h}{\partial Y}\right)+R=0$$

Where:

Kx and Ky= Components of the hydraulic conductivity along x and y axis [LT^{-1}]

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

H= Hydraulic head [L]

5.4 Model design

5.4.1 Model Geometry

The Model domain has a horizontal extent of 44.1 km by 84.9 km bounded by UTM/Zone 37/Adindan: - 566300 to 651200 East and 1287600 to 1331700 North. However, the irregular shape of the study area and the locally bounded nature of the aquifers reduces the model domain to an area of 1870 Km^2.

5.4.2 Discretization

In numerical models, the continuous natural phenomenon is replaced by a discretized domain which is called grid. Selecting the Grid size depends on hydraulic gradient, degree of aquifer heterogeneity, size of the model area, level of detail required and availability of data. (Anderson & Woessner, 2002)

The Model domain is discretized using nodes and Finite Difference cells/blocks. The cells are rectangular, block centered and have uniform and regularly spaced. This will help to have more computationally accurate result and operationally efficient

The model is horizontally discretized with regular grid spacing of 300m by 300m having 147 rows and 283 columns.

The number of model layers and the vertical nodal spacing depend on the magnitude of vertical head gradients and the vertical variability in K. (Anderson and wossner,2002)

Even though the number of stratigraphic layers is two, they are hydraulically linked and behave as one aquifer system. Due to this the model domain is one layer having 250m thickness. The layer type is confined/unconfined transmissivity variable. **(Figure 5.1)**

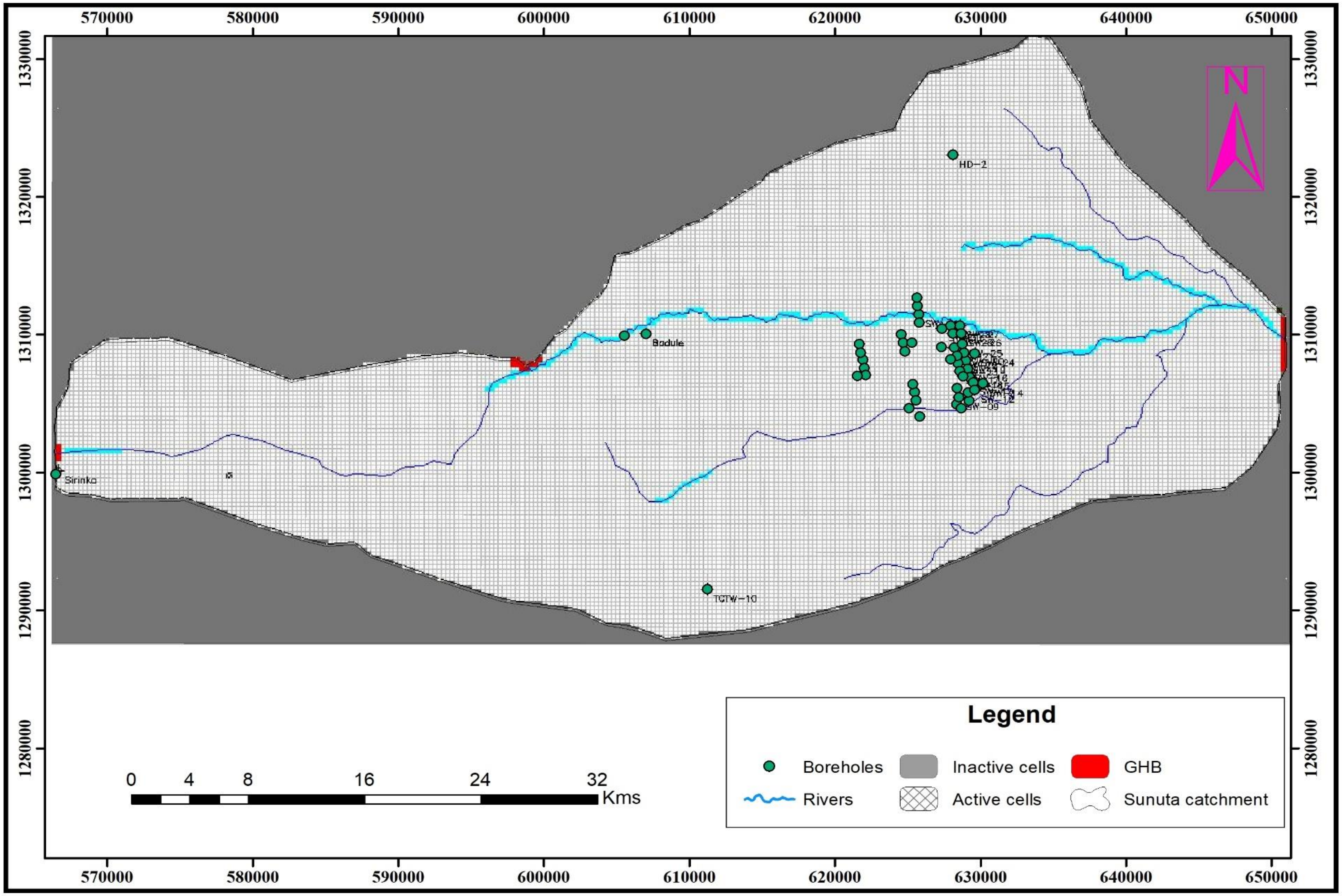

Figure 5.1**:- Model domain Discretization**

5.5 Model inputs parameter

5.5.1 Modeling Environment

Boundary

The flow model MODFLOW requires an IBOUND array, which contains a code for each model cell. A positive value in the IBOUND array defines an active cell (the hydraulic head is computed), a negative value defines a constant head or fixed head cell and the value 0 defines an inactive cell.

Top and bottom layer

The top and bottom elevations of the layer is typically input by the modeler from DEM of 30m by 30m spatial resolution

Initial and prescribed 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 head is measured at each well in the model domain and interpolated using ArcGIS software to have weighted head in the catchment.

Horizontal hydraulic conductivity

Hydraulic conductivity (K) is the primary aquifer parameter that governs groundwater flow. (Anderson and Wossner,2002). Flow of water in the aquifer is horizontal. The hydraulic conductivity of the model domain is estimated from pumping test data of 40 deep drilled wells. The map is prepared in ASCII format and applied to each active cell in the model domain.

General Head boundary

The General-Head Boundary (GHB) package is used to simulate head-dependent flow boundaries, where flow into or out of a GHB cell from an external source is provided in proportion to the difference between the head in the cell and the head assigned to the external source.

In the study area, General-Head Boundary is assigned at three main places considering inflow and outflow from the model domain and inter basin flow across surface and groundwater divides through highly fractured areas.

5.5.2 Stresses

Groundwater Recharge

Recharge is water that infiltrates at the land surface, flows through the unsaturated zone, and crosses the water table to enter the groundwater system. (Anderson and Wossner,2002).

The methods used to estimate the recharge was WetSpass model method. The estimated recharge was 61.1mm/year and it is simulated to the groundwater system using recharge packages.

Groundwater Pumping rates

The groundwater pumping rates (abstraction rates) is taken from the wells abstraction rate during pumping test and the irrigation pumping schedule. The estimated current groundwater abstraction rate of the model domain is 26,047.80 m^3/day.

5.6 Steady state simulation

In a steady state flow model hydrologic parameters and computed heads and fluxes are constant in time

5.6.1 Model calibration

Groundwater modeling would be easy to or understand if it were possible to characterize the natural world perfectly.

Model calibration is the primary way to assess model performance. It is the process of making adjustments, within justifiable ranges, to initial estimation of selected model parameters to obtain reasonable results between simulated and measured values.

The groundwater model calibration of the study area is performed using manual trial and error history matching method.

These results were compared with the calibration target (measured value) and if the error in the simulated results is acceptable, the model is considered as calibrated; if the level of error is unacceptable, the input parameter values are adjusted within a reasonable range and the model is run again until acceptable results are achieved. The distribution and comparison of the observed and simulated hydraulic head are presented in the form of graphical and diagram. **(Figure 5.2).**

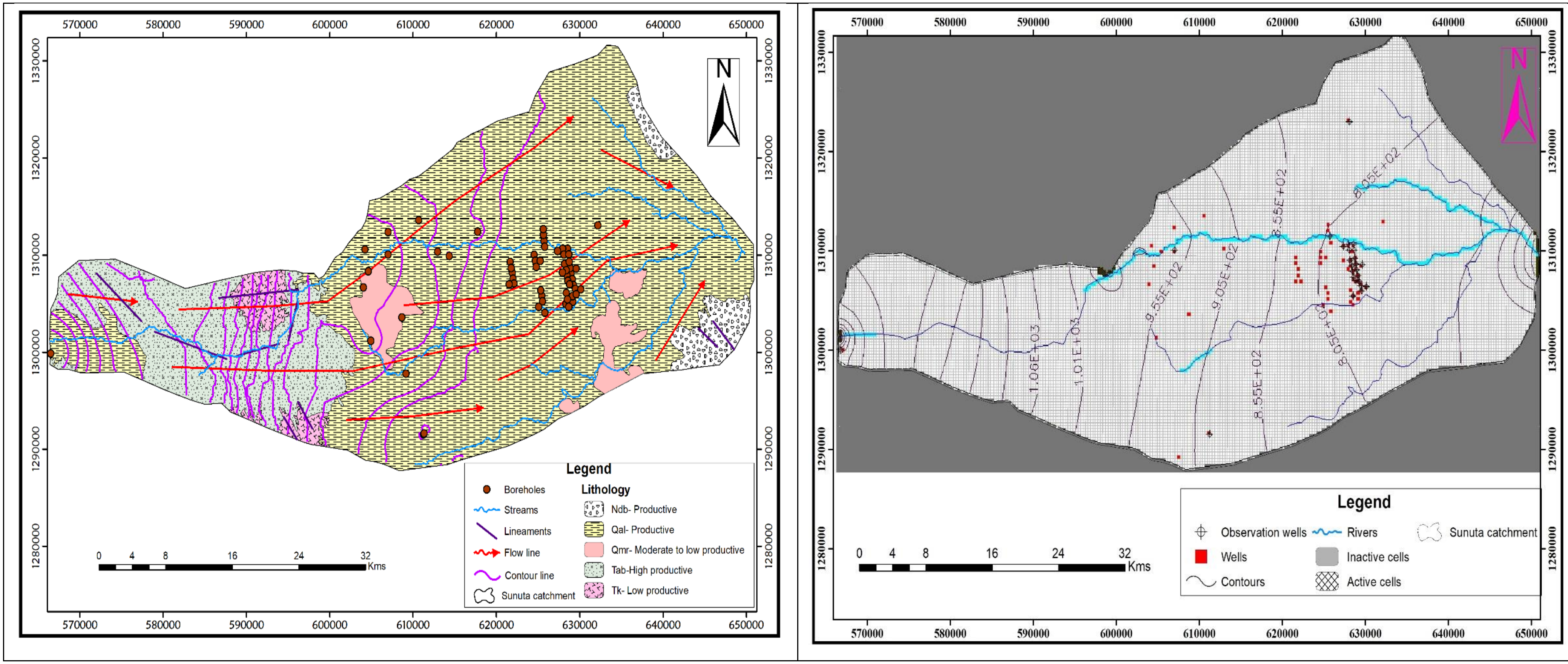

Figure 5.2: - Comparison of observed and simulated head map

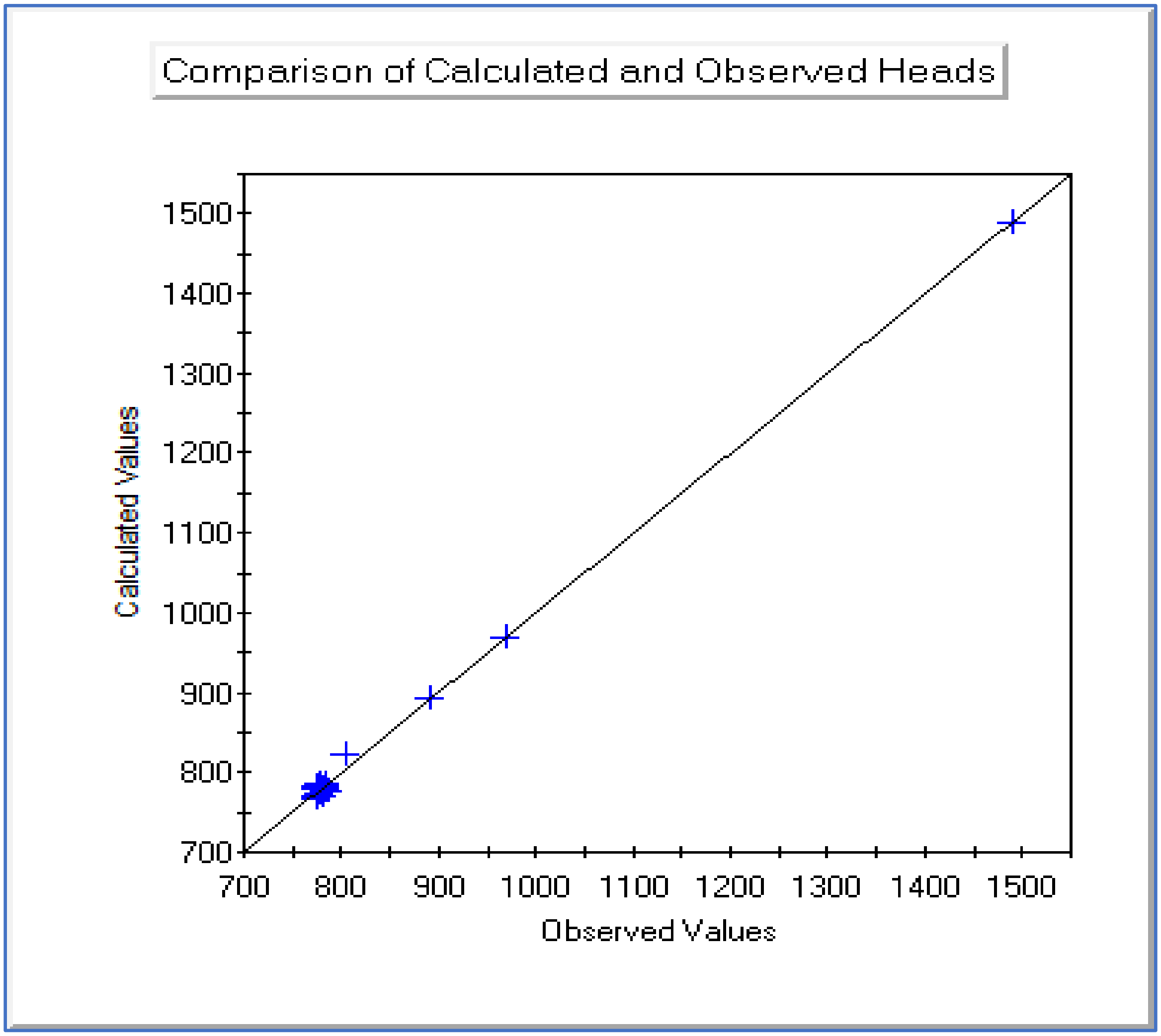

Figure 5.3**: - Scatter plot of simulated to observed fit of water levels**

5.6.2 Evaluation of calibration

The results of the calibration should be evaluated both qualitatively and quantitatively (Anderson and Woessner, 2002). The mean of the observed and simulated heads differences was used to quantify the average error in the calibration process. The three ways of expressing the average difference between simulated heads (hs) and measured heads (hm) are the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE). The main target of the calibration is to minimize these error values.

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

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

2. The mean absolute error (MAE) is the mean of the absolute value of the residual.

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

3. The root mean squared error (RMSE) is the average of the squared residuals.

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

Table 5-1: - Mean observed and simulated head differences

S. No	Well ID.	Simulated	Observed	ME (AVG (hm-hs))	MAE AVG((hm-hs))	RMSE (SQRT (AVG (hm-hs) ²)
1	TCTW-10	893.81	891	-2.81	2.81	7.91
2	Sirinka	1489.35	1490	0.65	0.65	0.42
3	Badule	970.19	970	-0.19	0.19	0.04
4	SW-44	786.31	785	-1.31	1.31	1.72
5	SW-13	780.59	776	-4.59	4.59	21.07
6	SW-18	780.88	783	2.12	2.12	4.49
7	SW-27	780.95	781	0.05	0.05	0.00
8	SW-28	780.98	778	-2.98	2.98	8.86
9	SW-29	777.30	783	5.70	5.70	32.52
10	SW-09	786.04	777	-9.04	9.04	81.63
11	SW-12	782.69	776	-6.69	6.69	44.71
12	SW-14	780.75	775	-5.75	5.75	33.10
13	SW-26	776.56	786	9.44	9.44	89.06
14	SW-30	781.53	783	1.47	1.47	2.15
15	SW-19	771.20	781	9.80	9.80	95.96
16	SW-23	774.11	777	2.89	2.89	8.36
17	SW-16	776.15	783	6.85	6.85	46.86
18	SW-20	768.36	776	7.64	7.64	58.30
19	SW-21	769.44	780	10.56	1.56	111.49
20	SW-17	779.29	782	2.71	2.71	7.32
21	SW-24	773.28	777	3.72	3.72	13.82
22	SW-15	779.89	780	0.11	0.11	0.01
23	SW-22	770.14	782	11.86	11.86	140.75
24	SW-25	769.07	774	4.93	4.93	24.31
25	HD-2	823.48	804	-19.48	19.48	379.50
				ME= 1.11	**MAE=4.97**	**RMSE= 6.97**

Chapter Six

6. Results and Discussions

6.1 Steady state simulated results

The simulated results of the steady state groundwater flow model are calibrated with the measured field data. Once the model is calibrated the outputs from the model (simulated hydraulic head contour and water budget) is manipulated.

6.1.1 Hydraulic head

The results of hydraulic head are computed using mathematical groundwater flow model and the analysis of the simulation was made by comparing the computed results with measured data. The analysis of the results (simulated and measured head) can be shown in **Table 6.1**.

Table 6-1:- Results of simulated head with measured data

Well ID.	Head	
	Simulated	Measured
TCTW-10	893.8	891
Sirinka	1489.4	1490
Badule	970.2	970
SW-44	786.3	785
SW-13	780.6	776
SW-18	780.9	783
SW-27	781.0	781
SW-28	781.0	778
SW-29	777.3	783
SW-12	782.7	776
SW-14	780.8	775
SW-30	781.5	783
SW-23	774.1	777
SW-16	776.2	783
SW-17	779.3	782
SW-24	773.3	777
SW-15	779.9	780
SW-25	769.1	774

6.1.2 Water budget

Water budget in steady state flow is the balance between inflow and outflow. In the model domain (Sunuta catchment) water budget simulation is balanced within a discrepancy of 0.00. In the study area the inflow terms are recharge and head dependent boundary whereas the outflow terms are rivers (Uwa river), wells and head dependent boundary.

The recharge of the study area (Sunuta catchment) is estimated using WetSpass method. The estimated recharge using WetSpass method was 61.1mm/year. The simulated recharge of the model domain is 50.2mm/year. The simulated value is close to the estimated recharge. However, it is below the estimated recharge. This difference may be due to the data gap and uncertainty during recharge estimation.

The groundwater discharged from the study area through natural discharges (rivers, springs) and groundwater abstraction from deep wells drilled for irrigation and domestic purposes. The current groundwater abstraction estimated from well pumping test data and information obtained from the project area was 26,047.80 m^3/day. And also, the groundwater is discharged through perennial rivers and springs at the eastern part of the study area

Table 6-2 **:- Simulated water budget result**

THE UNIT OF THE FLOWS is (m^3/day)			
FLOW TERM	IN	OUT	IN-OUT
WELLS	0.00E+00	0.00E+00	0.00E+00
RECHARGE	2.62E+05	0.00E+00	2.62E+05
RIVER LEAKAGE	7.35E+05	3.68E+05	3.67E+05
HEAD DEP BOUNDS	6.85E+04	6.97E+05	-6.29E+05
SUM	1.07E+06	1.07E+06	1.34E+01
DISCREPANCY (%)	0.00		

Theoretically the differences between the inflow and outflow (change in storage) in steady state condition within the model domain is zero. However, in the model analysis result the difference is not zero but it is close to zero. This is due to the uncertainty and the data gap during recharge estimation and analysis on hydraulic parameters.

6.2 Model Sensitivity analysis

Sensitivity analysis is the measure of uncertainty in the calibrated model caused by uncertainty in aquifer parameters and boundary conditions. Sensitivity analysis was performed by systematically changing the calibrated values of conditions (Anderson and Woessner, 2002).

The sensitivity of a given parameter was determined by fixing all calibration parameters at their calibrated values except for the selected parameter and run the model by incrementally increasing and decreasing its value by some percent from its calibrated value. (Anderson and Woessner, 2002).

The calibrated values of hydraulic conductivity and recharge were varied by using multiplier factors: 0.15, 0.3, 0.45, 1.15, 1.3 and 1.45.

The model is sensitive to both recharge and hydraulic conductivity. However, relatively the model is highly sensitive to decrease of the calibrated hydraulic conductivity and recharge and less sensitive to increasing of calibrated hydraulic conductivity and recharge. And also, the model is mostly sensitive to decrease of calibrated hydraulic conductivity. Generally, this show little uncertainty in the model will yield to wrong results. **(Table 6.2)**

Table 6-3:- Sensitivity analysis result

Parameter change	**Recharge**	**HK**
0.55	15.2	32.9
0.7	11.4	19.3
0.85	8.5	11
1	5.9	5.9
1.15	7.5	7.3
1.3	9.4	9.9
1.45	11.8	12.9

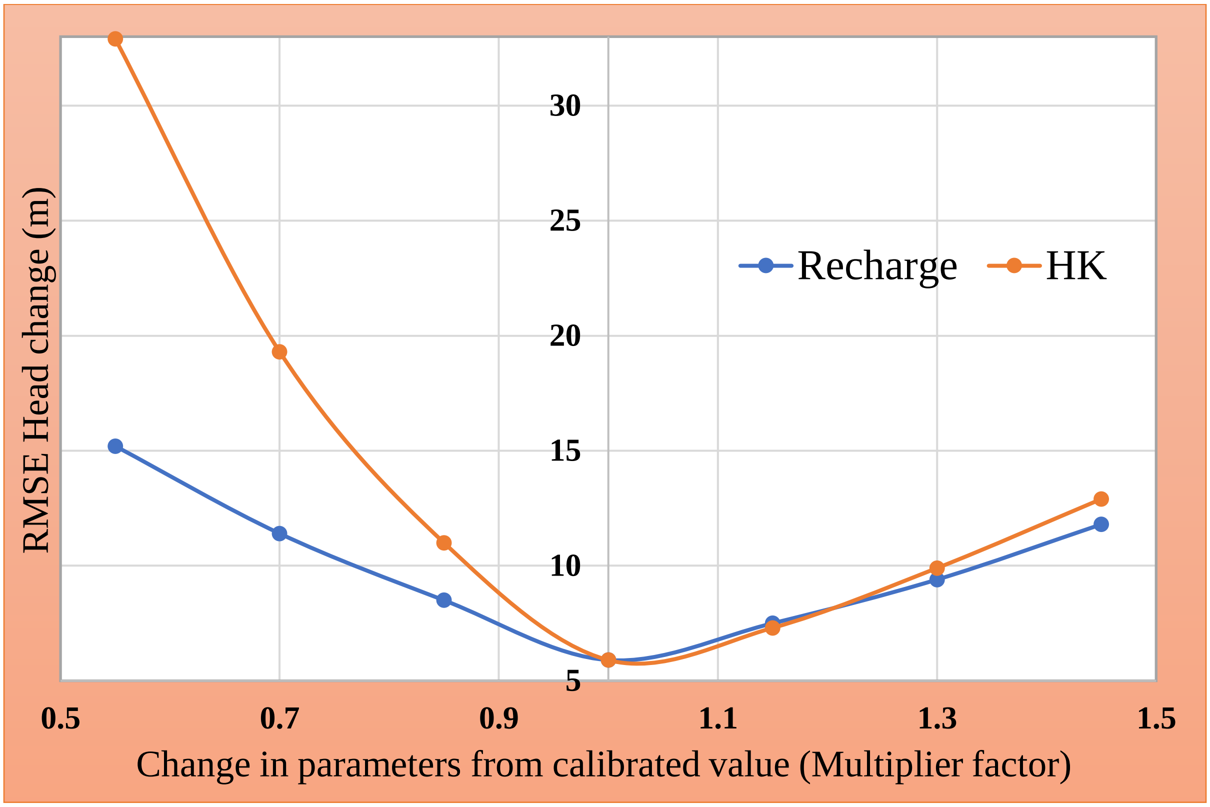

Figure 6.1:- Sensitivity Analysis of the Effect of selected parameters on the RMSE Value of Water level

6.3 Scenario analysis

Pumping scenarios were used to evaluate the response of the groundwater system under variable groundwater abstraction rates. The system response was compared with resulting changes in water level and groundwater outflow from the model domain.

The inventoried existing boreholes in the Sunuta catchment are 69. From these 50 boreholes are drilled for irrigation purpose and 19 boreholes are for water supply purposes. Most of the boreholes are found on the Sunuta plain for the irrigation uses. However, no recorded data was available concerning how the groundwater has been utilized currently. Based on the information obtained from SDG project office and irrigation site project focal person, the abstraction rate for the irrigation and water supply purposes are estimated. The total current abstraction rate of the catchment is 26,047.80 m^3/day. From the total abstraction rate, 20,291.40 m^3/day are abstracted for irrigation uses and 5,756.40 m^3/day for water supply purposes., From study area information obtained, Ministry of Agriculture drilled 48 boreholes before 5 years and additional 2 boreholes within 1 year for irrigation purposes. The organization plan shows that they classify the irrigation land into 8 lots. Each lot contains 250 hectares irrigation land. One lots which is 250 hectares need 6 boreholes which have abstraction rate of 50l/s pumped for 10 hours. However currently they use 11 boreholes out of 50 irrigation boreholes.

Based on the above information two scenarios were developed on the future abstraction rate under steady state condition.

Scenario 1: - Assume if all the planned lots (8 lots) are irrigated in addition to water supply abstraction, the total number of boreholes used are 69. Fifty boreholes for irrigation and 19 boreholes for water supply. The total water abstracted are **92,039.04 m^3/day.** The effects of the abstraction are evaluated based on the calibrated model.

Scenario 2: - Assume that additional boreholes are needed in the future for the expansion of the irrigation project and water supply boreholes are drilled for the community due to increasing population growth and settlement. Based on the assumption 22 additional boreholes (18 boreholes for irrigation of 3 lots and 4 boreholes for water supply) are used to analyze the effect of increased groundwater discharge over the model domain as compared to the calibrated model result. The amount of water abstracted in scenario two was **128,759.04 m^3/day** which is increased by 40% from the water abstracted in scenario one.

The model simulation result of Scenario one shows that for total abstracted water of **92,039.04m^3/day** from 69 boreholes was resulted in an average decline of water level by 27 **m** for the entire model. However, in western escarpments and western part of the rift floor in the model area shows that the head decline is lower than the boreholes found at central and eastern part of the model area. This shows that the wells are far apart and abstraction rate is lower. High head decline is observed at the central and eastern part of the model domain. This is due to the boreholes are found close to each other and the abstraction rate is high because the boreholes are drilled for the irrigation purposes.

The model simulation result of Scenario two shows that for total abstracted water of **128,759.04m^3/day** from 91 boreholes was resulted in an average decline of water level by **41m** for the entire model. However, in western escarpments and western part of the rift floor in the model area shows that the head decline is lower than the boreholes found at central and eastern part of the model area. This shows that the boreholes are far apart, small in number and abstraction rate is lower. High head decline is observed at the central and eastern part of the model domain. This is due to the boreholes are found close together, most of the additional boreholes are found in the plain and the abstraction rate is high because almost all boreholes are drilled for the irrigation purposes.

Estimated abstraction rate and average decline in hydraulic head for each pumping scenario is tabulated below. **(Table 6.3)**

Table 6-4:- Groundwater head decline in response to increased groundwater abstraction rate

S. No.	**Scenarios**	**Number of boreholes**	**Total abstraction rate (m^3/day)**	**Average decline in groundwater head in the model domain (m)**
1	Current abstraction	30	26,047.80	11
2	Scenario-one	69	**92,039.04**	27
3	Scenario-two	91	**128,759.04**	41

Graphical comparison of the groundwater levels simulated under different pumping scenarios

Model simulated groundwater heads under different pumping scenarios are plotted together in order to compare the variation in head distribution. As shown in the Figure 6.3, the plotted hydraulic head are non-pumping, current abstraction, scenario one and scenario two together

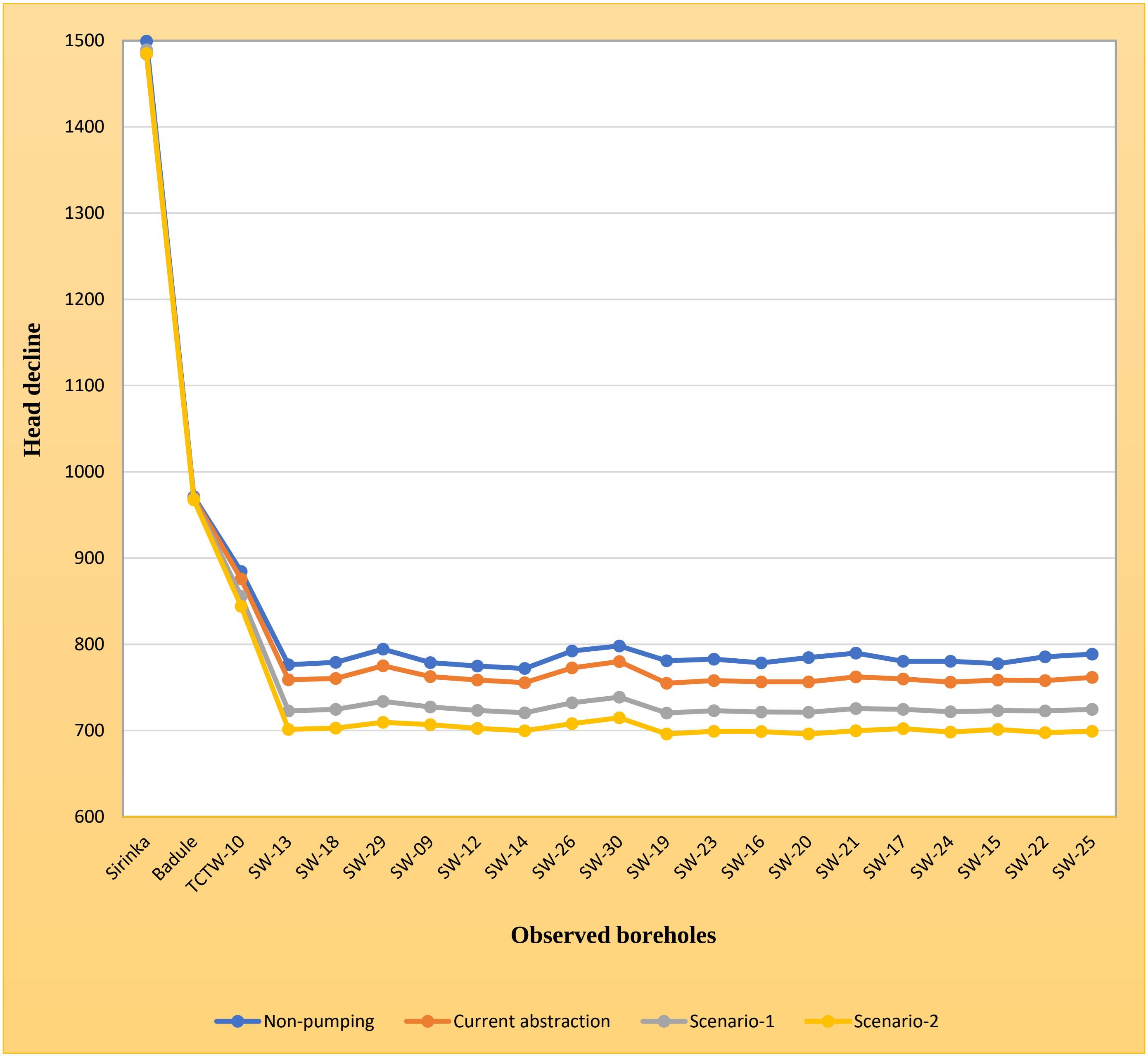

Figure 6.2:- Groundwater head conditions response to increased groundwater abstraction rate

6.4 Model limitation

Numerical models of groundwater flow are limited in their representation of the physical system because they contain simplifications and assumptions during conceptual model development. Errors are introduced during interpretation of the modeling process such as, converting the real world into conceptual model and the conceptual model into numerical model.

The degree of uncertainty in the model was raised, due to poor quality and limitation of the existing data such as model geometry (screen length and aquifer thickness) are not well documented and the available records of the water level measurements are not continuous and mostly are only single measurements.

The model was calibrated but not verified because there are no independent measured heads were able to validate the model. Moreover, the results from the model should not be interpreted as a perfect simulation, instead these results can be interpreted as a system response within reasonable and realistic model input parameters.

The uncertainty also occurred during defining the boundary conditions of the model domain. The boundary conditions were defined based on the surface physical features such as impervious geology, surface water divide and groundwater divide. The locations of the groundwater catchment boundaries are uncertain since they might not coincide with their surface expressions.

Chapter Seven

7. Conclusions and Recommendations

7.1 Conclusions

The study area is located in North-Eastern part of Ethiopia, in the lower Awash basin within Afar National regional state in Zone four and some part of Amhara National regional state in Northern Wollo. The center of the study area is found 690km North-East of Addis Ababa.

The total study catchment area is 1870km^2 of which 1476 km^2 belongs to Sunuta plain (rift floor/ lowlands) and 394 km^2 belongs to the mountainous area (rift escarpments and highlands). The altitude ranges between 2539masl at the highlands of Sirinka to 734masl in the sunuta plain of the rift floor. The catchment has a mean slope of 2.14% and an average altitude of 1025m.

The study area encompasses different climate zones from **Cool temperate (Dega)** to **Warm Temperate (Kola)** climatic zone with the mean annual rainfall ranging 1083-282 mm; maximum at Sirinka and minimum at Awura stations respectively.

Two major geological units are identified in the study area alluvial deposits ranging in grain size from gravels to clay size and Volcanic rocks dominantly basalt and some acidic rocks such as rhyolite and ignimbrite.

Hydrogeologically, the geological units are hydraulically connected and average hydraulic parameter is considered. Due to this it is considered as one hydrosratigraphic unit.

The groundwater source for the sunuta catchments are recharged through perennial streams, runoff during rainy season, groundwater inflow from upper highlands of Sirinka, Hara and from direct rainfall. The groundwater from the catchment is discharged through base flow (groundwater outflow) and well abstraction for irrigation and water supply purpose

The groundwater recharge of the study area is estimated using WetSpass model method.

WetSpass model requires the basic input data of distributed land use, soil texture, groundwater depth, elevation, slope, and climate data (rainfall, potential evapotranspiration, temperature, windspeed, number of rainy days) and provides the output in the form of spatially distributed recharge, runoff and actual evapotranspiration raster maps.

The estimated recharge was 61.1mm/year.

The transmissivity distribution of the area ranges between 67- 4,980m^2/day. the highest value (3,382-4,980m^2/day) is found at south eastern part of the study area which covers small part in the study area.

In the study area there are more than 69 deep boreholes drilled for irrigation and domestic use. Out of 69 drilled deep boreholes, 30 boreholes are used for current abstraction. The current abstraction rate for the irrigation and domestic uses are 20,291.40 m^3/day and 5,756.40 m^3/day respectively. Total current abstraction rate of Sunuta Catchment study area is 26,047.80 m^3/day and total planned abstraction rate for irrigation and domestic uses are 92,039.04 m^3/day.

The Electrical conductivity (EC) and Total dissolved solids (TDS) value of the study area ranges between 959 µs/cm to 1295 µs/cm and 425mg/l to 863mg/l respectively. The average value of EC and TDS of the area are 959 µs/cm and 662mg/l respectively.

The mathematical code MODFLOW software is applied in the study area

Model calibration is made for steady state flow and it was carried out by manual trial and error adjustments of the parameters

Model calibration carried out successfully because the deviations between the computed and the observed head values were within acceptable error. The model calibration had a Mean error (ME), the mean absolute error (MAE) and Root Mean Square Error (RMSE) value of about 1.11m, 4.97m and 6.97m respectively which confirms a reasonable agreement between the observed and computed head.

The sensitivity of the calibrated model was tested by systematically changing one parameter or input variable at a time and it was found that the model is highly sensitive to changes of hydraulic conductivity of the aquifer system and recharge rate. Both parameters have significant influence on the model simulated hydraulic heads

Two scenarios were developed on the future abstraction rate under steady state condition. The abstraction rate of Scenario one and two are 92,039.04 m^3/day and 128,759.04 m^3/day respectively. The head decline due to future abstraction rate are 27m and 41m respectively.

7.2 Recommendations

River discharge measuring stations have to be installed at Uwa, Awra and chereti river. Because there are no stations at upstream part which are a tributaries of Logia river

Estimation of the safe yield by conducting group pumping test and distance drawdown of boreholes should be made in order to establish the limits of pumpage for irrigation use, mainly during the dry season

Latest technology and appropriate irrigation methods (water saving techniques) should be applied just to maintain stable or decrease the groundwater quantities that used for agriculture. In addition, education of people via training courses should be organized in order to teach people to use methods to optimize water use.

Systematic and appropriate pumping plan would be useful and should be applied to ensure efficient use of water and prevent undue loss of water through over pumping of boreholes.

Further investigations should be made in the study area (Sunuta catchment), in order to understand better the groundwater reserves (recharge and abstraction rate), borehole separation distance and groundwater flow movement and thus, to develop a more detailed and realistic groundwater flow model for the whole catchment.

Finally, it would be very important to have available observation wells gauged with pressure transducer, which monitors the water level fluctuation in instant time and continuous recording of abstraction rate and water level with SCADA system and professional close follow up is necessary

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Annexes

Annex I: - Estimated planned Groundwater abstraction rate

Well ID	Easting	Northing	Elevation (m)	Abstraction (l/Sec)	Planned Abstraction (m³/day)
SW-19	628985	1308094	824	56	1998
SW-23	628445	1307923	826	53	1908
SW-16	629117	1307514	825	56	1998
SW-20	628859	1308685	823	38	1368
SW-21	628184	1309065	827	56	1998
SW-17	628578	1307344	827	52	1872
SW-24	629597	1308598	820	52	1872
SW-15	629256	1306899	823	53	1908
SW-22	628392	1308445	827	62	2237.4
SW-25	628745	1309301	819	58	2088
HD-2	628094	1323022	828	81	2923.2
SW-49	621674	1309303	859	30	1080
SW-51	621909	1308167	859	20	720
SW-52	622018	1307576	857	29	1044
SW-53	622113	1307069	857	40	1440
SW-54	621530	1306982	865	20	720
SW-44	625744	1311458	845	46	1656
SW-45	625646	1312069	836	46	1656
SW-46	625615	1312667	843	24	864
SW-50	621759	1308681	854	51	1821.6
SW-43	625793	1310860	844	50	1800
SW 37	624536	1310017		25	900
SW 38	624664	1309403		47	1692
SW 39	624795	1308773		50	1800
SW 42	625267	1309404		46	1656
SW-7	629196	1305200	819	64	2304
SW-8	628350	1304940	822	60	2160
SW-10	628394	1306098	827	60	2160
SW-11	629142	1305775	824	62	2232
SW-13	629481	1306516	819	64	2304
SW-18	628801	1306974	824	35	1260
SW-27	628564	1310651	823	73	2628
SW-28	627950	1310644	825	70	2520
SW-29	628107	1310054	830	50	1800

SW-32	625457	1305814	836	48	1728
SW-09	628526	1305426	821	63	2268
SW-12	629577	1305966	818	60	2160
SW-14	630152	1306444	815	80	2880
SW-26	628683	1310062	830	62	2232
SW-30	627350	1310427	833	32	1152
SW-31	625342	1306386	841	26	936
SW-33	625561	1305231	842	28	1008
SW-34	628685	1304650	821	55	1980
SW-35	625813	1304050	833	56	2016
SW-36	625085	1304650	835	27	972
SW-55	626721	1306644	834	50	1800
SW-56	622006	1305748	857	50	1800
SW-57	624336	1303340	841	50	1800
TCTW-010-14	611247	1291525	954	4	152.28
TCTW-018-14	614355	1309920	925	53	1908
SWTW1	566480	1299859		20	576
Badule#1	607011	1310053	28	28	806.4
Merto#1	627929	1308203	23	23	648
Badule#2	605536	1309896	27	27	766.08
Merto#2	627309	1309076	28	28	794.88
Kofoburur	617757	1312420	885	3	86.4
Fialu	632178	1313057	805	3	86.4
2 Badule	607015	1312377	980	4	115.2
1st badule	604222	1310570	1013	5	144
Jara	607624	1289396	983	3	86.4
Gofo mesg	612950	1310367	920	3	86.4
2 Badule	607015	1312377	980	3	86.4
ewa22	610679	1313591	938	3	86.4
Bolotomo	604031	1306661	1042	3	86.4
Fularba	604630	1308330	1013	2	57.6
1st badule	604222	1310570	1013	3	86.4
Fialu	632187	1313051	806	3	86.4
Regden 2	608643	1303577	928	3	86.4
Kerewayu	604920	1301166	983	3	86.4
Irrigation uses					**87,180.48**
Domestic uses					**4,858.56**
Total					**92,039.04**

Annex II: - Existing well data

Well ID	Easting	Northing	Elevation (m)	Total Depth(m)	SWL(m)	DWL(m)	DD(m)
SW-19	628985	1308094	824	218	42.7	59.86	17.16
SW-23	628445	1307923	826	212	48.8	64	15.2
SW-16	629117	1307514	825	210	42.05	57.34	15.29
SW-20	628859	1308685	822.6	200	44.65	108	63.35
SW-21	628184	1309065	827	192/176	46.8	72.3	25.5
SW-17	628578	1307344	827	196/138	44.52	83.68	39.16
SW-24	629597	1308598	820	200	43.1	74.9	31.8
SW-15	629256	1306899	823	200	42.73	83.15	40.42
SW-22	628392	1308445	827	196/124	45.34	63.78	18.44
SW-25	628745	1309301	818.8	203	45.06	73.57	28.51
HD-2	628094	1323022	828	204	24.45	39.96	14.93
SW-49	621674	1309303	859.00	246	73.65	142	68.35
SW-51	621909	1308167	859.00	224	77.97	96.06	18.11
SW-52	622018	1307576	857.00	250	75.42	145.48	70.06
SW-53	622113	1307069	857.00	240	73.78	122.82	48.72
SW-54	621530	1306982	864.60	244	75.4	113.89	38.49
SW-44	625744	1311458	845.20	240	60	108.24	48.24
SW-45	625646	1312069	835.60	246	56.67	97.04	40.37
SW-46	625615	1312667	842.60	248	58.18	99.12	40.94
SW-50	621759	1308681	853.70	246	79.54	84.03	4.49
SW-43	625793	1310860	844.00	216	58.6	85.65	27.05
SW 37	624536	1310017		225	59.26	71.36	12.1
SW 38	624664	1309403		220	63.5	77	13.5
SW 39	624795	1308773		180	65.3	77	13.5
SW 42	625267	1309404		218	61.1	71.27	10.17
SW-7	629196	1305200	819	204	41.57	45.37	3.8
SW-8	628350	1304940	822	229	44.8	47.19	2.39
SW-10	628394	1306098	827	202	46.33	49.86	3.53
SW-11	629142	1305775	824	251	43.18	54.57	11.39
SW-13	629481	1306516	819	195	42.66	47.03	4.37
SW-18	628801	1306974	824	203	40.9	43.99	3.09
SW-27	628564	1310651	823	202	42.43	50.43	8
SW-28	627950	1310644	825	208	47.43	62.89	15.46
SW-29	628107	1310054	830	251	47.2	88.6	41.4
SW-32	625457	1305814	836	174	56.73	71.07	14.34

SW-09	628526	1305426	821	251	44.36	45.44	1.08
SW-12	629577	1305966	818	204	42.50	67.82	25.32
SW-14	630152	1306444	815	228	39.87	52.8	12.93
SW-26	628683	1310062	830	214	44.20	58.87	14.67
SW-30	627350	1310427	833	174	49.67	81.86	32.19
SW-31	625342	1306386	841	196	58.00	66.23	8.23
SW-33	625561	1305231	842	180	55.50	58	2.50
SW-34	628685	1304650	821	185	52.55	62.98	10.43
SW-35	625813	1304050	833	235	55.16	67.37	12.21
SW-36	625085	1304650	835	183	56.51	69.8	13.29
SW-55	626721	1306644	834	50	2700		
SW-56	622006	1305748	857	50	2700		
SW-57	624336	1303340	841	50	2700		
TCTW-010-14	611247	1291525	954	601.7	63.2	220.15	156.95
TCTW-018-14	614355	1309920	925	409.98	23		
SWTW1	566480	1299859	1846	242	52.68	123.65	70.97
Badule#1	604222	1310570	1013		28.64		
Badule#2	607011	1310053		264	22.3		
Merto	627929	1308203		189	47.6		
Merto#2	627309	1309076		202	49		
Kofoburur	617757	1312420	885		25.69		
Fialu	632178	1313057	805				
Gofo mesg	612950	1310367	920		31.6		
2 Badule	607015	1312377	980		27.55		
Jara	607624	1289396	974	120	56.78		
ewa22	610679	1313591	938		32.5		
Bolotomo	604031	1306661	1042		52.6		
Fularba	604630	1308330	1013		36.8		
1st badule	604222	1310570	1013		28.64		
Fialu	632187	1313051	806		34.16		
Regden 2	608643	1303577	928		5.81		
Kerewayu	604920	1301166	983		18.27		

Annex III: - Hydraulic Conductivity(K) and Transmissivity (m^2/day) raw data

Well ID	Easting	Northing	Elevation (m)	T	K	SC
SW-19	628985	1308094	824	331.7	3.7	3.23
SW-23	628445	1307923	826	226.7	3.2	3.49
SW-16	629117	1307514	825	587	12.2	3.23
SW-20	628859	1308685	822.6	35.5	0.591	0.6
SW-21	628184	1309065	827	203	3.38	2.17
SW-17	628578	1307344	827	238.3	3.6	1.33
SW-24	629597	1308598	820	141.5	2.1	1.63
SW-15	629256	1306899	823	84	1.4	1.31
SW-22	628392	1308445	827	621	17.25	3.37
SW-25	628745	1309301	818.8	206	3.4	2.03
HD-2	628094	1323022	828	716	10.9	5.44
SW-49	621674	1309303	859.00			0.44
SW-51	621909	1308167	859.00	206.5	2.95	1.11
SW-52	622018	1307576	857.00	45.5	0.483	0.414
SW-53	622113	1307069	857.00	87.5	0.8	0.821
SW-54	621530	1306982	864.60	21.8	0.2	0.52
SW-44	625744	1311458	845.20	53.4	0.59	0.95
SW-45	625646	1312069	835.60	83.1	0.924	1.14
SW-46	625615	1312667	842.60	31.9	0.354	0.586
SW-50	621759	1308681	853.70	3020	32.2	11.27
SW-43	625793	1310860	844.00			1.85
SW 37	624536	1310017		122		
SW 38	624664	1309403		391		
SW 39	624795	1308773		952		
SW 42	625267	1309404		610		
SW-7	629196	1305200	819	4044.5	63.2	
SW-8	628350	1304940	822	15811	209.36	
SW-10	628394	1306098	827	10105	129.55	
SW-11	629142	1305775	824	831.4	10.14	
SW-13	629481	1306516	819	1553.71	22.32	
SW-18	628801	1306974	824	3174	42.32	
SW-27	628564	1310651	823	2855.82	39.66	
SW-28	627950	1310644	825	2770.27	38.48	
SW-29	628107	1310054	830	364.56	4.34	
SW-32	625457	1305814	836	779.82	14.44	
SW-09	628526	1305426	821	6878	84	
SW-12	629577	1305966	818	734	12	
SW-14	630152	1306444	815	564	8	
SW-26	628683	1310062	830	534	6.3	
SW-30	627350	1310427	833	242	3.4	

SW-31	625342	1306386	841	420	6.6	
SW-33	625561	1305231	842	420	7.78	
SW-34	628685	1304650	821	1098	21	
SW-35	625813	1304050	833	1706	24	
SW-36	625085	1304650	835	391	6.5	
TTW-5	614384	1344771	892	951		
TTW-6	618731	1334607	826	14700		
TCTW-010-14	611247	1291525	954	2		
Badule# 1	607011	1310053		458		
Badule# 2	605536	1309896		1750		
Merto# 1	627929	1308203		248		
Merto# 2	627309	1309076		600		

Annex IV: - Total dissolved solid (mg/l) and Electrical Conductivity (µs/cm)

Well ID	Easting	Northing	Elevation (m)	Ec(µs/cm)	TDS (mg/l)
SW-19	628985	1308094	824	973	680
SW-23	628445	1307923	826	850	560
SW-16	629117	1307514	825	1116	684
SW-20	628859	1308685	823	874	580
SW-21	628184	1309065	827	1163	780
SW-17	628578	1307344	827	1190	820
SW-24	629597	1308598	820	915	640
SW-15	629256	1306899	823	925	644
SW-22	628392	1308445	827	1293	900
SW-25	628745	1309301	819	580	400
HD-2	628094	1323022	828	1126	760
SW-49	621674	1309303	859	1076	680
SW-51	621909	1308167	859	967	560
SW-52	622018	1307576	857	953	620
SW-53	622113	1307069	857	920	560
SW-54	621530	1306982	865	1069	720
SW-44	625744	1311458	845	1154	720
SW-45	625646	1312069	836	1298	820
SW-46	625615	1312667	843	1116	690
SW-50	621759	1308681	854	994	600
SW-43	625793	1310860	844	1084	660
SW 37	624536	1310017			688
SW 38	624664	1309403			683
SW 39	624795	1308773			486
SW 42	625267	1309404			736
SW-7	629196	1305200	819	960	660
SW-8	628350	1304940	822	963	660
SW-10	628394	1306098	827	995	680
SW-11	629142	1305775	824	958	660
SW-13	629481	1306516	819	1045	680
SW-18	628801	1306974	824	859	568
SW-27	628564	1310651	823	901	600
SW-28	627950	1310644	825	941	660
SW-29	628107	1310054	830	1180	782
SW-32	625457	1305814	836	994	660
SW-09	628526	1305426	821	1035	698
SW-12	629577	1305966	818	1008	700
SW-14	630152	1306444	815	1018	680
SW-26	628683	1310062	830	937	660
SW-30	627350	1310427	833	1241	844

SW-31	625342	1306386	841	1010	656
SW-33	625561	1305231	842	974	652
SW-34	628685	1304650	821	822	550
SW-35	625813	1304050	833	940	640
SW-36	625085	1304650	835	945	637
TCTW-010-14	611247	1291525	954	1289	862
TCTW-018-14	614355	1309920	925	1216	790
SWTW1	566480	1299859		654	425
Badule#2	605536	1309896	27	830	621
Merto#2	627309	1309076	28	1290	645

Annex V: - Meteorological raw data

Climate stations	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
		Mean Rainfall (mm)											
Hara	19.8	22.3	54.9	59.4	61.5	17.4	169.0	262.3	88.9	44.8	20.5	14.3	835.0
Mile (AVA)	5.4	9.5	32.3	45.6	11.4	4.6	63.7	105.5	25.7	14.9	1.6	7.0	327.1
Kelewan	14.7	0.0	81.1	24.3	2.1	14.2	197.7	154.1	88.2	17.2	26.2	0.0	619.6
Sirinka	33.0	34.9	81.6	102.8	55.7	30.2	240.8	277.2	91.9	58.4	40.3	35.9	1082.7
Waama	6.4	13.6	7.8	30.8	21.5	7.3	106.7	237.5	49.9	4.6	0.0	1.1	487.3
Woldia	11.3	13.5	69.3	105.9	48.1	26.0	216.5	282.6	110.7	50.6	20.1	16.1	970.8
Awura	0.0	0.0	2.5	61.2	48.0	1.8	9.9	78.6	25.0	21.8	10.8	21.9	281.6
Chifra	21.2	8.8	34.2	51.7	35.1	42.1	103.1	119.7	22.3	19.1	7.0	0.0	463.9
Average	14.0	12.8	45.5	60.2	35.4	17.9	138.4	189.7	62.8	28.9	15.8	12.0	**633.5**
		Mean Temperature (ºC)											
Sirinka	17.3	18.3	19.8	20.9	22.2	23.5	22.3	21.3	20.8	19.2	18.0	17.2	20.1
Hara	19.4	21	22.2	23.6	24.7	26.1	24.8	23.6	23	21.9	20.5	19.7	22.5
Chifra	23.4	24.4	26.1	28.1	30.1	31.4	29.9	27.7	30.3	27.4	25.5	23.5	27.3
Awura	21.4	21.9	23.8	26.4	28.2	30	29	27.5	28.4	28.4	24	25.2	26.2
Ewa	16.1	16.7	16.7	18.2	19	19.5	20.2	19.6	19.2	17.3	16.1	16.2	17.9
Mile	18.2	20	19.6	20.2	21.5	23.1	20.6	19	20.7	21	19.8	19.8	20.3
Average	19.3	20.4	21.4	22.9	24.3	25.6	24.5	23.1	23.7	22.5	20.7	20.3	22.4
		Sunshine Duration (hours)											
Sirinka	6.8	8	8	8.1	8.8	7.1	4.8	6.2	6.5	8.2	7.8	7.3	7.3
Chifra	10	9.8	8.9	9.5	9	7.4	6.3	6.6	7.1	9	9.2	10	8.6
Average	8.4	8.9	8.5	8.8	8.9	7.3	5.6	6.4	6.8	8.6	8.5	8.7	7.9
		Windspeed (m/sec)											
Sirinka	1.3	1.4	1.4	1.3	1.3	1.5	1.3	1.1	1.0	0.9	1.1	1.4	1.2
Chifra	1.5	1.7	1.8	2.1	1.8	1.9	2.6	1.9	1.3	2.7	1.5	1.6	1.9
Mile	5.76	6.48	6.48	5.76	7.2	7.92	7.2	5.76	4.32	4.32	4.32	6.12	6.0
Average	2.8	3.2	3.2	3.0	3.4	3.8	3.7	2.9	2.2	2.6	2.3	3.0	3.0