ADDIS ABABA UNIVERSITY

SCHOOL OF EARTH SCIENCES

Numerical Groundwater Flow Modelling for Planning and Management of the Resource in Bacho Plain

Upper Awash Basin, Central Ethiopia

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

May, 2019

Addis Ababa University

School of graduate Studies

This is to certify that the thesis presented by Megersa Negera entitled: Numerical groundwater flow modelling for planning and management in Bacho Plain Upper Awash Basin, Central Ethiopia, submitted in partial fulfillment of the degree of Master of Science in Hydrogeology is prepared complying with the regulation and to the standard of the university.

Signed by the Examining Committee

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Declaration of Originality

I, Megersa Negera, confirm that the work contained in this thesis is my original work. It has not been previously submitted to any other universities. The thesis do not contain or copied previous materials of others except where reference is made and properly acknowledged.

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

Prof. Tenalem Ayenew Signature________________ Date_______________

Abstract

The Bacho catchment, model area, is located in upper Awash River basin. The model domain has an area of 4553km2.The area dominantly covered with volcanic rocks. The upper cover is a thin alluvial deposit at Bacho plain. Pyroclatic flows, ash, ignimbrite and basaltic rocks interlayered forming the top aquifer layer. Below these units massive and welded ignimbrite comes with extensive and recognizable thickness with low permeability and eventually the last model domain layer is a very thick scoraceous basalt that cover wide area with relatively better groundwater potential and permeability.

A groundwater flow model was developed for the Bacho Catchment in the upper Awash basin to analyze the groundwater flow characteristics and determine the aquifer parameters for future groundwater management and planning. This model will assist the decision makers to develop long term strategies to ensure environmentally responsible and economically sustainable use of this valuable natural resource.

The numerical model simulates groundwater flow within three hydrostratigraphic units; the top 150m unit comprises basaltic and pyroclastic rocks; the middle is 100m thick ignimbrite which act as confining layer; and the third is a unit with 300m thick scoraceous basalt layers which is the major aquifer in the model domain. Most water boreholes were developed in first and third hydrostratigraphic layers for domestic, industrial and irrigation purposes.

Conceptually developed model of research area was represented to numerical model by means of computer code_ processing modflow version 8.0.15. The area was discretized to three layers and a uniform grid size of 200m by 200m active model cells. Total perimeter boundary is about 492km of which 75% is no flow and about 25% is head dependent flow boundaries. The model was simulated with a steady state condition. Analytically determined aquifer parameters were encoded and five flow package namely, drain, head dependent boundary flow, recharge, river leakage and well packages were simulated.

Conceptual model was developed from the hydrological, geological and hydrogeological historical data and field observations. The conceptual model was translated in to mathematical expression using processing modflow code. The model was calibrated by trial and error method by comparing the observed and measured hydraulic head and water balance.

Recharge components to the aquifers are from rainfall, inter aquifer flow from Abay basin across the northern boundary and Awash River at upstream part. Discharge is predominantly through groundwater leakage to rivers, under aquifer outflow across the southern boundary to Ada'a plain and withdrawal by pumping. Groundwater is dominantly flow from north to south in general. In the upper layer groundwater flow is towards center of model area and dominantly towards Awash River at lower topography.

The model was most sensitive to recharge, horizontal hydraulic head, and river hydraulic conductance. It is less affected by change in vertical hydraulic conductivity and other aquifer parameters. The calibrated model recharge volume is estimated to be 1.07Mm^3/day. In flow from river leakage is approximated 0.330Mm^3/day and general head dependent inflow is about 0.683Mm^3/day. The final calibrated model total outflows is calculate to be 2.09Mm^3/day. At final model calibration resulted in the spatial recharge distribution ranges from 5.4x10^{-5}m/d to1.99x10^{-4} m/d; horizontal hydraulic conductivity varies from 0.44m/d to 9.2m/d and 0.07m/d to 45m/d in the top and bottom aquifer layers, respectively.

Recharge reduction by 50% and groundwater withdrawals scenarios were formulated to examine the aquifer response to such stresses. Accordingly, occurrence of both stresses simultaneously will cause surface water to lose 23.4% amount of water to sub-surface system and water level dropped with an average of 20.6m in the research boundary. However, increase of recharge through injection well will only rise water level by 2.65m and discharges much of the recharge water to Awash River. Introduction of 100 productive wells at expected potential area like center of Bacho and Holeta resulted in 3.8 m overall decline of head in the model area and less drawdown at Holeta water wells.

Most rivers and stream channels are losing type in the upper higher topographic locations while at lower Bacho flat land almost all river gains about 1.78Mm3/day of groundwater as baseflow. Hence, river _ groundwater interaction is very recognizable flow process in catchment.

Acknowledgement

First and for most I would like to thank the almighty God. Special appreciations is to my advisor Prof. Tenalem Ayenew for his assistance and advice in research work. Thanks to all staffs of Earth sciences specially the Hydrogeology Stream for capacitating me with your broad knowledge of the science devotedly which enable me to achieve the research work.

I am grateful to Ministry of Water, Irrigation and Electricity for hydrological data, national meteorological agency for providing meteorological data; federal Water Works Design and Supervision and Oromia Water Works Design and Supervision Enterprises for providing me necessary information and boreholes data. I express thanks to all zonal and woreda water sectors in the research area for your support ad contribution.

Heartfelt thanks to all my beloved family, particularly my father Negera Jira and mother Alemitu Segni thank you very much for supporting me during my tough times. Great appreciation to my sister Taru Negera you have special role in accomplishing this research work, without your encouragement and support I could not finalize it.

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ACRONYMS

DEM	Digital Elevation Model
DWL	dynamic Water Level
Eqn	Equation
FAO	Food and Agriculture Organization of United Nations
FD	Finite Difference
FE	Finite Element
GHB	General Head Boundary
GIS	Geographic Information System
GSE	Geological Survey of Ethiopia
K	hydraulic conductivity
KM	Kilo meters
LULC	Land use an Land cover
M	Meters
masl	meters above sea level
mbgl	meters below ground level
MCM	Million cubic meter
MOWIE	Ministry of Water Irrigation and Energy
NMA	National meteorological Agency
OWWDSE	Oromia Water Works Design and Supervision Enterprise
PCG2	Preconditioned Conjugate Gradient 2 package (model solver)
SWL	Static Water Level
WWDSE	Water Works Design and Supervision Enterprise
YTVL	Yerer Tulu Welel Vocanic Lineament

1. INTRODUCTION

1.1. Background

Groundwater is very essential resource for domestic water supply, agriculture and industrial use. It is the second most abundant fresh water, very reliable and adequate resource as compared to all other liquid fresh waters on earth. However, the groundwater is not available everywhere beneath the earth’s surface. It exists in pore spaces of soil sediments, and fractured & weathered rocks (aquifers). However, understanding the occurrence and flow of under groundwater is not easy. It require detail study of the resource with different methods and techniques. Groundwater flow modeling is one of these methods that enable to understand the groundwater flow nature and their aquifer properties at large. The model also helps to tell future events for the resource development and appropriate utilization of this resource. Consequently, this research work is intended to address groundwater flow nature and aquifer properties of Bacho catchment.

The research area is located in Awash Basin at western margin of rift valley. The catchment is specifically enclosed in the upper most part of Awash River Basin. The dominant geology is volcanic rocks in general and basalts, trachyte, rhyolite and ignimbrite in particular (Kazmin, V., 1979; Mengesha Teferea, 1996; Ketema Wogari 2006). According to Tesfaye Chernet (1993) the hydrogeology of the area has been classified as having moderate permeability and productivity.

The movement of groundwater in the subsurface is controlled by geomorphology, geology and geological structures. Darcy’s Law and continuity principles define the nature of groundwater movement in sub subsurface (Tenalem A & Tamiru A, 2001; Anderson, M.P. & Woessner, W.W., 1992). The same principles help also in modeling groundwater flow. A numerical groundwater model is a computer-based representation of the essential features of a natural hydrogeological system that uses the laws of science and mathematics (Anderson, M.P. & Woessner, W.W., 1992). The model has two components the conceptual and mathematical model Groundwater flow models are simplifications of real hydrogeological systems. The complex geological formations are simplified into a limited number of aquifer and aquitard layers. Groundwater modeling is an important tool to provide guidance for management of groundwater resource.

Groundwater flow model have multiple uses. It can be used as interpretative tools for investigation; used to predict future conditions for development; as planning and management tools to give directions for decision makers. It also helps to evaluate the recharge, discharge and aquifer storage of the basin.

Numerous studies have been conducted in upper part of Awash Basin by academia to characterize the aquifer of some portion of the watersheds discretely based on conventional methodologies. This study will utilize findings of previous works for the wider scale evaluation of the sub-basin using numerical groundwater flow modelling by computer program processing modflow.

In this research, reliable primary and secondary data have been collected and encoded into the program for simulation of the groundwater flow. Steady state and three layers model were designed to better understand and evaluate the catchment aquifer systems. Steady state condition was considered as time series data of aquifer parameters were hardly possible to acquire. Steady state condition is flow happened when the magnitude and direction of the flow velocity are constant with time while transient flow is when these parameters changes with time, so unsteady flow is time dependent while steady flow is independent of time (freeze and Chery, 1979).

Therefore, Bacho plain groundwater system was represented in the model as three hydrostratigraphic layers and simulated with steady state flow conditions. The catchment water balance and aquifer properties were identified form the calibrated model result. Eventually the model helps to simulate future scenarios of climate change and over pumping to propose sustainable aquifer yield which will help to plan and manage the groundwater resource of the study area.

1.2. Significance of the research

Most of the previous researchers have conducted study based on the conventional geological and hydrogeological methods to classify the aquifer types and its productivity. Some using remote sensing and GIS to identify the groundwater potential area and produce potential map. Most of them utilized similar methods in the estimation of recharge potential, that is base flow separation and analytical methods. In this research numerical groundwater flow modeling using modflow employed to evaluate the flow system.

Thus, this research intended to determine the general groundwater flow of the sub-basin, evaluate the model simulation under different scenarios to maximize the possible future impact of climate and to predict the impact of over abstraction of the resource.

In general, this research shall answer how much groundwater goes in and out from the aquifer system of the basin. How much of water passes the block to the other adjacent aquifer block. In addition, the model will simulated to give solution on how the groundwater resources will be exploited and managed without affecting the aquifer yielding capacity.

1.3. Objectives of Study

1.3.1. General

The overall objective of this research is to evaluate the groundwater flow system and water balance of the Bacho basin and implement different scenarios for future sustainable management and planning of the resource using the numerical groundwater flow modelling.

1.3.2. Specific

The specific objectives of this research are;

- Characterize the aquifer of the study area and construct hydrogeological map.
- Develop conceptual model of the Bacho catchment to define its numerical representation.
- Construct the groundwater flow of the research area using piezometric data; compare and calibrate with model potentiometric surface
- Investigating the effect of groundwater abstraction at a well on the flow regime and estimating the resulting drawdown.
- Identify sensitive parameters in the study area which impact the groundwater flow
- Analysis of different management scenarios on groundwater systems

1.4. Methodologies and Materials

Numerical modelling demand several information like climatic data, hydrogeological information and boundary conditions. Climatic data was gathered from National Meteorological Agency (NMA), hydrologic data from Ministry of Water Irrigation and Electricity, well data from Regional water sectors and geology from Geological Survey of Ethiopia. Furthermore, field observation conducted to fill the gap at places where insufficient data identified.

Secondary data collected and acquired from various offices and more importantly from document review. Data gathering standard format used to record and organize information from secondary documents and during field work. The geographical Information System extensively utilized to organize and preprocess geospatial data in to the requirement of numerical model.

Secondary documents like geology, DEM, satellite images and Google map were utilized to analyzed and generate raster maps for the model inputs.

To estimate the groundwater potential of the catchment numerical modelling using processing modflow version 8.0.15 is applied. Major river and tributaries of the basin are delineated by Soil and Water Assessment Tools (SWAT) and imported to model environment as DXF file. To generate model input like river dimensions, land use & land cover and other remotely sensed feature satellite and Google Earth images were used.

In general, several computer programs and tools applied in preparation, organization and analysis of ground data. Some of the major computer programs utilized are show on **Table 1.1**.

Table 1.1 Materials and software used

No	Description software and equipment	Usage
1	Processing Modflow Version 8.0.15	For numerical modeling
2	ArcGIS 10.4.1	For mapping
3	Surfer 12	For to prepare model input data
4	Google earth	Estimation river length and width
5	Excel	Data organization and analysis
6	Global mapper 18	For DEM processing and generating grid cell
7	Garmin GPS	For ground X,Y, & Z point data collection

The study mainly focus on quantitative approach, the reason why to follow this approach are groundwater modelling dominantly demand quantitative data. Both primary and secondary data are equally significant as an inputs to the model environment. As result of that, secondary data collected from documents and databases of government offices, NOGs and private drilling companies. Whereas primary data from field observations. Model outputs were evaluated, verified and calibrated against actual observed values of reliable well hydraulic heads. Climatic and hydrological daily data of 30 years were used to estimate recharge using soil and water balance method.

Based on the collected and organized data conceptual and numerical model developed. All parameters encoded in the modflow environment and simulated. Another important step after simulation is model calibration, which is comparing the model output against the actual observed hydraulic head. It is after this continually calibrations that the model output will be considered as reliable result for future prediction on how to manage the groundwater resource of the basin. The detail modeling procedure or protocol is illustrated below (Fig 1.1).

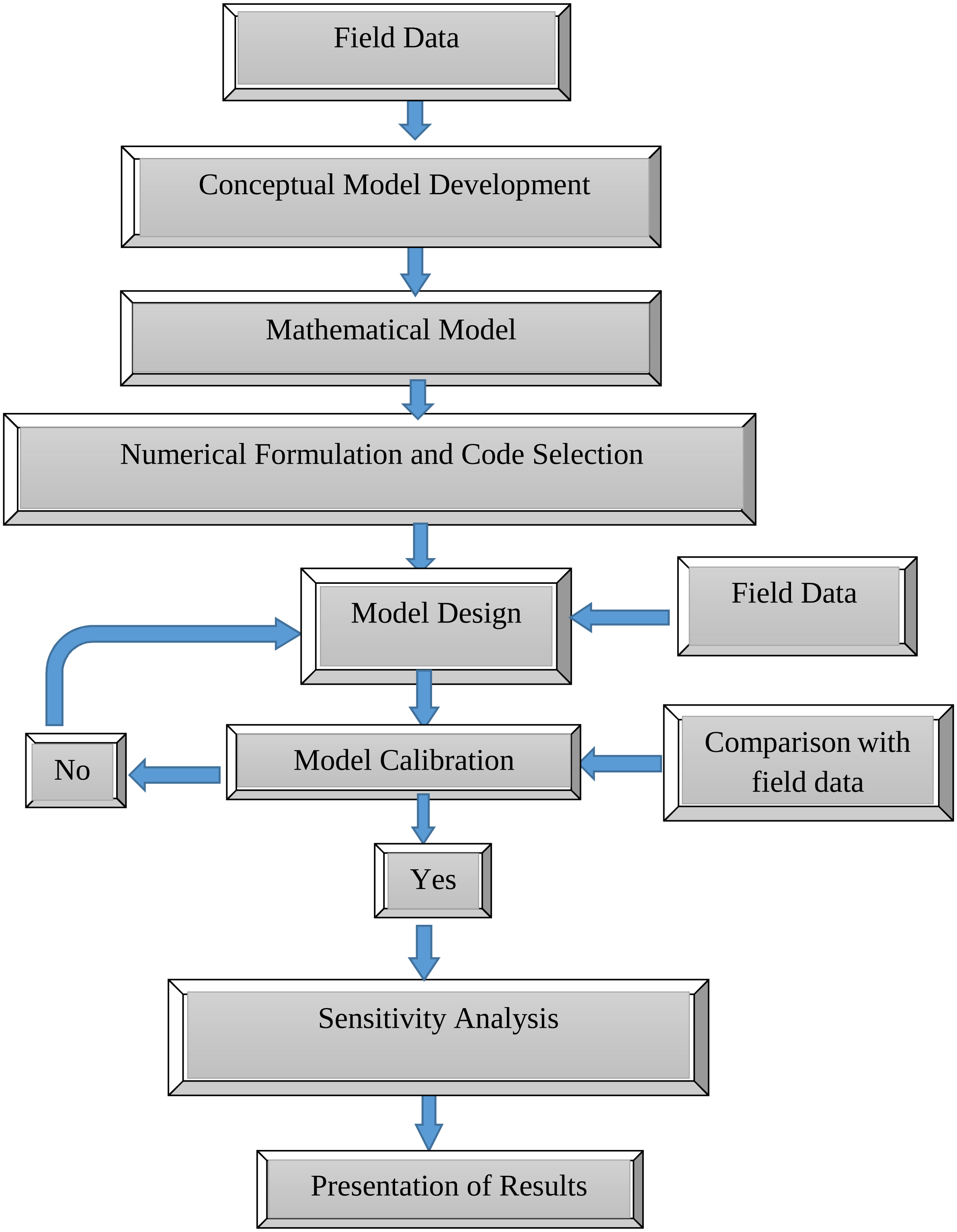

Fig 1.1 Model flow chart (adopted from Anderson and Woessner, 1992)

1.5. Previous Works and Literature Review

Awash basin in general and upper Awash in particular has been area of interest for several researchers. A number of studies conducted in the basin with different objectives and produced numerous useful findings. Among many some related and important literatures reviewed for this specific research purpose.

Geological Survey of Ethiopia (GSE) exhaustively studied and mapped geology and hydrogeology of Akaki and Addis Ababa sheet by 1:250,000 scale in 2010 and 2011 consecutive years.

According to WWDSE (2009) water level at south is above surface while at center of Bacho plain it is rises up to 5mbgl. Transmisivity of Bacho plain as analyzed from deep productive wells is higher than 10002/day. The estimated inflow from Abay Plateau to Bacho plain is 0.88MCM/day and exploitable groundwater potential is 1.76MCM/day. Safe yield of Bacho plain estimated to be 518,400m3/day or 6000lit/sec from 120 wells each discharging 50lit/sec.

Seifu Kebede (2013) documented the hydrogeologic properties of major aquifers of Addis Ababa and surrounding as; late Pliocene to quaternary fractured, vesicular and scoraceous basaltic units recognized as highly productive having discharge range from 3-89l/sec, and transmissivity (1833-100000m^2/day); upper Miocene Addis Ababa fractured and weathered basalt as moderately productive with discharge ranges (0.5-20l/s) and transmissivity (2-6000m^2/day); upper Miocene to Pliocene ignimbrites, welded tuffs ,ashes and associated basalt intercalation as least productive with discharge ranges (0.4-15l/s) and transmissivity (15-110m^2/day); lastly the Oligo –Miocene Tarmaber plateau unit basalt having discharge of 5-200l/sec and confined to semi confined nature.

2. BACKGROUND DESCRIPTION OF STUDY AREA

2.1. Location

The study area, Bacho plain, is located at upper and western part of Awash River Basin in central Ethiopia. Geographically the catchment is located in between 384929-465761 UTM_E (Longitude) and 926879-1028429 UTM_N (latitude). It has an area of 4553KM^2 having 492KM boundary perimeters. Administratively it is found in three zones of Oromia Regional State; namely, Special Zone surrounding Finfinnee, West Shewa and South West Shewa Zones.

The sub-basin boundary shape is delineated using ARC SWAT (Fig 2.1). Depending on hydrographic boundary, it is surrounded in the north by Abay River Basin, in the west By Omo_Gibe River Basin, and in the east by Furi and Wechecha mountains range that divides the sub-basin from Akaki Catchment.

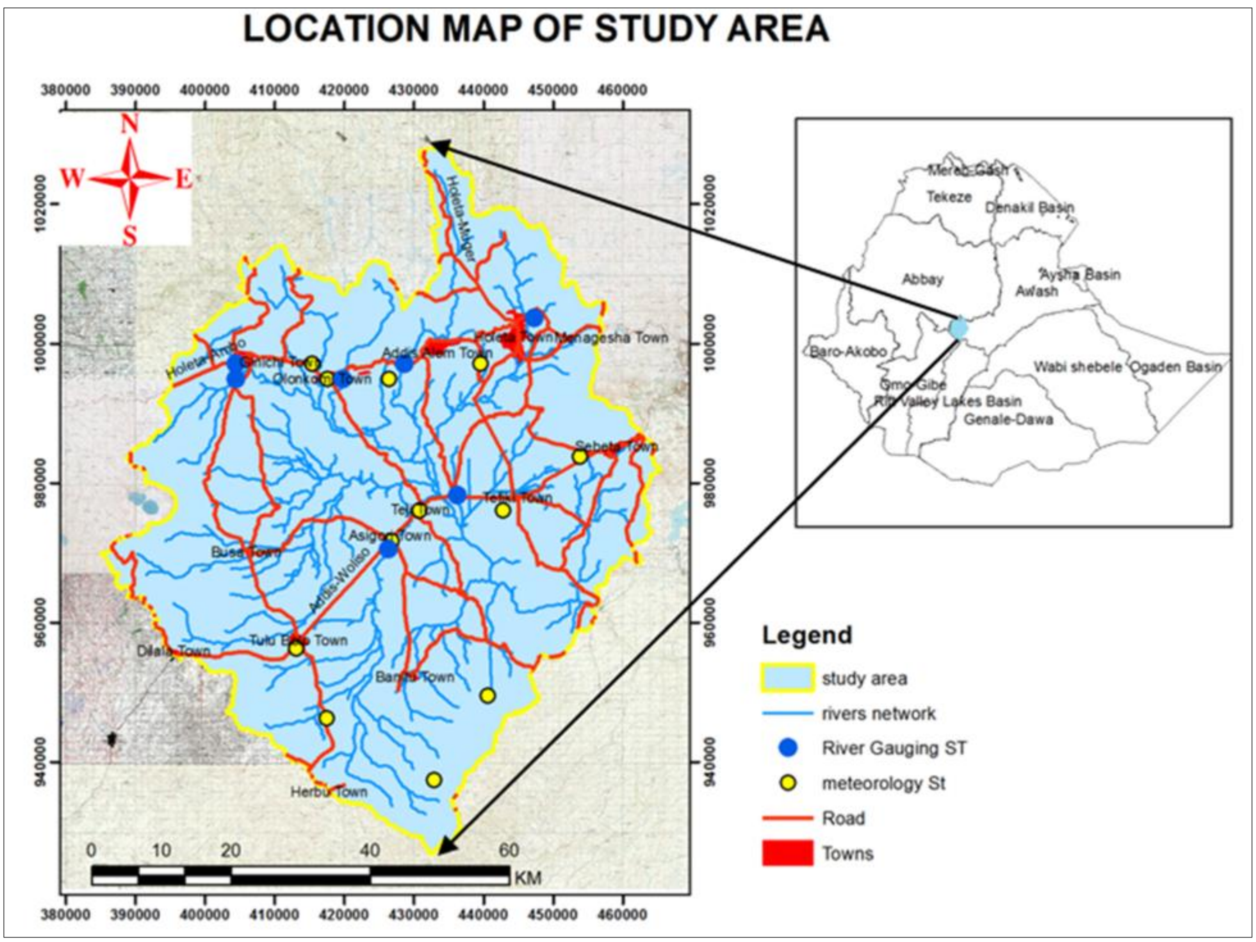

Fig 2.1 Location map of study area

2.2. Physiography and morphology

Bacho catchment is the upper part and water tower of Awash River Basin that completely located and drain in the Main Ethiopian Rift System. Physiography of study area probably resulted from volcanic and subsequent tectonic activities. Afterwards, erosion played significant role in reshaping this sub basin to acquire current morphology.

Volcanic plugs, shields and volcanic centers form long ridges and terrains which give the catchment current physical and hydraulic boundary. However, flat or plain topography of Bacho might be resulted from rift tectonic activity and subsequent deposition f sediment from high land. Drainage system greatly dissected the higher topography forming gullies and valleys.

In general, within the study boundary surface elevation greatly vary from 2000masl at Melka Kunture to 3555masl on high lands (Fig 2.2).

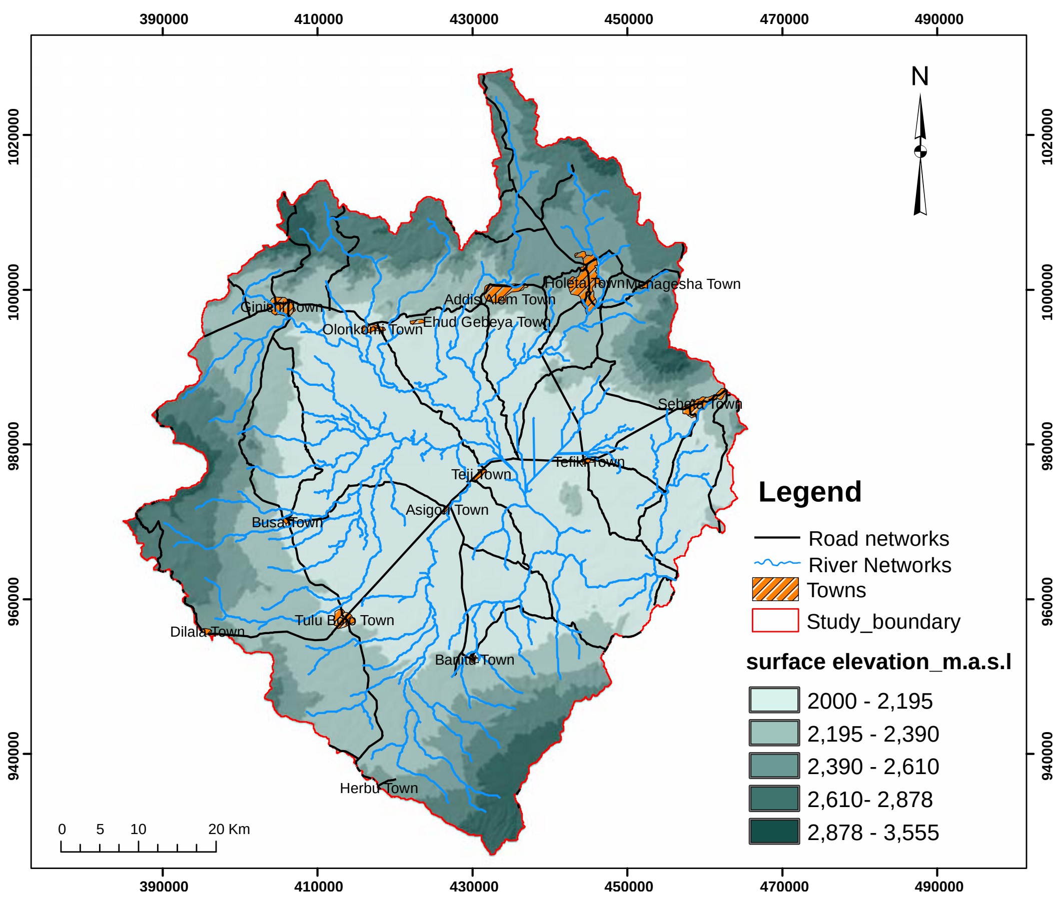

Fig 2.2 Topographic map of Bacho Plain

2.3. Hydrological Descriptions / Hydrology

Awash River originates from High lands of Ginchi and Holeta, which is the western escarpment of the Main Ethiopian Rift system.

The study boundary has a catchment area of 4553Km2 which is delineated fixing Awash River outlet at Melka Kunture. In the catchment all perennial and intermittent river drainage networks altogether forms dendritic pattern (Fig 2.3). At each tributaries, it has river gauging stations. In total six gauging stations used to analyze the hydrological assessment of the Bacho Plain.

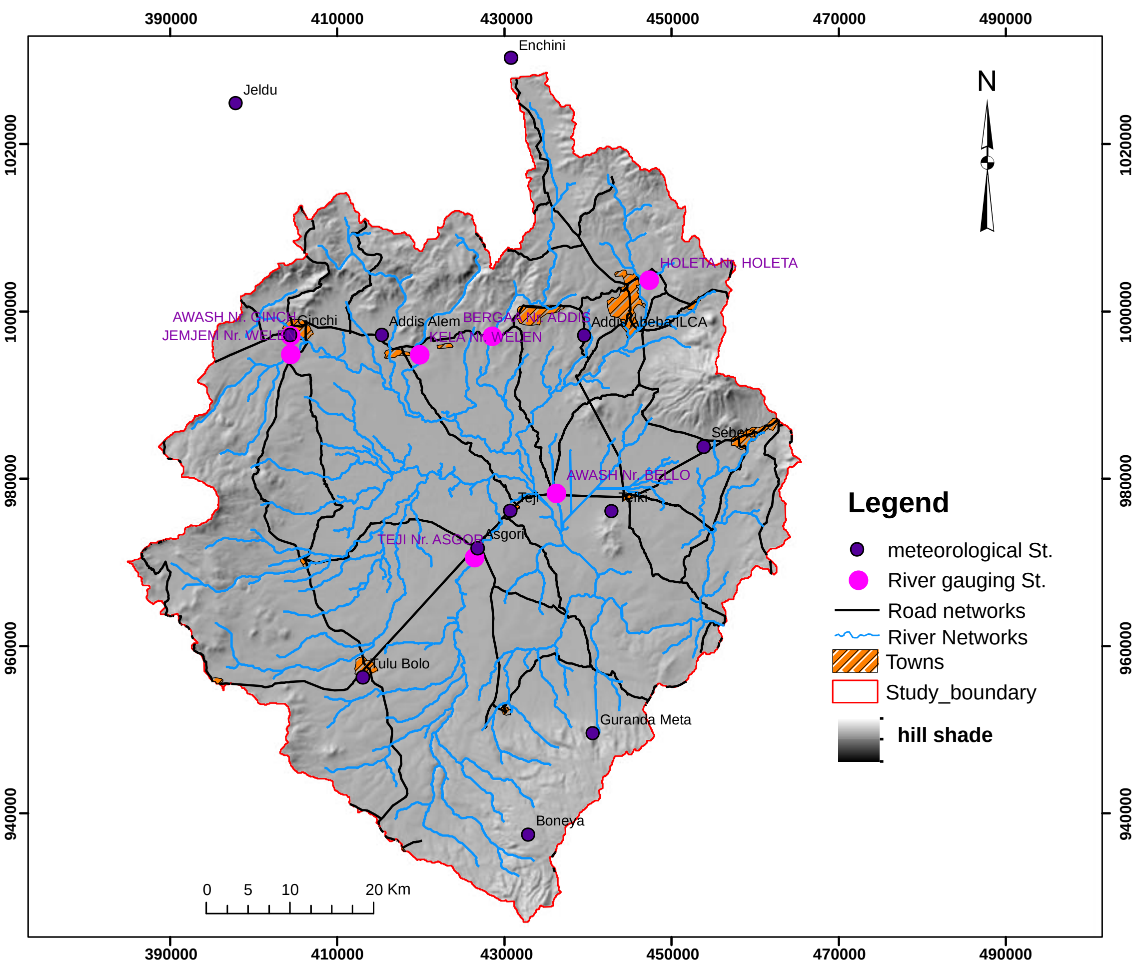

Fig 2.3. River networks and gauging stations

2.4. Soil, Land Use and Land Cover

Land use and land cover is main factors that govern groundwater recharge. Accordingly, in Bacho Catchment agricultural land is the dominant land use, cereals and vegetables intensively cultivated. The research area land use and land cover was studied recently by OWWDSE (2018). Almost 81% of the Bacho plain is intensively cultivated with cereals and vegetables. 7.5 % is shrub and grass land on higher altitude and sloppy topography. Forest covers only 2% of entire intended study area specifically forests grown densely at Sebeta, Menagesa (Menaesha National Park) and Ginchi area. The settlement pattern is widely dispersed and has insignificant pavement structures except at some towns; like Sebeta, Holeta and Ginchi towns (**Fig 2.4** & Table 2.1).

The estimated average rooting depth is in cultivated clay loam soil is less than 0.8m and for bush, shrub and forests it ranges from 1m to 2m. According to OWWDSE 2017, the available water capacity of root zones ranges from 100mm to 250mm. Shrubs and grass land have relatively deeper roots than cereal crops. The forests expected to have deeper roots and its available water capacity in clay loam is estimated to be 250mm. These data of land use and land cover employed to estimate recharge at nearby meteorological station using soil water balance method as discussed under section 3.2.3. Slope of the Bacho plain generally flat and less than 2% this topography would have facilitated recharge, however, thick clay soil overburden strongly hinder infiltration thus runoff is high (higher runoff coefficient).

Table 2.1. Bacho plain land use and land cover types

Types of LULC	Area coverage (km2)	Percent (%)
Cultivated Land	3661.95	80.8
Open Bush, Shrub & grass Land	338.76	7.5
Settlement	274.71	6.1
Forest	87.42	1.9
Wetland	66.54	1.5
Built-Up Area	52.97	1.2
Bare land	49.14	1.1

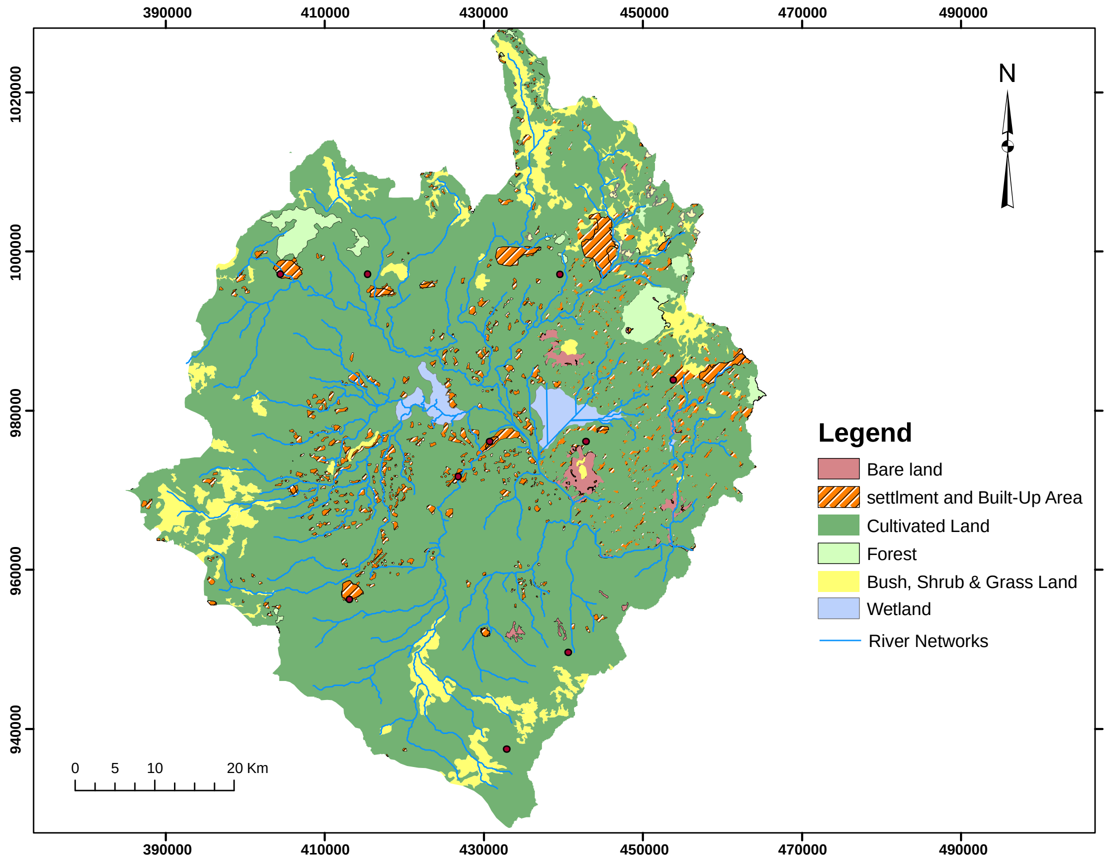

Fig 2.4. Land use and land cover map of study area (modified from OWWDSE, 2017)

2.5. Hydrometeorology

2.5.1. Climate

Climate is generally dependent of physiography in the country. The weather and climatic condition significantly vary with altitude. The higher the altitude the better rainfall the area gets annually and conversely the cooler air temperature. Topography of the study area ranges from 2000 to 3555masl. Based on the surface topography study area is traditionally classified the Woina Dega (sub-tropical) climatic zone.

Rainfall distribution vary all over the catchment. There are about 15 meteorological (one synoptic, four class-3 and ten class-4) stations evenly distributed in the Bacho plain. Long term (1980-2017) average rainfall using Theisson polygon method gives 1104mm/year for entire study area and mean temperature of 17.64^{0}C.

2.5.1.1. Precipitation

The study area has no climatic variation. However, precipitation varies in hundreds of mm per year in the catchment due to orographic effect. Higher topography gets much rainfall than low laying Bacho plain. Mean annual rainfall is higher at Sebeta (1374mm) station and minimum at the center of Bacho plain around Tefki and Taji with annual average of 850mm (Table 2.2). Rainfall in vicinity is characterized by mono modal pattern and the catchment experiences five consecutive rain months starting from May up to end of September (Table 2.2 & Fig 2.5). October to February is peak dry months. The rainfall distribution decreases across high altitude of Intoto Ridge towards lower plain of Bacho.

Spatial distribution of rainfall was analyzed by constructing Thiessen Polygon for 12 representative meteorological stations. Long term daily data of precipitation was collected from National Meteorological Agency. The data was arranged and organized using excel program (pivot table) in single vertical column to fill the missing data. The missing daily precipitation data was filled with normal ratio method considering maximum number of neighboring recording stations with aid of excel spreadsheet. The entire research catchment long term area weighted mean rainfall is estimate to be 1103.8mm/yr.

Table 2.2. Analyzed mean monthly and annual rainfall (in mm). (Source daily data from NMA 1980-2017)

SATIONS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN ANNUAL	YEAR OF DATA
Addis Ababa	12.28	30.51	61.97	87.97	81.10	114.91	229.22	243.20	135.38	28.14	4.71	6.03	1035.42	1980-2017
Addis Alem	17.75	32.81	66.03	65.80	86.77	139.65	262.98	234.58	141.32	30.35	27.21	13.10	1118.35	1997-2017
Ambo	21.58	31.55	51.71	70.39	101.99	159.52	227.25	210.83	113.56	36.02	9.57	9.48	1043.46	1984-2017
Asgori	15.09	31.48	62.18	83.58	75.39	138.85	252.43	253.10	110.85	18.77	5.86	5.61	1053.19	1980-2016
Boneya	8.35	25.39	39.74	61.80	62.92	98.48	206.67	218.21	107.39	13.68	4.26	4.86	851.77	1980-2017
Dilela	19.19	29.99	66.02	88.17	100.95	169.34	249.27	262.48	136.16	27.89	7.58	9.15	1166.19	1980-2017
Inselale	12.96	23.28	45.19	62.08	58.33	110.28	204.04	189.81	97.66	20.10	6.38	6.18	836.30	1980-2016
Ginchi	24.48	38.78	71.73	93.86	97.89	142.30	230.23	242.84	143.28	37.67	11.84	10.29	1145.19	1980-2015
G/Meta	9.88	23.00	47.35	70.56	69.56	115.66	240.61	271.85	161.05	26.69	5.73	4.21	1046.14	1980-2016
Inchini	25.70	28.98	73.18	82.56	91.58	155.40	281.35	261.06	136.80	43.84	19.90	16.70	1217.06	1980-2016
Jeldu	23.27	33.60	79.97	110.44	109.22	196.18	276.67	283.84	192.48	59.53	19.93	15.36	1400.49	1987-2016
Kimoye	15.24	36.28	69.37	80.27	88.62	126.78	240.32	219.03	115.60	27.07	29.21	29.47	1077.26	1980-2016
Olankomi	19.20	26.78	62.44	76.90	84.38	132.50	239.71	219.59	115.53	27.67	8.48	13.35	1026.54	1980-2016
Sebeta	11.83	52.17	71.31	101.58	102.37	168.87	310.41	359.10	145.90	29.18	13.43	7.74	1373.88	1980-2014
Tefki	6.59	22.59	28.79	64.41	78.86	117.00	172.89	209.55	131.30	30.61	14.67	8.17	885.43	2010-2016
Teji	12.25	30.90	50.40	74.45	72.84	124.61	219.14	216.86	102.60	19.26	6.93	8.94	939.18	1980-2016
Tulubolo	10.88	15.20	44.03	65.97	100.58	214.29	280.63	279.82	114.11	17.81	4.59	6.47	1154.38	1988-2016

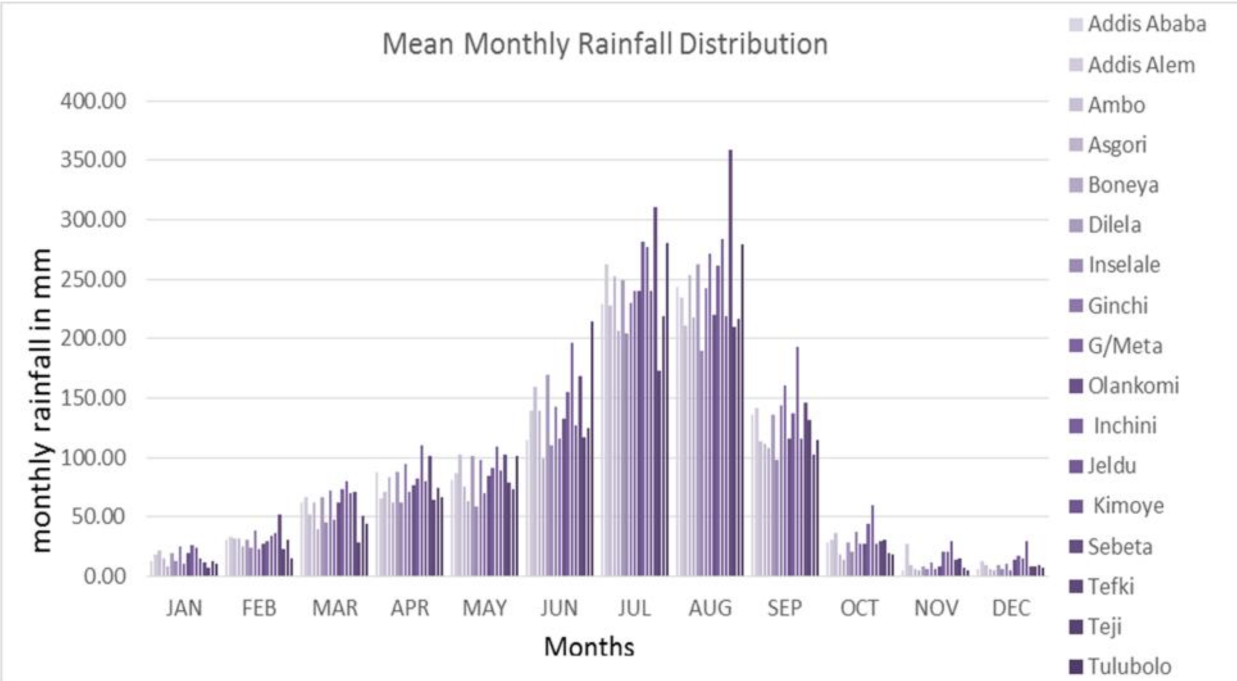

Fig 2.5 Mean monthly rainfall distribution of Bacho area- Upper Awash (1980-2017)

2.5.1.2. Temperature

Temperature in general depends on altitude and intensity and duration of sun shine hours. Topographic high exhibited lower daily temperature while higher temperature is characteristics of lower landscapes. During day and night temperature is significantly differ. It is higher in day time than night. This temperature change is accounted for the effect of sun radiation.

In Bacho plain surface elevation varies from 2000 to 3555 masl. This depicts that study area is relatively located at topographic high. Thus temperature is comparatively low. Mean monthly minimum and maximum temperature in the research area is 9.5°C and 25.82°C respectively. The mean annual temperature of the Bacho Plain is 17.64°C. Table 2.3 depicts that temperature variation within the catchment from station to station is not substantial; however, during daytime and night temperature considerably vary.

Table 2.3. Summary of mean monthly and annual temperature of study area (data source NMA)

Stations	mean monthly minimum (^{0}C)	mean monthly maximum (^{0}C)	mean annual (^{0}C)	Recording duration
Addis Alem	9.43	24.6	16.96	1997-2017
Asgori	8.47	27.2	17.82	1980-2017
Kimoye	9.88	25.1	17.49	1981-2017
Tafki	10.27	27.33	18.77	2010-2017

Tulu Bollo	9.45	24.89	17.17	1988-2017
Area average	**9.5**	**25.824**	**17.642**	

3. GEOLOGY AND HYDROGEOLOGY

3.1. Geology

3.1.1. Regional Geological Setting

The geological setup of the area dominantly associated with uplifting, subsidence, sedimentation and volcano-tectonic activities which resulted in the development of the Western Ethiopian plateau and the main Ethiopian rift valley. The main rock types includes, Paleocene (late Eocene to late Oligocene) fissural flood basalt with minor rhyolite, trachyte and pyroclastic flow, Neocene (Miocene-Pliocene) pyroclastic, rhyolite and trachytic flow and Pleistocene-Holocene basic to acidic volcanic and deposits including the resent lacustrine and alluvial sediments. Ashangi Group (Aiba basalt) is a Cainozoic volcanic rock, its main source was associated with rift faults and probably has a Paleocene to Miocene age range (Kazmin, V., 1975)

Foota basalt (Tarmaber Basalt) it is result of central volcanism. It is younger than Intoto Trachytes. The lower ignimbrite is formed from central volcanism and compositionally constitutes ignimbrites, agglomerates and ash deposits during Upper Pliocene to Miocene period. (Assegid, 2007).

Wechecha_Yere_Furi Trachyte and trachy basalts are formed after the lower ignimbrite. It was result of shield volcanic eruption. Following this unit Wechecha_Furi Ignimbrite erupted probably from satellite centers (Assegid, 2007). Eventually, tertiary sediments, quaternary tuff, basalt and alluvial sediment deposited along the river course and on vast plain land of Bacho area.

3.1.2. Geology of the Study Area

The study area is dominantly covered by volcanic rocks. Wechecha and Furi Ridge is ignimbrite (reference).

Tarmaber (Foota) Basalt (Mtb)

This basalt unit outcropped at the northern part of the area around ridges of Holeta and Ginchi. It covers about 434 km2 (10%) of the area. It forms mountain ranges and has higher elevation. It is characterized by sub horizontal layering with alternating layers of vesicular aphanitic basalt and porphyritic basalt (Assegid 2007). At some places, it has columnar joints and experiences spheroidal weathering. According to Assegid (2007), the unit has an estimated thickness of 480m.

Welded and partially welded pyroclastic flows (Nnwpp)

The unit is outcropped at the southern and southeastern margin of study boundary. It covers about 496km2 (11%) of the study region. The ignimbrite is fine grained, poorly welded and has developed fiamme. It prevalently intercalated with rhyolite lave flows, ash and unwelded tuff (Efrem B., 2010).

Welded pyroclastics with interbedded basaltic lava flows (Nnwp).

This unit is distributed around southern and southeastern boundary of study area. The surface outcropped covers about 85km2 (2%). This pyroclastic comprises of welded peralkaline pantelleritic fine grained ignimbrite and develop vitrophic fiamme (Tsegaye. A. et.al, 2005 and Efrem B. et.al, 2010). It is inter bedded with basaltic lava flows.

Gashe Megal Rhyolites (Ngmr)

The rhyolite lave flows and pyroclastic and interbedded lave flow are exposed at the southern margin of the study area around Boneya (Fig 3.1). It covers about 207km2 (5%) of total area. The unit composed of alkali feldspars, quartz and mica (Efrem Beshawered, 2010). The rhyolite forms sparsely distributed multiple dome of wide base and gentle slope.

Wechecha-Furi trachyte (Nwt)

The Wechecha-Furi ridge is comprises of trachytic lava flows, domes and pyroclastic materials. This unit outcropped on wechecha Mountain and at western margin of basin boundary. In total Wechecha_Furi Trachyte covers an area of 505 km2 (11%) of research space. It has aphanitic, medium to coarse grained and vesicular texture. At places and lower area, it shows columnar joints.

Alluvial sediments (Qal)

This sediment deposited at lower and flat topography of Bacho area, along the river channels and low laying land surface (Fig 3.1). It cover about 1879Km2 (42%) of the study area. The sediment is a mixture of sand, silt and clay. At some places as learned from well logs, the top part is covered by about 20m thick dark to brown clay soil overburden.

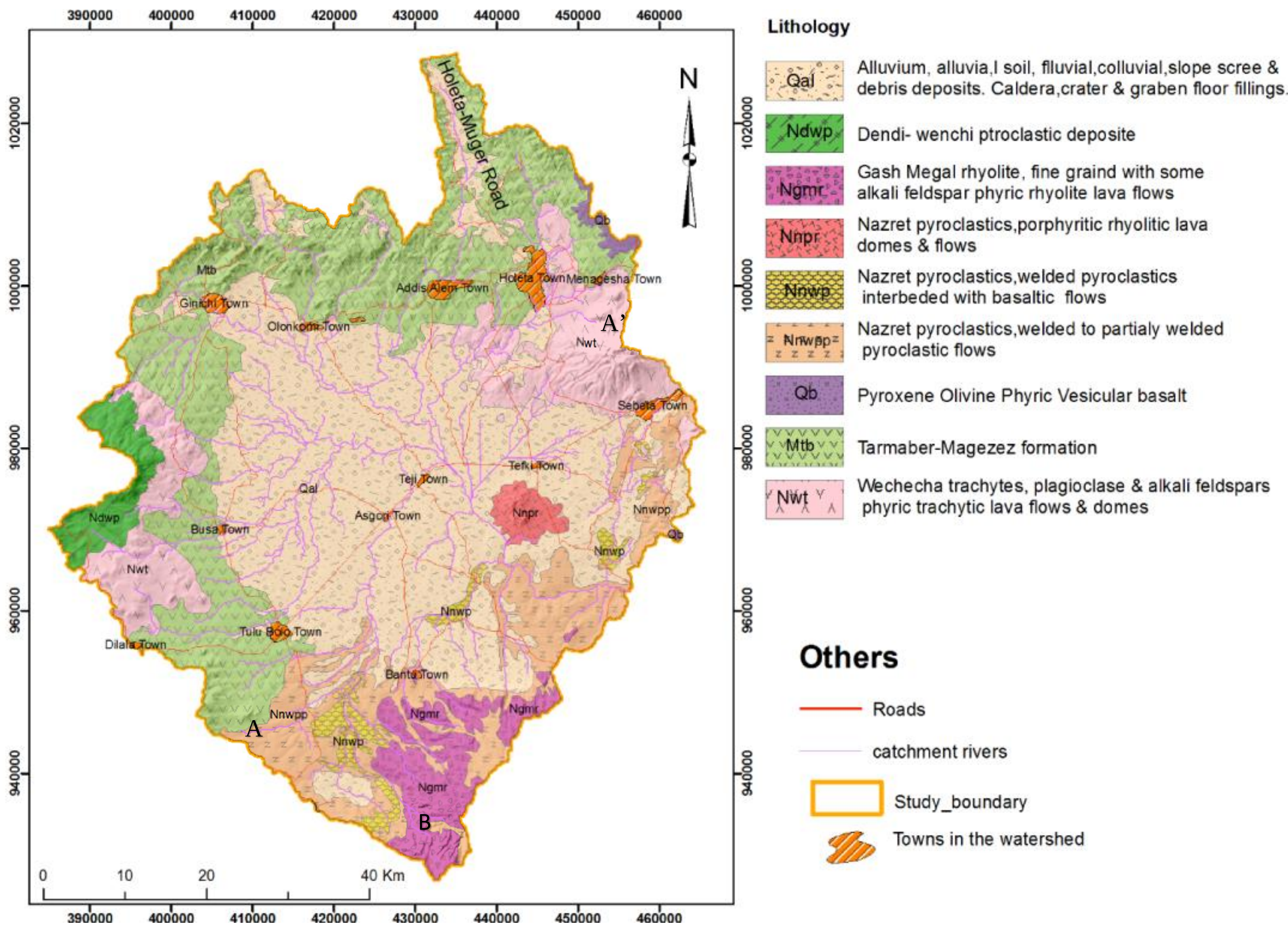

Fig 3.1 Geological map of the study area (modified from Addis Ababa and Akaki sheet geological map, GSE)

Table 3.1. Summary of lithology and areal coverage

No	Description of lithology	symbol	area_km^2	coverage (%)
1	Alluvium, alluvia,l soil, flluvial,colluvial,slope scree & debris deposits. Caldera,crater & graben floor fillings.	Qal	1879	41.8
2	Tarmaber (Foota) Basalt	Mtb	1142	25.4
3	Wechecha trachytes, plagioclase & alkali feldspars phyric trachytic lava flows & domes	Nwt	505	11.2
4	Nazret pyroclastics,welded to partialy welded pyroclastic flows	Nnwpp	499	11.1
5	Gash Megal rhyolite, fine graind with some alkali feldspar phyric rhyolite lava flows, pyroclastics and interbeded basic lavas	Ngmr	207	4.6
6	Dendi- wenchi ptroclastic deposite	Ndwp	110	2.4
7	Nazret pyroclastics,welded pyroclastics interbeded with basaltic lava flows	Nnwp	85	1.9
8	Nazret pyroclastics,porphyritic rhyolitic lava domes & flows	Nnpr	49	1.1
9	Pyroxene Olivine Phyric Vesicular basalt	Qb	19	0.4
	TOTAL AREA COVERAGE		**4494**	100.0

3.1.3. Geological Lineaments and Structures

The study area is located at the margin of Main Ethiopian Rift Valley. The effect of rift tectonics and rifting hugely affect the location. Faults and lineaments affect the local geology along several orientations. The digital elevation model interpretation indicates that most lineaments and fault have nearly same orientation as main Ethiopian rift (NE-SW), E-W and N-S trends. NE-SW is the dominate orientation of these structures (**Fig 3.2**). Fracturing and jointing has been observed on the outcropped basalts and welded tuff.

Most volcanic rocks like welded pyroclastic and basaltic rocks affected by dominantly by NE-SW, E-W, N-S trending geological structures. The dominant lineament orientation that hugely affect the study area rocks is NE-SW. The quaternary volcanic rocks severely affected by N-S, E-W and NE-SW oriented lineaments (Tilahun A. 2014). The trap series rocks (Tarmaber Basalt) were cut by old YTVL and NW-SE running faults.

The main Awash River and its major tributaries at most upper Northern side are oriented in nearly NS trend indicating that formation of stream paths are controlled by these NS running lineaments. However, most major and minor tributaries of Awash River in the central part of Bacho catchment are oriented predominantly in the NE-SW direction which is analogous to the MER system (**Fig 3.2**).

The lithologic cuttings description of about 14 boreholes drilled at Bacho Plane indicated that most consolidated rocks were intensively affected by fracturing and weathering. This in turn make the units to have better permeability and god storage capacity. Fracturing and joints are very common on welded pyroclastic and basaltic rocks in the area through which direct infiltration from rainfall occur. These geological lineaments contributed paramount importance in groundwater system of Bacho plane through enhancing recharge, improving aquifers properties and governing the groundwater occurrence and flow system.

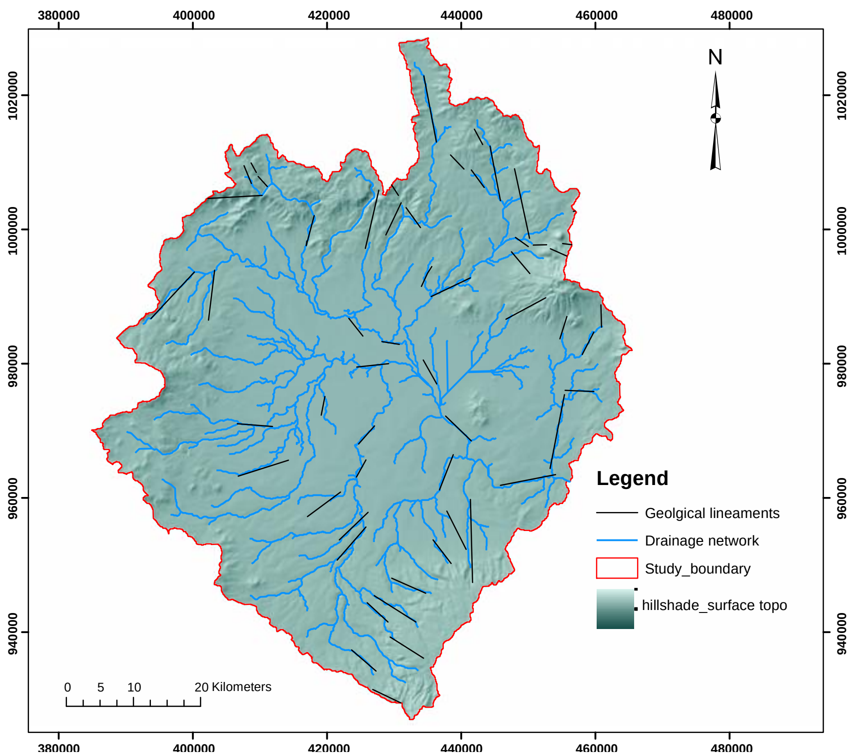

Fig 3.2. Geological lineaments and structures

3.2. Hydrogeology

Groundwater resources is the safest and dependable source of water in this research area like any other parts of the country. Yet the resource occurrence, quantity ad flow nature are less understood. As Ethiopian volcanic systems are very complex so is its hydrogeologic characteristics. Depth to water table vary within distance of hundreds meters; discharge significantly differ within same aquifer system; even a well become dry while there is productive water well exists with ten to twenty meters apart and overall the aquifer properties difficult to comprehensively define for entire single aquifer system. Subsurface water movement and occurrence is mainly related with geology and geological processes. Groundwater occurrence in the area is much related with climatic conditions, physical characteristics of rocks and geological processes.

The study catchment is entirely covered with quaternary and rap series volcanic rocks. The top flat land of Bacho was recently covered by alluvial sediments. Bacho Plain groundwater resource has been studied and developed for domestic, industrial and irrigation uses. The geological well logs and pumping test analysis illustrates that there are three major hydrostratigraphic units (WWDSE, 2009). The first top aquifer consists of fractured quaternary basalts, ash, thin pyroclastic flows and alluvial sediments forming unconfined aquifer. Underneath is welded ignimbrite which is less weathered and fractured. This middle unit acts as confining bed. Scoraceous basalt and scoria is the lower and comparatively most permeable and productive confined aquifer layer (Fig 3.4).

Water wells drilled at center of Bacho plane land indicate that the top aquifer unit comprises of thin alluvial sediments, interlayering of acidic and basaltic lava flows. The unit has primary and secondary porosity. As determined from pumping test results productivity and permeability vary from place to place. This is accounted for spatial variation of intensity of weathering and fracturing applied on the rocks. This hydrostratigraphic unit is water table aquifer and has an average cumulative layer thickness of about 150m; well discharge is less than1lit/sec to 57lit/sec with an average of 5.5lit/sec; the static water level is as shallow as 2-14mbgl at the center; very deep around topographic high and where pyroclastic rocks are thicker and dominant. For example, wells drilled around foot of Wechecha (Sebeta & Menagesha Area) have average SWL of 50mbgl. Several cold springs emerge at hill foot of Holeta, Menagash and Sebeta area as depression and contact springs, indicating that groundwater circulation is shallow.

Holeta catchment characterized with columnar, fractured and scoraceous basalt from top to 300m depths as learned from well geological log. Most wells do not exhaustively penetrate the local aquifers. The productive wells drilled at flower industries and town water supply are shallow. Their average depth is 120m and water level ranges from artesian to 25mbgl. Average transmissivity of Holeta catchment is 382m2/day, hydraulic conductivity varies between 1.02-90 m/day with mean of 20m/day (Ketema Wogari, 2006).

Underneath top aquifer layer, consolidated pyroclastic rock particularly ignimbiritic rock deposited. This unit is less affected by weathering and fracturing. Its thickness varies from 60 - 150m. Boreholes drilled through this unit indicated that it is dominantly massive, welded and slightly fractured at places. Consequently, its permeability is very low. However, at places where ignimbrites were intensively fractured ad weathered, water wells are productive and exhibit good discharge and permeable. In conclusion, this unit likely confines the bottom aquifer; it has low potential to store and transmit groundwater, horizontal flow is probably rare and there could be vertical flow to the lower aquifer unit and act as leaky layer.

The third hydrostratigraphic layer is thick scoraceous basalt and scoria. It has better porosity and permeability than rocks overlay it. About 18 boreholes with depth above 300 meters were developed at center of Bacho Plain. Although these wells are as deep as 482m, none penetrated the formation fully in the study region. However, borehole logs drilled at Akaka well field in similar lithology confirm that the thickness of the unit exceeds 300m. The pumping test analysis manifests that transmissivity is in the range of 24 - 2080m2/day. Their potentiometric surface rises to the level of 1m above the surface freely overflowing at Nacho well to 22 mbgl at Alengo Tulu Kebele. The average SWL for 18 wells is about 6.7mbgl this illustrates that the groundwater in the third hydrostratigraphic unit, the scoraceous basalt, is highly pressurized and very confined. Well discharge ranges from 19l/sec to 98l/sec with mean discharge of 48lit/sec (see *Appendix II*).

Seifu Kebede (2013) determined that most aquifer get recharged from current rainfall. Similarly, in the area the main source of water is recharge from rainfall. There is no artificial injection well to recharge the aquifers. Dense vegetation cover at Ginchi, Menagesha and sebeta have contributed in slowing runoff and enhance infiltration. Thick soil cover composed of clay silt and gravel helped in holding water as soil moisture and percolates down later to recharge the upper unconfined aquifer. Section 4.1.3 below discuss the estimation of recharge in the catchment.

The surrounding volcanic high lands of Intoto, Mengesha, Wechecha, Furi and Dendi are expected to contribute relatively more recharge to the groundwater system as it gets high rainfall distribution and due to occurrence of local and regional lineaments. As result, higher topography is delineated as recharge zone to the catchment while Bacho flat land is dominantly discharge zones (Fig 4.1). Groundwater is discharged naturally through springs at several places and as seepage to streams. In addition, in the catchment area more groundwater is discharged by pumping from several boreholes for domestic, industrial and irrigation uses.

Groundwater flow in the top unit is predominantly shallow and horizontal as the rocks nearly layered horizontally. In addition, existence of cold springs and seepage of groundwater to streams illustrates shallow circulation of the flow system in the top aquifer. Regional groundwater flow is highly likely dominated in the third layer. There are inter aquifer underflow at northern part and southern potion (see section 4.1.4 and Fig 4.2).

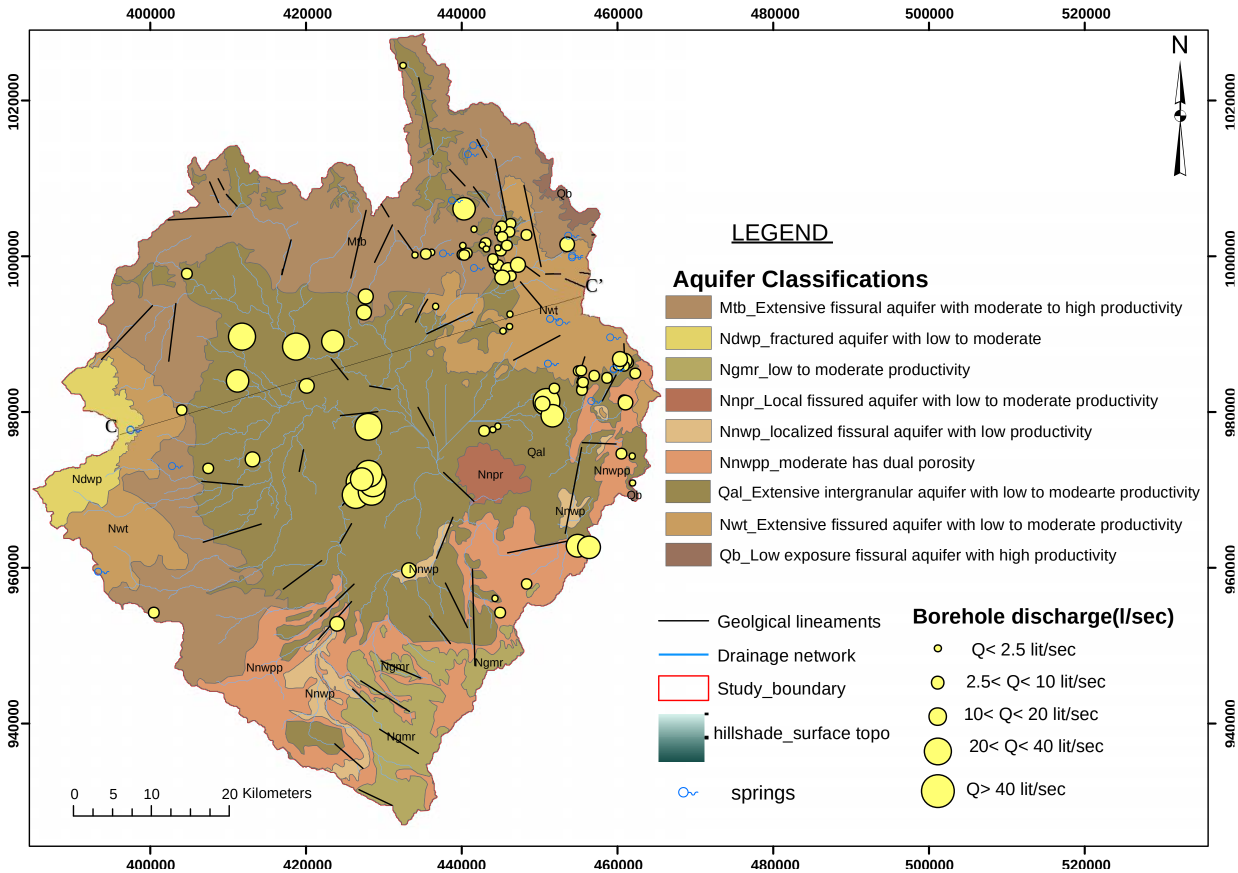

Fig 3.3. Hydrogeological map of Bacho Catchment

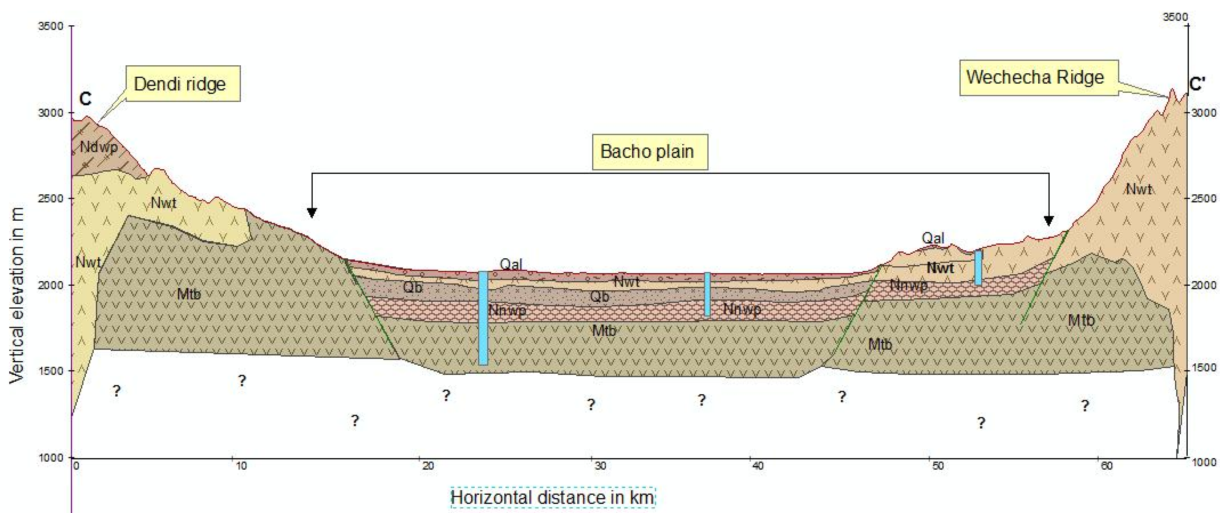

Fig 3.4 cross- section across Dendi-Wechecha (CC’)

4. GROUNDWATER FLOW MODELLING

4.1. Conceptual Model of the Study Area

A model is simplified representation of complex natural world. Conceptual model of groundwater system is a simplified and summarized representation of already known hydrogeological information qualitatively (Andreson and Woessner, 2015). It depicted hydrogeological units in the form charts, tables, cross sections and block diagram description. It is qualitative representation, while numerical model is typically quantitative. The model comprises and reflected in terms of the boundary conditions, recharge sources, aquifer hydraulic characteristics, hydrostratigraphy, geological and hydrogeological properties.

4.1.1. Hydrogeological description

Hydrogeological conceptual model provides a clear picture of the physical characteristics of the study area; like, hydrological, geological and hydrogeological settings depending on the data collected about the system. The main source of groundwater is direct recharge from precipitation occurred all over the area, interflow from external aquifer, and leakage from Awash River. Inter aquifer groundwater flow occurred from Muger sub-Basin (Abay Basin) to Northern and eastern side of the model domain (Tilahun Azagegn, 2014). On contrary, outflow from Bacho groundwater system is through pumping of boreholes for domestic, industrial, and irrigation use, groundwater outflow from the system at southern part, and leakage in to streams and flowing springs a depressions and mountain foots.

The top part of study area vastly covered with recent alluvial deposits, dominantly by quaternary basalt with pyroclastic material intercalations. At Bacho Palin as learnt from geologic well logs, there is middle semi confining pyroclastic aquifer unit (welded ignimbrite). It is only productive at places where affected by secondary structures like weathering and fracturing. Beyond these, it acts as leaky aquifer for the upper and lower basalt. Under the confining (welded ignimbrite) units highly permeable and porous Tarmaber fractured and scoraceous basalt is extensively found in the area as determined from the borehole lithological logs. This layer is best productive aquifer unit. Finally, the old either Ashange or Aiba basalt acts as confining aquitard in hydrogeologic system of Bacho_plain.

Hydrostartigraphy

Hydrostratgraghy is classifying hydrogeologic units depending on the similarity of their hydrogeologic properties. Seifu Kebede (2013) noted that four hydrogeologic units are known for the entire volcanic province of Ethiopian Plateau. Accordingly, in this localized Bacho catchment three hydrostratigraphic units documented based on their aquifer hydraulic properties, geology, groundwater occurrence and flow. Table 4.1 illustrate these three stratigraphic units in the study domain.

Hydrogeology of the research area is characterized from the analysis of hydraulic properties rocks, existing geological well logs, and pumping test data and from site observation. Volcanic rocks and alluvial sediments cover wider area and are the dominant geologic formations. The quaternary alluvial sediments consisting of clay, silt, sand and gravels cover the top plain topography and deposited along the rivers channels (Ketema. W., 2006; Solomon. K., 2007). The alluvial deposit characterized by low groundwater potential and shallow water table as manifested from shallow boreholes and hand dug wells developed on the top layer. Along the river valleys the depth to water level is as shallow as 4-8 meters.

The well lithological logs of several Bacho plain designates that underlying the top deposit, thin alternating layers of ignimbrites, trachyte and fractured basalt with some intercalations of paleosoil and sand. The top layer altogether has a thickness ranging from 80-180mbgl, on average about 150m. These pyroclastic and basaltic rocks have been affected by weathering and fracturing due to rift tectonic activity. Intensive fracturing and faulting cause better interconnection among the rocks and forms water table aquifer. The formations are relatively have good permeability in the range of 1.4 m/day to 55 m/day with average discharge 6.1 lit/sec (WWDSE, 2009 and pumping test reports).

The Chafe Donsa pyroclastic deposit, welded ignimbrite and pumice deposit cover large areal extent underlying the upper aquifer units. It confines the bottom scoraceous basaltic aquifer. It has non to low permeability due to the fact that welding reduces interconnection of the pore spaces, thus hinders movement of groundwater flow. This unit has an average thickness of 100 meters. This unit is taken leaky layer between adjacent top and bottom aquifers and has less storage property.

The lower layer is composed of laterally extensive scoraceous basalt and scoria. This hydrostratigraphic unit is relatively thick as learnt from lithological log of a well drilled to depth of 482mbgl. Analysis of pumping test data depicts its permeability ranges from 0.2-13.1 m/day (WWDSE, 2009). For the model domain 300m thickness was assumed.

Bacho rhyolites, Wecheca-Furi volcanic ridge, and other plugs of rhyolites acts a barrier and no flow boundaries to the model domain. Bottom boundary (confining) unit is expected to be massive Ashange Basaltic rock.

Table 4.1. Hydrostratigraphy of Bacho plain

Aquifers (layers)	Hydrostratigraphic Units Descriptions
Upper aquifer unit (Layer-1)	• Comprises alluvial deposits, fractured basalt and fractured and weathered ignimbrites and trachyte. • It is water table aquifer • Static water level ranges from 5 – 39mbgl • Transmissivity less than 50 m^2/day • Layer permeability varies from 2-10 m/day. Discharge ranges from 0.4- 38 lit/sec with mean of 6.1 lit/sec • Thickness ranges from 80-180m with mean of 100m
Confining bed (Layer-2)	• Pyroclastic material (welded ignimbrite) • It is confining layer for the bottom major aquifer • Have very low permeability but can give good productivity at fractured and weathered pockets • Assumed leaky aquifer • Aquifer ranges from 60m to 150, with average thickness of 100m
Lower aquifer unit (Layer-3)	• Tertiary Tarmaber scoraceous basalt and scoria • It is confined aquifer • Water level ranges from artesian to 71.5 mbgl. With discharge ranges from 0.5 to 98 lit/sec and mean of 41.7 lit/sec • Aquifer transmissivity 23.8 -2080 m2/day. It is very permeable • Aquifer has thickness above 300m

4.1.2. Aquifer Characteristics and Hydraulic Properties

The hydraulic conductivity of aquifers vary from rock to rock and even within same lithology it vary over wide range. Heath (1983) reported that basaltic aquifer has hydraulic conductivity ranging from 10-8 to 103 m/day. Similarly, aquifer property of Bacho plain groundwater system differs depending on lithology type and degree of fracturing and weathering.

Lithological well logs and analysis of their pumping test illustrates that three aquifer layers defined. Namely;

The upper porous and fractured water table aquifer having moderate permeability with transmissivity ranges from 57 to 1565 m2/day and water level very shallow near river channels and as deep as 31mbgl at Bacho plain (Table 4.2). This layer consists of alluvial deposits, fractured and weathered ignimbrite, trachyte, rhyolite and basalt. All together forms one aquifer system.

The middle pyroclastic confining bed (aquitard) has low permeability. At some spots its permeability has been improved due to development of secondary porosity by rift tectonic activity.

The scoraceous basaltic aquifer layer is predominantly confined, very porous and fractured. Its transmissivity ranges between 24 - 2080 m2/day and average discharge of 3603 m3/day.

Table 4.2. Statistical summary of shallow_ medium water wells in upper aquifers

Characteristics	Minimum	Maximum	Median	Mean	St. deviation	# of sample
Well Depth (m)	39.0	194.0	112.0	113.1	40.8	65
SWL (mbgl)	artesian	144.4	23.3	31.3	28.6	63
GWL (masl)	2007.0	2586.6	2236.0	2247.6	136.7	63
Q (L/Sec)	0.4	38.0	4.5	6.1	6.1	67
Cond. K (m/day)	1.4	55.2	5.2	17.6	19.7	7
Transm. T (M^2/day)	57.7	1567.0	116.7	294.2	432.2	13

Table 4.3 Statistical summary of deep water wells in lower aquifers

Characteristics	Minimum	Maximum	Median	Mean	St. deviation	# of sample
Well Depth (m)	206.0	482.0	350.0	345.0	82.7	23
SWL (mbgl)	artesian	71.5	7.2	11.2	15.2	23
GWL (masl)	1828.8	2512.7	2077.5	2087.0	154.0	22
Q (L/Sec)	0.5	98.0	35.5	41.7	25.5	23
Cond. K (m/day)	0.2	13.1	1.2	2.6	3.4	18
Transm. T (M^2/day)	23.8	2080.0	180.0	397.6	504.2	19

4.1.3. Ground Water Recharge and Discharge

Groundwater recharge is vertical downward flow of water to join water table. Sources of recharge to groundwater in general are from rainfall, river leakage, irrigation losses, and inter aquifer flow (Tenalem Ayenew, 1998). The main source of recharge in Bacho Plain comes from precipitation. Quantifying and measuring the groundwater recharge accurately is hardly possible as the process happened invisibly in complex geological environment. Only indirect estimate using multiple technics would help quantify the natural recharge.

In Bacho plain and the surrounding the major water source to groundwater system is recharge from precipitation. Many researchers estimated the possible annual recharge amount applying different principles. The summary of previous results are as follows;

Behailu Berhanu (2017) estimated minimum recharge of Upper Awash 51.5mm/year and maximum 157mm/year and mean recharge 91.25mm/year using baseflow separation. While Daniel Nuramo (2016) estimated recharge of Bacho as 319.5mm/year using water balance and 81.4mm/year using baseflow separation methods.

4.1.3.1. Recharge estimation by soil water balance method.

Soil water balance method is comparatively reliable for spatial and temporal estimation of recharge from precipitation which take into consideration different climatic factors; monthly precipitation potential evapotranspiration, topographic features (slope), soil types and vegetation covers or depth of plant roots (Thorenth waite and Matter, 1957). Potential evapotranspiration was adopted from FAO generated climate database.

Run off coefficients of the study area adopted from various research papers and area slope, vegetation cover and soil types are taken into consideration in analysis of recharge using soil water balance method.

Table 4.4 illustrates the summary of estimated groundwater recharge at 12 stations using this method and each station climate parameters analysis (excel spread sheet) is annexed under Appendix- I for detail information. Here baseflow separation method was not applied as there is an inter aquifer flow between Bacho to Ada'a sub-basins and underflow from Abay to study sub-basin. Thus the estimation of recharge by baseflow separation in this specific catchment could not be reliable and representative. Evenly distributed 12 meteorological stations were used to estimate the spatial distribution of recharge.

Table 4.4. Summary of estimated recharge result using soil water balance method* (unit mm/year).

Meteor. stations	Theisson polygon area(km2)	precipitation	AET	runoff coefficient	direct runoff	Recharge	weighted recharge	weighted Precipitation
Addis Alem	451	1118.3	868.2	0.16	178.9	71.2	7.3	114.6
Asgori	384	1053.2	836.2	0.16	168.5	48.5	4.2	91.9
Boneya	282	851.8	702.2	0.16	136.3	13.2	0.8	54.6
Enchini	92	1217.1	907.8	0.18	219.1	90.2	1.9	25.5
Ginchi	448	1145.2	916.0	0.14	160.3	68.8	7.0	116.6
G/ Meta	364	1046.1	836.2	0.16	167.4	42.5	3.5	86.6
Holeta	629	1188.2	913.2	0.14	166.3	108.7	15.5	169.9
Jeldu	1	1400.5	1019.9	0.18	252.1	128.5	0.0	0.3
Sebeta	360	1373.9	947.2	0.18	247.3	179.4	14.7	112.3
Tefki	358	885.4	739.5	0.14	124.0	22.0	1.8	72.1
Teji	226	939.2	760.8	0.14	131.5	46.9	2.4	48.1
Tulu Bolo	806	1154.4	804.9	0.16	184.7	164.8	30.2	211.3
							89.4	1103.8

* Each stations analysis using the soil water balance are annexed under Appendix I.

The soil water balance analysis indicates that recharge of study area significantly vary due to variation in slope, soil type and vegetation cover. Above all rainfall amount played the largest role in the groundwater recharge process. In general, recharge is at its lowest (less than 20mm/year) at center of the catchment and higher recharges at the western, northern and eastern margins of the boundary. Highest recharge, 179mm/year, is estimated surrounding Sebeta and Menagesha as there is good coverage of forest and above all rainfall distribution is the highest since last 30 years as compared to other stations in the study area. Area weighted mean recharge of the entire Bacho plain is about 89.38mm/year which is 8.1% of average annual rainfall depth for the whole study area (

Table 4.4). The daily recharge flux is approximately 2.45E-4m/day. The recharge volume is 1,115,173m3/day.

The study area has well distributed rainfall-recoding stations of long duration. In total 19 meteorological with 30 years record were analyzed to estimate the recharge quantity of the sub basin using soil water balance. These point data were interpolated using ARCGIS 10.4.1 and Theissen polygon developed (**Fig 4.1**).

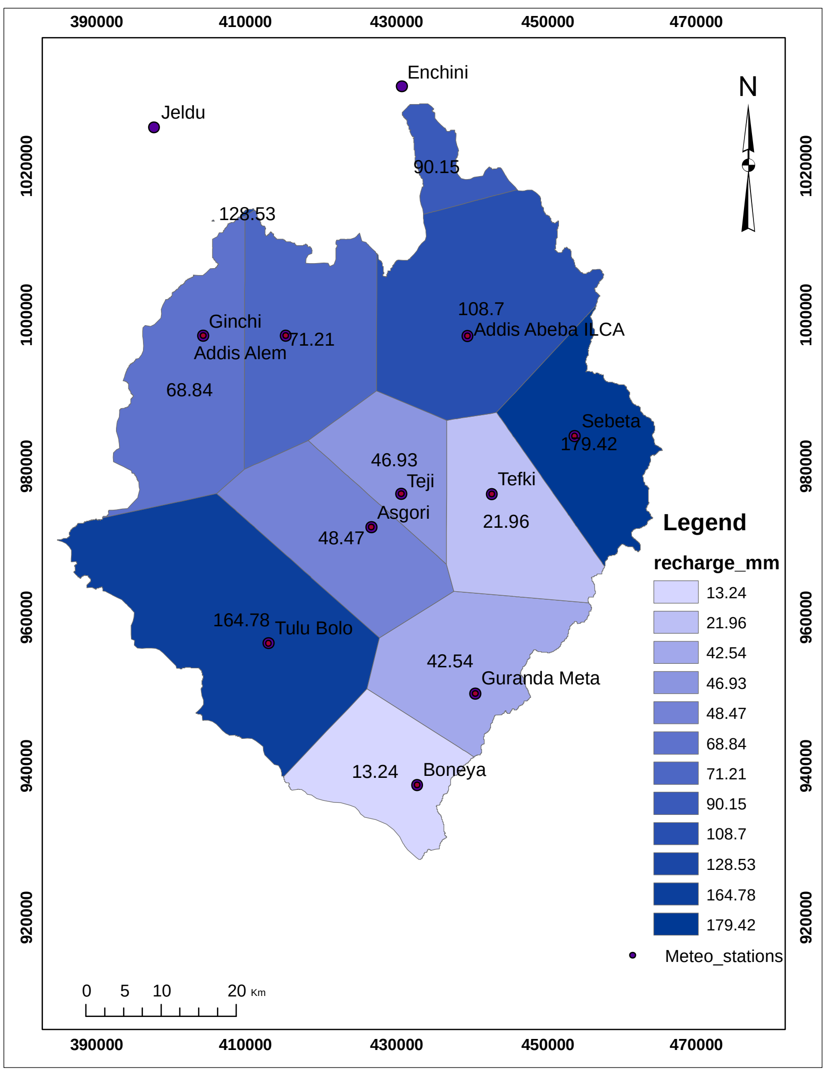

Fig 4.1. Recharge distribution of Bacho Catchment using Theissen polygon.

In the estimation of recharge, long term daily data of precipitation was collected from National Meteorological Agency (NMA) and potential evapotranspiration adopted from FAO developed local climate estimator using Locclim software.

4.1.3.2. Discharge

Groundwater discharge is withdrawal of water from saturated aquifer to ground surface (Freeze, R.A. & Cherry, J.A., 1979). It is upward flow of water against gravity from the saturated zone to surface as result of hydraulic head gradient. Groundwater naturally discharged to surface as spring or to surface water bodies as seepage through geological fractures and lithological contacts. Discharge of groundwater may also induced by evaporation and transpiration when the water table approached the plant root zones.

Discharge of groundwater happen in study catchment naturally as leakage to Awash River, seepages, springs, by pumping from boreholes and hand dug wells for water supply. The major discharges of groundwater are through withdrawal by pumping at central part and natural discharge to Awash River main course (gaining river). In the area several boreholes were developed for domestic, irrigation and industrial water supply. For this model only 71 boreholes were selected and encoded to the model environment with total daily discharge of 105,944m^3. Fifteen perennial springs with total daily flow of 3387m^3 were used in the model domain (*Appendix III*). Leakage of groundwater (baseflow) to Awash main river was not executed for the reason that there is inter aquifer inflow and outflow in the study area in particular and upper Awash in general.

4.1.4. Groundwater Flow and Movement

Groundwater flow nets comprises of equipotential (water tables or potentiometric) lines and flow lines. Heath (1983) noted that flow lines are perpendicular to equipotential lines as shown on Fig 4.2. Emerging of springs and seepages are dominantly concentrated at upper side of the catchment around Holeta, Ginchi and surroundings. This signifies that groundwater flow system is possibly shallow and local at the higher altitudes. On Bacho plain well geological logs and its hydraulic properties illustrate that there existed two aquifer systems. In the upper alluvial and basaltic aquifer groundwater is shallow and flow is local and intermediate. While the bottom aquifer is deep, confined and extensive hence it shows groundwater flow is relatively deep and regional.

Evenly distributed boreholes with water level point elevation was interpolated using ArcGIS (Kriging interpolation) to produce potentiometric surface for shallow unconfined and deep confined aquifers separately. The interpolation was made outside of the study boundary to see the interaction and relation of adjacent basins groundwater flow characteristics. This in turn helps to construct the ground flow networks and directions. Some portion of Abay basin (Muger sub-basin) flows towards Holeta catchment which is part of research area. In upper Awash Basin, most groundwater flow concentrated and directed to the middle Bacho plain and finally flows to Ada'a plain. It is clearly visible that groundwater of Gibe and Awash diverges along Ambo_ Waliso ridge. Groundwater hydraulic head contours are wider, gentle and very shallow at middle of Bacho flat land. It shows water level is almost relatively uniform and has very low hydraulic gradient. This could be due to flow of groundwater in all direction towards the plain land and probably resulted from damming effect of Wechecha, Furi and Debel domes and mountain ranges.

The groundwater flow in general resembles the topography and surface water flow as inferred from existing borehole water level records. Groundwater flows converges to Bacho Plain from all side. The general regional trend of Groundwater flow is from North to southeast and finally flow to Ada'a Plain mirroring the topographic decline.

The hydraulic gradient (spacing of hydraulic contour lines) is narrow at northern topographic highs around Holeta and Ginchi indicating steep and high hydraulic gradient; while very widespread potentiometric contour at middle of Bacho plane represents flat and low hydraulic gradient. **Fig 4.2** shows in general the hydraulic gradient and groundwater flow direction imitate the surface topography of the area.

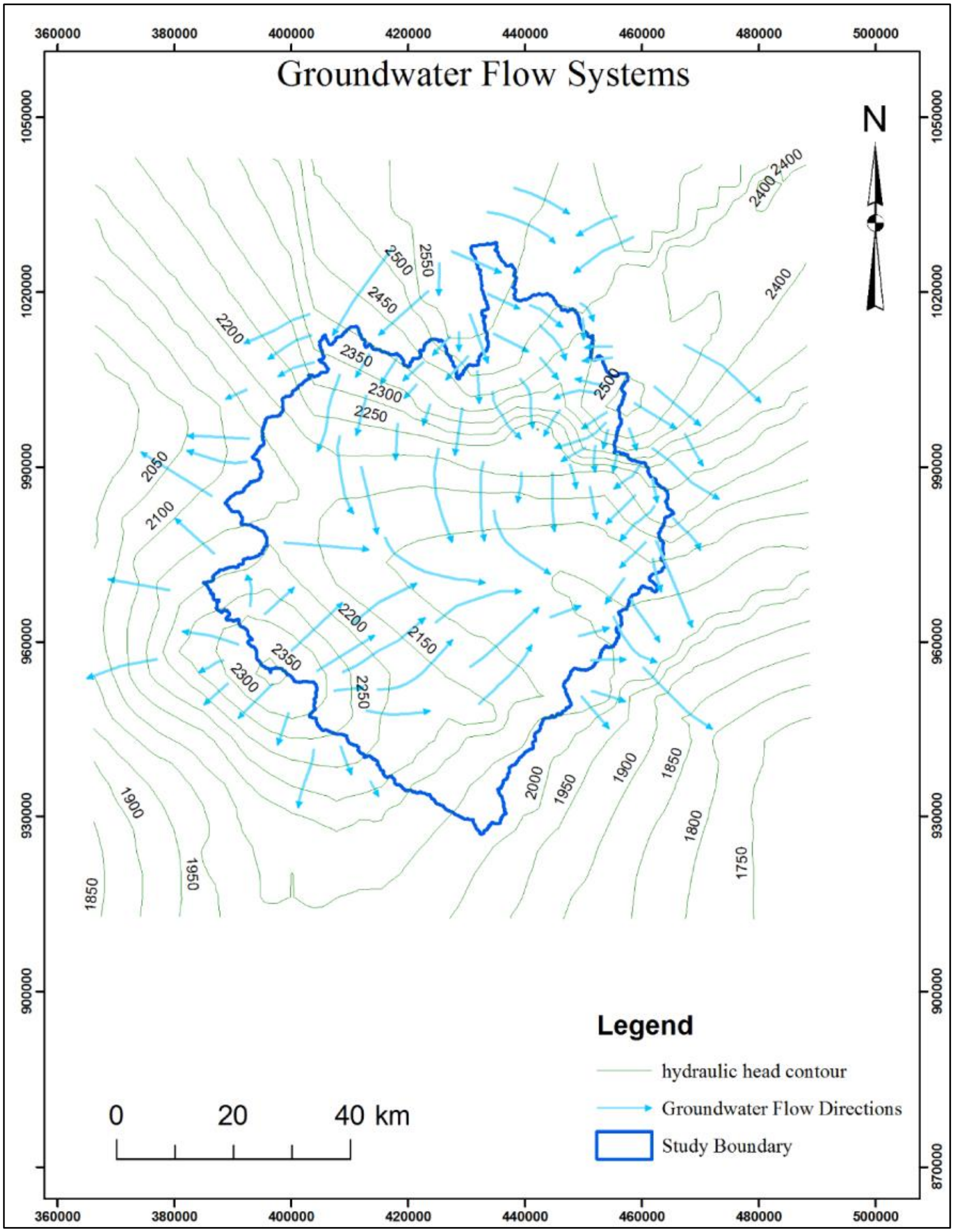

Fig 4.2. Bacho catchment groundwater level and flow patterns for deep aquifers

4.1.5. Boundary Conditions and Flow Barriers

Boundaries or barriers are either physical or hydraulic conceptually. Boundary conditions are key to represent the groundwater system of an area in to mathematical model (numerical modeling). It includes, groundwater divides, surface water bodies, impermeable bedrocks and geological structures (Anderson and Woessner, 1992). These boundaries govern the groundwater flow route and direction.

In study area, Bacho Plain, the groundwater boundaries are delineated from surface topographic, potentiometric and geologic maps. Most of the boundary are no flow boundaries along the perimeter. Dendi-Wenchi pyroclastic ridge bounds the catchment in the western side; Wechecha volcanic ridge bounds the domain in the eastern side. There is no surface water bodies on the area that act as hydraulic boundary. In general about 75% of the boundary perimeters are no flow boundaries while along the northern side and southern out let it is head dependent flow boundary (Tilahun. A., 2014 & Andarge. Y., 2013, WWDSE, 2009).

The local surface barriers are Tertiary Bacho Rhyolites, Wechacha and Furi volcanics, trachytes lavas have low permeability, and these units outcropped at west and east side boundaries of the study basin. These geological and physical barriers act as both surface and groundwater divides. The bottom-confining layer was thought to be relatively massive and impermeable old Ashange Basalt.

4.1.6. Aquifer/Model Geometry

The model domain is about 100km long across Holeta – Boneya transect. In the east-west direction width is nearly uniform with an average of 75kms. The lateral extent of the layers are assumed to be continuous and have uniform thickness all over the problem area (

Fig 4.4).

Based on the geological and hydrogeological information it was assumed that the vertical profile comprises three layers which are horizontally stratified. The 1st layer conceptualized as unconfined aquifer. While the remaining 2nd and 3rd layer are semi confined and confined aquifers. Since modeling is to simplify the existing complex geological situation into easily manageable model the problem domain is simplified and represented by three model layers

The Bacho plain is hydrogeologically defined as upper unconfined aquifer of 150m average thickness, middle aquitard confining layer with 100m thickness and lower major confined scoraceous basaltic aquifer with average thickness of 300m.

In general the aquifer system of Bacho catchment is two upper which is unconfined and lower scoraceous basalt which is confined water level become artesian and near to surface.

4.2. Groundwater Numerical Flow Modeling

4.2.1. Background

Groundwater flow models can be used as interpretative tools for investigation; used to predict future conditions for development; as planning and management tools to give directions for decision makers. It also helps to evaluate and estimate the amount of recharge, discharge and aquifer storage of the basin. Thus, numerical modeling is intended to be as tool to describe & understand the groundwater flow system the Bacho plain.

The numerical modeling is of two type; finite difference model and finite element model. Finite difference (FD) model is a model to replace the continuous aquifer with a set of discrete rectangular network of nodes arranged in a grid pattern at the center of the block. While in finite element model nodes are at edge of the triangular polygon (Anderson & Woessner, 1992; Fetter C.W. 2005). To represent the Bacho catchment with numerical model, steady state condition, two dimensional flow system and three aquifer layers were considered and the model domain discretized in to regular rectangular grid and finite difference block centered groundwater flow model.

The computer code applied in this numerical modeling is processing modflow. A modflow is three dimensional and block centered finite difference model. It can simulate groundwater flow, unconfined, leaky and confined saturated and porous aquifers with uniform temperature and density (Fetter C.W. 2005; Anderson & Woessner 1992).

The research boundary includes all areas that directly or indirectly influence the groundwater flow system of the model domain. The model domain comprises of catchment above the Melka Kunture Awash river outlet location

4.2.2. Governing equation

The governing equation of groundwater flow modeling is derived from Darcy's Law and principle of conservation of mass. For the sack of simplification of real complex nature of the groundwater system the equation embodied assumptions (Anderson and Woesserner, 1992).

The general governing differential equation for three dimensional (3D), transient groundwater flow for heterogeneous and anisotropic media is given as:

$$\frac{\partial}{\partial X}\left(Kx\frac{\partial h}{\partial X}\right)+\frac{\partial}{\partial Y}\left(Ky\frac{\partial h}{\partial Y}\right)+\frac{\partial}{\partial Z}\left(Kz\frac{\partial h}{\partial Z}\right)=Ss\left(\frac{\partial h}{\partial t}\right)-W \qquad \textbf{Eqn 4.1}$$

Where, **h**: is hydraulic head in (m)

Kx, Ky and Kz: are hydraulic conductivity in X, Y and Z directions (m /day)

Ss: is specific storage (1/ m)

t : Time step in (day)

W: a flux (volume of water per area of aquifer per time).Represents sink/source(m /day)

The numerical model of Bacho plain assumes steady state flow hence change in head with time is zero ($\partial h/\partial t=0$). Thus, Eqn 4.1 is simplified to Eqn 4.2:

$$\frac{\partial}{\partial X}\left(Kx\frac{\partial h}{\partial X}\right)+\frac{\partial}{\partial Y}\left(Ky\frac{\partial h}{\partial Y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial Z}\right)=\pm R \qquad \textbf{Eqn 4.2}$$

Where **R**: Represents sources/sinks; positive for recharge or negative for discharge

4.2.3. Boundary condition in numerical modeling

Boundary conditions define groundwater flow into and out of the model domain. Numerical model require boundary to represent the domain mathematically, unlike analytical mode which set boundary at infinity (Anderson and woessner, 2015). There are three types of boundary conditions in groundwater numerical model;

1. Specified Head boundary (Dirichlet conditions) where head at boundary is already determined from field. Head at lake or reservoir are an example of this condition.

Unfortunately, there is no such surface water body in the model area, therefore, no constant head boundary is defined in this model.

2. Specified flow boundary (Neumann conditions) – in this type, flux along the boundary specified. Most surface water divides nearly coincide with groundwater boundaries in the study area. About 75% of the boundary of the catchment is assumed as no flow boundary (Neumann condition). The area is bounded by volcanic ridges (rhyolite, Tarmaber Basalt, Dendi pyroclastics), lava domes, and volcanic shields (Wechecha) along which groundwater flow is nearly zero. Pumping wells are considered as specified flux boundaries in the model boundary conditions.
3. Head dependent Boundary condition (Cauchy conditions)-flow across the boundary is calculated depending on the hydraulic gradient using Darcy Law. Genera head boundaries at north and south, rivers and 15 springs are defined as Cauchy conditions in the model domain.

The catchment perimeter boundary was delineated by ArcSWAT from 30m resolution DEM. The produced boundary is mainly based on the surface physical characteristic. Most perimeters of these natural physical boundaries are generally recognized as surface water and groundwater divides (boundaries) as ridges and volcanic shields of the area characterized with low permeability geologic barriers. The exception is at the boundary between Upper North of Awash and some parts of Muger sub-basin in the Abay River Basin where there is inter aquifer flow across the boundary (Andarge Y., 2009, WWDSE 2009 & Tilahun A., 2014) and constructed potentiometric surface also manifests the existence of inter flow (Fig 4.2). At upper north water inter in to the system as lateral inflow and at south east water flows out of the system and hence the boundaries are defined as general head boundary conditions (Cauchy Condition) (Fig 4.3). The top layer is recharge layer through which rainfall percolates to join groundwater system. So top layer is specified flow boundary (Neumann condition).

4.2.4. Grid layout and discretization

The research area is spatially discretized in to 200 by 200 meters finite difference rectangular fine grid. Dimension of the model is 102km long and 80.6km wide in NS and EW directions, respectively. As result the entire area is partitioned into 510 rows, and 403 columns. The cells are designed to be fine gridded to approximately represent pumping wells, drains and steams in the model domain. The grid was designed in as much as possible to minimize the inactive cells, however, the research area perimeter boundary is irregular in shape hence unable to fit to nearly rectangular shape. As result the total active cells/nodes in problem domain are 113,825 while inactive cells which are outside the domain are 91,705. The model only calculate and produce solutions for active nodes or cells.

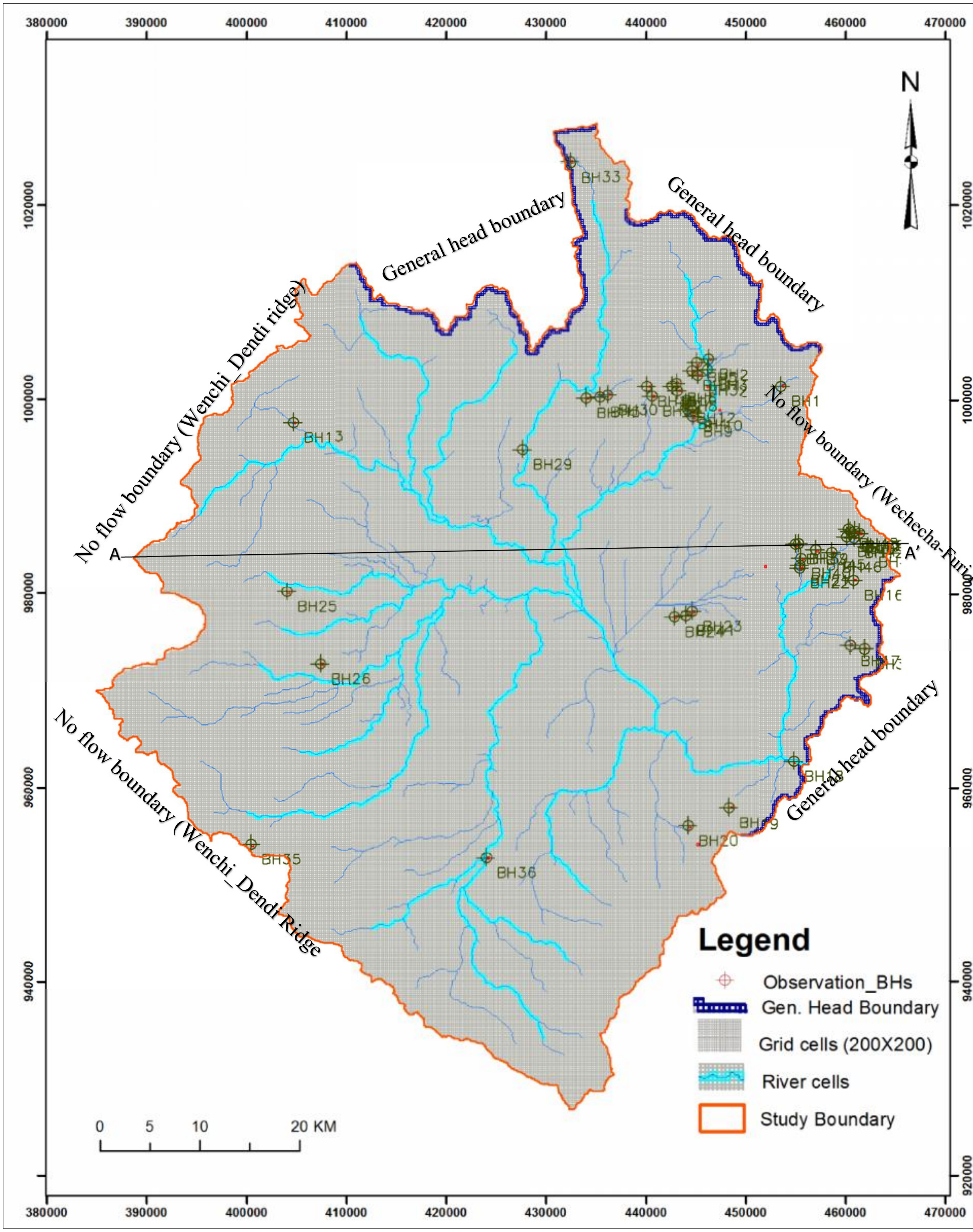

Fig 4.3 Plan view of model grid design and boundary conditions (only active cells)

4.2.5. Model Data Input / Model Parameterization

Layers properties

The different lithologic units of the catchment were vertically discretized in to three hydrostratigraphic layers. Continuous layer extent is anticipated in the model domain and the thickness of the layers averaged from the previous well logs data. Deep penetrating and representative water wells, lithological logs and pumping test data used to design model layers. Accordingly, 20 water well logs were analyzed and the three hydrostratigraphic layers were formulated to represent model layer properties. The stratigraphy of layers are generally assumed aligned horizontal as most FD flow models only allow simulation of horizontal layers (

Fig 4.4).

The top layer has an average thickness of 150mbgl and unconfined aquifer; the second is an aquitard with variable thickness, for the sake of this model an average thickness was of 100m considered, and the last main aquifer is confined scoraceous basalt s determined from log of Hara Jira bore hole drilled to 482mbgl and hence thickness of third layer considered as 300m. The overall model thickness is about 550 meters. The third layer is considered as confined aquifers for the reason that most boreholes sunk in the layer have artesian nature. Some wells are flowing to surface like Melka Kunture well and others their piezometer rises to top level as deep as 2 -10mbgl.

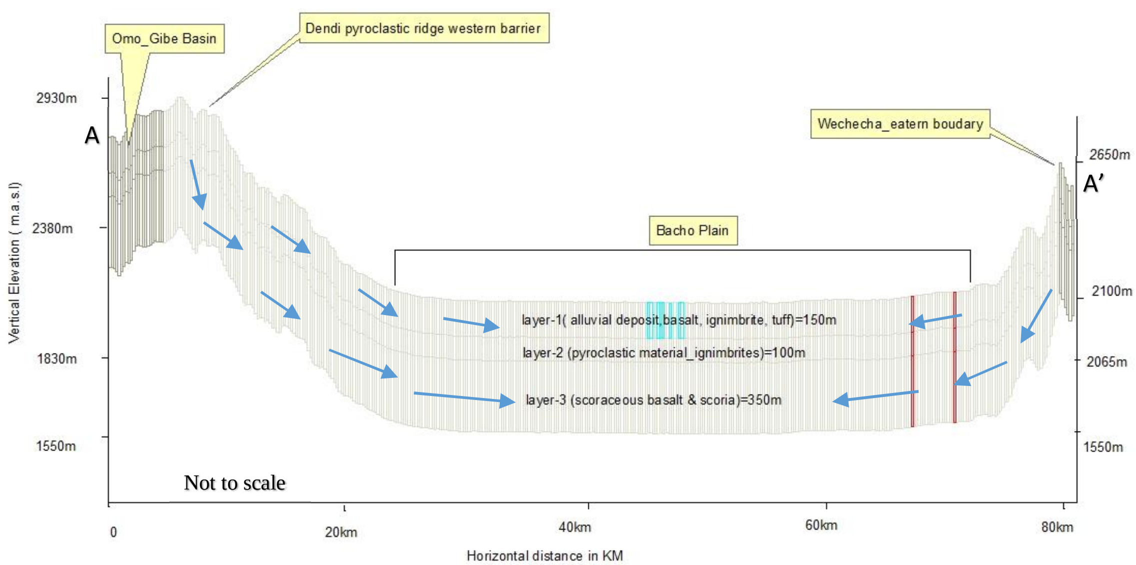

Fig 4.4. Cross section (AA') across Dendi_Wechecha viewing western and eastern boundaries and layers

Initial Hydraulic Head

Measured and observed hydraulic head of 90 boreholes and 15 springs were collected, organized and analyzed in ArcGIS. The boreholes have no time series head data. Hydraulic heads data were only one time measurement particularly during drilling and pumping test. As mater of this fact transient condition was not materialized in this model. Groundwater contour was developed using GIS_krigning interpolation method from representative and reliable groundwater levels at steady state. The interpolated data was resampled into 200 by 200m model grid size and imported to model environment. Practically, groundwater levels fluctuate from time to time; however, it is assumed that in long term the water levels become nearly constant.

Hydraulic conductivity

Pumping test data of deep wells drilled in Bacho plain indicates that transmissivity of the major scoraceous basalt ranges from to 43.4m^2/day at Ilu district to 2080m^{2}day around Melka Kunture, with mean of 351m^2/day. Eighteen deep wells drilled in the lower aquifer layer have hydraulic conductivity of minimum 0.17m/day to maximum 13.1 m/day with mean 2.55m/day (WWDSE 2009). However, shallow to medium wells drilled around Holeta have relatively higher hydraulic conductivity. The initial horizontal hydraulic conductivity was defined from pumping test results and from ranges of previously published values of hydraulic conductivity of rocks (Heath, 1983 & Freeze and Cherry 1979). Vertical hydraulic conductivities were approximated from its horizontal conductivity multiply by 1% to 10% depending on the nature of aquifer.

Fig 4.5. Initial Horizontal and Vertical hydraulic conductivities

Aquifer Layers	Initial Horizontal Hydraulic conductivity range (m/day)	Vertical Hydraulic Conductivity range (m/day)	No of zones
Layer-1	0.2- 20	$2x10^{-3}$ - 2	14
Layer-2	0.002-1	2×10^{-4} - 10^{-1}	8
Layer-3	0.0003- 6.7	$3x10^{-8}$ - $4x10^{-4}$	6

Recharge package

Annual recharge was estimated using soil water balance method as discussed on section 4.1.3.1. Daily estimated recharge rate in previous section is applied to top layer as groundwater source.

Groundwater recharge is applied to the most active cells. Accordingly, four averaged recharge zones recognized, spatially interpolated and organized with ArcGIS, Global mapper and surfer and eventually imported to model (Fig 4.6). The recharge rate calculated by soil water balance method was reclassified in to four zones (Fig 4.6). The recharge values resampled by 200m by 200m grid size to be accommodated into the model. Spatially distributed recharge values were used in the model stead of using lump sum value. Recharge was classified in to four zones depending on the rainfall distribution, land use and land cover.

The model calculates the recharge flow rate (Q_R) using equation 4.3

$$\mathbf{Q_R = I_R.\ DELR.\ DELC} \qquad \textbf{Eqn 4.3}$$

Where, $\mathbf{Q_R}$: is recharge flow rate in m^3/day

$\mathbf{I_R}$: is recharge flux in m/day

DELR.DELC: is map area of a model cell in m^2

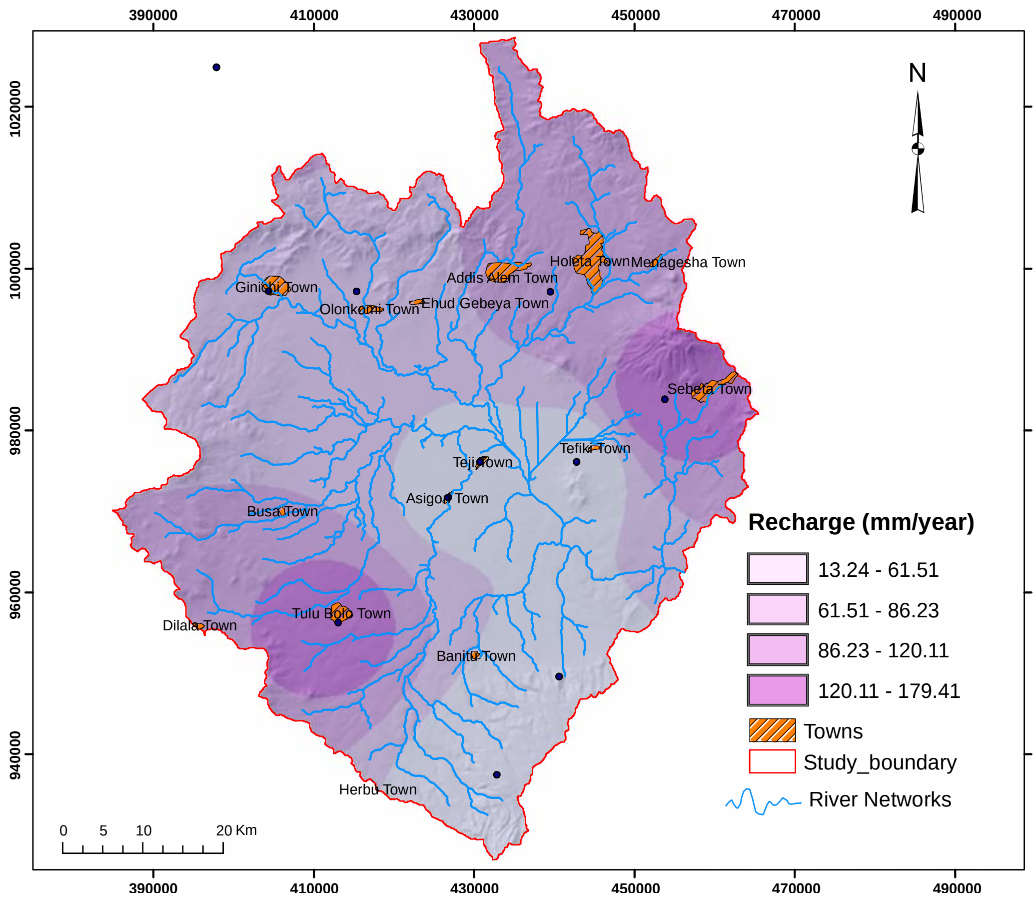

Fig 4.6. Zoned groundwater recharge spatial distribution

River package

The river package used to simulate the interaction of surface water and groundwater. Surface water bodies such as rivers, streams, lakes and swamps may either contribute water to the groundwater system, or act as groundwater discharge zones, depending on the hydraulic gradient between the surface water body and the groundwater system (Anderson & Woessner 1992). It is assumed that leakage is only through the riverbed sediment but not on side channel wall. As result this package requires hydraulic characteristic of the riverbed sediments (conductance), river stages, river bottom elevations and sediment thicknesses. The hydraulic conductance of river sediments were calculated using equation Eqn 4.4. Hydraulic conductivity of sediments were adopted from published hydraulic conductivity values. Conductivity on flat surface is very less than the high lands values since as we go downstream the deposit become finer and finer. Dimension of rivers were approximated from the 30by30m DEM and Google earth images. Thickness and texture of soils or sediments adopted from well lithologic logs, from previous research works and reports. On high lands deposit are very less on sloppy topography, at slope breaks coarser material deposited, like for instance around Holeta and Olankomi were well sorted gravels deposited. In such environment hydraulic conductivity expected to be relatively maximum and hence the river sediment hydraulic conductance will also increase accordingly. The calculated initial hydraulic conductance varies in the ranges from 22.8 to 2314 m^2/day over the model environment.

In this package flow into or out of the river system calculated from hydraulic gradient and river conductance.

$$\mathbf{Q_{riv}=C_{riv} * (H-h_{bot})} \qquad \textbf{Eqn. 4.3}$$

Where $\mathbf{Q_{riv}}$ I river leakage flow (m^3/ day); **H** is groundwater head & $\mathbf{h_{bot}}$ is river bottom elevation

River conductance ($\mathbf{C_{riv}}$) is defined by;

$$Criv = \frac{\mathbf{Kriv*L*W}}{\mathbf{M}} \qquad \textbf{Eqn. 4.4}$$

Where $\mathbf{C_{riv}}$: is river hydraulic conductance (m^2/day)

$\mathbf{K_{riv}}$: is river sediment hydraulic conductivity (m/day)

L: is river length in the each cell (m)

W: Width of river (m)

M: Thickness of riverbed sediment (m)

About 90% of perennial streams and rivers were included in the numerical model.

Well package

Injection and discharge wells are simulated in the model with well package. Groundwater of Bacho Plain have been developed for domestic, irrigation and industrial purposes. A total of 71 pumping wells have been collected and encoded into the model program but there is no injection well developed. As result, in this model only withdrawal of groundwater was simulated.

In well package, the discharge volume distributed over each layer for multiple aquifer layers. Well discharge, which is negative, defined specifically at each layer assuming the well penetrates the entire aquifer of the 3 layers. The total discharge of the well is sum of discharges from each layer. Each layer discharge proportion is determined by using layer transmissivity proportion (McDonald and Harbaugh, 1988).

$$\mathrm{Qi} = Qt\left(\frac{biKi}{b1K1+b2K2+b3K3}\right)$$ **Eqn. 4.5**

Where Q_i: is discharge rate for **i**th layer (m^3/day)

Q_t: is total measured discharge of the well (m^3/day)

b_iK_i: is **i**th layer thickness and hydraulic conductivity (layer transmissivity) (m^2/day)

b_1K_1, b_2K_2 and b_3K_3 are transmissivity of respective layers. (m^2/ day)

General Head boundary (GHB)

GHB simulates the external source of water that flow into the basin or outflow from the basin. The purpose of using this boundary condition is to avoid unnecessarily extending the model domain outward to meet the element influencing the head in the model. As a result, the General Head boundary condition is usually assigned along the outside edges (sides) of the simulation model domain.

The aquifers Abay plateau around Muger sub_basin and upper Awash is hydraulically inter connected by means of geological structures (Tilahun, A. 2014) and likewise Bacho and Ada'a aquifers are interconnected through porous lithology (scoraceous basalt). Thus, there exist inter-aquifer flow at northern and southern boundaries of Bacho catchment. One can also deduce from potentiometric surface map (Fig 4.2) that groundwater inflow at north side and outflow at southeast boundaries around Melka Kunture, hence the borders are assigned as general head boundary (GHB) conditions.

External source head and distance was estimated from the observed well heads and distances measured using ArcGIS. These data used to calculate the hydraulic conductance of GHB applying equation (4.7) and its value varies from 3.6 to 20 m^2/day in the model domain. The general head boundary in the model domain is mathematically calculate by Eqns 4.6 & 4.7:

$$\mathbf{Q = C\Delta h = C(h_B - h_{i,j,k})} \qquad \textbf{Eqn.4.6}$$

$$\mathbf{C = KA/D} \qquad \textbf{Eqn.4.7}$$

Where **Q**: is volumetric flow rate across GHB (m^3/day);

Δh: is difference between the user specified boundary head, $\mathbf{h_B}$ (m) and the model calculated head near the boundary, $\mathbf{h_{i,j,k}}$(m). $\mathbf{h_B}$ can be assigned by modeler at any point of interest to represent external source head.

C: is hydraulic conductance (m^2/day)

A: is surface area (L*W) of grid cell face exchanging flow with external source (m^2)

K: is hydraulic conductivity at the boundary (m/day)

D: is distance between the locations of h_B and $H_{i,j,k}$ (m)

Drain package

Drain is one of the head dependent flow in numerical modeling. In the drain package springs, seepages, and channel flow are simulated. Drain doesn't contribute water to the aquifer and it is only one way outflow. In this numerical modeling about 14 springs were represented as drain. In the area most springs originated dominantly at foot of escarpments and ridges in the upper northern part of the model domain around Ginchi and Holeta. They are characterized by contact, depression and fault controlled springs having variable discharge rates ranging from 43.2m^3/day to 864m^3/day.

The model execute spring flow Q_d as follows:

$$Q_d = C_d * (h - d) \quad \textbf{Eqn. 4.8}$$

$$C_d = K * L \quad \textbf{Eqn. 4.9}$$

Where Q_d: discharge rate to drain cell (m^3/day)

C_d: Drain hydraulic conductance (m^2/ day)

K: hydraulic conductivity (m/ day)

d: drain elevation to each drain cell (m)

h: hydraulic head in drain cell_ calculated head (m)

L: length of drain within a cell (m)

Using the above equations 4.8 & 4.9 the model calculate discharge of groundwater in the form of spring. In the drain package it is assumed that there will be no return flow in to aquifer system.

4.2.6. Model Simulation

Modflow is a computer code developed to simulate mathematically three dimensional groundwater flow through porous media by using finite difference method (Mc Donald and Harbough, 1988). As result, a computer program PM Modflow version 8.0.42 was selected to model the Bacho Plain with mathematical expression of steady state conditions. The model was designed in a 200m by 200m grid size, three layers of total 550m thickness, and appropriate hydraulic parameters were encoded. Five model packages namely, drain, recharge, GHB, river leakage and well packages were simulated. PCG2 (preconditioned conjugate gradient 2) was assigned to solve the variable parameters iteratively and simultaneously at nodes. In the model meter and day was used as measuring units. The model is simulated under steady state condition means there is no change in hydraulic head and storage over specified time period in the model environment.

A steady state solutions are often sufficient to address many modeling objectives, such as analyzing average groundwater flow patterns and flow rates; estimating average annual leakage from losing stream; calculating regional water table gradients; simulating flow directions influenced by long term pumping (Anderson and Woessner, 2015).

4.3. Calibration and Sensitivity Analysis

4.3.1. Model Calibration

Anderson and Woessner (2015) noted that model calibration is the process of varying the independent model parameters to calibrate a dependent variables such as hydraulic head against a known values of head and flux. Model parameters repeatedly changed with range of results of pumping test analysis, aquifer types and adopting values from experiment outcome of previous published works.

Pumping test results only represent well area not the full extent of the aquifer. Similarly, the experimental results of hydraulic properties of rocks are also not completely represent the complex heterogeneity of aquifers in real environment. As result, initial aquifer input parameters could not produce and replicate the easily measured values, for instance the hydraulic head. Hence, parameters continuously and reasonably changed to calibrate the model until the errors between simulated and observed hydraulic head were minimized and until the model can nearly reproduces the field measured heads and flow patterns.

Model calibration was conducted dominantly with available data of borehole history which was measured over wide range of years. As result, to avoid significant error only representative and reliable data were applied in the calibration processes. Model calibration with hydraulic conductivity was restricted between the ranges previously estimated from pumping test. For top layer from 0.1 to 55m/day for lower scoraceous basalt between 0.2-13m/day. The calibrated horizontal hydraulic conductivity for top aquifer layer ranges from 0.657 to 2.592 m/day, for the second layer 0.00057-0.864m/d and for the lower scoraceous aquifer ranges from 0.264 to1.35m/d. The calibrated vertical hydraulic conductivity ranges from 0.0016 to 1.6m/d for top layer; 0.00016 to 0.08m/d for middle and 3E-08 to 6.7E-8 for lower aquifer.

The general head hydraulic conductance in the model domain also adjusted nearly to resembles natural flow conditions

The final calibrated recharge values ranges from 6.305E-5m/day to 6.739E-4 m/day for the entire Bacho catchment. Lower recharge zone is around at central and southern part of study area and higher recharges were places of high rainfall and topography like; areas surrounding Sebeta, Ginchi, Holeta and Dendi.

4.3.1.1. Trial and Error Calibration

This kind of calibration is a modeler selects the input parameters and systematically change the values until the model replicates the observed hydraulic head. It takes long time and effort to conduct several simulation to attain required calibration target. The target in the calibration is to attain and simulate measured hydraulic head with calculated head. After each simulation the error analysis conducted, water budget results compared and distribution of heads analyzed in plan view. At instant where the calculated and observe head nearly resembles one another or attain acceptable error range, then at the point it is believed that the model replicates actual groundwater flow system. The final calibration input parameters assumed to be aquifer properties of the study area.

Thus, the model was run more than 80 times to obtain and achieve calibration target and goodness of fit to real groundwater flow system.

In the trial and error calibration there exist good head match between simulated and observed at northern and central part of model area. At some specific spots like round Holeta and Sebeta where there are dense wells calculated head significantly vary within hundreds of meters distance. This could be reflection of effect of geological structure or could be error from field measurements and umping test analysis.

The calculated head at some wells were very high which is technically unacceptable as compared with adjacent wells. The problem was related with wrong recording of elevation data and hence in well package these particular erroneous wells were removed from the model domain.

4.3.2. Model Evaluation

4.3.2.1. Hydraulic Head Comparison

Groundwater elevation contour maps show the spatial distribution of groundwater elevations and help identify areas of low and high groundwater level areas within a basin. Elevation contour map was produced from static water level data using ArcGIS (Fig 4.7). Comparison of the model generated potentiometric surface map after calibration against the measured potentiometric contour map indicates similar trend of groundwater flow directions and hydraulic gradients. However, differences were observed at western boundaries and wechecha_furi area. At these places water level simulated was by far lower than observed static water levels. This could perhaps accounted for, poor groundwater potential of pyroclastic materials, most groundwater flows to center of the area than stored there and over withdrawal of water at Sebeta altogether could result to excessive drawdown.

The simulated potentiometric surface better represent the effect of river on groundwater. For instance at Holeta catchment the river is gaining type; however, the interpolated observed head could not clearly pinpoint the river relation with groundwater. The arithmetic mean difference of the simulated and observed hydraulic head is about 6.5. At the center of the model domain groundwater level is more artesian than observed heads. Figure 4.7 clearly illustrate in general the groundwater flow direction is from north to south converging towards the flat land and finally flow to Ada'a plain. Similarly fig 4.7 (a) & (b) shows the hydraulic gradient is very step at northern high land and very wide and gentle flow at center.

In general, good much was attain between measured and simulated result of hydraulic head and groundwater flow directions.

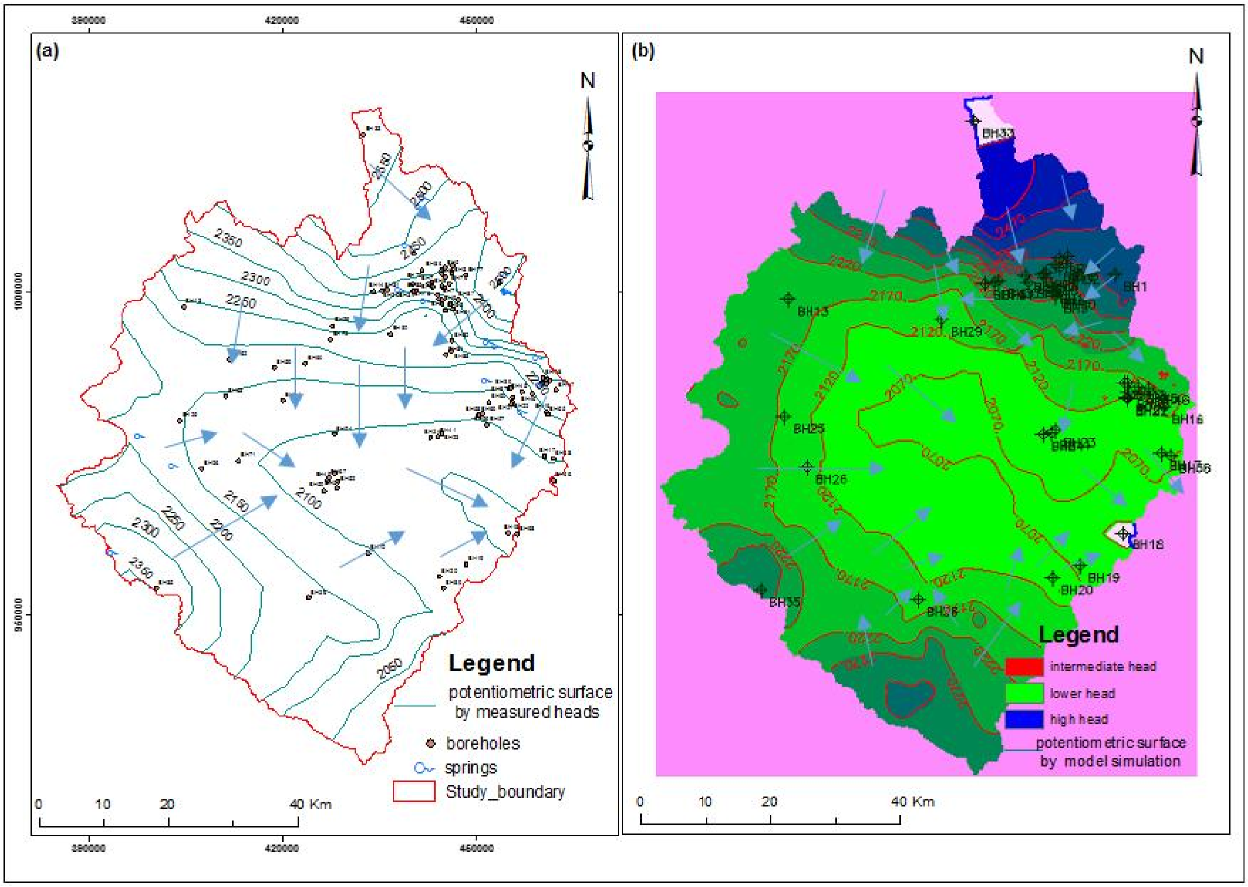

Fig 4.7. Comparison of potentiometric surfaces (a) groundwater surface produced from observed water level and (b) model simulated potentiometric surface.

The quantitative evaluation of the calibration was performed with statistical average of head differences between measured and calculated hydraulic heads. Three statistical averaging methods employed to evaluate performance of the model, namely; mean error (ME), mean absolute error (MAE) and root mean square error (RMSE). The calibrated model ME is 6.5, the MAE is 25.2 and the RMSE is 30.4 with calculated water balance discrepancy of 0.00%. In all model simulations for calibration the mean error was in reasonable range less than ten which is relatively acceptable. However, the MAE and RMSE calculated was resulted in very wide statistical error. The high values of MAE and RMSE could be attributed to the wide variation of morphology, unevenly distributions of boreholes and above all complex nature of the aquifer system in the model domain. It could also be as result of wrong elevation measurements and poor data quality as recognized during calibration processes. In addition, static water level was only measured once during drilling and pumping test. However, the model require head within specified time step this could not materialized due to limited resources for the research. The model usually calculates hydraulic head at node. So this create discrepancy of head between measured and simulated.

The calculated head in most wells approximately fit to the observed heads values (**Fig 4.8**).

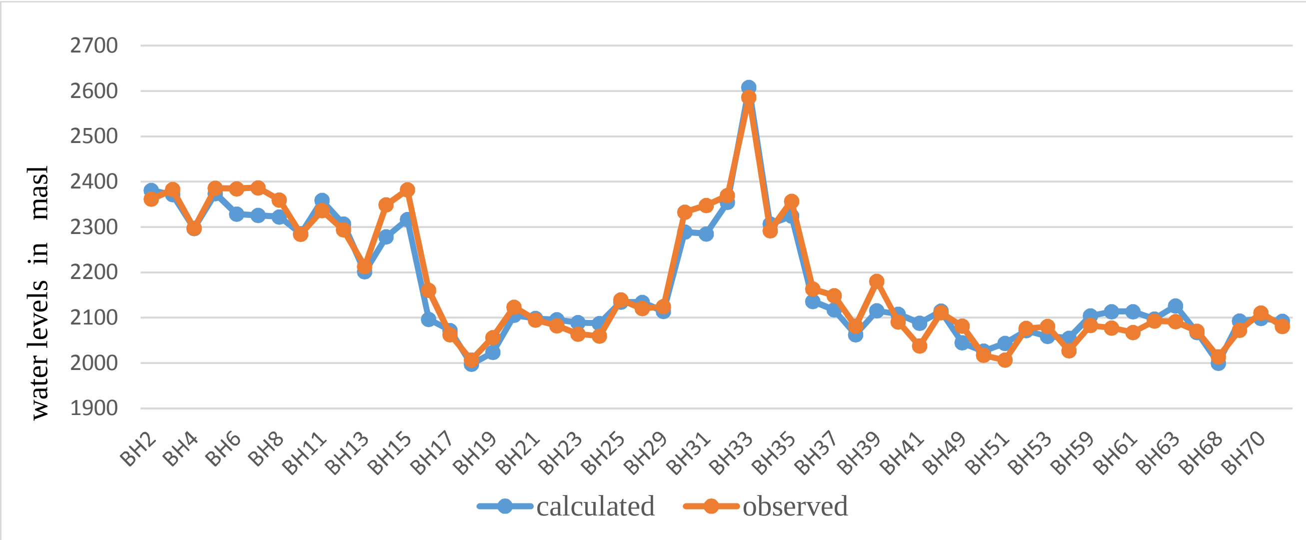

Fig 4.8. Graph indicating trend calculated and observed heads

The measured and simulated hydraulic heads are highly correlated as indicated on (Fig 4.8 &Fig 4.9). Their correlation coefficient (R^2) is 0.9286. The graph below indicates the existence of better linear relationship between the measured and calculated heads.

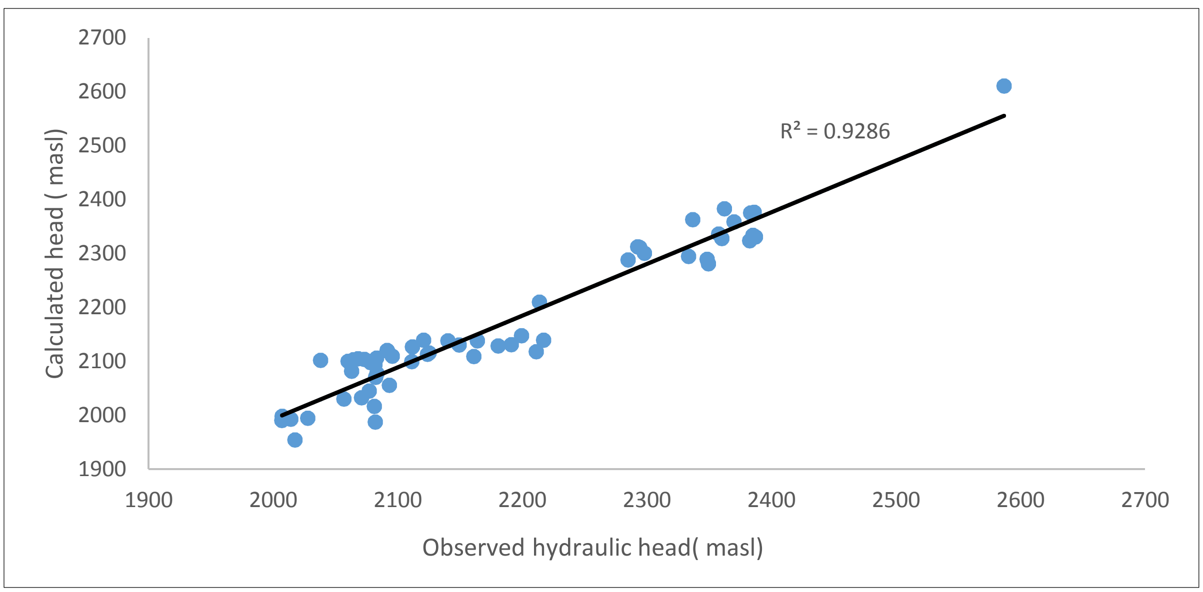

Fig 4.9. Scatter plot of observed against simulated hydraulic heads.

4.3.3. Sensitivity Analysis

Sensitivity analysis is measure of value change of model calibrated parameters that would vary model output results considerably. The analysis conducted by systematically changing values of aquifer parameters and boundary conditions (Anderson and woessner, 2015). Sensitivity test is important to understand impact of an increase or decrease of model input parameters and stresses on groundwater flow system.

After model calibration finalized, parameter sensitivity was evaluated manually by fixing all calibration parameters at their calibrated values and increasing or decreasing the value of selected parameter to analyze its sensitivity to the model. Uncertain aquifer parameters were identified during calibration stage; namely horizontal hydraulic conductivity, recharge, river conductance vertical hydraulic conductivity and general head conductance. Hence, these uncertain parameters were individually subjected to systematic increase and decrease of its calibrated value by 20% variation in every simulation keeping other parameter values constant. The change of head from the calibrated result was statistically evaluated at every change of parameter value.

The analysis illustrates that groundwater elevations were most sensitive to changes in horizontal hydraulic conductivities than any other parameter (Fig 4.10). The model was most sensitivity to changes in horizontal hydraulic conductivity values. However, the model was relatively less sensitive to an increase or decrease in recharge and vertical hydraulic conductivity as compared with most sensitive parameter. Variation of recharge values were also evaluated and the analysis shows it has higher effect on river leakage than head variation. The model in general very sensitivity to decrease of recharge than increasing it. The model outputs were slightly sensitive to river sediment and general head conductance.

Therefore, the sensitive aquifer parameters like horizontal hydraulic conductivity, recharge and riverbed sediment conductances have to be given due emphasis in the future groundwater flow investigation of the area than other parameters. Overall, the model outputs were sensitive to changes in horizontal hydraulic conductivity, vertical hydraulic conductivity and recharge.

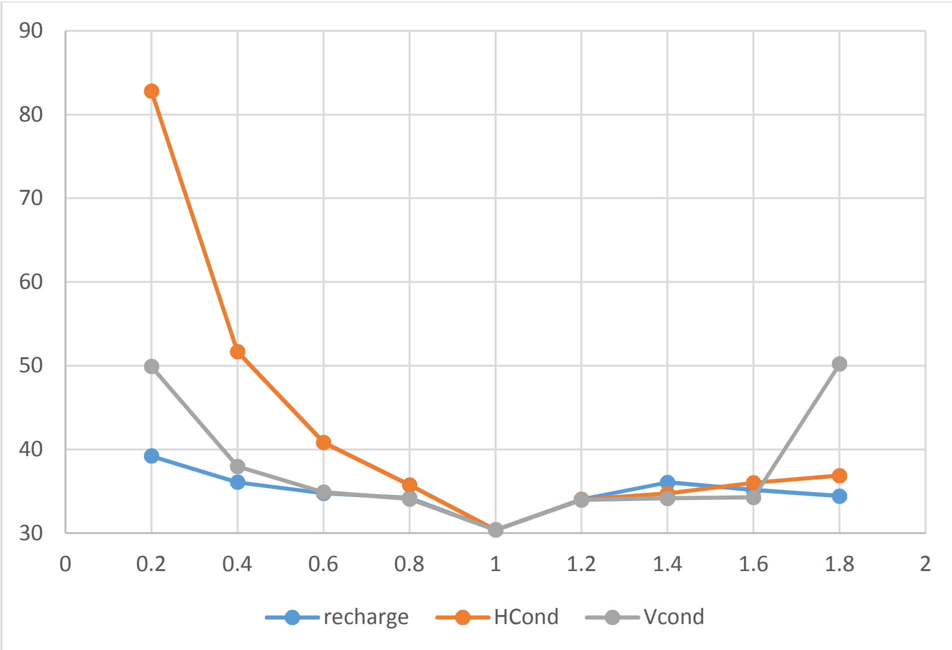

Fig 4.10. Model sensitivity to horizontal hydraulic (Hcond), Vertical hydraulic conductivity (Vcond) and recharge.

5. RESULTS AND DISCUSSIONS

5.1. Results of Model

The calibrated hydraulic values were verified with previously identified research and literatures pumping test results, local area knowledge and professional judgments.

The simulated hydraulic head surface map and potentiometric surface map produced with measured water level data nearly match at most locations. The groundwater flow is from north to south according to the result of the model as well as the conceptual model.

Horizontal hydraulic conductivity estimated by the model is in the range of 0.44 to 9.2m/day for upper aquifer and 0.07 to 45 m/day in the lower scoraceous basalt aquifer. The model result greatly vary from the initial estimate of hydraulic head.

The model point out that Sebeta and surrounding areas experience less groundwater movement. This was manifested by high drop of water level in the water wells simulated in the model. In general water wells developed approaching the catchment boundaries were facing significant drawdown. This illustrates that groundwater flow is low near no flow boundaries and the recharged water move vertically down to join relatively deeper water levels at higher topography. In addition the model indicated that recharge on ridges and mountains seems dry in the top layer but in the following layer it becomes wet. This could be attributed to lower water table level below cell node of top layer or higher gradient that causes downward movement of groundwater.

Surface water _ groundwater interactions

In the model area surface water _ groundwater interactions were well prevailed at higher and lower topography. Most rivers and streams losses leaks water into groundwater system on ridges of Entoto and Dendi. On other hand, the streams on Bacho flat area gains more than double of leaked surface water at higher altitudes (Fig 5.1 and Table 5.1). Thus, surface and groundwater interaction in research area is very plausible and both resources depend on each other.

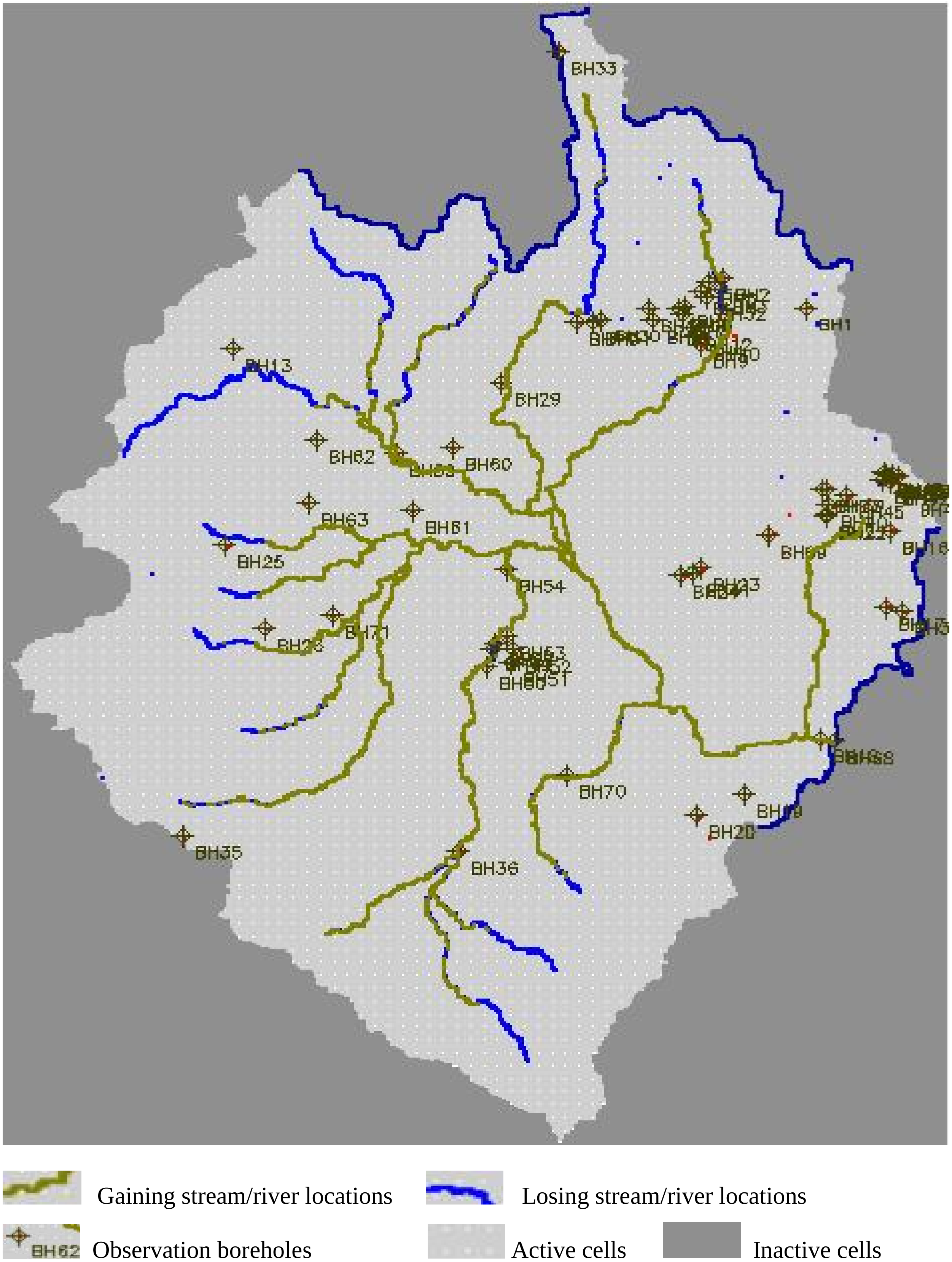

Fig 5.1. Map of calibrated model result of surface water- groundwater interaction locations

Groundwater flow results

The generalized groundwater flow in the Bacho catchment is from north to south. Local flow were characteristics of the upper aquifer and in the top aquifer flow is converging to center of Bacho plain and eventually leaks to Awash river and some flow through aquifer to Ada'a plain (Fig 5.2). The hydraulic gradient as shown on figure 5.2 is steeper at higher altitudes and gentler at lower plain land, it simulates the surface morphology. The lower scoraceous basaltic aquifer nearly flows strictly from north to southeast in the regional flow system.

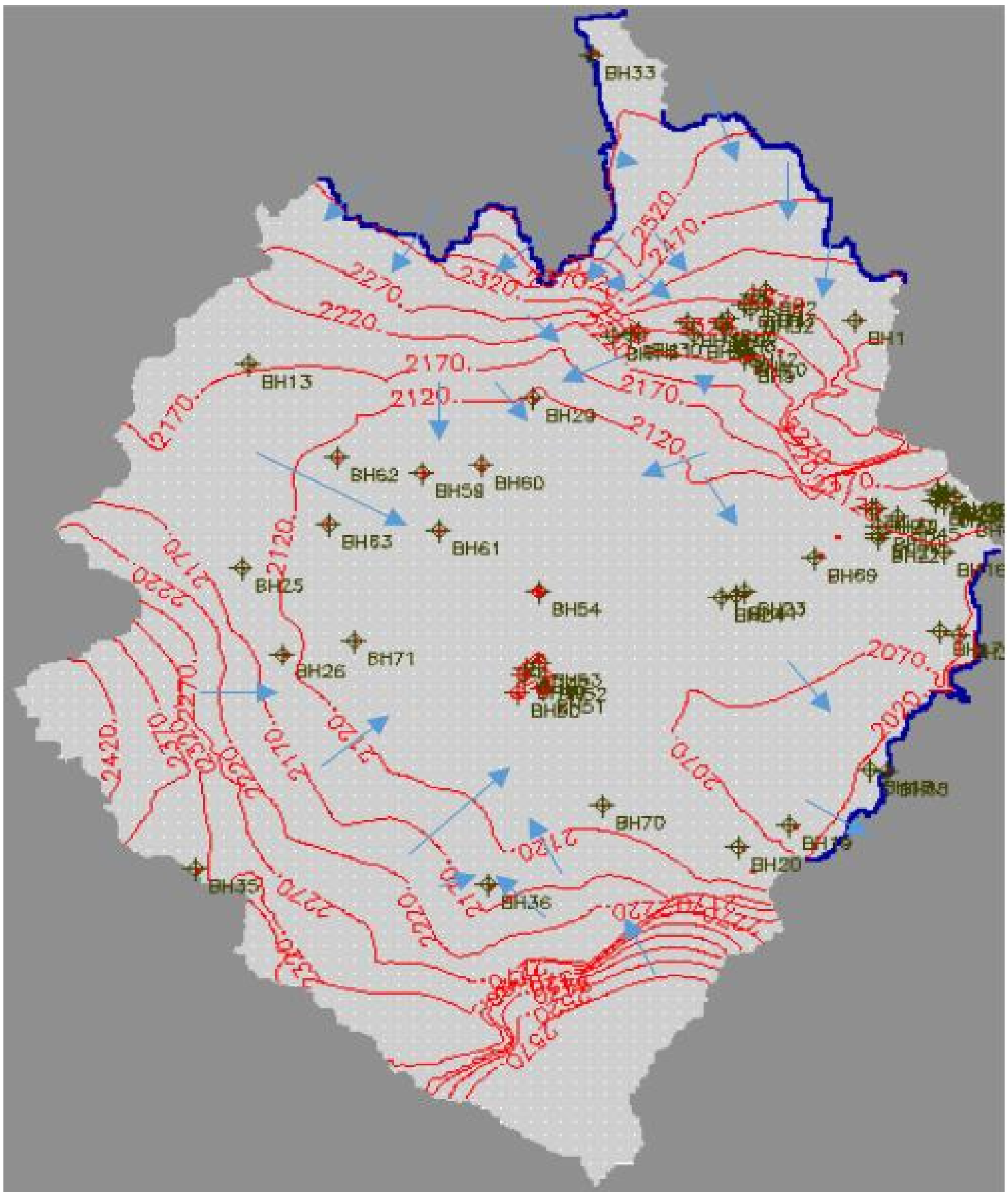

Fig 5.2. Groundwater level contours and flow direction in upper aquifer layer

Calibrated Recharge flux

Initial recharge input was estimated from soil water balance solution. The calibrated recharge was not in a considerable variation with conceptual model. It varies from 3.24E-05 m/day at center of the catchment to 6.2E-04 m/day at higher topography. As Fig 5.3 depicts that the western rides and eastern ridges represent most recharge zones while the center of the study area are very low recharging zones but the center is rather the most groundwater discharge zone.

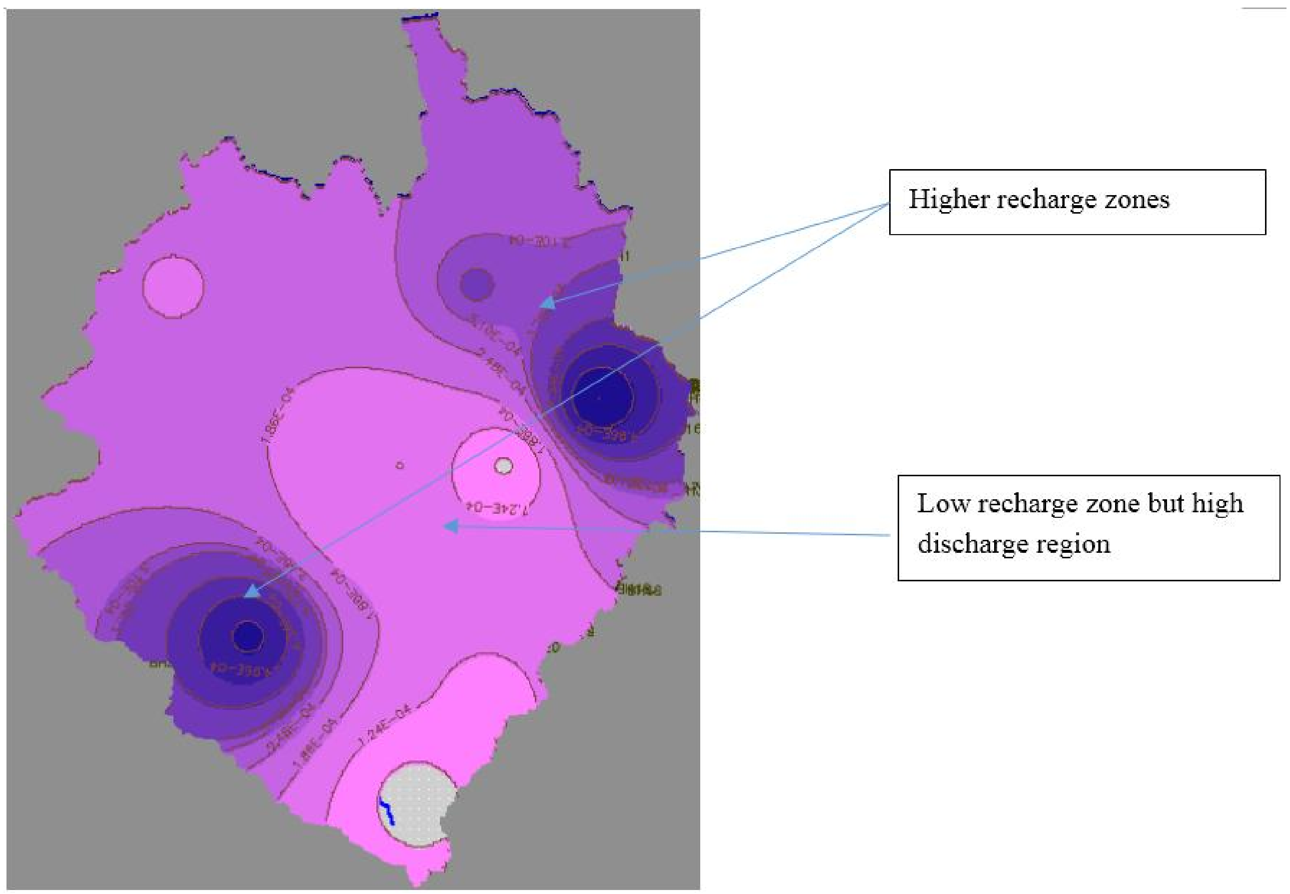

Fig 5.3. Calibrated recharge distribution map in the Bacho plain (in m/day)

5.2. Water budget results

The major output of groundwater water modeling after proper calibration is water balance of the model domain. The final steady state calibration resulted in total inflow water balance of 2,094,613 m^3/day and out flow 2,094,519 m^3/day with discrepancy of 93m3/day (Table 5.1).

The percentage of inflows were 51.2% from recharge, 32.6% from GHB, and 16.2 % from Awash River leakage. The percentage of outflows were 89.2% from Groundwater discharge to Awash

River, 6.13 % from GHB (inter aquifer flow), 4.69% by pumping from wells and 0.003% as drains. The model simulated that much of inflow to groundwater flow system is contributed from precipitation recharge and head dependent flows at northern boundary from adjacent Abay basin. On contrary, out flow the catchment in general is dominantly through leakage to Awash River.

Table 5.1. Summary of water budget

Water Budget Components	Inflow(IN) m^3/day	Outflow(OUT) m^3/day	In-Out m^3/day
Wells	0.00E+00	9.83E+04	-9.83E+04
Drains	0.00E+00	6.48E+01	-6.48E+01
Recharge	1.07E+06	0.00E+00	1.07E+06
River Leakage	3.39E+05	1.87E+06	-1.53E+06
Head Dep. Bounds(GHB)	6.83E+05	1.28E+05	5.54E+05
SUM	2.09E+06	2.09E+06	9.38E+01
DISCREPANCY [%]	0.00		

5.3. Scenario Analysis /modeling

The importance of groundwater modeling is it can assess the possible impacts on the system happened due to several factors; like climate change and human effect (over pumping). Andrson and Woessner (2015) reported that steady state models can be used to forecast the effects of a time averaged stress such as a long drought or projected long term pumping. The final calibrated model was used to simulate different scenarios that likely could occur in the future.

Using the calibrated steady state model, hypothetical increase of well withdrawals and adverse climatic effect (drought) was simulated. This hypothetical simulation was made to assess the response of groundwater to stresses. The scenario analysis, in general, may give indicative results for decision makers for future plan and management of the groundwater resources of Bacho catchment. Probably most water would leak to rivers or under aquifer flow dominates see the result after scenario. All scenario cases were hypothetical values but is highly likely to happen in the future.

Scenario-I. **Increase of recharge – by developing artificial wells**

Hypothetical 25 injection wells with average uniform flow rate of 4320m^3/day were inserted at upstream of the model domain around Holeta and Ginchi diverting the perennial rivers to the injection wells and similarly, another 25 injection wells were introduced with same rate at Bacho flat separately.

The simulation was run for both injection wells field independently. The model outcome analysis at 58 observation wells shows an average rise of 1.18m and 1.47m hydraulic head in the entire catchment for the upstream injection field and Bacho plain field respectively. Moreover the impact of an increase of recharge was significantly increases groundwater leakage to river and river leakage to groundwater declined. Outflow of groundwater to rivers increased by 3.78% from injection well fields at upstream (Ginchi and Holeta). Similarly, outflow to rivers increased by 5.1% when another 25 injection wells introduced at Bacho flat.

The combined 50 injection wells simulation in the catchment resulted in average rise of water level by 2.654m, increase of groundwater outflow to river by 8.81% and decrease of river leakage to groundwater by 5.79% of the model calibrated values. In addition, the result also depicts that outflow is increased by 4.01% and inflow decreased by 2.32% at head dependent flow boundaries.

Therefore, development of artificial recharge has significance importance in enhancing groundwater level in the long term and it helps to stabilize the level fluctuation caused by over pumping and sustain the resource during drought. The analysis shows in general development of injection wells will improve and sustain the flow system.

Scenario II- Decrease of recharge due to low rainfall and increase of withdrawal

The calibrated recharge values were decreased by 50% and increase of pumping by same 50%. Imposing both stresses simultaneously on the groundwater system of the catchment resulted in decrease of groundwater outflow by 23.3% and 24.4% to river leakage and general head boundary, respectively. On other hand such effect of drought and water withdrawal will rise river leakage to the groundwater system by 23.4% and head dependent flow by 5.4%. Groundwater level was declined for the entire catchment with an average of 20.6m. The model reveal that highest drawdown occur in wells around Sebeta area with zonal mean of 33m. On other hand lowest drawdown revealed in wells around Holeta catchment and evaluation of 25 water wells resulted in mean water level drop of only 5.8m which is nearly 1/5th of drawdown calculated at Sebeta.

In general most wells around Sebeta experienced relatively higher drop of water level and some shallow wells even went dry. Hence due attention required in future development of the local groundwater system. The over pumping and low rainfall scenario severely affects the groundwater and surface water flow systems.

Scenario III- increasing withdrawal through 100 additional wells

The calibrated model was subjected to additional 100 pumping wells with mean discharge of 25lit/sec to assess the future impact of over pumping in the Bacho aquifer system. Productive wells evenly distributed in the model domain and simulated under steady state condition.

The analysis of the scenario indicated that groundwater outflow through general head boundaries and to rivers decreased by 5.42 and 9.1% respectively. Inflow to groundwater increased by 1.8% and 5.42% from GHB and river leakages. The average drawdown of hydraulic head in the entire research area due to this over pumping will be 3.78m. Similar to scenario II once again the model flags higher drawdown around Sebeta area with mean water level drop of 7.15m analyzed from 15 observation wells clustered at Sebeta. However, at Holeta and center of the catchment water level drop is in the ranges from 0.19 to 2.76 meters.

In general, the calibrated model was stressed with different scenarios to evaluate the response of the aquifer system to the imposed stresses and to give direction for future planning and management. Accordingly, increasing recharge by developing injection wells at appropriate selected locations will contribute much surface water to groundwater system.

Over pumping of groundwater water will not significantly affect the good potential zones like Holeta and center of Bach plain. However, simulation result of scenario II and III demonstrate that ground water flow system at Sebeta and surrounding is very low. Therefore, proper monitoring and management of the resource needed at these specific locations.

5.4. Model Limitations

No model is completely perfect or not replace the real groundwater flow system. There are certain limitations in this numerical model;

- There could be uncertainty in model input parameters like recharge, hydraulic conductivity and conductance. These parameters are determined sensitive parameters as discussed in section 4.3.3 and greatly affect model outputs. Hence, additional new data of the parameters will improve mode output in future.
- Groundwater flow is always in dynamic movement. But this model assumes steady state condition due to lack of time series data record of hydraulic head and this could limit the model to fully represent the real groundwater flow system.
- The available hydraulic head of wells measured at different periods were used in the model. The model was simulated with these available data. This could limit the result of comparison of observed and simulated heads during calibration.
- Modflow was programed for porous aquifers; however Bacho plane is predominantly fissural aquifers with some porous media. Hence this may affect the model output values to some degree.
- Although the model grid size was smaller as compared to the study area size, yet, the model code over represent the borehole diameters and river dimensions by default to fit to model requirements. This could introduce some over estimation of river leakage into or out of groundwater system.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

Bacho plain is one of the sub basins in the Upper part of Awash River basin that has good groundwater potential. The catchment was densely populated and industrialization is widespread and booming in the area. Hence, the demand for this resource is increasing with time and groundwater development is extensively implemented. As result, this research was initiated to address the groundwater flow system and assess the stress conditions formulating scenarios using groundwater flow modeling with modflow modeling program developed by USGS.

Conceptual model of the study area was developed from geomorphology, geology, and hydrometeorology and hydrogeology data. This conceptualized model was translated to numerical flow modeling with mathematical expressions with aid of computer code processing modflow version 8.0.15. The catchment was discretized in to three layers and each layer designed further into 200m by 200m square grid aquifer blocks with total active cell area of 4553km^2.

Model input parameters were collected from field observations, secondary documents and from government offices. The data those fit to model code requirement were selected and utilized. Groundwater recharge was estimated using soil water balance method from 30 years meteorology data recorded at 12 meteorological stations distributed evenly within the study area. Accordingly, the catchment mean annual rainfall is 1104mm and mean annual recharge is about 89mm/year which is 8.1% of annual precipitation.

In all model simulations activities it always gives high balance of groundwater leakage to rivers. In the modeling processes of this catchment it was understood that sustainability of upper Awash in general and Bacho sub basin in particular depends on flow of groundwater resource. The modeling analysis illustrated that more utilization of groundwater through pumping will not endanger the natural flow of surface water system.

In general, results from the groundwater flow model indicate that first and third hydrostratigraphic layers have good hydraulic properties. The underlain confined scoraceous basaltic layer is relatively extensive and more permeable than any other units in the model domain. This aquifer unit is being the largest source yet not well developed to utilize its potential. Hence, the concerned decision makers need to focus on this unit for future development plan to utilize the resource extensively, sufficiently and sustainably.

Conceptual model was developed from the hydrological, geological and hydrogeological historical data and field observations. The conceptual model was represented in to mathematical formulation using processing modflow code. The model was calibrated by trial and error method by comparing the observed and measured hydraulic head and water balance. The calibration resulted in better match between the calculated and measured heads at most places.

Calibrated model water balance revealed that the research area is mainly acquire water sources from rainfall n form of direct recharge and under aquifer flow from Abay basin. The dominant subsurface water outflow is through leakage to Awash River systems. Groundwater discharge is higher in the Bacho plain land than any other places in the area.

The upper aquifer is very responsive to effect of drought and over abstraction. This indicates that the flow and potential of upper aquifer depends on recharge conditions. Low rainfall amount and distribution will impose stress on the aquifer. Hence, water well development in the upper aquifer should base on detail knowledge of the aquifer properties as it varies from place to place.

Three scenarios were simulated in to calibrated model to speculate future events on the groundwater flow system. Accordingly, increasing recharge through injection wells to the system only increases outflow. Its effect on hydraulic head is minimal. This probably indicate that the aquifers have low storage capacity as the water injected at one location displaces the already stored water ta other side of catchment.

The second scenario is the worst case; it enforces drought as well as over pumping stresses. According to model result this worst case scenario severely affect water level of the catchment causing mean drawdown of 20.6m. however, he analysis of this situation at sub catchment level illustrated that Atabala sub-catchment (Sebata area) have mean drawdown of 33m while Holeta sub-catchment being situated at upstream of study area, exhibited 5.8m which is the lowest water level drop. Justification of this occurrence need further future study.

Additional 100 hypothetical water wells with total discharge rate of 216,000m3/day was applied to the calibrated model. Depending on the model output development of 100 productive wells each discharging 25lit/sec will only cause an average water level drop of 3.78m in the entire research area. It also enhances river leakage to groundwater system.

6.2. Recommendation

- Groundwater management work is just only on paper not materialized on ground. Thus, it is recommended that monitoring wells need to be established at representative locations within the catchment to observe long term variability of the hydraulic head and effect of over pumping. At places where large volume of water abstracted would be preferable as monitoring sites. In addition, water wells those developed only in upper aquifer and wells those penetrated both upper and lower aquifer systems need to be managed and monitored separately. These data would help to refine and upgrade the model to simulate transient conditions which in turn enables us to forecast the future response of the aquifer to stresses in long term.
- Volcanic rocks here are very complex and so is their hydraulic properties. Variations of aquifer properties are observed within short distance during model calibration. Hence detail investigation of aquifers proposed to enhance the better fitness of the model to existing natural conditions. Extensive field measurement of hydraulic head, hydraulic conductivity and other sensitive parameters are required for future detail study of the catchment and to upgrade the accuracy and applicability of the model.
- Groundwater management is nonexistence in the study area. For instance the, water wells around Sebeta is very densely populated and induce huge drawdown as observed from the result of model analysis under water stresses. Drawdown is significant and most wells tend to become unproductive in lack of sufficient water reserve. This probably resulted from poor hydraulic conductive, less storage capacity of the rocks and the recharged groundwater flow is partly to Bacho plain and partly to Akaki catchment. Conductivity is poor, deep drawdown is generated as most wells developed near to groundwater divide. Therefore, this area need a series management of the resource. Well siting and spacing has to be regulated and determined based on the characteristics of the aquifers.
- For better evaluation of the Bacho catchment groundwater flow systems, the model need to be refined to unsteady state conditions with time series hydraulic data.

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APPENDICES

Appendix I: Recharge estimation for 12 Meteorological Stations using soil water balance.

Daily precipitation data for 30 years used (1980-1917). Data source: National meteorology Agency. PREC- precipitation; PET- Potential Evapotranspiration; ACPWL- accumulated Potential Water Loss; SM- Soil Moisture; AET- Actual Evapotranspiration.

A. water balance sheet for Addis Alem station. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	17.75	32.81	66.03	65.80	86.77	139.65	262.98	234.58	141.32	30.35	27.21	13.10	1118.35
PET	105.40	103.50	124.00	117.00	114.60	93.00	77.50	80.50	90.00	114.60	108.00	105.40	1233.50
PREC-PET	-87.65	-70.69	-57.97	-51.20	-27.83	46.65	185.48	154.08	51.32	-84.25	-80.79	-92.30	
ACPWL	-345.00	-415.69	-473.66	-524.86	-552.69					-84.25	-165.04	-257.34	
SM retained	35.63	25.02	18.73	14.50	12.61	59.27	200.00	200.00	200.00	131.25	87.63	55.23	**1039.88**
ΔSM	-19.60	-10.61	-6.30	-4.23	-1.88	46.65	140.73	0.00	0.00	-68.75	-43.62	-32.39	**0.00**
AET	37.35	43.42	72.32	70.03	88.66	93.00	77.50	80.50	90.00	99.11	70.83	45.49	**868.20**
Deficit	68.05	60.08	51.68	46.97	25.94	0.00	0.00	0.00	0.00	15.49	37.17	59.91	**365.30**
Surplus							44.75	154.08	51.32				**250.15**

B. water balance sheet for Asgori station. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	15.09	31.48	62.18	83.58	75.39	138.85	252.43	253.10	110.85	18.77	5.86	5.61	1053.19
PET	114.70	113.60	131.10	120.20	122.20	93.60	79.00	82.00	91.20	120.30	116.50	114.50	1298.90
PREC-PET	-99.61	-82.12	-68.92	-36.62	-46.81	45.25	173.43	171.10	19.65	-101.53	-110.64	-108.89	
ACPWL	-420.67	-502.79	-571.71	-608.33	-655.13					-101.53	-212.17	-321.05	
SM retained	24.41	16.19	11.47	9.55	7.56	52.81	200.00	200.00	200.00	120.38	69.23	40.17	**951.77**
ΔSM	-15.76	-8.22	-4.72	-1.92	-1.99	45.25	147.19	0.00	0.00	-79.62	-51.15	-29.07	**0.00**
AET	30.85	39.70	66.90	85.50	77.39	93.60	79.00	82.00	91.20	98.39	57.01	34.68	**836.21**
Deficit	83.85	73.90	64.20	34.70	44.81	0.00	0.00	0.00	0.00	21.91	59.49	79.82	**462.69**
Surplus							26.24	171.10	19.65				**216.98**

C. water balance sheet for Boneya station. Available maximum water capacity 100mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	8.35	25.39	39.74	61.80	62.92	98.48	206.67	218.21	107.39	13.68	4.26	4.86	851.77
PET	110.50	110.40	135.50	124.30	130.40	102.10	89.90	93.10	99.80	126.60	117.20	115.30	1355.10
PREC-PET	-102.15	-85.01	-95.76	-62.50	-67.48	-3.62	116.77	125.11	7.59	-112.92	-112.94	-110.44	
ACPWL	-438.44	-523.45	-619.21	-681.71	-749.19	-752.80				-112.92	-225.86	-336.29	
SM retained	1.25	0.53	0.20	0.11	0.06	0.05	100.00	100.00	100.00	32.33	10.45	3.46	**348.45**
ΔSM	-2.22	-0.71	-0.33	-0.10	-0.05	0.00	99.95	0.00	0.00	-67.67	-21.88	-6.99	**0.00**
AET	10.57	26.11	40.07	61.90	62.97	98.49	89.90	93.10	99.80	81.35	26.14	11.85	**702.24**
Deficit	99.93	84.29	95.43	62.40	67.43	3.61	0.00	0.00	0.00	45.25	91.06	103.45	**652.86**
Surplus							16.82	125.11	7.59				**149.53**

D. water balance sheet for Enchini station. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	25.70	28.98	73.18	82.56	91.58	155.40	281.35	261.06	136.80	43.84	19.90	16.70	1217.06
PET	105.40	103.50	124.00	117.00	114.60	93.00	77.50	80.50	90.00	114.60	108.00	105.40	1233.50
PREC-PET	-79.70	-74.52	-50.82	-34.44	-23.02	62.40	203.85	180.56	46.80	-70.76	-88.10	-88.70	
ACPWL	-327.25	-401.76	-452.59	-487.03	-510.05					-70.76	-158.85	-247.55	
SM retained	38.94	26.83	20.81	17.52	15.61	78.02	200.00	200.00	200.00	140.41	90.38	58.01	**1086.52**
ΔSM	-19.06	-12.11	-6.02	-3.29	-1.90	62.40	121.98	0.00	0.00	-59.59	-50.02	-32.38	**0.00**
AET	44.77	41.10	79.20	85.85	93.49	93.00	77.50	80.50	90.00	103.44	69.93	49.08	**907.84**
Deficit	60.63	62.40	44.80	31.15	21.11	0.00	0.00	0.00	0.00	11.16	38.07	56.32	**325.66**
Surplus	-19.06	-12.11	-6.02	-3.29	-1.90	62.40	203.85	180.56	46.80	-59.59	-50.02	-32.38	**309.22**

E. water balance sheet for Ginchi station. Available maximum water capacity 150mm. All units in mm

parameters	January	February	March	April	May	June	July	August	Septembe	October	November	December	total (mm/year)
PREC	24.48	38.78	71.73	93.86	97.89	142.30	230.23	242.84	143.28	37.67	11.84	10.29	1145.19
PET	117.30	120.00	137.50	128.90	121.90	96.10	80.90	112.10	93.10	124.40	121.30	116.90	1370.40
PREC-PET	-92.82	-81.22	-65.77	-35.04	-24.01	46.20	149.33	130.74	50.18	-86.73	-109.46	-106.61	
ACPWL	-395.62	-476.84	-542.61	-577.66	-601.67					-86.73	-196.18	-302.80	
SM retained	10.73	6.24	4.03	3.19	2.72	48.92	150.00	150.00	150.00	84.14	40.56	19.93	**670.45**
ΔSM	-9.19	-4.49	-2.22	-0.84	-0.47	46.20	101.08	0.00	0.00	-65.86	-43.58	-20.63	**0.00**
AET	33.67	43.26	73.94	94.70	98.36	96.10	80.90	112.10	93.10	103.53	55.42	30.92	**916.02**
Deficit	83.63	76.74	63.56	34.20	23.54	0.00	0.00	0.00	0.00	20.87	65.88	85.98	**454.38**
Surplus	-9.19	-4.49	-2.22	-0.84	-0.47	46.20	149.33	130.74	50.18	-65.86	-43.58	-20.63	**229.17**

F. water balance sheet for Addis Alem. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	9.88	23.00	47.35	70.56	69.56	115.66	240.61	271.85	161.05	26.69	5.73	4.21	1046.14
PET	110.50	110.40	135.50	124.30	130.40	102.10	89.90	93.10	99.80	126.60	117.20	115.30	1355.10
PREC-PET	-100.62	-87.40	-88.15	-53.74	-60.84	13.56	150.71	178.75	61.25	-99.91	-111.47	-111.09	
ACPWL	-423.09	-510.49	-598.65	-652.39	-713.22					-99.91	-211.39	-322.47	
SM retained	24.12	15.58	10.03	7.66	5.65	19.21	169.92	200.00	200.00	121.36	69.50	39.88	**882.92**
ΔSM	-15.77	-8.54	-5.55	-2.36	-2.01	13.56	150.71	30.08	0.00	-78.64	-51.85	-29.62	**0.00**
AET	25.65	31.54	52.90	72.92	71.57	102.10	89.90	93.10	99.80	105.33	57.58	33.83	**836.22**
Deficit	84.85	78.86	82.60	51.38	58.83	0.00	0.00	0.00	0.00	21.27	59.62	81.47	**518.88**
Surplus	-15.77	-8.54	-5.55	-2.36	-2.01	13.56	150.71	178.75	61.25	-78.64	-51.85	-29.62	**209.92**

G. water balance sheet for Addis Alem. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	23.27	33.60	79.97	110.44	109.22	196.18	276.67	283.84	192.48	59.53	19.93	15.36	1400.49
PET	117.30	120.00	137.50	128.90	121.90	96.10	80.90	112.10	93.10	124.40	121.30	116.90	1370.40
PREC-PET	-94.03	-86.40	-57.53	-18.46	-12.68	100.08	195.77	171.74	99.38	-64.87	-101.37	-101.54	
ACPWL	-361.81	-448.21	-505.73	-524.19	-536.88					-64.87	-166.25	-267.78	
SM retained	32.76	21.27	15.95	14.55	13.65	113.73	200.00	200.00	200.00	144.60	87.10	52.43	**1096.04**
ΔSM	-19.66	-11.49	-5.32	-1.41	-0.89	100.08	86.27	0.00	0.00	-55.40	-57.49	-34.68	**0.00**
AET	42.94	45.09	85.29	111.85	110.11	96.10	80.90	112.10	93.10	114.93	77.42	50.04	**1019.87**
Deficit	74.36	74.91	52.21	17.05	11.79	0.00	0.00	0.00	0.00	9.47	43.88	66.86	**350.53**
Surplus	-19.66	-11.49	-5.32	-1.41	-0.89	100.08	195.77	171.74	99.38	-55.40	-57.49	-34.68	**380.62**

H. water balance sheet for Holeta station. Available maximum water capacity 200mm. Precipitation and PET for Hole

parameters	January	February	March	April	May	June	July	August	Septembe	October	November	December	total (mm/year)
PREC	18.96	49.90	70.86	89.82	94.81	117.76	249.50	264.47	168.66	40.92	8.98	13.97	1188.62
PET	105.40	103.50	124.00	117.00	114.60	93.00	77.50	80.50	90.00	114.60	108.00	105.40	1233.50
PREC-PET	-86.44	-53.60	-53.14	-27.18	-19.79	24.76	172.00	183.97	78.66	-73.68	-99.02	-91.43	
ACPWL	-350.57	-404.17	-457.31	-484.49	-504.28					-73.68	-172.70	-264.13	
SM retained	34.66	26.51	20.32	17.74	16.07	40.83	200.00	200.00	200.00	138.37	84.34	53.39	**1032.23**
ΔSM	-18.74	-8.15	-6.19	-2.58	-1.67	24.76	159.17	0.00	0.00	-61.63	-54.03	-30.94	**0.00**
AET	37.70	58.05	77.04	92.40	96.48	93.00	77.50	80.50	90.00	102.55	63.01	44.92	**913.15**
Deficit	67.70	45.45	46.96	24.60	18.12	0.00	0.00	0.00	0.00	12.05	44.99	60.48	**320.35**
Surplus	-18.74	-8.15	-6.19	-2.58	-1.67	24.76	172.00	183.97	78.66	-61.63	-54.03	-30.94	**275.47**

I. water balance sheet for Sebeta station. Available maximum water capacity 250mm. All units in mm

parameters	January	February	March	April	May	June	July	August	Septembe	October	November	December	total (mm/year)
PREC	11.83	52.17	71.31	101.58	102.37	168.87	310.41	359.10	145.90	29.18	13.43	7.74	1373.88
PET	105.40	103.50	124.00	117.00	114.60	93.00	77.50	80.50	90.00	114.60	108.00	105.40	1233.50
PREC-PET	-93.57	-51.33	-52.69	-15.42	-12.23	75.87	232.91	278.60	55.90	-85.42	-94.57	-97.66	
ACPWL	-371.22	-422.54	-475.23	-490.65	-502.89					-85.42	-180.00	-277.65	
SM retained	56.63	46.12	37.36	35.12	33.45	109.32	250.00	250.00	250.00	177.64	121.69	82.34	**1449.67**
ΔSM	-25.71	-10.51	-8.76	-2.23	-1.68	75.87	140.68	0.00	0.00	-72.36	-55.95	-39.35	**0.00**
AET	37.54	62.68	80.07	103.82	104.04	93.00	77.50	80.50	90.00	101.53	69.38	47.09	**947.17**
Deficit	67.86	40.82	43.93	13.18	10.56	0.00	0.00	0.00	0.00	13.07	38.62	58.31	**286.33**
Surplus	-25.71	-10.51	-8.76	-2.23	-1.68	75.87	232.91	278.60	55.90	-72.36	-55.95	-39.35	**426.72**

J. water balance sheet for Tefki station. Available maximum water capacity 100mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	6.59	22.59	28.79	64.41	78.86	117.00	172.89	209.55	131.30	30.61	14.67	8.17	885.43
PET	110.50	110.40	135.50	124.30	130.40	102.10	89.90	93.10	99.80	126.60	117.20	115.30	1355.10
PREC-PET	-103.91	-87.81	-106.71	-59.89	-51.54	14.90	82.99	116.45	31.50	-95.99	-102.53	-107.13	
ACPWL	-409.55	-497.37	-604.08	-663.97	-715.51					-95.99	-198.51	-305.65	
SM retained	1.66	0.69	0.24	0.13	0.08	14.98	97.97	100.00	100.00	38.29	13.74	4.71	**372.49**
ΔSM	-3.04	-0.97	-0.45	-0.11	-0.05	14.90	82.99	2.03	0.00	-61.71	-24.56	-9.03	**0.00**
AET	9.63	23.56	29.24	64.52	78.91	102.10	89.90	93.10	99.80	92.32	39.23	17.20	**739.51**
Deficit	100.87	86.84	106.26	59.78	51.49	0.00	0.00	0.00	0.00	34.28	77.97	98.10	**615.59**
Surplus	-3.04	-0.97	-0.45	-0.11	-0.05	14.90	82.99	116.45	31.50	-61.71	-24.56	-9.03	**145.92**

K. water balance sheet for Teji station. Available maximum water capacity 100mm. All units in mm

parameters	January	February	March	April	May	June	July	August	Septembe	October	November	December	total (mm/year)
PREC	12.25	30.90	50.40	74.45	72.84	124.61	219.14	216.86	102.60	19.26	6.93	8.94	939.18
PET	110.50	110.40	135.50	124.30	130.40	102.10	89.90	93.10	99.80	126.60	117.20	115.30	1355.10
PREC-PET	-98.25	-79.50	-85.10	-49.85	-57.56	22.51	129.24	123.76	2.80	-107.34	-110.27	-106.36	
ACPWL	-422.22	-501.72	-586.82	-636.67	-694.24					-107.34	-217.60	-323.97	
SM retained	1.47	0.66	0.28	0.17	0.10	22.61	100.00	100.00	100.00	34.19	11.35	3.92	**374.74**
ΔSM	-2.45	-0.80	-0.38	-0.11	-0.08	22.51	77.39	0.00	0.00	-65.81	-22.84	-7.43	**0.00**
AET	14.70	31.70	50.78	74.56	72.91	102.10	89.90	93.10	99.80	85.08	29.77	16.37	**760.77**
Deficit	95.80	78.70	84.72	49.74	57.49	0.00	0.00	0.00	0.00	41.52	87.43	98.93	**594.33**
Surplus	-2.45	-0.80	-0.38	-0.11	-0.08	22.51	129.24	123.76	2.80	-65.81	-22.84	-7.43	**178.41**

L. water balance sheet for Tulu Bolo station. Available maximum water capacity 200mm. All units in mm

parameters	January	February	March	April	May	June	July	August	September	October	November	December	total (mm/year)
PREC	10.88	15.20	44.03	65.97	100.58	214.29	280.63	279.82	114.11	17.81	4.59	6.47	1154.38
PET	114.70	113.60	131.10	120.20	122.20	93.60	79.00	82.00	91.20	120.30	116.50	114.50	1298.90
PREC-PET	-103.82	-98.40	-87.07	-54.23	-21.62	120.69	201.63	197.82	22.91	-102.49	-111.91	-108.03	
ACPWL	-426.26	-524.66	-611.73	-665.96	-687.58					-102.49	-214.41	-322.44	
SM retained	23.74	14.51	9.39	7.16	6.43	127.12	200.00	200.00	200.00	119.80	68.46	39.89	**1016.50**
ΔSM	-16.15	-9.22	-5.12	-2.23	-0.73	120.69	72.88	0.00	0.00	-80.20	-51.34	-28.57	**0.00**
AET	27.04	24.42	49.15	68.20	101.32	93.60	79.00	82.00	91.20	98.00	55.93	35.04	**804.90**
Deficit	87.66	89.18	81.95	52.00	20.88	0.00	0.00	0.00	0.00	22.30	60.57	79.46	**494.00**
Surplus							128.75	197.82	22.91				**349.48**

Appendix II. Borehole data used in the model (Q represent discharge)

BH-ID	UTME	UTMN	Elevation (masl)	DEPTH (m)	SWL (mbgl)	GWL (masl)	Q_L/S	Q M^3/Day
BH1	453522	1001474	2562	115.25	57.84	2504.2	14.6	-1261.4
BH2	446266	1004147	2399	147.5	37	2362.0	7	-604.8
BH3	446155	1003073	2390	90	7	2383.0	5	-432.0
BH4	444168	998992	2305	98	7.2	2297.8	5	-432.0
BH5	445099	1003816	2416	130	30	2386.0	7	-604.8
BH6	443050	1001649	2409	130	24	2385.0	3.3	-285.1
BH7	442635	1001366	2412	220	25	2387.0	0.5	-43.2
BH8	443132	1000869	2390	116	30	2360.0	2	-172.8
BH9	444677	998215	2306	100	5.9	2300.1	5.6	-483.8
BH10	444677	998808	2306	100	21.3	2284.7	5.6	-483.8
BH11	444642	1002960	2386	66	49.4	2336.6	2	-172.8
BH12	443984	999625	2304	70	10	2294.0	3.7	-319.7
BH13	404656	997733	2235	81	21.5	2213.5	3.5	-302.4
BH14	434015	1000129	2354	147	4.8	2349.2	1.5	-129.6
BH15	440110	1001337	2419	153	36.62	2382.4	1.5	-129.6
BH16	460810	981473	2228	102	67.1	2160.9	4	-345.6
BH17	460464	974637	2101	61.1	38.14	2062.9	3.5	-302.4
BH18	454852	962780	2009	56	2	2007.0	38	-3283.2
BH19	448328	957872	2142	139	85.4	2056.6	3.25	-280.8
BH20	444245	956023	2220	158	96.38	2123.6	2	-172.8
BH21	455450	983014	2110	120	14.56	2095.4	6.6	-570.2
BH22	455426	982736	2099	150	16.33	2082.7	5.35	-462.2
BH23	444624	978143	2074	65.4	9.6	2064.4	0.75	-64.8
BH24	442842	977555	2074	100	14.15	2059.9	3.4	-293.8
BH25	404050	980200	2150	98.5	9.95	2140.1	8	-691.2
BH26	407400	972711	2140	172	19.45	2120.6	4	-345.6
BH27	461412	986324	2280	145	44.56	2235.4	4	-345.6
BH28	460937	986565	2278	114	46.12	2231.9	19.5	-1684.8
BH29	427635	994816	2132	125	7	2125.0	15	-1296.0
BH30	436160	1000453	2370	153	36.62	2333.4	1.5	-129.6
BH31	435382	1000251	2358	206	9.93	2348.1	7.89	-681.7
BH32	445180	1002459	2393	101	23.3	2369.7	3.5	-302.4
BH33	432432	1024464	2598	161	11.45	2586.6	2.5	-216.0
BH34	440595	1000333	2374	170	81.46	2292.5	7.4	-639.4
BH35	400409	954207	2379	48	21.58	2357.4	4	-345.6
BH36	424000	952736	2169	112	5.37	2163.6	10	-864.0
BH37	455000	985200	2200	126	50.86	2149.1	3.5	-302.4
BH38	461900	974300	2120	0	38.1	2081.9	0.6	-51.8
BH39	455300	985250	2218	101	37.5	2180.5	4.45	-384.5
BH40	455550	983750	2138	181	46.8	2091.2	4	-345.6
BH41	444000	977700	2055	100	17.12	2037.9	0.4	-34.6
BH42	460850	985850	2260	106	43	2217.0	6.5	-561.6
BH43	460500	986500	2285	100	27.12	2257.9	9.1	-786.2
BH44	460121	985966	2239	120	39.7	2199.3	6.67	-576.3

BH-ID	UTME	UTMN	Elevation masl	DEPTH m	SWL mbgl	GWL masl	Q_L/S	Q M3/Day
BH45	457030	984617	2200	140	88.52	2111.5	5	-432.0
BH46	458646	984363	2482	161	44.15	2437.9	5.5	-475.2
BH47	462260	984901	2294	180	82.75	2211.3	6.67	-576.3
BH48	460295	986769	2222	158	31	2191.0	17	-1468.8
BH49	426873	970945	2082	402	0.3	2081.7	98	-8467.2
BH50	426362	969316	2018	420	0.6	2017.4	84.3	-7283.5
BH51	428420	969695	2025	347	18.2	2006.8	56	-4838.4
BH52	428539	970788	2092	380	15.1	2076.9	42.13	-3640.0
BH53	428060	972015	2083	415	2.06	2080.9	68	-5875.2
BH54	428016	978061	2050	397	22.34	2027.7	75	-6480.0
BH55	454868	963109	0	352	3.3	-3.3	63.4	-5477.8
BH56	450887	981258	2041	436	12.17	2028.8	58	-5011.2
BH57	451632	979475	2077	482	7.18	2069.8	25	-2160.0
BH58	450187	981027	2082	440	8.7	2073.3	8	-691.2
BH59	418679	988365	2082	445	0	2083.0	62.05	-5361.1
BH60	423439	988990	2077	450	0	2078.0	34.05	-2941.9
BH61	420071	983317	2071	350	3.2	2067.8	19.12	-1652.0
BH62	411777	989671	2119	250	25.83	2093.2	56	-4838.4
BH63	411189	983944	2091	300	0	2091.5	38.58	-3333.3
BH65	461039	981162	2199	244	71.45	2127.6	19	-1641.6
BH66	461930	970844	2201	183.2	144.4	2056.6	2.3	-198.7
BH67	427126	971361	2075	308	4.2	2070.8	35.5	-3067.2
BH68	456314	962592	2014	290	0	2014.0	35.5	-3067.2
BH69	450359	981037	2084	280	11	2073.0	19	-1641.6
BH70	433200	959670	2111	194	0	2111.0	19.2	-1658.9
BH71	413137	973900	2090	122	8.5	2081.5	16.74	-1446.3
BH72	427395	992768	2109	220	4	2105.0	17.47	-1509.4
BH73	444997	1000718	2356	91.2	37.5	2318.5	6	-518.4
BH74	444626	1001031	2366	0	40	2326.0	0.5	-43.2
BH75	445942	998199	2394	99	0	2394.0	14	-1209.6
BH76	445773	1001323	2388	74.5	30.35	2357.7	3.1	-267.8
BH77	448290	1002698	2413	78	10.2	2402.8	4.5	-388.8
BH78	440079	1000151	2410	112	0	2410.0	6	-518.4
BH79	441584	1003445	2453	50	11	2442.0	1	-86.4
BH80	436632	993521	2186	39	11.7	2174.3	1	-86.4
BH81	446338	997431	2256	125	13.2	2242.8	5	-432.0
BH82	446166	992510	2261	50	7	2254.0	2	-172.8
BH83	446120	990922	2249	50	13	2236.0	1	-172.8
BH84	445271	990389	2225	50	5	2220.0	1.5	-129.6
BH85	440280	1000112	2354	167	94	2260.0	4.5	-388.8
BH86	444580	1003443	2447	54	9	2438.0	1.8	-155.5
BH87	440274	1006055	2525	300	12.33	2512.7	35.5	-3067.2

Appendix III. Perennial springs simulated as drain in flow package.

site_name	X_UTM	Y_UTM	Elev_M	water_Level (m)	discharge (l/s)	Q_ m3/day
kimoye	437919	1000411	2397	2397	1.5	-129.6
Menagesha Mariam	441957	998620	2572	2572	1	-86.4
Kolobo	454152	1002643	2610	2610	1.5	-129.6
Yubo	439169	1007250	2555	2555	0.5	-43.2
Telecha	441080	1013103	2673	2673	3	-259.2
Gajoo	441757	1014339	2644	2644	2	-172.8
Yesus Tebel	454438	999971	2600	2600	1.7	-146.88
Beite	454469	1000092	2519	2519	3	-259.2
Burka Abaduka	459444	989690	2562	2562	2	-172.8
Roghe	457026	981375	2087	2087	10	-864
	393670	959467	2664	2664	2	-172.8
	397814	977586	2644	2644	3	-259.2
	451367	986181	2190	2190	1	-86.4
	451751	992074	2813	2813	2	-172.8
	459831	985582	2227	2227	5	-432

Appendix IV. Range of values of hydraulic conductivity of different rocks

(adopted from freeze & Cherry 1979; Heath 1983)