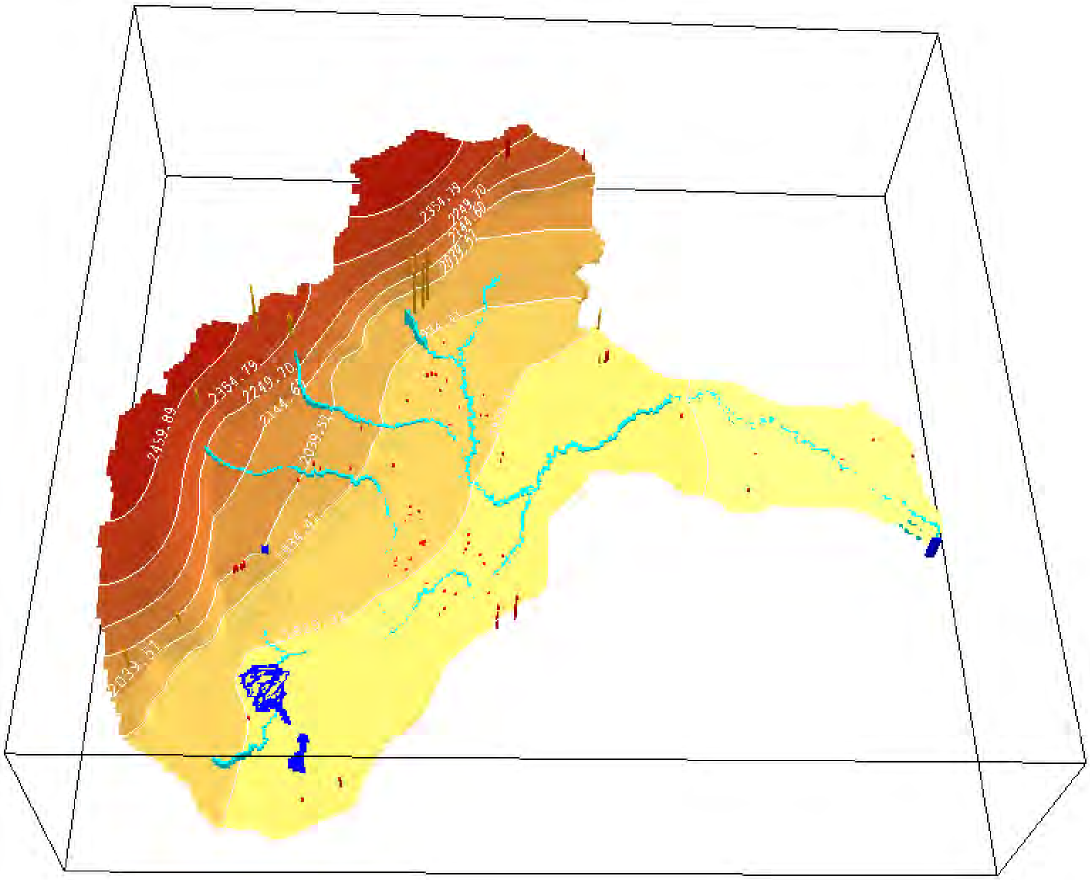
Numerical Groundwater Flow Modeling of the Meki River Catchment, Central Ethiopia



By
Dereje Birhanu Mitiku

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 Civil Engineering (Hydraulics Stream)

October, 2011

Addis Ababa University

School of Graduate Studies

Institute of Technology

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Certification

The undersigned certify that he has read the thesis entitled**: Numerical Groundwater Flow Modeling of the Meki River Catchment, Central Ethiopia** and hereby recommend for acceptance by the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science.

Prof. Tenalem Ayenew
(Supervisor)

Date

Declaration

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

Dereje Birhanu Mitiku
School of Graduate Studies
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October, 2011

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

Prof. Tenalem Ayenew
Addis Ababa University

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Abstract

The Meki river catchment aquifer is located in the central Ethiopian rift valley. This unconfined aquifer is one of the most important groundwater reservoirs of the country. A total catchment of 2319 km^2 was selected to study the groundwater flow system using a numerical groundwater flow model (Processing Modflow Pro (Version 8.0.15)). A three dimensional steady-state finite difference groundwater flow model is used to quantify the groundwater fluxes and analyze the subsurface hydrodynamics in the Meki river catchment by giving emphasis to the well field that supplies water to the community. The area is characterized by Quaternary volcanics covered with lacustrine, alluvial, talus, and pyroclastic deposits. The model is calibrated using head observations from 95 wells. The simulation is made in a one layer unconfined aquifer with spatially variable recharge and hydraulic conductivities under well-defined boundary conditions. The calibrated model is used to forecast groundwater flow pattern, the interaction of groundwater and surface water, and evaluate the behavior of the groundwater system under possible future utilization scenarios . A sensitivity analysis conducted indicates that the model is more sensitive to decrease in recharge and increase in hydraulic conductivity but less sensitive to increment or decrement of pumpage.

The simulation result indicates that the groundwater flows from western escarpment to east directions finally join Lake Ziway. Lakes and rivers play important role in recharging the aquifer. Simulations made under different possible future utilization scenarios including increase in pumping rate results in substantial regional groundwater level decline, which will lead to the drying of springs, and shallow hand dug wells. It has also implications of reversal of flow from contaminated rivers in to productive aquifers close to main river courses; decrease in recharge caused more inflow from Lakes as well as increase stream flow but decrease drains, and disappearance of Lake Tuffa results in increased recharge and groundwater outflow through springs. The sensitivity and scenario analysis provided important information on the data gaps and the specific sites to be selected for monitoring that may be of great help for transient model development. This study has laid the foundation for developing detailed predictive groundwater model, which can be readily used for groundwater management practices.

Keywords: Central Ethiopian, Meki, Modeling, Modflow, Volcanic aquifer, groundwater management

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List of Acronyms

AAiT	Addis Ababa Institute of Technology
ASTER	Advanced Spaceborne Thermal Emission and Reflection
D.D	Draw down
DEM	Digital elevation model
GIS	Geographical information system
GUI	Graphical user interference
ITCZ	Inter Tropical Convergence Zone
JICA	Japan International Cooperation Agency
K	Hydraulic conductivity
MAE	Mean Absolute Error
M.a.s.l	Meter above mean sea level
MCM	Million cubic meters
ME	Mean Error
MER	Main Ethiopian Rift
MODFLOW	Modular 3 dimensional finite difference groundwater flow models
MoWE	Ministry of Water & Energy
OIDA	Ontario International Development Agency
PCG2	Preconditioned Conjugate Gradient2
Q	Well yield
RMS	Root Mean Squared Error
SWL	Static Water Level
T	Transmissivity
USGS	United states geological survey
UTM	Universal Transverse Mercator
WEAP	Water Evaluation and Planning System
WFB	Wenji Fault Belt
WGS84	World Geodetic System dating from 1984

Chapter 1

1. Introduction

1.1 Background

Groundwater is an important natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply (Kemper, 2004). It has been estimated that between one third and one half a billion people in Sub-Saharan Africa use protected or unprotected groundwater for their daily water supply (Carter and Bevan, 2008).

Meki river catchment has an abundance surface and groundwater resources; however, due to climatic change, industrialization, high population growth, the amount of water available is decreasing and its quality is degrading. In a country like Ethiopia, where rain fed agriculture is the main source of economy and ensures the wellbeing of many people, water resources are essential. Nevertheless, if the water resources are not utilized properly in an integrated planning manner, its sustainability and its support to food security to the country will become endanger. Therefore proper planning of water resources development as well as utilization is very essential.

Groundwater plays significant role in the region and presently used for almost all town and village water supply of the sub basin. The integral approach considers both surface and sub-surface water as the major resource of the region. It is observed that there are a lot of boreholes, shallow wells, dug wells, wind pumps and springs over the region which serve as community water supply.

Regardless of its high documentations, modeling studies related to the Meki river catchments is quite recent and little experience has been accrued in this context for the area. Groundwater modeling is a result of careful understanding of hydrology, hydrogeology and dynamics of groundwater flow in and around the study area. The final model can be used as a tool to help understand the flow system, to confirm that estimates of aquifer properties are reasonable, to estimate aquifer properties in areas without data and also to see the response of the system for different scenarios which help us to better understand the system.

1.2 Objectives

The general objective of this study is to understand the groundwater flow system and response for different stresses through simulation of regional groundwater flow in the aquifer as single layer system under steady-state conditions.

The specific objectives are:

- To organize and synthesize the available information and previous work;
- To Construct a GIS database, based on the MODFLOW input files, for development of the numerical model;
- To develop steady-state numerical ground water flows model of the catchment;
- To provide a steady-state calibrated water level, hydraulic parameter and recharge of the hydrogeological system of the area;
- To conduct sensitivity analysis of the aquifer system and identify the most influential parameter that direct future emphasis of study for the groundwater management;
- To evaluate the behavior of the groundwater system under possible future utilization scenarios; and,
- To assess the groundwater balance using the calibrated model.

1.3 Methodology

1.3.1 Data collection

This part of the work includes deskwork and field investigation for gathering the essential data in order to achieve the research objective.

The deskwork will carry out the essential literature review on modeling books, previous work, and water well inventory and well completion reports. It also includes collection of Topographic map, Geologic map, Hydrogeological map, Digital elevation model , Meteorological data, Hydrological data and modeling software like Processing Modflow Pro (Version 8.0.15) , Arc GIS 9.3 , Surfer 10, Global Mapper 12, Aquatest and so on.

Following the deskwork a field survey has been conducted. This study was aimed at measuring width of river and water level, observation of hydrogeological features, the confirmation of the secondary data collected at the deskwork and detail filed visit for specific sites for confidential conceptual model development of the study area. The data source was Ministry of Water & Energy, Ethiopian Mapping Agency, National Meteorological Agency, Geological Survey of Ethiopia, AG Consult, Consulting Hydrogeologists & Engineer and Water Works Design & Construction Enterprise.

1.3.2 Data analysis and synthesis

It involves the analysis and synthesis of the available data with a help of modeling code of MODFLOW interfaced by Processing Modflow Pro (Version 8.0.15) that consider the physical condition of the study area which can be represented with governing equation. This part of the work embarks the modeling protocol like conceptual model development, defining model geometry and boundary, assigning the hydrogeological parameter, running the model and calibration.

1.3.3 Modeling protocol

The paper approaches the problem of understanding the flow system of the Meki river catchment with the very deterministic and numerical model which approximates physical law with finite difference. It is a method developed by United State Geological Survey (McDonald and Harbaugh, 1988). The paper used the power of the GIS and Surfer for all spatial data and conceptual models that has been done in the research. The above listed procedure can be summarized with the flow chart shown on Figure 1.1 below.

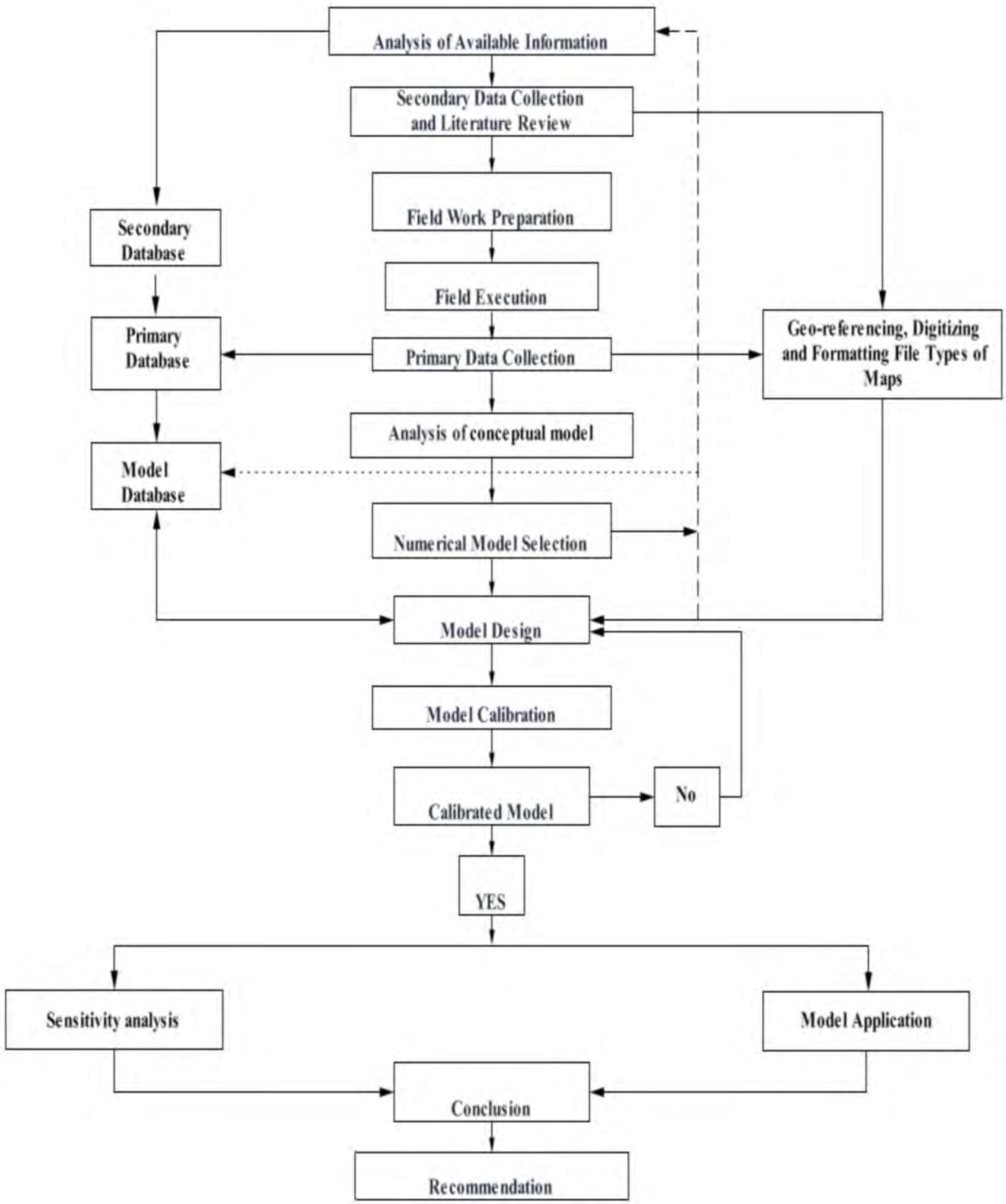

Figure 1.1 Flow chart of the modeling protocol

1.4 Literature review

1.4.1 Review of previous study

The central Ethiopian rift valley has been the interest of many researcher and organization, thus a number of essential works carried out over the hydrology, water resource potential assessment, and hydrogeology, climate, and land use of the basin. Among them the prominent work listed below will be reviewed for the benefit of the research.

In 1975 a detail study was conducted by Land Resources Division, Ministry of Overseas Development, England that focuses on the Ziway-basin mainly on Lake Ziway and Meki River and proposed different development scenarios, Dagnachew Legesse, 2002 in his Ph.D. thesis analysis the hydrological response of Ziway–Shalla basin to changes in climate and human activities and Hawi Abate, 2007 studied the impact of land use change and climate variability on catchment runoff which is a modeling study on Meki river basin .

Di Pola, 1972 presented an overall account of the geology, stratigraphy, structural patterns and geological map with an approximate scale of 1:60,000 of the main Ethiopian rift within $7^0$00‟ to 8^0 40‟N latitudes, Tesfaye Chernet, 1982 presented a regional geological and hydrogeological map of Ziway–Shalla basin including regional classification of rocks in to different permeability groups, and Haile Gashew, 1998 studied hydrogeology and hydrology of lake Ziway area and its surroundings.

Italo consult in 1970 has made water resources assessment in the Ziway–Langano-Abijata-Shalla Basin. The main aim of the study was to divert Meki river into Awash river for extension of irrigation in the Amibara area, and JICA and OIDA, 2001 in the project study of Meki irrigation and rural development, the primary emphasis was given to the assessment of water resource potential in Meki - Abijata basin. Accordingly, hydrological analysis and lake water balance were part of the study and application of physically based distributed hydrological model for estimation of major components of the hydrologic cycle of Meki river basin was done by Temesgen Alemyirga, 2008.

Halcrow ,1989 analyzed groundwater and surface water potential of the area in the work entitled „rift valley lakes integrated natural resource development master plan‟, Tenalem Ayenew, 1998 in his

Ph.D. thesis analyzed general hydrology and hydrogeology of Ziway–Shalla basin ,the study includes evaluation of groundwater and surface water interaction, water balance and recharge estimation of sub catchments , Tenalem Ayenew, 2001 done numerical groundwater flow modeling of the central main Ethiopian rift lake basin, Tenalem Ayenew, 2003 also done evapotranspiration estimation using thematic mapper spectral satellite data in the Ethiopian rift and adjacent highlands and Alemu Dribssa ,2006 in his MSc thesis study groundwater–surface water interaction and analysis of recent changes in hydrologic environment of Lake Ziway catchment.

In all studies conducted so far, more work is done on hydrology, hydrogeology, climate, and land use of the basin except the numerical groundwater flow modeling of the central main Ethiopian rift lake basin which is done by Tenalem Ayenew, 2001. There is limited consideration of the role of numerical groundwater flow modeling of the catchment under consideration. Moreover, the current research is expected to describe groundwater flow system of the catchment so that it will increase the knowledge on understanding the flow system. It is also expected to have to have the following output: water balance of the study area, calibrated hydraulic parameter, sensitive hydraulic parameter and predictions which provide useful information for policy makers and general public to manage the resource on sustainable basis.

1.4.2 Groundwater modeling

A groundwater model may be defined as a simplified version of the real groundwater system that approximately simulates the excitation- response relations of the groundwater system. The real system is very complicated and difficult to use it directly for the purpose of planning and making management decisions. The simplification is introduced in the form of a set of assumptions that express our understanding of the nature of the system and its behavior. These assumptions will tend to smooth out the effect of various heterogeneities. Because the model is a simplified version of the real system, there exists no unique model for a given groundwater system (Bear and Verruijt, 1987).

A computer program or code solves a set of algebraic equations generated by approximating the partial differential equations (governing equation, boundary conditions, and initial conditions) that form the mathematical model (Anderson and Woessner, 1992).

The selection of an appropriate modeling code and GUI for a particular study is a matter of ensuring that the code has the capability to adequately represent the essential features and flow processes of the groundwater system being studied. It is also important to ensure that the selected code has been verified and benchmarked against standard test problems, to confirm that the code accurately solves the equations that comprise the mathematical model.

Groundwater models are an attempt to represent the essential features of the actual groundwater system by means of a mathematical counterpart (Todd, D.K., 2005). These models have a capacity to test and quantify the consequences of various errors and related model-based forecasts.

Groundwater models according to Todd are physically based mathematical models derived from Darcy"s law and the law of conservation of mass. Various established solution techniques based upon either finite difference or finite element approximations, or a combination of both, are available for solving the governing equations of the model. The accuracy of the solutions (model predictions) is dependent upon the reliability of the estimated model parameters and the accuracy of the prescribed boundary conditions.

The finite difference method requires a rectangular element shaped discretization of the aquifer and the finite element method consists of a triangular discretization. Discretization is the process of subdividing the continuous hydrogeologic units into discrete segments or cells. Finite element method is easy to define the boundaries of irregularly shaped aquifers and to ensure that node points coincide with monitoring wells or varies types of geographic features. The mathematical basis for finite element methods is more complex than for the finite difference method (Todd, D.K., 2005).

There are several ways to classify groundwater flow models, models can be transient or steady state and one, two, or three spatial dimensions. Steady state flow occurs when at any point in a flow field the magnitude and direction of the flow are constant with time (Anderson and Woessner, 1992).

Selecting the appropriate conceptual model for a given problem is one of the most important steps in modeling process. The key data requirements in the process of conceptualization include data about hydro-stratigraphic units, surface water bodies, physical and hydraulic boundaries, recharge and discharge zones. The most common numerical methods to solve flow problems are finite differences and finite elements. Finite difference grids are easy to understand and require less input data than finite element grids (Anderson and Woessner, 1992). The finite difference method, as applied in the computer code MODFLOW, was used in this study. The code is based on theory of Darcy‟s law and the continuity equation. The program supports seven additional packages, which are integrated with the original MODFLOW (Chiang and Kinzelbach, 2001).

Once the conceptual model is translated into a numerical model in the form of governing equations, with associated boundary and initial conditions, a solution can be obtained by transferring it into a numerical model and writing a computer program (code) for solving it. This includes, design of grid, setting boundary and initial conditions and preliminary selection of values for aquifer parameters.

The input parameters include model grid size, layer elevations, boundary conditions, hydraulic conductivity, recharge, and additional model input for steady state condition. Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria (Anderson and Woessner, 1992). Sensitivity analysis is useful in determining which parameter or parameters most influence the model results. These parameters will be emphasized in the future data collection attempting to improve model accuracy.

Chapter 2

2. General overview of the area

2.1 Location

Meki river catchment is located in the central main Ethiopian rift valley. Meki town is located about 120 km from the capital city of the country, Addis Ababa. The area stretches from the edges of the western escarpment of the rift valley in the west and to Lake Ziway in the east. Geographically, it is located approximately between $7^0 51$"E and $8^0 27$"E Longitude $38^0 15$"N and $38^0 51$"N latitude (UTM: 415131-489329E and 865165-935680 N, Zone 37, Northern Hemisphere) respectively.

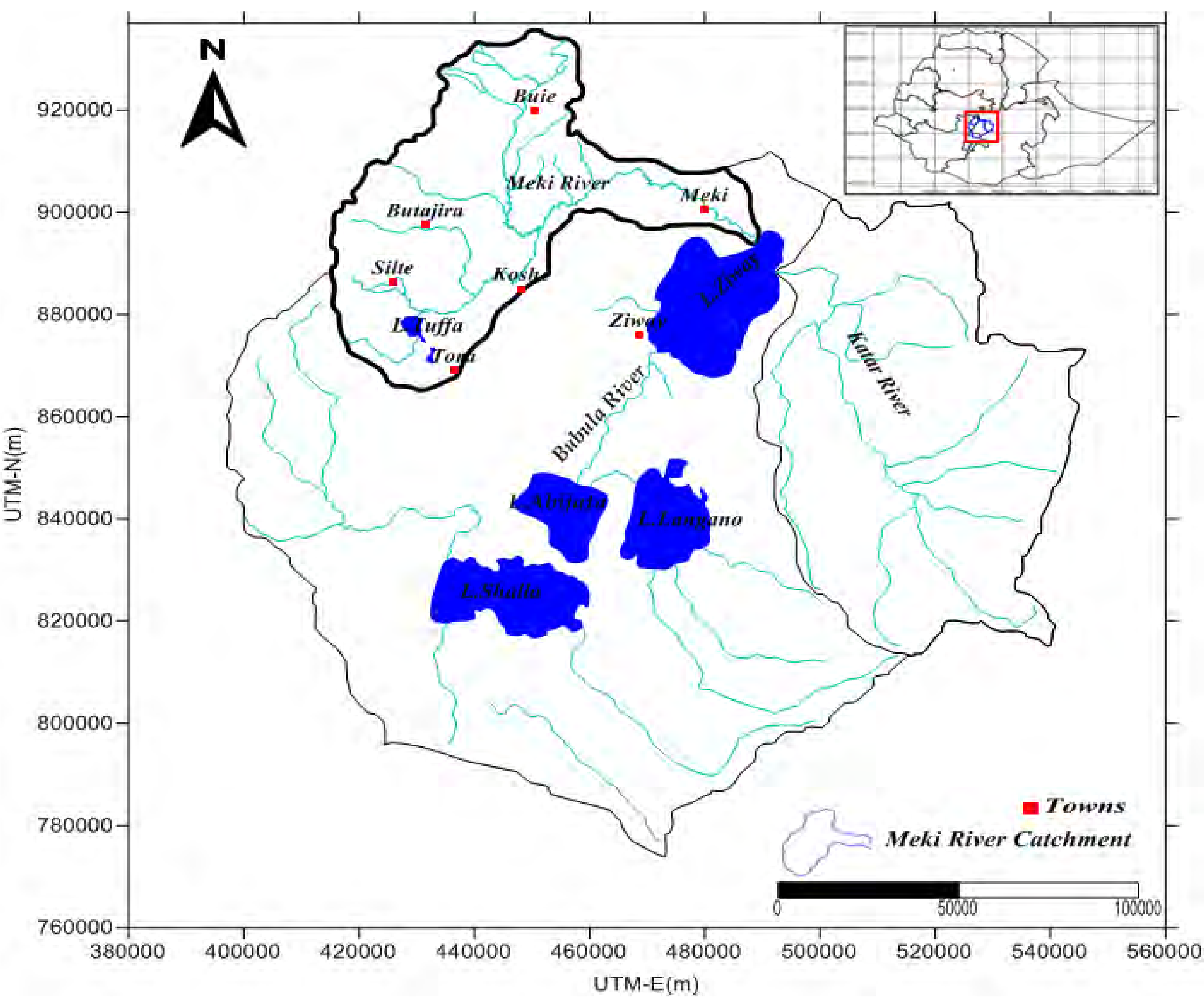

Figure 2. 1 Location map of the Meki river catchment within the Ziway-Shalla basin

The total area of Meki river catchment is about 2318.58 km^2. Topography of the area is primarily determined by the rift system of faulting. The study area lies within altitudes ranging from 3600 in the west to 1600m.a.s.l to Lake Ziway with a mean elevation of 2056m.a.s.l.

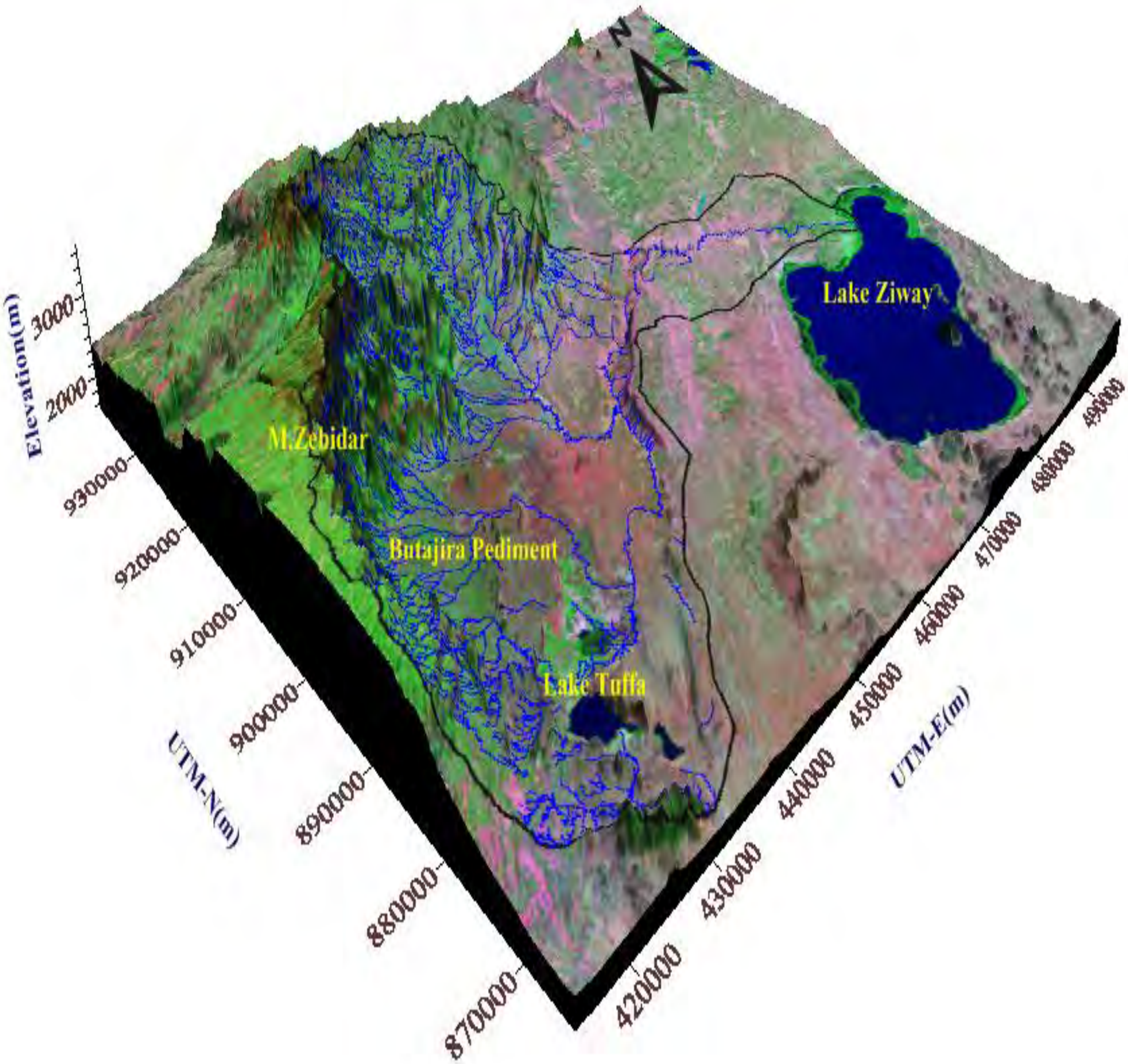

Figure 2.2 Topography and drainage of the study area

2.2 Topography and drainage

The upper riches of the basin are steep and mountainous while the lower basin is flat with a broad valley (Figure 2.2).The area can be divided into three physiographic areas: the high plateaux on the western summit of the area with elevation range of (2295 – 3611m), the transitional escarpment (1856 – 2294m) and the rift floor (1636 – 1855m) (Hawi Abate, 2007).

The floor of the rift valley is not uniformly flat, but it is occupied by some reliefs of volcanoes, rising for about 500 m or more, such as it occurs on the plateaux, especially along the escarpments limiting the rift, where some reliefs, more than 1000m high, occur.

The very great height of the plateau above sea level has caused the rivers to cut deep canyons. There are numerous examples where faulting on plateau has determined section of river courses. Whilst the large scale of physiography of Ethiopia dominated by the tectonic, on smaller scale other factors are important, especially the denudation caused by rivers, volcanic structures including cones, craters, lava flows, and amelioration of relief caused by deposition.

The western plateau of the Gurage highlands with elevation ranging from 3500 to 3600m.a.s.l. is the perennial sources of the Meki river while the tributaries in the escarpment and rift floor are almost intermittent sources. The Meki river drains from the western mountains and escarpments including a vast swampy area and travels for about 100 km before draining to the Ziway Lake. Lake Ziway mainly receives its water from this river in addition to the inputs from Katar river, groundwater, precipitation and the runoff from the dry lake catchment surrounding the lake.

The highland is characterized by higher drainage density than the escarpment and flat areas of lacustrine deposits in the southern part of the study area, which lack drainage due to differences in rock permeability, climate and slope (Tesfaye Chernet, 1982). Rift faults have affected the drainage of the area both by determining the river courses and by impounding river water and causing some marshy areas, in the southern part of the study area (Tesfaye Chernet, 1982).

2.3 Climate

Climate of the study area consists of three ecological zones: humid to dry humid, dry sub-humid or semi-arid and semiarid or arid lands (Makin et al., 1976). Accordingly, highland areas west of Butajira are categorized under humid to dry sub-humid land. The areas east of Butajira around Lake Abaya are dry sub-humid lands. The rest of the area which is around the lake is in semiarid or arid zone. Rainfall and temperature in the area show strong altitudinal variations. The average annual rainfall varies spatially and ranges from around 715 mm/year in the rift floor to more than 1100 mm/year at extreme highland areas.

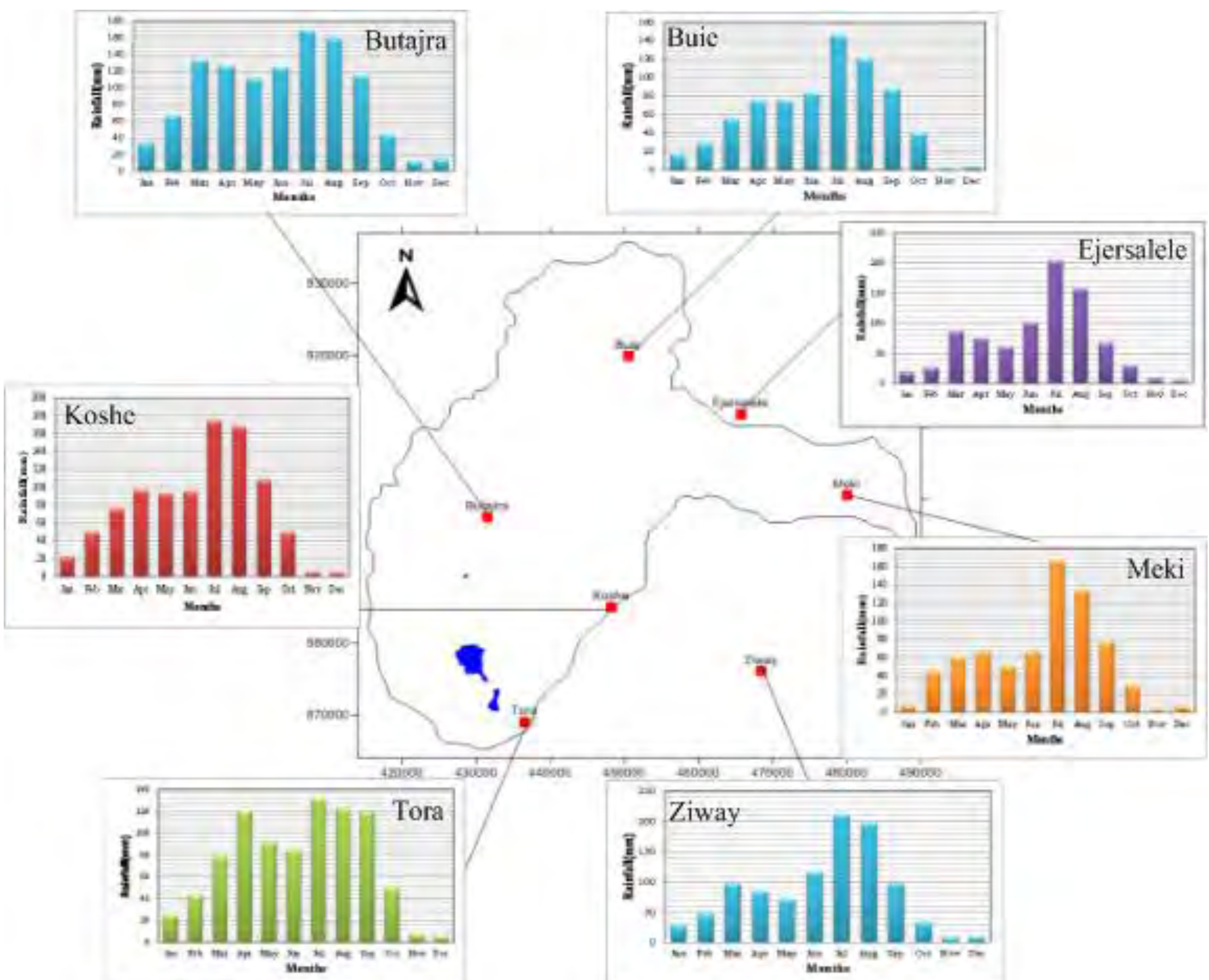

Figure 2. 3 Some of the meteorological stations in the study area and rainfall distribution patterns (1986_2004)

The average annual prevailing mean temperature ranges from about 11^{0}C in the highlands to around 26 ^{0}C in the rift. The average monthly temperature of the basin is 18.8^{0}C with ranging 9.3 ^{0}C in Dec and Jan to 27.75^{0}C in May and April. The Mean monthly temperature diagram shown below, overview the detail.

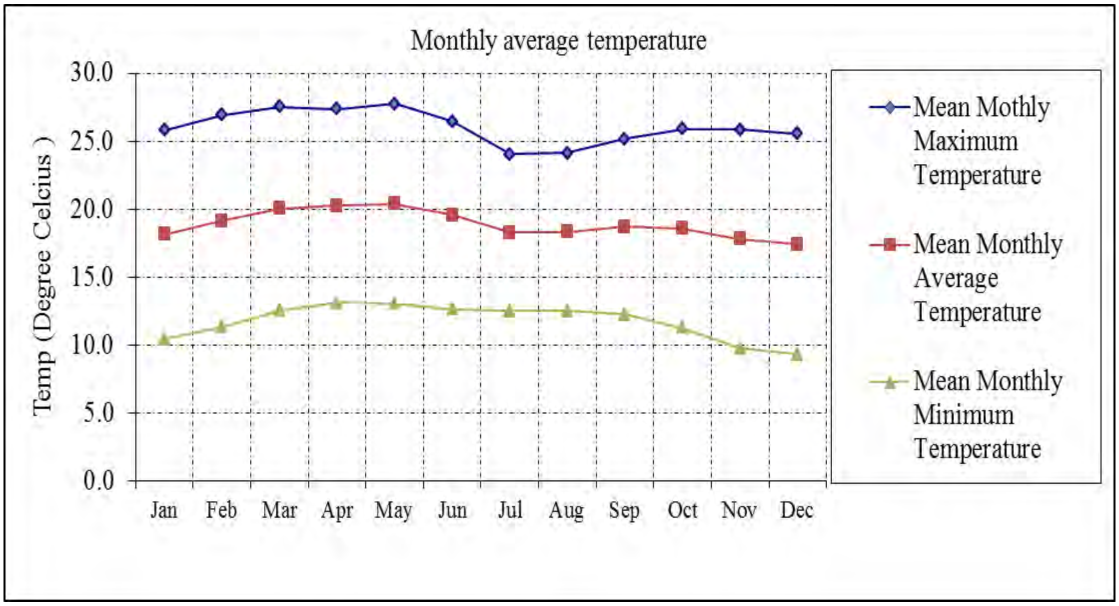

Figure 2. 4 Mean monthly temperature of the study area (1986_2004)

The mean monthly wind speed prevailing in the basin is 1.8 m/s with average 7.9 sunshine hours per day. The relative monthly temperature decrement is associated with low sunshine hour, high wind speed and relative humidity. The area is also characterized with mean monthly relative humidity of 67.5 %.which ranges from 52.2 % in November up to 90.3 % in August. The relative humidity shows high value between May to November.

2.4 Soil

The land use/ cover and soil map of the study area is obtained from rift valley lakes master plan study report by Halcrow Consulting Group report in the form of shape file having a scale of 1:250 000 . Soil in the study area is closely related to parent material and degree of weathering (Makin et al., 1976). Basalt, ignimbrite, acidic lava, volcanic ash and pumice, and riverine and lacustrine alluvium are the main parent materials (Di Paola, 1972). Generally the dominate soil types of the study area are

Chromic Cambisol, Eutric Cambisol, Eutric Vertisol, Haplic Luvisol, Leptosol, and Vitric Andosol. The spatial distribution of the dominate soil types is shown in Figure. 2.6.

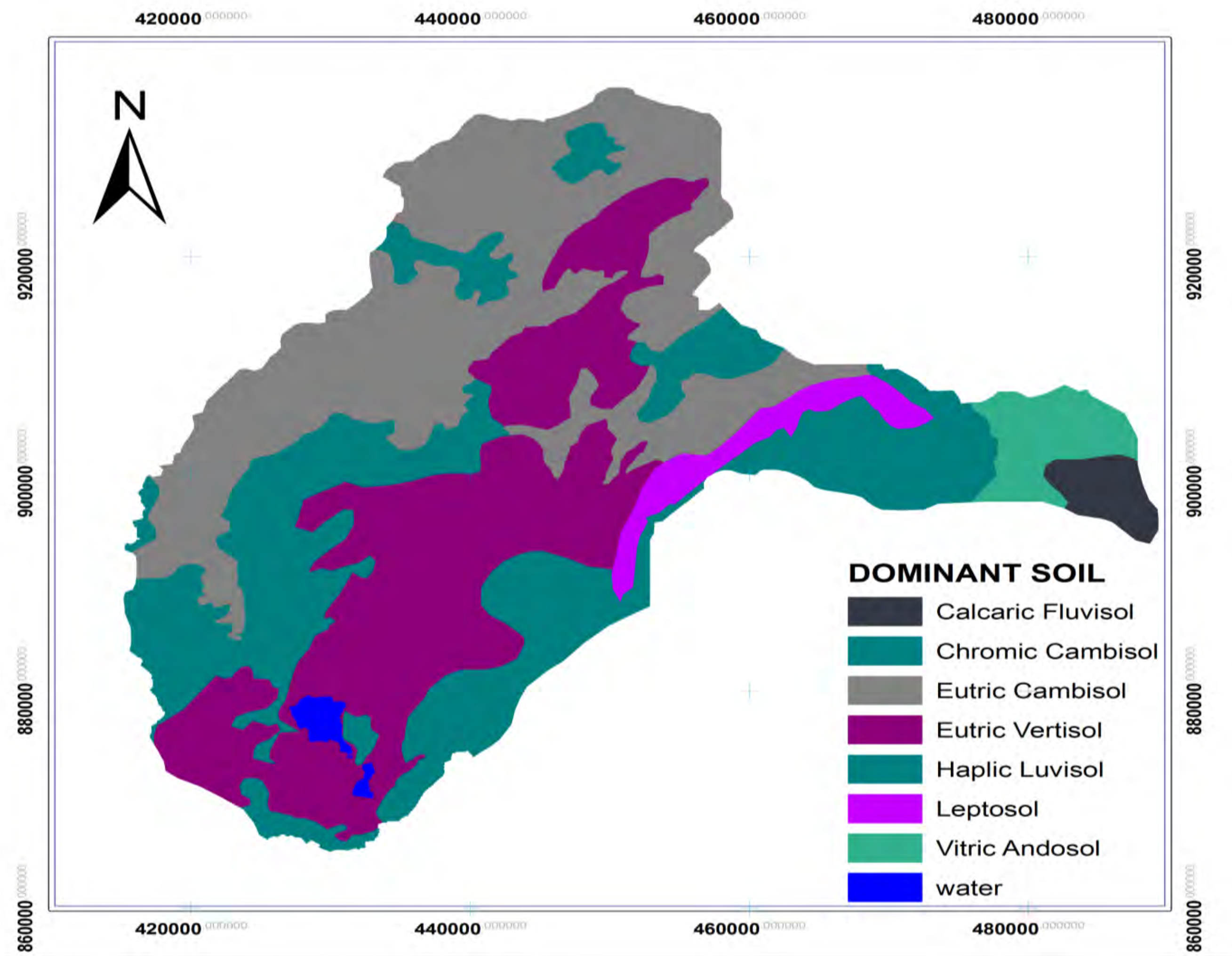

Figure 2. 5 Dominant soil type of the study area (Source: Halcrow, 2007)

2.5 Land use and cover

The land cover of the catchment is controlled with topographical, climatic and ecological conditions. The land cover has made dramatic change with the past years in association with the population growth of the rift valley basin. The major land use and cover is categorized as forest, grassland, intensively cultivated, marshland, moderately cultivated, shrub land, and water body that covers 9%, 1%, 51%, 3%,29%,6% and 1% of the study area respectively.

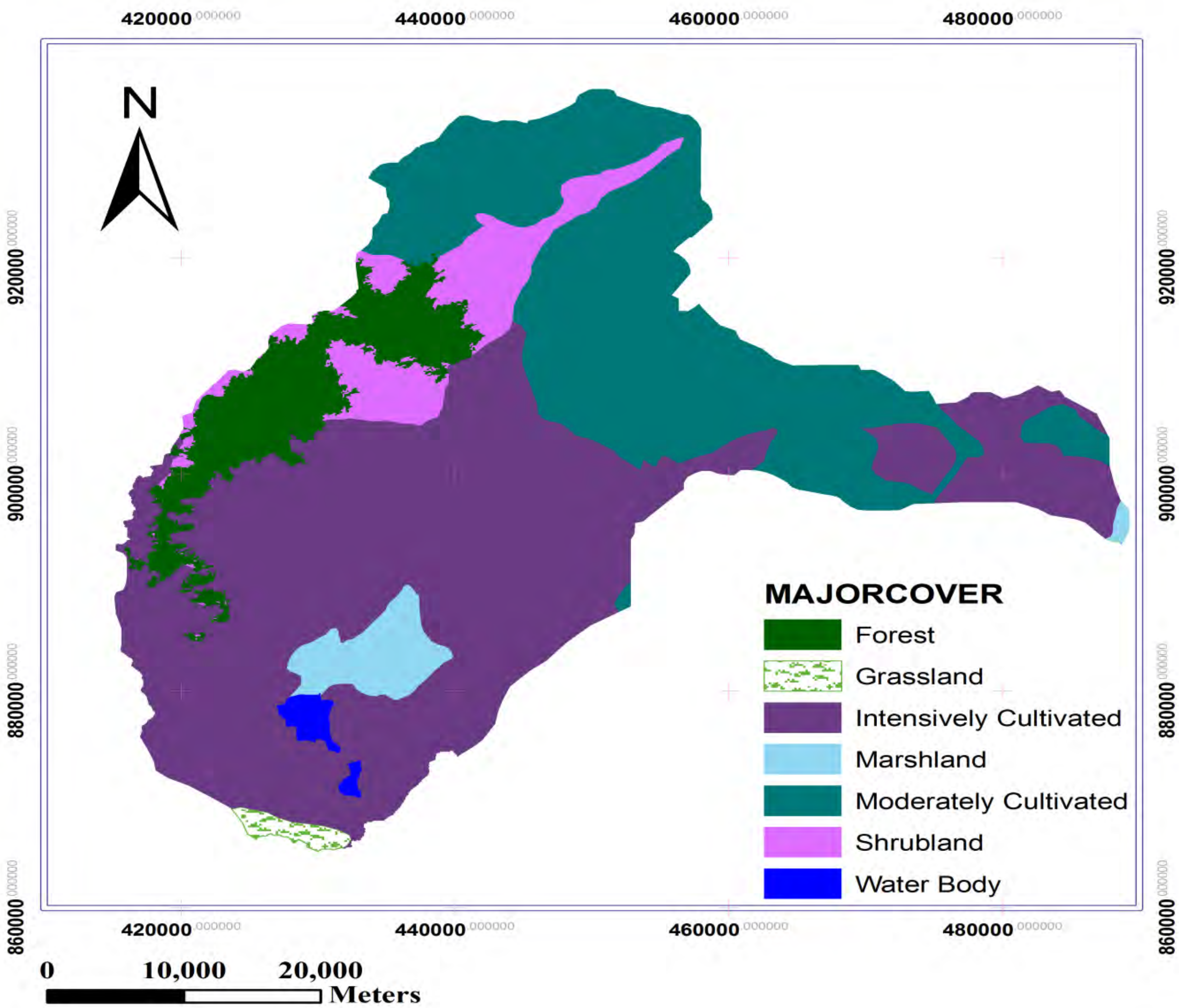

Figure 2. 6 Major land use and cover of the study area (Source: Halcrow, 2007)

2.6 Hydrometeorological setting

2.6.1 Precipitation

The seasonal distribution of rainfall over the country is governed by the position of Inter Tropical Convergence Zone; ITCZ (Tenalem Ayenew, 1998; Dagnachew Legesse, 2003).The ITCZ represents a low-pressure area of convergence between Tropical Easterlies and Equatorial Westerlies along which equatorial wave disturbances take place. The shifting of this low pressure area governs the availability of rain driving wind direction.

The rainy season from June to September is controlled by ITCZ which lies to north of Ethiopia at that time. Hence, the study area intercepts most of the monsoon rainfall from Atlantic and Indian oceans. The dry period, from October to February is when the ITCZ lies to the southern of the country. In these months, the north easterly trade wind traversing Arabia dominates the region and therefore, produces very little or no rainfall in the area.

During March, the ITCZ is located in south of Ethiopia moving northwards. At that time low pressure is developed in Sudan and Arabia while high pressure develops over Gulf of Aden and Indian Ocean. The high pressure generates a moist easterly air current over southeast Ethiopia producing spring (Bulg) rain from March to May.

The rain fall analysis of the catchment is very essential part of the study which finally controls the recharge of the study area. The rainfall spatial and temporal distribution is analyzed based on meteorological station listed in table 2.1.

Table 2. 1 Mean annual precipitation of the study area

Station	**UTM-E(m)**	**UTM-N (m)**	**Mean rainfall(mm)**
Buie	450500	919850	1,011.79
Kulumsa	518000	886400	821.50
Butajira	431500	897500	1,110.11
Koshe	448250	885000	944.36
Hombole	475500	925000	961.80
Adami tulu	467500	868800	697.90
Meki	480000	900500	715.64
Abosa	469500	886500	780.64
Tora	436500	869000	886.40
Alem tena	494300	917000	791.60
Ziway	468500	876000	739.50
Silte	426000	886300	1,000.10
Lemen	525000	841000	1,405.40
Ejersa lele	465700	911800	853.40
Mito	416166.613	861191.69	932.90

2.6.2 Spatial distribution of rainfall

Precipitation of the study area was analyzed based on the 15 stations found in and around the catchment and the average aerial depth of precipitation over the catchment has been determined using Thiesen polygon and Ishyetal methods.

The Thiesen polygon and Ishyetal contours has been constructed using all 15 stations. Accordingly, the catchment gets mean annual precipitation of 975.97 mm and 992mm respectively.

Table 2. 2 Arial mean depth of precipitation using Thiesen polygon and Ishyetal method

Station	Isohyet range(mm)	Area enclosed(km^2)		Weighted area (%)		Mean value of Isohyet	Mean annual ppt	Weighted precipitation(mm)	
		By polygon	Between Isohyets	Thiesen	Ishyetal			Thiesen	Isohyetal
Lemen	> 1150	0.56	136.76	0.0242	5.9	1175	1,405.40	0.34	69
Butajira	1150-1100	506.4	293.25	21.841	13	1125	1,110.11	242.45	142
Buie	1100-1050	594.9	324.04	25.656	14	1075	1,011.79	259.59	150
Silte	1050-1000	360.8	437.89	15.563	19	1025	1,000.10	155.64	194
Koshe	1000-950	249.8	412.86	10.774	18	975	944.36	101.74	174
Mito	950-900	19.43	339.61	0.838	15	925	932.9	7.82	135
Tora	900-850	172.6	67.27	7.4421	2.9	875	886.69	65.99	25
Ejersa lele	< 900	217.3	34.97	9.373	1.5	875	846.52	81.56	13
Abosa	850-800	2.89	74.93	0.1246	3.2	825	780.64	0.97	27
Meki	800-750	194	71.86	8.365	3.1	775	715.64	59.86	24
	750-700		76.7		3.3	725			24
	<700		48.45		2.1	675			14
	$\sum$	2319	2318.59	100	100			975.97	992

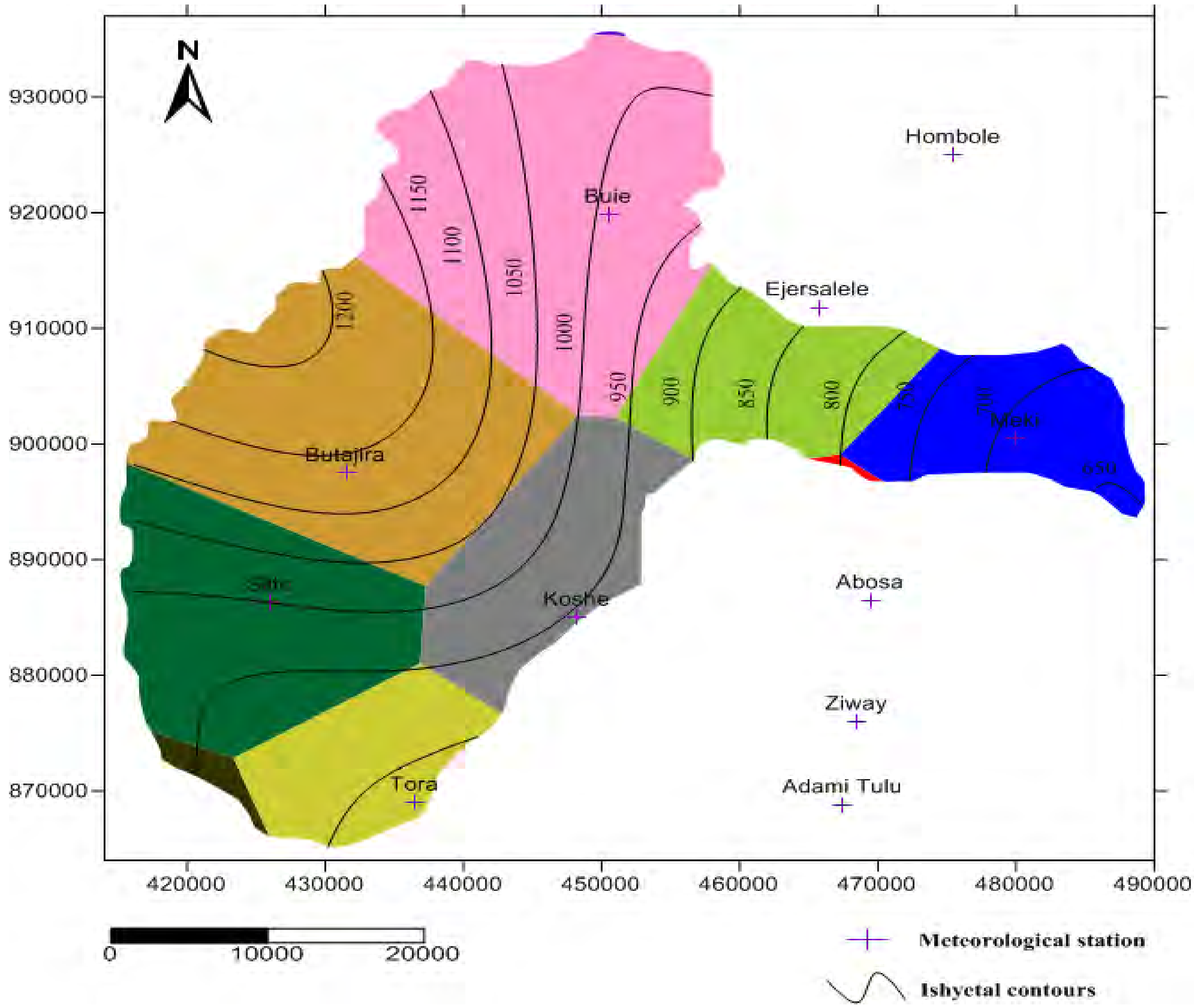

Figure 2. 7 Thiesen polygon and Isohyetal map of the study area

2.6.3 Hydrological setting

In Meki river catchment there are only two gauging stations. The station on the main Meki river; at Meki Town, which is the gauge station before the river enters lake Ziway and the second station is situated at the Irinzaf stream, which is tributary of Meki river. The Irinzaf stream station is found at Butajira Town; currently it is disrupted by a pipeline crossing the river. Although the headwaters of the Meki river is at an altitude of about 3000 m, the river rapidly descends the rift valley escarpment to below 2,000 m.a.s.l before being joined by several major tributaries, including the Lebu, the Akamujas, Irinzaf and the Weja.

The catchment of Meki river includes small terminals Lake Tuffa, Goletsh and Kuntane swamp. Some of the runoff enters these water bodies; during the summer season the overflow from these waters body enters Weja river, which is tributary of Meki river.

According to the stream flow data recorded at Meki town (1963 – 2004), average annual runoff volume of the river is 291 MCM.

Table 2. 3 Mean monthly flows (in m^3/s) of Meki river at Meki town

year 1963-2004	**Average discharge (m^3/s)**												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Measured	0.94	2.28	5.01	7.01	7.31	6.29	18.75	29.64	19.93	8.77	3.29	0.9	9.81

Chapter 3

3. Geological setting

3.1 Geology

3.1.1 General overview

The rift system is one of the largest structural features of the Earth's crust, extending for a distance of 6000km from Mozambique to Syria, equivalent to 1/6th of the earth's circumference (Mohr, 1970). In, Ethiopia the rift system extends over 1000km in a general NE direction. It covers 150,000km^2 and it can be divided into two broad units: The Main Ethiopian Rift (MER 5^0-9^{0}N and37^{0}30'-40^{0}E) and the Afar depression.

Dipola, 1972 reported his observation of out crops of Mesozoic sediments in the rift valley. These Mesozoic sediments crop out at western rift margin, east of Guraghe Mountains .It is underlain by Biotitic gneiss, which also exposed at the same locale. The overlaying upper sandstone was probably subjected to a long period of uplift and erosion, that 200 m thick cretaceous upper sand stone, which uncomfortably underlies the trap basalt at Ambo 100km to the north is absent in Guraghe area (Woldegabriel et al., 1990).

The pyroclastic formation includes typical ignimbrites, sillars and layered pumice. In the MER, these are the most ancient formation out cropping on the floor of the rift valley. Its age is upper Pliocene, according to Mohr, 1971 that assumed the same age for the rift ignimbrites and the last ignimbrite cover of the plateaux. Several layers constitute the pyroclastic formation with variable thickness, from 0.5-1m up to 20m or more in a single unit. In many cases, paleosols are observed between ignimbrite sequences.

Lacustrine sediments are quite important formation, which cover an area of 4,000km^2 in the Main Ethiopian Rift. The thickness of sediments on the floor of lakes basin is not accurately known. Sediments are probably thickest in tectonic trough, which correspond in part to the topographic lows occupied by lakes (Llyod, E.F., 1975). Variable sediment thickness occurs, ranging from about 40m in

Bulbula river, and 50m in Boru and Meki rivers, up to 100m between Mojo and Koka. The maximum thickness of sediment as calculated from gravity data (west of Shalla- Abiata trough) is 580m, which could have deposited in 290,000 years. Alluvial deposits composed of silt, sands and gravel occur along the foot of the rift escarpments and the lower reach of rivers such as Meki, Bulbula, Ketar, Weja, Irinzaf Irisho and Dobena.

3.1.2 Local geology

The geology of the study area except for Paleozoic deposits comprises rocks from Precambrian age up to recent. The geological formation in the study area starting from the oldest formations to the recent ones is described as follows.

Precambrian rocks:

In the Rift Valley NW of the study area, East of Guraghe Mountains a metamorphic rock (Biotitic gneiss) is exposed due to uplifting (Dipola, 1972). A high grade metamorphic rock biotitle gneiss cut by quartz field spathic pegmatite veins and minor migmatites is overlain by 150m – 200m thick typical Adigrat sandstone, cross-bedded quartz sandstone with coarse, medium and fine grained.

Mesozoic sediments:

Dipola ,1972 reported his observation of out crops of Mesozoic sediments in the rift valley. These Mesozoic sediments crop out at western rift margin, east of Guraghe Mountains. About 30 m thick limestone overlies about 200 m thick sandstone. It is underlain by Biotitic Gneiss, which is also exposed at the same locality.

Tertiary upper Miocene to Pliocene volcanic rocks:

Northeast of the study area is exposed to rhyolites and ignimbrites formation, basaltic rock is exposed in the plateau north and northwest of Butajira Town. Volcanic rock occupies the western escarpment and the plateau and considered as upper Miocene in age (Kazmin and Seifemichael, 1980) which includes ash flow tuffs, pantellritic ignimbrites and un-welded tuffs while the Dino formation is made up of Dino ignimbrites. These rocks outcrop at the NW part of the plateau part in the study area. Alkaline and peralkaline stratoid silicics; ignimbrites, un-welded tuffs, ash flows, rhyolites and trachyte‟s formation occupies the main part of the escarpment west, northeast and north of Butajira. The rocks of this formation are at places highly weathered and some sections show series of weathered layers.

Quaternary volcanic and sedimentary rocks:

Dino formation includes peralkaline silicis of ignimbrites, tuffs; water lain pyroclastic and occasional lacustrine beds which are overlain by coarse, un-welded pumiceous pyroclastic .This formation covers mainly the Tora-Koshe-Dugda ridge and are made up of lithic and pumiceous tuff. Recent basalts in the Butajira-Siltie area consist of a lot of scoria and their texture varies from aphyric to porphyritic.

Lacustrine sediments cover quite a vast area in the study area. It consists of layers of alternating silt and clay with volcanoclastic sediments, sands, ashes, transported pumice slit, clay and diatomite. Lacustrine deposits in the study area occur in two areas. The major part is the Ziway plain deposit and the second one, which is composed, of lacustrine, alluvial, and pyroclastic deposits, forms the Kuntane-Inseno-Kela plain fan and talus deposits occur in the Butajira crescent and along the pediment plains of the escarpment.

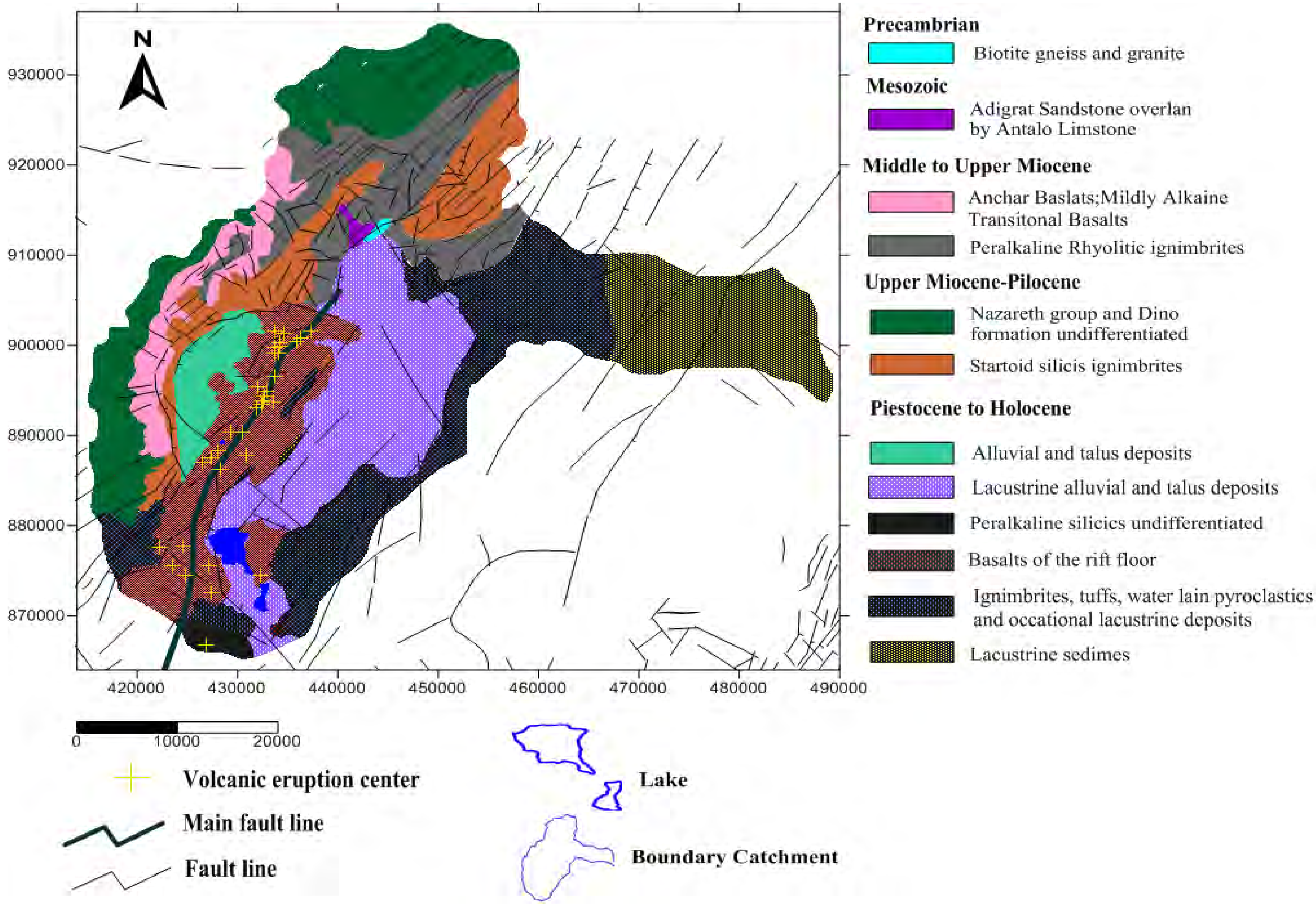

Figure 3. 1 Lithological units and structural map of the area (modified from AG consult)

3.2 Structure

3.2.1 Geological structures

The geological structures relate to the tectonic events that formed the Main Ethiopian Rift, the Wenji Fault Belt, volcanism and collapse structures and Holocene faults. The present symmetrical rift was fully defined by 3.5 million years when a paroxysm of ignimbrite of the Munisa crystal tuff erupted from large caldera located on the rift floor (Caroline et al., 1999). This is followed by a line of hundreds of young faults and volcanic centers along the rift floor close to the eastern escarpment initiated around 1.6 million years known as the Wenji Fault Belt (Mohr, 1971).

The western Ziway fault resulted in the development of the Tora-Koshe-Dugda Ridge/Horst, which limited the sediment flux from the western escarpment to Kuntane-Inseno-Kela basin. Faulting related to the WFB continued into recent associated with fissure basaltic eruptions and superimposed scoria cones especially in east Ziway areas. These recent eruptions resulted in deposition of pyroclastic sediments associated with lacustrine deposits.

In the western escarpment, fault lines oriented in WNW direction cut the main NE and N trending fault systems of the MER. In Butajira area fault systems form semicircular depression. This has resulted in the crescent shaped Butajira plain. The shape of the faulted basin and the transverse faults cutting the general NE trend of the MER in Butajira area indicates that the Butajira area is a tectonic collapse or caldera.

Recent basaltic and cinder cones have erupted following the MER fault trend, which separated the Butajira–collapse structure from the Inseno-Kela plain. Therefore, the sediment fluxes from the western escarpment mainly coarse sediments remain in the Butajira-Crescent, while very fine and limited sediment reaches the Kuntane swamp.

The tectonic development and associated volcanism have resulted in the following morphologically distinct areas the western rift escarpment, Butajira Crescent, Cinder Cones and basalt flows, Kuntane-

Inseno-Kela plain, Tora-Koshe Dugda ridge, Ziway plain, and finally Gademotta Caldera which is out of the study area.

3.2.2 Effect of faulting system on the modeled zone

Groundwater flow in unconfined aquifers is influenced by topography, but in fractured and dipping sedimentary rocks, it is also influenced by structure. The impact of faults on near surface processes is reflected in vegetation patterns and the structure of drainage networks, aquifer structure and hydraulic head patterns.

Faults have great influence on transport processes in the subsurface as well as on water-related phenomena at the surface, and should accordingly be taken into consideration in studies related to groundwater modeling, water-management, contamination and environmental impact. Faults that have an enhanced vertical permeability are difficult to detect when horizontal groundwater flow is studied, which is probably the main reason why they are rarely described. Though, these faults may form important preferential paths to vertical groundwater flow.

For Meki river catchment the effect of faults and fractures can be simulated using increased hydraulic conductivity since it facilitates easy passage of surface water into the aquifer. Therefore the effect of tectonic activities on the modeled area can be safely discarded using the hydraulic conductivity‟s.

Chapter 4

4. Conceptual model

4.1 General overview

A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross-section (Anderson and Woessner, 1992). The development of a conceptual model depends on the amount of data available, the model scale, the purpose of the model and the simplicity or complexity of the area under study.

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

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

In groundwater flow modeling, the main features of physical facts to be considered on conceptualizing the flow system are; boundary condition, aquifer characterization (type of aquifer and quantitative and spatial distribution of hydraulic conductivity, storativity and leakage coefficient), water table and potentiometric map, hydrology of the main water bodies, the rate and distribution of recharge, stress on the aquifers, springs, possible contaminant source and so on).

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

The development of this conceptual model take in to account the fact stated above and followed the major steps of defining hydrostratigraphic unit , analyzing water budget component and defining flow system as of Anderson and Woessner, 1992, procedure of building conceptual model.

The conceptual model of the Meki river catchment, the region under study, consider every previous verified investigation, hydrometeorological data, boreholes and literature review with judgment of the modeler.

4.2 Geometric characteristics

The aquifer area extends about 74km from west to east direction and 70km from south to north direction. Previous study conducted in the north west of Lake Ziway, around Butajira – Ziway areas, reveals that the main aquifers depending on geomorphological features have highly variable aquifer thickness.

The Butajira Crescent which is characterized by a complex mixture of sediments composed of unsorted to poorly sorted alluvial, talus or fan deposits, debris flow and volcano-elastic deposits have sediment thickness varies from 80 m to about 120m, Basaltic Cinder Cones region which is dominantly composed of Scoria Cones and associated vesicular basalts have a thickness high over 100 m in the central part where the volcanic centers and vents are located.

Kontane-Inseno-Kela plain which is covered by pyroclastic fall and reworked water lain pyroclastic deposits, lacustrine, alluvial, debris flow or talus deposits and fan deposits have sediments thickness varying from few meters in the west to several meters (more than 260 meters and more) in the center and along Weja river.

Tora-Koshe- Dugda ridge is mainly composed of pyroclastic deposits such as tuff and ignimbrite, and finally Ziway plain is composed of lacustrine sediments mixed with pyroclastic fall deposits cover the entire area having a sediments thickness from few meters in the north and northwest, south to several meters (more than 300 meters and more) in the center.

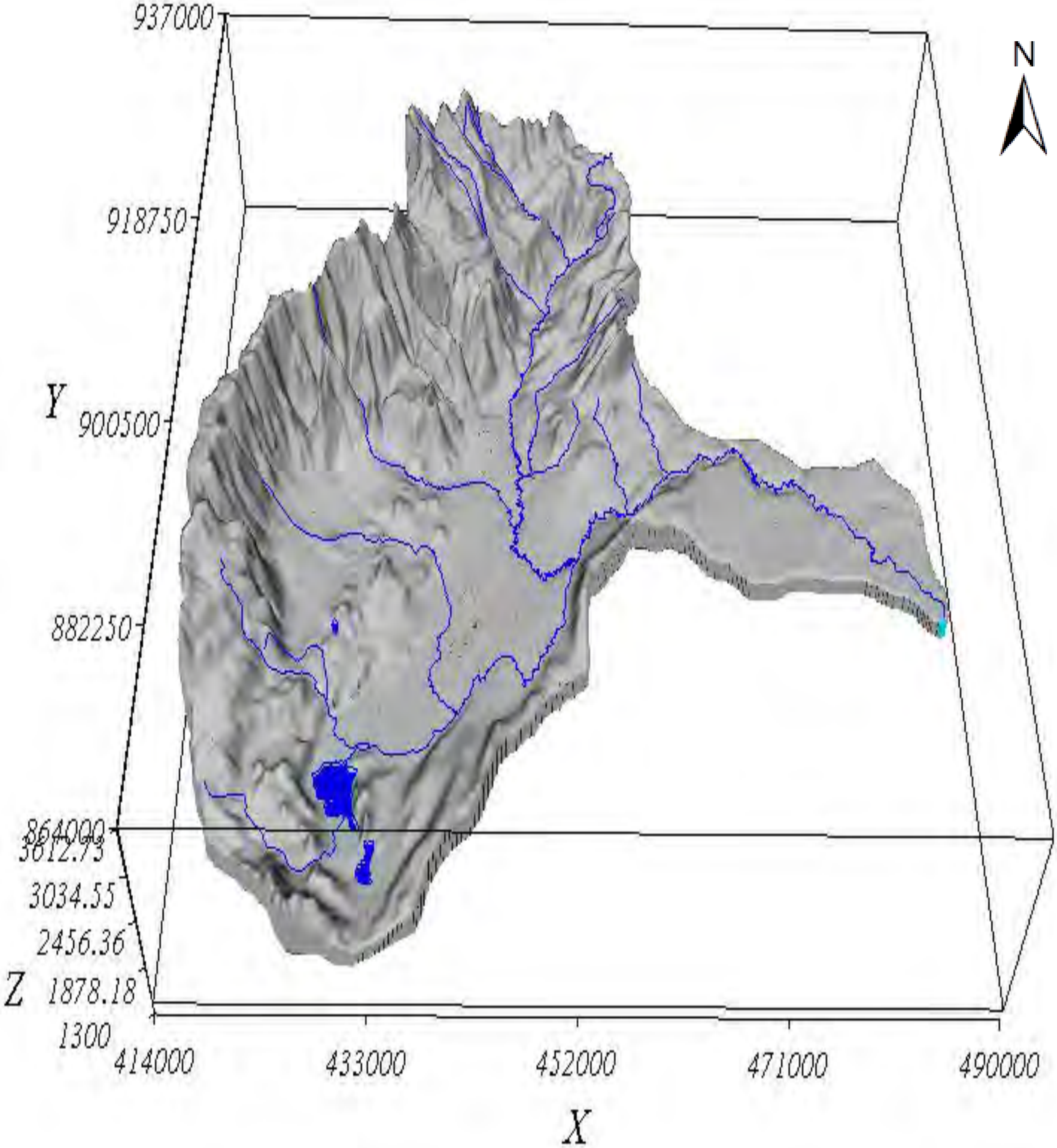

Figure 4. 1 DEM showing aquifer thickness

4.3 Surface water hydrology

4.3.1 Lakes

In general, lake recharges an aquifer when the groundwater surface is below the bottom of the lake, but drain to the aquifer when the groundwater surface is above the bottom of the lake.

The primary lakes within the study region are Lake Abaya, Goletsh Lake and Crater Lake known as Har-Shetan. The area between Lake Abaya (Tuffa) and Dobena river area have very flat plain fed by flood and seasonal streams from west of Butajira area. Mostly this part of the plain gets flooded during the summer and develops temporary lake, which shrinks during the dry season. It is mostly water logged during the rainy season. This is because of the flat topography surface runoff from the west and east and the input of the springs, shallow groundwater and overflow from the lake.

4.3.2 Rivers

In the study area groundwater level is affected by fluctuation of perennial river stages originating from highlands of Gurage and travels a distance of about 100 Km from the highlands at altitude of 3,600 m to 1, 636 m before draining into Lake Ziway.

Water flows from the river into the aquifer and the groundwater becomes elevated when there is an increase in river stage with respect to the altitude of the groundwater level. A decrease in river stage with respect to the groundwater level causes water to flow from the aquifer into the river and result in the decrease of groundwater level. The extent of the change in the groundwater level elevation in response to river stage fluctuations depends on the magnitude of the change in the river stage, the length of time the river remains at the current river stage, the hydraulic properties of the aquifer material, and the distance from the river to the point of interest.

Due to the time required for the change to propagate into and through the aquifer the groundwater level increase or decrease in response to increase or decrease in river stage is more obvious in areas closer to the river. Therefore, the area of the aquifer that is affected by an increase or decrease in river stage depends on the length of time that the river stage remains at the new altitude. Changes in the groundwater level at distant locations from the river are the result of long term river-stage changes typically caused by seasonal high and low flows or long-term river-stage management.

Meki river streambed deposits are typically composed of lacustrine sediments mixed with pyroclastic deposits such as tuff and ignimbrite, alluvial, debris flow or talus deposits and fan deposits. The lacustrine deposits vary from clayey silt to fine sand deposits and whereas the fluvial deposits vary from silt to cobble size and sometimes up to boulder size, thus it is well connected hydraulically to the underlying lacustrine sand aquifer.

Weja and Irinzaf streams have smaller streambed hydraulic conductivities and have less effect on groundwater flow than the larger Meki river, locally the bottoms of the river channels can be above the top of the groundwater level. In the study area there are numerous smaller streams and drainage channels, mainly in the western part of the catchment.

Seasonal streams of the catchment, which carry a lot of water and sediment during rainy seasons to Lake Abaya (Tuffa), may affect groundwater flow locally during floods when they supply recharge to the aquifer or when the groundwater level rises above stream bed and aquifer drains into the stream.

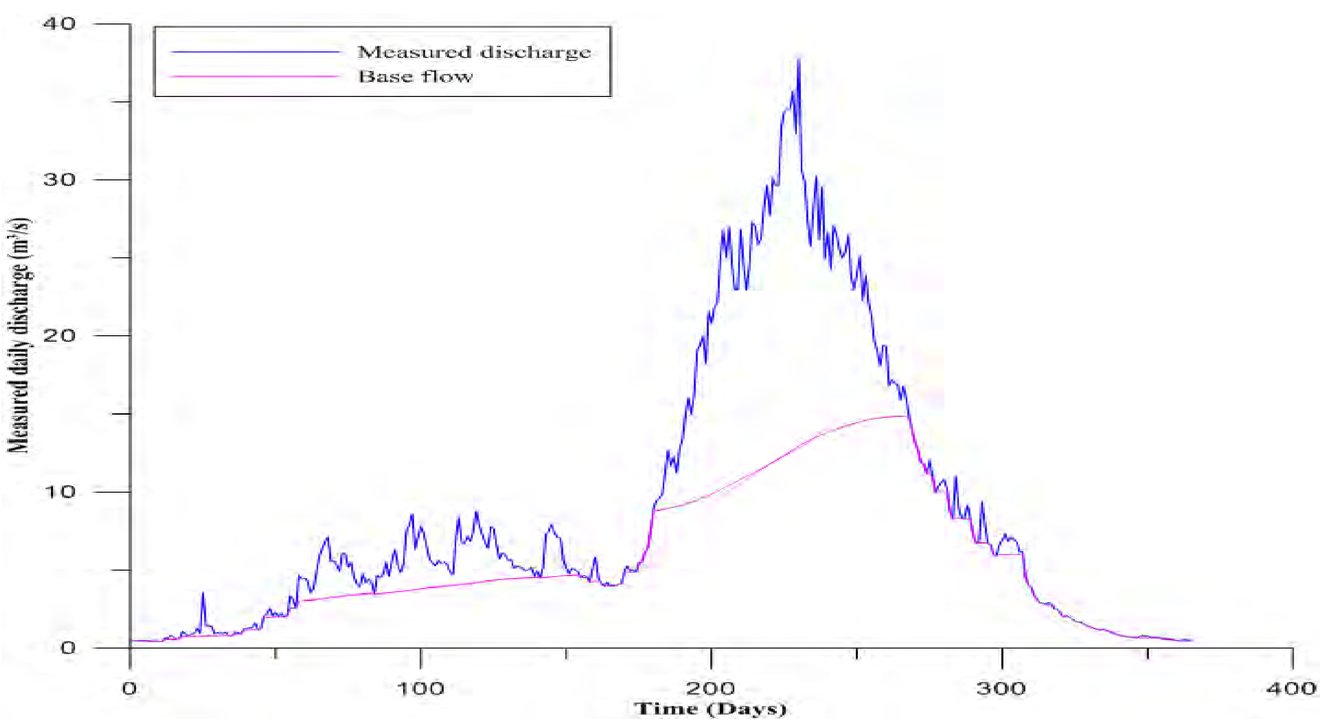

Figure 4. 2 Daily hydrograph of Meki river (1998-1999)

The separation of surface runoff and base flow has been made using a computer code known as Time-Plot, developed by Gabriel Parodi, which uses daily flow values and an attenuation coefficient that is controlled by the slope, land-use and land cover conditions of a water shed possessing a value in the range of 0.9-0.995 and point out surface runoff from the catchment is 100 mm/year.

4.4 Hydrogeology

4.4.1 Aquifer hydraulic properties

The hydraulic properties of the aquifer used in the conceptual model and for the first run of the numerical model were obtained from the existing data, fieldwork, indirect and direct, qualitative and quantitative approach. Characterization of hydraulic properties of the aquifer involves use of existing pumping test data, geologic map, hydrogeological map, soil map, lithology obtained from well logs, aquifer thickness, water table depth, structures and surface water features, etc. so as to see the lateral distribution and nature of the aquifer. The spatial distribution and magnitude of hydraulic properties of the aquifer are not well-known for the study area. The aquifer hydraulic conductivities were adjusted during model calibration.

4.1.1.1 Horizontal hydraulic conductivity

Hydraulic conductivity is the most essential aquifer parameter that determines the flow system of a model. It is a measure of the ability of fluid to move through aquifer media. It is dependent on the properties of both porous media and the fluid. It is obtained through pump test analysis, laboratory and literature review. In this model, it is also obtained from the pump test analysis and literature review.

The spatial distribution of the hydraulic conductivity of the area is highly variable due to the presence of different geologic structures and it is demonstrated on the results of the analysis of pumping test data. Pumice flow and ash with subordinate obsidian lava flows have the least in the area which is 0.01m/day and goes up to 20 m/day in the scoria vesicular basalt, which has a medium range of values. Transmissivity ranges from 1m^2/day to more than 500 m^2/day, which is the characteristics of the fractured volcanic rocks and the variability in lithology of the lacustrine sediments, more or less similar variations are also found in Ziway-Shalla basin (Tenalem Ayenew, 1998).

Table 4.1 Hydraulic characteristic of wells in the study area

Borehole ID	UTM-E (m)	UTM-N (m)	Depth (m)	D.D. (m)	T(m^2/day)	K(m/day)	Q (l/sec)	Aquifer lithology
BH-2	453276	901204			12.71	0.71		Tuff/ignimbrite
BH-6	441974	890758	63	2.65			6.5	Sediment
BH-10	426285	887327	118				3.3	_
BH-11	426927	887719	174	5.4	37.8	0.9	3.4	scoria/vesicular
BH-12	415084	877224	183		-	-	App. 3.5	_
BH-15	436818	892494	65	2.13			3.5	sediment/scoria
BH-16	435517	877276	109	44.05	6	0.25	5.14	tuff
BH-17	439069	878182	194	32.58	7	0.29	3.1	sand/pyroclastic
BH-18	438154	876204	187	16.36	12.3	0.45	3.4	sand/pumice sand
BH-22	447247	889418	106		15	0.36	app. 6	Sediment
BH-26	432756	897440	154	11.33	69.26		8	Scoria/ignimbrite
BH-28	432084	897957	65	3.79	241.92		10	Scoria/ignimbrite
BH-30	430990	896373	86	14.54	95.62	2.66	6	Scoria/ignimbrite
BH-31	435852	869258	251		63.24	2.11	4	
BH-32	453015	883724	267		171	4.75	3.2	_
BH-33	447720	875620	300		15	0.36	2.56	_
BH-34	446742	872640	294	3.87	81.55	2.72	3.6	volcanic ash/fine
BH-35	432428	886909	90		8.29	0.35	3	_
BH-37	431086	898842	77.5	12.83	30	0.96		Sand and gravel
BH-38	467854	877491	143.7	2.64	354.24			Lacustrine Deposit
BH-39			71	4.92	95.28	3.97		
BH-40			132	9.36	36	1		
BH-41	432501	898201	52	14.35	16	0.67		Gravel
BH-42	436926	899049	84	2.8	187.76	20.86		Scoria & vesicular basalt
BH-43	426927	887719	174	5.4	37.8	0.9	7	fractured basalt
BH-44	432428	886909	80	23	8.29	0.35	3	gravel, tuff and ignimbrite
BH-45			102	8.2	100	4.35		
BH-46			104	7.3	100	4.39		
BH-47	430838	899162	80	15.42	137	3.81		Sand and gravel
BZDP/TW3	446999	886227			218.88			

The initial hydraulic conductivity map used as an input for the first simulation process is shown in figure 4.2. The hydraulic conductivity of an aquifer has a directional value and in this model as the model area is conceptualized as isotropic and single layer unconfined aquifer. It has no vertical flow and have same value for in x and y direction.

The study area; based on the geomorphological features, is classified into in to six zones. Each zone has specific hydrogeological significance. Therefore, based on the geological, geophysical survey report, test drilling results and literature reviews; the hydraulic conductivity in the study area appears to be having the following distribution.

The western escarpment or highlands of Gurage Mountain have permeability ranging from 0.1 m/day to 1m/day (Tenalem Ayenew, 1998). The rocks comprising this zone are highly welded ignimbrites, tuff, rhyolite and trachyte without visible large faults. The upper weathered rock and soils are permeable; however, the underlying volcanic sequences are massive.

Butajira Pediment, Kuntane-Inseno-Kela plain, Tora-Koshe-Dugda ridge and North Eastern area based on the characteristics of ignimbrite, fracturing and weathering grade, the units possess 5m/day to 10m/day permeability value (Tenalem Ayenew, 1998).

High conductivity zone of the study area consists of recent basalts and highly fractured ignimbrites; and scoria cones along the major fault east of Butajira. Hydraulic conductivity in these areas is largely related to joints, faults, vesicles and fragment size of scoria, the unit posse 10m/day to 20m/day permeability value (Tenalem Ayenew, 1998).

Ziway plain covers large area around the lake Ziway. It has a varying transmissivity between $95m^2$/day to $355m^2$/day and hydraulic conductivity of 1m/day to 5 m/day. The lithological groups found in this area are ignimbrites overlain by lacustrine sediments such as: clay, diatomite, shale beds and reworked pumice.

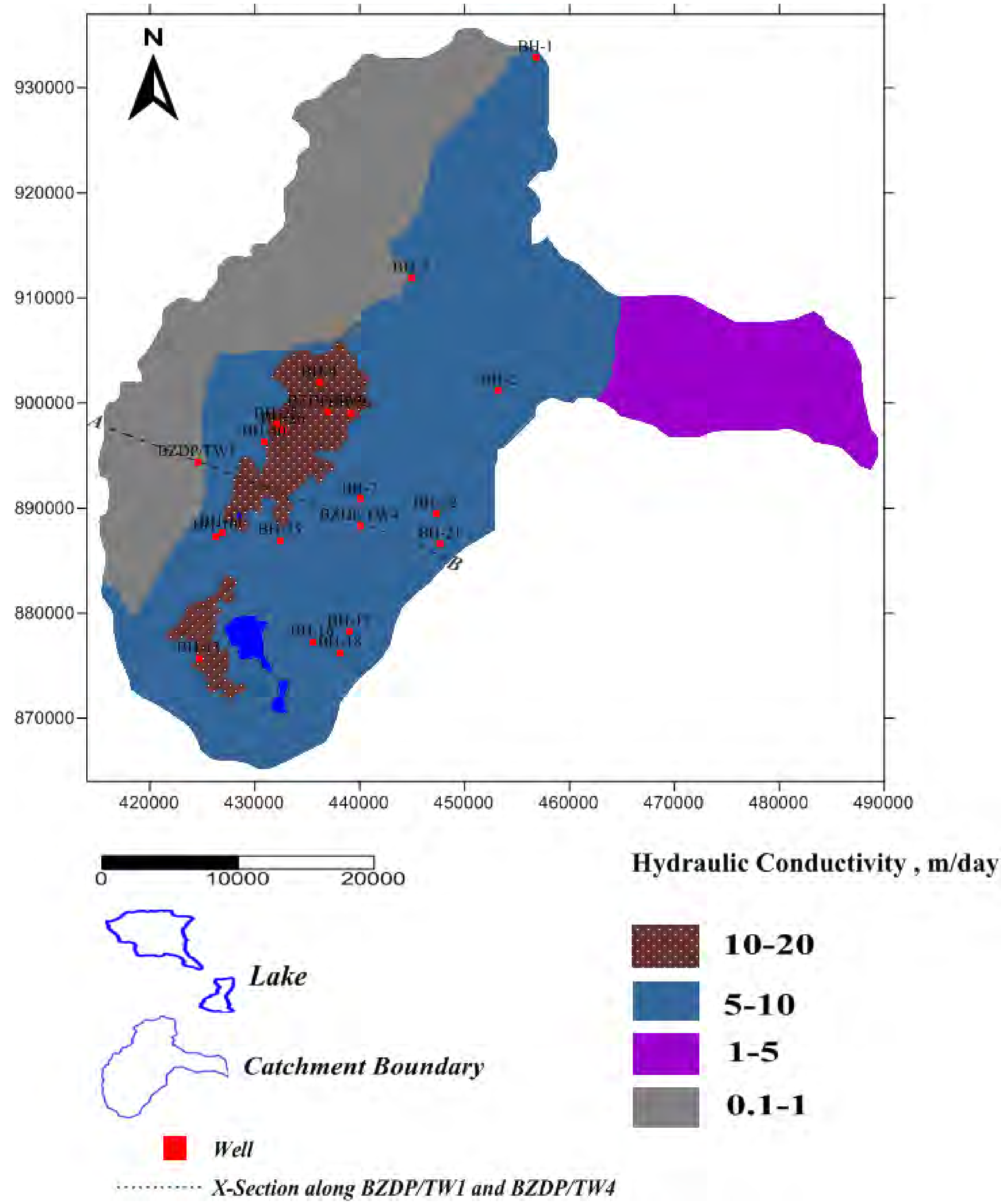

Figure 4. 3 Hydraulic conductivity range map, in m/day (Taken from Tenalem Ayenew, 1998)

4.4.2 Groundwater level and movement

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

The balance between groundwater recharge and discharge controls groundwater levels and storage. The common practice in the country for borehole construction, use to position the screen in various depth of the borehole and difficult to identify the water level for particular aquifer system in a multi-aquifer geological profile.

Groundwater flow directions have been estimated based on the available data. The groundwater flow within the study area is mainly from the western escarpment towards Lake Ziway, which indicates that it is the main recharge source. The groundwater level is generally flat to gentle slope except at Tora-Koshe-Dugda ridge and the Cinder Cone areas. In these areas the groundwater contour shows steep slope showing lower permeability, probably due to the nature of the rocks or the fault systems separating these zones.

The groundwater level drops from about 2000 m in Butajira Crescent to 1800 m.a.s.l in Kuntane Inseno area. The Cinder Cone and basaltic flows, which erupted along probably, a regional fault acts as barrier or low permeability zone resulting into steep groundwater slope. This area hosts the Crater Lake Har-Shetan. Groundwater level observations at Tora-Koshe-Dugda Ridge, Kuntane-Inseno-Kela plain, Cinder Cones and basalt, and Butajira Crescent have been observed since February 2006-2007 by AG Consult, Consulting Hydrogeologists & Engineer.

The result indicates that the aquifer close to the lake shows rise in the water table with the lake level rise indicating that the aquifer close to the lake is recharged from the lake water. The groundwater in the Tora-Koshe-Dugda ridge did not indicate changes in the water table throughout the monitoring period. Which is an indication of the aquifer having either very high storage value or it doesn‟t receive significant recharge from seasonal rainfall.

The monitoring well close to the fault line separating Kuntane-Inseno-Kela plain from Tora-Koshe-Dugda ridge, have shown significant water level changes. This indicates that the aquifer receives both direct recharge and also lateral groundwater inflow. This can indicate that the fault zone in this area has low storage coefficient resulting in high fluctuation in the groundwater level. The well at the middle of Kuntane-Inseno-Kela plain has also very low response to seasonal variations. This is because the aquifer at this plain has higher storage.

The well in the Cinder Cone areas has also shown no variation in water level. This can indicate high storativity of the scoria formation. The observation site at Butajira Crescent has shown significant water level variation (up to 6 m). This is because of the low storage parameter of the clayey sediment at this locality.

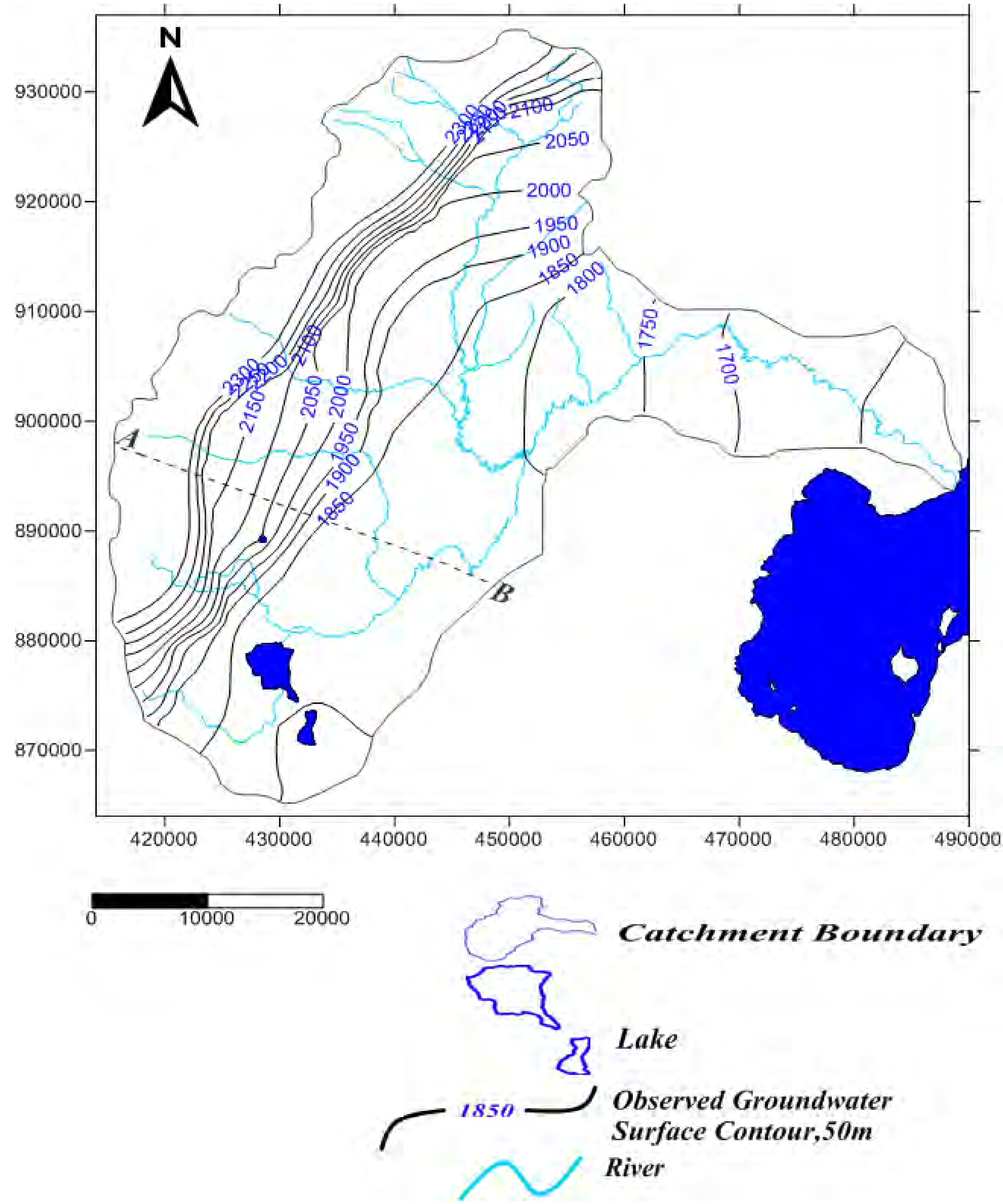

Figure 4. 4 Observed groundwater contour

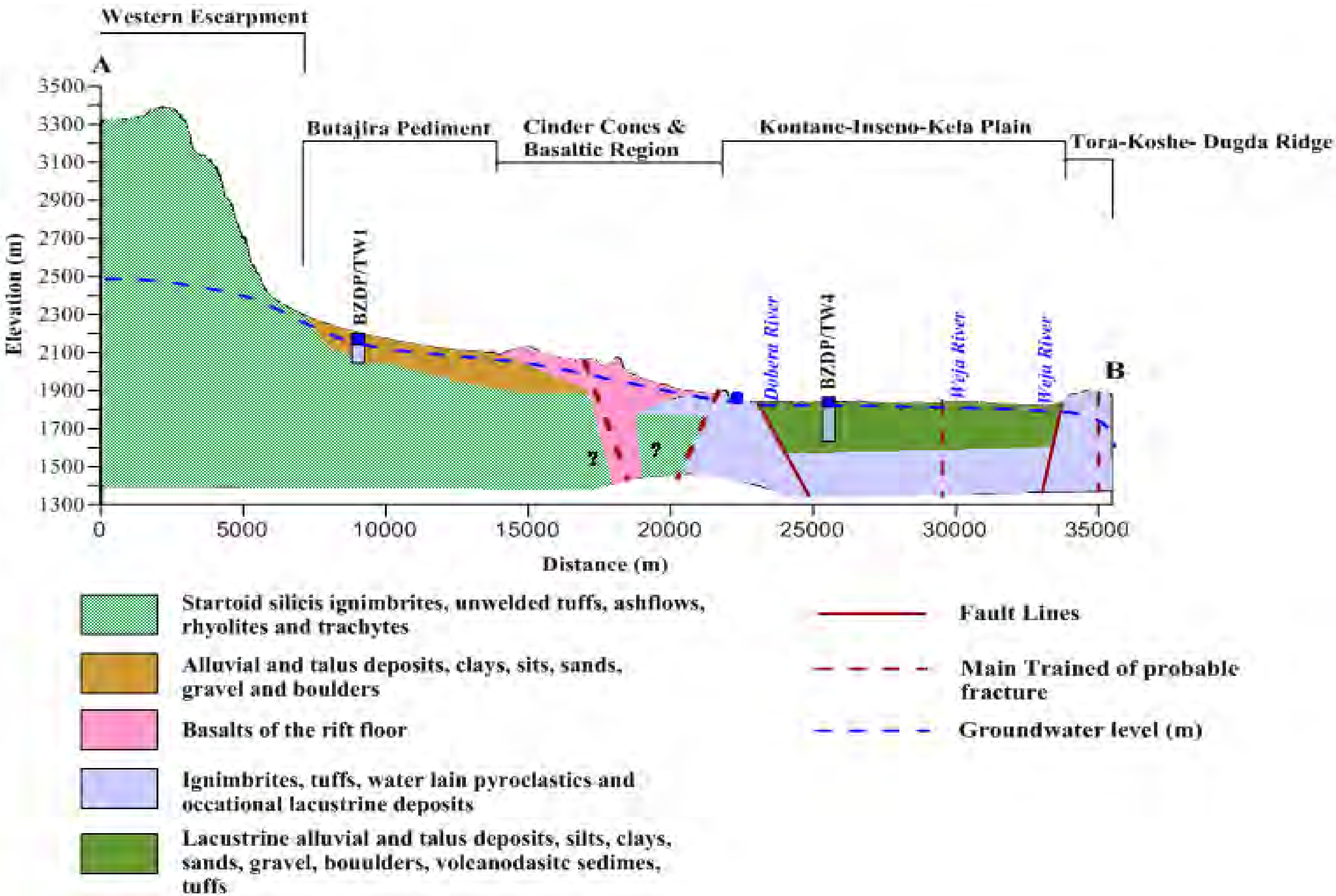

Figure 4. 5 The conceptual profile model showing the groundwater-surface water interactions (Modified from AG consult)

4.4.3 Occurrence of groundwater

For the occurrence of groundwater in the study area the major geologic units are the Quaternary sedimentary deposits and the volcanic formations. The Mesozoic sedimentary formations, except the small outcrop at the escarpment close to Kela village normally occur at greater depth probably over 1000m as can be estimated from the rift displacement in the area.

The Quaternary sedimentary deposits which are varying in composition from clay to gravel and depositional environment varying from lacustrine to fluvial, fan and tulus deposits occur in the area. The dominant lacustrine deposit occurs in Ziway plain. This sediment is composed of clay and silt deposits alternating with reworked pyroclastic deposits such as pumice, ash, volcanic shards. In the shore areas this sediment is mainly composed of gravels and sands derived from pyroclastic materials. The thickness of this deposit is generally over 200m. This formation in spite of its variability is one of the major aquifers in the study area. Ziway plain sediment is therefore one of the major aquifer to be considered for groundwater development.

The second area of sediment deposition was the Kuntane-Inseno-Kela plain. This plain is characterized by sediment deposits composed of lacustrine, fluvial, pyroclastic, talus and fan deposits. It has thick sediment deposits of over 200 m. This area is also major aquifer zone in the study area. Finally the Butajira Crescent which is characterized by gravel and sand deposits with clay and silt derived from fan, talus (debris flow) and river deposits with an average thickness of about 80 m. This area is also considered area of good aquifer in spite of its limited areal extent.

The major volcanic formations in the study area are of the Quaternary pyroclastic deposits. The older volcanic formations (Tertiary Volcanic Rocks) are situated in the escarpment areas and deep under the Quaternary formations. There are minor rhyolite and basaltic formations situated west of Lake Ziway and around Butajira. With regards to groundwater, the major formations are the rift pyroclastic deposits. These formations can be considered as major volcanic aquifers in the study area.

The older volcanic rocks composed of rhyolites and basalts are situated in the escarpment and deep under the Quaternary formations in the rift valley area. These rocks can be important fracture aquifers in fractured areas. Therefore, these formations especially in the rift fracture zones can be important aquifers.

The Mesozoic sedimentary formations (the limestone and sandstone) are situated over 1000m below the current ground surface under the Tertiary volcanic formations. These formations are deep potential groundwater aquifers. The small exposure around Kela village is situated in the escarpment and is not important as a potential source for groundwater.

4.4.4 Spatial distribution of recharge

Recharge is the volume of the water that joins the saturated zone of the aquifer. It is a term used to describe many of the processes involved in the addition of water to the saturated zone (Wilson and Miller, 1978).

Groundwater recharge to the aquifer may occurs naturally from precipitation, rivers, canals, lakes, as man induced phenomena (irrigation, urban recharge). Recharge could also be direct, indirect or localized based on the source and mechanism by which water reaches the water table. The quantity and type of recharge depends on topography, geology, climate, soil zone, land use and cover, drainage, geographic location, vegetation, structure and other.

Generally the western rift escarpment of the catchment gets the highest recharge due to its high amounts of rainfall, characteristic mountain chains and escarpment slopes which have vertical to steep slopes and strongly dissected. This facilitates infiltration instead of runoff, and its fracture and joints directing stream channels feeding the aquifer. Many springs except thermal ones emanate in the escarpment and its foothills. These springs emerge as contact and fracture springs. Contact springs usually yield little water and the discharge significantly goes down during dry season. In contrast fracture springs, which emerge from fractures, and faults show little seasonal variations and yield more water.

From previous water balance analysis of recharge estimation done by AG Consult, Consulting Hydrogeologists & Engineer, using Simple Water Balance method, Chloride method, Bucket Model and WEAP model indications that the annual recharge to Meki river catchment is 119.71 mm/year, which is 12 % of the annual rainfall. As a result zonation of recharge condition of the study area is given in figure 4.5 showing seven different recharge zones of the catchment.

The highlands of Gurage Mountain gets large amount of recharge. This area receives high rainfall and discharges its surface and subsurface flow to the low-lying areas. Results from Thiesen polygon analysis of the study area indicate that the major recharge areas for the catchment that facilitate infiltration and shallow circulation of groundwater as a result of the large amount of direct recharge. This is due to the characteristic features of the area, such as joint and fracture zones affecting this area, its high drainage density, high amount of rainfall and elevated altitude with vertical to steep slopes and strongly dissected, which favors infiltration over surface runoff and a value of 5.75×10^{-4}m/day is given as initial input for the model and the north eastern escarpment area have relatively smaller amount of recharge which is 3.91×10^{-4}m/day due to its rainfall distribution difference.

The Butajira Crescent is situated at the foot (pediment plain) of the western rift escarpment influenced by the recharge from the escarpment, runoff coming from the escarpment, and direct rainfall on the plain it has lower recharge relative to the highland due to reduced infiltration by the steep slope and undulating topography. It has fast and shallow groundwater and springs coming from direct recharge of this area and the highland. This plain receives groundwater recharge mainly from the runoff emanating from the rainfall in the mountains and an initial value of 3.81×10^{-4}m/day is assigned.

The Scoria Cones region is another group of the zonation located to the east of Butajira Pediment and dominantly composed of Scoria Cones and associated vesicular basalts. Groundwater recharge derives from subsurface groundwater flow from the Butajira Crescent area and direct recharge from rainfall. However the major source is the groundwater inflow. The aquifers in this area receive groundwater flow from the Butajira Crescent area and a recharge amount of 3.66×10^{-4}m/day is assigned as initial input. The absence of soil cover and the less permeable volcanic products of this plan are the reason for lower amount of recharge compared to the other three recharge zones.

The Kuntane-Inseno-Kella plain is structural trough which is bounded from the west by Scoria Cones and associated vesicular basalts and to the east by Tora-Koshe Dugda horst (ridge). This area receives recharge from several streams from the western escarpment and direct rainfall and groundwater inflow and has a better recharge compared to Cinder Cone. It is covered by pyroclastic fall and reworked water lain pyroclastic deposits, lacustrine, alluvial, debris flow or talus deposits and fan deposits. Due to the flat topography, surface runoff from the west and east and the input of the springs, and overflow from the Lake Abaya the area between Lake Tuffa and Dobena river is hold water during the rainy season. Therefore, during rainy season the recharge will increase but for this modeling an initial value of $3.7691x10^{-4}$m/day is assigned.

Tora-Koshe-Dugda ridge is characterised by deep groundwater and direct recharge is considered in small amount for this area because in the model recharge is applied to highest active cell but these ridge has very deep groundwater over 130 m. Therefore, an initial value of $6.0x10^{-6}$m/day is assigned for the model input. This area also serves as the eastern boundary to the Inseno-Kela valley and mainly composed of pyroclastic deposits such as tuff and Ignimbrite.

Finally Ziway plain which cover most of the floor around Lake Ziway with relatively lower amount of rainfall and characteristic evapotranspiration have a better recharge compared to Koshe ridge with a value of 2.4x10-5m/day. The plain mainly receives water from groundwater inflow from nearby aquifers and direct rainfall also contributes some amount. Figure 4.5 shows initial recharge values for the numerical model estimated based on previous works. However, the final recharge estimation will be drawn through a groundwater flow modeling calibration.

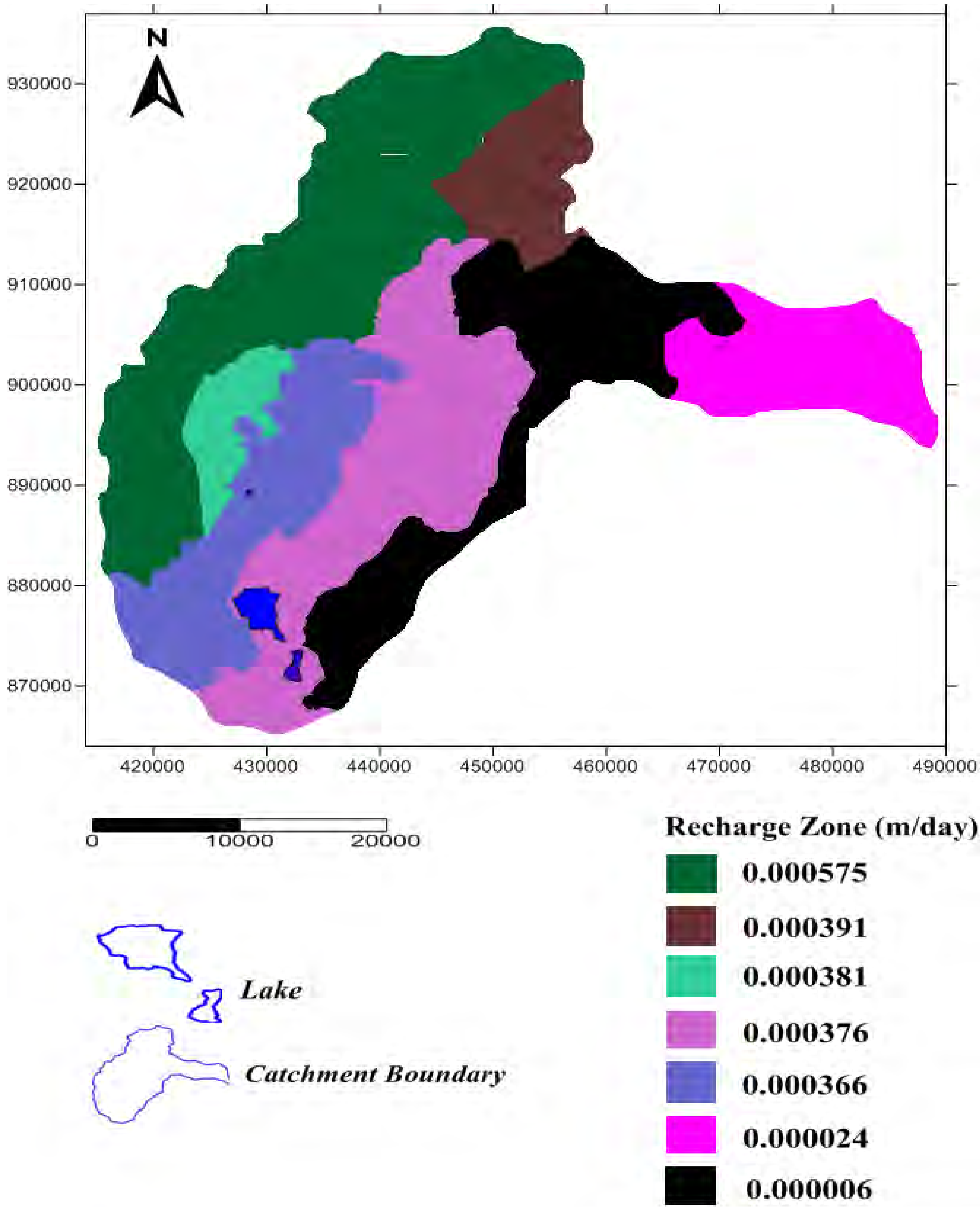

Figure 4. 6 Spatial distribution of recharge rate

4.4.5 Groundwater discharge

Aquifer system is not only with an input of a recharge but also releases its resource out of the system. The major removal of groundwater from aquifer system of the study area is possibly occurred through abstraction of water wells, springs, base flow to surface water body, inter basin or aquifer system transfer and evapotranspiration. In the study area discharge to streams occurs as springs and seeps, there are several perennial springs with good discharge originating from the western escarpment and flowing to streams finally draining to Lake Ziway.

The base flow represent the interaction of the aquifer system with the perennial stream with a concept of groundwater maintain the flow of stream during dry season. Based on this concept, groundwater flow as base flow has been estimated by Time plot.

The base flow analysis is conducted on the gauged catchments of Meki river using mean daily data which shows the occurrence of high interaction of the river and the aquifer system. The Meki river catchments release 176.16 MCM/year as base flow to the stream. The other seasonal river also releases a significant amount of ground water to the aquifer system.

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

In the study area there are several fault controlled by hot and cold springs in the western escarpment and central part of parts of the catchment as shown in figure 4.7, these springs are fast, shallow circulating groundwater where the faults causes the eastward flowing groundwater to emerge as spring flow. Springs are usually treated as nonlinear head dependent discharge boundaries that have zero flow when the head in the aquifer becomes lower than the altitude of the spring. In the catchment under study, there are a number of small sprigs with discharge less than 0.2 l/s which is almost insignificant discharge and a very few prominent springs with large discharge greater than 10 l/s.

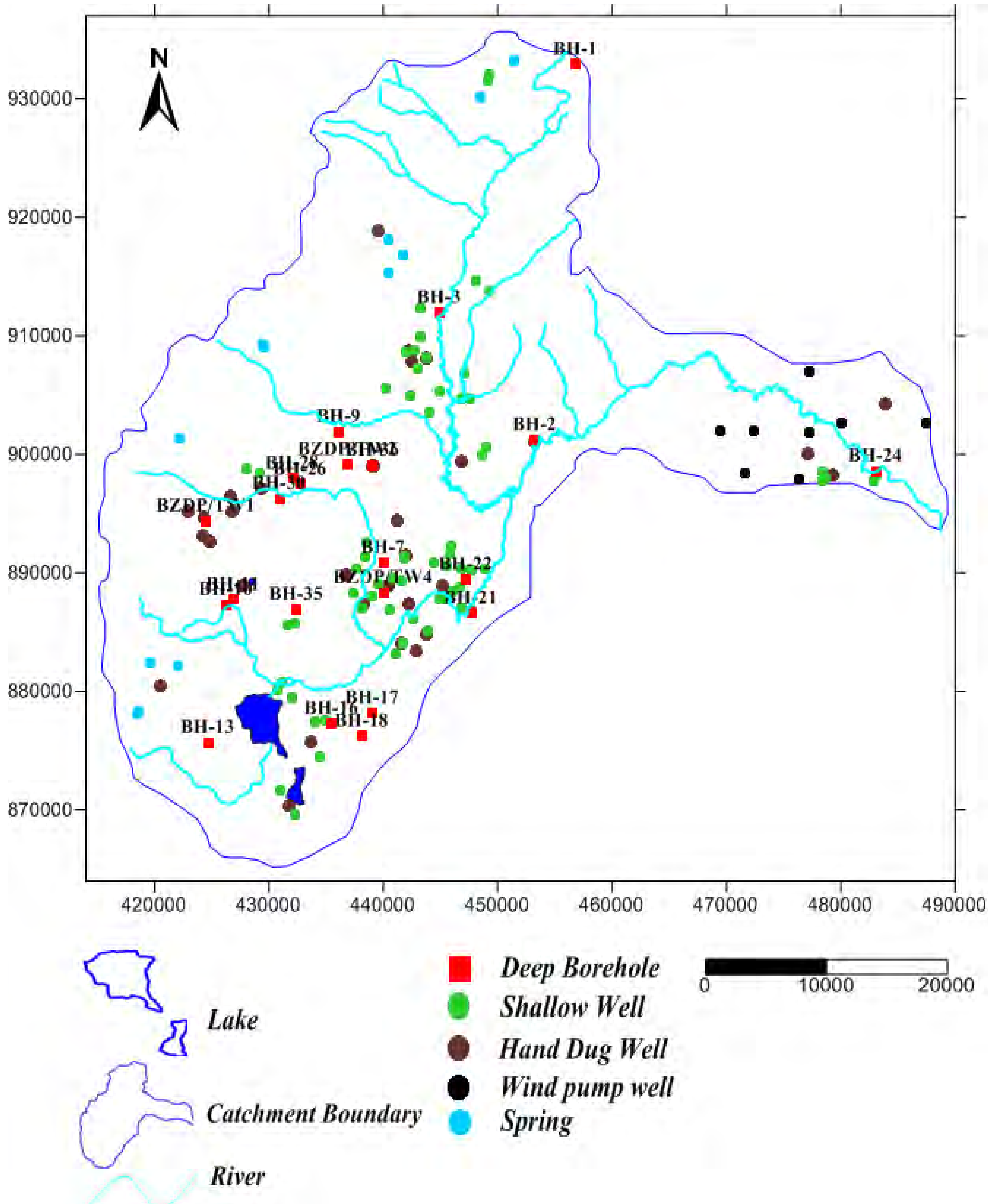

Figure 4. 7 Spatial distribution of groundwater abstraction well

The spatial distribution of well withdrawal and quantities of water withdrawn from the study area may affect substantially groundwater levels in the study area. Well withdrawals in the study area occur from irrigation, domestic, stock wells and industries. In the study area there are several wells which are not included in the model due to limitation in their location or pumping data, and some are not put to use and functional at all during this time.

Within the catchment there are about 106 water points with location and certain with pumping data, and all are active including deep boreholes, machine drilled shallow wells, hand dug wells, wind mills, and protected springs (large, medium and Small) and from this active wells 78 wells are treated in well package and the rest 28 springs are treated in drain package.

4.5 Water balance

The water balance is the budget of the aquifer system up on which the model is governed quantitatively. In a steady state water balance, inflow and outflow of groundwater from the aquifer system is balanced throughout hydrological period. In a steady state, it is assumed that the inflow and out flow groundwater in the aquifer system is equal with negligible change in storage within the hydrological year.

The general water balance of the catchment can be easily explained by a simple water accounting method which includes different components in the catchment. Precipitation in a catchment partly becomes surface runoff; some part is lost as interception loss, actual evaporation from soil surface, actual transpiration, soil moisture recharge, and the remaining infiltrates into the groundwater which recharge the aquifer system.

Based on the simple water balance analysis conducted: the Meki river catchments has aerial precipitation of 992mm/year, evapotranspiration loss of 766.20mm/year (Tenalem Ayenew, 2003), surface runoff from the catchment is 100 mm/year and 119.71mm/year is infiltrated to the ground as recharge which feeds the aquifer system. The remaining, 6.09mm/year discrepancy, could be interception loss, soil moisture recharge and groundwater outflow from the catchment to neighboring catchments through deeper routes or fault zones.

4.6 Input data processing for the model

The information gathered from different sources and field have different format. In order to construct the model using the information gathered from different sources a process of checking, selection, format conversion and organization had to be carried out to prepare the appropriate data for the model input. Most of the investigations carried out around the Meki river catchment and Lake Ziway areas have been spread among a great number of different organizations, and it is difficult to gather and organize the existing information needed for the new research activity.

The important procedures in data processing are removing wells where water levels might be measured inappropriately because of problems with the datum, organizing all necessary information in tables using excel, and converting maps in a format that is acceptable by the modeling software. Geographic Information System (GIS) was used to get a better general picture of the study area and assist in making some important decisions, like boundary condition.

The digital elevation model used for the study area is the ASTER DEM of the Main Ethiopian Rift with resolution of 30 meter by 30 meter. The original DEM covered a large area than the desired region so a sub catchment has been selected to increasing the computing and processing speed of the computer. In addition to the previous work Global Mapper is also used to prepare top elevation of the model area from ASTER DEM data to Surfer Grid (ASCII Format) by specifying the mesh size used in MODFLOW in the x and y direction then the working environment of the study area is assigned as input by specifying the projection UTM, Zone 37 (Northern Hemisphere), and datum WGS84 is used in this study, and the working environment lies within (UTM 414000-490000 E and 864000-937000 N).Now the file is ready to import to MODFLOW.

Finally using Surfer different maps of segment, polygon and point were overlaid for differentiating zonation of hydrogeological parameters, location and distribution of observation wells, model boundaries, water point alignment with respect to structures, model boundaries and for other analysis using as background during the construction of the numerical model and in different variations of the conceptual model for the period of calibration process by importing it to MODFLOW.

Chapter 5

5. Numerical model

5.1 General overview

Numerical models are used when complex boundary conditions exist or where the value of parameters varies within the model (Zheng and Bennett, 1995). For study region numerical modeling is constructed using Processing Modflow Pro (Version 8.0.15). Processing Modflow Pro is an enhanced version of Modflow which allows the user to define a groundwater model using a conceptual model approach, where by properties and boundaries are defined spatially using vector-based arcs, polygons, and points. These can represent, for example, aquifers, lakes, rivers, and wells which contain specific boundary condition data, such as material properties, stages, recharge, and pumping rates.

MODFLOW can simulate transient or steady-state saturated groundwater flow in three dimensions. It offers a variety of boundary conditions, including specified head, areal recharge, evapotranspiration, drains, rivers, and streams. Aquifers units may be confined or unconfined, or treated as convertible between confined and unconfined states. The three dimensional capabilities and versatility in boundary conditions offered by MODFLOW are necessary to simulate groundwater flow in the Meki river catchment due to the relatively complex stratigraphy, geology, and boundary conditions of the model domain.

Constructing a numerical groundwater flow model of Meki river catchment helps us to have a better understanding of the aquifer system and to develop a tool for evaluating aquifer responses to various water management alternatives. However, due to the steep faults/block faulting oriented in the N-E direction, the geological conditions are very complex and assumption of different model layers is difficult because of the non-uniform and highly variable and complex lateral and vertical relationship between the aquifer layers and the overlying confining beds. Therefore, Meki river catchment were simulated by MODFLOW using the steady-state option, unconfined aquifer, and single layer approach which is more practical to avoid complications as a result of many unknown parameters and geometrical condition of multilayer approach.

5.2 Governing equations

The basic principle of groundwater flow basically lies on Darcy"s law. When this law is put together with an equation of continuity, which describes the conservation of fluid mass during flow through a porous medium,can be described by the general flow equation in three dimensions for a heterogeneous anisotropic material :

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (5.1)$$

Where:

k_{xx}, $k_{yy}$and k_{zz} are values of hydraulic conductivity in the x, y and z directions along Cartesian Coordinate Axes, which are assumed to align with principal directions of hydraulic conductivity (LT^{-1});

h is hydraulic head (L);

W is a volumetric flux per unit volume and represents sinks and/or sources (T^{-1}),

S_s is the specific storage of the porous material (L^{-1}), and

t is time (T).

Derivations of the above equation can be found in Anderson and Woessner, 1992. In order to simulate Meki river catchment aquifer system, equation 5.1 is updated according the prevailing field condition. Based on the assumption of the conceptualized model as steady state unconfined aquifer and single layer with no possible flow in Z direction, the above equation is modified to Boussinesq equation and is given by:

$$\frac{\partial}{\partial x}\left(k_x h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y h\frac{\partial h}{\partial y}\right)-W=S_y\frac{\partial h}{\partial t} \qquad (5.2)$$

Assuming the transmissivity as $T_x = k_x h$ and $T_y = k_y h$,

Where:

h is the saturated thickness (L), and

S_y is the specific yield (dimensionless).

For this study, a hydraulic property within the layer is assumed isotropic. Because the available data within the study area is limited to horizontal properties of the aquifers and it is difficult to establish a relation regarding the anisotropy unites. Due to the above reason the k_x and k_y value are assumed to have the same vale at any given location and it is logical to replace them by a single value k to describe the horizontal hydraulic conductivity. Since the study area is stimulated considering a steady state condition the term $\partial h/\partial t$ will become zero. Therefore, Boussinesq equation can be re-written as:

$$\frac{\partial}{\partial x}\left(kh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(kh\frac{\partial h}{\partial y}\right) \;=(+)-W \qquad (5.3)$$

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

Because of its continuity in space and time, generally equation 5.3 cannot be solved analytically for practical applications involving complex systems as Meki river catchment. As a result, numerical methods are employed where a set of spatially and temporally discrete points replace the continuous system described by equation 5.3 in a process of discretization. Equation 5.3 is then replaced by a set of simultaneous algebraic equations that describe the distribution of hydraulic head at each point, and flow through the system in response to this head distribution. These simultaneous equations are set up in matrix form and then solved. There exist several techniques to solve the set of simultaneous equations. In this model, the Preconditioned Conjugate Gradient 2 (PCG2) was used as a solver. Discussions of the finite-difference method, which is the numerical technique used in this study, can be found in Anderson and Woessner, 1992.

5.3 Spatial discretization

In the numerical modeling, the continuous problem domain is replaced by discretized model consist of an array of nodes and associated finite difference cell (Anderson and Woessner, 1992).The finite difference grid representing the Meki river catchment covers approximately 2318.58 Km^2. Figure 5.1 illustrates the model grid in plain view. Additionally it shows that the model domain in MODFLOW exceeds the study area defined in the conceptual model. So, we defined the IBOUND by first establishing the lateral extent of the formations in each layer using the catchment boundary map and assigned a cell as active if the formation covered more than 50 percent of the cell area.

The model domain spans approximately 73 km in the north-south direction and 76 km in the east-west direction. The finite difference grid has 380 columns, 365 rows, and one vertical layer for a total of 138,700 cells. Each cell size has a uniform grid size of 200 m by 200 m. The southwest corner of the model grid is located at UTM: 414000 Easting and 864000 Northing. The irregular shape of the region under study treated with quadrangular finite difference model approach may increase the number of inactive cell and reduce the number of active cell in the model.

The regular grid spacing facilitated data input from a Geographic Information System (GIS) and analysis of model output by the GIS, and the grid size minimized errors in flow-path analysis that would be caused by a large grid size. The model size is large but meets the objective to understand the regional ground water flow system. Figure 5.1 show the model grid, boundary conditions, flow packages (drains, rivers and well package); active, inactive and constant head representing the four lakes.

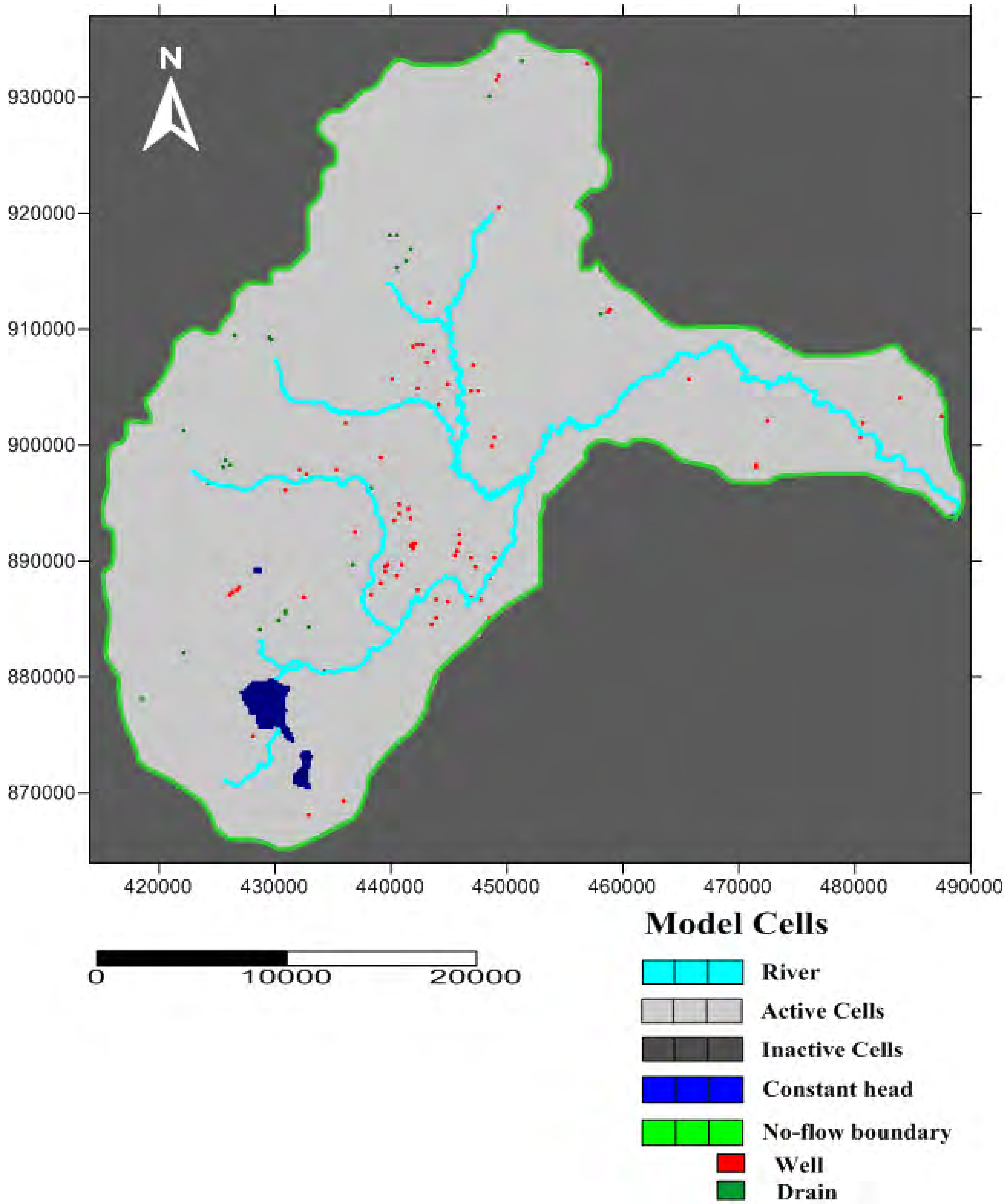

Figure 5. 1 Model grid design and lateral boundary conditions

5.4 Top of the layer

The top of the aquifer layer is assumed to be the ground elevation and drawn from the 30m by 30m resolution ASTER digital elevation model. As mentioned in the conceptual model, the model uses a single layers defined by horizontal and vertical collections of rows and columns. The DEM data is processed to generate grid file to be in a format compatible to the Processing Modflow Pro (Version8.0.15) and imported to the model with elevation referenced according to its geographic position. The imported grid elevation has an elevation range of 1599m to 3500 m.

5.5 Bottom of the layer

Assigning the bottom elevation is a difficult task as the aquifer thickens is variable. According to the Butajira Ziway areas development study report, the aquifer thickness around Meki river catchment varies from few meters in the west to several meters (more than 260 meters and more) in the center and along Weja river except along the Gurage chain of mountain with high elevation. In order to avoid drying of cells during simulations elevated zones were given relatively higher thickness at the cells. Even though the thickens of the aquifers are very rough it can be simply obtained by subtracting 80 meters up to 260meters and more depending on the hydrogeological conditions of each plain for staring the simulation and finally modified a bit in few areas during model calibration process. The top and bottom elevation of the study area is shown in Figure.5.2.

5.6 Boundary condition

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain (Anderson and Woessner, 1992). In steady state simulation, the boundaries largely determine the flow pattern. Setting the boundary is the critical step on the modeling and controls the water entrance and exit point of the model system.

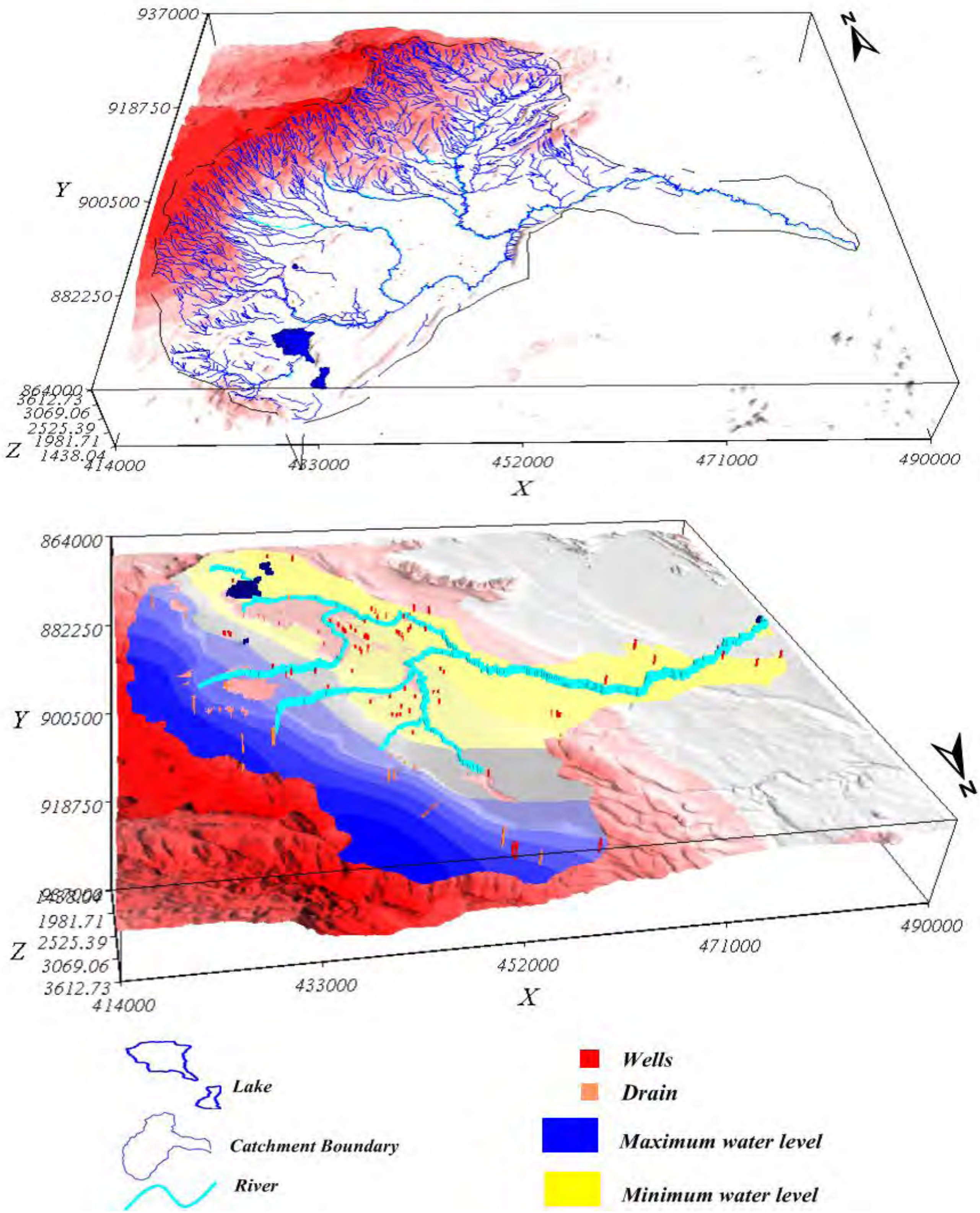

Figure 5. 2 3D-View of top and bottom elevation of the study area

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

Boundaries in the Meki river catchment regional groundwater flow model are divided into two broad categories. The first group includes boundaries related to the geographic extent of the regional aquifer system, such as contacts with effectively impermeable bed rock units. The second group includes boundaries within the model extent related to hydrologic processes or features, such as stream systems.

5.6.1 Geographic boundaries

The geographic boundaries of the Meki river catchment regional groundwater model were chosen to correspond as closely as possible with natural hydrologic boundaries across which groundwater flow can be assumed negligible, such as groundwater divides, or can be reasonably estimated.

In the study area major topographic divides are often considered no-flow boundaries because topographic divides are typically coincident with ground water divides. Groundwater on either side of a groundwater-divide flows away from the divide and not across it, so the divide itself acts as a no-flow boundary.

Topographic divides often coincide with groundwater divides because highland areas commonly have larger amounts of precipitation and recharge than surrounding areas, so the water table surface develops a coincident high elevation region from which groundwater flow diverges. The boundary of the Meki river catchment is generally taken as a closed boundary system considering the entire geographical boundary and simulated with no flow.

5.6.2 Hydrological process boundaries

This Boundary condition is the major category in the model of Meki river catchment that relates hydrologic processes including recharge, groundwater flow to and from streams, well withdrawal and groundwater outflow to the Lake Ziway.

Recharge from precipitation is represented as specified-flux boundary condition. Recharge to the groundwater system was given by considering sources of groundwater from infiltration of precipitation and deep percolation of applied irrigation water. It is simulated as a specified flux to the uppermost layer of the model using seven different zones based on the previously developed conceptual model.

The first and second zone in the conceptual model that is high direct recharge over the western escarpment and north eastern escarpment is given initial value of 5.75×10^{-4}m/day and 3.91×10^{-4}m/day m/day respectively. Butajira crescent with moderate recharge is given an initial value of 3.81×10^{-4}m/day. The forth zone which is intermediate recharge zone over Kontane-Inseno-Kela plain is given a value of 3.7691×10^{-4}m/day. The Scoria Cones region with relatively small recharge has a value 3.66 $\times 10^{-4}$m/day. The Ziway plain with a better recharge than that of Tora-Koshe-Dugda ridge is assigned a value of 2.4×10^{-5}m/day. The last zone due to the depth of the aquifer is found at a deeper depth an initial value of 6.0×10^{-6} m/day is assigned. Finally, during model calibration these recharge values were adjusted.

The major perennial streams are another important boundary condition which facilitates the movement of groundwater to and from perennial rivers. The flux of water between the groundwater system and rivers is generally dependent on the hydraulic head in the groundwater system and is simulated as a head-dependent flux boundary. Cells in the model that correspond to the locations of perennial streams are mathematically represented in a manner that allows ground water to move between the aquifer and stream with a direction and magnitude that depends on the head relations. In order to simulate the interaction of the surface and groundwater interaction the model used the river package. The river package is used to simulate the flow between an aquifer and an overlying or under lying source of reservoir but usually river.

In a model cell the interaction of the river and aquifer can be mathematically represented by the MODFLOW by the relation of hydraulic head of model and the stage of river both on the upper table and bottom of river and the aquifer (Q_{riv}) is calculated from;

$$Q_{riv} = C_{riv}(h_{riv} - h) \quad , \quad h > B_{riv}$$
$$Q_{riv} = C_{riv}(h_{riv} - B_{riv}) \quad , \quad h < B_{riv} \qquad 5.4$$

Where:

Q_{riv} is the leakage rate $[L^3 T^{-1}]$;

$C_{riv} = \frac{k_{riv} L_{riv} w_{riv}}{M_{riv}}$

h_{riv} is head in the river[L];

h is the head in the aquifer directly below the river; [L];

B_{riv} is bottom of the streambed [L];

C_{riv} is the streambed conductance which accounts for the length $[L^2 T^{-1}]$;

W_{riv} is the river channel width within the cell; [L];

M_{riv} is the thickness of the riverbed sediments [L]; and

K_{riv} is the vertical hydraulic conductivity. $[L T^{-1}]$.

In the model grid river cells are shown in figure 5.1. These include Meki river and Irinzaf, Lebu, Akamuja, and Weja perennial tributaries. The movement of ground water to or from streams is a function of the head in the stream, h_{riv}, also known as stream stage. Stream stage is the elevation of the water surface in the stream, and a single value must be chosen to represent the stream across the entire cell. Stream stages used in this simulation were determined by picking an approximate median stream elevation within the cell based on the observed field value, and ASTER DEM derived from a 30m by 30m resolution.

The rate of water movement to and from a stream in response to a given head gradient is controlled by streambed conductance, C_{riv}. Direct measurements of streambed conductance are rare and these terms are usually derived empirically during model calibration.

Table 5.1 Major stream model input summary (modified from Makin et al., 1976)

No	Major Stream	Conductivity(m/day)	Thickness Bed (m)	Head of the River (m)	Width (m)
1	Meki river	0.09-0.12	0.75-0.9	1637.3-2001	7.25-15
2	Lebu river	0.12	1	1879.66-2164.54	7
3	Akamuja river	0.12-0.27	1	1834.43-2371.59	8.5
4	Irinzaf river	0.076-0.27	1	1815.54-2296.69	7-8.5
5	Weja River	0.13	1	1808.68-1938	6 -10

The drain package was used to simulate effects of features such as spring, which remove groundwater from aquifer at a rate proportional to the head difference between the aquifer and the drain. When the hydraulic head in the aquifer is greater than the drain elevation, groundwater flows into the drain and is removed from the groundwater model. Discharge to the drain is zero when the hydraulic head is lower than or equal to the median drain elevation. Recharge from the drain is always zero, regardless of the hydraulic head in the aquifer.

The exchange rate of water between the model cell and the outside source or sink is given by the equation:

$$Q_d = C_d(h - d) \qquad 5.5$$

Where:

Q_d is the discharge rate to a drain cell $[L^3 T^{-1}]$;

C_d =KL is drain hydraulic conductance $[L^2 T^{-1}]$;

K is Equivalent Hydraulic Conductivity $[LT^{-1}]$;
L is the length of the drain within a cell [L];

h is the hydraulic head in a drain cell. [L]; and

d is Elevation of the Drain [L].

The initial values of C_d, ranging from 10–20 m^2/day, were distributed across the model cells to the drain package.

The final hydrological process boundary condition in this discussion is groundwater withdrawal, which is simulated as a specified flux. In the study area there are irrigation, public water supply and individual domestic wells pumping from the aquifer. Specified fluxes are removed from cells corresponding to the geographic locations of the wells and springs.

5.7 Initial conditions

Initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation (Anderson and Woessner, 1992). If the field measured head values were used as initial conditions, the model response in the early time steps would reflect not only the model stress under study but also the adjustment of model head values to offset the lack of correspondence between model hydrologic inputs and parameters and the initial head values (Franke et al., 1991).

Therefore, in the model, user specified initial head distribution obtained from the first steady state simulation was used as initial and prescribed hydraulic head for the model, where the first steady state simulation uses initial and prescribed hydraulic head by subtracting 20 m from top of layer of the model obtained from a 30 m by 30 m resolution ASTER DEM of the catchment.

5.8 Hydraulic properties

In this model groundwater flow within the layer was assumed to be horizontal. Hydraulic conductivity can be defined as the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic conductivity is a function of both the medium and the fluid. Transmissivity which is the product of hydraulic conductivity and saturated thickness is the rate at which water flows through a vertical strip of the aquifer one meter wide and extending through the full saturated thickness, under the hydraulic gradient of one (100 %). It indicates how much water will move through the formation.

The very essential parameter in the aquifer system is the hydraulic conductivity that defines the flow rate of the groundwater in the aquifer system. The model uses the spatial distrbution of the hydraulic map described in the conceptual model to begin the model simulation. The model used a hydraulic conductivity within a range of 0. 1 m/day to 20 m/day.

Finally using trial and error model calibration, sub zone delineation and estimated values were determined within reasonable limits estimated during the conceptual model. Since it is unconfined aquifer, the model was allowed to calculate changes in the transmissivity as the saturated thickness changes in the aquifer. The effective porosity was set to 0.25, a default effective porosity value in MODFLOW.

5.9 Stresses

5.9.1 Recharge

Recharge is a specific flux boundary which is independent of the head of the cell but MODFLOW consider it as a property for spatially distributed all over the model area. Recharge to the model consisted of infiltration from direct precipitation, stream infiltration draining the eastern escarpment and artificial recharge of irrigation-return flow. Recharge was applied to the active model area as a spatially varying, specified flux to the highest active cell. In general, precipitation recharge varies spatially with land surface permeability, which is a function of soil characteristics and land use, and spatial distribution and intensity of rainfall. The recharge stated used on the conceptual model is also used as an input to model parameter.

The recharge is applied with recharge package. As it is a boundary property, the recharge has a mathematical code that assume the volumetric rate of flow in to cell described with multiplication of the recharge rate by the horizontal area of the cell. MODFLOW uses recharge flux to calculate the recharge flow rate applied to the model cell and recharge flow rate is calculated from;

$$Q_R = I_R \cdot DELR \cdot DELC \qquad 5.6$$

Where:

Q_R is the recharge flow rate $[L^3T^{-1}]$

I_R is the Recharge Flux $[LT^{-1}]$

$DELR \cdot DELC$ is the map area of a model cell

5.9.2 Discharge

In the study area, discharge from groundwater systems includes groundwater withdrawal, groundwater outflow to the adjacent Lake Ziway and discharge to stream and springs. In the model, different MODFLOW packages were used to simulate these discharge components.

Discharge to streams were modeled using the river package and was used to simulate the hydraulic connection between groundwater and surface water by allowing streams to gain or lose water, based on the difference between the surrounding hydraulic head and stream stage, through riverbed material of a specified hydraulic conductance (McDonald and Harbaugh, 1988). Estimated riverbed conductance was based on model calibration. Model cells were designated as river cells along major streams and tributaries where the groundwater table intersected the land surface.

In the study area, pumping wells were simulated with the well package. For recharge rate of the well negative values are used to indicate pumping wells, while positive cell values indicate injection wells. The injection or pumping rate of a well is independent of both the cell area and the hydraulic head in the cell. MODFLOW assumes that a well penetrates the full thickness of the cell. Because there was limited well-construction data available, all wells were assumed to be fully penetrating in the layer.

High yielding springs supplying water to community and surrounding areas were simulated using drain package which remove groundwater from aquifer at a rate proportional to the head difference between the aquifer and the drain.

Chapter 6

6. Calibration and sensitivity analysis

6.1 General overview

Groundwater flow model calibration is the process of adjusting selected model parameters within an expected range until the difference between models predicated heads and the field observed heads are within selected criteria for best performance of the model (Mercer and Faust, 1983).

In order to provide some assurance that the model reflects the behavior or appearance of the flow system, it must be calibrated prior to use as a predictive tool. Model calibration is accomplished by finding a set of model parameters, boundary conditions, and excitations or stresses that produce simulated heads and fluxes that match measurement values within an acceptable range of error.

The process of estimating unknown parameters is one of the most difficult and critical steps in the model application that requires observed value up on which the modeler will attempt to match. This observed value is known as calibration target. Calibration targets provide a means of assessing calibration quality because an error term (residual) is computed for each target location. A residual is computed as the field measurement minus the model computed value. The range of errors helps to determine whether the quality of the calibration is adequate to meet the overall goals of the study.

The parameter estimation of a flow model is accomplished by finding a set of parameters, hydrologic stresses, or boundary conditions so that the simulated values match the measurement values to a reasonable degree. The targets may be measurements of head, concentration, drawdown, or groundwater flow (called stress in the following discussion).

Model calibration can be performed by the hand operated trial and error adjustment of aquifer parameters or by inverse models. The inverse solving method approaches a problem to get a set of hydrogeological parameter in order to meet observed value and the forward solving method use an aquifer system parameter to calculate the head.

In this model the calibration target is taken with observed hydraulic head or the static water level measured on the production well. The model applies the trial and error method which gives satisfactory results for the steady state calibration and met the overall goals of the study.

6.2 Calibration method

6.2.1 Calibration target

The model is calibrated to steady state condition with observed head measured at the available production well. In addition the water balance is checked every time with regards to input values of recharge and outputs from wells and springs. The groundwater level measurement is taken during the construction and inventory time of the borehole. Because, there is no practice of monitoring the existing well standing water level and no accessing means like an observation pipe installation to easily measure the water level.

The Meki river catchment regional steady-state groundwater model was calibrated to average conditions using the data from 2000 to 2007. This period was chosen because much of the data collection for the study occurred during this time. The model uses 95 calibration target distributed with in the basin. These head observations were not evenly distributed throughout the model domain but were distributed in the south-east part of the study. The time of measurements of some wells were somewhat uncertain, as a result, head data were examined carefully and unusual values due to measurement or location errors were removed from the calibration data set before the final 95 wells were selected.

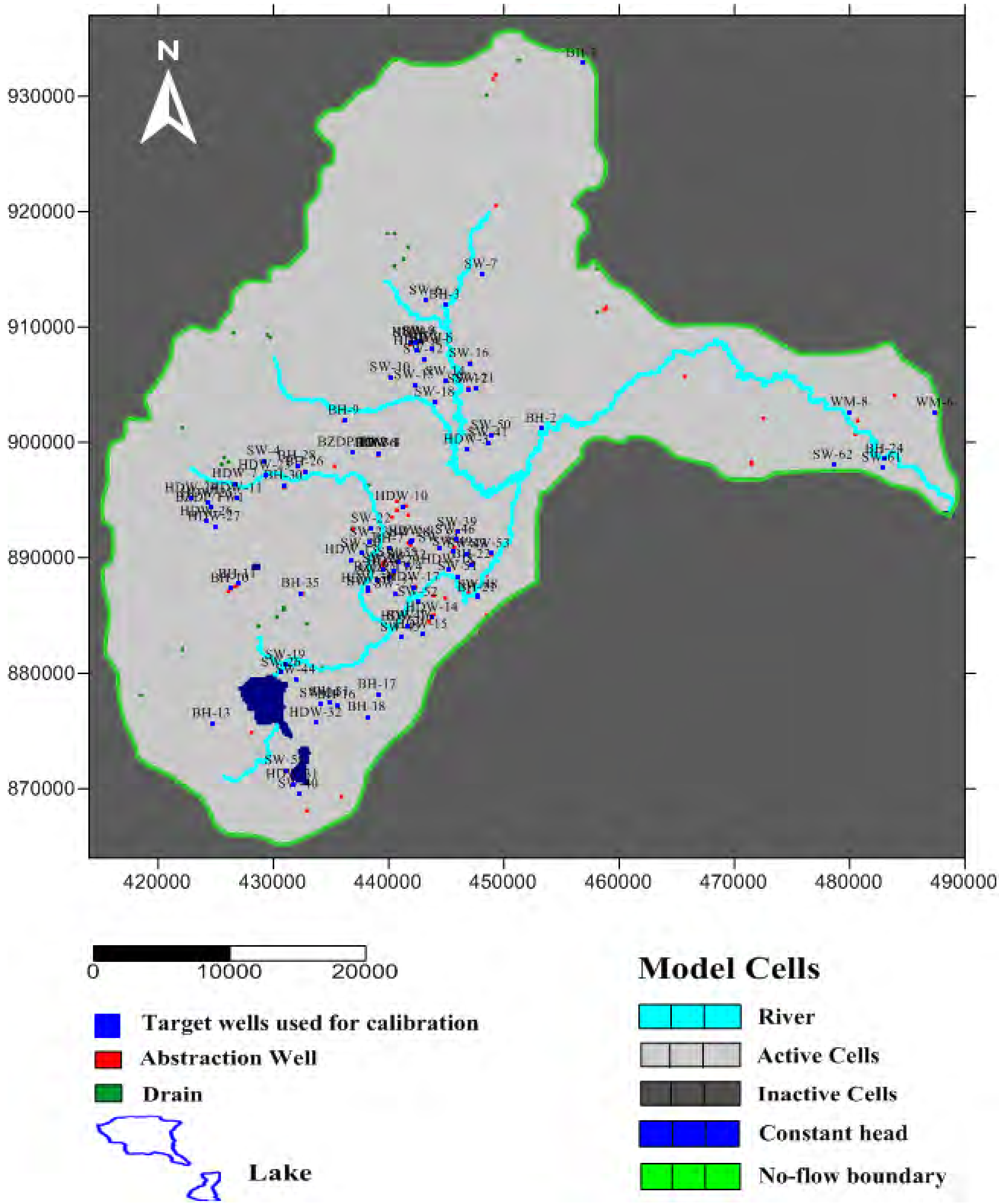

Figure 6. 1 Spatial distribution of target wells for calibration

6.2.2 Calibration techniques

Before the calibration of the model, there were criteria established to assess the simulation results in relation to measured data. The first calibration criterion for the simulation was that the simulated groundwater surface and hydraulic gradient generally match those of the estimated one, which is done by comparison of the calculated and observed value.

In addition the model calibration process has to also maintain the estimated base flow on the gauged part of the river, water budget and other important inflow and out flow component of a steady state aquifer system.

The model calibration is expected to fulfill the criteria set stated above. Basically, there are two way of finding model parameter: (1) Manual trial and error calibration (2) Automated parameter estimation (Anderson and Woessner, 1992). The Meki river catchment is calibrated with a help of the modeler high judgment participation manual trial and error adjustment.

6.2.2.1 Manual trial and error calibration

This calibration technique relies on the modeler prior information and knowledge about the area. The modeler uses his knowledge to evaluate the response of aquifer parameter or boundary changes on the simulated head to match the observed head.

The model tries to determine the aquifer parameter with information of the head distribution over the aquifer system. It results a set of aquifer system parameter that minimize the difference between the simulated and observed head.

In trial and error calibration, the aquifer parameter will be modified or adjusted until the sequential model run match simulated head to calibration target. Accordingly, the model use adjustment, dominantly, in the hydraulic conductivity and minor adjustment on the recharge and river conductance. In model calibration process, a satisfactory result for the steady state calibration is found which meet the overall goals of the study.

6.3 Evaluation of the calibration process

The result of the calibration is evaluated both quantitatively and qualitatively and tries to use the Anderson and Woessner, 1992 protocol suggestion to evaluate the calibration which includes matching of contour map of measured and simulated head, calibration statistics and scatter plot used to evaluate the result of the model.

6.3.1 Contour map comparison

Evaluating the calibration of the model using couture map comparison is done by visual judgment of simulated and measured heads the area. Meki river catchment modeling could be categorized as regional studies and matching simulated and measured map trend is very essential to calibrate the model. Accordingly, the model simulated contour of the hydraulic head is approach to match the measured contour one. The simulated heads is found to follow almost the same trend as of the observed ground water contour. The simulated head approximate the observed contour with reasonable accuracy.

However, it will be very unusable to achieve identical simulated and measured contour in the context of complex aquifer with inherited nature of head difference in small distance and poor ground water data management of the country.

6.3.2 Calibration statistics

To afford a complete indication of the quality of the calibration, summary statistics on the difference between simulated and measured water levels were calculated after model calibration. The mean error (ME), mean absolute error (MAE) and root mean squared error (RMS) are common ways to express the average difference between simulated and measured water levels (Anderson and Woessner, 1992). The objective of the calibration is to minimize these error values. The calibrated model has ME -3.51 m, MAE 7.35 m and RMS 8.31 m.

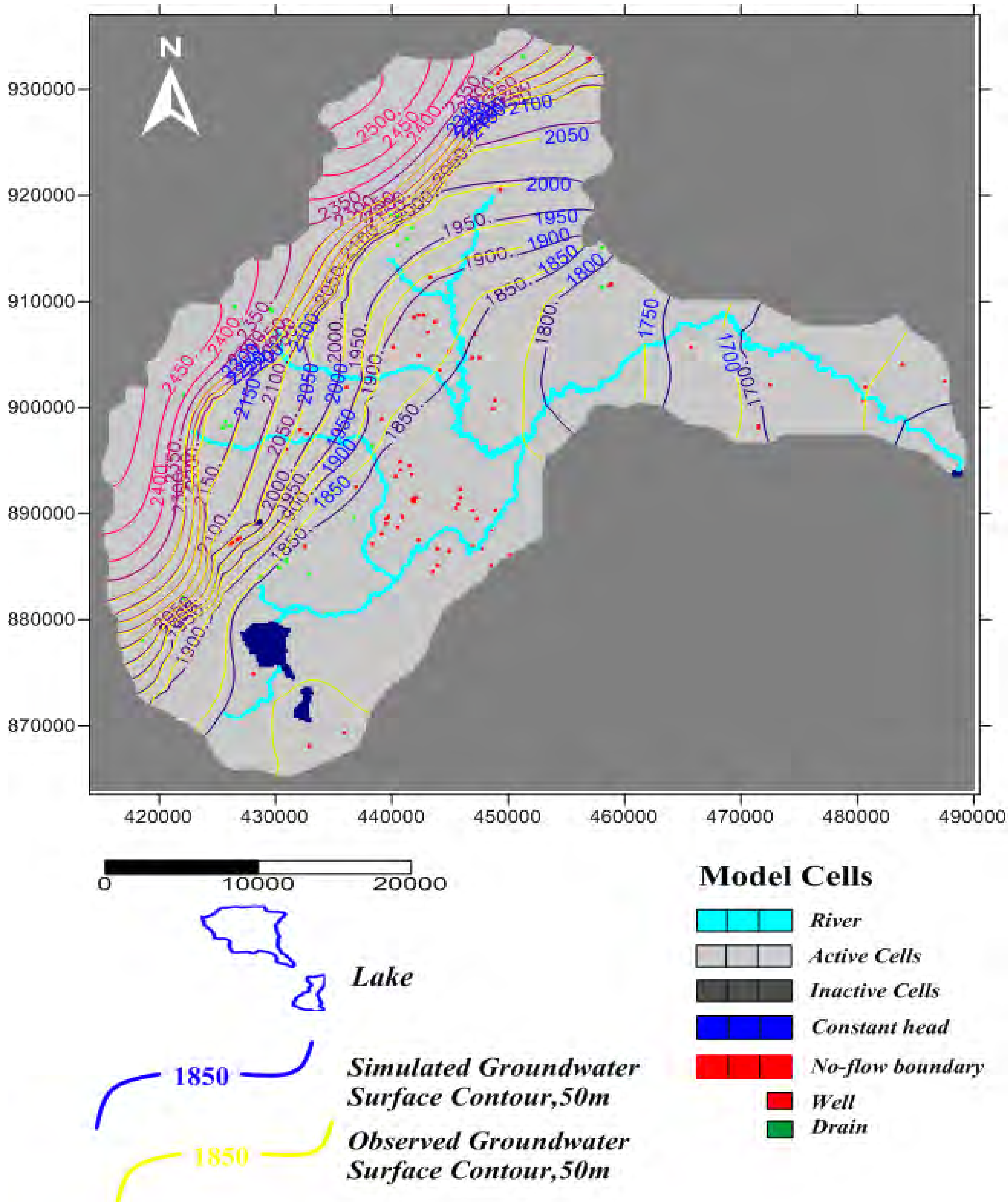

Figure 6. 2 Contour comparison of model-simulated and observed steady-state water table

1. The mean error is the mean difference between measured heads (h_m) and simulated heads (h_s).

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)\,i \qquad 6.1$$

2. The mean absolute error (MAE) is the mean of the absolute value of the differences in the measured and simulated heads.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(h_m - h_s)\,i\right| \qquad 6.2$$

3. The root mean squared error (RMS) is the average of the squared differences in measured and simulated heads.

$$RMS = \sqrt[2]{\left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)\,i^2\right]} \qquad 6.3$$

The above error measures can only be used to evaluate the average error in the calibrated model. The RMS is usually thought to be the best measure of error if errors are normally distributed. The maximum acceptable value of the calibration criterion depends on the magnitude of the change in heads over the problem domain (Anderson and Woessner, 1992). The overall statistics computed from the simulated head and observed head are described in appendix xi.

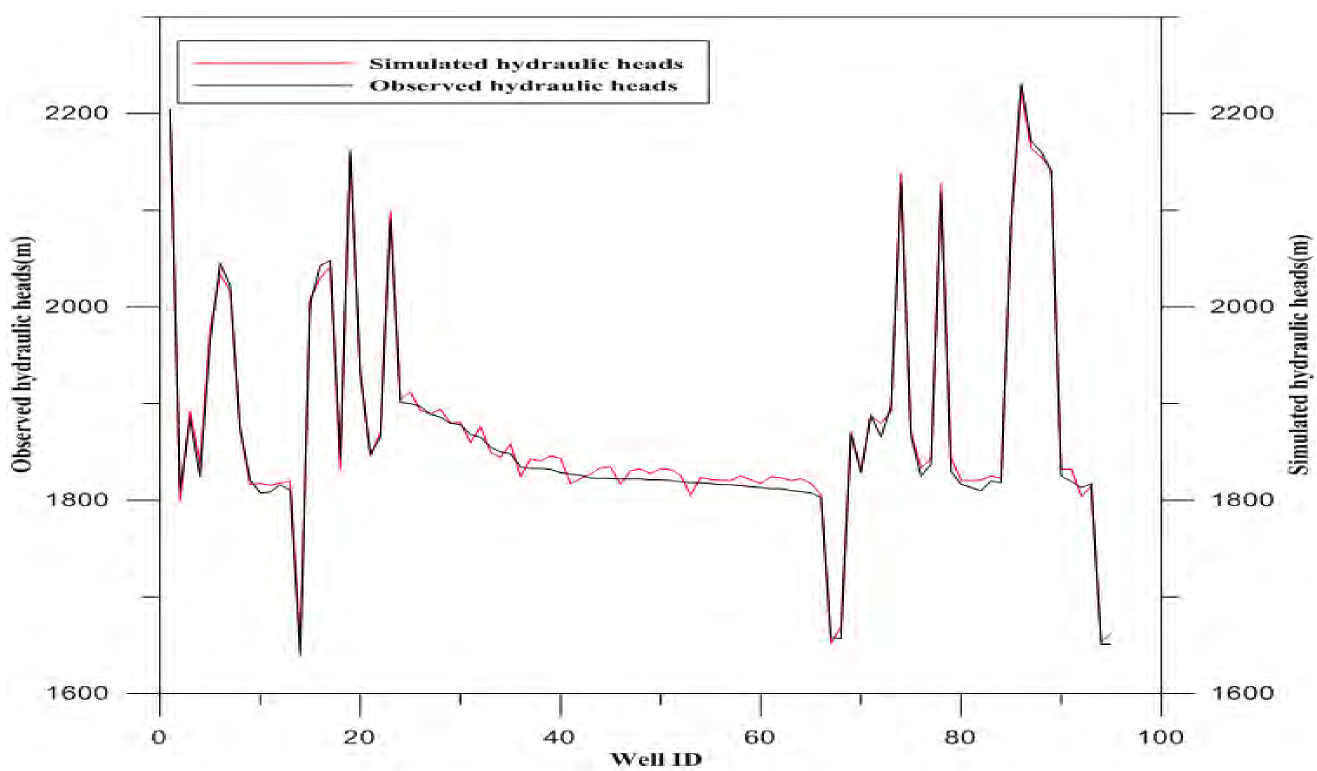

Figure 6. 3 Comparison of observed and simulated hydraulic head for 95 wells.

6.3.3 Plotting calibration results

Model generated scatter diagram showing the calibrated fit between the observed and simulated heads is shown in figure 6.4. The scatter plots are visually examined whether points in a plot show deviation from the straight line in a random distribution or have systematic deviation, where systematic deviation of the plots can indicate systematic error in adjusting the parameter values. The scatter plot shows a correlation coefficient of 0.996 and variance of 68.9.

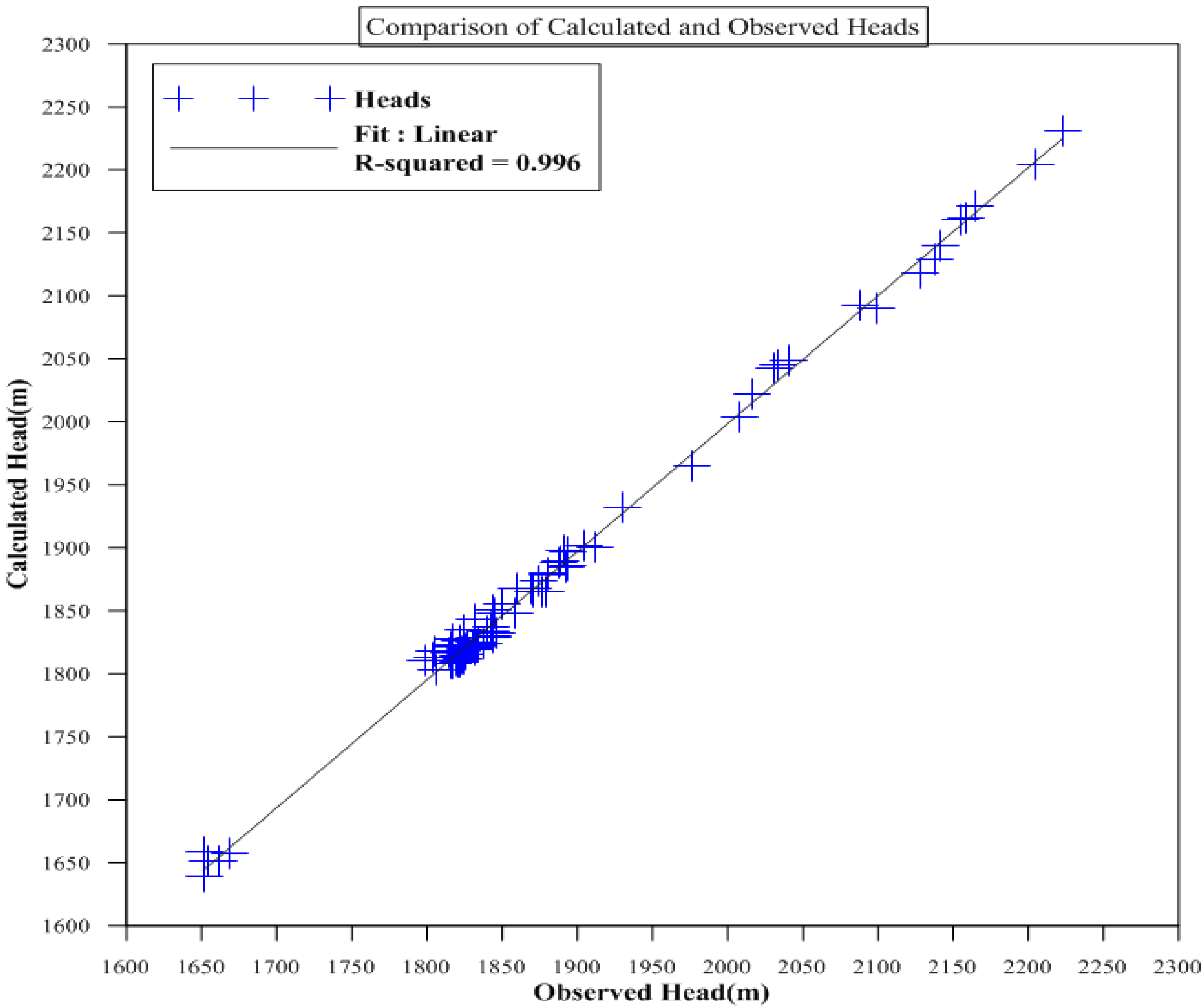

Figure 6. 4 Linear regressions of observed and simulated hydraulic heads for all wells.

6.4 Sensitivity analysis

Model sensitivity analysis is performed to quantify the uncertainties in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Anderson and Woessner, 1992). To test the response of the calibrated model to a range of values for various input parameter, a sensitivity analysis is done. Sensitivity analysis help to determine which model parameters have the greatest effect on a model. Results of the analysis can guide future data collection efforts that will reduce model errors. It is done by varying the values of one input parameter while keeping all others constant.

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

Model sensitivity was determined for variations in hydraulic conductivity, pumpage and recharge. The results of the sensitivity analysis for this study were evaluated by calculating the MAE between measured and simulated heads in the modeled area for a decrease or increase in percent, from the calibrated value, of that parameter. “Calibrated Model” at the center of the plot (Figure 6.5) represents the final model and the corresponding MAE that is 7.35. The greater the deviations of the water level from its calibrated model value, the greater the sensitivity of the model to an increase or decrease for that parameter. To test the sensitivity of the above parameters, the calibrated values of each parameter were separately increased and decreased by 20,40,50,60 and 65 percent and then simulated to see the resulting heads.

In the model, simulated water levels were more sensitive to the decrease in the recharge values, mainly away from 40 percent. But it is more sensitive to the increase of hydraulic conductivity values, especially above 30 percent. Compared to recharge and hydraulic conductivity the model is not that much sensitive to the decrease or increase of pumpage.

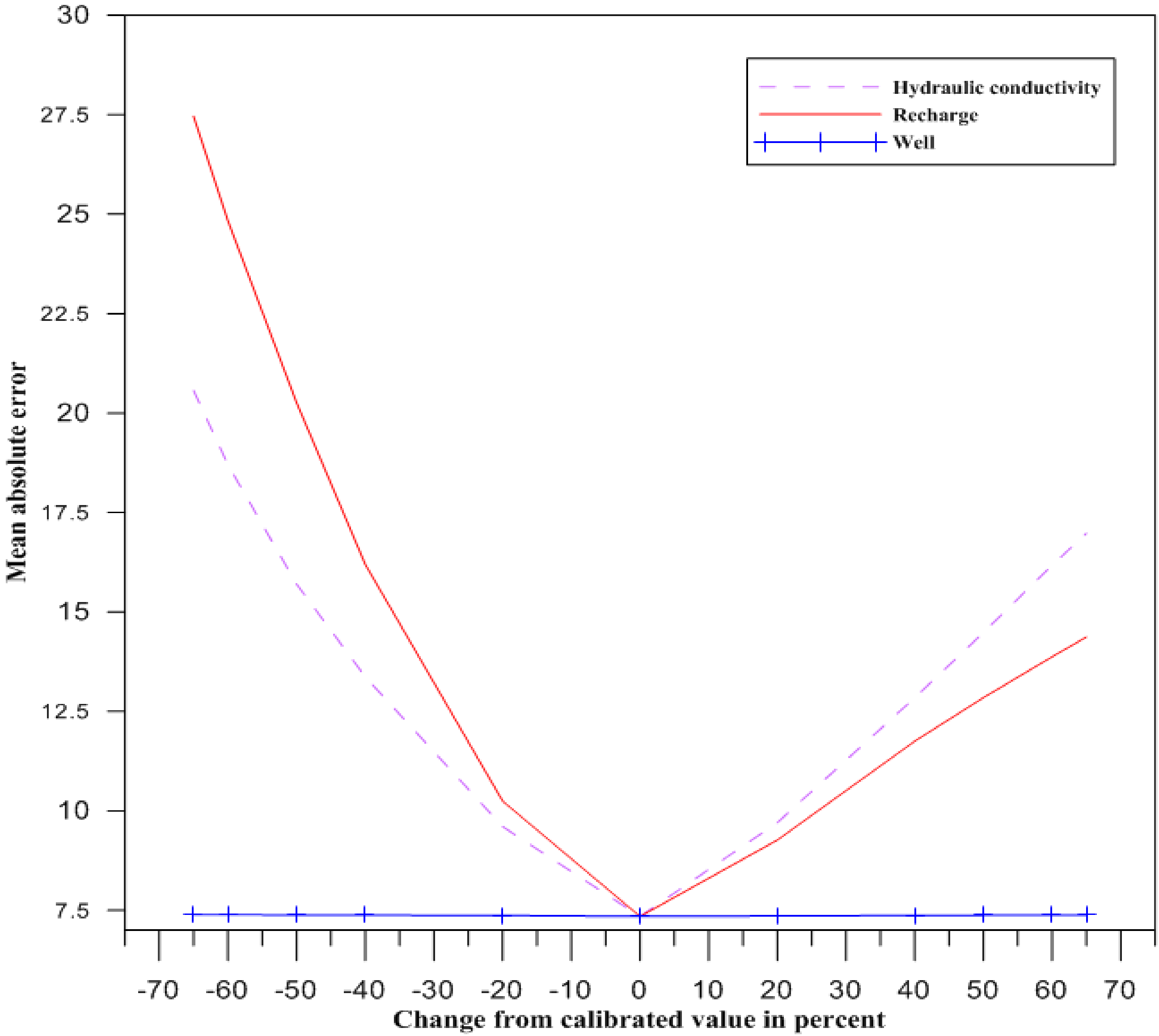

Figure 6. 5 Model sensitivity to recharge, hydraulic conductivity and pumpage.

6.5 Model limitation

The steady-state groundwater flow model of the Meki river catchment provides a regional-scale simulation of groundwater flow in the aquifer system of the study area. A groundwater model is a simplified approximation of actual conditions. The groundwater model results depends on the accuracy of the input data and has corresponding limitations in model precision, because the database management of the hydrogeology of the country is so poor and with limited vital parameter. Therefore the user of the model should consider the deficiency of the data that encountered the modeler.

The model was discretized using a uniform grid cell size of 200 meter by 200 meter. As a result of this discretization, the conditions within the node, such as groundwater level and flow, are reduced to one average value for the entire node. Therefore, the model is not suitable for analysis of site-specific problems or issues. Hydrologic parameters and aquifer unit geometry in portions of the model area are not well known at this scale. For instance, aquifer thickness and hydraulic conductivity can change at intervals smaller than the current model resolution, especially where structures are extensive. Model uncertainty could also stanch from random error in the field measurements used for model calibration, which is translated through model calibration to uncertainty in the calibrated parameter values.

Extremely cracked and current tectonic areas can have a widely variable hydraulic conductivity. Therefore groundwater level and flow in these areas may be simulated indirectly by increasing the hydraulic conductivity; the effects of these structures on the aquifer system may not be appropriately addressed with the models. Calibration of the model could be improved by reefing further the spatial discretization of some parameters, such as hydraulic conductivity or recharge; however, with scarcity of more field data, finer discretization is not reasonable. From the research objective point of view, the model is adequate for studying groundwater withdrawal and other effects at the regional scale.

The geological condition of the area is too complex and the model is assumed as a single layer, unconfined and homogeneous aquifer system which ignores the natural heterogeneity of the earth and the user is expected to take in to account all the assumption used on the paper assumption. Therefore, further refinement of the model would be possible with additional data which improve the accuracy of model prediction parameter to apply it for a detail analysis.

Chapter 7

7. Model result and analysis

7.1 General overview

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

7.2 Simulated groundwater flow

MODFLOW calculates the hydraulic heads distribution of the groundwater surface. The simulated head distribution shows the groundwater surface flow from western escarpment to east directions finally join Lake Ziway. The simulated head of Meki river catchment is shown in Figure 7.1. The groundwater level is generally flat to gentle slope except at Tora-Koshe-Dugda ridge and the Cinder Cone areas. In these areas the groundwater contour shows steep slope probably due to the nature of the rocks or the fault systems separating these zones.

The groundwater has a slope of 0.1 % at Ziway plain; Tora-Koshe-Dugda ridge has 1.4%, Kuntane Inseno Kela plain 0.3% and Cinder Cone and Basaltic areas 3.7 %.The groundwater level drops from 2000 m in Butajira Crescent to 1800 m.a.s.l in Kuntane Inseno area.

7.3 Simulated water budget

Using the calibrated model, water budget of the whole model domain was calculated with a percent discrepancy of -0.02. It includes the following inflow components to the groundwater flow system: (1) Recharge from constant head boundary, with a value of 9.88×10^4 m^3/day. (2) Groundwater recharge from precipitation, which is 6.99×10^5 m^3/day and (3) Groundwater inflow from river leakage with value equal to 1.52×10^5 m^3/day.

The simulated groundwater outflow from the system includes (1) Discharge to constant head boundary, which is 2.63 × 105 m^3/day, (2) Groundwater outflow through river leakage with value equal to 6.64 × 105 m^3/day, (3) Groundwater outflow by well withdrawal with a value equal to 2.26 × 10^4 m^3/day and (4) Groundwater outflow through drains which is equals to 1.16 × 10^3 m^3/day.

Generally, these values are somewhat different from the estimates made in the water balance of the conceptual model, which could be due to the larger aquifer thickness considered in the model and those parameters which are not considered in the model. The inflow and outflow components of the water balance and steady-state hydrologic budget of the study area calculated by the model is shown in table 7.1.

Table 7.1 Simulated water budget of Meki river catchment

Hydrologic budget component	**Cubic meter per day(m^3/day)**	**Million cubic meter per year (MCM/year)**
Inflow		
Recharge from precipitation	699698.31	255.39
River leakage to aquifer	151918.59	55.45
Inflow from Constant-head boundaries	98868.39	36.09
Total inflow	950485.29	346.93
Outflow		
Groundwater discharge to streams	664285.38	242.46
Well withdrawal	22570.28	8.24
Drains	1157.57	0.42
Outflow to Constant-head boundaries	262635.09	95.86
Total outflow	950648.32	346.99
Budget error (inflow-outflow)	-163.03	-0.06
Percentage of discrepancy (%)	-0.02	

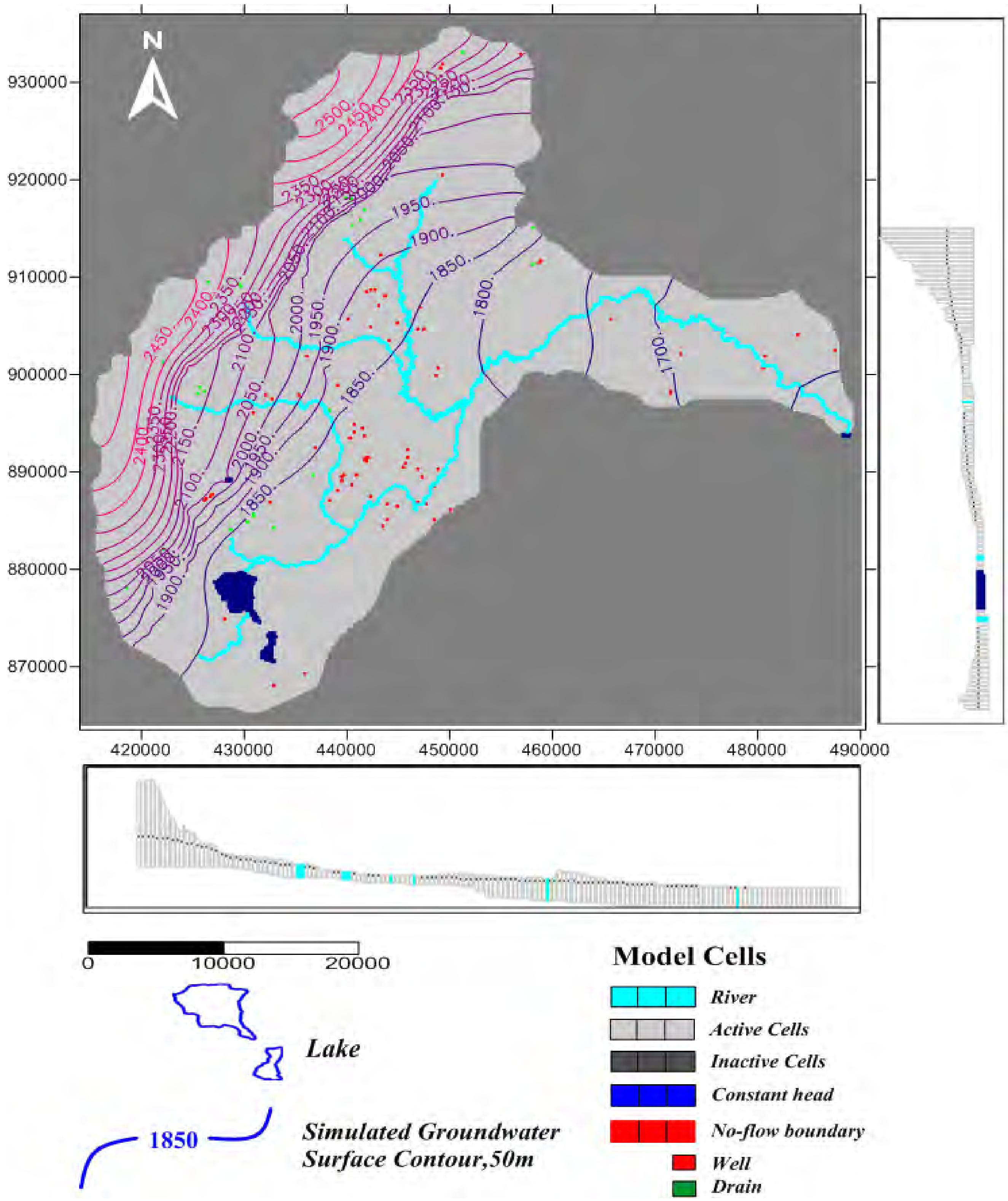

Figure 7. 1 Model-calculated steady-state water table and cross section along Row-170 and Column-80.

7.4 Calibrated aquifer system parameter

7.4.1 Hydraulic conductivity for the calibrated model

In addition to the trial and error methods used, zone delineation for hydraulic properties was determined by considering potential structural features and geology to achieve best possible fit to observed data. In the calibration process, the modeler considers the fact of the increment of conductivity as one goes from western escarpment toward the Lake Ziway.

The presence of structures and a scare data resource makes the resulting horizontal hydraulic conductivity and transmissivity data spatially variable in the study area; it was very difficult to refine the parameter value. Therefore, the calibration accuracy obtained using the larger zones shown in figure 7.2 was considered sufficient to fulfill the objectives of this study.

The simulated hydraulic conductivity value varies from 0.15m/day up to 20.23m/day is within the range of the conceptual model assigned value taken from Tenalem Ayenew, 1998 which is about 0.1m/day near western escarpment to 20m/day around scoria conies region.

7.4.2 Recharge rate for the calibrated model

The recharge is the most essential parameter of the aquifer system that governs the water budget system. During calibration, the model was not as sensitive as the hydraulic conductivity. There is little change between calibrated and the estimated parameter. The mean annual recharge over the study area is about 119.88 mm/year. In the model the mean recharge considered is about 110.15 mm/year with 9.73 mm/year discrepancy. The calibrated recharge rate for each hydrogeological zone is shown in figure 7.3.

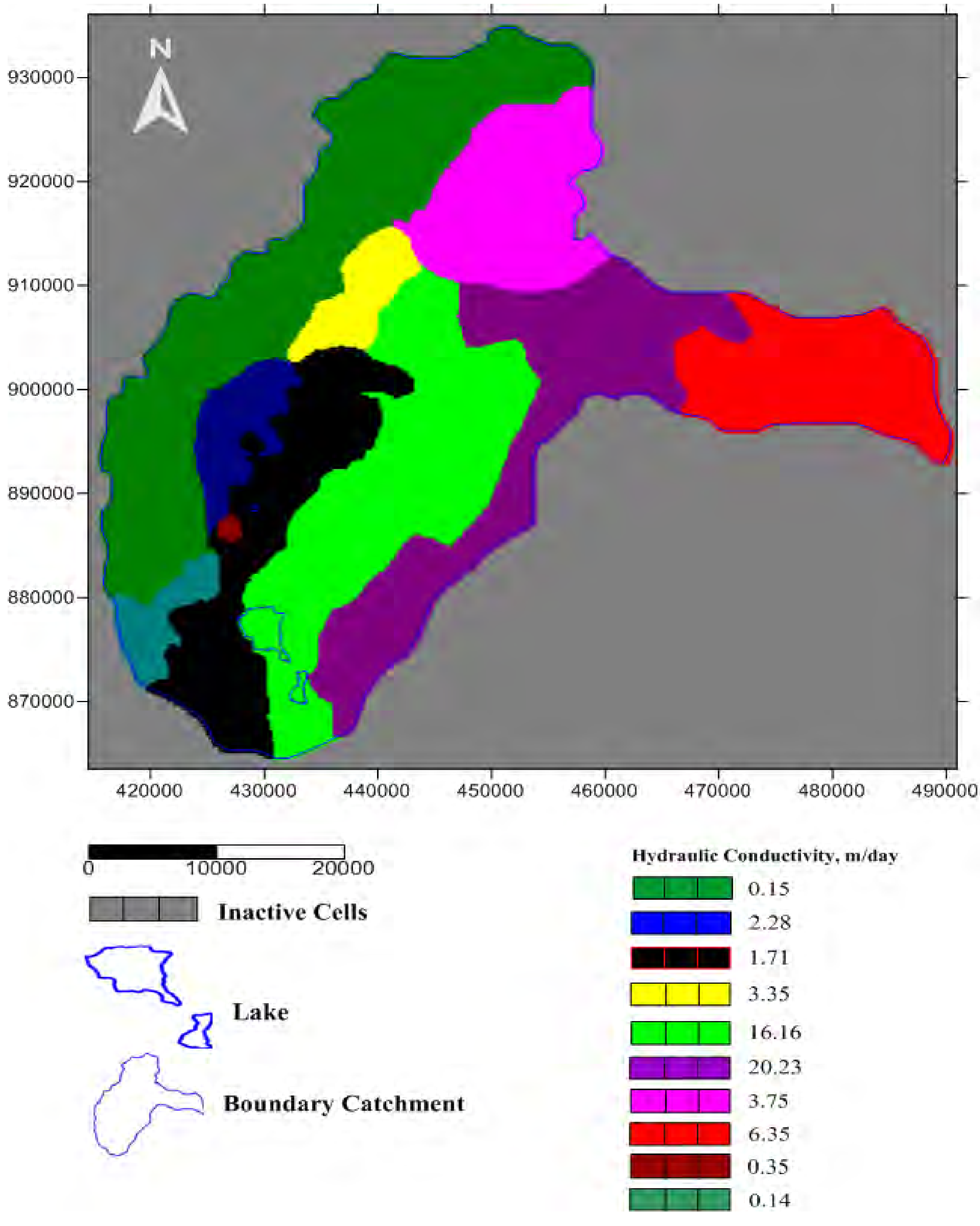

Figure 7. 2 Calibrated hydraulic conductivity map of Meki river catchment

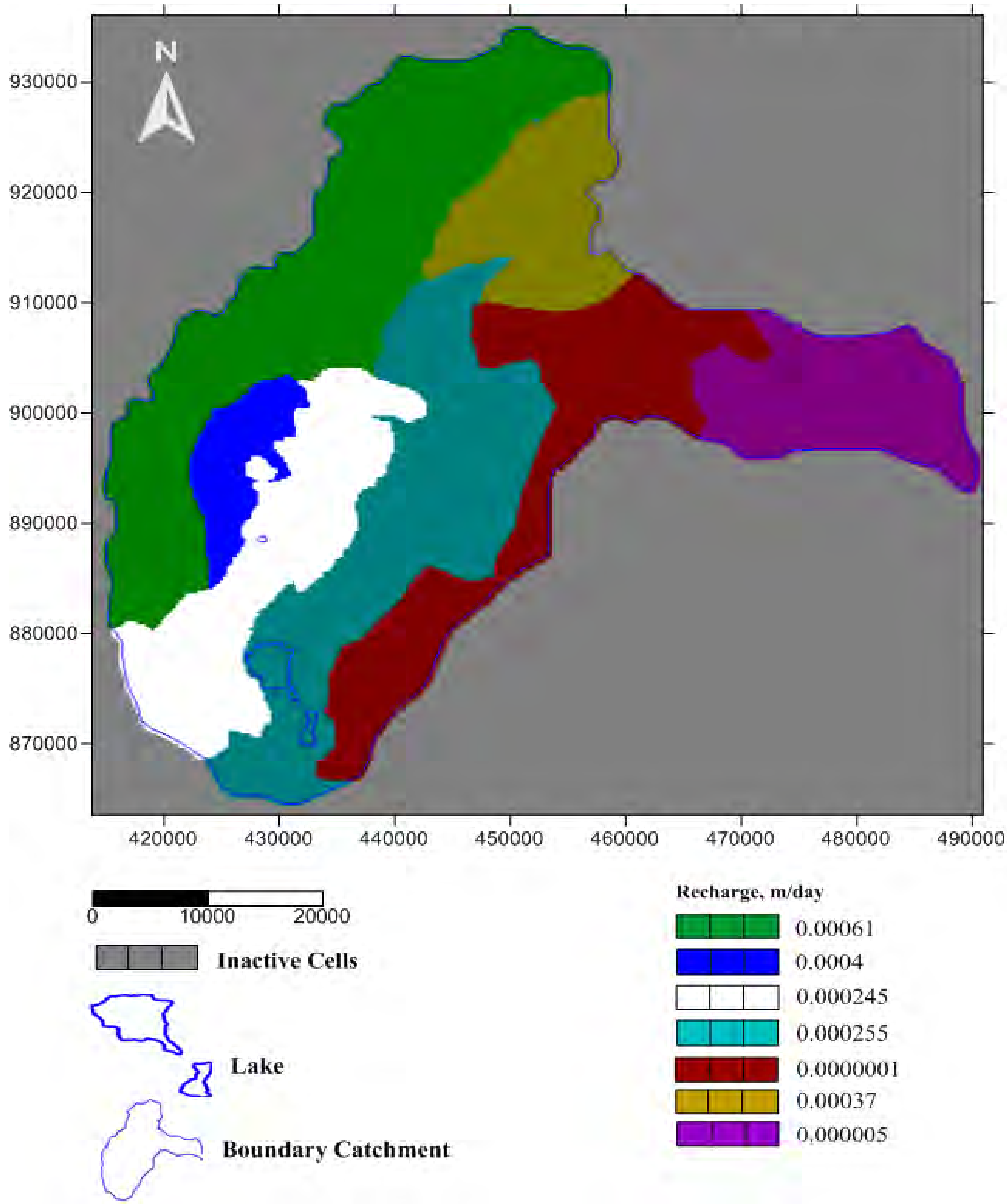

Figure 7. 3 Calibrated recharge rate of Meki river catchment

7.5 Scenario analysis

The main advantage of numerical groundwater flow modeling is to adapt the result for a different scenario analysis. The calibrated flow model helps as a tool to evaluate the response of an aquifer system to potential future stresses. Management actions involving changes in the quantity and distribution of pumpage or altered hydrologic conditions which could be drought conditions or conditions of altered recharge that may result, for example, from land use and climate changes can be simulated. The response of the aquifer-system can be compared to evaluate the effectiveness of these probable changes of stresses in such a way that it satisfies management goals.

Although water levels simulated for a given scenario may not accurately represent the values in the real system, the relative differences in water levels can be compared to provide useful information for planning and decision making. The paper presented simulation of three scenarios with the aquifer system response to increased withdrawals, decreased recharge and complete disappearance of Lake Tuffa. For all scenarios, all model parameters were unchanged from those specified in the steady state simulation.

The first scenario, which is increment of pumpage by 50 percent, was selected to represent possible future changes in water use in the basin, or to investigate the effects of water-management practices that could mitigate potential adverse effects of increased water withdrawals. The heads calculated for this scenario shows a maximum decline of the water level by 4.56 meter and a minimum of 0.007 meter.

The second scenario simulated by the model is a decrease in recharge by 25 percent which could be the case if mild drought conditions were imposed on the aquifer system while water extraction is maintained at current rates. The decrease in recharge caused more inflow from constant-head boundaries as well as increase stream flow but decrease drains. Simulated drought condition showed a reduction of water level up to 54.49 meter and a minimum of 0.022 meter.

The third scenario is the removal of Lake Tuffa, which is one of the constant-head cells in the model. This is in consideration of the disappearing Lake Tuffa, which could be due to some climatological or land use changes. The maximum head increment is 3.54 meter near to Lake Tuffa but for those areas which is far away from Lake Tuffa shows no decrement in water level. Simulation without Lake Tuffa results in increased recharge and groundwater outflow from drains. Table 7.2 shows the resulting water balance from the three different scenarios with the steady state model calculated water balance. Values of the difference between the simulated water level in the scenarios and those specified in the steady state simulation are shown in appendix xii.

Table 7.2 Water balances of three scenarios and the calibrated steady state model in m^3/day

	IN				OUT				IN-OUT			
Flow term	**Calculated**	**Increased Pumpage by 50%**	**Decreased recharge by 25%**	**Lake Tuffa removal**	**Calculated**	**Increased Pumpage by 50%**	**Decreased recharge by 25%**	**Lake Tuffa removal**	**Calculated**	**Increased Pumpage by 50%**	**Decreased recharge by 25%**	**Lake Tuffa removal**
Constant head	98868	99203	106989	20586	262635	261798	240549	166359	-163767	-162596	-133560	-145773
Wells					22570	33855	22570	22570	-22570	-33855	-22570	-22570
Drains					1158	1139	855	1250	-1158	-1139	-855	-1250
Recharge	699698	699698	524960	702979					699698	699698	524960	702979
River leakage	151919	153109	173487	150298	664285	655381	541396	683849	-512367	-502271	-367909	-533552
SUM	950485	952010	805436	873862	950648	952173	805370	874029	-163	-163	66	-167
Discrepancy [%]	-0.02	-0.02	0.01	-0.02								

Chapter 8

8. Conclusions and recommendations

8.1 Conclusion

This research describes a conceptual model of groundwater flow in the aquifer and documents the development and calibration of a numerical model to simulate groundwater flow. The approaches to achieve the objective of the research involve data collection, analysis and synthesis with understanding the flow system of the Meki river catchment with the very deterministic and numerical model which approximates physical law with finite difference. It is a method developed by US Geological Survey (McDonald and Harbaugh, 1988).

Fundamental input parameters used for conceptual model development, MODFLOW simulation and calibration of the regional steady state groundwater model required layer top elevation taken from ASTER DEM and layer bottom elevation is found by subtracting the aquifer thickness which varies from 80 to more than 260 meter. The dominate aquifers property of the study area is unconfined. The second input to the model is boundary conditions and for active cell 1 is assigned which includes all working area, for inactive cell 0 is assigned for area outside the catchment but for Lake constant-head cell with -1 value is assigned. The other input parametric is initial hydraulic head that is specified to each cell and the first steady-state simulation uses initial and prescribed hydraulic head by subtracting 20 m from top of layer. The other important parameter in the model is horizontal hydraulic conductivity and for first simulation a value of 0.1m/day to 20 m/day is used which is adopted from Tenalem Ayenew, 1998.

The flow packages treated in the model are drain, recharge, well, and river package. In drain package 28 springs are treated with a drain hydraulic conductance value ranging from 10–20 m^2/day. In recharge package recharge from direct precipitation is specified to each cell that varies from 5.75 x 10^{-4}m/day in western escarpment to 6.0x10^{-6}m/day in Tora-Koshe-Dugda ridge. In well package 78 abstraction wells are treated varying from -43.2 m^3/day to -864 m^3/day in a cell. Finally in river package Meki, Lebu, Akamuja, Irinzaf and Weja river is treated with conductivity, thickness of the river bed, width and head of the river with initial value ranging from 0.09m/day to 0.27m/day,0.75m to 1 m, 6m to 15 m and 1637.3 m.a.s.l to 2371.59 m.a.s.l respectively.

Model calibration was completed by varying the model parameters within acceptable ranges to produce the best fit between simulated and observed hydraulic heads in the modeled area. Water level measurements for 95 wells that were used for estimation of groundwater level of the aquifer were considered for calibration of the steady state model. The Meki river basin is calibrated with manual trial and error adjustment. The result of the calibration is evaluated using Anderson and Woessner, 1992 protocol. Summary of statistics on the difference between simulated and observed water levels indicates that the calibrated model has RMS of 8.3 meter, MAE of 7.5 meter and ME of -3.5 meter, which indicates a model bias toward underestimating head values. The scatter plot shows a correlation coefficient of 0.996 and variance of 68.9.

The simulated head distribution shows the groundwater surface flow from western escarpment to east directions finally join Lake Ziway. The groundwater has a slope of 0.1 % at Ziway plain; Tora-Koshe-Dugda ridge has 1.4%, Kuntane Inseno Kela plain 0.3% and Cinder Cone and Basaltic areas 3.7 %.The groundwater level drops from 2000 m in Butajira Crescent to 1800 m.a.s.l in Kuntane Inseno area. Water budget of the whole model domain was calculated with a percent discrepancy of -0.02 which includes inflow recharge from constant head boundary 9.88×10^4 m^3/day, recharge from precipitation 6.99×10^5 m^3/day and river leakage 1.52×10^5 m^3/day. The simulated groundwater outflow from the system includes discharge to constant head boundary 2.63×10^5 m^3/day, river leakage 6.64×10^5 m^3/day, well withdrawal 2.26×10^4 m^3/day and drains 1.16×10^3 m^3/day that makes the total outflow and inflow 9.51×10^5 m^3/day and 9.50×10^5 m^3/day respectively.

The simulated hydraulic conductivity value varies from 0.15m/day to 20.23m/day which is within the range of initially assigned value taken from Tenalem Ayenew, 1998 which is about 0.1m/day near western escarpment to 20m/day around scoria conies region. However, there is little variation between calibrated and estimated recharge rate. The mean annual recharge rate over the study area is 119.88 mm/year while that of simulated is 110.15 mm/year with 9.73 mm/year discrepancy.

A sensitivity analysis was conducted to examine the response of the numerical model calibrated to steady state conditions to changes in model parameters including horizontal hydraulic conductivity, recharge rate, and pumpage for an increment and decrement value of 20%, 40%50%, 60% and 65%.The model was found more sensitive to decrease in recharge and increase in hydraulic conductivity but insensitive to increment or decrement of pumpage compared to recharge and hydraulic conductivity.

The model is also simulated for three scenarios including increased withdrawals by 50% which result in decreased water level and groundwater outflow through river leakage and drain, decrease in recharge by 25% caused more inflow from constant-head boundaries as well as increase stream flow but decrease drains. Finally, simulation without Lake Tuffa results in increased recharge and groundwater outflow from drains.

8.2 Recommendation

The Meki river catchment groundwater flow model could be enhanced with further hydrologic and geologic research work, data collection and interpretation, and the use of additional MODFLOW options and packages. Therefore as soon as a new data is available, the model could be updated and recalibrated. After all it is my recommendation to further research work, data collection, and MODFLOW options that could enable refinements, and in turn increase the utility of the groundwater flow model.

- Within the study area, there are no observation wells (non-pumping wells) that are continuously monitored and evenly distributed in the catchment. Monitoring of water levels, at least in each hydrogeological zone, would provide insight and valuable calibration points for future refinement of the model.

- The hydraulic relation between the perennial rivers and the groundwater system is not understood completely .For example, the present simulated flows assume that river sediments are uniform in all parts of the river, but the river actually consists of a variety of main channel and backwater sediments from the western highlands. Knowledge of the sediment hydraulic properties could allow a better estimation of the distribution of groundwater discharge into or from the river, and a more refined simulation of the groundwater-surface water interaction that results from existing and that could result from future high-capacity water withdrawals. Similarly, data are also lacking for some river bottom thickness and river width. Besides, the model could be improved by additional data on the spatial distribution and flow duration of important streams in the area. Therefore , a detailed study of the relation between selected streams and the groundwater system would be needed if the groundwater flow model is required to approximate smaller-scale stream gains and losses accurately which facilitate a better estimates of river hydraulic conductance.

- Many springs in the basin are not simulated clearly because of the regional nature of the model. Thus, the relation of the springs to the groundwater flow system is poorly understood. An understanding of the spatial and temporal sources of water to springs could be gained by additional field investigation and modeling. Also further study is suggested in the wetland areas of the basin and small Lake Abaya as these areas have impact on the groundwater balance.

- The current study only considers recharge within the catchment boundaries. However, recharge can be available out of the catchment, and further study is suggested using other techniques such as isotope hydrology also installing additional surface water gauging stations is recommended to study accurately recharge to aquifers.

- To increase the effectiveness of the model, several features could be added. Climatic variations such as drought and significant recharge events can be simulated if the model is run in transient mode. The addition of MODFLOW packages such as stream routing would improve the calibration procedure and explicitly couple the groundwater to the surface water systems.

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Appendices

Appendix I: Mean monthly precipitation (1986_2004)

Gauge station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly mean
Ejersa Lele	18.83	26.65	86.74	75.49	61.29	101.68	203.82	157.72	67.96	30.89	9.93	5.52	846.52
Buie	30.10	48.27	97.72	86.22	72.41	116.74	211.47	197.68	98.16	34.65	8.56	9.82	1,011.79
Butajira	34.05	66.36	133.67	126.08	110.94	124.12	169.01	159.34	115.06	44.24	12.59	14.65	1,110.11
Koshe	21.76	50.08	76.59	97.09	92.95	95.39	174.43	168.06	108.12	49.70	5.24	4.94	944.36
Meki	7.87	45.28	60.09	67.18	50.46	66.27	166.75	134.17	77.59	29.67	3.61	6.69	715.64
Tora	25.41	43.69	79.57	120.38	92.13	85.25	132.54	123.32	119.40	50.60	8.36	6.03	886.69
Ziway	17.56	30.01	55.49	75.53	75.46	83.87	146.38	121.32	88.15	40.34	2.36	3.97	740.44
Abosa	8.38	54.29	57.25	64.29	81.37	82.39	165.71	143.69	83.53	30.84	1.98	6.91	780.64
Mitio	10.6	75.443	74.254	126.343	109.168	77.844	112.965	116.527	124.185	54.373	26.735	24.705	933.14

Appendix II: Mean maximum temperature (1986_2004)

	Mean maximum temperature (^{o}c)											
Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	DEC
Ziway	26.97	28.32	29.22	28.98	29.57	27.86	25.35	25.61	26.83	27.69	27.28	26.82
Alem Tena	27.42	28.89	29.77	30.05	30.56	29.46	25.89	26.18	27.19	27.70	27.36	26.94
Kulumsa	23.11	24.16	24.86	24.69	24.62	23.37	21.29	20.98	21.41	22.75	22.79	22.57
Butajira	26.09	26.68	26.75	26.36	26.52	25.56	24.16	24.32	25.55	25.98	26.37	26.03
Buie	25.49	26.54	26.98	26.77	27.49	26.00	23.62	23.50	24.76	25.31	25.40	25.35

Appendix III: Mean maximum temperature (1986_2004)

Station	Mean maximum temperature (^oc)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	DEC
Ziway	26.97	28.32	29.22	28.98	29.57	27.86	25.35	25.61	26.83	27.69	27.28	26.82
Alem Tena	27.42	28.89	29.77	30.05	30.56	29.46	25.89	26.18	27.19	27.70	27.36	26.94
Kulumsa	23.11	24.16	24.86	24.69	24.62	23.37	21.29	20.98	21.41	22.75	22.79	22.57
Butajira	26.09	26.68	26.75	26.36	26.52	25.56	24.16	24.32	25.55	25.98	26.37	26.03
Buie	25.49	26.54	26.98	26.77	27.49	26.00	23.62	23.50	24.76	25.31	25.40	25.35

Appendix IV: Mean monthly temperature (1986_2004)

Station	Mean monthly temperature (^oc)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ziway	19.83	21.06	22.14	22.27	22.67	21.63	20.17	20.27	20.60	20.38	19.45	19.12
Alem Tena	19.49	21.03	21.95	22.29	22.56	22.09	20.15	20.37	20.82	20.09	18.68	18.18
Kulumsa	15.67	16.73	17.69	18.18	18.07	17.14	16.09	15.85	15.86	16.57	15.82	15.22
Butajira	18.93	19.23	19.69	19.75	19.55	19.06	18.37	18.36	19.05	19.07	18.98	18.75
Buie	16.74	17.60	18.69	18.71	19.15	17.83	16.59	16.66	17.15	16.77	16.06	15.88

Appendix V: Mean minimum temperature (1986_2004)

Station	Mean minimum temperature (^oc)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	NOV	DEC
Ziway	12.70	13.79	15.06	15.56	15.77	15.39	14.98	14.94	14.37	13.07	11.62	11.42
Alem Tena	11.56	13.17	14.14	14.53	14.57	14.72	14.41	14.56	14.44	12.48	10.00	9.42
Kulumsa	8.23	9.30	10.52	11.66	11.51	10.90	10.90	10.72	10.31	10.40	8.86	7.87
Butajira	11.76	11.78	12.63	13.13	12.58	12.56	12.59	12.39	12.55	12.15	11.58	11.47
Buie	7.99	8.66	10.40	10.66	10.81	9.67	9.55	9.81	9.54	8.24	6.73	6.41

Appendix VI: Mean wind speed (in m/s) at 2 m (1986_2004)

Station	Mean wind speed (in m/s) at 2 m. a.m.											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ziway	1.39	1.40	1.31	1.27	1.47	1.95	1.83	1.56	1.11	1.23	1.46	1.51
Kulumsa	2.57	2.46	2.19	2.13	2.16	1.94	2.14	1.72	1.32	2.71	2.98	2.81
Buie	2.05	2.13	2.10	1.93	1.98	1.58	1.47	1.39	1.35	1.88	2.02	2.03

Appendix VII: Mean monthly relative humidity (%) (1986_2004)

Station	Mean monthly relative humidity (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ziway	67.73	66.31	66.37	67.67	68.36	69.44	76.14	77.31	75.14	67.16	64.76	66.50
Kulumsa	57.60	54.64	57.45	61.23	61.85	68.44	77.09	80.65	78.29	62.21	56.03	57.76
Buie	67.08	63.80	66.15	65.18	64.92	73.80	80.33	81.31	76.33	65.42	61.79	60.47

Appendix VIII: Mean monthly sunshine hours (hours/day) (1986_2004)

Station	Mean monthly sunshine hours (hours/day)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ziway	9.50	9.36	8.35	8.35	9.19	8.39	6.42	6.60	7.04	13.88	10.22	10.08
Kulumsa	8.01	7.84	7.28	6.79	7.44	7.03	5.29	5.19	5.57	7.46	8.69	8.74
Buie	8.86	8.37	8.23	8.12	8.24	6.77	5.00	5.41	6.78	8.71	9.86	8.95

Appendix IX: Mean monthly river discharge (m^3/s) at Meki town (1963_2004)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	-	-	-	-	75.17	11.14	56.42	75.57	42.95	7.24	0.94	1.18
1964	1.54	0.65	0.78	3.32	4.24	10.05	39.31	70.45	62.11	39.13	4.98	2.95
1965	1.79	1.33	1.98	1.84	0.94	0.78	11.60	37.71	32.35	26.46	3.76	0.99
1966	0.75	12.77	12.45	23.22	12.05	4.80	22.12	70.17	74.52	23.57	5.00	1.50
1967	1.04	0.57	0.88	6.39	46.53	12.01	58.08	72.18	34.07	45.15	48.88	10.34
1968	2.42	12.18	10.15	84.44	68.44	13.14	28.92	70.51	57.25	16.52	2.57	1.68
1969	0.75	9.82	19.33	10.27	12.71	7.93	23.60	33.72	22.05	3.68	0.59	0.21
1970	4.03	2.19	17.21	2.35	2.50	1.75	25.99	41.62	20.28	6.04	1.61	0.87
1971	0.74	0.46	0.55	2.15	5.09	17.66	30.95	38.88	20.90	2.94	0.97	0.40
1972	0.40	4.85	10.13	12.75	9.30	3.95	13.81	25.96	13.95	3.33	0.61	0.00
1973	0.08	0.00	0.00	0.01	0.62	1.03	17.50	24.41	25.42	12.19	0.97	0.09
1974	0.19	0.00	1.78	1.08	1.22	2.60	21.80	25.63	28.11	7.36	0.89	0.19
1975	0.11	0.24	0.01	0.60	0.44	4.47	27.19	28.11	44.89	12.07	1.96	0.49
1976	0.26	0.09	2.39	2.04	5.87	2.08	14.83	18.86	13.94	2.04	5.43	0.74
1977	2.50	3.94	0.66	3.52	9.95	6.45	31.52	28.75	18.78	17.92	24.47	2.84
1978	0.46	1.30	5.27	1.20	0.74	3.86	13.21	29.34	16.01	14.27	-	-
1979	2.97	5.86	7.91	20.89	13.19	2.98	23.36	30.57	13.96	12.85	3.53	1.16

1980	0.81	0.96	1.27	2.19	1.54	4.95	16.66	21.07	9.53	4.35	0.82	0.53
1981	0.40	0.49	13.69	20.03	-	-	-	30.14	22.23	5.11	0.62	1.14
1982	0.92	1.77	1.49	7.03	7.12	2.53	8.26	30.07	9.64	16.62	2.58	1.74
1983	0.53	2.76	4.62	11.87	17.96	13.97	9.92	33.42	21.39	7.53	1.61	0.89
1984	0.62	0.49	0.45	0.32	2.60	4.58	9.81	9.82	12.97	1.08	0.35	0.29
1985	-	-	-	-	-	-	-	-	-	-	-	-
1986	0.09	0.52	0.87	4.89	2.56	-	-	-	-	1.90	0.20	0.04
1987	0.01	0.28	7.70	18.25	17.26	14.63	7.52	6.26	7.31	-	0.41	0.04
1988	0.04	0.41	0.15	3.07	2.22	2.85	15.81	23.26	22.48	12.62	2.91	0.92
1989	0.14	2.43	3.30	9.65	2.93	3.90	15.17	15.77	17.62	9.72	1.65	0.89
1990	0.31	11.35	20.20	21.69	5.28	5.82	17.08	19.81	15.17	6.42	1.86	0.87
1991	0.50	2.60	7.17	2.84	0.89	3.76	24.49	34.90	20.14	3.48	0.87	0.66
1992	-	-	-	-	-	-	-	-	-	-	-	-
1993	4.92	0.98	0.98	13.44	17.52	12.31	25.19	57.52	19.90	11.61	4.45	0.89
1994	0.80	-	0.60	-	-	-	-	60.03	47.13	4.39	0.98	0.62
1995	-	-	-	-	-	-	-	-	-	-	-	-
1996	-	-	-	-	-	-	-	-	24.51	5.55	1.99	1.21
1997	0.32	0.27	0.99	9.95	2.89	4.36	16.60	16.60	5.40	-	6.18	0.92
1998	1.60	0.74	12.12	3.27	11.77	5.23	27.62	70.11	29.24	23.12	2.55	0.42
1999	0.09	0.07	2.84	0.12	0.51	2.84	20.64	22.42	10.16	23.55	4.73	0.28
2000	0.02	0.00	0.00	0.05	0.83	0.64	6.31	14.02	11.01	8.25	2.96	0.94
2001	0.01	0.18	3.06	1.91	4.61	10.89	-	-	-	2.55	0.94	0.52
2002	4.08	3.12	1.58	-	-	-	-	-	12.46	2.46	1.95	1.63
2003	1.00	0.58	-	-	2.20	4.92	-	-	-	3.99	0.37	0.81
2004	0.93	0.29	0.70	-	0.74	2.18	-	-	-	-	-	-

Appendix X: Groundwater level

Borehole ID	UTM-E (m)	UTM-N (m)	Observed SWL(m)	Top layer	Bottom layer
BH-1	456837	932873	2204.00	1	1
BH-2	453276	901204	1810.00	1	1
BH-3	444918	911937	1884.14	1	1
BH-7	440025	890823	1824.30	1	1
BH-9	436158	901900	1964.10	1	1
BH-10	426285	887327	2045.00	1	1
BH-11	426927	887719	2021.68	1	1
BH-13	424695	875670	1874.00	1	1
BH-16	435517	877276	1820.81	1	1
BH-17	439069	878182	1807.67	1	1
BH-18	438154	876204	1808.38	1	1
BH-21	447700	886562	1816.00	1	1

BH-22	447247	889418	1810.00	1	1
BH-24	483074	898580	1639.00	1	1
BH-26	432756	897440	2003.30	1	1
BH-28	432084	897957	2042.60	1	1
BH-30	430941	896250	2048.00	1	1
BZDP/TW4	440020	888300	1842.85	1	1
BZDP/TW1	424544	894351	2161.40	1	1
BZDP/TW2	436926	899128	1932.45	1	1
BH-35	432428	886909	1847.74	1	1
BH-36	439098	899051	1865.30	1	1
SW-4	429210	898363	2090.00	1	1
SW-6	443290	912291	1901.00	1	1
SW-7	448077	914575	1900.00	1	1
SW-8	441925	908580	1897.00	1	1
SW-9	442690	908750	1889.00	1	1
SW-10	440195	905619	1886.00	1	1
SW-11	443712	908129	1880.00	1	1
SW-12	443068	907198	1878.00	1	1
SW-14	444979	905272	1868.00	1	1
SW-15	442310	904952	1865.00	1	1
SW-16	447042	906854	1855.00	1	1
SW-17	446896	904607	1850.00	1	1
SW-18	444039	903498	1848.00	1	1
SW-19	431103	880724	1834.50	1	1
SW-20	437645	890366	1833.00	1	1
SW-21	447562	904659	1833.00	1	1
SW-22	438525	892515	1832.00	1	1
SW-23	438398	891339	1828.50	1	1
SW-24	434096	877393	1827.00	1	1
SW-26	430723	880064	1825.75	1	1
SW-27	440559	886885	1823.00	1	1
SW-28	441913	891311	1822.50	1	1
SW-29	439526	889020	1822.50	1	1
SW-31	434916	877533	1822.00	1	1
SW-32	441620	889345	1822.00	1	1
SW-33	439032	888026	1822.00	1	1
SW-34	444425	890845	1821.00	1	1
SW-35	440854	889603	1821.00	1	1
SW-37	438206	887054	1820.40	1	1
SW-39	445997	892208	1819.00	1	1
SW-40	432214	869559	1818.00	1	1
SW-41	448674	899951	1818.00	1	1
SW-43	446858	890325	1817.00	1	1
SW-44	431974	879460	1816.00	1	1
SW-45	441090	883120	1816.00	1	1
SW-46	445831	891566	1815.00	1	1
SW-47	441700	884120	1814.00	1	1
SW-48	447780	886782	1813.00	1	1
SW-49	445587	890527	1812.00	1	1

SW-50	448953	900604	1812.00	1	1
SW-51	446061	888355	1810.00	1	1
SW-52	442590	886150	1809.00	1	1
SW-53	448875	890353	1807.70	1	1
SW-58	431044	871595	1803.00	1	1
SW-61	482846	897802	1658.00	1	1
SW-62	478622	898040	1657.00	1	1
HDW-1	439098	899051	1868.00	1	1
HDW-3	446791	899390	1828.50	1	1
HDW-4	442478	907914	1887.85	1	1
HDW-5	443732	908096	1865.45	1	1
HDW-6	442293	908704	1897.30	1	1
HDW-7	426692	896415	2129.00	1	1
HDW-8	439118	899060	1867.07	1	1
HDW-9	442017	891450	1825.00	1	1
HDW-10	441186	894429	1837.40	1	1
HDW-11	426836	895151	2118.30	1	1
HDW-13	436810	889806	1829.65	1	1
HDW-14	443812	884830	1816.40	1	1
HDW-15	442910	883379	1813.00	1	1
HDW-16	441641	884059	1809.70	1	1
HDW-17	442203	887428	1819.80	1	1
HDW-18	445207	888966	1817.90	1	1
HDW-23	429313	897129	2092.00	1	1
HDW-24	422929	895181	2230.80	1	1
HDW-25	424292	894735	2171.00	1	1
HDW-26	424247	893157	2160.50	1	1
HDW-27	424926	892693	2140.00	1	1
HDW-29	440456	888867	1825.00	1	1
HDW-30	438218	887357	1819.40	1	1
HDW-31	431708	870363	1813.00	1	1
HDW-32	433720	875735	1817.00	1	1
WM-6	487438	902563	1651.00	1	1
WM-8	480034	902598	1651.00	1	1

Appendix XI: Model-calculated steady-state water levels and observed water levels for all wells.

OBSNAME	Calibrated Model		Residual	Absolute Residual	$(h_m-h_s)^2$
	Calculated value(h_s)	Observed value(h_m)			
BH-1	2204.68	2204.00	-0.68	0.68	0.458329
BH-2	1799.03	1810.00	10.97	10.97	120.297
BH-3	1892.01	1884.14	-7.87	7.87	61.9369
BH-7	1837.47	1824.30	-13.17	13.17	173.5016
BH-9	1976.08	1964.10	-11.98	11.98	143.5923
BH-10	2033.73	2045.00	11.27	11.27	127.0805
BH-11	2016.67	2021.68	5.01	5.01	25.08006
BH-13	1874.47	1874.00	-0.47	0.47	0.2209
BH-16	1816.16	1820.81	4.65	4.65	21.58532

BH-17	1817.23	1807.67	-9.56	9.56	91.41272
BH-18	1815.32	1808.38	-6.94	6.94	48.17748
BH-21	1817.60	1816.00	-1.60	1.60	2.569609
BH-22	1819.53	1810.00	-9.53	9.53	90.74468
BH-24	1651.37	1639.00	-12.37	12.37	153.0911
BH-26	2007.89	2003.30	-4.59	4.59	21.04974
BH-28	2030.43	2042.60	12.17	12.17	148.0116
BH-30	2041.31	2048.00	6.69	6.69	44.74272
BZDP/TW4	1831.44	1842.85	11.41	11.41	130.1881
BZDP/TW1	2158.77	2161.40	2.63	2.63	6.906384
BZDP/TW2	1930.67	1932.45	1.78	1.78	3.171961
BH-35	1845.63	1847.74	2.11	2.11	4.456321
BH-36	1870.37	1865.30	-5.07	5.07	25.7049
SW-4	2098.82	2090.00	-8.82	8.82	77.84533
SW-6	1904.92	1901.00	-3.92	3.92	15.38208
SW-7	1911.72	1900.00	-11.72	11.72	137.2647
SW-8	1893.30	1897.00	3.70	3.70	13.6974
SW-9	1889.33	1889.00	-0.33	0.33	0.107584
SW-10	1893.95	1886.00	-7.95	7.95	63.15481
SW-11	1879.87	1880.00	0.14	0.14	0.018225
SW-12	1880.39	1878.00	-2.39	2.39	5.688225
SW-14	1859.55	1868.00	8.45	8.45	71.4363
SW-15	1876.13	1865.00	-11.13	11.13	123.8101
SW-16	1849.72	1855.00	5.29	5.29	27.93123
SW-17	1844.38	1850.00	5.62	5.62	31.59564
SW-18	1858.35	1848.00	-10.35	10.35	107.1432
SW-19	1824.15	1834.50	10.35	10.35	107.1225
SW-20	1842.93	1833.00	-9.93	9.93	98.62476
SW-21	1840.19	1833.00	-7.19	7.19	51.65297
SW-22	1845.98	1832.00	-13.98	13.98	195.3006
SW-23	1843.33	1828.50	-14.83	14.83	220.0179
SW-24	1816.79	1827.00	10.22	10.22	104.3462
SW-26	1822.36	1825.75	3.39	3.39	11.51924
SW-27	1827.00	1823.00	-4.00	4.00	15.992
SW-28	1833.89	1822.50	-11.39	11.39	129.7777
SW-29	1834.11	1822.50	-11.61	11.61	134.7457
SW-31	1816.60	1822.00	5.40	5.40	29.16
SW-32	1830.71	1822.00	-8.71	8.71	75.91637
SW-33	1832.46	1822.00	-10.46	10.46	109.4953
SW-34	1827.43	1821.00	-6.43	6.43	41.35776
SW-35	1832.85	1821.00	-11.85	11.85	140.3514
SW-37	1831.46	1820.40	-11.06	11.06	122.4121
SW-39	1825.55	1819.00	-6.55	6.55	42.85012
SW-40	1805.35	1818.00	12.65	12.65	160.0225
SW-41	1823.64	1818.00	-5.64	5.64	31.79832
SW-43	1821.29	1817.00	-4.29	4.29	18.36123
SW-44	1820.56	1816.00	-4.56	4.56	20.8301
SW-45	1820.27	1816.00	-4.27	4.27	18.25853
SW-46	1825.15	1815.00	-10.15	10.15	103.0428

SW-47	1820.79	1814.00	-6.79	6.79	46.07694
SW-48	1817.48	1813.00	-4.48	4.48	20.08832
SW-49	1824.28	1812.00	-12.28	12.28	150.8967
SW-50	1823.16	1812.00	-11.16	11.16	124.5233
SW-51	1820.21	1810.00	-10.21	10.21	104.142
SW-52	1822.29	1809.00	-13.29	13.29	176.6507
SW-53	1817.33	1807.70	-9.63	9.63	92.69838
SW-58	1805.63	1803.00	-2.63	2.63	6.911641
SW-61	1651.84	1658.00	6.16	6.16	37.98257
SW-62	1668.27	1657.00	-11.27	11.27	127.0805
HDW-1	1870.37	1868.00	-2.37	2.37	5.6169
HDW-3	1831.18	1828.50	-2.68	2.68	7.203856
HDW-4	1887.26	1887.85	0.59	0.59	0.344569
HDW-5	1879.58	1865.45	-14.13	14.13	199.6004
HDW-6	1891.56	1897.30	5.74	5.74	32.98205
HDW-7	2138.34	2129.00	-9.34	9.34	87.31034
HDW-8	1869.93	1867.07	-2.86	2.86	8.1796
HDW-9	1833.97	1825.00	-8.97	8.97	80.4609
HDW-10	1842.07	1837.40	-4.67	4.67	21.83693
HDW-11	2127.83	2118.30	-9.53	9.53	90.72562
HDW-13	1843.86	1829.65	-14.21	14.21	201.8673
HDW-14	1820.61	1816.40	-4.21	4.21	17.74937
HDW-15	1820.21	1813.00	-7.21	7.21	52.01294
HDW-16	1820.75	1809.70	-11.05	11.05	122.1025
HDW-17	1825.18	1819.80	-5.38	5.38	28.89063
HDW-18	1822.56	1817.90	-4.66	4.66	21.7156
HDW-23	2087.57	2092.00	4.43	4.43	19.59833
HDW-24	2222.85	2230.80	7.96	7.96	63.28203
HDW-25	2164.44	2171.00	6.57	6.57	43.09923
HDW-26	2155.12	2160.50	5.38	5.38	28.91213
HDW-27	2141.70	2140.00	-1.70	1.70	2.879809
HDW-29	1831.96	1825.00	-6.96	6.96	48.38594
HDW-30	1832.17	1819.40	-12.77	12.77	163.0984
HDW-31	1804.05	1813.00	8.95	8.95	80.0846
HDW-32	1814.34	1817.00	2.66	2.66	7.059649
WM-6	1653.79	1651.00	-2.79	2.79	7.795264
WM-8	1662.07	1651.00	-11.07	11.07	122.6335

Appendix XII: Water level difference between simulated and those resulting from scenarios

No.	Observation Name	Calibrated Value	Observed Value	Difference Between Calibrated and Scenario Water Levels		
				Recharge Decrease by 25%	Pumpage Increase by 50 %	Removal of Lake Tuffa
1	BH-1	2204.68	2204.00	-54.49	-1.99	0.00
2	BH-2	1799.03	1810.00	-1.59	-0.05	0.00
3	BH-3	1892.01	1884.14	-7.28	-0.08	0.00
4	BH-7	1837.47	1824.30	-1.91	-0.23	0.04

5	BH-9	1976.08	1964.10	-18.45	-0.76	0.01
6	BH-10	2033.73	2045.00	-21.19	-3.78	0.31
7	BH-11	2016.67	2021.68	-16.82	-4.57	0.26
8	BH-13	1874.47	1874.00	-11.66	-0.06	3.43
9	BH-16	1816.16	1820.81	-0.33	-0.03	-0.40
10	BH-17	1817.23	1807.67	-0.38	-0.04	-0.20
11	BH-18	1815.32	1808.38	-0.34	-0.04	-0.32
12	BH-21	1817.60	1816.00	-0.38	-0.14	-0.01
13	BH-22	1819.53	1810.00	-0.66	-0.25	0.00
14	BH-24	1651.37	1639.00	-0.02	-0.02	0.00
15	BH-26	2007.89	2003.30	-23.89	-1.82	0.03
16	BH-28	2030.43	2042.60	-25.97	-1.94	0.03
17	BH-30	2041.31	2048.00	-26.09	-1.26	0.04
18	BZDP/TW4	1831.44	1842.85	-1.31	-0.18	0.04
19	BZDP/TW1	2158.77	2161.40	-31.91	-0.32	0.05
20	BZDP/TW2	1930.67	1932.45	-14.40	-0.64	0.02
21	BH-35	1845.63	1847.74	-3.71	-0.22	0.58
22	BH-36	1870.37	1865.30	-7.40	-0.73	0.01
23	SW-4	2098.82	2090.00	-30.37	-0.55	0.03
24	SW-6	1904.92	1901.00	-10.45	-0.17	0.00
25	SW-7	1911.72	1900.00	-7.81	-0.06	0.00
26	SW-8	1893.30	1897.00	-10.57	-0.22	0.00
27	SW-9	1889.33	1889.00	-9.93	-0.21	0.00
28	SW-10	1893.95	1886.00	-11.04	-0.26	0.00
29	SW-11	1879.87	1880.00	-8.85	-0.22	0.00
30	SW-12	1880.39	1878.00	-9.07	-0.23	0.00
31	SW-14	1859.55	1868.00	-6.32	-0.21	0.00
32	SW-15	1876.13	1865.00	-8.47	-0.25	0.00
33	SW-16	1849.72	1855.00	-6.10	-0.17	0.00
34	SW-17	1844.38	1850.00	-4.82	-0.17	0.00
35	SW-18	1858.35	1848.00	-5.32	-0.21	0.00
36	SW-19	1824.15	1834.50	-0.59	-0.02	1.95
37	SW-20	1842.93	1833.00	-2.67	-0.19	0.09
38	SW-21	1840.19	1833.00	-4.71	-0.15	0.00
39	SW-22	1845.98	1832.00	-3.02	-0.23	0.06
40	SW-23	1843.33	1828.50	-2.62	-0.20	0.06
41	SW-24	1816.79	1827.00	-0.30	-0.02	-0.49
42	SW-26	1822.36	1825.75	-0.37	-0.01	3.54
43	SW-27	1827.00	1823.00	-0.92	-0.13	0.03
44	SW-28	1833.89	1822.50	-1.88	-0.42	0.02
45	SW-29	1834.11	1822.50	-1.51	-0.21	0.05
46	SW-31	1816.60	1822.00	-0.33	-0.03	-0.39
47	SW-32	1830.71	1822.00	-1.42	-0.24	0.02
48	SW-33	1832.46	1822.00	-1.29	-0.16	0.06
49	SW-34	1827.43	1821.00	-1.35	-0.25	0.01
50	SW-35	1832.85	1821.00	-1.56	-0.25	0.03
51	SW-37	1831.46	1820.40	-1.21	-0.12	0.08
52	SW-39	1825.55	1819.00	-1.26	-0.23	0.01
53	SW-40	1805.35	1818.00	-0.40	-0.03	-0.19
54	SW-41	1823.64	1818.00	-1.81	-0.16	0.00
55	SW-43	1821.29	1817.00	-0.86	-0.27	0.00
56	SW-44	1820.56	1816.00	-0.31	-0.01	1.50
57	SW-45	1820.27	1816.00	-0.41	-0.06	-0.03

58	SW-46	1825.15	1815.00	-1.22	-0.25	0.01
59	SW-47	1820.79	1814.00	-0.43	-0.07	-0.02
60	SW-48	1817.48	1813.00	-0.37	-0.14	-0.01
61	SW-49	1824.28	1812.00	-1.09	-0.25	0.01
62	SW-50	1823.16	1812.00	-2.09	-0.16	0.00
63	SW-51	1820.21	1810.00	-0.58	-0.15	0.00
64	SW-52	1822.29	1809.00	-0.52	-0.10	-0.01
65	SW-53	1817.33	1807.70	-0.53	-0.18	0.00
66	SW-58	1805.63	1803.00	-0.28	-0.01	-0.74
67	SW-61	1651.84	1658.00	-0.03	-0.02	0.00
68	SW-62	1668.27	1657.00	-0.19	-0.05	0.00
69	HDW-1	1870.37	1868.00	-7.40	-0.73	0.01
70	HDW-3	1831.18	1828.50	-1.43	-0.07	0.00
71	HDW-4	1887.26	1887.85	-9.87	-0.22	0.00
72	HDW-5	1879.58	1865.45	-8.82	-0.22	0.00
73	HDW-6	1891.56	1897.30	-10.28	-0.22	0.00
74	HDW-7	2138.34	2129.00	-31.28	-0.37	0.03
75	HDW-8	1869.93	1867.07	-7.33	-0.70	0.01
76	HDW-9	1833.97	1825.00	-1.90	-0.40	0.02
77	HDW-10	1842.07	1837.40	-2.83	-0.33	0.02
78	HDW-11	2127.83	2118.30	-29.97	-0.38	0.04
79	HDW-13	1843.86	1829.65	-2.99	-0.19	0.13
80	HDW-14	1820.61	1816.40	-0.47	-0.12	-0.02
81	HDW-15	1820.21	1813.00	-0.44	-0.09	-0.04
82	HDW-16	1820.75	1809.70	-0.42	-0.07	-0.02
83	HDW-17	1825.18	1819.80	-0.81	-0.15	0.01
84	HDW-18	1822.56	1817.90	-0.79	-0.17	0.00
85	HDW-23	2087.57	2092.00	-28.80	-0.52	0.03
86	HDW-24	2222.85	2230.80	-38.93	-0.24	0.04
87	HDW-25	2164.44	2171.00	-32.58	-0.31	0.04
88	HDW-26	2155.12	2160.50	-31.21	-0.33	0.06
89	HDW-27	2141.70	2140.00	-29.70	-0.35	0.06
90	HDW-29	1831.96	1825.00	-1.41	-0.22	0.04
91	HDW-30	1832.17	1819.40	-1.26	-0.12	0.08
92	HDW-31	1804.05	1813.00	-0.25	-0.01	-0.17
93	HDW-32	1814.34	1817.00	-0.22	-0.02	-1.26
94	WM-6	1653.79	1651.00	-0.04	-0.17	0.00
95	WM-8	1662.07	1651.00	-0.05	-0.04	0.00