Modeling for Inter-Basin Groundwater Transfer Identification between Middle Abay River Basin and Upper Awash River Basin

By:

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A thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial fulfillment of the Degree of Master of Science in Hydraulic Engineering.

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Approval by Board of Examiners

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Dedication

To my mother Kibe Balcha whom I love very much

Abstract

Groundwater flow models are important for the identification of inter-basin groundwater transfer between adjacent basins. Numerical groundwater model, TAGSAC has been used to study the inter-basin groundwater transfer (IBGWT) between middle Abay River basin and upper Awash River basin. Three steady state groundwater flow models (for middle Abay River basin, upper Awash River basin and for the two combined basins) were first created and calibrated for the inventoried wells. The first two models were created by considering the surface water divide between the two basins as a no flow boundary. The third model avoids the surface water divide which justifies IBGWT. The calibration target for this study was the hydraulic head; hydraulic conductivity and surface recharge were used as calibration parameters. The goodness of fit indicators (GoFIs) that was obtained for the third model was better than the other two models. This indicates the evidence of IBGWT between the two basins; i.e. groundwater flows from middle Abay River basin to Upper Awash River basin and from Upper Awash River basin to middle Abay River basin. In addition, the groundwater head distribution for third model showed that the groundwater divide and surface water divide were not coincident. And groundwater is easily accessed within a shallower depth in the Upper Awash River basin compared to the middle Abay River basin.

Keywords: Inter-Basin Groundwater Transfer, Numerical Groundwater Modeling, TAGSAC, Middle Abay River Basin, Upper Awash River Basin, Ethiopia

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List of Acronyms

BCM:	Billion Cubic Meters
DEM:	Digital Elevation Model
EPM:	Equivalent Porous Medium
FDM:	Finite Difference Method
FEM:	Finite Element Method
GOFI:	Goodness of fit indicator
IBGWT:	Inter-basin groundwater transfer
m.a.s.l.:	meters above sea level
MAE:	Mean Absolute Error
ME:	Mean Error
Mm^3:	Million cubic meters
MoWE:	Ministry of Water and Energy
m/yr:	Meter per year
NMSA:	National Metrological Service Agency
REV:	Representative Elementary Volume
RMSE:	Root Mean Square Error
SqKm:	Square Kilometer
WWDSE:	Water Works Design and Supervision Enterprise
3D:	Three dimensional

1 Introduction

Groundwater is subsurface water which occurs beneath the earth's surface. It's an important earth's hydrological cycle; groundwater is mostly derived from surface waters (precipitation, lake, reservoir, river, sea, etc.) and percolates into the ground beneath the water table.

Nowadays, groundwater has become a major source of water supply throughout the world. Its use in irrigation, industries, and domestic uses continues to increase. Shortages of groundwater in areas where excessive withdrawals have occurred emphasize the need for accurate estimates of available sub surface resources and the importance of proper planning to ensure the continued availability of water supplies (Todd & Mays, 2005).

Groundwater is a valuable resource due to the storage capacity of groundwater reservoirs and the small flow rates. The increasing groundwater demand for the use of water supply is a major concern for groundwater quality. The major sources and causes of groundwater pollution can be the disposal of wastes on or into the ground from domestic uses, industries, the use of fertilizers pesticides, herbicides on agricultural fields and dissolved carbonate rocks, pyrite, salt…etc. Groundwater pollution is difficult to detect, difficult to control and difficult to be restored to its original state.

Previous studies have shown that Ethiopia has a greater potential of groundwater sources. Therefore, it's important to study the quantity and quality of this source of water by understanding the hydrological cycle, solute transport within the basins and identify if there is an inter-basin ground water transfer.

Inter-basin groundwater transfer is a process by which groundwater moves from one topographic basin to another through an intervening structural or topographic barrier. It is an important hydrological process that has not been given a special attention among researchers in the study of groundwater hydrology. For a better understanding and management of groundwater flow, the possible occurrence of this hydrological process must be studied.

The possibility of an inter-basin groundwater transfer between the Abay River basin and Awash River basin has been studied by different researchers and governmental offices. These researches used different approaches for the identification of the inter-basin groundwater transfer, but the results were conflicting to one another. The aim of this research is to identify if there is possibility of an inter-basin groundwater transfer between middle Abay River Basin and upper Awash River Basin by using groundwater models.

Groundwater models are used to predict the groundwater flow processes using mathematical equations based on certain simplifying assumptions. Mathematical models can be solved analytically or numerically. Either type of solution may involve computer applications. Ground water models are useful tools to represent or approximate the real system.

1.1 Statement of the problem

The groundwater water flow system and the aquifer system of Abay River basin and Awash River basin have been studied by different researchers for possible inter-basin groundwater transfer (IBGWT). Though these studies use different approaches for the identification the result obtained were conflicting to one another. The potential for groundwater to move from basin to basin is related to the relative altitude and geological structure of the individual basin. Where the rocks that form the boundary between these adjacent basins are sufficiently permeable, there will be flow into or out of the basin. This study will try to work with the premise that IBGWT can at least be detected using head data. Identifying the regional head and checking the geological structure of the two basins can give full information, about the possibility of IBGWT. Thus if the geologic character between the two adjacent basin are similar, then a numerical groundwater model will be developed to show the hydraulic head distribution across the two adjacent basins which ultimately show the possibility of IBGWT.

The aim of this research is to identify if there is a groundwater flow from the middle Abay River basin to upper Awash River basin or not and to identify if there is a possibility of inter-basin groundwater transfer between these two basins by using numerical groundwater models.

1.2 Objective

The main objective of this research is to identify the possibility of inter basin groundwater transfer between middle Abay and upper Awash River basins along their watershed divide through using numerical groundwater modeling.

Specific Objectives

- To draw the groundwater table variation map and flow direction map across the two adjacent basins,
- To redraw/ revise the hydrogeology map,

- To draw the groundwater accessibility map,

1.3 Structure of the thesis

The thesis was organized in six (6) chapters. Chapter 1 provides the general introduction, statement of the problem and objective of the study. Chapter 2 deals with the literature review on inter-basin groundwater flow and groundwater modeling. Chapter 3 states the material and methods used for this thesis, it includes location of the study area, data collection, processing and analysis, groundwater modeling and model conceptualization. Chapter4 is the result and discussion part of the work; it mainly presents the results found from the model calibration. The conclusion and recommendation of this work is stated in Chapter 5. And the lists of the References used for this thesis are presented in Chapter 6.

2 Literature Review

2.1 Inter-basin Flow

Inter basin flow is when a groundwater flows from one basin to another through an intervening structure or topographic barrier (Nelson & L.Mayo, 2004). It is not uniform between all basins but it is common and is a function of the hydraulic gradient between basins and hydraulic conductivity of the intervening rocks. The study of Inter-basin groundwater flow transfer has been recognized by scientific studies over the past century (Belcher, et al. 2009).

Water budget imbalances, Chemical evidence and groundwater head data could be used to study the evidences of inter basin flow between basins. Water budget principle can quantify if there is a gain or loss in watershed that is studied. But usually requires careful measurements of stream discharge and evapotranspiration unless the inter-basin transfer is large enough to be obvious from even approximate estimates of the other fluxes. However, water budgets are too inaccurate to recognize inter-basin transfers. This is because water budget evidences can only show the net gain or loss among basins, not the actual rates of inter-basin seepage and/or out seepage (Genereux, et al., 2001).

Chemical evidence of inter-basin transfer need not take the form of a budget discrepancy; it is often based on observation of stream water that is chemically distinct from water draining hill slopes locally within a watershed. This type of chemical evidence can quantify only a positive inter-basin transfer (gain of groundwater) into the watershed. Water budget and chemical evidences are used to study the possibility of inter-basin groundwater transfer at small watersheds. In a regional scale of identification of inter-basin groundwater transfer groundwater head data is used (Genereux, et al., 2001).

Groundwater head data can show the direction of inter basin transfer through the difference in hydraulic gradient. For an accurate estimation of groundwater flow transfer rate information on hydraulic conductivity and cross-sectional area of the aquifer that is studied should be known (Genereux, et al., 2001).

2.2 Previous Studies

Several researches have been done both by governmental offices and individuals on the study of groundwater flow in Abay and Awash River Basin. But most of the researches did not include the concept of IBGWT in their studies. Even though the concept of IBGWT has been used in the study of groundwater hydrology in different parts of the world, such a practice is rarely exercised in Ethiopia. But the theory of IBGWT is very important in the study and proper management of groundwater flow. Recent studies by ((Yitbarek, 2009), (WWDSE, 2010), (Azagegn, 2015)and few M.Sc. studies in Addis Ababa University) have applied the theory of IBGWT in their researches.

According to (Yitbarek, 2009) there exists an inter basin groundwater transfer between Abay River Basin and Awash River Basin. By studying the Litho-hydrostratigraphic relationships correlated from the drilling data of the exploratory boreholes coupled with the respective geological structure scenarios and a simple regional steady state numerical groundwater flow model was also used to study the existence of an IBGWT. The numerical groundwater flow model that was developed in this study was for the watershed of the Upper Awash basin by taking into consideration the groundwater inflow from the adjacent Blue Nile basin. A course grid resolution was used (i.e. 2km x 2km) to model the groundwater flow system.

From converging evidences from hydraulic properties of rocks together with hydro chemical data and environmental isotopes supported with simple steady state regional numerical groundwater model (with course grid resolution 2km x 2km) for the Upper Awash groundwater basin (Azagegn, 2015) estimated a total volumetric annual inflow of nearly 590Mm^3 into the system of the Upper Awash groundwater basin. Out of the total recharge to the Upper Awash groundwater basin, nearly 26% (153Mm^3) is an inflow from the Blue Nile basin through horizontal exchange. The study concluded that evidences from geological studies in agreement with the groundwater level measurements showed that there is an IBGWT from the middle Blue Nile basin to Upper Awash basin. The geological and geophysical investigation of this study showed that a significant portion of the Muger sub basin and small part of Jema sub basin contribute to recharge the volcanic aquifer of the upper Awash Basin. This displays that the surface water and groundwater divides do not coincide at regional scale.

Reports by (WWDSE, 2008) and (WWDSE, 2010) identified that the regional groundwater flow direction extending from Abay Plateau to Awash River Basin. As reported in (WWDSE, 2008) the recharge at Abay plateau flows to Upper Awash Basin through two main directions (through Becho plain and along Legedadi areas) and nearly 100% of Abay plateau is the recharge area of the lower basalt aquifer in Upper Awash basin. The mean annual recharge of the Ada'a-Becho aquifers system is estimated to be 687 Mm^3 with 70% of recharge contributed by Upper Abay River Basin.

From field hydrogeological observation i.e., high yield artesian wells close to water divide of the Awash and Abay basins showed the evidence of inter-basin groundwater transfer from the plateau zone (part of Abay plateau) to the part of the Awash River basin).(Azagegne, 2008)

To investigate the groundwater dynamics between Holeta River catchment from the Upper Awash River basin and tributary streams of Muger River catchment from the Abay River basin; (Hailu, 2016) used an integrated hydro geochemistry and isotope hydrology approach together with water level measurements. And found that the groundwater divide doesn't coincide with the surface water divide, which is fallen in the Tributary streams of Muger River catchment and there is an inter-basin groundwater transfer between the tributary streams of Muger River catchment and Holeta River catchment.

(Mohammed & Ayalew, 2016) Developed a numerical groundwater model (TAGSAC code); to identify the inter-basin groundwater transfer (IBGWT) between upper Awash River basin and upper rift valley lakes basin of Ethiopia. The results of the research showed that there was an IBGWT between the basins and the surface water divide is not coincident with the groundwater divide.

This research will try to identify if there is possibility of an inter-basin groundwater transfer between middle Abay River Basin and Upper Awash River Basin by using a numerical groundwater model with finer grid resolution (. i.e. 1km x 1km) than the previous studies that was done on these two basins.

The previously done numerical groundwater flow models by (Azagegn, 2015) and (Yitbarek, 2009)only modeled the Upper Awash basin to study the IBGWT between the two adjacent river basins. This was because of the data required for the modeling is more available in the Upper Awash basin than the Middle Blue Nile basin. But this study will try to model the groundwater flow systems of both the Upper Awash and middle Abay River Basins to identify the possibility of IBGWT between the two basins.

2.3 Groundwater

2.3.1 Groundwater Potential

The importance of groundwater resources can hardly be overstated, so it follows that a conceptual understanding of its movement is of great interest and consequence (Mayo, 2014).

The first comprehensive study of the national water resources master plan study attempted to quantify both the surface and sub-surface water resources potential of the country (WAPCOS, 1990) based on basin divisions. As reported by (Belete & Semu, 2013) the total estimated rechargeable groundwater for Awash River Basin varies between 1.3 to 2.2 BCM, while the usable amount is estimated to be in the order of 0.14 BCM. According to (Alemayehu, 2006) the total groundwater reserve of Ethiopia is about 185 BCM; with a mean groundwater recharge of 200 mm for the entire country.

Ethiopia has an abundant surface and groundwater resources potential of which groundwater has a larger share (Energy, 2014).The groundwater potential of Ethiopia is a very controversial topic. It varies from an estimate of around 2.5 BCM to 185 BCM. This extremely high discrepancy in the potential is a challenge to the experts and decision makers (Alemayehu, 2006).

2.3.2 Groundwater Recharge

Precipitation is the principal source for replenishment of moisture in the soil water system to recharge groundwater. The amount of moisture that will eventually reach the water table is going to recharge aquifer system in sub-surface.

Groundwater recharge is important in the proper management of a groundwater basin (USDA, 1967). As the rainfall over Ethiopia is extremely variable in both space and time the recharge to the groundwater system is also variable. The groundwater recharge rate of Ethiopia varies from zero to 250mm/year (Kebede, 2013). Rainfall on the highlands is the main source of recharge for the groundwater system. The major recharge occurs in the northeastern and southwestern plateau where annual rainfall is high. Rapid infiltration occurs in areas which is covered by fractured volcanic and to a lesser extent in sedimentary rocks (Alemayehu, 2006).

According to Ethiopian Geological Survey as reported in (Energy, 2014) the preliminary estimated amount of yearly groundwater recharge of the country is about 28,000 Mm^3. But recent studies indicated that the potential is much greater than this amount. Most of the developed groundwater resource is mainly used for domestic and industrial water supply.

According to Zebene Lakewe (MoWE) studies indicated in (Gebreselassie, 2014) showed that the country's groundwater is recharged by 36 BCM per year from precipitation and other surface water. Based on the rough assessment of the groundwater potential of the country by (Abebayehu, et al., 2015) reported that the annual groundwater recharge may reach up to 60 BCM; the Abay river basin contributing 19.851 BCM and Awash river basin 3.3996 BCM.

The groundwater recharge variation in middle Blue Nile basin and Upper Awash basin as it has been estimated by (Azagegn, 2015) using Base flow separation method; the groundwater recharge distribution varies from 46mm to 200mm.

The upper Awash River basin above the Becho plain area is assumed to contribute recharge into the upper aquifer of the region. The confined part of the upper Awash plains aquifer (lower basalt aquifer) is mainly recharged over the extended plateau of the Abay basin, above the gorges of Abay River and its tributary rivers. In these areas the lower aquifer is part of the regional groundwater and its main recharge area is situated in Abay Plateau but its discharge area is in Awash River basin (Azagegne, 2008).

The rock units exposed along the Yerer Tulu Wolel Volcanic Lineament zone and the Main Ethiopian Rift margin promote more recharge than the rock units exposed away from these zones. This regional weak zone appears to be the major recharge area. (Azagegne, 2008)

According to the water balance model the mean annual rechargeable water into the upper Awash plains groundwater aquifer systems is more than 965 Mm^3, with 67% contributed by Upper Abay basin (Abay Plateau). This result is dependent on the underlying geologic conditions and structural set up which allows deep percolation. Part of the Abay plateau adjacent to the upper Awash is the area that contributes recharge to the groundwater system of the upper Awash besides the recharge with in the Upper Awash (WWDSE, 2008).

The groundwater recharge of the Upper Awash basin was estimated by using the water table fluctuation method. The average aerial annual recharge of the area is estimated to be 85mm, which accounts about 8.7% of the mean annual aerial precipitation of the study area (Yitbarek, 2009).

2.3.3 Fractured Media

A fractured medium consists of solid rock with some primary porosity cut by a system of cracks, micro cracks, joints, fracture zones, and shear zones that create secondary porosity and form a network for flow when interconnected. In order to develop a conceptual model for a fractured system, it either requires a gross simplification or a detailed description of the aquifer properties controlling flow. Information on the primary permeability of the rock matrix and the secondary permeability created by the network of fractures are required to describe a flow through a fractured medium (Anderson & Woessner, 1992).

According to (Cook, 2003) the most common approaches to model fractured systems are: (i) the equivalent porous medium approach, (ii) the discrete fracture approach, and (iii) the dual porosity approach.

2.3.3.1 Equivalent porous medium approach

Fractured material is represented as an equivalent porous medium (EPM) by replacing the primary and secondary porosity and hydraulic conductivity distributions with a continuous porous medium having so called equivalent or effective hydraulic properties. The parameters are selected so that the flow pattern in the EPM is similar to the flow pattern in the fractured system. An EPM approach assumes that the fractured material can be treated as a continuum and that a representative elementary volume (REV) of material characterized by effective hydraulic parameters can be defined. Simulation of flow in fractured systems using this conceptual model requires definition of effective values for hydraulic conductivity, specific storage, and porosity (Anderson & Woessner, 1992).

2.3.3.2 Discrete fracture approach

A discrete fracture model assumes that water moves only through the fracture network. The discrete fracture approach is typically applied to fractured media with low primary permeability such as crystalline rocks. Flow through a single fracture may be idealized as occurring between two parallel plates with a uniform separation equal to the fracture aperture (Anderson & Woessner, 1992).

2.3.3.3 Dual porosity approach

If the rock matrix containing the fracture network has significant primary permeability, a dual porosity model may be used. In this conceptual model, flow through the fractures is accompanied by exchange of water and solute to and from the surrounding porous rock matrix. Obviously, the fracture network as well as the properties of the porous blocks must be described prior to modeling. Aquifer tests may indicate whether a system behaves as a dual porosity system and results can be interpreted to estimate hydraulic conductivities (Anderson & Woessner, 1992).

2.3.4 Groundwater Modeling

A model is the simplified version of a real system and phenomena that take place within it, which represent or approximately simulates the real system (Bear & Cheng, 2010). Groundwater models are used to analyze flow situations in order to understand the flow system (Anderson & Woessner, 1992). Groundwater models can be classified as steady state or transient; confined, unconfined or combination of confined and unconfined; one dimensional, two dimensional, quasi three dimensional, or three dimensional (Todd & Mays, 2005).

But groundwater models are not alternative method for field investigation but it's a valuable tool used to predict the groundwater flow processes using mathematical equations based on certain simplifying assumptions. This mathematical model can be solved either by using analytical method or numerical method. Either type of solution may involve computer applications.

Recently, computer aided numerical solutions are the major tool for solving problems in practice. The rapid progress in computer technologies has made computers faster, with larger storage capacities, with parallel computing capabilities, etc. It is possible to solve larger and more complex problems faster, cheaper, and more accurately (Bear & Cheng, 2010).

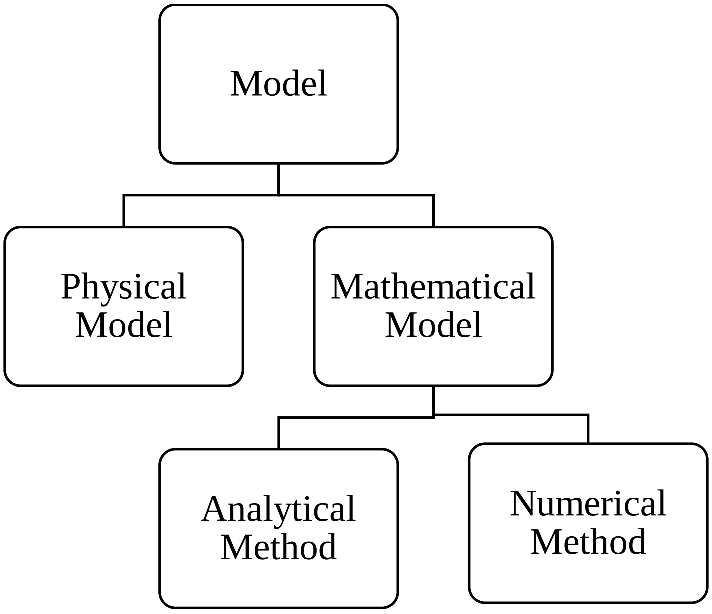

Figure 2.1 Model

2.3.4.1 Analytical Method and Numerical Method

Analytical methods simplify groundwater flow equation by assuming homogenous porous medium and one or two-dimensional flow. Except for the applications to well hydraulics, analytical methods are not widely used in practical applications. Numerical methods are much more versatile and, with the widespread availability of computers, are now easier to use than some of the more complex analytical solutions.If groundwater problems become more complex (variation in hydrogeologic paramters), the system becomes too complicated for solutions obtainedwith analytical methods. In these cases, numerical methods have to be used. The introduction of computer programs increased the application of numerical methods and these methodsreplaced almost completely the use of analytical methods in groundwater modelling(Fetter, 2001).The numerical methods that are widely used in groundwater modeling are finite difference method and finite element method.

2.3.4.1.1 Finite Difference Method

Finite difference method widely used and accepted by many governing bodies. It is the most popular groundwater simulator available. The finite difference method is easy to understand, calculate and fewer input data are needed, the solutions are mass-conservative. However, the finite difference method is not without weakness. Although grids are easy to create, they cannot be efficiently refined around areas of interest, such as wells and model boundaries. And also Finite difference grids are rectangular and the area modeled is not. Special problems like movement of water table and seepage face are difficult to handle (Anderson & Woessner, 1992).

The grid is created using structured, rectilinear (rectangular) grids. Compute a value of the head at the node which also is the average head for the cell that surrounds the node. The node represents the finite difference cell.

2.3.4.1.2 Finite Element Method

The finite element method can also be used to solve the groundwater flow equation. Finite elements are easier to adjust the size of individual's elements as well as the location of the boundaries with the finite element method. This method is better to handle internal boundaries such as fault zones and water tables.

Finite element methods are able to approximate irregular shaped than the finite difference method. It uses triangular mesh to represent the model domain. The use of triangles allows for a more efficient refinement around wells and boundaries. The triangular mesh can more easily adapt to variable stratigraphy such as sloping or pinch outs, and allows for versatile discretization of non-rectangular model domains. And it allows more flexibility in designing a grid.

Finite element model defines the variation of head within an element by means of interpolation, heads are calculated at the nodes for convenience, but head is defined everywhere by means of basis functions.

Finite element models simulate point sinks and sources more accurately than finite difference model and no correction is needed (Anderson & Woessner, 1992). A disadvantage of finite element models is that the input of data required to define the grid is more laborious than for finite difference models. Finite element models require that each node and element be numbered. The finite element method treats each element separately and then assembles equations for all elements into a global matrix equation.

2.3.5 Groundwater Flow Equation

Before deriving a governing equation for groundwater flow, a conceptual model of the system is needed. There are two conceptual views of gorund water system, the aquifer view point and the flow system view point. Aquifer view point is based on the concept of confined and unconfined aquifers. It is suited for analysis of flow to pumping wells and is the basis for Theim, Theis and Jacob.Ground water flow is strictly horizontal through the aquifers and srticly vertical through confining beds.Flow system view point allows for both vertical and horizontal flow in two dimensional and three dimensional profile(Anderson & Woessner, 1992).

The governing equation is derived by mathematically combining a water balance equationwith Darcy's law.The derivation is done by referring to a cube ofporous material that is large enough to be representative of the properties of the porous medium and yet is small enough so that the change of head within the volume is relatively small. This cube of porous material is known as a representative elementary volume or REV. Its volume is equal to $\Delta x \Delta y \Delta z$ Figure **2.2**(Anderson & Woessner, 1992).

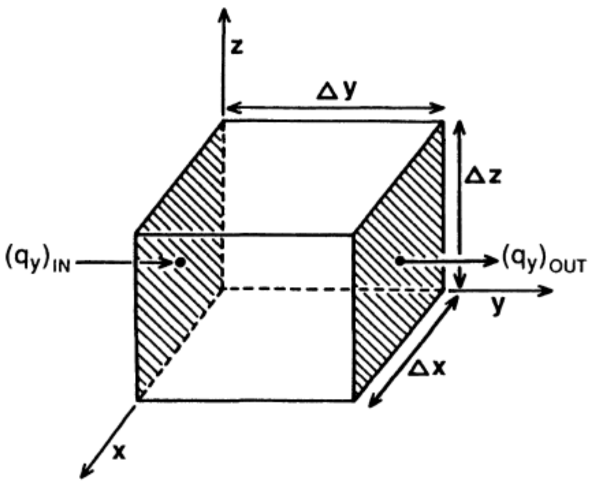

Figure 2.2 Representative elementary volume (REV)

The flow of water through the REV is expressed in terms of the discharge rate (q),whose magnitude in the three coordinates will be q_x, q_y, and q_z

$$\boldsymbol{q} = \boldsymbol{q_x i_x} + \boldsymbol{q_y i_y} + \boldsymbol{q_z i_z} \quad (2.1)$$

Where i_x, i_y, i_z are unit vectors along the x, y, and z axes.

The water balance equation (or conservation of mass) states that:

$$outflow - inflow = change\ in\ storage \quad (2.2)$$

Consider flow along the y axis of the REV in Figure 2.2. Influx to the REV occurs through the face $\Delta x \Delta z$ and is equal to $(q_y)_{IN}$. Flux out is equal to $(q_y)_{OUT}$. The volumetric outflow rate minus volumetric inflow rate along the y axis is:

$$[(q_y)_{OUT} - (q_y)_{IN}]\Delta x \Delta z \quad (2.3)$$

It can also be written as:

$$\frac{(q_y)_{OUT} - (q_y)_{IN}}{\Delta y}(\Delta x \Delta y \Delta z) \quad (2.4)$$

And dropping the IN and OUT subscripts, the change in flow rate through the REV along the y axis is:

$$\frac{\partial q_y}{\partial y}(\Delta x \Delta y \Delta z) \quad (2.5)$$

Similar expressions can be written for the change in flow rate along the x and z axes. The total change in flow rate is equal to the change in storage and is expressed as:

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)\Delta x \Delta y \Delta z = Rate\ of change\ in\ storage \quad (2.6)$$

The existence of sink (e.g. a pumping well) or source of water (e.g. injection well or some other source of recharge) within the REV is undeniable. The volumetric inflow rate of such sources is represented by $R^*\Delta x\Delta y\Delta z$. Here the $R^*$is defined to be intrinsically positive when it is a source of water; therefore, it is added to the right-hand side of Eq. (2.6).

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - R^*\right)\Delta x \Delta y \Delta z = Rate\ of\ change\ in\ storage \quad (2.7)$$

The change in storage is represented by specific storage (S_s). It is defined as the volume of water released from storage per unit change in head (h) per unit volume of aquifer (Anderson & Woessner, 1992)i.e.

$$s_s = -\frac{\Delta v}{\Delta h \Delta_x \Delta_y \Delta_z} \quad (2.8)$$

The sign convention is that the ΔV is intrinsically positive when the Δh is negative, or in other words, water is released from the REV when head decreases. The rate of change in storage in REV will be:

$$\frac{\Delta v}{\Delta t} = -s_s \frac{\Delta h}{\Delta t}\Delta_x \Delta_y \Delta_z \quad (2.9)$$

Combining Eq. (2.7) and Eq. (2.9):

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -s_s \frac{\partial h}{\partial t} + R^* \quad (2.10)$$

Darcy law is used to set the relationship between q and h. Darcy law in three dimensions is written as (Anderson and Woessner, 1992):

$$q_x = -K_x \frac{\partial h}{\partial x} q_y = -K_y \frac{\partial h}{\partial y} q_z = -K_z \frac{\partial h}{\partial z} \tag{2.11}$$

Substituting these expressions in Eq. (2.10) the desired groundwater flow equation is formulated:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = s_s \frac{\partial h}{\partial t} + R^* \tag{2.12}$$

Where K_x, K_y, and K_z are components of the hydraulic conductivity.

In the above derivation it is assumed that K_x, K_y, and K_z are collinear to the x, y and z axes. If the geology is such that it is not possible to align the principal direction of the hydraulic conductivity tensor with the rectilinear coordinate system, a modified form of equation that utilizes the hydraulic conductivity tensor is required.

$$K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \tag{2.13}$$

By using a global coordinate system for the entire problem domain and a local coordinate system for each REV in the grid, the off-diagonal terms in the hydraulic conductivity tensor could have zero value (Anderson & Woessner, 1992).

$$K = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \tag{2.14}$$

2.3.6 Boundary Conditions

Computer simulations of groundwater flow systems numerically evaluate the mathematical equation governing the flow of fluids through porous media. This equation is a second order partial differential equation with head as the dependent variable. In order to determine a unique solution of such a mathematical problem, it is necessary to specify boundary conditions around the flow domain for head (the dependent variable) or its derivatives. These mathematical problems are referred to as boundary value problems. Thus, a requirement for the solution of the mathematical equation that describes groundwater flow is that boundary conditions must be prescribed over the boundary of the domain. Boundary conditions also represent any flows that are hydrologic boundaries can be mathematically represented in more than one way. The determination of an appropriate mathematical representation of a boundary condition is dependent upon the objectives of the study.

In the groundwater flow modeling process, boundary conditions have an important influence on the areal extent of the model. Ideally in developing a conceptual model, the extent of the model is expanded outward from or head constraints within the flow domain. The selection of the boundary condition is critical to the development of an accurate model. Not only is the location of the boundaries important, but also their numerical or mathematical representation in the model. This is because many physical features the area of concern both vertically and horizontally so that the physical extent coincides with physical features of the groundwater system that can be represented as boundaries. The effect of these boundaries on heads and flows must then be conceptualized, and the best or most appropriate mathematical representation of this effect is selected for use in the model.

The hydrogeologic boundaries are represented by the following three types of mathematical conditions (Uhegbu & Igboekwe, 2011).

1. Constant Head Boundary: This is a type of specified head boundary condition, in which the head is known and the source of water has a constant water level at the model boundary. This condition is used in modeling an aquifer that is in good interaction with a lake, river or another external aquifer. These are usually where the groundwater is in direct contact with surface water such as a lake or a river and drains interact freely with the aquifer. It is mathematically known as Dirichlet boundary.
2. Constant Flux Boundary: This is a type of specified flux boundary condition also known as the second type of boundary condition, and mathematically known as Neumann's condition or recharge boundaries. Entering or leaving the aquifer is prescribed/constant flux. This boundary condition is used in simulating rainfall or distributed discharge for instance evaporation and also used in specifying known recharge to the aquifer owing to induced recharge
3. No flow Boundary (across which minimal flow occurs): This is a very special type of the prescribed flux boundary and is referred to as no-flux, zero flux, impermeable, reflective or barrier boundary. No flow boundaries are impermeable boundaries that allow zero flux. They are physical or hydrological barriers which inhibit the inflow or

outflow of water in the model domain. No flow boundaries are specified either when defining the boundary of the model grid or by setting grid blocks as inactive (i.e. hydraulic conductivity = 0).

3 Materials and Methods

3.1 Description of the Study Area

3.1.1 Location of the Study Area

The study area is located in the central part of Ethiopia. The capital city, Addis Ababa, is located at the Southeastern part of the study area. The location of study area is 8^0 39' 2.13''N to 10^0 11' 2.55'' N Latitude and 37^0 37' 9.47'' E to 39^0 2' 56.92'' E Longitude. The total area is 17,352 SqKm out of which 82.7% (14,350 SqKm) and 17.3 % (3,002SqKm) is in part of the middle Abay River Basin and Upper Awash River Basin respectively.

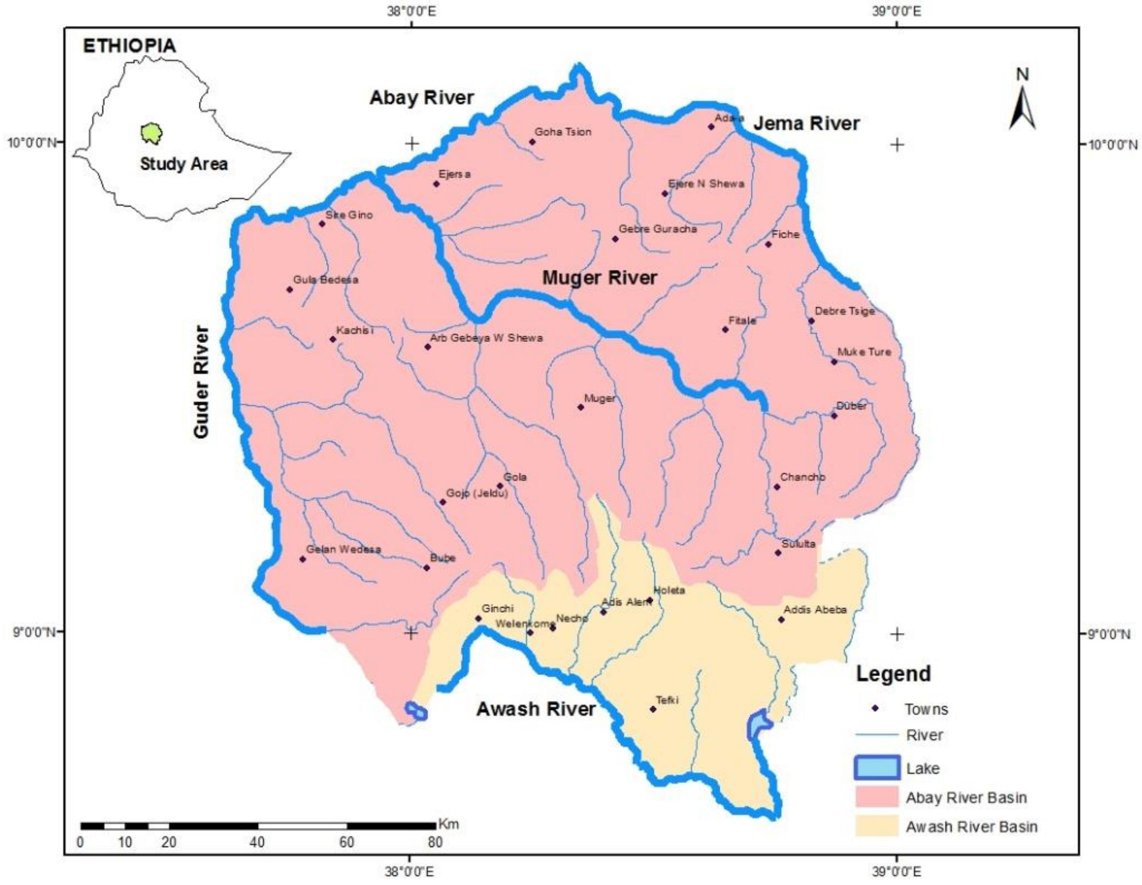

Figure 3.1 Study Area Location

Boundary conditions are uncertain, particularly if the model boundaries do not correspond to the natural physical boundaries of the aquifer. The study area is selected in a way that it can be bounded by natural physical boundaries in order to avoid boundary condition uncertainties.

The study area is bounded by Guder River in the northeastern direction, Jema River in the northwestern direction; middle Abay River in the northern direction and upper Awash River in southeastern direction. Guder, Muger and Jema Rivers flow nearly parallel and join the Abay River.

3.1.2 Hydrometeorology

The study area is characterized by varying climatic zones ranging from hot and humid lowlands to cold and dry highlands. The average annual precipitation of the area varies between 800mm and 1200mm. The mean monthly temperature varies between 2.1^{o}c and 31.1^{o}c (Azagegn, 2015).

3.2 Data processing

The first step in groundwater modeling is planning, which is to determine the purpose of the model. The purpose will determine which method shall be used to model the groundwater flow system. Models are designed to answer specific questions; the main objective of this study is to answer if there is an inter basin groundwater transfer between the two adjacent river basins. The second step is to develop a conceptual model of the system using all available field data. This includes information about the boundary conditions, the hydrogeological and the hydrological conditions of the system. The conceptual model can be represented either by two dimensions or three-dimensional diagrams. This step also includes data collection, review and analysis; the collected data should be checked to ensure that there are no possible errors. The next step is model design; in this step the previously developed conceptual model is put into the form that is suitable for modeling. In other words, it is to convert the conceptual model into a mathematical model. The last step is calibration and sensitivity analysis. In this step the accuracy of the model is checked by how well the model output is able to match with the observed data. This is done by altering the key parameters of the model, and this is usually done by a trial and error method till the observed data matches with the model output. The above modeling protocol is adopted from (Merz, 2013) and (Anderson & Woessner, 1992).

3.3 Modeling for inter-basin groundwater transfer

The methodology adapted to model the inter basin groundwater flow is from (Mohammed & Ayalew, 2016). To analyze the possibility of inter basin groundwater transfer between the two adjacent basins; first three groundwater models are created. The first two models are created by assuming that there is no groundwater flow interaction between the two adjacent basins. The two basins are separated by considering the surface divide as Neumann boundary condition with zero flux. The third model is created by assuming there is no barrier between the two basins and there is a free movement of groundwater flow between the basins. This is by considering that the watershed divide doesn't exist for this model.

The three groundwater models are:

Model 1: The groundwater flow model for the middle Abay River basin, it is bounded by middle Abay River, Guder River, Jema River and watershed divide with the Awash River Basin.

Model 2: The groundwater flow model for the Upper Awash River basin, it is bounded by the Upper Awash River and the watershed divide with the middle Abay River Basin.

Model 3: The groundwater flow model for the combination of Upper Awash and middle Abay River basins, it is bounded by Upper Awash River, middle Abay River, Guder River and Jema River

Each of the above three models will be calibrated for all the observed data (well & spring inventory data). This is done by changing the hydrogeological parameters and surface recharge. In order to identify the possibility of inter basin groundwater transfer; the results of the first two models will be compared with the third model which is the combination of the two basins. This is done by taking only the results of the wells/springs that are found in the upper Awash River Basin from the combined model (Model 3) and comparing it with the results of the independent upper Awash model (Model 2). The same procedure is also performed for the other model. The measure of goodness of fit indicator (GoFI) is used for comparison.

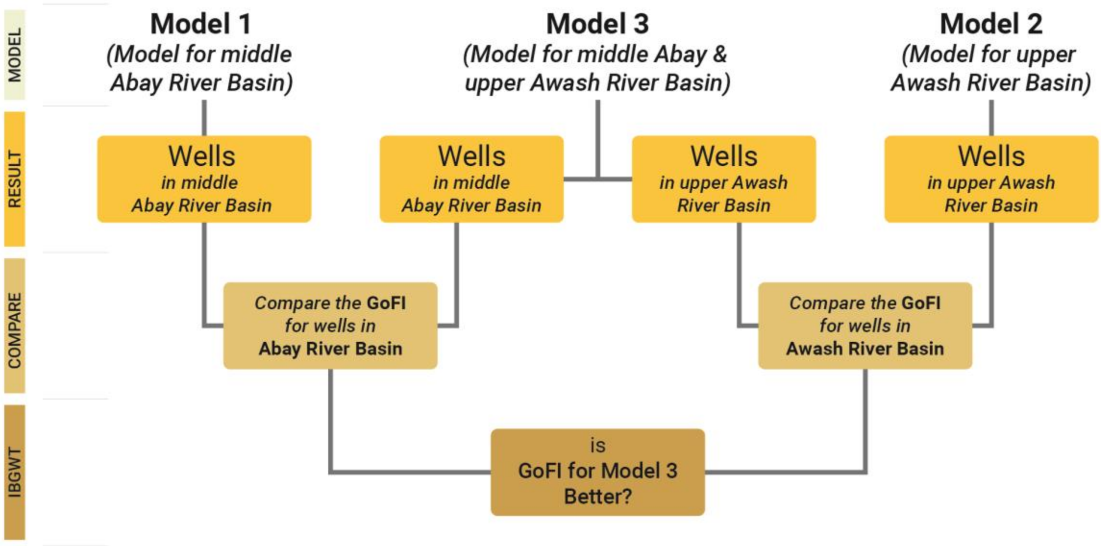

Figure 3.2 Flow chart for inter basin groundwater transfer identification

3.4 Data Collection and Analysis

Prior to the groundwater modeling work, existing data were first collected from different offices such as: metrological data, well inventory data, geological map and topographic data. The collected data has been checked for data quality and consistency. Computer software like ArcGIS 10.2.2, Matlab7.11.0 (R2010b) programming language and Surfer 10 were used for data quality checking and analysis.

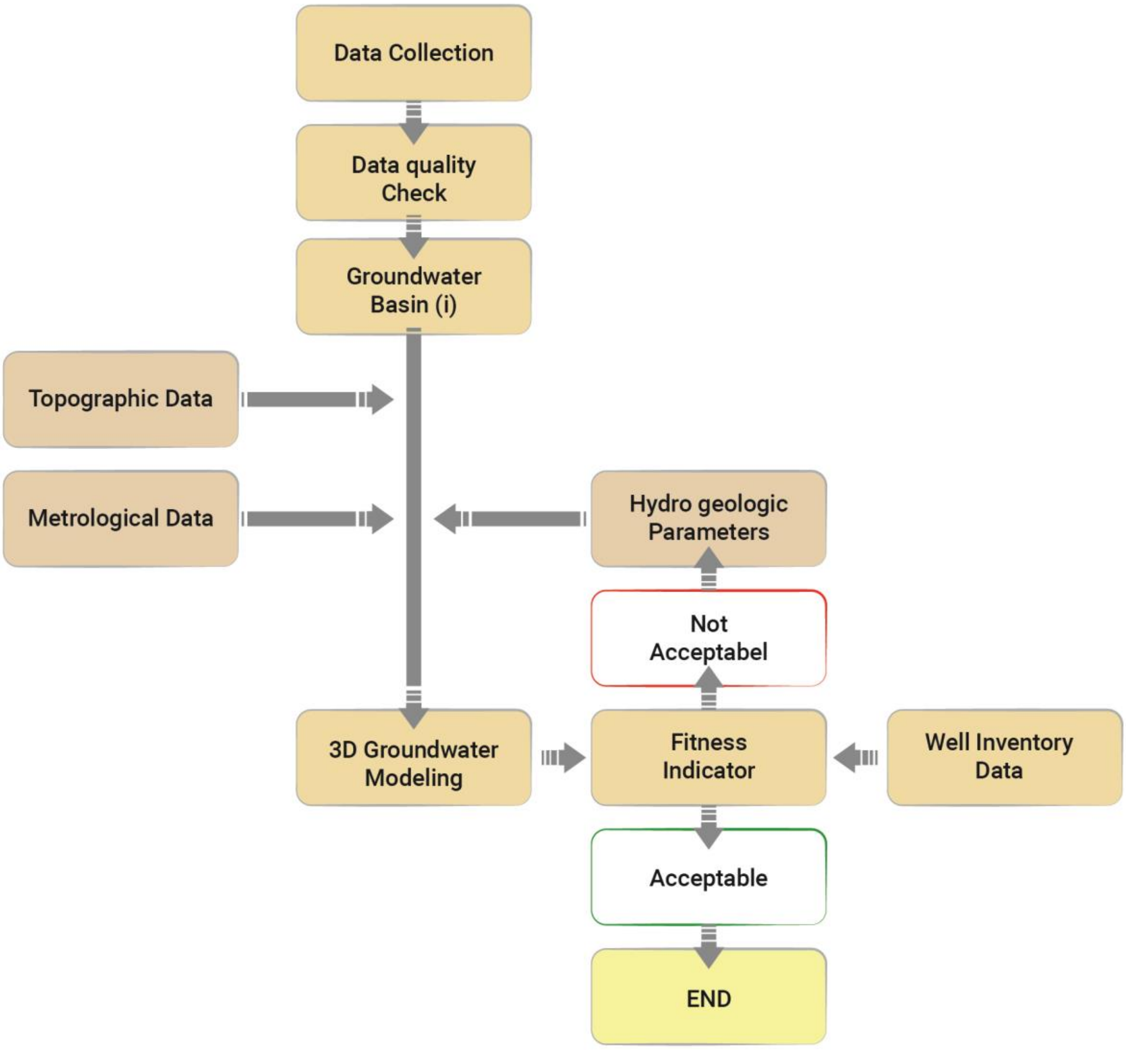

Figure 3.3 Groundwater modeling flow chart

3.4.1 Meteorology

The meteorological data was collected from the National Meteorological Service Agency (NMSA). Within and nearby the study area 83 metrological stations were found. Among the 83 metrological stations only the 62 metrological stations were found to contribute to the study area. The data collected has been checked for data consistency and accuracy. Thiessen polygon method was adopted to assign the annual rainfall distribution over the study area.

The Thiessen Polygon method is the most common approach used in hydrometeorology to determine the areal rainfall average over an area. This is done by sub dividing the watershed into polygonal subareas using rainfall stations as their centers. These polygonal subareas are the areas of influence of each rainfall stations. The subareas are used as weights in estimating the watershed average depth(Warren & Gary, 1996).

The weighted average is calculated by:

$$P_{av} = \frac{\sum P_i A_i}{\sum A_i}$$

Where: P_{av} is the weighted average areal rainfall, P_i is the mean annual rainfalls recorded at each rain gauge stations, A_i area of each polygonal subarea

The weighted average annual rainfall over the study area estimated by Thiessen Polygon method is 1293.85mm. The Thiessen Polygon analysis is shown in Table below.

Table 3.1 Mean annual rainfall with polygon area

Station Name	UTM E	UTM N	Annual Rainfall (mm)	Polygon Area (km^2)
Addis Ababa	475200	1001000	1206.73	588.50
Addis Alem	426600	998000	1175.86	527.60
Akaki Beseka	478300	980100	1060.65	109.00
Alem Gena	463100	989700	1200.70	178.10
Ali Doro	447000	1078000	1388.09	241.90
Ambo	378500	990900	1269.42	529.60
Bete Nigus	371200	1101000	1172.99	199.50
Bicho	389600	1016000	1409.73	343.10
Biriti	417300	1079000	1212.65	405.80
Boneya	462900	972900	1128.90	188.40
Chancho	472800	1022000	1271.56	496.60
Chobi	374700	1031000	1351.00	656.80
Chulute	360000	1064000	1444.23	382.80
Daleti	453800	1063000	1365.78	468.00
Debra	465200	1047000	1195.47	168.60
Debre Genet	423800	973800	1076.99	12.64
Debre Libanos	484900	1074000	1306.79	117.80
Debre Tsige	475700	1067000	1383.94	218.60
Dedu	335600	1070000	1491.60	17.88

Degem	460400	1087000	1434.10	302.00
Dilela	381500	954200	1204.34	9.97
Duber	493300	1045000	1395.47	316.10
Ejere	448200	1104000	1282.98	537.80
Fetire	482900	1107000	1269.79	67.20
Fiche	471500	1085000	1333.10	331.60
Filikilik	422400	1117000	982.88	177.10
Gebre Guracha	435300	1081000	1320.93	263.00
Ginchi	403400	995500	1245.41	629.30
Goja	400200	1024000	1436.51	157.90
Gola	409900	1024000	1361.91	243.90
Gorfo	482000	1037000	1320.68	292.50
Gosha Tsiyon	420500	1106000	1046.85	169.90
Guder	360900	978300	1317.04	50.31
Gundo Meskel	466400	1135000	1265.18	19.59
Holota	447000	1006000	1328.97	617.40
Hose	402200	1097000	1121.39	544.00
Inchini	433900	1026000	1398.02	415.40
Jemo Lefo	392800	1071000	1408.09	785.30
Kachisi	372000	1056000	1394.09	636.30
Kembolcha	410100	1052000	1289.24	297.00
Kere Dobi	360800	1081000	1296.36	364.80
Ketket	412500	1039000	1286.36	184.20
Kewo	334800	1097000	1353.65	6.79
Kombolcha_EW	336100	1047000	1621.30	70.98
Lemen	463600	947300	1103.86	24.00
Lemi	491400	1086000	1378.00	1.54
Mekoda	431000	1051000	1335.76	342.90
Melka Kunture	457300	961700	1012.23	219.10
Minare	421300	1064000	1242.62	328.00
Muger	454900	1049000	1033.79	184.10
Muke Turi	484600	1057000	1412.14	317.90

Mulo	460800	1032000	1278.16	254.00
Rob Geba	355800	1016000	1488.02	270.80
Sebeta	454400	986300	1096.73	157.70
Sendafa	497700	1010000	1188.62	96.82
Shikute	393100	1042000	1343.37	347.40
Shino	420900	1026000	1387.72	235.00
Tefki	443100	977400	1133.43	338.10
Tulu Miki	428700	1098000	1150.10	311.80
Weberi	504900	1065000	1375.36	74.04
Welenkombi	444800	1038000	1372.10	371.20
Wenoda	507900	1033000	1429.22	107.00

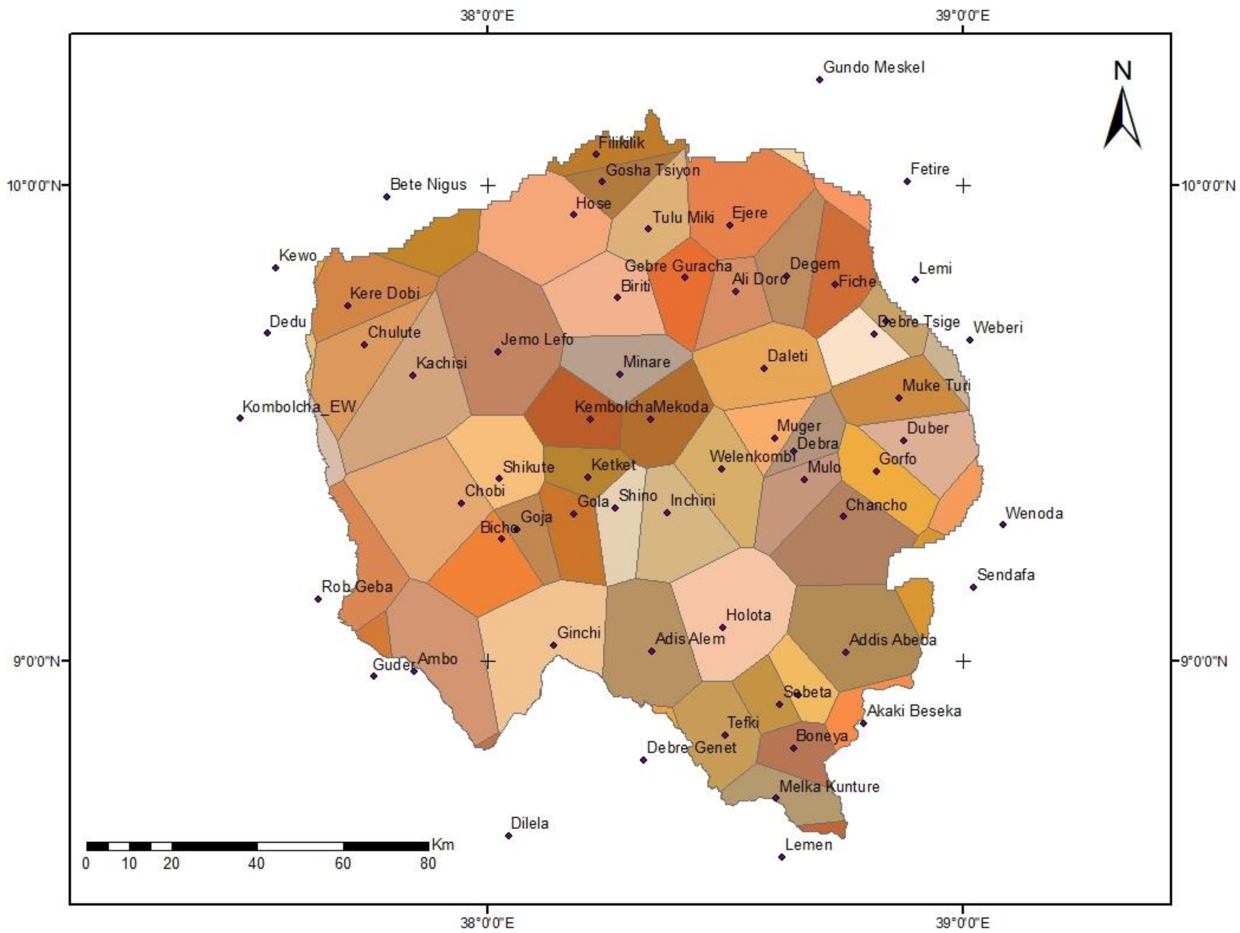

Figure 3.4 Thiessen Polygon Constructed for the Study Area

3.4.2 Topography

The topographic data was obtained from the Digital Elevation Model (DEM) of resolution 30m x 30m. The Digital Elevation Model (DEM) data has been modified by using ArcGIS 10.2.2 software. This is done by using the ArcHydro tool (i.e. DEM reconditioning), imposing the stream/ river data which is the linear feature on to the raw DEM. And another ArcHydro tool (i.e. Fill Sinks) were used to modify the elevation by filling the sinks until it drains to the neighboring cell. The top elevations were defined from the modified DEM and the missed elevations were filled by using interpolation. The elevation of the study area varies between 943 m.a.s.l and 3514 m.a.s.l.

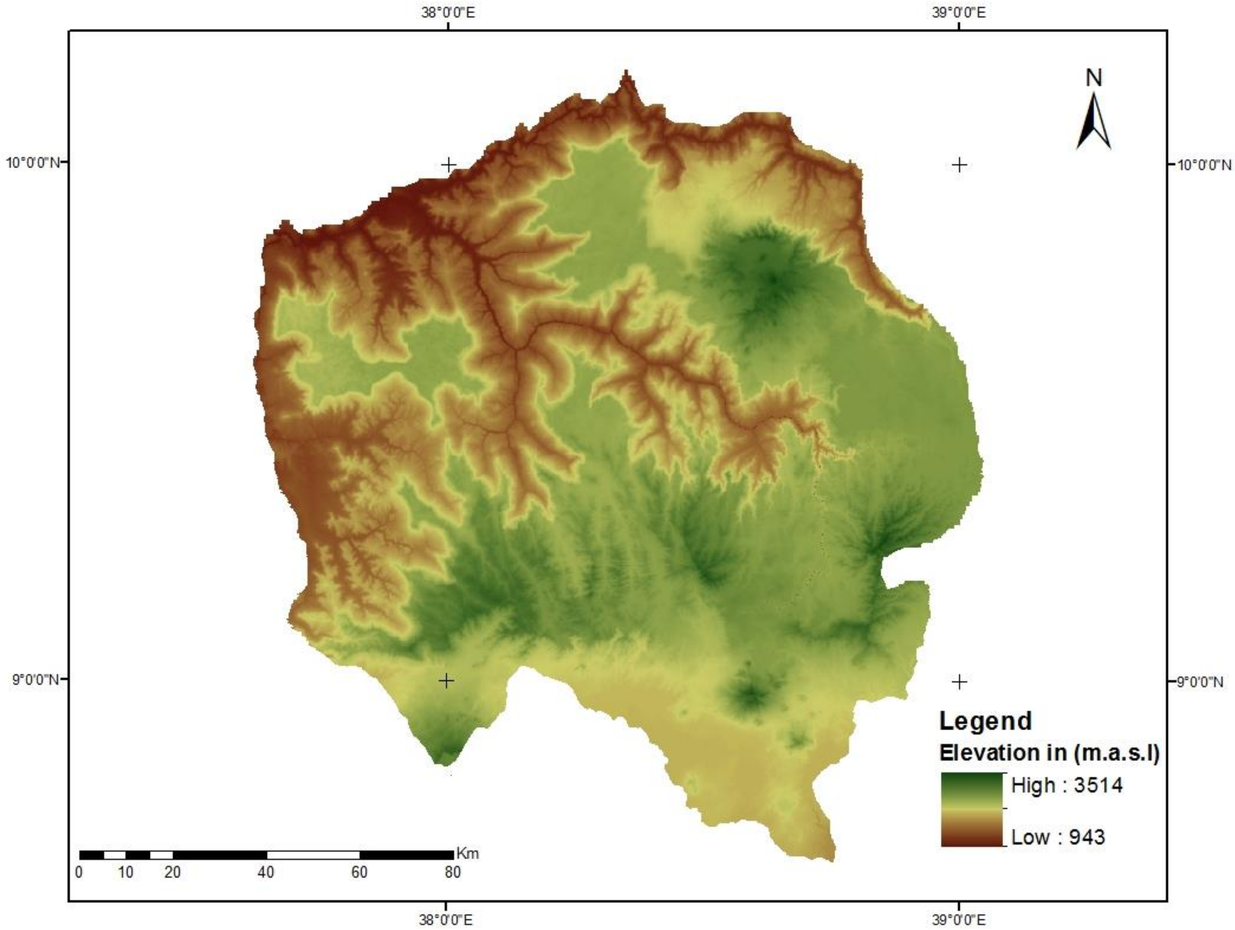

Figure 3.5 Topographic Map of the study area

3.4.3 Well and spring inventory

A total of 1234 wells/springs were inventoried within the study area boundary from Water Works Design and Supervision Enterprise (WWDSE) and previously done researches. After data quality and consistency check only 762 wells/spring holding information on location (UTM coordinate), static water level and well depth were used for this study. From these 653 wells are located in the upper Awash River Basin and 139 wells in the middle Abay River basin. The selection was based on the location and distribution in the area. The maximum well depth and minimum well depth that are available within the study area are 880m and 7m respectively.

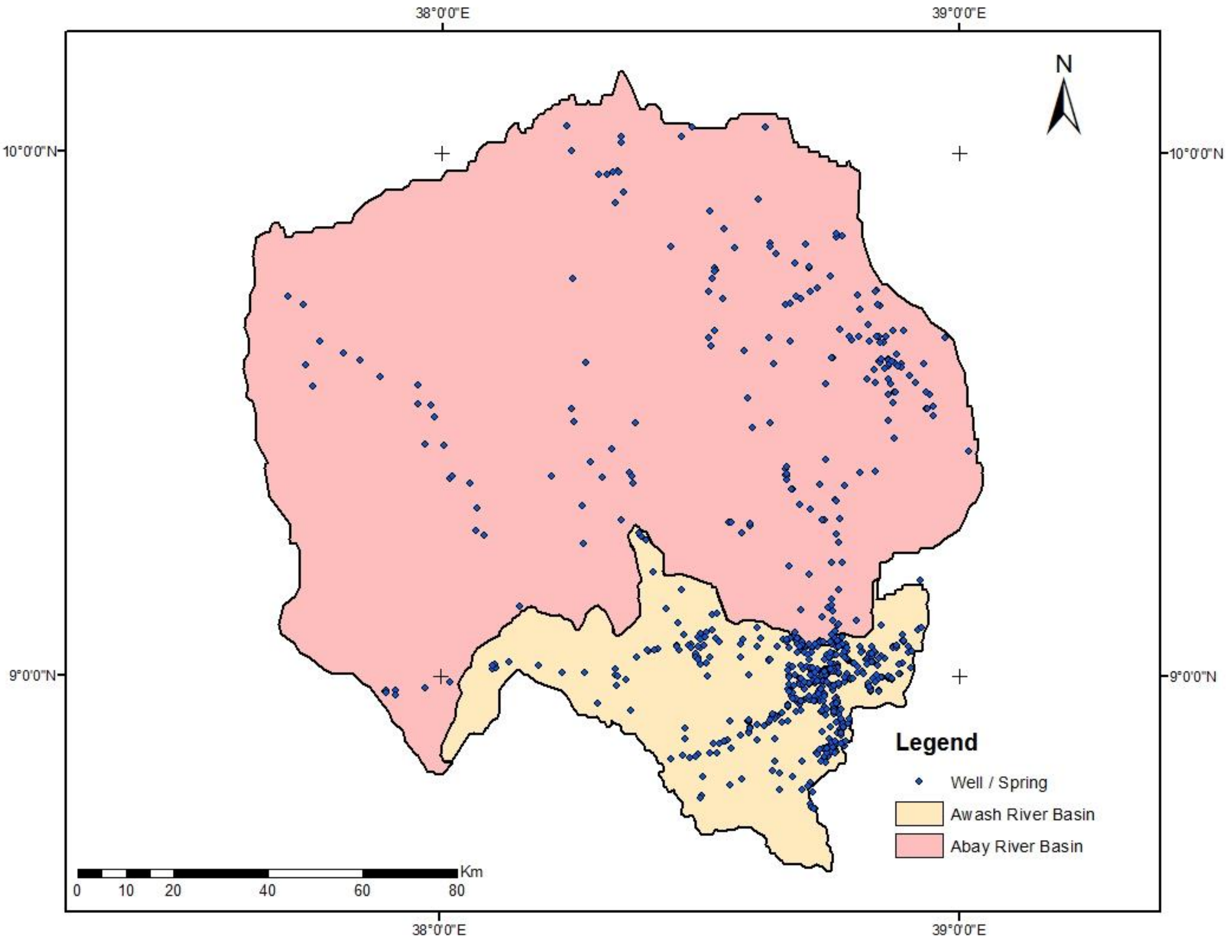

Figure 3.6 well/ spring location of the Study Area

3.4.4 Geology

The geologic map of Ethiopia has been done by different offices (Water Works Design and Supervision Enterprise, Ethiopian Mapping Agency and others). For this study the geological map of Ethiopia that was developed by WWDSE was used mainly to know the geologic characteristics of the aquifer within model domain. ArcGIS 10.2.2 was used to delineate the geological map within the study area boundary. The study area is composed of 14 geologic characteristics, as shown in Table **3.2**.

Table 3.2 Geologic Characteristics

ID	Geology
ARl	Alghe Group: Biotite and hornblende gneisses, granulite and migmatite with minor metasedimentary gneisses
Ja	Adigrat formation: Triassic - Middle Jurassic Sandstone
Jb	Abay formation: Middle - Jurassic limestone shale and gypsum
Jt	Antalo formation: Limestone
Ka	Amba Aradom formation: Sandstone, conglomerate and shale
Nc	Chilalo formation (lower part): Trachyte, trachy basalt, peralkaline rhyolite with subordinte alkaline basalt
Nn	Nazret series- Ignimbrites, unwelded tuffs ash flows, rhyolite flows, domes and trachyte
NQtb	Bishoftu formation: Alkaline basalt and tarchyte
Ntb	Tarmaber megezez formation: Transitional and alkaline basalt
P2a	Ashangi formation: Deeply weathered alkaline and transitional basalt flows with rare interactions of tuff, often tilted (includes Akobo basalts of SW Ethiopia)
P3a	Aiba Basalts: food basalts woth rare basic tuff
PNa	Tarmaber Gussa formation: Alkaline to transitional basalts often forming shield volcanoes with minor trachyte and phonolite flows
Q	aluvial and lacustrine deposits: sand, silt, clay, diatomite, limestone and beach sand
Qb1	Plateau Basalt - Alkaline basalt and trachyte

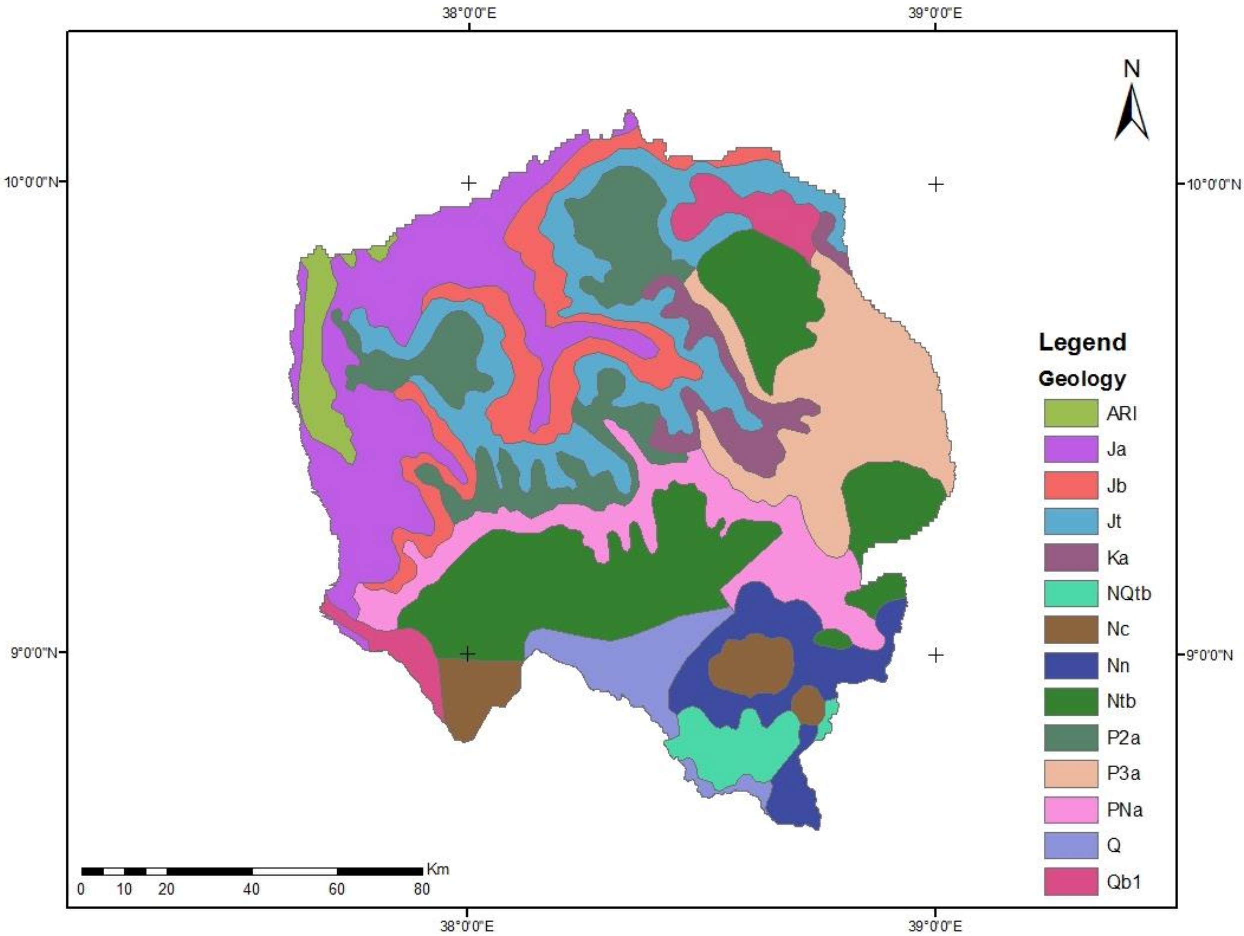

Figure 3.7 Geological Map of the Study Area (source: WWDSE)

3.5 Conceptual Model

A conceptual model is a descriptive representation of the groundwater flow system to be studied and it incorporates an interpretation of the geological & hydrological conditions. The main purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily. The data that are needed to formulate the conceptual model are the hydrogeologic data and topographic data of the groundwater system and these data are also used to check model calibration. The more the conceptual model approximates to the field situations the more accurate is the numerical model (Anderson & Woessner, 1992).

A complete reconstruction of field system is not feasible and partly because there is rarely sufficient data to completely describe the system in full details therefore simplifying assumptions are required. The conceptual model should therefore be kept as simple as possible while retaining sufficient capacity to adequately represent the physical elements of the hydrological behavior (Vijai & Rohit, 2011).

Preparation of conceptual model involves identification of the study area, deciding appropriate boundary conditions (Vijai & Rohit, 2011). A conceptual model was developed for the study area prior to the numerical modeling. In this study, ArcGIS 10.2.2 has been extensively used for the development of the conceptual groundwater flow model for the study area.

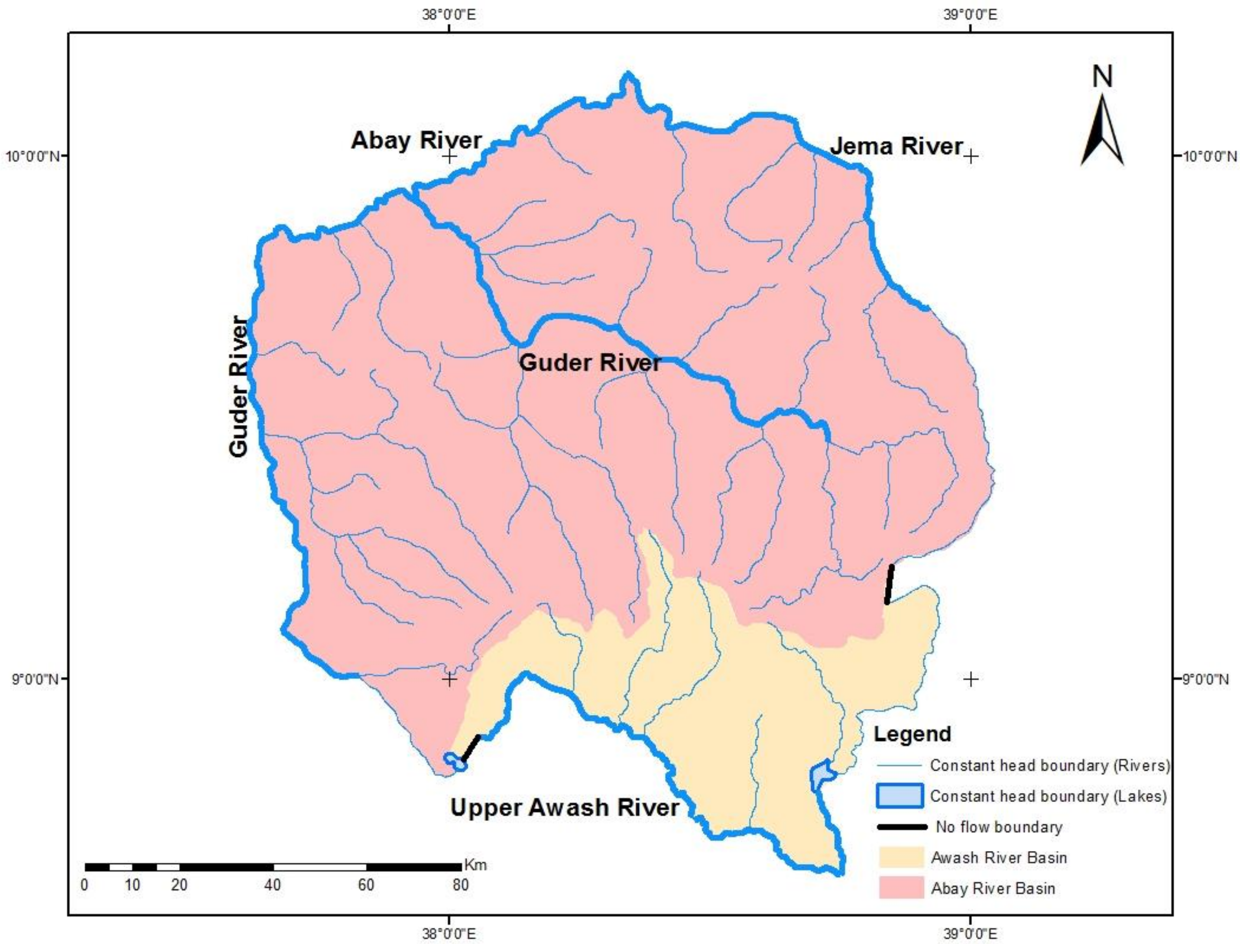

Figure 3.8 Boundary Conditions

3.6 Groundwater Modeling

3.6.1 Model selection

Due to the heterogeneities in geologic materials and structural complexities in the Upper Awash River Basin and middle Blue Nile Basin (Azagegn, 2015); a three-dimensional finite element method was chosen to simulate the three-dimensional groundwater flow system.

Finite element method has several advantages over the other numerical methods; irregular or curved aquifer boundaries, anisotropic and heterogeneous aquifer properties, and sloping soil and rock layers can be easily incorporated into the numerical model, the accuracy of solutions to groundwater flow is very good and simulate point sinks and sources more accurately than finite difference method.

The finite element method is implemented with different shapes of elements; triangular elements and trapezoidal elements. Triangular elements are defined by three nodes one at each corner. These nodes serve the purpose of locating unknown heads; that is they are the points within the model domain at which the heads are computed (Herbert & Mary, 1982). For this study triangular elements are selected to develop the finite element mesh.

For this study TAGSAC code was adopted to solve the groundwater flow equation. TAGSAC is a numerical groundwater model which solves a three-dimensional groundwater flow equation in heterogeneous porous media using the Finite element method. Compared to the other groundwater flow models the data requirements of TAGSAC code is minimal.

3.6.2 Discretization

In a numerical groundwater modeling, the continuous groundwater basin will be replaced by a discretized groundwater basin consisting of an array of nodes. The nodal grid forms the framework of the numerical model. The determination of the space between the nodes will depend on the overall size of the modeled area and the computation capacity of the computer. A small number of nodes are preferred in order to minimize data handling, computer storage and computation capacity. But as the number of the nodes increase the level of accuracy will also increase (Anderson & Woessner, 1992).

Due to the size of the model domain and computational capacity of the computer, the element size of the triangular mesh is limited to 1,000m. The elements represent the hydrogeological parameters and nodes represent head. Each node is represented by (X, Y, Z) Cartesian coordinates and is assigned with nodal number. Each of the triangular prisms is described by six nodes.

3.6.3 Boundary Conditions

Boundary conditions are a key component of the conceptualization of a groundwater system. A mathematical model consists of a governing equation, boundary conditions, and initial conditions. Boundary conditions are important to determine the mathematical solutions. The critical step in a numerical model designing is the correct assignment of boundary conditions. Whenever possible it's preferred to use natural hydrogeologic boundaries as the boundaries of the model (Bear & Cheng, 2010). In steady state simulations, the boundaries largely determine the flow pattern (Anderson & Woessner, 1992).

For the assignment of boundary conditions of the study area, natural boundaries were used as much as possible. A constant head boundary was set to all the rivers only to the location where its perennial (Upper Awash River, middle Abay River, Guder River, Jema River and Muger River) and the two lakes for all the three models (Model 1, Model 2 and Model 3) as shown in Figure 3.8. The watershed divide between the two River basins is treated as a no flow boundary for Model 1 and Model 2.

The top surface elevation was extracted from 30m x 30m resolution DEM and by subtracting the top layer elevation from the aquifer thickness the bottom layer elevation was obtained. An aquifer thickness of 1500m is considered for the 3D groundwater flow models. And it is assumed that there is an impervious layer at 1500mbelow the surface and this serves as the bottom boundary of the model. Since it's in a very large depth its effect will be minimal. Therefore, the boundary of the bottom surface is taken as no flow boundary conditions. The top surface is assigned to recharge boundary.

3.6.4 Recharge Boundary

Water seeping into an aquifer is known as recharge; Recharge occurs where permeable soil or rock allows water to readily seep into the groundwater. The main source of water entering the model is from the top surface boundary condition, which is the rainfall recharge. Rainfall recharge to the groundwater depends on surface lithology. And it ranges from 1% to 50%; 40% to 50% rainfall recharges groundwater in high porous medium; 5 to 25 % in moderately porous medium (Raymond, 1992). Since recharge is one of the parameters that is used in the model calibration, during the calibration process the recharge fraction was set to vary from 5% to 25%.

4 Result and Discussions

4.1 Model Discretization

The number of nodes generated for the three groundwater models were 33838, 7434 and 41650 for Model 1, Model 2 and Model 3 respectively. The number of elements generated for the three groundwater models were 33276, 7026 and 40791 for Model 1, Model 2 and Model 3 respectively. Figure 4.1, Figure 4.2 and Figure 4.3 shows mesh generated for Model 2, Model 1 and Model respectively.

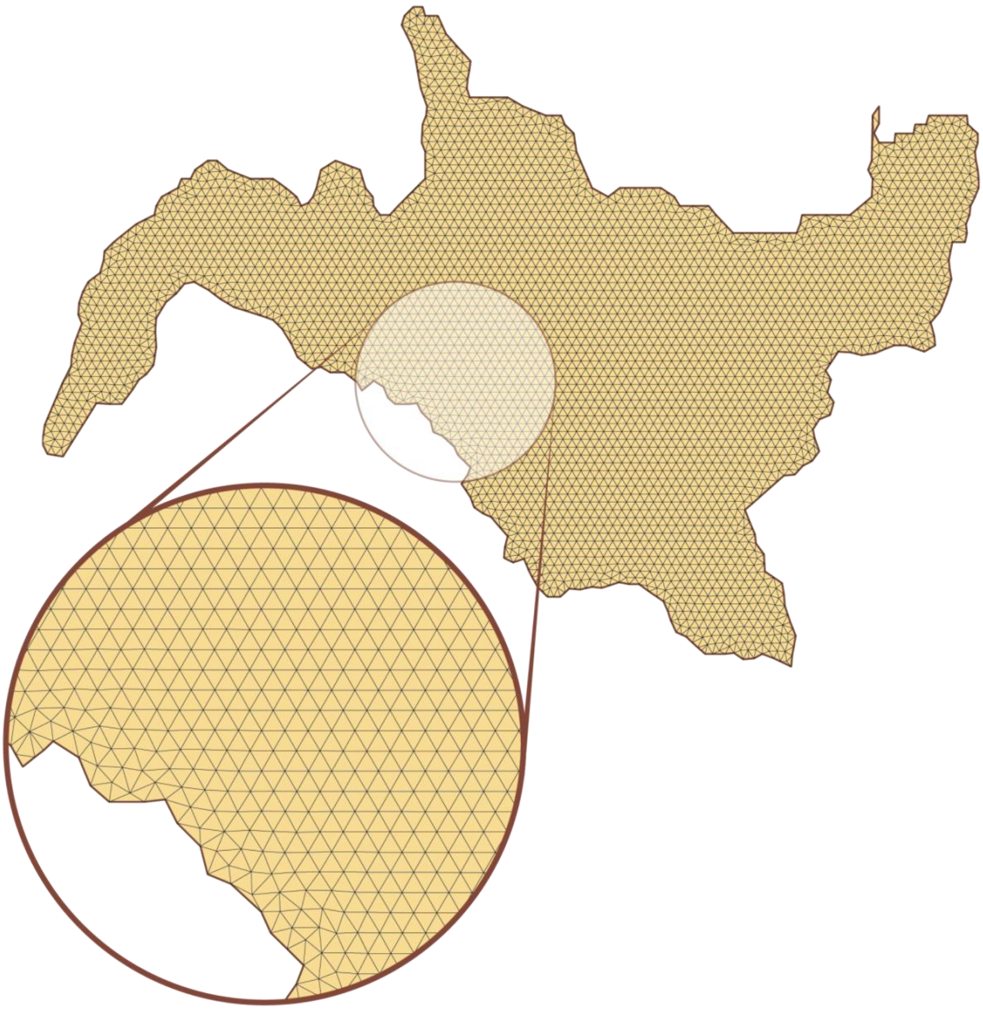

Figure 4.1 Mesh generated for Model 2

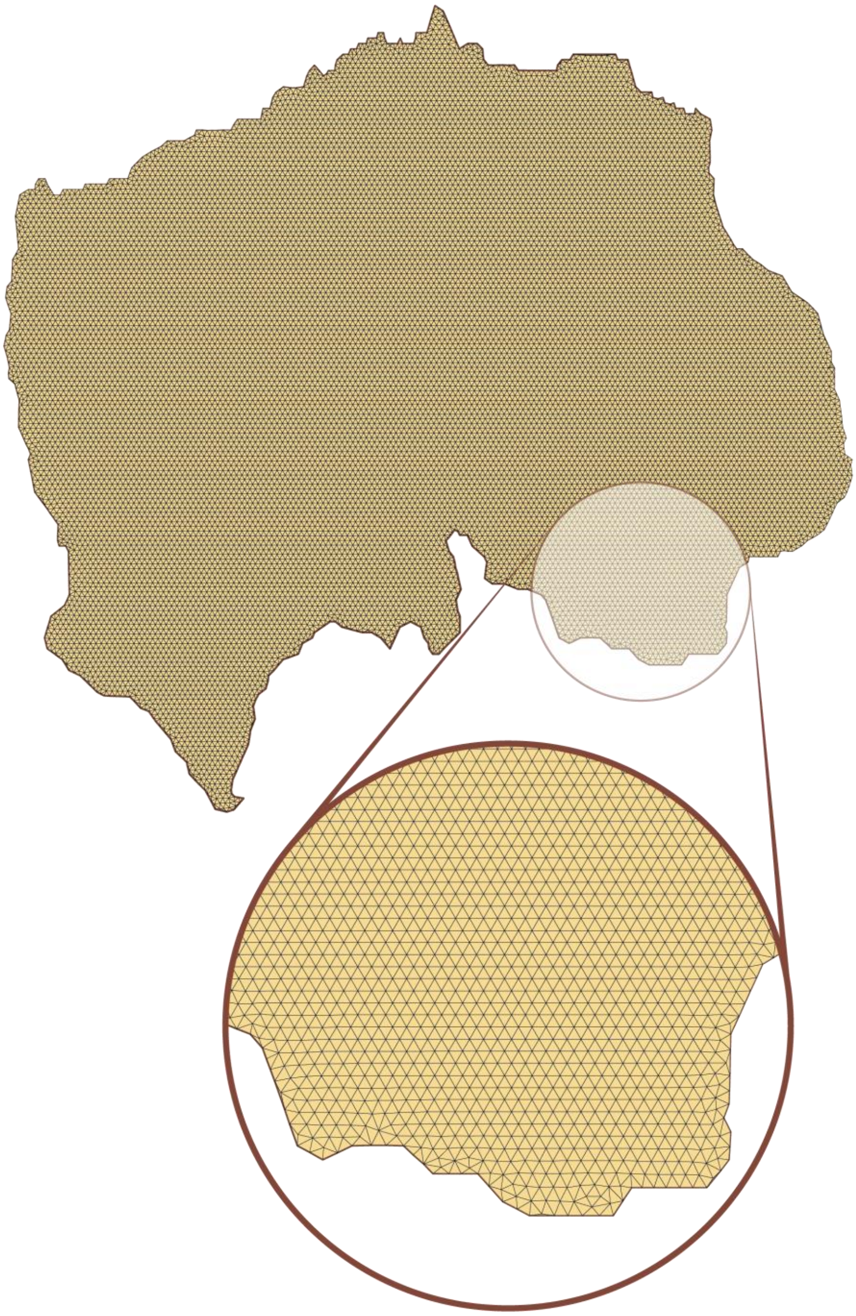

Figure 4.2 Mesh generated for Model 1

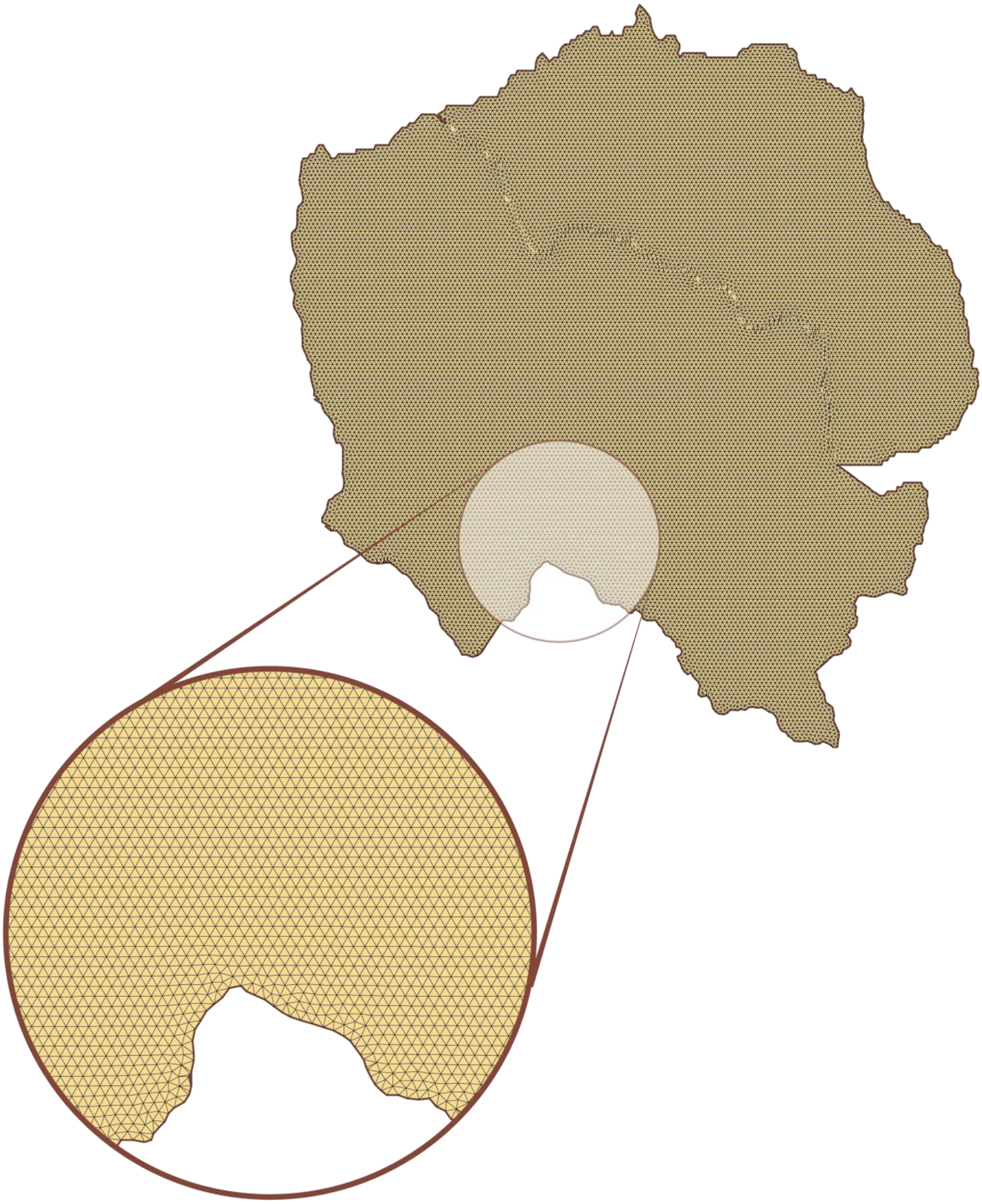

Figure 4.3 Mesh generated for Model 3

4.2 Model calibration results

Calibration refers to a demonstration that the model is capable of producing field measured heads which are the calibration values. Calibration is accomplished by adjusting a set of parameters (recharge rate and hydrogeological parameters) to produce simulated heads that match field measured values (Anderson & Woessner, 1992).This is done by using the trial and error technique. The trial and error technique imply a manual parameter adjustment where initial parameter values are adjusted in a sequential model run to match simulated heads to observed ones. For this study the trial and error technique is used to calibrate the groundwater flow models. The calibration target for this study is the hydraulic head; hydraulic conductivity and surface recharge were used as calibration parameters. In order to evaluate calibration results it is helpful to know how well the calibrated model matched each of the calibration targets. A flow model is said calibrated, when the simulated head match the observed ones within an acceptable margin of error.

A steady state calibration was done by using the observed heads (static water level) from 762wells/springs. And the effectiveness of the calibration was checked by using the lumped quantitative performance measures. The lumped quantitative performance measures of calibration are used to average error in the calibration. The three ways that are commonly used to express the average difference between simulated and measured heads are:

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

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

   Where *n* is the number of calibration measurements. Because both positive and negative residuals are used in the calculation, this value should be close to zero for a good calibration.

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

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

   The MAE measures the average magnitude of the errors in a set of predictions, without considering their direction.

3. The root mean squared error (RMSE) or the standard deviation is the average of the squared differences in measured and simulated heads.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)^2{}_i}$$

The RMSE is used as the basic measure of calibration for heads.

Scatter plots are used to assess the quality of calibration simulations. Observed head versus the head computed by the model are plotted. In an ideal calibration, the points will fall on a straight line with a 45-degree slope; which means the computed head equals the observed head. The degree of scatter about this theoretical line is a measure of overall calibration quality(Anderson & Woessner, 1992).In this study, the coefficient of determination (R^2**)** between the observed and simulated values was found to be 0.918, 0.696 and 0.796 for Model 1, Model 2 and Model 3 respectively. This values of the correlation coefficient (R^2) being closer to 1 indicates a good performance of the models (Model 1 and Model 3).

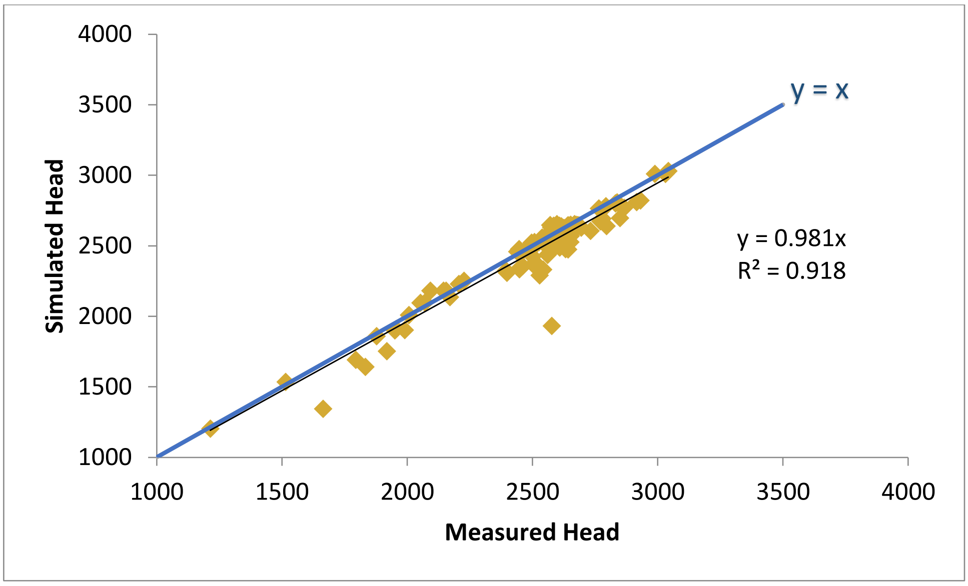

Figure 4.4 Simulated versus measured head comparison for Model 1

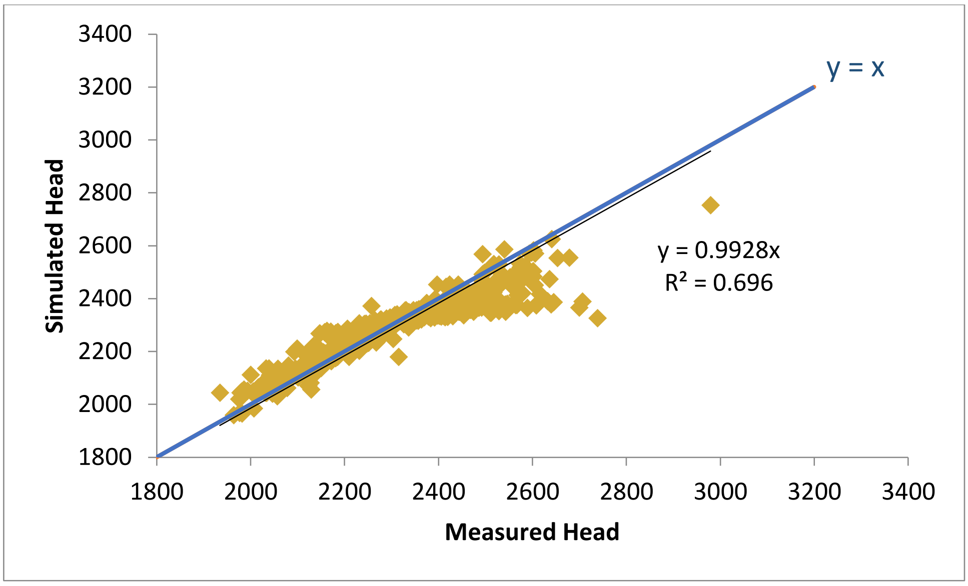

Figure 4.5 Simulated versus measured head comparison for Model 2

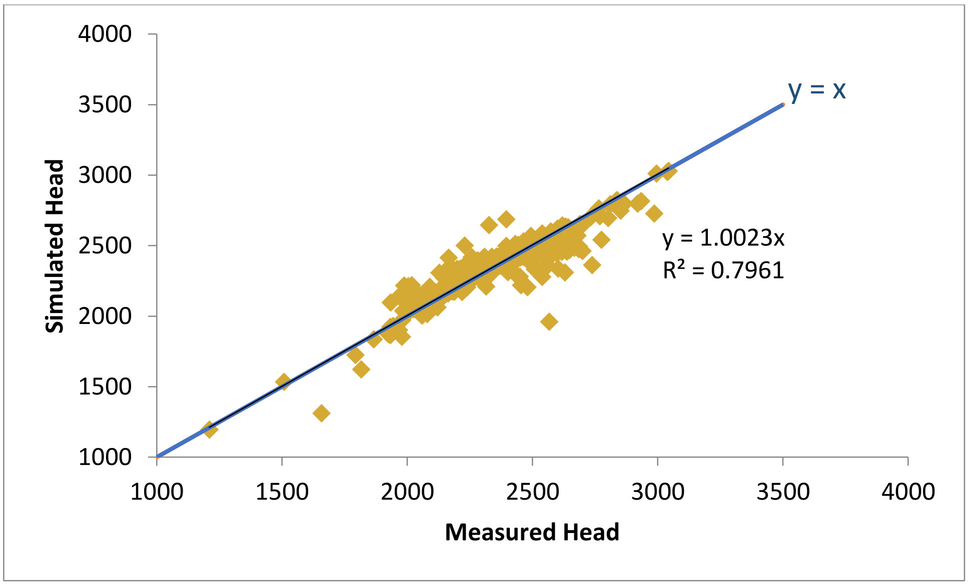

Figure 4.6 Simulated versus measured head comparison for Model 3

Head measurements could be subjected to measurement error associated with the accuracy of the water level measuring device, the operator, and the location and accuracy of the elevation survey point. And another source of error is caused by scaling effects. The maximum acceptable value of calibration criterion depends on the magnitude of the change in head over the problem domain. As a general calibration criteria RMSE equal to or less than 10% of the observed head range in the aquifer being simulated is better (Anderson & Woessner, 1992). The observed head range value for Model 1 is from 1213.88m to 3041.76m, Model 2 is from

1934.60m to 2978.97m and Model 3 is from 1209.93m to 3043.3478m.As it shown in Table **4.1** the RMSE value for all the models (Model 1, Model 2 and Model3) is less than 10 %of the observed head range in each model, which indicate that the models were well calibrated.

From Table **4.1** it is evident that Model 3 for the whole wells represents a better result than that of the other models. This clearly shows that the evidence of the influence of the two basins on each other and the no flow boundary that was set between the Abay basin and the Awash basin for both models, Model 1 and Model 2 doesn’t help in improving the model accuracy. Model 1 represents a better result than the result of Model 3 for the wells observed in the Abay basin. From this result it can be observed that Abay basin is slightly influenced by the Awash basin. But the Awash basin is highly influenced by the Abay basin.

Both (Yitbarek, 2009) and (Azagegn, 2015) tried to model the groundwater flow system of Upper Awash aquifer system to study the inter basin groundwater transfer between Abay River basin and Awash River basin using a finite difference method approach with 2km x 2km grid size. A root mean squared error of 6% was achieved at the end of the calibration for the observed head range in Upper Awash aquifer by (Yitbarek, 2009) and RMSE of 39m was achieved by (Azagegn, 2015).

This study tried to model the groundwater flow system of both the middle Abay River basin and the upper Awash River basin, by using a finite element method approach with 1km x 1km grid size and a RMSE of 4.465% was achieved at the end of the calibration. As compared with previously done researches, these findings are better because of the finer grid size used and also the study tried to model both basins to study their inter basin groundwater transfer. But to study IBGWT between two basins the water budget imbalances and Chemical evidence have to be studied in addition to the groundwater modeling.

The results from the wells along the surface watershed divide including the wells in Addis Ababa city and its surroundings shown in Table **4.2** indicates the evidence of inter basin groundwater transfer between the two adjacent basins i.e. middle Abay River basin and upper Awash River basin. Model 3 represents better the wells observed in upper Awash River basin than Model 2. This clearly shows that the influence of the neighbor middle Abay River basin on upper Awash River basin; in Model 2 this influence was blocked by the no flow boundary assumed. The presence of the no flow boundary between the middle Abay River basin and upper Awash River basin in Model 2 doesn’t help in improving the model accuracy for the wells along the surface watershed divide.

Table 4.1 Summary of calibration errors.

Models	ME	MAE	RMSE	RMSE %	R^2
Model 1 (middle Abay)	46.835	60.054	94.361	5.144	0.918
Model 2 (upper Awash)	12.799	46.297	68.561	6.560	0.696
Model 3 for whole wells	**9.349**	**59.910**	**81.860**	**4.465**	**0.796**
Model 3 for wells in Model 1	76.990	87.800	120.675	6.558	0.894
Model 3 for wells in Model 2	-28.504	53.722	70.405	6.677	0.772

Table 4.2 Summary calibration errors for the wells along the surface watershed divide

Models`	ME	MAE	RMSE	Intercept	R^2
Model 1 (middle Abay)	-1.896	34.722	47.230	1.001	0.914
Model 2 (upper Awash)	31.930	53.978	77.080	0.985	0.063
Model 3 for whole wells	-14.507	57.323	70.700	1.005	0.203
Model 3 for wells in Model 1	55.428	77.625	96.230	0.977	0.597
Model 3 for wells in Model 2	-20.276	55.648	67.998	1.007	0.163

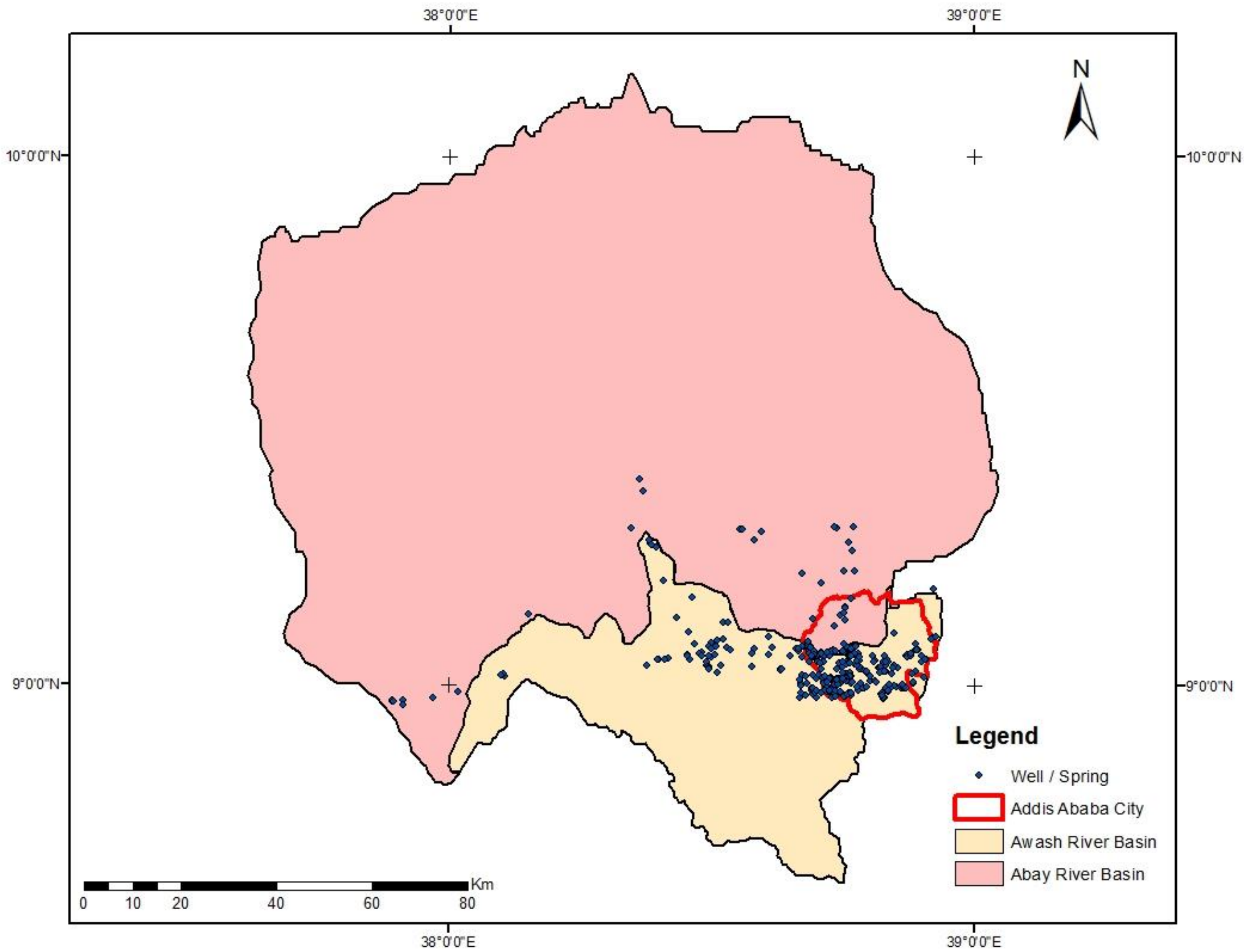

Figure 4.7 well/ spring along the surface watershed divide

Table 4.3 Summary of calibration errors (for Well depth ≥ 250m)

Models	ME	MAE	RMSE	Intercept	R^2
Model 1 (middle Abay)	-23.159	23.923	**32.149**	1.009	0.830
Model 2 (upper Awash)	2.123	41.958	**57.810**	0.997	0.839
Model 3 for whole wells	-33.090	61.269	**80.941**	1.013	0.800
Model 3 for wells in Model 1	-23.159	23.923	**30.780**	1.009	0.829
Model 3 for wells in Model 2	2.123	41.958	**57.810**	0.997	0.839

Table 4.4 Summary of calibration errors (for Well depth < 250m)

Models	ME	MAE	RMSE	Intercept	R^2
Model 1 (middle Abay)	52.897	63.183	**97.907**	0.979	0.923
Model 2 (upper Awash)	14.942	47.168	**70.522**	0.992	0.641
Model 3 for whole wells	2.991	58.881	**82.732**	0.997	0.789
Model 3 for wells in Model 1	52.897	63.183	**97.907**	0.979	0.923
Model 3 for wells in Model 2	14.942	47.168	**70.522**	0.992	0.641

The results of the models for well depth greater than 250m and for well depth less than 250m has been compared to see the performance of the models based on the well depth. As it can be seen from Table **4.3** and Table **4.4** the models represent good results for the well depth ≥ 250m than that of the well depth < 250m. This is because the model is regional groundwater flow model and it simulates better for the deep wells which are influenced by the regional groundwater flow systems than the shallow wells.

4.3 Hydrogeology

The hydraulic head is computed for the three models by varying the hydraulic conductivity for the ten geologic zones of the area and the surface recharge. The study area is classified into fourteen geological zones but only ten of them are taken as hydrogeologic calibration parameters of the area. This is because of their small size relative to the other ten geologic zones and also their location in the model basin. By using the trial and error process for the model calibration, the parameters in Table **4.5** are selected as the best from the other combinations. The hydrogeologic map of the study area was drawn by using the results from the calibrated model. The hydrogeolgic map of the study area is shown in Figure **4.8** and Figure **4.9**. The results of the horizontal and the vertical hydraulic conductivity showed that the horizontal hydraulic conductivity is more dominant than the vertical hydraulic conductivity. Higher hydraulic conductivity values indicate that groundwater flows faster in that region and lower hydraulic conductivity values indicate groundwater flows slower in that regions. The results of the horizontal and the vertical hydraulic conductivity classified as low, medium and high respective to the study area hydraulic conductivity values are shown in Figure **4.8** and Figure **4.9** respectively.

Table 4.5 Geologic parameters of the study area for classified geological zones.

Model Basins	Geology no.	K_x(m/yr)	K_y(m/yr)	K_z(m/yr)	Recharge
Model 1 (middle Abay River Basin)	2	4.32E-01	4.32E-01	4.32E-02	15%
	3	6.91E-01	4.32E-01	6.91E-02	
	4	6.05E-01	4.32E-01	6.05E-02	
	6	8.64E-01	1.73E-01	8.64E-02	
	7	5.18E-01	8.64E-02	5.18E-02	
	9	8.64E-01	5.18E-01	8.64E-02	
	10	3.46E-01	8.64E-02	3.46E-02	
	11	4.32E-01	1.73E-01	4.32E-02	
	12	2.28E-02	2.28E-02	2.28E-03	
Model 2 (upper Awash River Basin)	7	3.46E-01	8.64E-02	3.46E-02	10%
	9	4.32E-01	2.59E-01	4.32E-02	
	12	1.47E+00	6.91E-01	1.47E-01	
	13	1.73E+00	4.32E-01	1.73E-01	
Model 3 (middle Abay River Basin and upper Awash River Basin)	2	8.64E-01	6.91E-01	8.64E-02	10%
	3	6.91E-01	6.05E-01	6.91E-02	
	4	8.64E-01	7.78E-01	8.64E-02	
	7	4.32E-01	3.46E-01	4.32E-02	
	9	1.73E+00	1.56E+00	1.73E-01	
	10	8.64E-01	7.78E-01	8.64E-02	
	11	8.64E-01	7.78E-01	8.64E-02	
	12	6.05E-01	5.18E-01	6.05E-02	
	13	1.73E+00	1.64E+00	1.73E-01	
	14	5.18E-01	4.32E-01	5.18E-02	

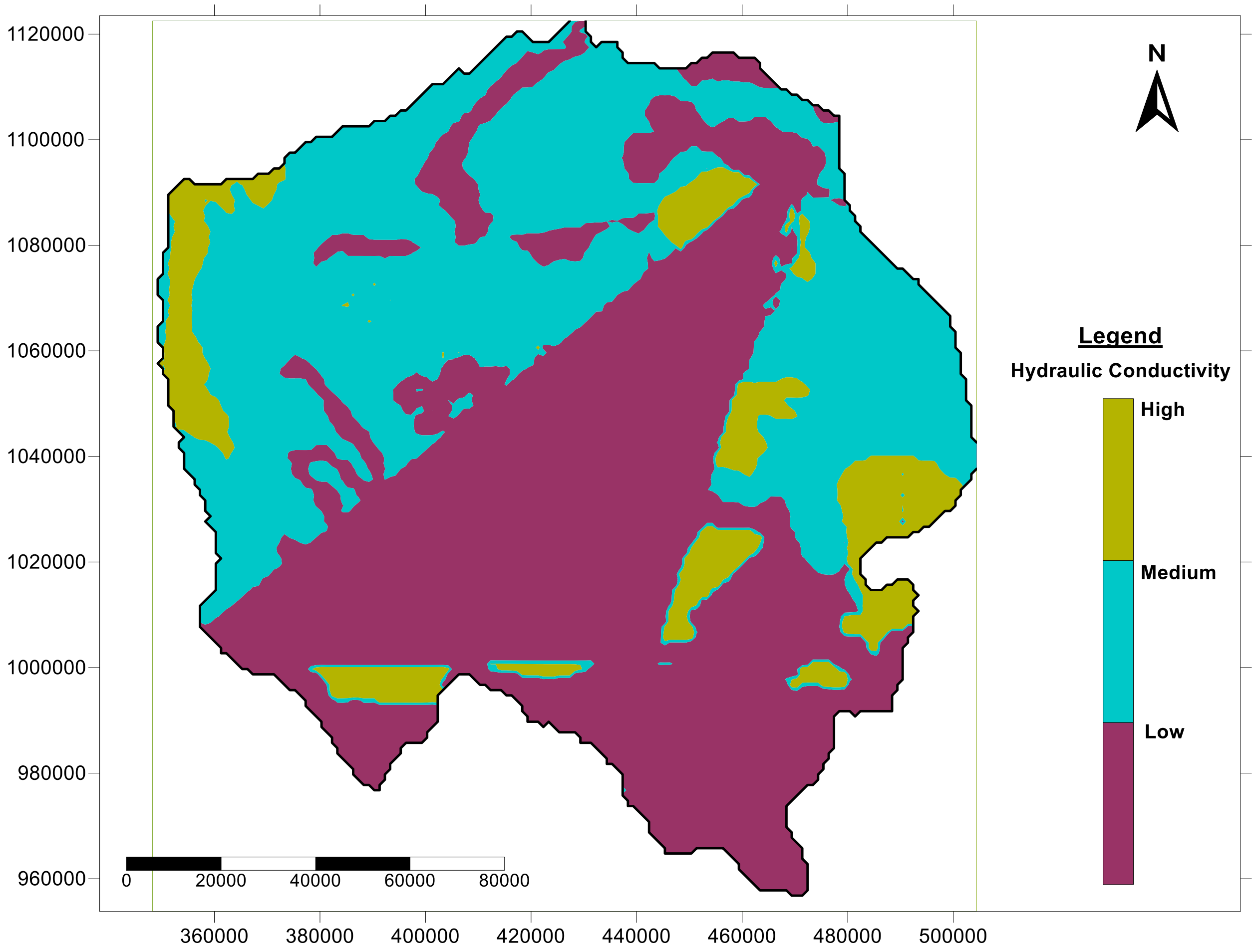

Figure 4.8 Hydrogeologic map with horizontal hydraulic conductivity, k_x.

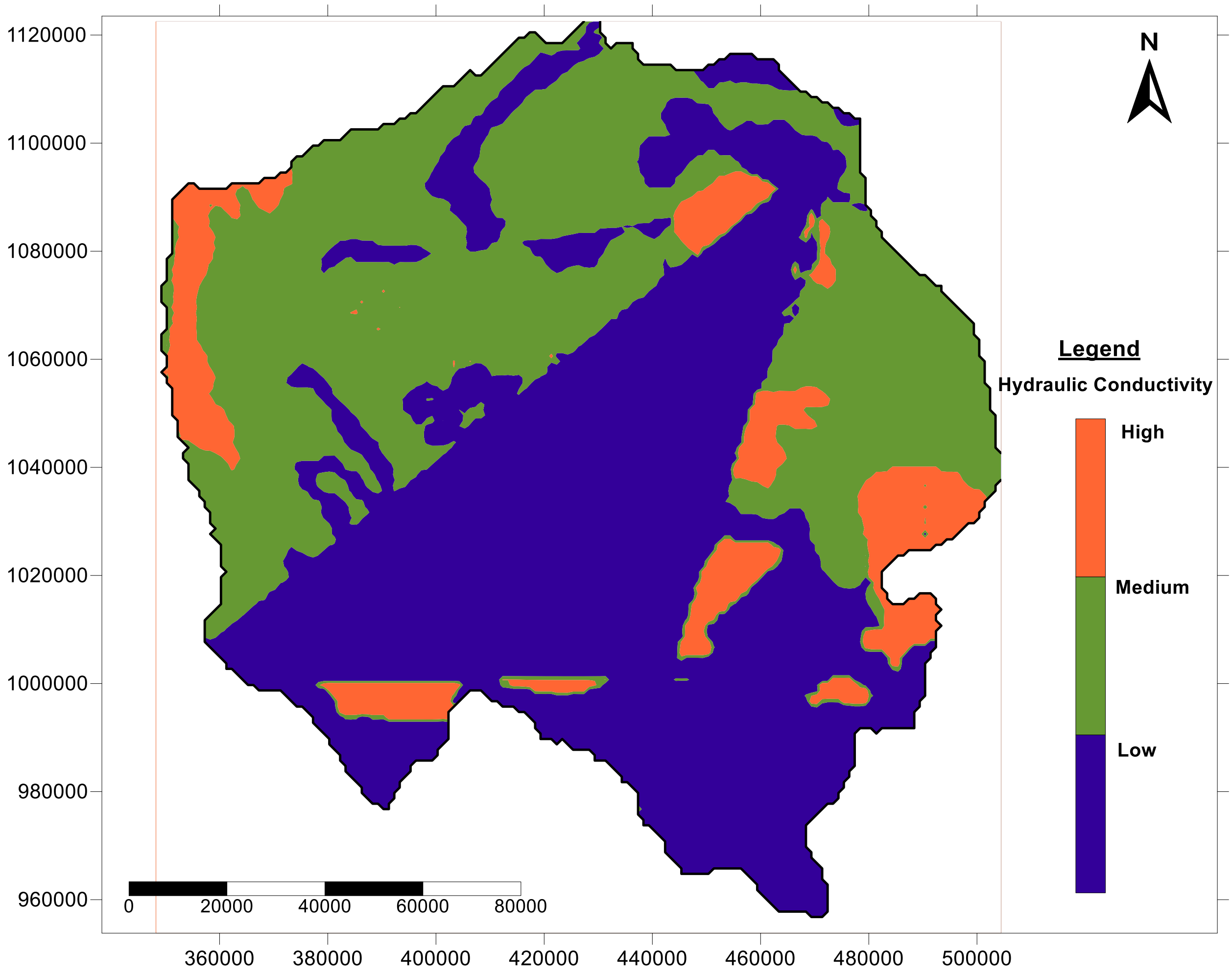

Figure 4.9 Hydrogeologic map with vertical hydraulic conductivity, k_z.

4.4 Groundwater flow direction

Generally, groundwater flows from a higher head to a lower head. By using the hydraulic heads from the calibrated model, groundwater flow directions with groundwater level contour map were plotted for all the three groundwater models as shown in the figure below. Narrow contour spacing corresponding to high hydraulic gradients indicates rapid change in elevations of water level compared with those of wider spacing contours. As it is seen from the groundwater level contour map, groundwater flows following the general surface topography and finally converges into the respective river flow directions. The groundwater level in the study area ranges from 900m to 3150m. The groundwater flow direction array shows the magnitude and the direction of flows. The length of the arrow indicates the magnitude of the flow, in which the longer arrow the higher the magnitude. Which means arrow with higher magnitude shows that the groundwater flows faster in that area and slower for arrows with lower magnitude.

From the groundwater flow direction map of Model 1 shown in Figure **4.13**, majority of the flow direction arrow indicates that groundwater flows away from the watershed divide and flows in to their respective rivers (i.e. Guder River, Muger River, Jema River and middle Abay River). And the groundwater flow direction map for Model 2 in Figure **4.12** also showed that groundwater flows away from the watershed divide into the Upper Awash River and into its tributaries. This is because of the no flow boundary that was set along the watershed divide for both Models.

The groundwater flow direction map and the groundwater level contour map for Model 3 showed that there is an inter basin groundwater transfer between the middle Abay River basin and upper Awash River basin. As it is shown in the Figure **4.10**, majority of the groundwater flow direction around the watershed divide moves from the middle Abay River Basin to the upper Awash River Basin.

In Figure **4.11** the groundwater divide and surface divide is shown. It indicates that the groundwater divide doesn't coincide with the surface water divide. And it also indicates that there is an evidence of inter basin groundwater transfer between the middle Abay River basin and upper Awash River basin. In regions AB, CD, EF, GH, JK groundwater is flowing from the upper Awash River basin to the middle Abay Basin and in regions BC, DE, FG, HI groundwater is flowing from middle Abay River basin to upper Awash River basin

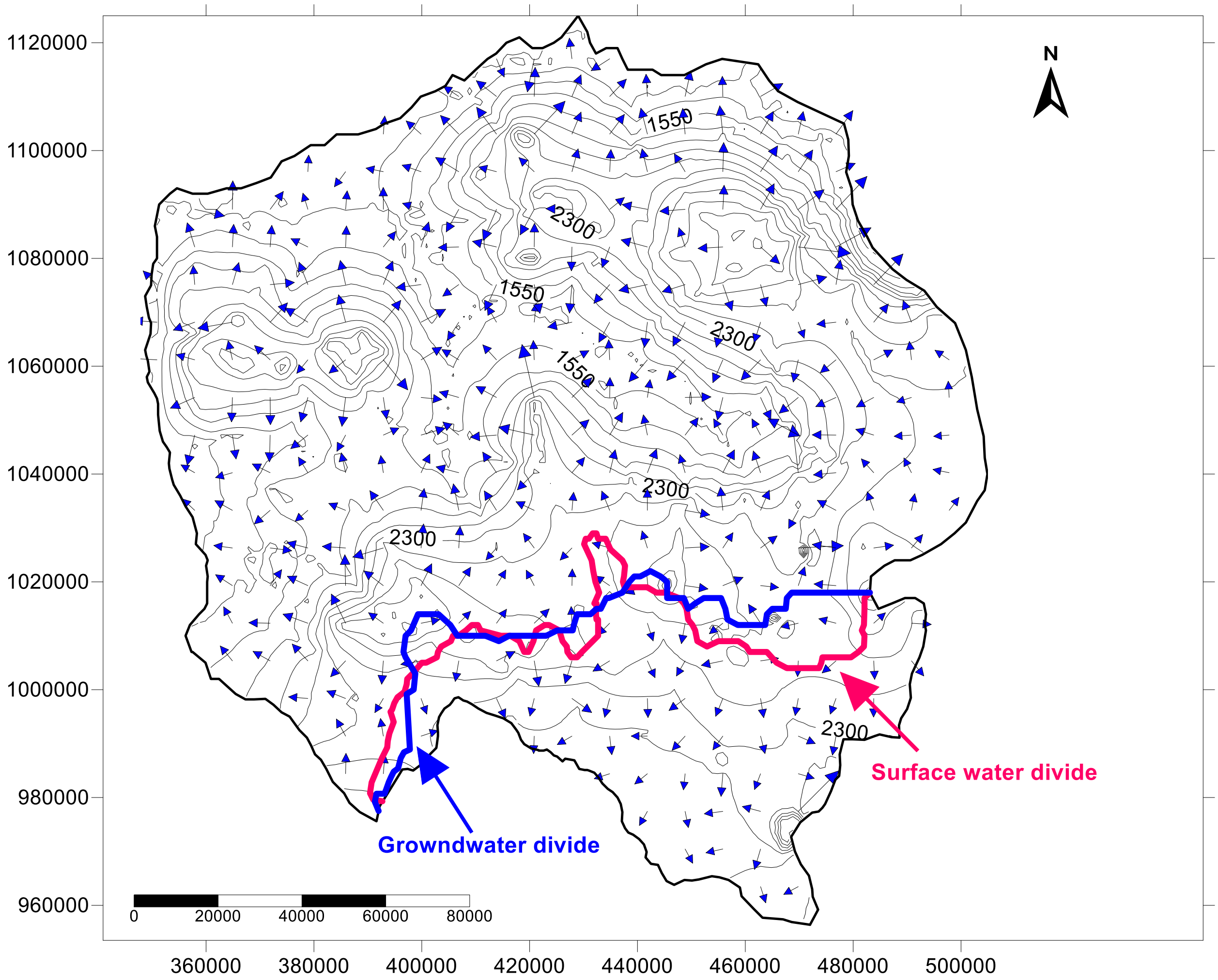

Figure 4.10 Simulated groundwater head and flow direction for Model 3

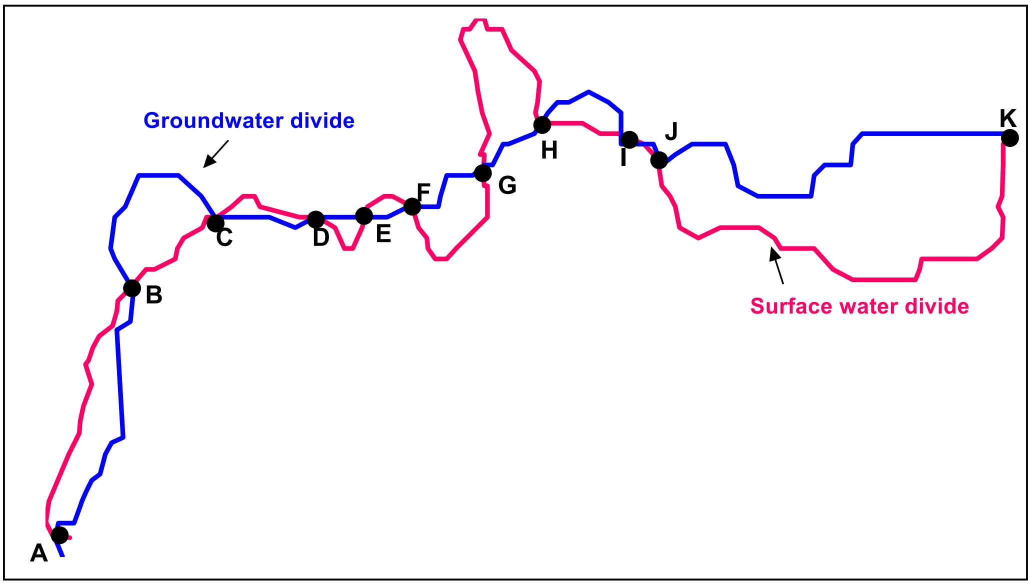

Figure 4.11 Groundwater divide with surface water divide

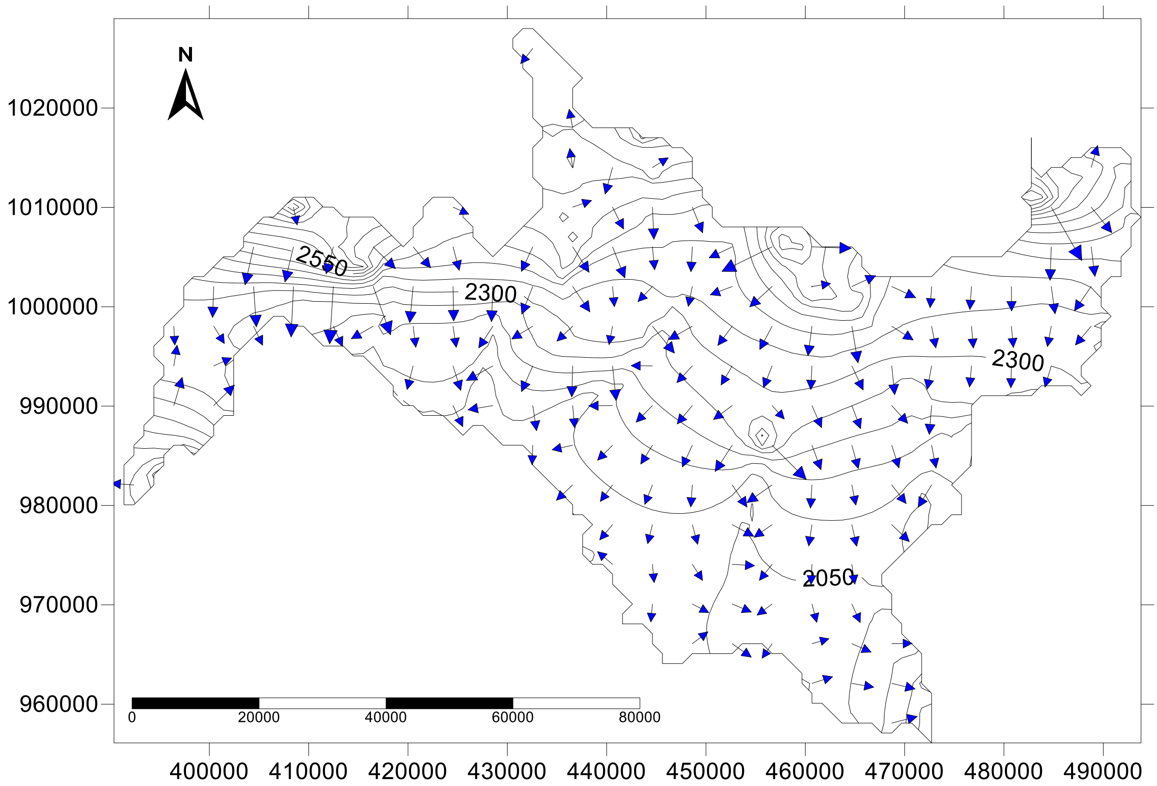

Figure 4.12 Computed groundwater head and flow directions for Model 2

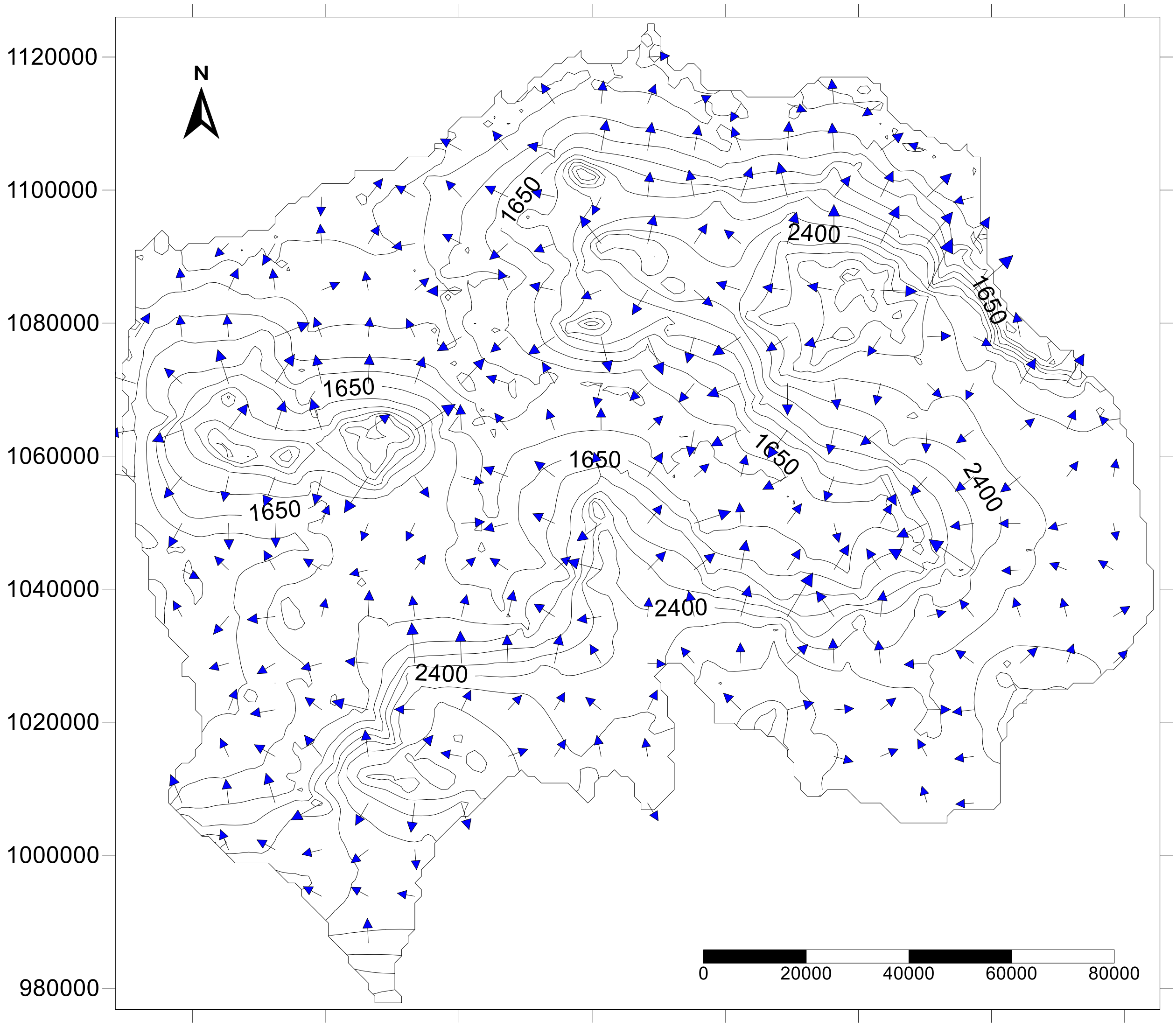

Figure 4.13 Computed groundwater head and flow directions for Model 1

4.5 Groundwater Accessibility

By using the results of the hydraulic head from the calibrated model, the groundwater accessibility map was drawn as shown in Figure **4.14**. The groundwater accessibility map of the study area shows that the groundwater accessibility depth varies from 0 m to 1050m below the surface ground level. Shallow groundwater level is dominant over the study area which can be easily accessed 150m below the surface ground level. Majority of the areas within the upper Awash River Basin of the study area, groundwater can be accessed within a shallower depth i.e. 150m below surface ground level. This shows that groundwater is easily accessed in this Basin compared to the middle Abay River basin which shows a significant amount of variation of groundwater accessibility depth within a shorter distance. This is because of the surface topography of the basin which varies abruptly.

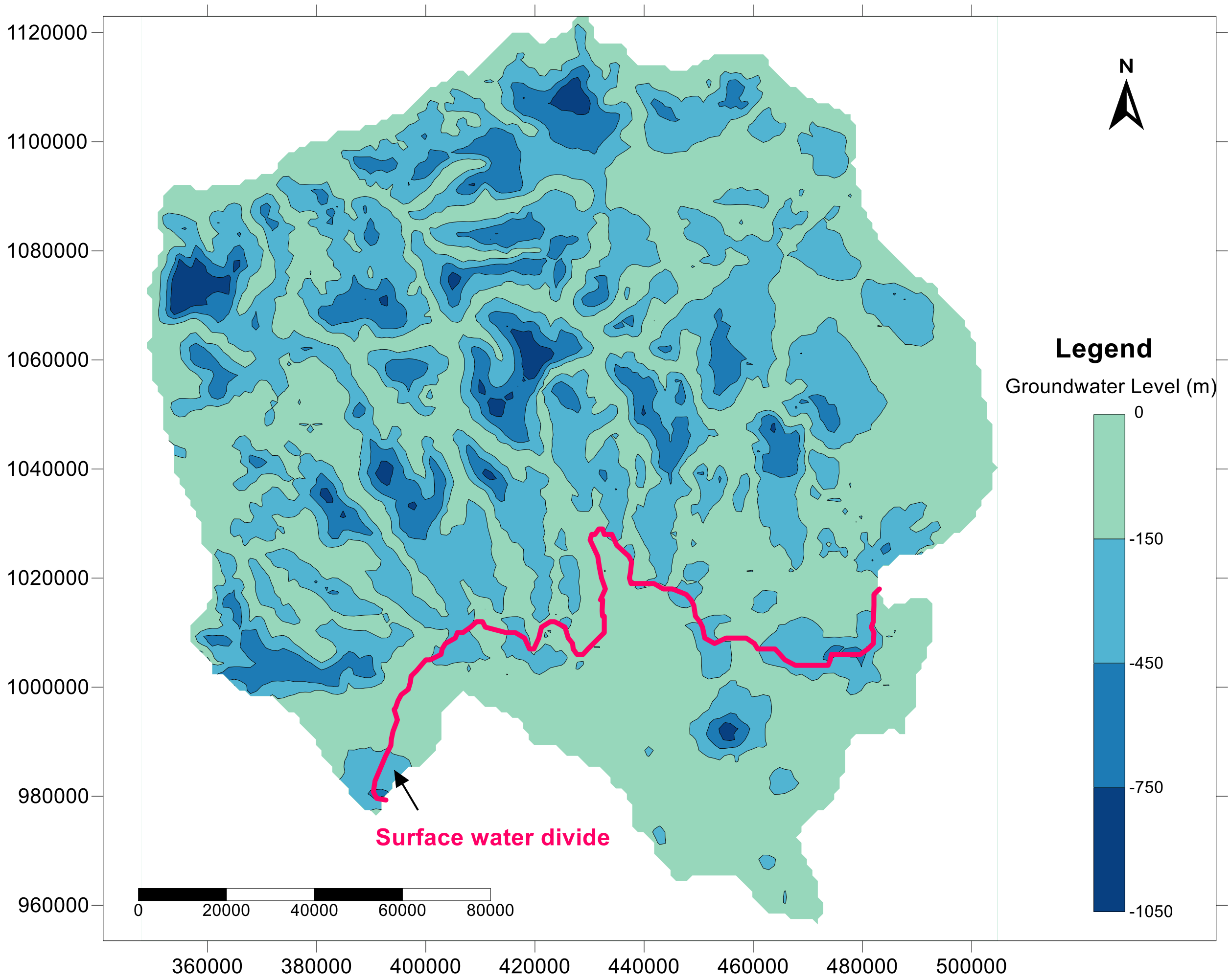

Figure 4.14 Groundwater Accessibility

5 Conclusion and Recommendation

5.1 Conclusion

To study the evidences of inter basin groundwater flow between basins, Water budget imbalances, Chemical evidence and groundwater head data could be used. Among this groundwater head data was used for this study, which was done by making use of groundwater flow system modeling. Groundwater head data can show the direction of inter basin transfer through the difference in hydraulic gradient. But water budget imbalances and chemical evidence should also be used together with groundwater head data for an accurate result.

To identify the IBGWT three groundwater models were created first (Model 1 for middle Abay River basin, Model 2 for upper Awash River basin and Model 3 for combined middle Abay River basin and upper Awash River basin). The first two models (Model 1 and Model 2) were created by assuming that there is no groundwater flow interaction between the two adjacent basins. The two basins are separated by considering the surface water divide as a no flow boundary. The third model (Model 3) was created by avoiding the surface water divide between the two basins and treating the two basins as one. The calibration of these three models was made by changing the recharge and hydrogeologic parameters of the basins.

A total of 762 well/ springs (139 for Model 1, 623 for Model 2 and 762 for Model 3) were inventoried for the model calibration. The simulated and measured hydraulic head at these well/spring locations is tested for measure of goodness of fit. The goodness of fit indicator, RMSE obtained for the Model 1, Model 2 and Model 3 were 5.144%, 6.560% and 4.465% respectively. All the results are below the recommended value for calibrated model. The result obtained from Model 3 clearly indicates that there is an evidence of IBGWT between middle Abay River basin and upper Awash River basin. And it also showed that the assumption that the groundwater divide and surface water divide are coincident is not valid for this case.

Groundwater can be accessed within a shallower depth i.e. 150m below surface ground level, in majority of the areas within the upper Awash River Basin of the study area. This shows that groundwater is easily accessed in this Basin compared to the middle Abay river basin which shows a significant amount of variation of groundwater accessibility depth within a shorter distance.

In general, this study has provided that there is an evidence of IBGWT between the two basins (middle Abay and upper Awash River basins). And the surface water divide and groundwater divide are not coincident. These results are useful to study the cross contamination of the groundwater flow system.

5.2 Recommendation

- As the size of the grid decrease the level of the model result accuracy will increase; which means the finer the groundwater model grid, the more accurate will the results be. So, if finer grid spacing is used the level of the model accuracy will increase and the model can better simulate the real groundwater flow system.
- Transient groundwater modeling can better simulate the actual groundwater flow system than a steady state groundwater modeling. But due to lack of data a steady state groundwater modeling was used in this study.
- For a better identification of the IBGWT between two basins the Water budget imbalances and Chemical evidence have to be studied in addition to the groundwater flow modeling.
- The result of this study indicated that there is an evidence of inter basin groundwater transfer between the middle Abay River basin and upper Awash River basin; i.e. groundwater flows from middle Abay river basin to upper Awash river basin and from upper Awash river basin to middle Abay River basin. This result is only if the groundwater flows according to the natural flow system, if there is an artificial withdrawal (like pumping) of the groundwater from either of the basins this result might change.
- The study faced both data quantity and quality problems. A further and detailed investigation has to be done to better understand the groundwater flow system of the area.
- The result of this study should be used to assess the potential for internal and cross contamination of the groundwater

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APPENDEX: well/spring data used in the numerical model

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
1	472772	1018752	2554	2	848
2	473693	1032100	2504	12.5	880
3	474556	983625	2162	39	219
4	475300	983800	2122	0	93
5	475300	984000	2115	0	129
6	474800	984700	2146	1	71
7	475650	984750	2119	57	0
8	476400	984800	2133	12	90
9	475050	985050	2124	5	24
10	474645	985501	2144	92	68
11	474648	985501	2144	86	117
12	474641	985622	2154	8	68
13	475000	985800	2164	0	120
14	476750	985800	2142	53	86
15	475000	987800	2164	28	172
16	482896	991871	2248	14	205
17	481230	992312	2262	22	200
18	475750	993650	2313	97	149
19	476963	994106	2341	73	132
20	476800	994200	2344	52	151
21	484821	994284	2324	42	368
22	477463	994346	2328	92	170
23	475600	994500	2323	41	139
24	483750	994550	2346	51	230
25	483453	994606	2337	1	182
26	476235	995275	2353	84	151
27	487300	995300	2364	88	120
28	478450	995600	2358	87	171
29	479450	995800	2353	32	0
30	478350	996700	2373.3	0	0
31	482770	997150	2387	35	137
32	477515	997474	2405	19	216

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
33	481650	997725	2416	43	145
34	476450	998100	2437	11	85
35	480395	998100	2440	9	0
36	476500	998250	2448	22	58
37	476100	998300	2435	17	54
38	480029	998401	2466	20	144
39	480431	998457	2455	15	181
40	480400	998500	2458	30	47
41	484190	998500	2492	45	140
42	476200	998600	2473	10	66
43	480629	998771	2487	14	96
44	475600	998900	2422	20	90
45	483350	999064	2501	59	116
46	475200	999200	2450	39	51
47	489127	999697	2441	39	280
48	482070	999823	2539	80	117
49	476105	1000050	2477	50	105
50	481878	1000148	2577	76	140
51	486000	1000707	2485	12	54
52	478850	1000950	2736.7	0	0
53	485925	1000975	2486	8	200
54	481337	1001017	2637	23	135
55	489200	1001025	2446	31	0
56	486200	1001042	2472	18	100
57	486000	1001115	2483	10	130
58	475000	1001300	2545	74	168
59	486712	1001378	2448	0	133
60	475800	1001500	2570	97	210
61	488243	1002102	2475	26	96
62	488161	1002129	2475	63	102
63	487800	1002200	2478	25	80
64	488150	1002300	2476	26	175
65	491300	1004800	2448	5	95
66	482263	1038145	2571	22	66
67	486182	1045145	2529.8	0	0

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
68	485000	1048933	2636.4	0	0
69	482960	1066600	2585.5	0	0
70	483180	1073086	2450.4	0	0
71	475697	979915	2060	10	448
72	472846	980785	2062	8	120
73	472836	980785	2062	8	481
74	472779	978788	2060	10	486
75	473597	981135	2073	22	500
76	474204	980459	2072	21	250
77	474918	980486	2077	22	480
78	471185	979580	2055	37	500
79	470469	979211	2054	15	506
80	472630	979912	2064	8	533
81	471909	979461	2060	9	501
82	473583	979260	2066	18	484
83	469612	978592	2056	23	514
84	472245	977865	2059	28	500
85	471476	977396	2056	34	480
86	471521	976630	2059	40	552
87	473944	978722	2070	30	492
88	473386	980122	2066	11	549
89	472460	981553	2067	0	500
90	471918	979657	2058	9	272
91	470557	976837	2056	54	269
92	471289	977837	2054	27	500
93	469835	978303	2054	53	540
94	468849	970179	2045	55	493
95	468353	972311	2054	62	480
96	468006	971498	2063	58	496
97	471909	978486	2058	108	480
98	489977	1000102	2344	10	500
99	438871	977186	2062	13	443
100	447224	978514	2061	13	440
101	449082	980399	2067	11	440
102	463973	991974	2341	45	405

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
103	463590	992116	2366	80	432
104	472912	1001627	2568	59	312
105	474203	1002351	2544	16	546
106	479316	999941	2642	118	271
107	479175	999755	2625	107	250
108	470682	987316	2218	0	357
109	466336	1000658	2519	97	420
110	465724	1002753	2602	85	332
111	470158	1001882	2611	62	506
112	470503	1002189	2637	99	410
113	480887	997740	2414	63	220
114	457823	1002833	2619	3	104
115	448290	1002698	2412	10	0
116	449177	1002158	2477	0	0
117	447200	998889	2295	0	126
118	446338	997431	2259	13	125
119	446632	994813	2242	1	80
120	453522	1001474	2568	58	115
121	457162	1001115	2625	7	115
122	459689	998340	2593	0	48
123	446266	1004147	2391	37	148
124	446155	1003073	2389	7	90
125	444997	1000718	2360	38	91
126	444626	1001034	2386	40	0
127	444168	998992	2294	7	98
128	445168	997226	2239	0	98
129	445942	1001323	2395	0	99
130	445773	1001323	2388	30	75
131	445099	1003816	2400	30	130
132	443050	1001649	2407	24	130
133	442635	1001366	2409	25	220
134	443132	1000869	2386	30	116
135	444677	998215	2288	6	100
136	444677	998808	2309	21	100
137	444642	1002960	2426	49	66

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
138	443984	999625	2311	10	70
139	444209	998733	2286	7	98
140	441584	1003445	2456	11	50
141	437892	1008952	2591	4	13
142	404656	997733	2232	22	81
143	427193	994953	2125	2	0
144	427164	996290	2157	0	37
145	434015	1000129	2341	5	147
146	440110	1001337	2422	37	153
147	465419	987294	2263	15	120
148	460810	981473	2229	67	102
149	460464	974637	2093	38	61
150	461930	970844	2204	144	183
151	462743	1002521	2626	35	250
152	463635	988675	2283	27	83
153	469672	993830	2324	17	167
154	455450	983014	2110	15	120
155	455426	982736	2105	16	150
156	453850	973096	2055	56	59
157	451420	971692	2066	58	60
158	444624	978143	2064	10	65
159	445354	969451	2092	39	71
160	445144	969045	2088	45	86
161	453538	982154	2088	8	80
162	442842	977555	2067	14	100
163	442811	977625	2065	10	179
164	447966	980422	2064	54	80
165	461412	986324	2277	45	145
166	459676	984947	2204	28	96
167	460937	986565	2277	46	114
168	463599	988583	2283	19	130
169	463742	985378	2363	18	125
170	427635	994816	2119	7	125
171	429252	993949	2110	15	45
172	436160	1000453	2360	37	153

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
173	435382	1000251	2356	10	206
174	466050	993650	2366	71	137
175	445180	1002459	2390	23	101
176	471400	988250	2208	6	88
177	432432	1024464	2607	11	161
178	474125	1001050	2565	28	154
179	466200	1001008	2540	23	53
180	467200	1001017	2536	35	152
181	473400	999600	2498	21	58
182	441366	977899	2062	8	10
183	441901	981393	2064	6	7
184	474200	997400	2427	0	200
185	441831	983807	2078	6	50
186	471300	998200	2453	17	88
187	469800	996300	2368	17	52
188	469900	996000	2350	14	67
189	469800	996200	2369	7	60
190	440595	1000333	2386	81	170
191	469725	994250	2328	17	142
192	472000	995100	2331	44	56
193	471300	995050	2326	0	114
194	469700	994500	2339	7	152
195	474395	995211	2352	59	153
196	468000	993200	2295	17	48
197	471200	993700	2305	23	85
198	473000	992700	2289	111	121
199	472900	992500	2280	90	156
200	474300	992700	2280	89	129
201	475600	994500	2323	41	139
202	473200	992400	2287	40	72
203	473100	991900	2285	113	154
204	473848	990072	2255	39	100
205	473600	988300	2192	11	102
206	473900	989000	2225	35	201
207	475000	987800	2164	28	172

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
208	475335	980717	2074	17	179
209	475300	983800	2122	0	93
210	473900	1001050	2566	15	200
211	475300	984000	2115	0	129
212	474300	1001005	2521	22	83
213	468400	1001016	2548	3	192
214	466600	1001003	2518	23	153
215	468300	1001003	2545	41	63
216	468800	1001007	2540	18	42
217	468900	1001007	2548	72	116
218	469900	1001000	2589	7	80
219	474000	999400	2475	7	50
220	473300	999300	2479	18	27
221	475600	998900	2422	20	90
222	463600	988200	2281	28	64
223	470000	996400	2353	14	44
224	470100	996100	2351	30	45
225	473400	996400	2354	0	200
226	473400	996300	2352	0	249
227	473100	996400	2348	0	249
228	473200	996300	2347	57	0
229	473200	996400	2347	0	100
230	473300	996100	2347	0	78
231	473300	996200	2348	8	56
232	473300	996300	2347	59	60
233	473400	995800	2347	6	50
234	472900	995900	2359	2	32
235	473000	996300	2348	2	80
236	472700	996300	2355	7	20
237	472500	996300	2361	9	41
238	471400	995900	2346	26	67
239	471600	995800	2352	19	34
240	471500	995900	2349	17	34
241	471400	995800	2344	12	64
242	471400	996000	2348	23	32

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
243	471500	996000	2350	19	46
244	471550	995950	2352	23	44
245	471500	995800	2348	16	52
246	471300	995800	2342	8	85
247	471800	995500	2345	8	62
248	471300	995400	2332	0	101
249	471300	994800	2315	4	62
250	470900	994800	2307	1	119
251	471700	995100	2326	7	62
252	471700	995000	2321	11	80
253	471700	994900	2316	10	56
254	469300	995500	2356	16	107
255	471700	986600	2259	26	81
256	471200	995700	2343	3	192
257	471300	996200	2353	6	47
258	471700	996300	2358	41	96
259	466300	993100	2336	60	112
260	466250	993050	2338	50	142
261	467200	993600	2331	48	84
262	468100	993100	2303	50	80
263	468100	993200	2299	45	83
264	471000	993800	2306	68	76
265	473334	997204	2371	4	355
266	472000	993500	2281	51	92
267	473100	992600	2289	36	84
268	473500	992900	2306	123	162
269	474300	993300	2319	126	214
270	473100	991800	2283	56	94
271	473100	991900	2285	113	154
272	473050	991800	2281	94	136
273	470465	991100	2223	16	124
274	470250	991500	2235	8	40
275	470300	991200	2229	10	20
276	470400	992100	2240	11	91
277	471400	991000	2248	26	38

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
278	473800	990250	2260	38	75
279	473750	990050	2253	52	146
280	473500	987900	2184	9	91
281	473230	988879	2210	14	68
282	473900	989000	2225	45	202
283	474000	989100	2226	18	58
284	474100	989000	2221	35	126
285	474050	996650	2382	10	400
286	473300	987700	2160	45	103
287	473300	987300	2157	35	120
288	468100	1016250	2579	3	193
289	475000	985800	2164	0	120
290	475662	980783	2071	27	52
291	465600	1001855	2555	56	83
292	476000	980900	2068	13	40
293	465243	1003393	2635	26	115
294	472400	998500	2458	5	43
295	472500	996600	2369	7	29
296	465507	1002282	2562	2	178
297	470950	995225	2319	0	115
298	472700	996500	2356	3	186
299	470500	994500	2326	42	170
300	466900	1001005	2537	20	150
301	471400	995900	2346	17	88
302	474225	982650	2155	31	178
303	474429	986829	2183	41	187
304	475300	983800	2122	0	140
305	455000	985200	2238	51	126
306	464300	990600	2292	14	52
307	473000	992700	2289	24	90
308	474050	1000875	2560	15	156
309	473326	986813	2157	25	87
310	462500	987000	2309	84	137
311	461900	974300	2127	38	0
312	459700	998075	2581	10	67

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
313	464000	997000	2510	51	100
314	463700	988500	2278	19	130
315	470800	982900	2109	0	114
316	473566	978610	2066	24	122
317	461500	1001023	2590	82	110
318	466200	988800	2249	0	100
319	466400	987600	2255	18	125
320	473069	979881	2061	6	116
321	473108	979851	2063	7	103
322	473350	1003000	2685	10	150
323	466175	1001800	2566	26	0
324	465900	1002875	2613	16	110
325	464600	1003075	2633	14	96
326	466440	1001760	2564	18	66
327	474075	989600	2236	24	60
328	473760	987300	2182	23	0
329	473925	987175	2182	16	72
330	455475	994995	2838	61	152
331	467150	992150	2280	29	94
332	455350	985100	2188	70	128
333	455300	985250	2198	38	101
334	455525	984000	2146	63	124
335	455550	983750	2138	47	181
336	444000	977700	2068	17	100
337	460850	985850	2251	43	106
338	460500	986500	2296	27	100
339	468650	995450	2342	26	126
340	468650	999800	2488	69	172
341	467100	1000550	2514	12	142
342	464500	1003150	2629	6	0
343	474500	995450	2346	66	201
344	468800	996600	2372	50	124
345	468200	1001600	2572	46	150
346	469050	994450	2329	27	120
347	468425	996350	2329	20	68

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
348	469280	993350	2303	20	122
349	468875	993750	2304	11	130
350	473900	993100	2313	118	201
351	470950	993300	2298	19	120
352	467250	999800	2513	59	70
353	474250	996800	2386	40	205
354	474175	996550	2377	40	120
355	472700	999800	2503	12	120
356	468100	1001625	2582	32	150
357	463850	993100	2403	84	150
358	470450	990125	2224	15	0
359	471400	988250	2208	13	84
360	472900	1003550	2710	4	0
361	465651	1001575	2545	7	76
362	467853	999379	2467	3	0
363	472150	993300	2278	51	150
364	463266	1001971	2604	53	111
365	465243	1003930	2689	26	115
366	470110	993850	2322	35	150
367	474957	982383	2147	24	135
368	466350	1001000	2541	16	153
369	469727	993542	2314	22	120
370	460121	985966	2254	40	120
371	470316	991064	2228	10	170
372	467000	996300	2364	52	132
373	463908	995127	2463	40	147
374	465410	1002944	2604	11	124
375	465161	1003103	2613	18	67
376	472541	996743	2371	52	90
377	464538	991302	2309	5	94
378	469804	993691	2322	27	170
379	474000	1001000	2570	40	201
380	457030	984617	2218	89	140
381	474788	982924	2159	24	124
382	473466	987247	2170	9	65

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
383	458646	984363	2190	44	161
384	470983	992553	2261	33	96
385	486000	1000707	2485	12	54
386	472975	1011144	2614	12	114
387	471799	999371	2478	8	114
388	472200	995700	2358	15	67
389	473209	996728	2355	0	300
390	472500	998700	2479	14	0
391	473900	985100	2171	8	72
392	463972	1000788	2517	0	174
393	464721	996788	2480	200	200
394	462260	984901	2284	83	180
395	471500	990500	2224	12	200
396	464031	1002909	2586	0	200
397	465578	999808	2471	0	193
398	467135	989840	2243	3	213
399	468261	990357	2240	4	213
400	470277	989578	2218	13	230
401	469245	990260	2232	0	240
402	465741	989188	2254	3	134
403	468512	989680	2230	0	130
404	469458	990594	2233	0	181
405	468196	990422	2241	5	180
406	467723	990028	2236	4	161
407	470790	990330	2219	0	240
408	465591	989872	2267	8	257
409	465295	990132	2273	10	200
410	463985	991540	2323	25	185
411	466600	1001250	2532	7	196
412	471125	989636	2211	11	153
413	470070	991000	2233	10	170
414	469500	989600	2224	4	150
415	463800	994650	2460	41	147
416	463595	995915	2486	66	158
417	466308	989421	2249	4	185

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
418	469322	1001428	2571	0	240
419	468196	998300	2425	26	200
420	470530	991988	2235	35	170
421	460295	986769	2314	31	158
422	447549	1007893	2509	24	203
423	421795	1040108	2447	20	146
424	474421	1013070	2608	18	304
425	450359	981037	2076	11	280
426	440274	1006055	2530	12	300
427	427395	992768	2101	6	220
428	455620	1026514	2603	8	273
429	473911	1031930	2519	1	324
430	431584	998853	2319.1	0	0
431	410870	997013	2191.4	0	0
432	459831	985582	2226.5	0	0
433	455287	985619	2234.4	0	0
434	468338	1076180	2735.5	0	0
435	464032	1073742	2804.7	0	0
436	466350	1074642	2764.9	0	0
437	469877	1077013	2737.2	0	0
438	455664	1027096	2597	0	0
439	451249	985378	2153.3	0	0
440	460950	976800	2110.1	0	0
441	466600	1001990	2572.6	0	0
442	463259	1002487	2605.3	0	0
443	469300	966775	1953.5	0	0
444	468500	967750	1967.4	0	0
445	468750	967100	1963.2	0	0
446	450887	981258	2079	12.17	436
447	451632	979475	2070	7.18	482
448	450187	981027	2074	8.7	440
449	423439	988990	2074	0	450
450	430759	1035489	2486	0	0
451	430128	1037894	2482	0	0
452	430592	1037170	2492	0	0

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
453	474424	1001212	2491	40	260
454	475068	1001254	2525	105	258
455	475945	1000580	2478	44	252
456	475638	999991	2444	23	0
457	474238	1002373	2544	68	0
458	470504	1002135	2629	0	232
459	470218	1001886	2602	0	233
460	472608	1002066	2572	0	0
461	471026	1002023	2631	23	222
462	466842	993128	2294	38	250
463	482682	994124	2282	38	0
464	481681	994296	2280	12	260
465	482349	995063	2310	52	210
466	482109	993423	2277	37	228
467	484883	994701	2313	16	250
468	485228	994341	2301	12.4	250
469	485664	994125	2291	1	250
470	481462	998906	2452	72	200
471	480321	997370	2374	10	0
472	482994	998429	2422	44	203
473	482849	991509	2224	7	270
474	480604	992935	2250	0	260
475	481101	991646	2228	25	250
476	481061	992052	2232	28	270
477	480760	992453	2252	22	260
478	467660	996912	2349	12	270
479	468268	996584	2324	5	250
480	468505	995156	2284	0	250
481	487881	997599	2366	0	200
482	486723	1000881	2410	17	250
483	464527	990017	2264	13	228
484	468110	1001421	2562	66	250
485	470994	987635	2206	58	0
486	466130	994219	2371	85	250
487	468148	989664	2216	1.3	182

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
488	477550	997650	2394	18.86	216
489	469150	1001150	2541	0	240
490	480999	999648	2496	12	228
491	481519	999648	2491	5	200
492	473400	999600	2471	21	57.9
493	473100	992600	2259	36	84
494	473900	989000	2206	45.4	201.5
495	468100	993200	2287	45	83
496	471200	993700	2279	23.3	85
497	471300	998200	2437	16.5	87.5
498	469800	996300	2356	16.5	51.9
499	469900	996000	2334	13.7	67.1
500	471500	995900	2333	17	34
501	471400	995800	2321	12	64
502	471400	996000	2330	23	32.4
503	471500	996000	2334	19.4	46
504	471500	995800	2326	16	52
505	471300	995800	2321	7.6	85
506	471400	995900	2328	16.8	88
507	473100	991900	2263	112.7	153.9
508	473100	991800	2265	56.4	93.9
509	473100	991900	2263	112.7	153.9
510	471300	994800	2287	4.1	62
511	469800	996200	2344	7	60
512	471300	995050	2312	0	114
513	471300	995400	2309	0	100.5
514	468800	1001007	2514	18	42
515	473300	987700	2145	44.7	103
516	473100	996400	2331	0	249
517	471700	994900	2301	10.4	55.5
518	474300	1001005	2514	22	83
519	473000	996300	2333	1.83	80
520	472000	995100	2303	44	56.4
521	473300	996200	2330	7.6	56.4
522	473300	996100	2333	0	77.7

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
523	473300	996300	2330	59	60
524	467200	1001017	2516	35.3	150
525	471400	991000	2216	25.9	38.1
526	471400	988250	2187	5.93	88
527	471700	986600	2243	26.1	81
528	474050	996650	2352	9.8	400
529	468196	990422	2223	4.8	180
530	465243	1003393	2606	26.17	115
531	475300	984000	2106	0	128.5
532	474928	982697	2152	0	104
533	471500	990500	2200	12.28	200
534	466600	1001250	2508	7.26	196
535	465243	1003930	2654	26.17	115
536	466350	1001000	2512	15.65	153
537	470888	987426	2202	0	114
538	466600	1001003	2508	22.6	153
539	475000	1001300	2523	73.54	168
540	468100	1001625	2559	31.69	150
541	470950	995225	2305	0	115
542	470900	995075	2288	0	121.5
543	473300	987300	2145	35.39	120
544	473300	999300	2451	18	27
545	476078	1000763	2490	0	252
546	468482	1030170	2533	45	300
547	473008	1010984	2610	0	123
548	433779	1000228	2336	1.1	193.2
549	430267	987498	2058	0	0
550	487089	997218	2382	0	0
551	484379	1066656	2565	0	0
552	466430	994219	2338	0	250
553	445643	973409	2122	0	0
554	466662	970715	2050	0	0
555	464607	973547	2134	0	0
556	466690	976790	2061	0	0
557	378351	991473	2177	22.5	147

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
558	378444	991683	2169	89.48	143
559	378447	991365	2176	32.89	130
560	474740	1028068	2606	0	0
561	482111	1056765	2628	0	0
562	464612	1034331	2443	19	150
563	391948	993451	2402	0	0
564	489669	996423	2350	0	0
565	487268	995400	2350	0	280
566	465017	995123	2414	37.58	250
567	480506	1057527	2649	0	0
568	435083	1016838	2570	0	0
569	477181	1065914	2630	3	21
570	471304	1027754	2540	3	65
571	420468	995608	2153	5	21
572	487920	1003552	2458	0	0
573	502053	1042307	2635	0	0
574	478667	1066530	2610	6	150
575	478884	1037765	2570	8	150
576	456092	1047297	1500	20	150
577	488219	1067941	2636	2	12
578	481165	992219	2235	27.59	270
579	481213	991853	2232	25.52	250
580	480717	993193	2257	0	260
581	480863	992647	2241	0	260
582	485841	1067849	2605	6	8
583	432500	1024270	2585	2.1	182
584	484874	1061850	2614	0	0
585	485003	1061595	2614	0	0
586	470851	1027852	2473	0	157
587	440140	1000993	2380	0	0
588	475165	1001449	2522	106.4	260
589	448223	1081244	2853	6	60
590	406722	1009647	3005	6	150
591	486042	1061037	2621	1	10
592	484876	1060344	2651	4.32	4.75

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
593	486122	1061084	2621	0.44	0
594	485112	1060794	2643	0	13
595	485646	1061481	2627	0	13.5
596	489927	1000153	2348	9.69	500
597	401157	996412	2305	24.5	302
598	401801	996640	2313	31.2	246
599	401587	997298	2301	21.52	302
600	400975	997008	2290	19	302
601	490754	1056754	2671	4	6
602	480850	1065676	2626	5	15
603	459862	1086322	3010	32.94	141
604	465729	1002755	2575	52.4	270
605	468094	1001478	2561	66.25	250
606	482884	1061461	2622	2	0
607	440303	1006061	2514	0	300
608	444577	998364	2273	0	140
609	444677	998215	2273	5.9	100
610	448532	1008047	2502	0	0
611	428348	1027771	2507	0	0
612	479631	995410	2329	0	0
613	474463	1022973	2571	5	50
614	485982	1052616	2634	2	150
615	487685	1060862	2643	0	13
616	487590	1060127	2635	2.4	5
617	487021	1060473	2627	3	4.2
618	377136	1058057	2052	41	123
619	476660	1066674	2639	0	0
620	493757	1054356	2656	0	0
621	482000	1059755	2622	2	16
622	427131	996390	2135	0	50
623	474590	1068254	2641	6	43.4
624	471985	987830	2194	0	0
625	461197	1084145	3030	2	50
626	469191	989547	2213	4.15	230
627	486738	1001391	2435	8.14	250

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
628	493003	1051307	2639	25.4	492
629	493215	1051415	2636	5.7	90
630	494345	1051950	2647	25.4	492
631	492919	1054913	2663	5	15
632	489334	1058282	2650	5	50
633	473800	1024726	2608	0	0
634	386800	992200	2367	0	0
635	478950	1072305	2584	10	25
636	466601	1001250	2508	0	133
637	485290	994522	2302	12.42	253
638	473900	985100	2144	8	72
639	472700	996500	2358	2.6	186
640	472500	996600	2353	7	29
641	472900	992500	2264	89.6	156.2
642	473500	992900	2283	123.3	162
643	475578	1035082	2604	0	0
644	433672	1023691	2580	45.9	602
645	424332	1036895	2455	0	216
646	380457	991815	2197	0	147
647	486257	1054859	2639	7	10
648	486419	1054881	2639	0	0
649	485504	1056537	2618	0	0
650	485511	1056545	2618	14	181
651	473400	996400	2334	0	200
652	473400	996300	2330	0	0
653	475000	987800	2147	27.8	172
654	468800	996600	2336	50.35	124
655	481368	997713	2396	88.37	260
656	472700	999800	2463	11.7	120
657	469300	995500	2329	16	107
658	474300	1001014	2514	0	108
659	472500	996300	2368	8.7	41
660	464387	1034248	2451	20	180
661	471700	995100	2306	7.4	62
662	474000	989100	2198	18	58

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
663	471700	995000	2306	10.8	80
664	453986	1025102	2602	3	250
665	484862	1057540	2618	6.4	8.4
666	483172	1061127	2623	28.15	180
667	484835	1054492	2641	0	0
668	474238	1002370	2544	67.94	184
669	472000	993500	2256	50.5	92
670	483377	1061889	2633	1.7	13
671	473400	995800	2327	6	50
672	469900	1001000	2554	7	80
673	472900	995900	2347	1.5	32
674	438871	977181	2051	12.65	443
675	468100	1016250	2570	3	193
676	482163	993603	2269	36.35	250
677	484971	994879	2311	15.64	290
678	485733	994302	2291	74	210
679	432020	1025151	2599	2.5	180
680	472826	980785	2045	8.18	121.5
681	472600	997500	2363	0	96
682	459800	998250	2566	0	68.5
683	471400	995900	2328	26.1	88
684	448502	978502	2051	12.56	440
685	474300	993300	2298	126	214
686	466200	1001008	2510	22.6	53
687	468227	1081132	2932	15	110
688	472700	996300	2345	6.8	20
689	474000	999400	2455	6.8	50
690	467200	993600	2319	48	84
691	483800	1065398	2587	1.5	15
692	483052	1065400	2600	1	2
693	447488	1004519	2401	0	0
694	475154	1018844	2573	2	68
695	473038	1008484	2649	4.2	460
696	473595	981135	2072	11	500
697	474918	980496	2063	21.8	392

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
698	471909	979461	2044	8.8	500.8
699	415726	995659	2156	0	0
700	466306	1008828	2653	4.2	460
701	469142	966835	1922	0	0
702	450215	1089393	2804	0	0
703	448316	1080574	2844	0	0
704	497025	1066349	2577	0	0
705	448147	1080415	2825	0	0
706	459891	1085626	3032	0	0
707	453668	998788	2575	0	0
708	464923	992809	2322	0	0
709	475208	1003085	2622	0	0
710	469414	1001640	2557	0	0
711	457026	981375	2065	0	0
712	472633	983922	2117	0	0
713	451196	1027438	2673	0	0
714	473890	1087756	1912	0	0
715	457146	1004953	2649	0	0
716	449761	1074642	2693	0	0
717	463999	1018139	2616	0	0
718	491646	1015075	2620	0	0
719	482298	1076328	2009	0	0
720	482754	1073368	2413	0	0
721	482345	1066564	2600	0	0
722	482195	1076192	2136	0	0
723	466350	1074642	2771	0	0
724	441075	1108904	1662	0	0
725	480642	1069101	2644	0	0
726	486175	1045151	2513	0	0
727	470338	1035426	2558	0	0
728	486762	1062813	2606	0	0
729	454124	1002590	2604	0	0
730	438835	1085623	2543	0	0
731	494307	1049796	2632	0	0
732	443366	1111042	1125	0	0

No.	UTM E	UTM N	Elevation (m)	SWL (m)	DEPTH (m)
733	447470	1064576	1951	0	0
734	413501	1037036	2585	0	0
735	468163	1081306	2926	0	0
736	447624	1078948	2742	0	0
737	459951	1048382	1745	0	0
738	457250	1095777	2158	0	0
739	464186	1065719	2558	0	0
740	473823	1088329	1822	0	0
741	475032	1087994	1965	0	0
742	426391	1042935	2517	0	0
743	470776	1007219	2671	0	0
744	483313	1005608	2596	0	0
745	492323	1060902	2665	0	0
746	451615	1027364	2662	0	0
747	484180	1059881	2627	0	0
748	484181	1059882	2627	0	0
749	447123	1093293	2433	0	0
750	385386	1052257	1906	0	0
751	472110	1009390	2677	0	0
752	380547	990709	2245	0	0
753	472859	1009905	2647	0	0
754	491203	1004462	2437	0	0
755	441088	1013105	2700	0	0
756	386845	1043913	1776	0	0
757	465410	1075177	2829	0	0
758	478357	1075318	2565	0	0
759	492039	1005044	2452	0	0
760	466264	996974	2393	0	0