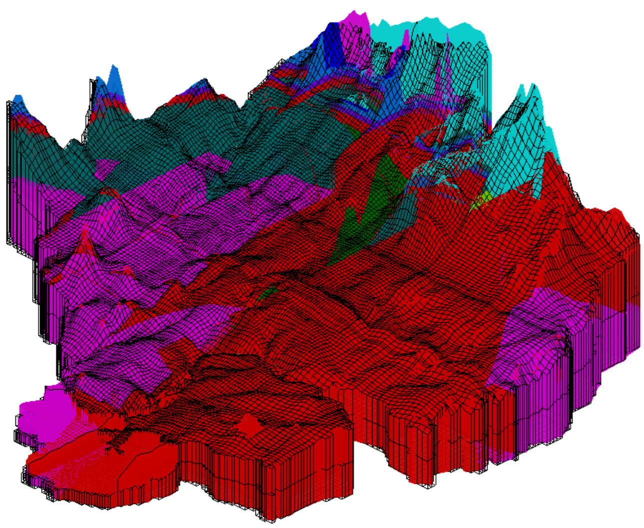
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIROMENTAL ENGINEERING

Effect of Shallow Groundwater on City Infrastructural Plan

The Case of Addis Ababa



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Thesis Submitted to School of Graduate Studies, Addis Ababa Institute of Technology, in partial fulfillment of the requirements for the Degree of Masters of Science in Civil & Environmental Engineering (Hydraulic Engineering major).

September 2020 G.C

Addis Ababa

Ethiopia

Addis Ababa University School of Graduate Studies

Addis Ababa Institute of Technology

This is to certify that thesis prepared by **Abdulfeta Amane** entitled on ***"Effect of Shallow Groundwater on City Infrastructural Plan the case of Addis Ababa"*** submitted in partial fulfilment of the requirements for the Degree of Master of Science in Civil and environmental Engineering under Hydraulic Engineering complies with the regulations of University and meets the accepted standards with respect to originality and quality.

Date defended 1/09/2020

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Certification

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Date

ABSTRACT

The main aim of this paper is to Understand and address impact of shallow Groundwater in Addis Ababa city infrastructural development plan which plays a vital role for the present and future urbanization of the city. In this study a three dimensional (3D) steady state GMS based groundwater modeling MODFLOW was used to characterize and assess the shallow groundwater flow. This model develop soil stratigraphy from borehole log data and need the hydrogeology data, recharge and river boundary conditions as its input for aquifer parameter. Thus a simplified two layer conceptual model was created by the perennial rivers in the basin as constant head boundary and the top surface as a recharge boundary from annual rainfall. This conceptual groundwater model includes the river and precipitation as inflow to the groundwater or source and discharging well with depth less than 100m were used as outflow from aquifer or sink. Up on all the given input hydraulic heads was generated and simulated. In the calibration 115 shallow wells were used. The calibration was made to an accepted level of error value of head difference 0-5 meter for each well by the software. The model clearly shows the groundwater hydraulic head and flow direction follows the general topography of the study area. Beside the master plan was analyzed and described by looking into the hydraulic head together with the city infrastructural plan. For selected sites in the city sub-model were developed for further analysis on effect of shallow groundwater on city infrastructural plan.

Key words:-*Infrastructural plan, MODFLOW, MODPATH, Shallow Groundwater, Addis Ababa.*

ACKNOWLEDGMENTS

I gratefully acknowledge ERA (Ethiopian road authority) for giving me this chance to study in Addis Ababa Institute of Technology University. I want to say thank AAiT (Addis Ababa Institute of Technology University) form beginning up to the end of my study with a lots of knowledge through continuous assessments and courses.

I wish to express my deepest appreciation and gratitude to my advisor Dr. Mebruk Mohammed, for proposing the research problem, knowledge and advice, sharing me his time for valuable discussions, giving me his personal research materials and guiding me throughout my thesis. Even though COVID-19 dynamics changed our way of meeting, he is very supportive and willing for discussion.

Ethiopian Ministry of Water and Energy, National Metrological Agency and Ministry of geological survey, Ethiopian water work design and supervision and Addis Ababa city planning commission for their unprecedented collaboration during secondary data collection.

I wish to express my appreciation to my class mates for their friend ship, support, sharing information .special tanks to my best friend Abdulkerim Oumer being with me in time of pressure and stress and reviewing my paper work.

My unique entire family no words can express my deep feeling of appreciation for their valuable support throughout my academic life always with me. I would like to express my special sincere to my elder and younger brother Abrar Temesgen and Ramato Amane for their great support in material and advice to use my time effectively and successfully complete my dream

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LIST OF ACRONYMS

AALRTS: Addis Ababa light rail transport service

GMS: groundwater modeling system

GW: Groundwater

MASL: meter above sea level

GSE: Geological survey of Ethiopia

MOWE: Ministry of Water and Energy

FEM: Finite Element Method

FDM: Finite Different Method

DEM: Digital Elevation Model

WWDSE: Water Works Design and Supervision

GIS: Geographical information System

RMSE: Root Mean Square Error

ME: Mean Error

MAE: Mean Absolute Error

NE, NW, SE, SW: North-East, North-West, South-East, South-West

E-W, N-S: East-West, North-South

UTM: Universal Transverse Mercator

NMSA: National Metrological Service Agency

GWL: Groundwater Level

SWL: Static water Level

DWL: Dynamic water level

Keq: Effective Hydraulic Conductivity

Kh: horizontal hydraulic conductivity

Kv: Vertical hydraulic conductivity

UG: unstructured grid

PEST: Parameter estimation method

1. INTRODUCTION

1.1 Background

Urbanization alters topography and natural vegetation, stream flows and flooding characteristics, temperatures both above and below the land surface, and water quality of surface streams and groundwater. Major physical changes to the groundwater system include changes in water table elevation; a dramatically altered permeability field created by construction and utility system emplacement; and altered groundwater recharge. Subsurface permeability may increase by orders of magnitude in certain preferred zones, which makes prediction and remediation of subsurface contaminants difficult. Groundwater recharge commonly increases because of: Leakage from water distributions systems, sewer lines, detention ponds, and storm drains; over irrigation of lawns, gardens, and parks; Artificial recharge; reduced evapotranspiration and Infiltration through "impervious" cover this, coupled with pumping of shallow groundwater, controls water table fluctuations. The impacts shallow groundwater systems on city infrastructural plan are predictable and should be considered in urban planning from geotechnical, environmental, and water resources perspectives.

City infrastructural development is accommodated by increases in numbers and in sizes of cities due to increase in population shift from rural areas to urban areas. Hydrogeological effects of urbanization include altered topography and vegetation, increasing shallow groundwater temperatures, changes to water table elevations, and a multitude of changes associated with construction and pumping, and pollution of groundwater and surface waters. City development tends to level off the landscape for ease of construction and for roadway design. Over time, low --lying areas are filled in and elevated areas lowered. In very old cities, younger construction cover successively older city structures.

Shallow GW has relationship with urbanization and the change in natural environmental directly or indirectly such as weather, topography etc. changes in the rates and distribution of evapotranspiration can alter recharge and groundwater flow directions. Clearly, impervious cover will decrease and may even eliminate transpiration by native vegetation. Conversion from using local aquifer systems to large surface water systems or imported water can cause rising water tables, which can, in turn, can cause engineering problems (flooding of basements, tunnels, and utility systems; mass wasting, etc.) and new boggy areas. Various construction activities and designs affect groundwater. If the water-table is close to the surface or if deep foundation or subways are being built, dewatering or depressurization may be required that can lower water tables for considerable periods of time (Powers et al., 2007). Pumping for production of groundwater or for remediation of subsurface contamination can create similar effects. In certain cases, the construction may form subsurface dams that can locally alter the groundwater flow field.

This research tries to address the possible effect of shallow groundwater on infrastructural development of Addis Ababa city. There is no consideration of shallow groundwater while developing plan, there was great deal of impact on socioeconomic degradation of the city. To alleviate the problem researcher should be done to overcome the effect or to minimize the impact. As the whole this research tries to deliver the impact of shallow groundwater on city infrastructural plane such as building, road, bridge, industrial parks and low cost building (condominium) area. This is done by modeling the study area of Addis Ababa using GMS (ground water modeling) software and showing places of flooded, wit and dry area. Contrary to this Structures such as building roads and deep foundation structure acts us a barrier for the flow of ground water and alter the direction of flow.

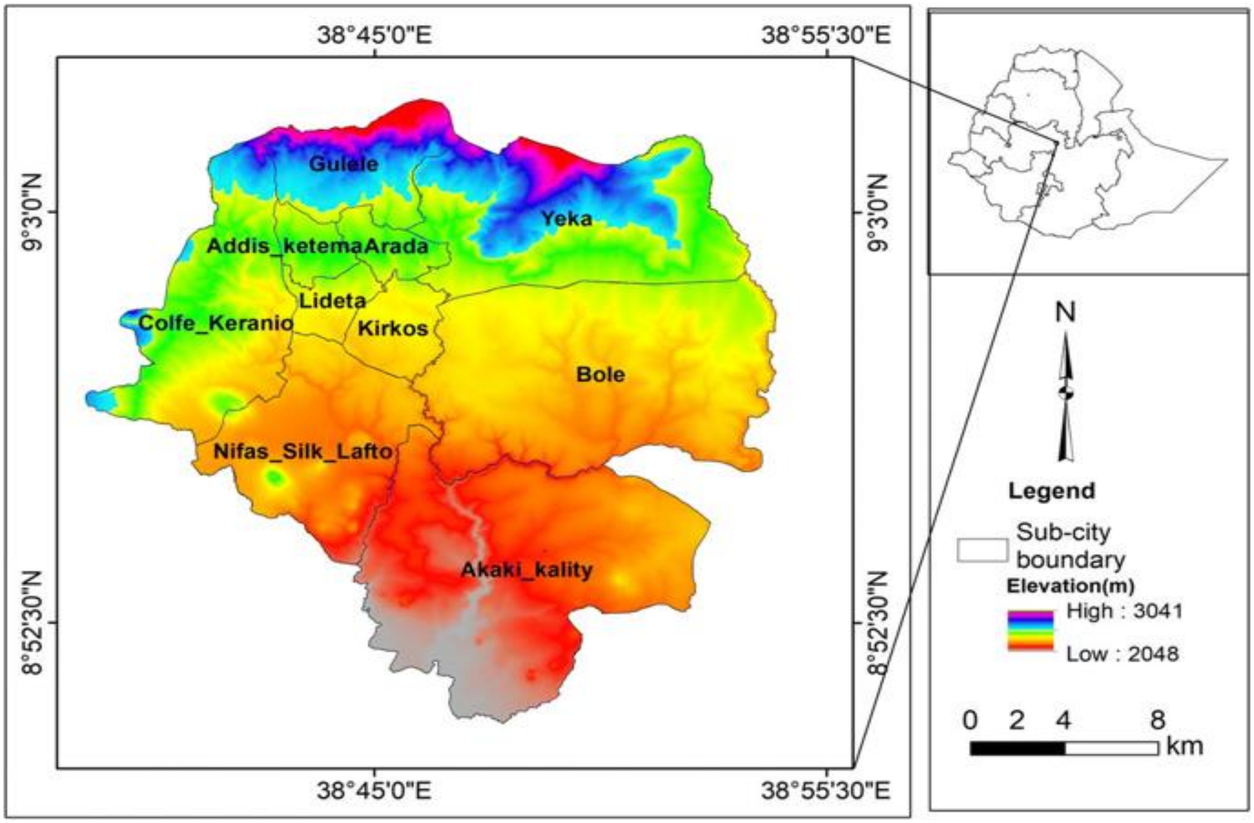


Figure 1.1 Topographic and administrative Map of the study area

After all the study area shallow GW head developed. The developed map is overlaid with the city different infrastructural map using ArcGIS software. The result was discussed and analyzed to see to the effect of shallow groundwater on the city infrastructural plan. Finally the possible way of minimization and overcoming the problem was suggested by this research.

1.2 PROBLEM STATEMENT

The increasing proportion of people living in cities and towns through the process of urbanization is one of the main features of world development. The same is true Addis Ababa is the fastest growing city among all Ethiopian cities and towns. This rapid growth can cause complexity, in the size and number of infrastructures development in the city to meet the population demand. This was observed everywhere in the city number and size of building is growing up, the road construction is increasing. Rail ways, brigs, industrial and residential area developed each year. This alter the near surface and the groundwater flowing region character.

Underground structures and infrastructures such as deep foundation, asphalt paved roads, rail way that are constructed deep in the ground and in general urbanization of Addis Ababa city development, locally affect the groundwater level of the aquifers in the city. Actually, in the last decades, an increasing trend in groundwater level due to the deindustrialization process was observed in urban aquifers all around the world (Dean, J. & Sholley M., Groundwater basin recovery in urban areas and implications for engineering projects). The water table rising in these urban areas was the result of a deindustrialization process, with the related decrease in groundwater pumping, which was not properly managed, and it therefore caused serious damages to underground structures and infrastructures. This research envisions the same may be true for Addis Ababa; hence the research will try to identify the possible shallow groundwater level variation in the city effect on the infrastructural development plan and vice versa (where the effect of the infrastructure development on the shallow groundwater level variation)at some points well be developed and described.

1.3 Objectives

1.3.1 General objective

To understand the effects of shallow groundwater flow flux on Addis Ababa city infrastructure development plan.

1.3.2 Specific objective

To accomplish the above main objective this research try to address the following specific objectives.

- Develop and describe the shallow ground water table map of the capital city
- Identify the effect of groundwater on infrastructural development plan of the city
- The positive and negative impact of shallow groundwater table on the city infrastructure

1.4 Scope of the research

The study comprised three stages; desk study, numerical modeling, and data analysis and interpretation coupled with report writing. The desk study includes literature search and review and/or collection of available data. The sources of data used in this stage comprise published and unpublished reports, both local and international. Prior to numerical modeling a 3D numerical model of the study are were created using GMS and ArcGIS. Satellite images, geological explanations, shallow groundwater well data analysis, view in particular outlook; the geomorphologic and environmental features.

The model considers the shallow aquifers of the whole Addis Ababa. The model was done using GMS software which uses only borehole log data and by creating horizon. Even though, there are deep boreholes up to 500m, the lithology data are assigned up to 100m of depth from the surface to represent shallow and very shallow aquifer of the study area. The aquifers of northern and central part of Addis Ababa city and in the mountain area are largely due to weathered and fractured volcanic rock with minor sediments deposited between different series of lava flows. In general, the aquifers are complex and highly variable.

It was calibrated in steady state with reference to the water table observed from observation well of static water level. The model doesn't consider transient state of GW flow model. Since in transient model sessional variation of groundwater table fluctuation well be considered. This may require different years of data to run the MODFLOW model in GMS, so it is beyond the scope of this research.

The modeling is finite deference based MODFLOW model rather than finite element method using GMS comprehensive software. Interpolation was done to 3D finite difference grid. The interpolation is done either to the grid nodes or to the grid cell centers depending on whether the grid is a mesh-centered or cell-centered grid. When a MODFLOW simulation is solved, MODFLOW writes out a head or drawdown value for every cell of the finite difference grid to the solution files. However, some of the cells are either outside the problem domain or they have gone dry during the course of the simulation. These cells are flagged by MODFLOW in the output file by writing special values for the cells.

1.5 Organization of the research paper

This research paper is organized in six chapters. The first chapter deals with the general introduction, statement of the problem, the general and specific objectives of the research and the overall scope of the study.

The second chapter bounces the literature review about effect of shallow groundwater on the capital city infrastructural development. It also includes the description of, shallow groundwater, groundwater recharge assumption of groundwater in the study area, Limitations, boundary conditions, hydraulic conductivity and nature of the aquifer.

The third chapter discusses on methodology of the research, solution techniques, processing and analysis. These chapter covers about the physical nature of the study area from which how to develop the conceptual model and how the conceptual model is converted to 3D numerical model. It also discusses the different type of data collected from different offices and given in to the model. The chapter finally tells physical overlay of the model output with the city infrastructural plan.

The fourth chapter talks about the result and discussion of this research work. These unit try to discuss about how the model generate the hydraulic head and hydrologic carictraztion of the study area. It also have a brief discussion about calibration of the observed hydraulic head with the observed head of well and validation of the result.

Chapter five is the conclusion and recommendation section of this research. This chapter was the most difficult part of the study and it requires deep focus on the result and how to draw out the conclusion. And what should be done for the present and future has been discussed on this small section of the study.

Lastly in chapter six lists of the references were included. It includes books, magazines and different important materials used as a reference to write this research paper are listed.

2. LITERATURE REVIEW

On this research the literature review focuses on the relationship between shallow groundwater and city infrastructural planning conducted before by different scholars. Even though there is no direct studies has been done before in this case on the study area, this paper will try to review different international and national research done on the related topic.

2.1 Shallow Groundwater

Ground water is rainwater that has percolated into the underground. There are two main types of ground water, namely: shallow and deep. The saturated zone beneath the water table is called an aquifer, and aquifers are huge storehouses of water. Four categories of aquifers occur in Addis Ababa:

1. Very shallow aquifer (below 30 meter)
2. Shallow aquifer (30-100 meter)
3. Deep aquifer (100-250 meter) and
4. Very deep aquifers (beyond 250 meter).

Shallow ground water: - In this study shallow groundwater means the water table which can be reached by city infrastructure or the nearest water table or the nearest hydraulic head found in the well. Form the four classification of groundwater aquifer according to (Supplement to Task Force Report on Aquifer Management for Addis Ababa and Vicinity, February 2013) the very shallow and shallow aquifer are considered us shallow GW and used in modeling. It can be reached by means of hand dug wells in areas where rainwater has been trapped in the underground such as in valleys, downstream of earth dams and near swamps, seasonal water courses, rivers and lakes. In this study shallow groundwater was simulated which has a depth of up to 100m from the surface ,us it has been stated above .the shallow aquifer have used for many purposes of infrastructural development in the capital city. These serve as the source of drinking water for AAWSA, but at the same time they are also increasingly used by private parties such as industries and horticultural farms. For the moment the shallow aquifer contributes importantly to the water supply of Addis Ababa through the Akaki well fields and through wells drilled in different parts of the city.

Deep ground water:- The deep and very deep aquifer in the above classification of (Supplement to Task Force Report on Aquifer Management for Addis Ababa and Vicinity, February 2013) are considered us deep aquifer below 100m from the surface. Which is rainwater that has percolated deep into the underground during centuries or thousands of years. This water source can only be reached by drilling deep boreholes from where water is extracted using electric powered submersible pumps that deliver water to storage tanks. Recharge of rainwater to deep boreholes may take hundreds of years. Most deep boreholes do therefore suffer from sinking water levels or high salinity of the water before they finally may run dry. Due to these constraints and the high cost of construction, operation and maintenance of deep boreholes, this subject is not considered relevant for this website.

In recent years investigation of the deep and very deep aquifers has revealed possibility of finding large discharge wells and significant numbers of wells have been drilled for Addis Ababa water supply. The shallow and deep aquifers underlay both Addis Ababa and Oromia Region. There are no as such serious conflicts yet, but in the near future the intensified use for agriculture requires more coordination and regulation.

2.1.1 Groundwater Recharge

Groundwater (GW) recharge is defined as the fraction of total precipitation falling into a drainage basin, which eventually reaches the water table in the saturation zone of an aquifer (Jukić and Jukić, 2004). It is a fundamental component of GW systems (Sanford, 2002), because information on GW recharge rates is often necessary for water resource management, inputs to regional GW models and predictions of climate change impacts (De Silva and Ruston, 2007). Thus, GW recharge is a critical hydrological parameter, which may need to be estimated at a variety of spatial and temporal scales depending on the application. Since GW recharge cannot be measured directly, it is often estimated by using the results of hydro geologic and geologic investigations, hydro meteorological data, observed discharges or GW level hydrographs (Jukić and Jukić, 2004). As shallow groundwater is the first to get the recharged rainwater, its importance in shallow groundwater flow analysis is vital and demanding. Throughout the year, in Addis Ababa, there are 132 rainfall days, and 1165mm of precipitation is accumulated. However, the recharge in this city has been estimated to be 128.15 mm per year (11% of the annual rainfall indicated earlier). Considering the rainfall recharge as the sole recharge to the shallow groundwater would make the analysis erroneous as the recharge can take place through the sewer lines, leak water supply pipes and/or open pit latrines.

2.2 Use of Groundwater model

Groundwater Modelling is an efficient tool for groundwater management and remediation. Models are a simplification of reality to investigate certain phenomena or to predict future behavior. The challenge is to simplify reality in a way that does not adversely influence the accuracy and ability of the model output to meet the intended objectives. Decision makers use models to predict the behavior of a groundwater system prior to implementation of a project or to implement a remediation scheme. Clearly, it is a simple and cheap solution compared to project establishment in reality. Groundwater models can be interpretive, predictive or generic. Objectives of groundwater modelling can be listed as Prediction of groundwater flow and groundwater head temporally and spatially. Investigating the effect of groundwater abstraction at a well on the flow regime and predicting the resulting drawdown. Investigating the effect of human activities (e.g. infrastructure development, wastewater discharge, agricultural activities, and landfills) on groundwater quality and quantity. Analysis of different management scenarios on groundwater systems, quantitatively and qualitatively.

2.3 Types of Groundwater Model

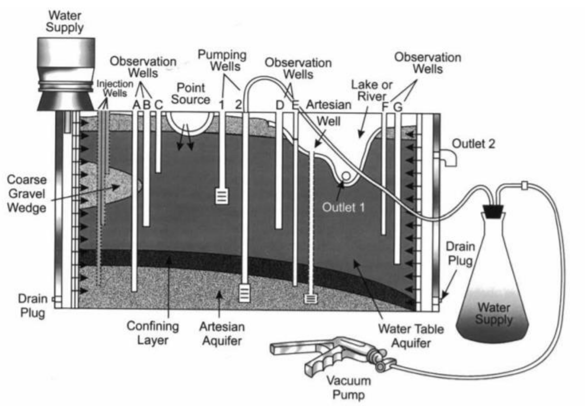
Model can be classified into three categories: physical, analogue and mathematical models. Physical models (e.g. sand tanks) depend on building models in the laboratory to study specific problems of groundwater flow or contaminant transport. The most famous analogue model is the flow of electricity. The electric analogue is based on the similarity between Ohm's law of electric current flow and Darcy's law of groundwater movement. As electric current moves from high voltage to lower voltage, so does the groundwater, which moves from high head to lower head. Mathematical models are based on the conceptualization of the groundwater system into a set of equations. These equations are formulated based on boundary conditions, initial conditions, and physical properties of the aquifer. Mathematical models allow an easy and rapid manipulation of complex models. The mathematical models can be solved either analytically or numerically. Some approaches use a mixture of analytical and numerical solutions. Analytical solutions are available only for simplified groundwater and contaminant transport problems. They were developed before the use of numerical models.

2.3.1 Physical models

The physical groundwater model can be used to understand and visualize many groundwater concepts including groundwater movement, groundwater contamination, and potential land use activities that may impact groundwater. The groundwater model is a glass tank filled with sand, gravel, and clay to represent a slice of the earth. The model simulates how water and contaminants move through different aquifers allowing people to understand nature groundwater.

The physical groundwater flow model is used to demonstrate groundwater movement principles. Constructed with clear Plexiglas, the model allows viewers to watch how the water within a groundwater system travels. For example, the movement of water towards a pumping well can be easily observed.

Water is introduced into the model using inverted quart jars at the ends of the model. A vacuum pump is used to "pump" water from the represented wells; some wells were in the unconfined aquifer, the other are in the confined aquifer. Observation wells show the ground water flow patterns as the wells are pumped. Colored water is used to easily demonstrate the water movement patterns. Colored water can also be used to show how contaminants might move within a ground water system. The "contaminants" can be introduced at the surface or injected at different points within the aquifer.



A B

figure 2 A:- physical model and *figure2 B:-components of physical model*

2.3.2 Numerical models

Numerical models involve numerical solutions of a set of algebraic equations at discrete head values at selected "nodal" points (Figure below). The most widely used numerical methods are finite difference and finite element methods. Other methods have been developed, such as the boundary-element method.

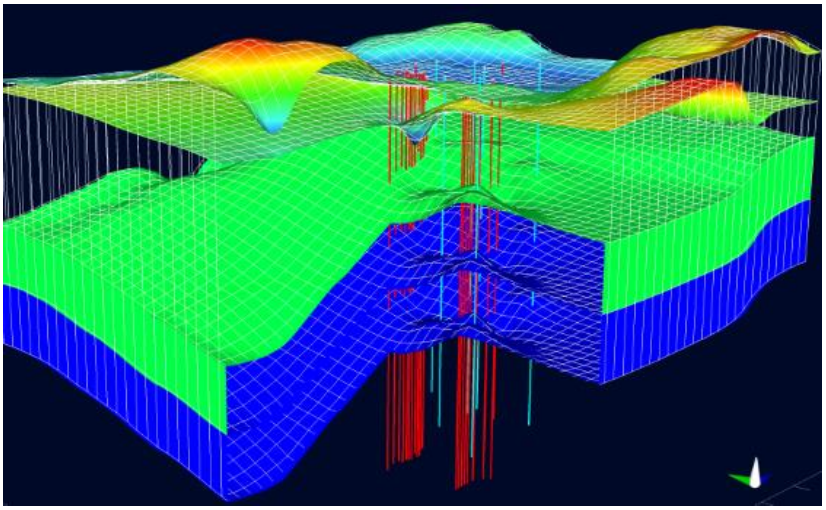


Figure 2.2 :- Numerical model by finite deference mesh method

2.3.2.1 Finite difference method

Finite difference method (FDM) has been widely used in groundwater studies since the early 1960s. FDM was studied by Newton, Gauss, Bessel and Laplace (Pinder and Gray 1977). The accuracy of the method depends on grid size and uniformity. The approximation of the derivative improves as grid spacing approaches zero; however, numerical dispersion and truncation error increases. There are three different methods of finite difference approximation: forward, backward and central difference, depending on the way the finite difference is implemented. The central difference gives the best results as the truncation error is of second order O (Δx) 2 (Pinder and Gray, 1970). The general governing equation for transient, heterogeneous, and anisotropic conditions is given by:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial x}\right)=S_s\frac{\partial h}{\partial t}-W \quad \ldots\ldots\ldots\ldots\ldots (1)$$

WhereKx,Ky, and Kz are hydraulic conductivity in x, y and z directions, respectively. W is the sink or source term and Ss is specific storage. For simplicity, consider a one-dimensional case of Equation (1) and solve for h using the finite difference method. These yields: -

$$\frac{\partial^2}{\partial x^2}=\frac{\partial}{\partial x}\left(\frac{\partial h}{\partial x}\right)=\frac{1}{\Delta X}\left[\frac{h_{i+1}-h_i}{\Delta X}-\frac{h_i-h_{i-1}}{\Delta X}\right]=\frac{h_{i-1}-2h_i+h_{i+1}}{\Delta X^2} \quad \ldots\ldots\ldots\ldots (2)$$

Where h_i, h_{i+1} are the head at node i, and node i+1 respectively (Figure 2.3). Irregular spacing can be used to increase accuracy at selected areas of the grid, but this increases associated error more than regular-spaced grids. As a rule of thumb for expanding a finite difference grid, the maximum multiplication factor should not be higher than 1.5

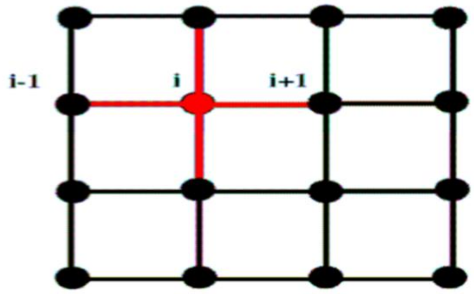


Figure 2.3 The finite difference method

The fig below shows the discretization (square mesh) of the study area using GMS with two layer and refined around well. The mesh include active and inactive cells.

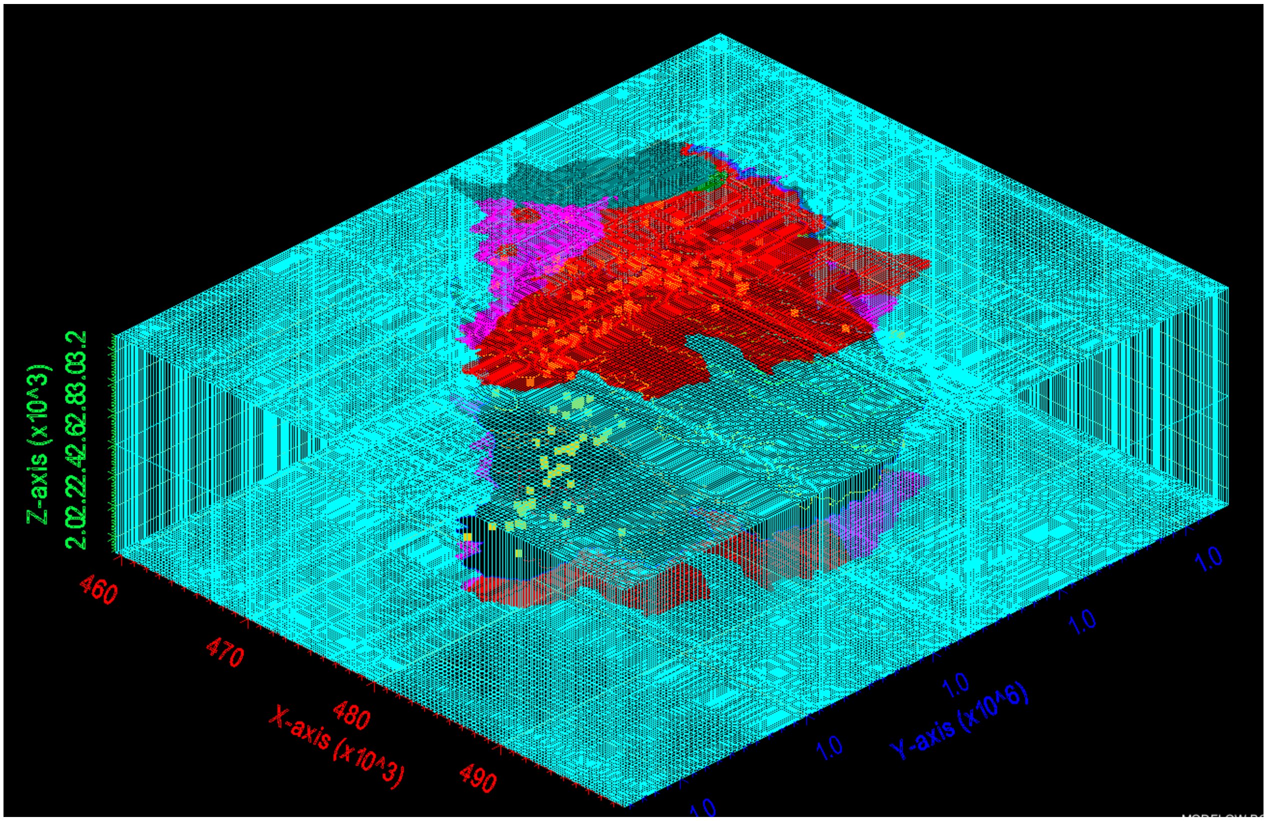


Figure 2.4 Discretization of model domain into FDM in 3D view.

2.3.2.2 Finite Element Method

The basis of the finite element method is solving integral equations over the model domain. When finite element method is substituted in the partial differential equations, a residual error occurs. The finite element method forces this residual to go to zero. There are different approaches for the finite element method. These are: basis functions, variational principle, Galerkin's method, and weighted residuals. Detailed description of each method can be found in Pinder and Gray (1970).

Finite element method discretizes the model domain into elements (Figure 7). These elements can be triangular, rectangular, or prismatic blocks. Mesh design is very important in the finite element method as it significantly affects the convergence and accuracy of the solution. Mesh design in the finite element method is an art more than a science, but there are general rules for better mesh configuration. It is highly recommended to assign nodes at important points like a source or sink, and to refine mesh at areas of interest where variables change rapidly. It is better to keep the mesh configuration as simple as possible. In the case of triangular mesh, a circle intersecting vertices should have its center in the interior of the triangle.

The weighted residual method is being widely used in groundwater finite element problems. The Russian engineer B. G. Galerkin introduced this method in 1915 (Pinder and Gray 1970). To illustrate the weighted residual approach, consider a groundwater or solute transport problem. This problem over a domain B can be written as:-

$$L(\emptyset(x,y,z)) - F(x,y,z) = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where L is a differential operator, φ(x, y, z) is the dependent variable (i.e. groundwater head) and F(x, y, z) is a known function.

The weighted residual method replaces the dependent variable φ(x, y, z) by an approximation function (, $\widehat{\emptyset}$) ˆφ x y z. The later approximation function is made up of a linear combination of a new function that satisfies the boundary conditions of the main problem. It can be written as:

$$\widehat{\emptyset}(x,y,z) = \sum_{i=1}^{m} N_i(x,y,z).\emptyset_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where Ni is an interpolation function, $\emptyset_i$ is the unknown nodal value of dependent variable at node i, and m is the number of nodes. Because (, $\widehat{\emptyset}$) ˆφ x y z is an approximation, there will be a residual R(x, y, z) at each node. This residual is given by:

$$R(x,y,z) = L((\widehat{\emptyset}(x,y,z) - F(x,y,z) \neq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

The weighted residual method forces the residual in Equation (5) to go to zero. This requires:

$$\iiint_B^{\cdot} W(x,y,z).R(x,y,z)dxdydz = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

Where W (x, y, z) is a weighting function and B is the problem domain. Equation (6) can be written in terms of approximation function as follows:

$$\iiint_B^{\cdot} W(x,y,z).\left[L\left(\widehat{\emptyset}(x,y,z)\right) - F(x,y,z)\right]dxdydz = 0 \ldots\ldots\ldots\ldots\ldots \text{(7)}$$

In case of a steady state, two-dimensional groundwater flow problem, Equation (7) can be written as:

$$\iint_B^{\cdot} W(x,y,z)\left[\frac{\partial}{\partial x}\left(k_x\frac{\partial\hat{h}}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_x\frac{\partial\hat{h}}{\partial y}\right)\right] = dxdy = 0 \ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

To solve Equation (8), the weighting function W (x, y, z) needs to be identified. There are different methods of weighting residuals in addition to Galerkin's approach. More details on weighting residuals methods can be found in Gray and Pinder (1970) and Reddy (2006). The main characteristics of the finite element method are: properties and source/sink are assigned at nodes, nodes are located at flux boundaries, and it suites aquifer anisotropy better than FDM. Advantages of this method include: a better mesh configuration, which suites irregular model boundaries, anisotropy is well incorporated, the governing system of equations is symmetric and irregular shapes can be used to represent elements.

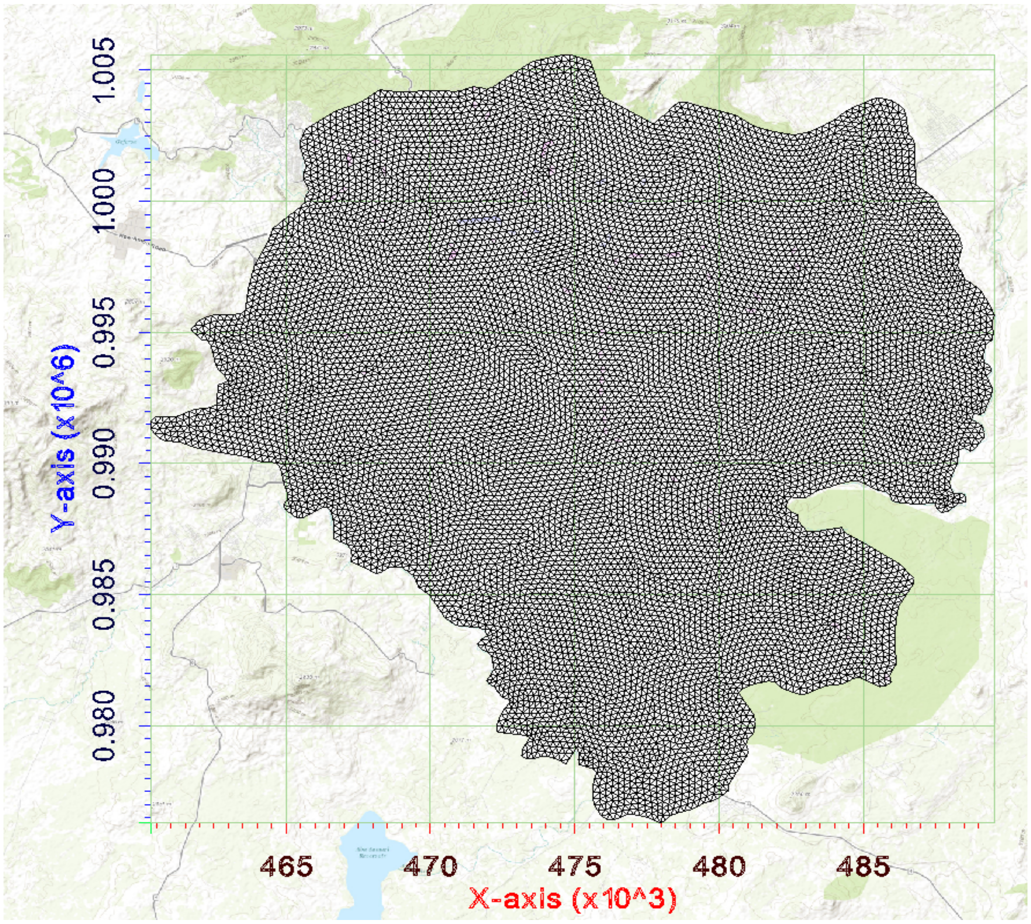


Figure 2.5 Discretization of the model area into a finite element mesh.

The finite element method has some disadvantages. The finite element mesh is not easy to build and consumes time, especially in complicated problems. Also, there is less documentation on the finite element method compared to finite difference method. Unlike the finite difference method, mass balance in the finite element method can be achieved for the entire domain but not for every element. The most well-known finite element based groundwater models are FEFLOW (Wasy, 2005), Femwater (Lin, et. al. 1997), and MODFE (Torak 1993). In this study to build TIN from raster we use the finite element discretization method. Which the most important for interpolation with different data.

2.3.3 Conceptual Model

A conceptual model is a descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrological conditions. Information about water balance is also included in the conceptual model.

A conceptual model is necessary in order to obtain a numeric model. Many aspects of the conceptual model are not possible to represent in numerical model, because the hydrogeological systems are very complex (Wagener, et al. 2007).

Groundwater exploration is defined as "all operations or work that allow the localization of aquifers or underground reservoirs from which water can be obtained in suitable quantity and quality for the intended purpose" (Custodio and Llamas, 1997.) The results of hydrogeological explorations are translated into conceptual models. As shown by Andersson and Woessner (1992), a conceptual model is a pictorial representation of the flow system of groundwater, often in the form of a block diagram or cross section. Conceptual models also include the characteristics of the hydraulic parameters of each unit, the positions of the phreatic and piezo metric surfaces and also groundwater flow conditions. Besides these things, recharge areas and processes must be identified and reserves must be evaluated. The purpose of creating a conceptual model is to simplify the issue being examined and organize the data so the system can be analyzed effectively. Simplification is necessary because a complete reconstruction of the system is impossible. A conceptual model gives the basic idea or visual understanding of how the study area groundwater flow and processes operate.

The key issues that the conceptual model should include are:

- Aquifer geometry and model domain (in this case Addis Ababa city map)
- Boundary conditions
- Aquifer parameters like hydraulic conductivity, porosity, storativity, etc.
- Groundwater recharge
- Sources and sinks identification
- Water balance

2.4 Groundwater modeling Parameters

Groundwater flow strongly depends on groundwater recharge and hydraulic conductivity. Both are spatially variable fields, and their estimation is an ongoing topic in groundwater research and practice. Among the different techniques of estimating recharge reviewed this research consider numerical approaches in which measured time series of hydraulic head are used to estimate groundwater recharge. The key question to be addressed in the present study is under which conditions it is possible to infer both the recharge and the spatial distribution of hydraulic conductivity from the observed hydraulic-head measurements.

2.4.1 Hydraulic conductivity

Hydraulic conductivity is measurement of the ease of a particular fluid passing through the pore space of a porous medium (i.e., conductive properties of a porous medium for a particular fluid) (Obasi et.al. 2013). The proportionality constant in Darcy's law, which depends on medium and fluid properties i.e. grain size, density and viscosity of fluid. Additionally, the hydraulic conductivity is defined as the flow volume per unit cross-sectional area of porous medium under the influence of a unit hydraulic gradient. It is empirical constant to be measured in laboratory. Real subsurface materials always have a complex and irregular distribution of hydraulic conductivity.

The hydraulic conductivity distribution in the study area is described by using the heterogeneity and anisotropy. When the geologic medium in the study area is a heterogeneous material the value of hydraulic conductivity (K) varies spatially, and in a homogeneous material K is independent of location. Anisotropy in the study area implies that the value of hydraulic conductivity (K) at a given location depends on direction. Isotropy implies that hydraulic conductivity (K) is independent of direction at a given location (Fitts, 2002). The hydraulic conductivity of a given medium is a function of the properties of the medium and the properties of the fluid. If hydraulic conductivity is dependent on the direction of groundwater movement, the aquifer is anisotropic and the hydraulic conductivity is a second rank tensor.

$$k = \frac{Cd^2\rho g}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

C: shape factor, a medium property **d**: representative grain diameter, a medium property: fluid density, **g**: gravity$\gamma = rg$: specific weight of fluid, driving force exerted by gravity on a unit volume of the fluid ([g] = kg/m3 * m/s2 = (kg * m/s2)/m3 = N/m3 force per unit volume) μ: Dynamic viscosity, resistance of the fluid to shearing Groundwater model is three dimensional, the hydraulic conductivity is expressed by

$$k = \begin{matrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{matrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

2.4.2 Recharge

The groundwater recharge in the study area is defined as the process of downward movement of water through the saturated zone under the force of gravity or in the direction determined by hydraulic conditions. The groundwater recharge varies in a wide range governed by the rainfall distribution, topography, land use and geology. The major recharge to the aquifer comes from precipitation and river channel losses. Main direct recharge is assumed to take place in all areas except where low permeable lacustrine soils exist (Tenalem et.al. 2008).

Direct recharge occurs from precipitation reaching the land surface. In urban areas this is expected to decrease because of runoff from roofs and paved surfaces diverting recharge. This also occurs if the soils are less permeable because of compaction. The diverted water generally flows onto streets and storm drains where present. The net effect of impervious cover and storm drain is increasing flood peaks and decreasing flood lag times as has been demonstrated repeatedly since Leopold (1968). However, the impervious cover also reduces evapotranspiration losses and, as is indicated below, not all precipitation reaching roadways and parking lots becomes surface runoff.

Although it is commonly stated, that groundwater recharge is reduced with urbanization because of the increase in impervious cover, the reverse is the more common condition – urbanization increases ground water recharge. In some cases, groundwater dependent ecosystems are augmented by increased urban recharge (Sharp et al., 2009). Asquith and Roussel (2007), Drouin-Brisebois (2002), and Scheuler (1994) all indicate little difference in stream baseflows between urbanized and undeveloped watersheds.

2.5 Groundwater Modeling Assumption

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions. Groundwater models, however, even as approximations, are a useful investigation tool that groundwater hydrologists may use for a number of applications.

Groundwater modeling for the study area requires some assumptions that can be modeled by the researcher are:

- Darcy's law is valid which means the groundwater flow in the study area is assumed to laminar.NR <1(laminar, NR is Reynolds number) so Darcy's law is applicable (Todd, page 90).
- The fluid is considered to be slightly compressible and homogeneous.
- The fractured and the continuum medium of the study area maybe represented by equivalent porous medium of having different hydraulic properties depending the nature of the aquifer.
- The porosity and saturated hydraulic conductivity are constant with time.
- The model takes two layer having the variable hydraulic conductivity and porosity value from the surface up to the bed rock floor of the model.
- The rivers in the study area is taken us a constant head boundary and the boreholes are a constant flux boundary.

Application of existing groundwater models include water balance (in terms of water quantity), gaining knowledge about the quantitative aspects of the unsaturated zone, simulating of water flow in the saturated zone including river-groundwater relations, assessing the impact of changes of the groundwater regime on the environment, setting up/optimizing monitoring networks, and setting up groundwater protection zones.

2.6 Limitations of the Groundwater Model

The ability of groundwater models to accurately predict the behavior of groundwater flow in real-world situations is poor. At best groundwater models, despite their high degree of precision, are qualitative predictors of future behavior. A major cause of the lack of accuracy is the severe discrepancy between the scale of measurement necessary to understand aquifer parameters for accurate modeling and the scale of measurement generally made under the constraints of limited time and limited budgets. In teaching groundwater modeling, it is important that researches should be aware of the shortcomings of modeling. Undoubtedly, any model they create will be an extreme idealization of nature and will be non-unique. A non-unique model is one that inherently possesses error. Given these shortcomings, the worth of modeling in making planning decisions can only be derived from analysis of qualitative trends in the overall results

This research is done using groundwater modeling system (GMS) which uses different types of module depending on the type of data and research type. To simulate the groundwater head it uses MODFLOW model to obtain groundwater contour map which uses finite difference approach to model the study area. The advantages of the finite difference method are that it is easy to implement, well documented and produces reasonably good results. However, finite difference method has some disadvantages.

The main disadvantage is that it does not fit properly to an irregular model boundary. In addition, the distribution of grids, their size, and whether they are of equal size highly affects the accuracy and computation. Output accuracy of the finite difference method is not good in the case of solute transport modelling. Mass balance is not guaranteed if conductivity or grid spacing varies (Cirpka 1999). The most widely used finite difference based groundwater model is MODFLOW (Harbaugh and McDonald 1996).

2.7 Addis Ababa city Infrastructure Development plan

The government is carrying out large scale infrastructure development in urban as well as rural areas. This is a good opportunity that will facilitate the urbanization and urban development processes. At present, the opening up of new streets and mass transport lines around Addis Ababa that go even beyond the city and its surrounding is enhancing investment and socio economic interaction between Addis Ababa and the surrounding towns.

Mass transit attracts/enables high density development along corridors. In view of the scarcity of land in the capital, inner city redevelopment could strategically focus on densification along these corridors. In addition, mass transport route development enables to re-structure the city in a polycentric manner. By connecting centers to different parts of the city, it is possible to avoid needless commuting. Through mass transit route development, it is possible to achieve high mobility, increased connectivity and improved urban quality. Moreover, urban redevelopment is key for improving urban quality, allowing for better provision of green open spaces, plazas, squares, and parking space through surgical planning; and to get vacant/open areas for regeneration and to implement decentralized service provision.

The population of the city and its surrounding almost doubles every 15 years (Addis Ababa city planning and development office 2019). However, the corresponding urban services have always lagged far behind the demand. A good example is the existing housing problem especially in Addis Ababa. The direct provision of decent housing by the public sector and the creation of fertile ground for other actors to play the lead role are both necessary. In the past ten years, the government has tried to address the housing issue in the city by providing land for self-help housing and for real-estate developers, and by directly involving in the construction of low-cost housing. Although much has been achieved in terms of the number of the constructed houses and other related outcomes, it has had little effect as compared to the magnitude of the need. This government initiative has surpassed expectations but it is still not enough. What is more important at this juncture though is that at least the Addis Ababa City Government cannot go on providing vacant land for housing. It is time to make a shift from focusing only on green field housing development. If housing development uses gray area, as it had for example at Lideta or Arat Killo, it would also serve in regenerating neighborhoods. If integrated with mass transport route and boulevards, it could go beyond revitalizing communities to serve as an engine of economic growth. It is relevant to point out here that such kind of large scale housing development should not jump here and there looking for less dense or vacant areas. Rather, it should focus on strategically selected corridors and spots for maximum development effect.

2.7.1 Groundwater and surface water contamination and solid west disposal site plan

The ever-increasing economic, social and administrative activities in the city generate various sorts of wastes that need to be properly managed. About 25% of the solid waste generated in Addis Ababa is indiscriminately dumped within residential neighborhoods, while the remaining 75% is collected but disposed-off in unsanitary manner at Reppi controlled dumping site(Addis Ababa city west disposal and management office). The Reppi site has served beyond its design period and has been a source of serious public and environmental health threats. The practice of waste separation at source is almost absent and only 10% of the solid waste is reused/recycled, including organic waste that is composted.

Similarly, the availability of household level sanitation facilities leaves a lot to be desired. About 70% of the population uses pit-latrines as onsite sanitation facility, while the available few public toilet (1 public toilet: 50,000 population) are either inaccessible, out of use or mismanaged. Moreover, the Addis Ababa Water Supply and Sewerage Authority's (AAWSA) recent business plan indicates that only 6.5% of the population in Addis Ababa is connected to the municipality-managed centralized sewerage system that employs waste stabilization pond treatment technology. The use of such type of technology is not suitable for a city like Addis Ababa in view of escalating land values and presence of large settlements. Despite the preparation of a sewerage master plan for Addis Ababa a decade ago, its implementation has been partial. Currently, the AAWSA is executing three major sewerage system development related projects that aim at serving about 4 million inhabitants by 2030.

Pollution of surface and ground water resources, which emanates from domestic and industrial wastewater discharges as well as urban runoff, is another critical problem faced by the city. There is a high concentration of different categories of industries that utilize and/ or manufacture large amounts of chemicals including leather, food and beverages, textile, plastic, and printing. Most of these industries discharge their untreated wastewater effluents into nearby rivers and drainage systems. The effluents contain various categories of organic matter, nutrients and heavy metals that are often beyond the permissible concentration levels indicated in the Ethiopian ambient guideline standard for water quality. The available studies on ambient surface and groundwater qualities indicate the presence of high concentrations

In general, the Structure Plan for environmental protection and development aims at contributing to the livability of Addis Ababa by:

- Ensuring clean environment;
- Providing adequate, accessible, networked and functional green spaces;
- Ensuring sustainable natural resource utilization and management, and
- Reducing exposure to natural disasters.

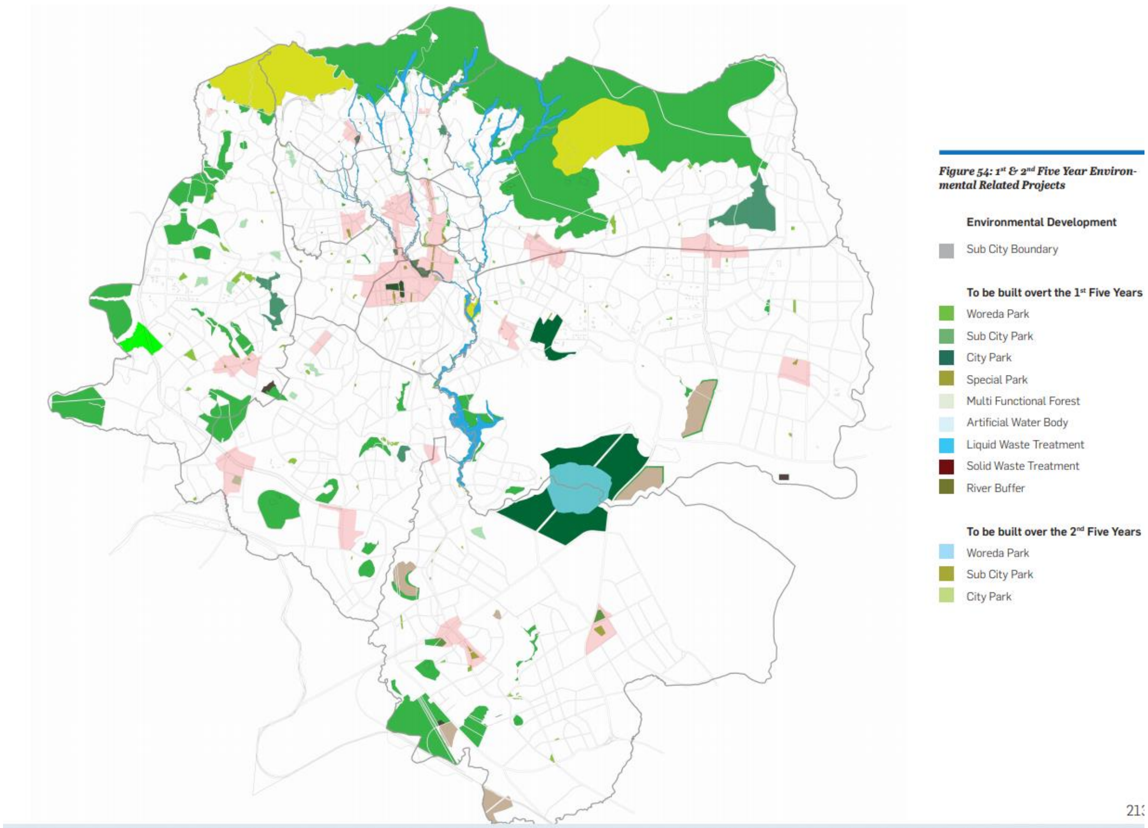


Figure 2.6:-Environmental development plan(Addis Ababa city structure plan by Addis Ababa city planning project office 2017-2027)

3. METHODOLOGY OF THE RESEARCH

The objective of the study is to develop and describe the effect of shallow groundwater on existing and planned infrastructure. To achieve this objective the shallow groundwater system in the capital city shall be well understood for which a numerical groundwater modeling technique-based GMS software was used. Accordingly, this section at first describes the methodology that defines the input data needs and the procedures adopted in creating the numerical groundwater model using GMS, then the effect analysis through GIS overlay will be discussed. To model a given groundwater aquifer system and to identify the effect of shallow GW on city infrastructure a modeling producers has been followed and model result is discussed.

- Mathematical model, and conceptual model creation
- Computer simulation.
- Groundwater modeling the shallow aquifer
- Result overlay with infrastructural plan map and discussion

To do this research a well understood producers have been followed. The first step was clearly defined the problems of the research that faced and this was described in the problem of statement. To tackle this problem reading research papers that are done by different governmental and non-governmental organizations, plans, articles journal and magazines that has similar with this research. This helps to start up our findings on the study are and to further see more other related problems and to see other options of tackling the problem.

Data are collected from different offices such as ministry of water, irrigation and energy, Ethiopian geological survey, Addis Ababa water and sewerage authority, Ethiopian water works design and supervision, Addis Ababa city planning commission etc. From appointed government offices different data are obtained to see the finding in more detail. The necessary data that are Important for the research are hydrogeological data, geological data, rivers, lakes and stream data, borehole log data etc.

Modeling is the next step of the study which is started by finding collected and properly arranged data. Groundwater modelling using groundwater modeling system software which a powerful tool for water resources management, groundwater protection and remediation. Decision makers use models to predict the behavior of a groundwater system prior to implementation of a project or to implement a remediation scheme. Clearly, it is a simple and cheap solution compared to project establishment in reality.

The result of GW head from the model is the groundwater table distribution across the city of Addis Ababa. The final step is to overlap the existing and planned infrastructure development of the city with the groundwater table obtained in the prior step. This final step will identify the reseporical effect of the groundwater and infrastructure development.

3.1 Description of the study area

Addis Ababa is located in the central highlands of Ethiopia, with the altitude that ranges from 2100 m.a.s.l to 3200 m.a.s.l which covers an area of about more than 540 $km2$ with a population of more than 4.8 million inhabitants in 2020GC. Its geographic location is between 38.6380^o and 38.906^{o}east and 8.832^o and 9.09^o north. The administration of the city is divided in to ten sub-cities: Bole, Arada, Cherkos, Kolfe Keraniyo, Addis ketema, Lidata, Akaki-Kaliti, Gullele, Nefas-Silk Lafto and Yeka.

Addis Ababa was established as the capital city of Ethiopia in 1886 and has grown to become the largest urban and commercial center in the country. Infrastructure can be define as the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance societal conditions. The principal sources of water were the numerous springs located at the foot of the Entoto mountain range and manually Duggen wells located in the lower areas. The morphology of the Addis Ababa area is complex. Entoto Ridge, which constitutes the northern boundary of Addis Ababa, has ragged topography characterized by steep slopes rapids and water falls. Towards the south, the morphology changes to quite gentle slopes though there are some hilly features.

3.1.1 Surface topography

Addis Ababa lies at an elevation of 2,355 meters and is a grassland biome, located at 9°1′48″N 38°44′24″E. The city lies at the foot of Mount Entoto and forms part of the watershed for the Awash. From its lowest point, around Bole International Airport, at 2,326 meters above sea level in the southern periphery, Addis Ababa rises to over 3,000 meters in the Entoto Mountains to the north.

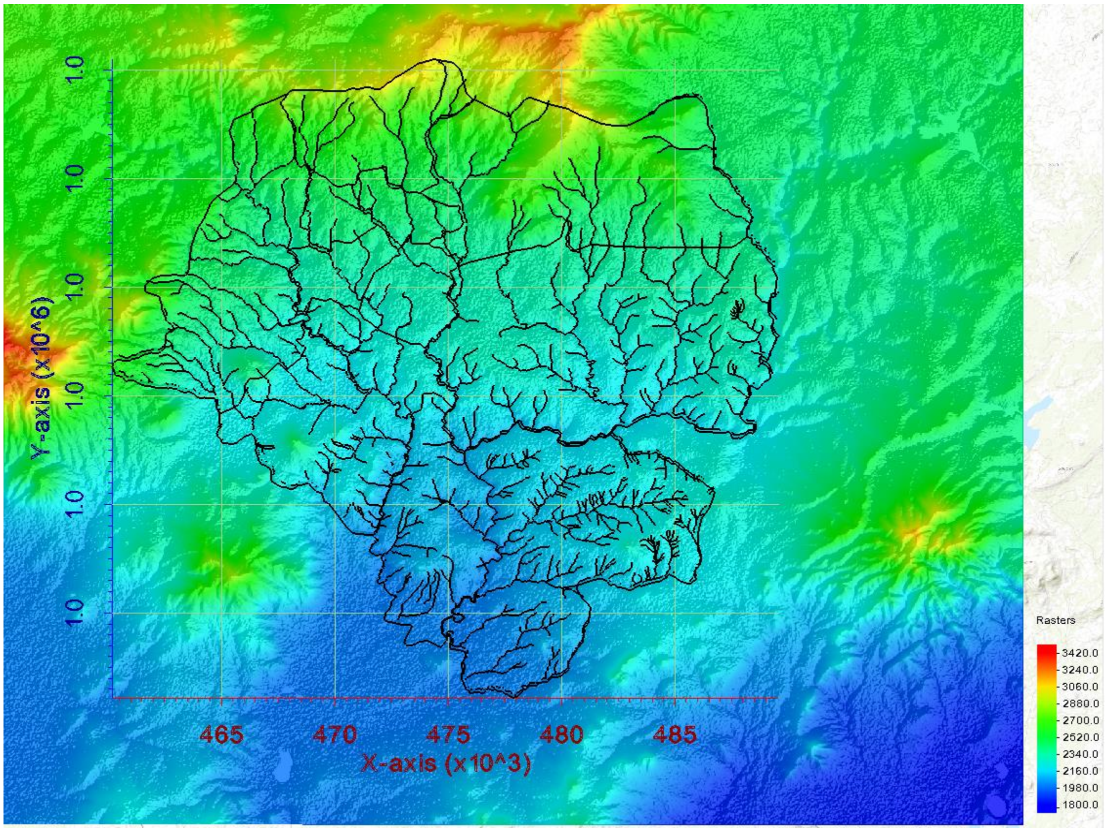


Figure 3.1:- Topographic elevation and surface drainage map of Addis Ababa

3.1.2 Metrology

Addis Ababa has a subtropical highland climate with precipitation varying considerably by the month. The city has a complex mix of highland climate zones, with temperature differences of up to 10 °C (18 °F), depending on elevation and prevailing wind patterns. The high elevation moderates temperatures year-round, and the city's position near the equator means that temperatures are very constant from month to month. As such the climate would be maritime if its elevation was not taken into account, as no month is above 22 °C (72 °F) in mean temperatures. Mid-November to January is a season for occasional rain. The highland climate regions are characterized by dry winters, and this is the dry season in Addis Ababa. During this season the daily maximum temperatures are usually not more than 23 °C (73 °F), and the night-time minimum temperatures can drop to freezing. The short rainy season is from February to May. During this period, the difference between the daytime maximum temperatures and the night-time minimum temperatures is not as great as during other times of the year, with minimum temperatures in the range of 10–15 °C (50–59 °F). At this time of the year, the city experiences warm temperatures and a pleasant rainfall. The long wet season is from June to mid-September; it is the major winter season of the country. This period coincides with summer, but the temperatures are much lower than at other times of year because of the frequent rain and hail and the abundance of cloud cover and fewer hours of sunshine. This time of the year is characterized by dark, chilly and wet days and nights. The autumn which follows is a transitional period between the wet and dry seasons. The highest temperature on record was 30.6 °C (87.1 °F) 26 February 2019, while the lowest temperature on record was 0 °C (32 °F) recorded on multiple occasions.

3.1.3 Geology and hydrogeology of the study area

Succession from bottom to top (stratigraphically) are Basalts, Entoto Silicics, Addis Ababa Basalts, Nazareth Group and Bofa Basalts. The urban geo-morphology is directly dictated by the tectonic and volcanic activities of the nearby Afar Rifting System. The western, north and north eastern land mass is either part of or is bounded mainly by mountain plateau that include Furi, Wochecha, Jemo and Entoto mountain ranges. The central part of the urban land mass has been characterized by rolling land features and denuded small hills. Many faults and fault-like structures which vary in length are observed in the wider expanse of the city. The existing fault development is strongly related to the regions' tectonic and volcanic activities. Similarly, the types and characteristics of groundwater, soil and rock in the area have been influenced by the regions' geo-environmental conditions and activities as well as man- made urban activities.

Rocks and soils for construction: Addis Ababa and its environs lies on volcanic regime where volcanic products like basalt, Rhayolites, Ignimbrite and scoracious material and tuffs predominate. In most parts of the successively upgraded area, these geological materials have been exposed to a long term weathering process. As a result, large quantities of red-brown and black clays, which are playing significant role in the construction sector, have developed. The Structure Plan identifies and delineates around 2500 ha of land in important sites for potential exploitation of aggregates and sub-base materials to serve the construction sector for the plan period (groundwater study of Addis Ababa area 2001).

3.1.4 Geological setting

The geology of the area consists complete succession of Precambrian basement, Paleozoic and Mesozoic sediments, Tertiary and Quaternary volcanic and quaternary sediments. In general the dominant lithological units from the oldest to the youngest are lower ignimbrite Entoto rhyolite, trachyte and ignimbrite, Wechecha-Yere-Furi ignimbrite/trachyte & tarchy basalt, Quaternary plateau basalts of central Ethiopia and Quaternary supper facial deposits. According to the studies conducted by different geologists on the city of Addis Ababa area (Kebede Tsehayu & Tadesse Hailemariam, 1990, Seureca, 1991, Morton and al, 1979, Antonio Vernier & Tesfaye Chernet, 1985, Gasparon and al, 1993 and BCEOM/Suereca 2000), the following rocks are exposed generally from the north to the south (figure 3.2). They are:Trachytes, rhyolites, basalts and pyrocalstics of Entoto Mountain and northern and northeast Addis Ababa. Basalts of the central and southern Addis Ababa known as Addis Ababa Basalt; Ignimbrites of the eastern (Bole area) and central Addis Ababa (Ledeta area);

Trachy-basalts, trachyte, ignimbrite and tuff forming the volcanic mountains of Wechecha, Furi and Yerer; Basaltic lava, spatter and cinder cones and maars of Akaki and Lacustrine deposits, Alluvial and residual soils: Lacustrine soils occur around Bole, Lideta, Mekanisa, between Abasamuel Lake, Akaki town and small Akaki River and their thickness of this deposit varies between 5m and 50m.

Since Addis Ababa is located at the edge of the Ethiopian Rift, there are a number of fault systems having a general trend of the rift system (NE - SW) and some faults and lineaments-oriented E-W, N-W and NE - SE. The density of faults and lineaments increases to the southeast of the town towards the rift valley.

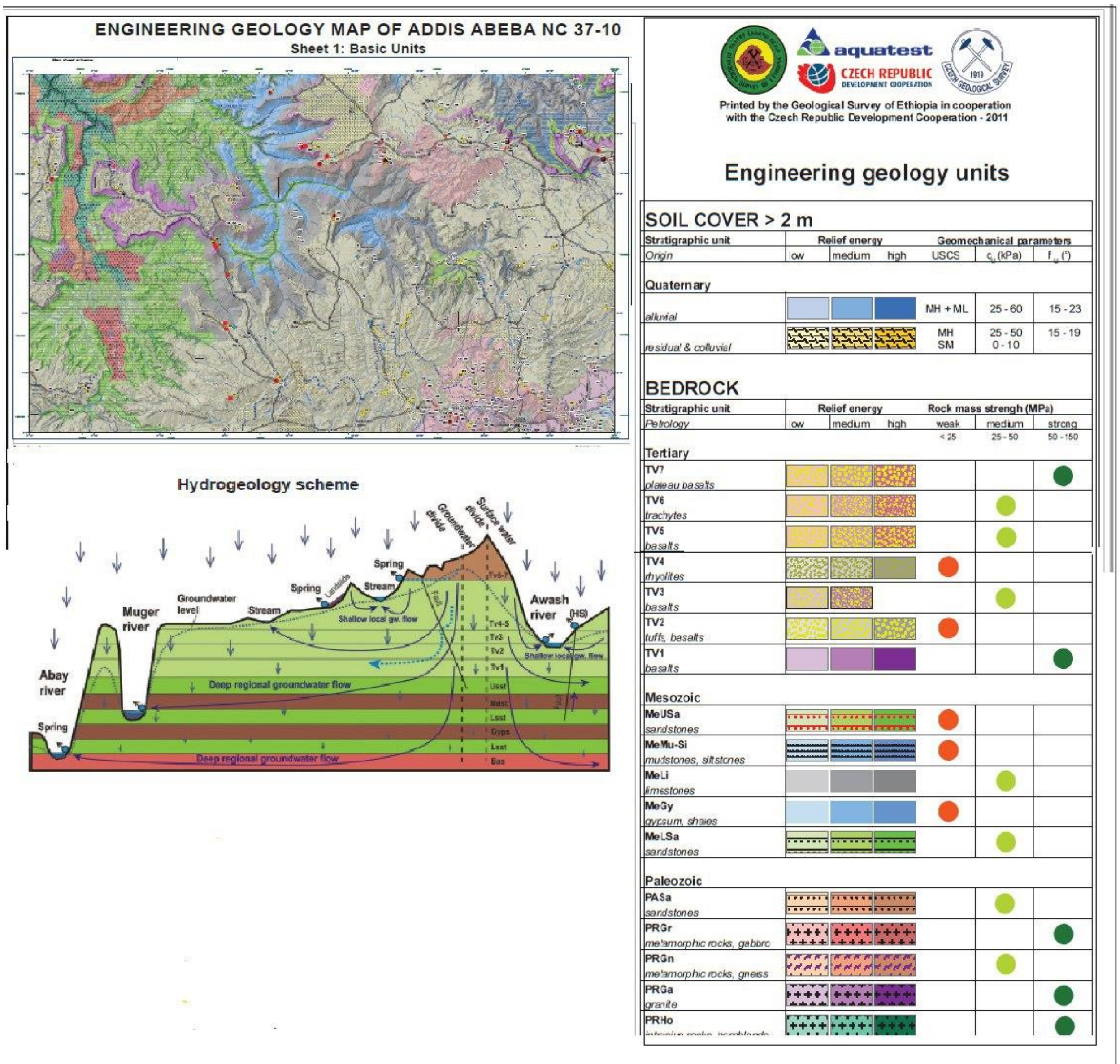


Figure 3.2: - geological map of Addis Ababa prepared by geological survey of Ethiopia (GSE)

3.1.5 Hydrogeology of the study area

Addis Ababa city found at the edge of the main Ethiopian rift valley. The dominant geological formation found in the city area is volcanic rocks (ignimbrites, ryholites, basalts, scoria, etc.). Generally, from north south the geological formation changes from trachytes and ryholites at the north to basalts at the center to basaltic lava and cinder cones to the south. The aquifers of northern and central part of Addis Ababa city and in the mountain area are largely due to weathered and fractured volcanic rock with minor sediments deposited between different series of lava flows.

The aquifers at the southern part of the city (Akaki well field) are mainly young volcanic rocks of lava flow and tectonic fractures. In general, the aquifers are complex and highly variable. The thickness of the aquifers is not yet determined.

3.1.6 Hydrology of the study area

The occurrence of groundwater is mainly influenced by lithology, geological structures, and geomorphology and climate conditions. Lithology, geological structures and geomorphologic setting of the area strongly influence the quantity, quality and movement of groundwater. Since the climate condition throughout the area seems uniform, it has the same effect through the entire area. The geology of the area provides usable ground water and good transmission of rainfall to recharge aquifers, which produce springs and feed perennial rivers.

Fractures, joints and weathering surfaces of different lithological units play a vital role in facilitating the infiltration amount and rate and also ground water flow. The majority of productive aquifers are characterized by their high degree of weathering and intense fracturing. Fractured volcanic rocks and karst limestone are the major potential rock units for storage and movement of ground water. In addition, the inter-granular pour spaces of sandstone and alluvium also have significant role in occurrence of ground water. The main recharge for ground water of the area is precipitation, although surface water and Perennial River and streams are also act as local recharges. The classification of different lithological units are made by Ethiopian Geological Survey based on hydrogeological characterization of various rock types. This classification is also done based on desk study and field inventory. The technical report used the qualitative and quantitative parameters to classify the hydrogeological unites in to Aquifer/Aquitard system. Since the quantitative parameters such as permeability, transmissivity, aquifer thickness and yield are not sufficient to make classifications, it is obligatory to assess the qualitative parameters in order to achieve on complete classification. The quantitative classification is based on the ground water point inventory data and from well completion report and pump test data and this research try to show this part more in detail in the borehole modeling section. The major hydrogeological units are characterized into pours, fissured and/or karst permeability and impermeable rocks.

The root along the bank of the river in city have river sediment deposit which have high hydraulic conductivity. Such kind of soil stratigraphy increase the shallow GW and the water table become near surface for considerable period of wet season .

The rapid urbanization is added with this kind of natural environment may cause flooding. Due to rapid urbanization and population increase, low-income communities are forced to settle in flood-prone areas additionally the poor drainage systems of the city also intensify the risk of flooding as well. The reduction of green structures and the increase in the impervious area in urban areas generates more surface runoff even from regular storms and the situations will be more worst when poor people settle in areas which are vulnerable to flooding such as riverine and low-lying floodplains.

3.2 Data collection and Data type

In this study data collection become difficult because until now such studies has not been done before on shallow GW in the study area. Even though it was difficult both data collection techniques: primary and secondary method of data collection from site and offices was collected respectively. Secondary data are collected through literature studies and document analysis from those concerning organizations.

Some of the most important data are collected from the listed offices. The geological map of Addis Ababa from geological survey of Ethiopia (GSE), lithological data taken from water work design and supervision (WWDS), and well & spring inventory were collected from ministry of water, irrigation and energy and the rest from different governmental and non-organizations. The digital elevation (raster), the topo map, and different necessary dates are collected using internet or web access.

3.2.1 Well inventory data

The well inventories data are the constraint input parameters for groundwater model; therefore collecting these well inventories data is a necessary survey for this research basically focusing on the shallow GW level that means static water level and dynamic water level. The well inventory data are collected from ministry of water, irrigation and energy show there are more than 500 wells in the city. As the concern of this study is to understand the shallow groundwater situation wells having less than 100m depth were selected for further analysis as shown in the map (figure 3.3).

The well inventories data includes: -

- ❖ The location, X and Y coordinates of (borehole, wells and springs) in UTM
- ❖ The water table depth (the static water level and dynamic water level of the well).
- ❖ The well yield, geology of the borehole site is also essential for more clarity of the data.

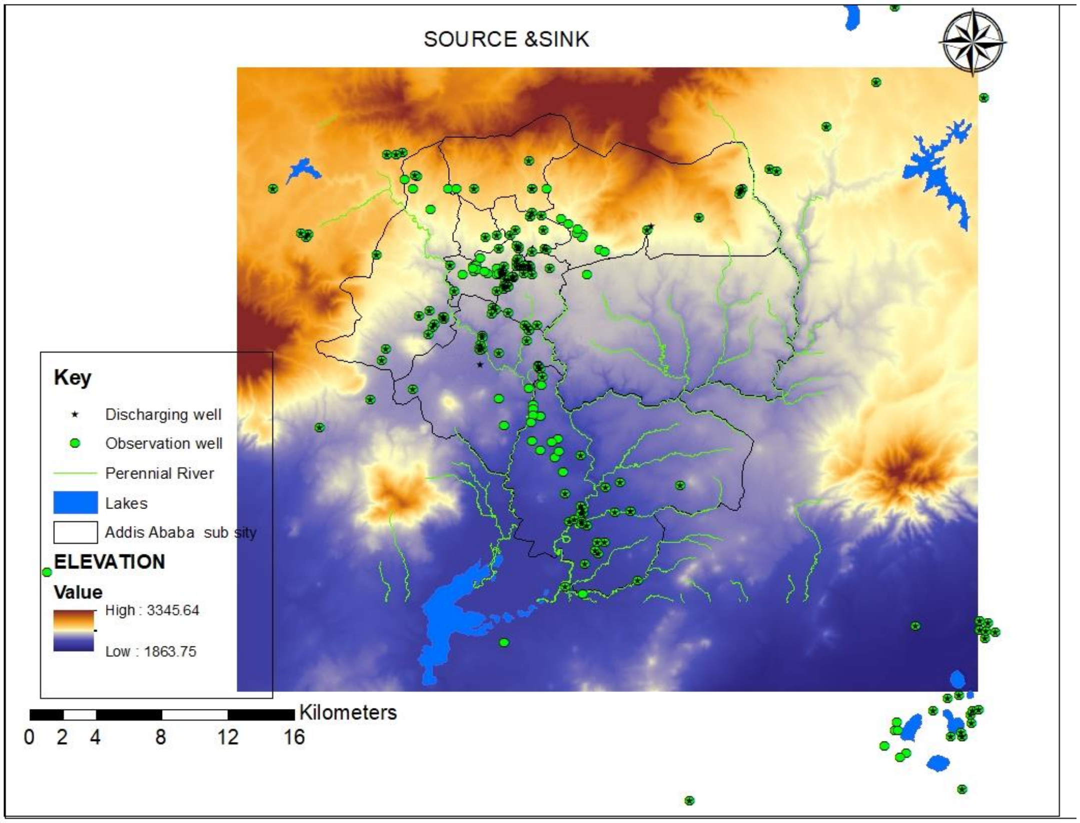


Figure 3.3: - Well inventory & source sink data using

3.2.2 Rainfall data

In addition to the well inventories data the model need the rainfall (the annual and the monthly rainfall records, which are essential to define the recharge in the study area. The rainfall records are taken from the national metrological agency (NMSA) in daily, monthly and grid rainfall data basis as per the accessibility of the data from the organization shown in (figure 3.4). Throughout the year, in Addis Ababa, there are 132 rainfall days, and 1165mm of precipitation is accumulated.

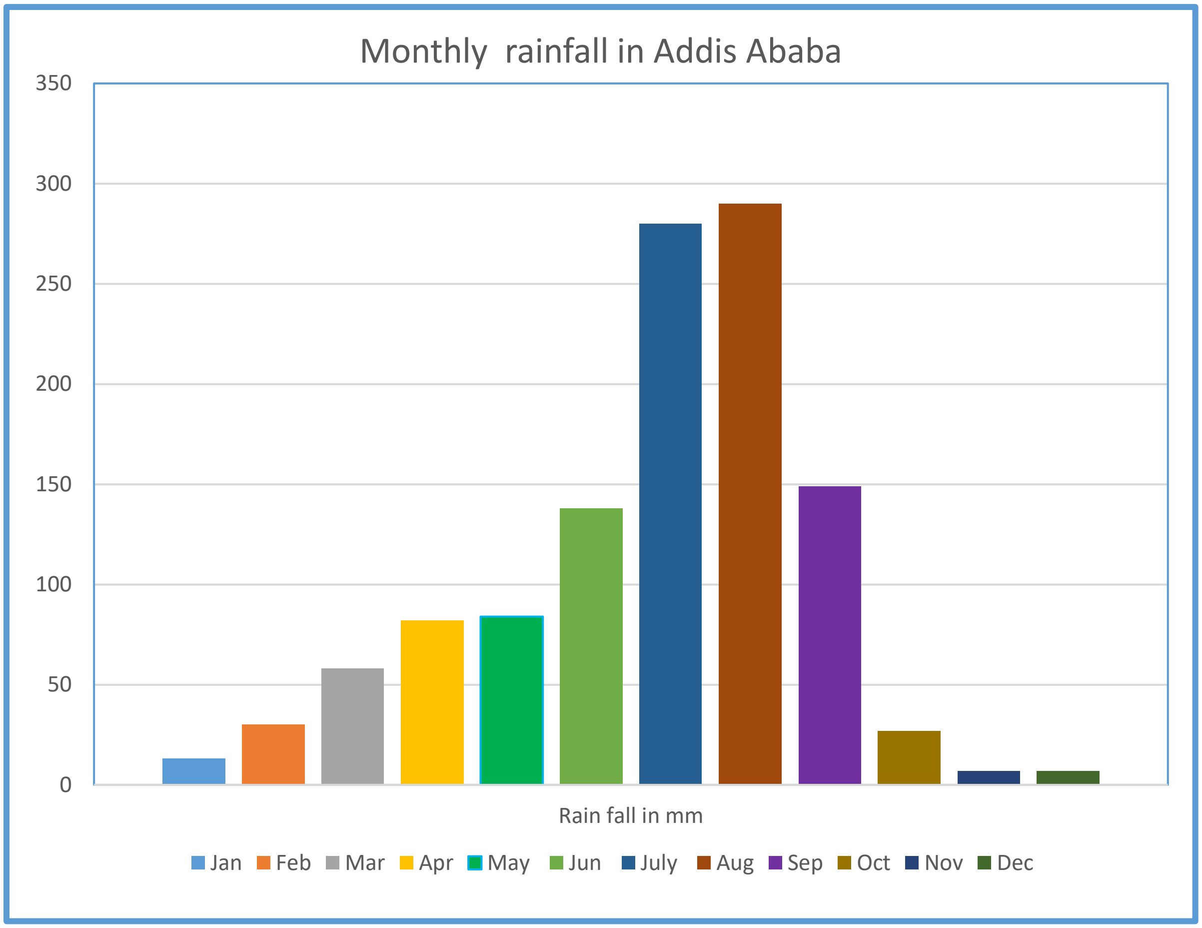


Figure 3.4:- Average monthly rainfall (mm) in Addis Ababa

3.2.3 Drainage Data

Drainage data are important for this research to know and model the shallow GW since river are recharging or discharging to the GW. It is probably a common conception that the water flowing in rivers and streams comes from precipitation runoff from the landscape into the river. Of course that is true, but it is not entirely true. What I mean is, GW contributes to streams in most physiographic and climatic settings to a certain degree; some of the water flowing in rivers comes from seepage of shallow GW into the streambed. The water flowing in rivers still originates from precipitation, but it is not all from surface runoff. This groundwater seepage is vitally important to the hydrologic settings of the study area because it is responsible for keeping water in rivers during times of no rainfall (base flow conditions).

Akaki River consists of two main branches, the confluence of which is at the Aba-Samuel reservoir. The western branch of the river, the Little Akaki, raises north-west of Addis Ababa on the flanks of Wechacha Mountain and flows for 40 km before it reaches the reservoir. The eastern branch of the river, the big Akaki, rises north-east of Addis Ababa and flows into the Aba-Samuel reservoir after 53 km flow. In the Addis Ababa city, there are dissimilar perennial and intermittent streams which are tributaries of the little or Big Akaki Rivers, and towards the south approximately all streams or big tributaries crossing the city in different direction join either of the rivers.

The perennial streams in the city are Bantyiktu, Kurtume, Kebena and Ginfile as shown in the (figure 3.5) below. The remaining streams are intermittent in nature. Streams are intense on the top of the mountain forming radial and dendritic drainage patterns. All the major streams of the catchment originate in its northern part and maintain the name Akaki as they leave the lake passing via a gorge up to 100m deep which extends for about 8 km prior to joining the Awash River.

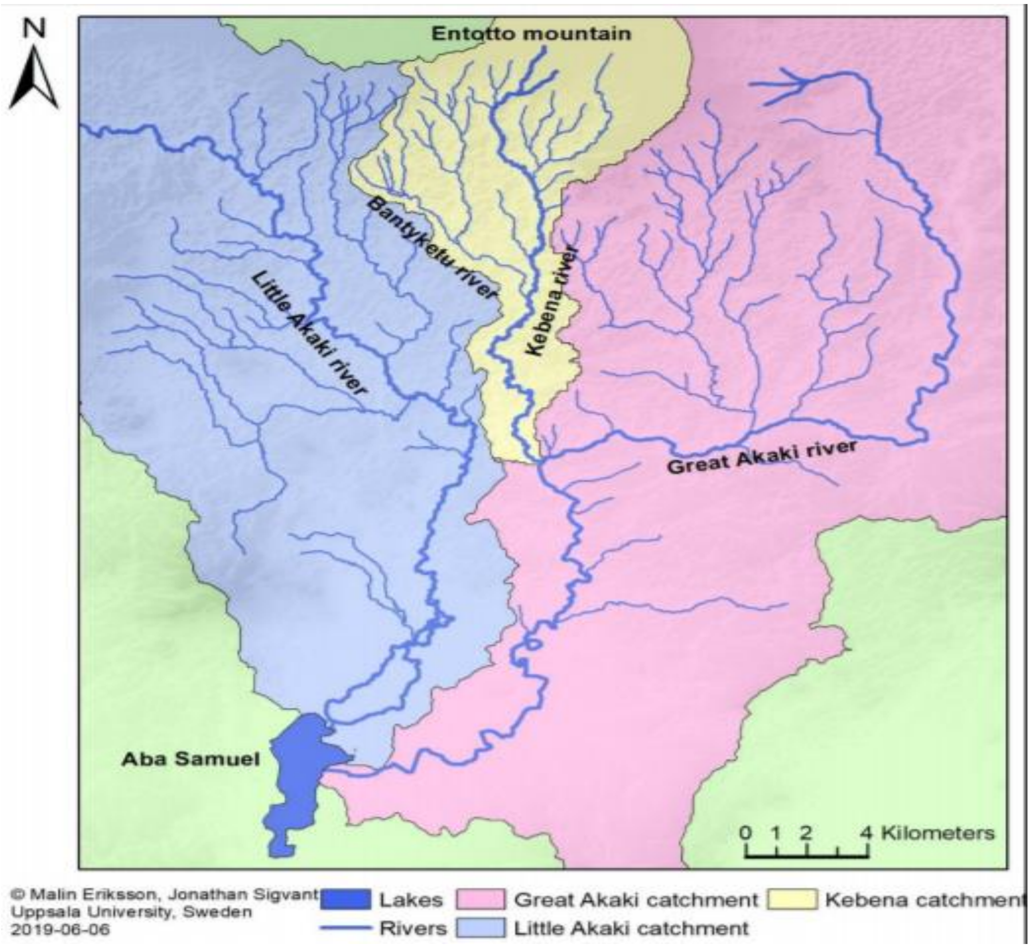


Figure 3.5:- Drainage map of Addis Ababa (Source Jonathan Sigvant and Malin Eriksson. 2019)

3.2.4 Lithology and hydrogeology data

The lithology of the wells are very important for borehole modeling in GMS to show the aquifer property down the surface of the study area and assign hydraulic conductivity. The created borehole model shown (figure 15) blow is converted to solid model by interpolation of the single borehole log in to wide area by horizon method of interpolation automatically by the software.

Lithology data were collected from water works designed and supervision enterprise. It refers to the nature of the soil and rock down the surface of the earth. The data are collected during borehole drilling and well development. The Borehole module of GMS visualizes boreholes created from drilling logs and to construct three-dimensional cross sections between boreholes. These cross sections show the soil stratigraphy between boreholes. Once a set of cross sections is built, the cross sections can be displayed in 3D space to help characterize and visualize the soil stratigraphy of the study area.

Table 3.2:-Borehole log data and soil stratigraphy

No.	well Index	UTME	UTMN	Depth, m	SWL	DWL, m	DD, m	Q (l/s)	Transmissivity (m^2/day)	Specific capacity, l/s/m
1	KDPW-01	479316	999941	271	118.36	141.33	23.48	50	4.46E+2	2.13
2	KDPW-02	479310	999940	250	107.3	153.9	45.7	15	4.82	0.33
3	DCPW-01	463973	991974	405	45.25	83.1	37.48	54	83.9	1.44
4	DCPW-02	463590	992116	432	80.1	144.7	63.85	50	144.7	0.78
5	MKPW-01	470682	987316	357	Artesia	141.22	141.22	50	1.4E+1	0.35
6	MCPW-01	466336	1000658	420	96.8	99.57	2.77	53	728	19.13
7	KHPW-01	482076	999660	236	32	63.72	31.96	55	0.263	1.72
8	MCPW-02	466841	1000105	392	73.9	126.39	18	52.48	5.2x10-2	2.92
9	APW-01	467840	1001410	406	126	202	76	43	7.56	0.57
10	SAPW-01	465819	1002574	339	84.62	179.3	94.6	55.5	62.6	0.59
11	TBH-01	470158	1001882	505	61.65	172.28	110.63	32	45.3	0.29
12	TBH-02	470503	1002189	410	99.15	209.7	110.55	30	0.66	0.27
13	KPW-01	474203	1002351	546	158.02	224.41	66.39	14.3	28.7	0.22
14	SBH-01	469302	1001458	550	147	215	68	6	0.97	0.09
15	KMPW-01	472720	1002256	312	58.85	110.03	52.13	10	2.01	0.19
16	KSPW-01	483763	999358	550	225	-	-	-		

No.	well Index	UTME	UTMN	Depth, m	SWL	DWL, m	DD, m	Q (l/s)	Transmissivity (m^2/day)	Specific capacity, l/s/m
17	AASPW-01-16	465635	1001021	473.5	35.42	72.9	37.48	60	2.65E+03	1.60
18	AMPW-01-16	465517	1002276	517	71.23	193.82	122.59	12	7.28	0.1
19	GKPW-01-16	477067	1001053	500	81.68	117.79	36.11	53	1.64E+02	1.47
20	IEPW-2	476287	1000116	409	95.3	124.53	29.23	57	3.39E+05	1.95
21	SMPW-01-16	473314	1002774	287.3	85.15	188.88	103.73	35.5	2.59E+04	0.343
22	F1PW-01-16	475466	1000729	512.69	142.38	163.82	21.44	53	5.66E+2	2.47
23	F2PW-01-16	475976	1001005	500	153.25	169.78	16.58	37.5	8.18E+2	2.261
24	SGPW-01-16	472585	982237	537.37	41.4	188.4	147	15.5	3.03E+4	0.1054
25	SPW-01-16	476370	983392	302	Artesia	-	-	103	-	-
26	H19PW-01-16	474402	1001122	505	136.57	151.51	14.94	53	1.45E+2	3.547
27	KGPW-01-16	474716	985017	394	Artesia	15.85	15.85	69	3.46E+2	4.353
28	GPW-01-16	471925	990400	352	21.80	51.14	29.34	58.1	4.03E+2	1.98
29	LPW-01-17	472456	995639	500	Artesia	-	-	-	-	-
30	24KPW-01-17	477052	995894	468	83.5	213.8	130.3	8.5	2.32E+1	0.065234
31	BHSPW-01-17	476933	994457	500	62.8	145.2	82.4	37.5	2.70E+01	0.455
32	NSPTCPW-01-17	473446	991371	507	93.20	137.98	44.78	72	3.47E+2	1.6

The lithology of the study delivers upright diffusion of rainfall and surface water bodies to recharge aquifers, which produce springs and feed perennial rivers and which are the main sources for swamp area this may affect the infrastructural development in different way. In some places of the study area observed that projects are stopped due to swamp and bad geological nature of the stratigraphy.

Figure 3.6:- Swamp area around Megenagna low cost residential building.

3.2.5 Addis Ababa city infrastructural plan map

Addis Ababa city infrastructural plan was developed by Addis Ababa city planning commission project office. The Addis Ababa City Development Plan (2004-2014) had comprised a statutory structure plan, an action oriented strategic development framework and a management reform component. The statutory structure plan had provided an overall framework for the spatial development of the city. The action oriented strategic development plans had prioritized six key urban issues to be implemented in five years (i.e. housing, urban road network and transport, manufacturing, Industries and large storage facilities, environment, and inner-city renewal and upgrading); and proposed implementation mechanisms and financial investment requirements.

Land use plan is the spatial interpretation of the infrastructural Structure Plan. The different major land use zones are environment (green frame), urban mass transport axes, urban centers, major industrial areas, major street network and major water bodies /swamps. The above-mentioned major land use categories appear on the land use map in the following form as shown (figure 3.7)

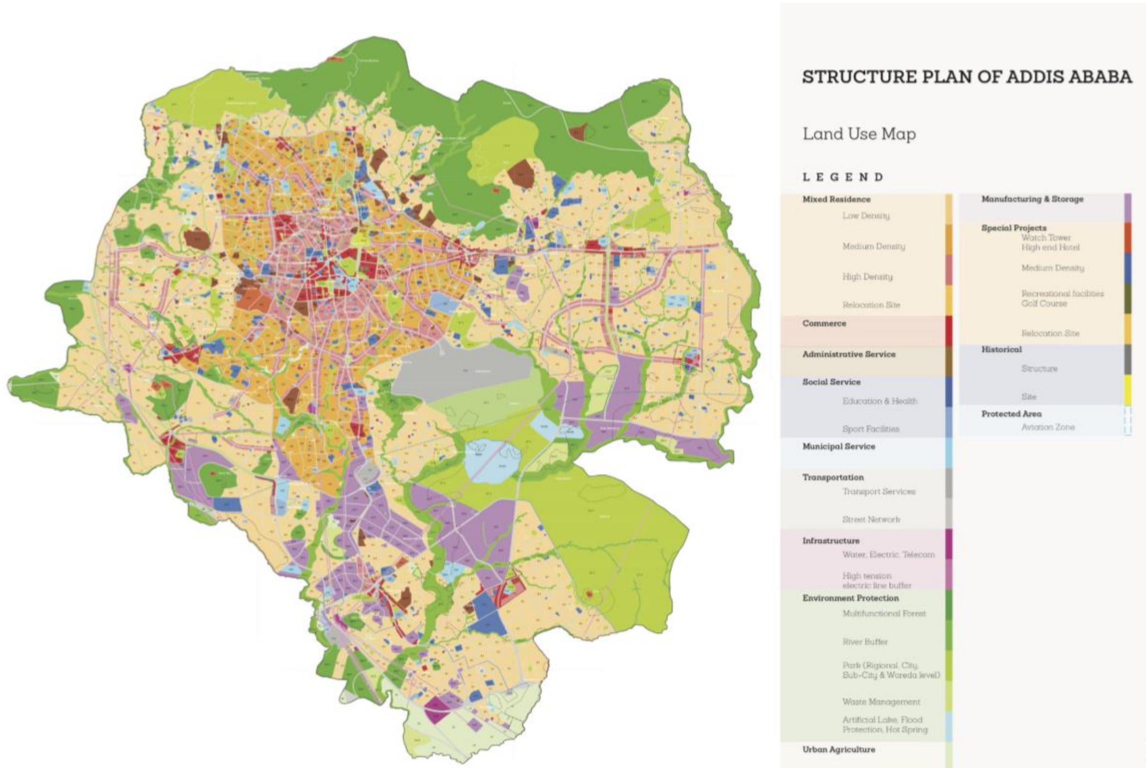


Figure 3.7:-Addis Ababa city Structural plan map by (source Addis Ababa city planning commission project office 2019)

3.3 Groundwater Modeling

Groundwater modelling is a way to represent a system in another form to investigate the response of the system under certain conditions, or to predict the behavior of the system in the future. Groundwater modelling is a tool for water resources management, groundwater protection and remediation. Numerical models provide a means to synthesize existing hydrogeologic information into an internally consistent mathematical representation of a real system or process and, thus, are useful tools for testing and improving conceptual models or hypotheses of groundwater-flow systems (Konikow and Reilly, 1999).

The objective of the study is to Identify and show the effect of shallow GW on infrastructural plan of the city and infrastructural development on the shallow GW of the city. To achieve this objective GW modeling procedure like conceptual model development, defining model geometry and boundary conditions, defining hydrogeological parameters, simulation run and calibration are required (See Figure 3.8) below.

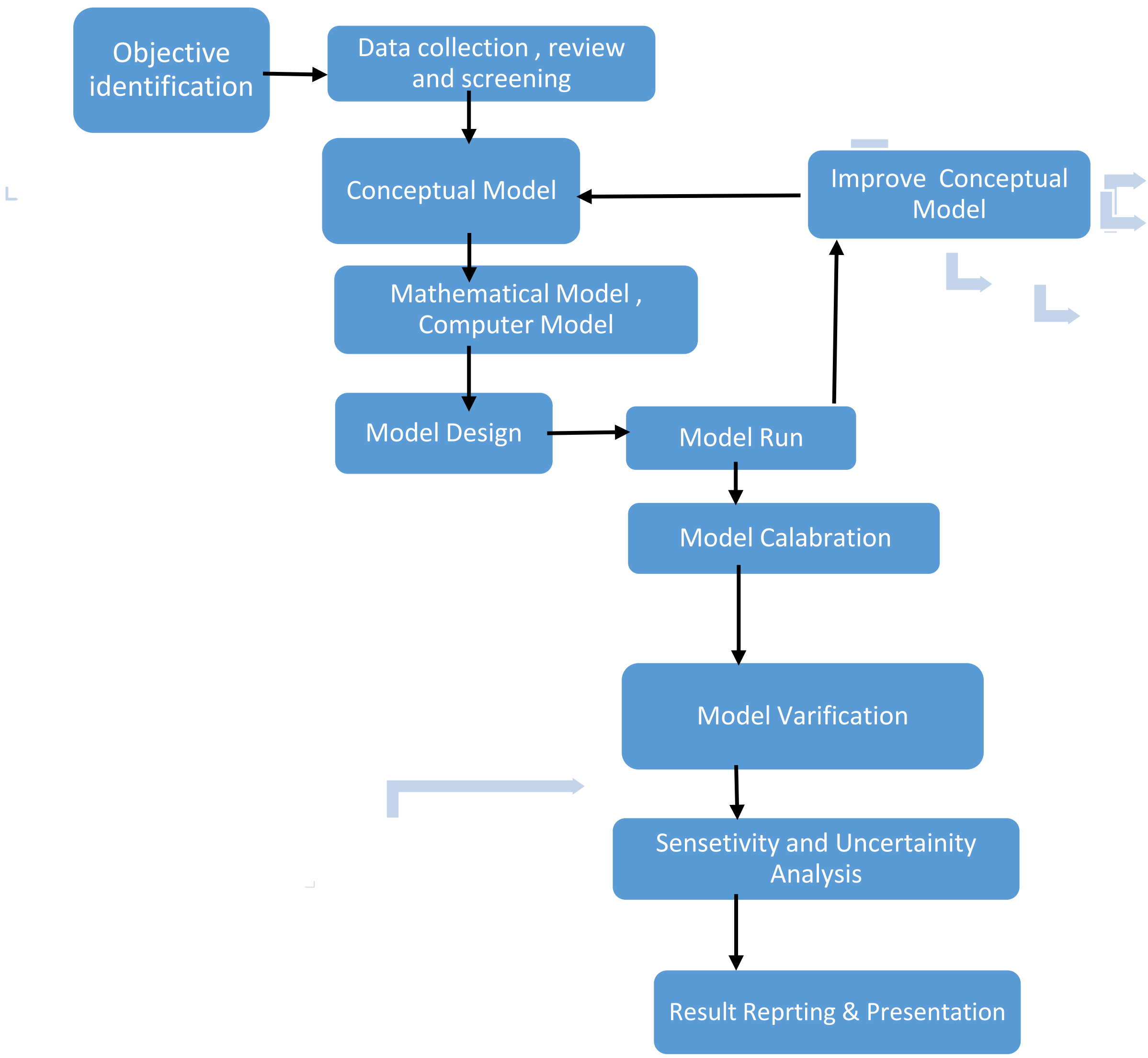


Figure 3.8:-Stepwise methodology of groundwater modelling.

Most these approaches, procedures and or decisions depend on the model used for the analysis. Thus, the next section provides the selected model and the associated reasons for selection.

3.3.1 Conceptual Model

The Map module is often used as a starting point for many projects. Often, a project starts with an image then, on a coverage, the module tools are used to create feature objects over the image to represent boundaries and structures. Then the feature objects are converted to other data types for further processing. In GMS, the term conceptual model is used in two different ways. In the generic sense, a conceptual model is a simplified representation of the site to be modeled including the model domain, boundary conditions (BCs), and material zones. It also has a conceptual model object, which can be defined in the Map module.

The conceptual model object can contain coverages. A conceptual model object can be defined in the Map module using feature objects, such as points, arcs, and polygons. The conceptual model was constructed of the numerical grid. Once the conceptual model object is defined, a grid can be automatically generated to fit the conceptual model. The boundary conditions and model parameters are computed and assigned to the proper cells. The MODFLOW data are converted from the conceptual model to the cells of the grid. This approach to modeling fully automates the majority of the data entry and eliminates the need for most or all of the tedious cell-by-cell editing traditionally associated with MODFLOW modeling.

This research contain many conceptual model object consists of several coverages. One coverage is typically used to define the sources and sinks such as shallow wells, Akaki Rivers both big and little Akaki as shown below (figure 3.9). Another coverage (or the same coverage) is used to define the recharge zones. Other coverages can be used to define the zones of hydraulic conductivity within each layer. Building a conceptual model requires good information on geology, hydrology, boundary conditions, and hydraulic parameters. A good conceptual model should describe reality in a simple way that satisfies modelling objectives and management requirements (Bear and Verruijt 1987). The key issues that the conceptual model should include are:

- Aquifer geometry and model domain
- Boundary conditions
- Aquifer parameters like hydraulic conductivity, porosity, storativity, etc.
- Groundwater recharge
- Sources and sinks identification
- Water balance

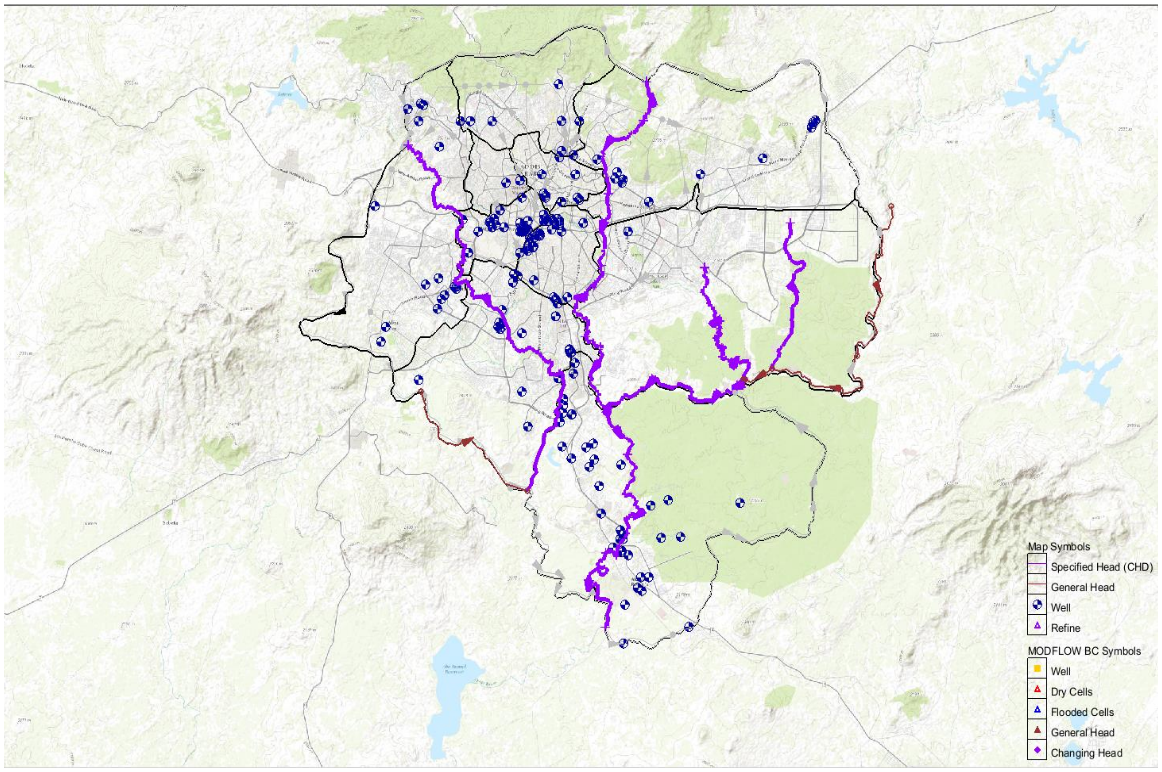


Figure 3.9:- Conceptual module of study area using GMS

3.3.1.1 Boundary condition

Different types of physical features has different boundaries and their equivalent mathematical representations.

Constant head boundary: This is a special case of a specified head boundary, which occurs where part of the boundary surface of an aquifer coincides with a surface of essentially constant head (Franke et. al. 1987). Constant head boundaries assume that the head is constant over time. Head around Lake Abasmual are this type of boundary.

Specified head boundary: This is a generalized form of constant head boundary. This occurs when head can be specified as a function of time and location. Rivers and streams, which are in hydraulic connection with an aquifer, are examples of specified head boundary. Akaka River and small tributaries to Akaka are flowing from north to south.

No flow boundary: This is a special case of a specified flux boundary. This occurs at a line normal to streamline (i.e. normal to flow direction). This case normally occurs where impermeable media exist. A water divide can be used as a no-flow boundary but with caution, as position of the water divide may move with time as a result of stresses on the aquifer .The bottom most layer is assumed to represent such boundary condition.

Specified flux boundary: This is a generalized case of a no-flow boundary. This occurs when flow across the boundary can be specified in time and location. An example of a specified flux boundary is recharge across the water table in a phreatic aquifer. The top surface of the model is taken as specified flux boundary.

Head-dependent flux boundary: This occurs when flux across a boundary depends on head adjacent to that boundary. A semi-confined aquifer, where the water head depends on the flux through the semi-confining layer, is an example of this type of boundary.

Free-surface boundary: The water table and the fresh-saline water interface in a coastal aquifer are examples of free-surface boundaries. Pressure head at free-surface boundary is always zero and the total head equals elevation head.

Boundary conditions comments

- Always use natural boundaries when possible.
- Boundary conditions always influence a steady state solution but may not influence a transient solution.
- A steady state solution with all specified flux boundary conditions (including no flow) without specified head or head-dependent internal boundaries may not converge or may not give a unique solution.
- A specified head boundary acts as an infinite source or sink.
- A water divide should be used as a no-flow boundary with caution.

The **General Head Boundary** (GHB) conceptually is a fixed head far from the model where it is assuming as a fixed head with time (i.e. river, head will not be affected by the model stresses with time). The purpose of using this boundary condition is to avoid unnecessarily extending the model domain outward to meet the element influencing the head in the model. As a result, the general head condition is usually assigned along the outside edged of the model domain.

The General Head package is similar to the Drain (DRN) and River (RIV) packages in that flow in or out of a cell is proportional to a difference in head. General Head cells are often used to simulate lakes. General Head conditions are specified by assigning a head and a conductance to a selected set of cells. If the water table elevation rises above the specified head, water flows out of the aquifer. If the water table elevation falls below the specified head, water flows into the aquifer.

In both cases, the flow rate is proportional to the head difference and the constant of proportionality is the conductance.

A set of selected cells can be specified as general head cells using the Point Sources/Sinks command in MODFLOW menu or general heads can be assigned using the conceptual model in the Map module. When the general head attribute is assigned to a polygons, the head and conductance are applied uniformly over the entire polygon. When assigned to an arc, the conductance is applied uniformly over the arc, but separate head values are applied to each of the nodes on the ends of the arc and the head is assumed to vary linearly between the nodes. When the attribute is assigned to a point, the head and conductance values are assigned directly to the cell containing the point. Once a set of cells have been specified, the General Head Package dialog can be used to view and edit the values assigned to the cells.

3.3.1.2 Groundwater Recharge

Estimation of groundwater recharge is necessary to assess hydrogeological conditions of the area. Groundwater recharge is defined as the fraction of total precipitation falling into a drainage basin, which eventually reaches the water table in the saturation zone of an aquifer (Juckik and Juckik , 2004) Quantifying recharge is important to sustain long-term groundwater use, make intelligent groundwater allocation decision and water management strategies (Ebrahimi and Ghazavi, 2016).

Recent days most of the indirect methods like groundwater fluctuation method, soil water balance approach and tracer techniques are utilized to employ to determine the groundwater recharge. These techniques are necessary to required regular field monitoring. Some of the recharge determination techniques, data are required on temporal scales ranging from days to thousands of years (Adhikary et al. 2012). Estimation of groundwater recharge is difficult without availability of hydrological data. In this adequate situation empirical models are useful to quantify the groundwater recharge. The empirical methods,

Using simple mathematical relations, can give quick recharge value for water resource decision making process. Increasing demand for recharge estimation is forcing the researchers to develop new approaches through understanding of aquifer recharging process (Scanlon and Cook, 2002). The various researchers are proposed different formulas to calculate ground water recharge. In Addis Ababa climatic condition the empirical formula after Bhattacharya's formula (1954) Kriashna Rao's formula (1970), was used since it requires only meteorological statistics as an input and limited climatological homogenous areas.

Groundwater recharge was determined as a function of rainfall data.

Bhattacharya's formula (1954)

$P=3.47(R-38)^{0.4}$ ………………………………………….. (11)

Where P=recharge in mm/year

R=annual rainfall in cm/year

Applying the above equation, amount of

$P= (116.5-38)^{0.4} =19.87$mm/year

Kriashna Rao's formula (1970),

$G=K (P-X)$…………………………………………………… (12)

Where, G= groundwater recharge (mm)

K=Constant (0.25 for sandy soil table below)

X=annual rainfall (mm), which yields no groundwater recharge

P= precipitation (mm)

Table 3.2:- Relationship b/n precipitation of rainfall (P) with groundwater recharge (G)

G= 0.2(P-400)	for an area with annual rainfall (p) in b/n 400 and 600mm
G=0.25(P-400)	for an area with annual rainfall (p) in b/n 600 and 1000mm
G=0.3(P-500)	for an area with annual rainfall (p) in b/n 1000 and 2000mm
G=0.35(P-600)	for an area with annual rainfall (p) more than 2000mm

In this study case $G=0.3*(p-500)^{0.4} =0.3(1165-500)^{0.4} =4.04$mm/year

The two recharge values estimated by Bhattacharya's formula (1954) and Kriashna Rao's formula (1970), are closer to one another thus, the average ground recharge due to rainfall precipitation in the study area is approximated to 11.95mm/year, which is equal to 0.00000327m/day. The value which may be high or too low values were changed after calibration or PEST (parameter estimation method).

3.3.2 Tools used for Groundwater Modeling

This study uses the software GMS and other accessary software such as ArcGIS10.7 and AUTOCAD to describe and implement the objective of the study. All the software are important to develop the model step by step discretization of the main objective. First the study area coordinate system (UTM) and location of the conceptual modeling area is developed using ArcGIS.

The developed conceptual model in ArcGIS is in shape file format of the study area is imported to groundwater modeling system software. The conceptual model approach involves using the GIS tools in the Map module to develop a conceptual model of the site being modeled. The location of sources/sinks, layer parameters such as hydraulic conductivity, model boundaries, and all other data necessary for the simulation can be defined at the conceptual model level without a mapping to grid.

3.3.2.1 Use of GIS software

In the present work, Groundwater Modeling System, was used with GIS based graphical preprocessing tools to automate and streamline the modeling process. It seamlessly interfaces with MODFLOW and several other preeminent groundwater models, and provides advanced graphical features for viewing and calibrating model results. GMS uses a Conceptual Modeling approach to create and manage numerical models using GIS based objects. The conceptual model approach allows users to build models conceptually independent of their numerical grid. Other powerful features Include 3D Model conceptualization, site visualization, advanced geo statistics, and stochastic modeling. GMS also has advanced tools for data import, data export and data visualization and animation.

The GIS module allows manipulating ESRI type GIS data, such as shape files. DEMs (digital elevation models), and images that include elevation data such as a GeoTIFF, are referred to as "raster". GMS supports a large number of DEM formats. After importing, DEMs are listed under “GIS Layers" in the Project Explorer along with other images. The raster icon is different from the image icon to indicate it includes elevation data. The values at the pixels can represent a wide variety of data, including (but not limited to) concentrations, elevations, or flow rates.

Raster can be interpolated to most other objects, including the z values of feature objects and to MODFLOW layers. The interpolation is done by finding the raster cells that the object's points are in and assigning to the points the values from the raster cells. Multiple raster can be interpolated to another object at once by simply selecting multiple raster in the Project Explorer, right-clicking and selecting the appropriate interpolation command. This will result in the creation of multiple datasets on the object being interpolated to. Raster catalogs are used to create solids using the horizons to solids method.

3.3.2.2 Use of GMS software

The entire GMS system consists of a graphical user interface (the GMS program) and a number of analysis codes (MODFLOW, MT3DMS, etc.). Several types of models are supported and facilities are provided to share information between different models and data types. Tools are provided for site characterization, model conceptualization, mesh and grid generation, geostatistics, and post-processing Three-dimensional geostatistics (interpolation) can be performed in GMS using the 3D Scatter Point module. The module is used to interpolate from sets of 3D scatter points to 3D meshes and 3D grids. Several interpolation schemes are supported, including kriging. Interpolation is useful for defining initial conditions for 3D ground water models or for 3D site characterization.

Groundwater modeling system (GMS) software is selected from other software since it help and simplify the study by importing different maps, shape file and DEM (digital elevation models) from ArcGIS to GMS. Which is used to simplify the conceptual modeling and converting to numerical model. It also creates borehole model and convert to solid and solid cross-section which is the main part of this study to characterize and show soil stratigraphy of the study are in 3D.

3.3.2.3 Borehole model

First Borehole module visualizes boreholes created from drilling logs around the study area are collected to construct three-dimensional cross-sections between boreholes. There are 21 boreholes all over the study area that have clear and real data to characterize the stratigraphy which are mapped as shown below (figure 3.10) in their real location in x, y coordinate and in z direction different soil type colored.

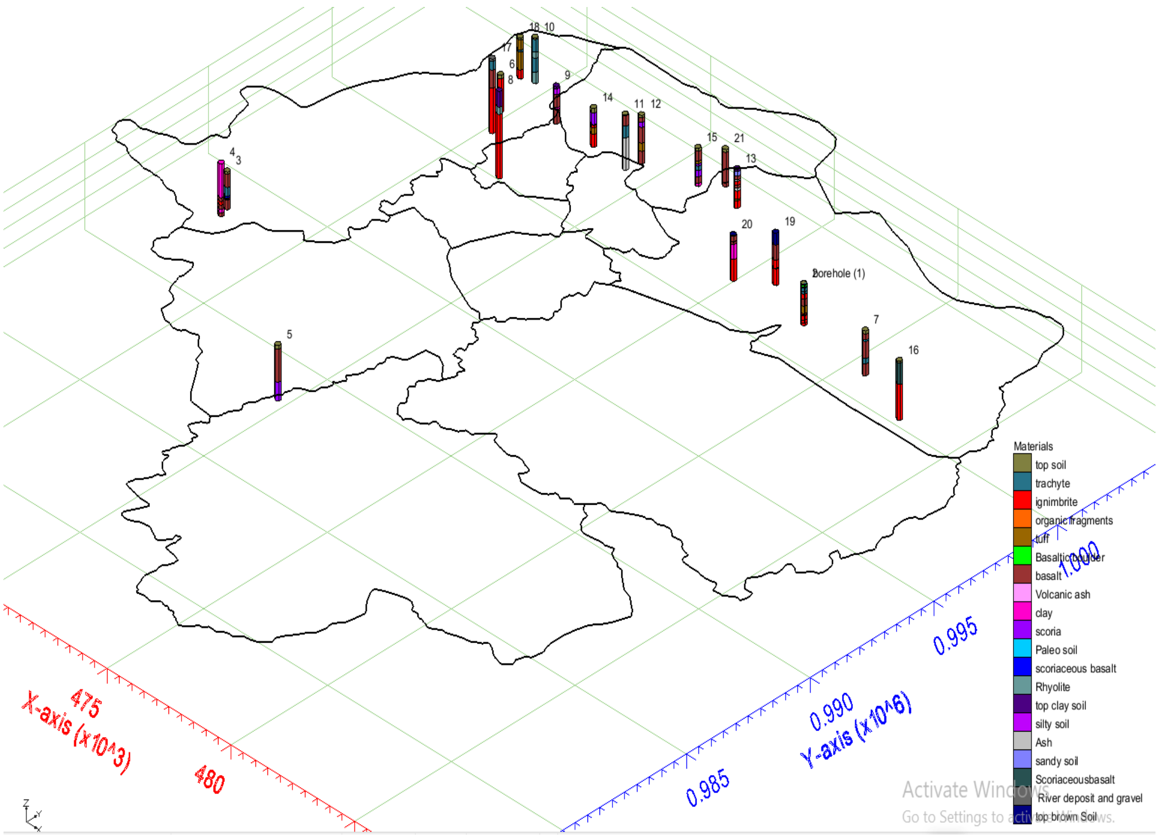


Figure 3.10:-borehole location and different lithology of study area

On boreholes, horizons are defined at borehole contacts. Each contact included in the construction of the solid must have a non-zero horizon ID. If wanting to ignore a contact, this can be done by leaving the horizon ID set to zero. Horizons are numbered in the order that the strata are "deposited" (from the bottom up). To automatically assign horizon IDs to boreholes, use the Boreholes | Auto Assign Horizons menu command. Depending on the number and complexity of the boreholes, this command can take a considerable amount of time. In this study all boreholes have been assigned to 37 horizons and generate solid model of the stratigraphy as shown in (Figure 3.11). Each horizon coverage has assigned soil type and automatically generated. The whole aquifer lithology were obtained by interpolating from boreholes and generating solids. The upper bound of the aquifer or the surface elevation is equal to the top elevation of TIN (triangular irregular networks) the RASTER data.

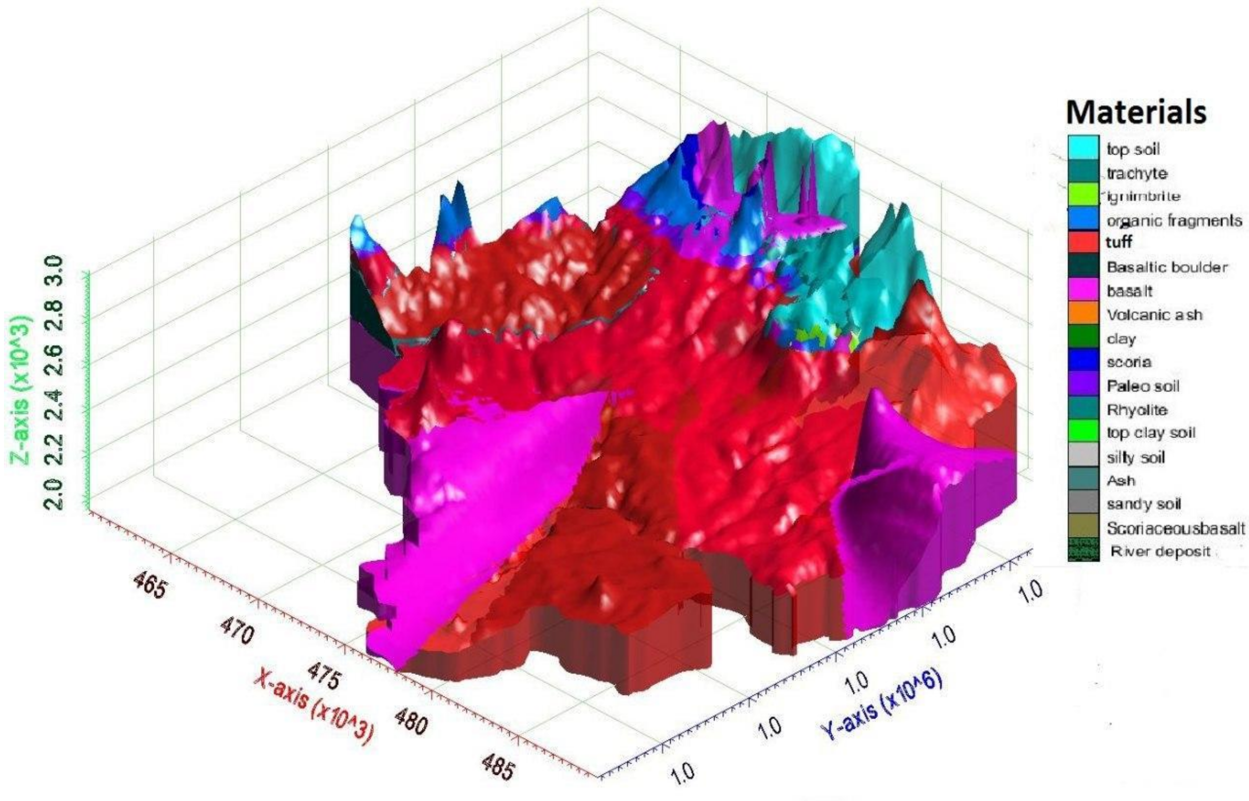


Figure 3.11:-Solid model from borehole log data of study area in GMS

Cross Sections from Solids (Figure 3.12): - These cross sections show the soil stratigraphy between boreholes. Once a set of cross sections is built, the cross sections can be displayed in 3D space to help characterize and visualize the soil stratigraphy at a site. Solids together and cross section cut through the solids show the nature of the aquifer down from surface of soil the cross section at any point. Again, note how the bottom most material matches across both sets of solids. Each of the colors represents a different type of soil.

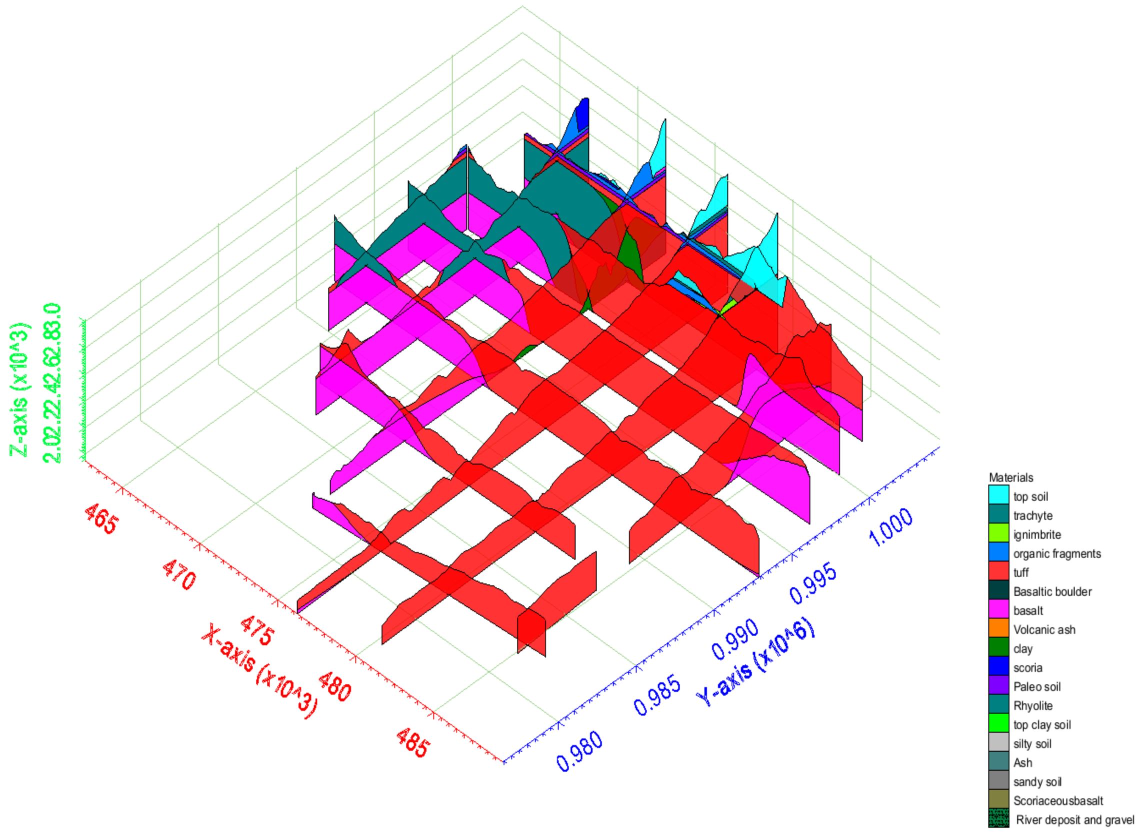


Figure 3.12:-Solid cross-section and stratigraphy characterization in GMS

3.3.2.4 MODFLOW model

The *"Solids to MODFLOW*" command represent tool for modeling complex stratigraphy in a completely grid-independent fashion. As part of the overall conceptual model building process, the stratigraphy at a site is modeled as a set of solids. The solids are built using tools in the Borehole, TIN, and Solids modules. These solids can represent a wide variety of complex stratigraphic relationships. Then assign hydraulic conductivity (K_h andK_v) and storage coefficients to the solids as material properties and a multi-layer grid is constructed where the boundary of the grid occupies the same region of the solids in plain view. The "Solids to MODFLOW" command can then be used to automatically define the elevation arrays in MODFLOW. If the grid is refined or edited in any way, this command can be selected again to rebuild the arrays in seconds with no further user intervention. Together with the feature objects in the Map module, a set of solids can be used to build a completely grid-independent conceptual model regardless of the complexity of the site.

Following is the set of steps required to use the Solids to MODFLOW command:

i. Building the Solids
ii. Material Properties
iii. Creating the Grid

When using Boundary matching, match layers to solids Execute Solids to MODFLOW .The Solids to MODFLOW command brings up a dialog listing the three basic options associated with the Solids to MODFLOW command. Each option utilizes a different approach for converting the solid stratigraphy to the MODFLOW BCF input arrays.

The three options are: -

- Boundary Matching
- Grid Overlay
- Grid Overlay with Keq (equivalent hydraulic conductivity)

The third option is best method to convert solid to MODFLOW and obtain reasonable result from the rest. The Grid Overlay option is one of the basic options for the Solids to MODFLOW. The Grid Overlay option is similar to the Boundary Matching option. While the Boundary matching has the many drawbacks. It can result in very thin layers at certain locations in the grid such as transition points at the boundary of a solid that pinches out to a sharp edge. In some cases, these thin layers can cause stability problems with MODFLOW or with a subsequent transport analysis. For such cases, the Grid Overlay method or the Grid Overlay with Keq method may provide superior results. With the Grid Overlay option, no layer range assignments are necessary.

Once the solids and grid are created, the Solids to MODFLOW command can be immediately selected. For each vertical column of cells, GMS intersects a vertical ray through the cell center and finds the highest and lowest intersection, i.e. the top and bottom of the entire set of solids. These elevations become the top and bottom elevation of the entire grid. The elevations of any intermediate layer boundaries are then linearly interpolated between these two extremes. The material properties are then assigned by computing the xyz coordinates of the center of each cell and determining which solid encloses the cell center. The material properties from that solid are then assigned to the cell.

Grid Overlay with K Equivalent option is one of the three basic options for the Solids to MODFLOW command. This option is very similar to the Grid Overlay option. One of the problems with the Grid Overlay option is that if there is a relatively thin layer in the solids and the layer does not happen to encompass any cell centers or it encompasses few cell centers, the layer will be under-represented in the MODFLOW grid. This becomes particularly important if the layer is meant to represent a low permeability layer. For such cases, the Grid Overlay with K Equivalent option may give superior results. The Grid Overlay with K Equivalent method is identical to the Grid Overlay method in terms of how the elevations of the grid cells are defined. The two methods differ in how the material properties are assigned. Rather than simply assigning materials based on which solid encompasses the cell centers, the Keq method attempts to compute a custom K_h and K_v value for each cell. When assigning the material properties to a cell, GMS computes the length of each solid in the cell (from a vertical line at the cell center that intersects the solids) and computes an equivalentK_h,K_v and storage coefficient for the cell that takes each of the solids in the cell into account. Thus, the effect of a thin seam in a cell would be included in the K_h and K_v values for the cell. The equivalent K_h is computed as follows:

$$K_h = \frac{\sum k_{hi} M_i}{\sum M_i} \qquad (13)$$

Where K_{hi} is the K_h of a solid and M_i is the length of the same solid intersected at the cell center. The equivalent K_v is computed as follows:

$$K_h = \frac{\sum M_i}{\sum \frac{M_i}{K_{vi}}} \qquad (14)$$

Where K_{vi} is the K_v of a solid and M_i is the length of the same solid intersected at the cell center.

3.3.2.5 MODPATH Model

“Koshe” or Reppi municipal solid waste landfills create lots of environmental pollution due to landfill gas combustion, leakage of leachate and foul smells. Among all these, leakage of leachate affects the surrounding environment the most, especially the surface and groundwater bodies because the leachate consists of high concentrations of heavy metals, organic compounds and toxic contents. Recently, several cases have been reported around the world related to pollution of water bodies which were caused by municipal solid waste landfills the same is true in the study area of Addis Ababa *koshe* selected site. A groundwater-flow model that was previously developed by the U. S. Geological Survey which was used in an analysis of groundwater flow using GMS. MODPATH is a particle tracking code that is used in conjunction with MODFLOW. After running a MODFLOW simulation, the area of solid west disposal site or *Koshe* site which designate the location of a set of particles. The particles are then tracked through time assuming they are transported by advection using the flow field computed by MODFLOW. Particles can be tracked either forward in time or backward in time. Particle tracking analysis are particularly useful for delineating capture zones or areas of influence for wells and deep river gorges which gain groundwater.

3.3.3 Modeling Problem Discretization

Contrary to investigative methods, numerical methods yield approximate solutions to the governing equation through the discretization of space and time. MODFLOW model and borehole model are the two most important components of GMS software that can discretize the problem domain in to solution. Two basic approaches are provided for constructing a MODFLOW model: the model can be completely defined using the tools in the 3D Grid module, or the model can be defined with the aid of the feature objects in the Map module. Also, scatter points and solids can be used to define layer elevation, and boreholes can be used with TPROGS to create material sets for the 3D grid. The basic steps in building a MODFLOW model include: Build a 3D grid defining the extents of the model. Two approaches are available:

- MODFLOW Grid Approach
- MODFLOW Conceptual Model Approach

Initialize MODFLOW Assign boundary conditions and model stresses, including sources and sinks. Define layer elevations Assign material properties Run MODFLOW. A MODFLOW model can be created in GMS using one of two methods: assigning and editing values directly to the cells of a grid (the grid approach), or by constructing a high level representation of the model using feature objects in the Map module and allowing to automatically assign the values to the cells (the conceptual model approach). Except for simple problems, the conceptual model approach is typically the most effective.

Since this research cover the whole Addis Ababa city it very difficult to model in the first approach and so the second approach or conceptual model approach is selected.

3.3.3.1 Three-dimensional grid (3D grid)

Once the feature object coverages defining a conceptual model have been completely defined, the conceptual model is ready to be converted to a numerical model-. The first step in this conversion process is to create a grid using the Map to 3D Grid command. Typically, the Grid Frame command is used prior to this command to define the location and dimensions of the grid. If one or more refine points are defined in the conceptual model (available when "Refinement" is selected in the Coverage Setup dialog), the number of rows and columns in the grid will be automatically determined when the grid is created.in this study all discharging wells are allowed to refinement. If refine points are not defined, the number of rows and columns must be entered. In this study refine points are specified with the Base size equals 250m Bias 1.5 m and Max size 500m depicted below (figure 3.13). The base size is the size in which the cell to be right at the refine point. The Max size is the largest size that the user would like the cells to be in the entire grid. The bias determines how quickly the cell size will vary as they move away from the refine point.

Each cell in a 3D grid has attributes associated with it. Each grid cell can be specified as active or inactive and each cell has a material associated with it. To edit the cell attributes associated with a numerical model see Cell Properties.

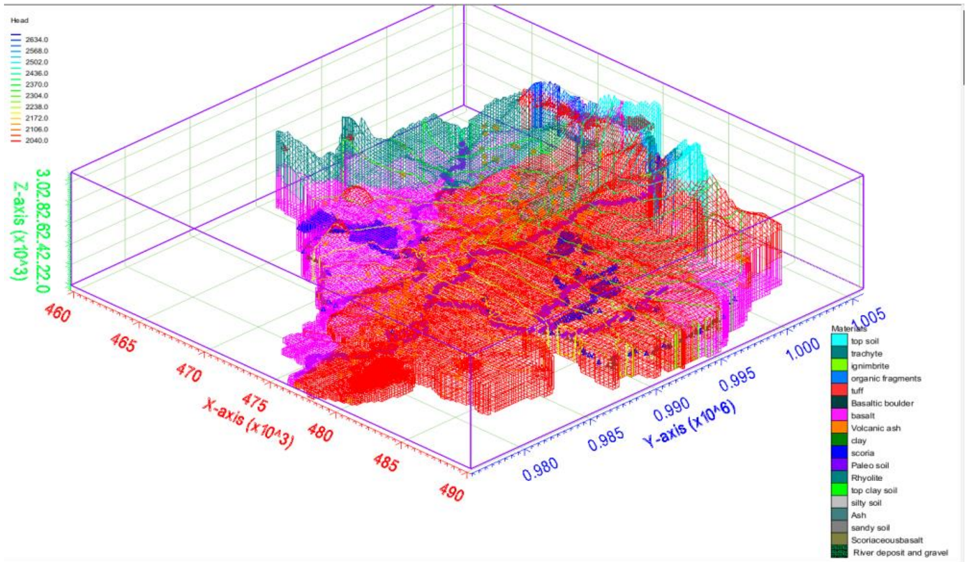


Figure 3.13:- 3D grid with their lithology assigned to each grid mish

3.3.3.2 Unstructured Grid (UGrid) Model

The UGrid module is used with unstructured grid (UGrid) geometric objects. Unstructured grids are very flexible. They can include many types of cells including 2D and 3D cells and cells with any number of faces and nodes. This type of geometric object is used with MODFLOW-USG which uses a finite volume approach. Eventually UGrids will be used for all the things that 2D grids and 3D grids are currently used for. A UGrid is similar to the old 3D grids and meshes available in GMS but much more flexible. UGrids can use any type of cell, meaning cells with any number of faces and nodes. This flexibility allows for more realistic modeling of geologic features such as pinchouts. Interfaces to the following 3D finite difference models are provided in this mode. MODFLOW-USG is a version of MODFLOW based on finite volume calculations, thus allowing for many different types of grid cells. This allows the model grid to more accurately match the model domain and be more efficiently refined in areas where more accuracy is desired. The UGrid module support the following types of unstructured grids

Regular (not refined): – A grid with rectangular cells that are not refined.

Quadtree: – A grid with rectangular cells that are refined in a quadtree manner around any points, arcs and polygons which specify the refinement attribute and refinement size. The cells surrounding the points, arcs, and polygons are also refined to smooth change from coarse cells to refined cells.

Nested: – A grid with rectangular cells that are refined like the quadtree option, but the surrounding cells are not smoothed.

Voronoi: – A grid with cells of various sizes and shapes which meet the Voronoi criteria. The mesh is refined around wells that are marked as refine points based on the specified refinement size stated above. The mesh is constructed to honor all arc geometry. If refinement is specified as an attribute on arcs or polygons it is ignored

The study area have many curves on the conceptual model and when map to MODFLOW command is done it obtains nicely drown boundary curves and no missing geologic stratigraphy.

The Map to UGrid command creates a UGrid from feature objects. Solids, conceptual map model, and others can be converted to unstructured grid by this method. As shown in the (figure 3.14) blow the solid model of stratigraphy is converted to Voronoi type of (**Ugrid)** model. It can be interpolated with DEM and crate the top surface of the model with the topographic elevation.

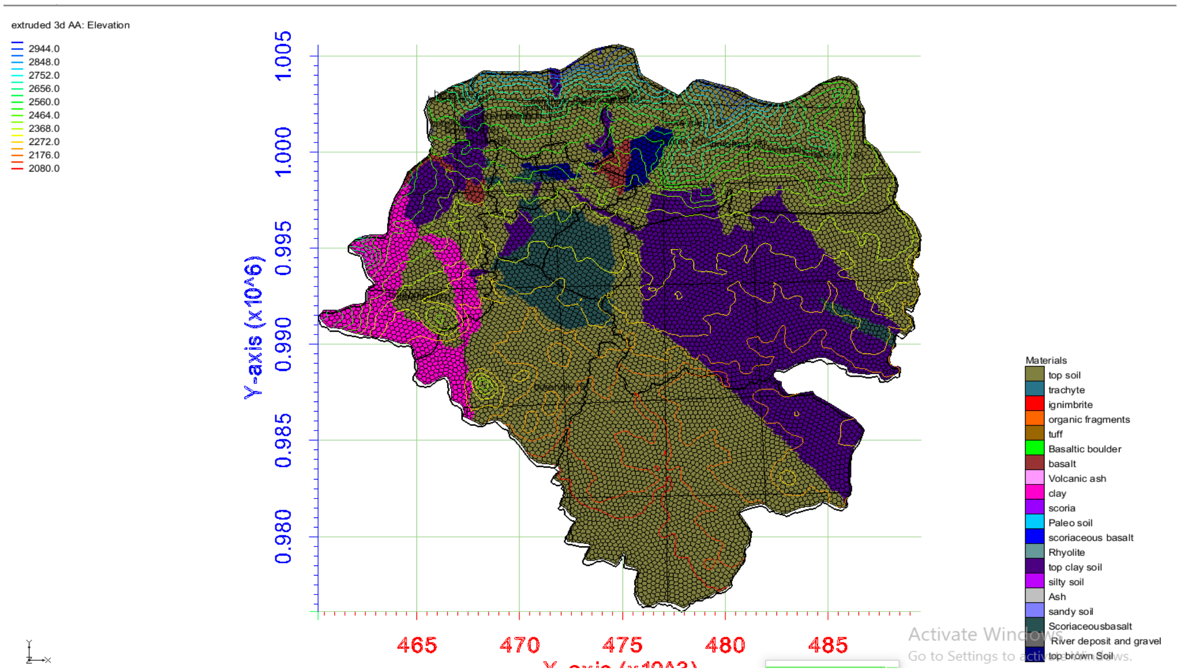


Figure 3.14:- Veroni type Ugrid model of the study area.

3.3.4 Hydraulic Head Generation

GMS software is a graphical user interface for many groundwater models such as FEMWATER, SEEP2D, SEAM3D, MT3DMS, MODFLOW (with many packages), RT3D, MODPATH, MODAEM, and SEAWAT. In this study, the MODFLOW model has been chosen due to its high efficiency and its extensive use in groundwater studies. This model simulates the flow in three dimensions using finite difference method for both steady-state and transient conditions. The MODFLOW numerical model is constructed based on the combination of two basic equations the Darcy equation and the principle of conservation of mass, or mass balance

The three-dimensional groundwater flow with constant density through a heterogeneous and anisotropic porous medium can be described by the equation.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial x}\right)\pm W=S_s\frac{\partial h}{\partial t}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (15)$$

WhereK_{xx}, K_{yy}, and K_{zz} are hydraulic conductivity coefficients (L/T) in $x, y, and\ z$ directions, respectively; h is the pressure head (L);Ss is specific storage (1/L); and W is recharge/discharge rate per unit volume (1/T). The environment is unconfined, isotropic, and heterogeneous (K_{xx} =

$K_{yy} = \; K_{zz} \; = K$), and hence, the governing equation based on Dupuit assumptions in two-dimensional form can be written as

$$\frac{\partial}{\partial x}\left(K_h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h \frac{\partial h}{\partial x}\right) \pm W = S_y \frac{\partial h}{\partial t} \qquad (16)$$

Where Sy the specific yield which is (dimensionless)

Due to the lack of long-term monitoring data for observational/operational wells, amounts of inflow/outflow to/from the Addis Ababa aquifer are unknown and therefore, the simulations are limited to steady-state conditions. Although applying the steady-state groundwater model simulation in Addis Ababa aquifer is a forced choice, this research try to consider the real-world features in the modeling.

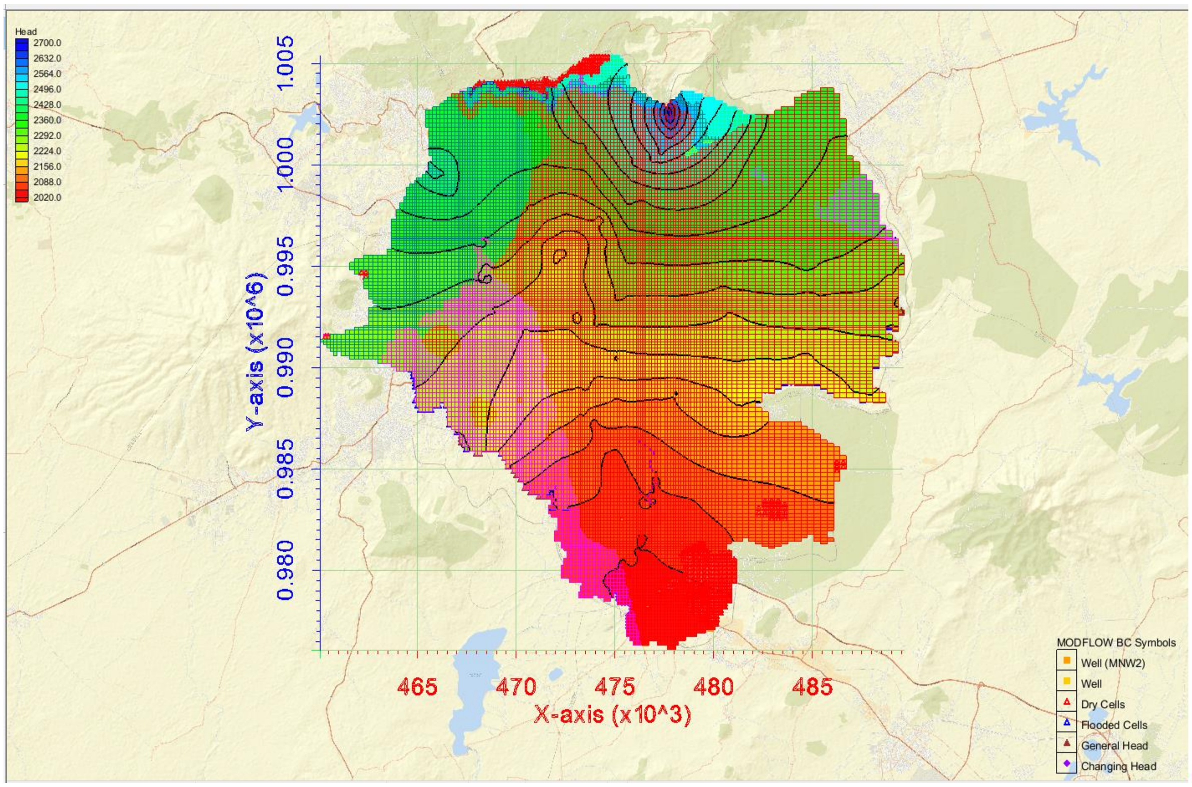


Figure 3.15:- plan view of hydraulic head of Addis Ababa using GMS

3.3.4.1 Model calibration and results

An important part of any groundwater modeling exercise is the model calibration process. In order for a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate observed aquifer behavior. Calibration is a process wherein certain parameters of the model such as recharge and hydraulic conductivity are altered in a systematic fashion and the model is repeatedly run until the computed solution matches field-observed values within an acceptable level of accuracy.

There are generally two kinds of calibration process; the first one is a trial-and-error process that should be manually changed repeatedly calibration parameters. This method can be considered as a fundamental first step for history matching because it can give the modeler much insight about the site modeled and how parameter changes affect different areas of the model and types of observations. The second type is automated parameter estimation which in many cases can calibrate the model quickly. GMS contains an interface to the mentioned calibration called PEST (Parameter Estimation). PEST calibration can be performed in two ways including zonal and pilot point. The first approach (i.e., zonal) is the most common one and is applied in this study.

3.3.4.2 Model Verification and Validation

The term "validation" is not completely true when used in groundwater modelling. Oreskeset.al. (1994) asserted it is impossible to validate a numerical model because modelling is only approximation of reality. Model verification and validation is the next step after calibration. The objective of model validation is to check if the calibrated model works well on any dataset. Because the calibration process involves changing different parameters (i.e. hydraulic conductivity, recharge, pumping rate etc.) different sets of values for these parameters may produce the same solution. Reilly and Harbaugh (2004) concluded that good calibration did not lead to good prediction. The validation process determines if the resulting model is applicable for any dataset. Modelers' usually split the available measurement data into two groups; one for calibration and the other for validation.

3.3.4.3 Sensitivity Analysis

Sensitivity analysis is important for calibration, optimization, risk assessment and data collection. In groundwater models, there are a large number of uncertain parameter. Coping with these uncertainties is time-consuming and requires considerable effort.

Sensitivity analysis indicates which parameter or parameters have greater influence on the output. Parameters with high influence on model output should get the most attention in the calibration process and data collection. In addition, the design of sampling location, and sensitivity analysis can be used to solve optimization problems. The most common method of sensitivity analysis is the use of finite difference approximations to estimate the rate of change in model output as a result of change in a certain parameter. The Parameter Estimation Package "PEST" uses this method (Doherty et. al. 1994). Some other more efficient methods of sensitivity analysis have been used. Automatic differentiation has been used for sensitivity analysis in groundwater models and it produces precise output compared to finite difference approximations (Baalousha 2007).

3.3.4.4 Uncertainty Analysis

Uncertainty in groundwater modelling is inevitable for a number of reasons. One source of uncertainty is the aquifer heterogeneity. Field data has uncertainty. Mathematical modelling implies many assumptions and estimations, which increase the uncertainty of the model output. There are different approaches to incorporate uncertainty in groundwater modelling. The most famous approach is stochastic modelling using the Monte Carlo or Quasi Monte Carlo method. The problem with stochastic models is that they require a lot of computations, and thus they are time consuming. Some modifications have been done on stochastic models to make them more deterministic, which reduces computational and time requirements. Latin Hypercube Sampling is a modified form of Monte Carlo Simulation, which considerably reduces the time requirements (Zhang and Pinder 2003).

3.4 Addis Ababa city Infrastructural map

Addis Ababa is running out of vacant land in the city proper. There is a growing need of space for residence, services, access, recreation and working area. But as mentioned previously, available resort remains in intensively re-using the built-up area (redevelopment). But the "how" and the "where" are major questions that need to be answered. Hence, it requires new plan with new ideas to guide the next decade of urban development by.

- Coordinating mixed use housing development and redevelopment along mass transit lines and business corridors;
- Inserting green spaces, related functions and public spaces to increase the livability and image of the city;
- Providing production premises to MSEs nearby market areas or accessible routs; and
- Filling the gap in the provision of basic services.

Urban structure is the backbone of any urban Centre. It determines settlement patterns and movement of people. The determination of urban structure (or frame) is based on the existing framed structure, topography and envisaged future urban development. The major premises and framing elements behind the Structure Plan of the city are hereunder described.

Topography: topography determines the nature of all urban physical elements. Particularly mountains and rivers shape the overall settlement system and the green frame primarily rests on mountains and rivers. For three critical and important reasons the green frame is considered as a determining structure of the city.

- Protection of the environment from natural and man-made hazards;
- Recreation; and
- Food security.

Street System: Street system is also a major framing element for urban land use. Urban forms, in most cases, are dictated by the pattern of streets. In addition, it determines where and how new development areas are established. Addis Ababa's street system is a combination of radial, loop and grid pattern. Except for developing alternative routes and connecting missing links, the existing pattern will remain as it is and will provide for an important frame for the structure of the city.

Centers: multi-functional activity nodes are binding poles of all land use around which functions structure themselves. The decision to choose polycentric arrangement is the result of careful analysis on the whole urban form, street network, and efficiency of the transport system. The built environment of the capital is horizontally expanded, and there are only limited major streets that in most cases are radiating from one spot.

Major development axes: Integrated high density-mixed use development especially on urban corridors with mass transport lines is the other determining spatial frame. Here, commercial, residential, service, environment and other major uses converge.

Residential areas: one of the major challenge is how and where to provide housing for the current as well as future demand. For Addis Ababa, vertical densification is the only available option.

Manufacturing and storage: Manufacturing is expected to be the leading driver of the country's economy. Even though a city of Addis Ababa's stature is expected to specialize in services, manufacturing and storage will also contribute in framing the urban form. This land use is approached in two ways: MSEs in the core, and special zones for large scale industrial establishments.

3.4.1 Major Land Use Considerations

Land use plan is the spatial interpretation of the Structure Plan. The different major land use zones are environment (green frame), urban mass transport axes, urban centers, major industrial areas, major street network and major water bodies' swamps. The above-mentioned major land use categories appear on the land use map in the following form: Although there are major redirections regarding the overall concept, the proposed spatial area organization is similar to the previous city development plans. City centers are organized in a hierarchical polycentric pattern. What makes the new Structure Plan different is that centers are now organized up to Woreda level.

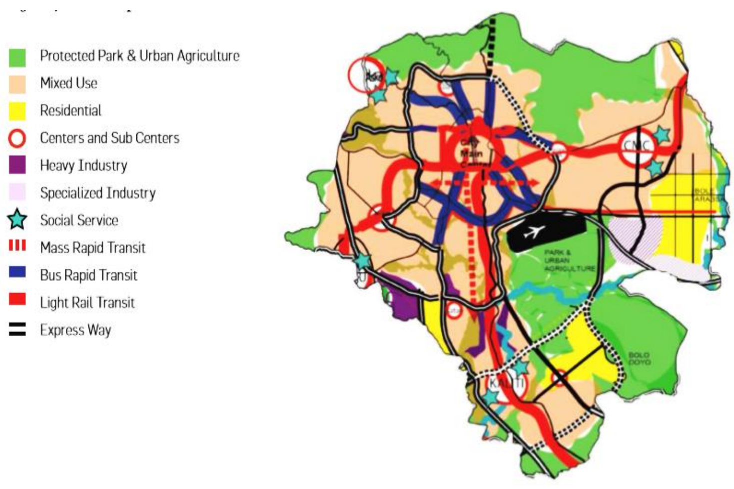


Figure 3.16 :-. Concept land use plan map of Addis Ababa prepared by Addis Ababa city planning commission 2019

3.4.2 Geo-environment

Addis Ababa Structure Plan integrates Geo-environmental considerations, by identifying and delineating potential geo-environmental hazardous areas, and natural resources for protection and development use. Succession from bottom to top (stratigraphically) are Basalts, Intoto Silicics, Addis Ababa Basalts, Nazareth Group and Bofa Basalts.The urban geo-morphology is directly dictated by the tectonic and volcanic activities of the nearby Afar Rifting System. The western, north and north eastern land mass is either part of or is bounded mainly by mountain plateau that include Furi, Wochecha, Jemo and Entoto mountain ranges. The central part of the urban land mass has been characterized by rolling land features and denuded small hills.

Many faults and fault-like structures which vary in length are observed in the wider expanse of the city. The existing fault development is strongly related to the regions' tectonic and volcanic activities. Similarly, the types and characteristics of groundwater, soil and rock in the area have been influenced by the regions' geo-environmental conditions and activities as well as man- made urban activities.

Rocks and soils for construction: Addis Ababa and its environs lies on volcanic regime where volcanic products like basalt, Rhayolites, Ignimbrite and scoracious material and tuffs predominate. In most parts of the built up area, these geological materials have been exposed to a long term weathering process. As a result, large quantities of red-brown and black clays, which are playing significant role in the construction sector, have developed. The Structure Plan identifies and delineates around 2500 ha of land in important sites for potential exploitation of aggregates and sub-base materials to serve the construction sector for the plan period.

Groundwater potential for drinking, industry, therapeutic use and recreation: There is significant groundwater in different parts of the urban region. Even though rising and falling land forms predominate, there is a potential to exploit groundwater in areas where pockets of depression exist. Accordingly, places for potential groundwater abstraction have been identified and delineated with buffers to minimize contamination.

In certain areas, hot water gushes out to the surface from deep water wells. This may be due to the presence of shallow magma ascending to the surface through the existing fault lines in the fracture zone by joining the groundwater. Accordingly, in Bole sub-city (Weregenu locality), more than 240 ha. Of land has been delineated. Further investigations should be made to harness and convert this potential to productive use in the health (thermal therapy) and hospitality sectors.

Wetlands and environmental sensitive areas: Wetlands are natural entities that can have various environmental functions. Research has shown that wetlands play a crucial role in the defence against flooding and pollution, and as areas for recreation. Aquatic species conservation is another function of wetlands. Accordingly, to foster economic and environmental advantages from wetlands, more than 10 ha wetland area is identified and delineated by the Structure Plan.

Geo-hazards and environmental constraints: The general area is found in close proximity to the East African Rift System where tremors of earthquake shocks are reported daily (Addis Ababa University Observatory). Although there is lack of reliable data with regards to Addis Ababa and its environs, lives have been lost and properties damaged because of recurrent geo- hazards such as floods and landslides. Accordingly, flood and landslide prone areas are identified and delineated.

Knowledge and skills: In any type of planning, performance quality and outcomes strongly depend on the quality of available data and in the skills of interpreting these data. Technology allows man to easily analyze very complex data. The geological, hydro-geological and seismological data obtained from the authorized government institute, the Geological Survey of Ethiopia (GSE), does not permit to accurately predict and/or discriminate geo-hazard vulnerable areas and locate available natural resources. The scale of the map describing the existing situation is too small (1:250,000) to produce credible outputs at the urban scale. Most appropriate scale for urban planning is 1:24,000. If this is not possible, a scale of 1:50,000 must be used. Apart from fulfilling data quality gaps, additional expertise in the area of interest and technological upgrading are crucial.

3.5 Overlaying of city infrastructural map and hydraulic head

The overlay process uses a spatially indexed collection of different types of information that is then interpreted based on a question at hand. In its simplest form the overlay operation is merely a stack of map layers that show where things co-occur. In its most advanced from the overlay analysis is able to express causal relationships where temporal sequences also can be an integral part. Regardless of technical implementation – either undertaken as a manual overlay of transparent map sheets as shown blow (figure 3.17) or through digital overlay of spatial data, a basic requirement is a common spatial frame of reference and accurate geocoding.

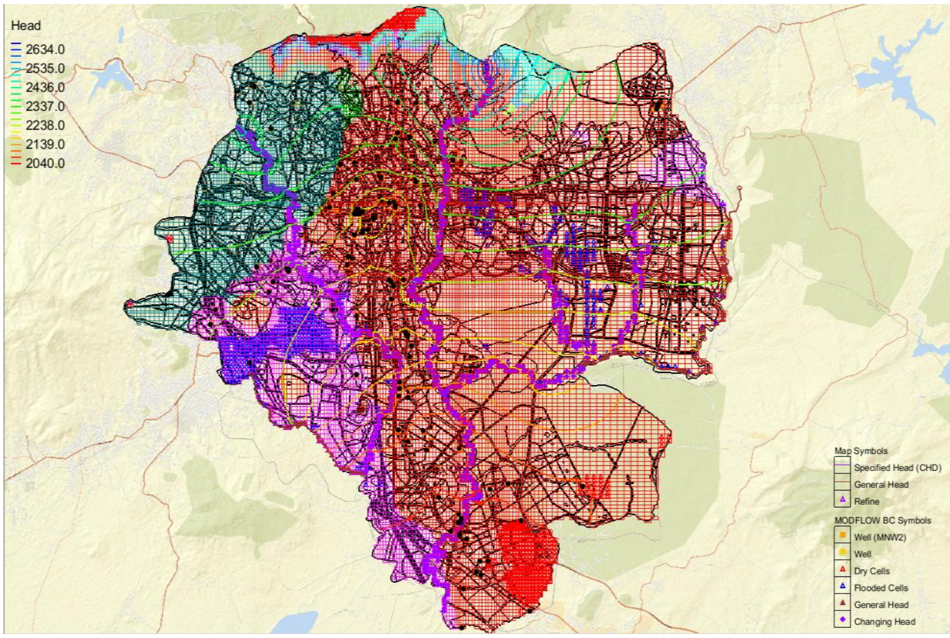


Figure 3.17:-Manual overlay analysis grid in plan view of study area

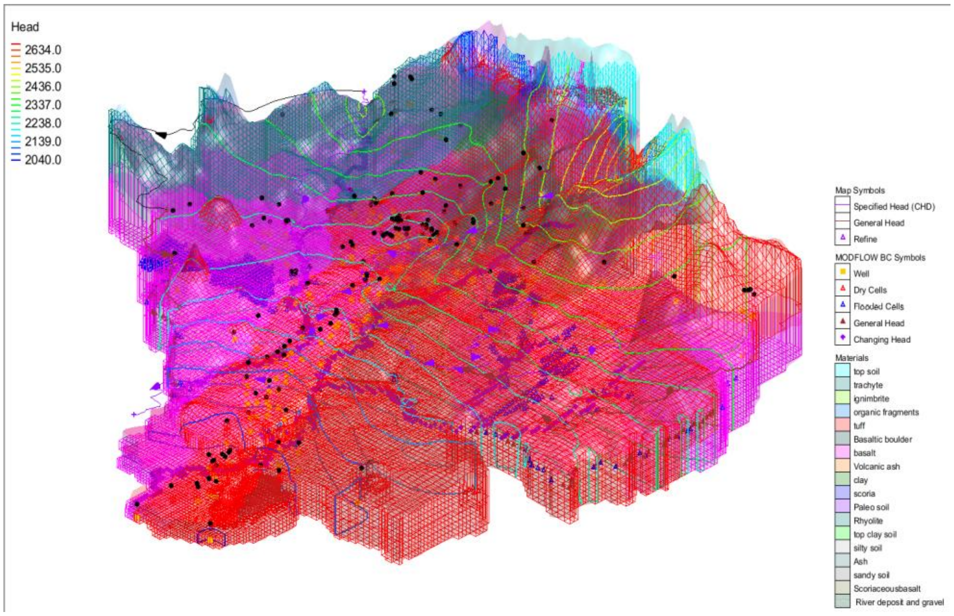


Figure 3.18:- 3D view of manual over lay analysis and model discretization

3.5.1 GIS Implementation

As previously illustrated the manual overlay process with transparent map sheets shown above, we will however use also digital implementation of overlay analysis, typically performed in a GIS. Digital map data is commonly represented in a raster or vector data set. These are usually geocoded at a certain scale and resolution but can be modified numerically so that data collected at different scales can be analyzed together. It is important to note here that although it is technically possible to overlay data produced at vastly different scales, this is typically not recommended. When the geometric overlay is performed all spatially corresponding pixels will form a new pixel that can be associated with information from the source layers.

Once the geometric stage is complete various forms of analyses can be performed on the information that is associated with each new spatial unit. From the simplest to more complex tasks we can separate between descriptive, deductive, and inductive overlay analysis. Many times the spatial combination of layers is of most interest, such as if and to what extent certain characteristics intersect or overlap in space. This is simply a description of the results from the first geometric stage. Deductive reasoning is a type of inference where a conclusion is reached based on a set of facts and an inference rule or logic to interpret those facts. A third major type of overlay analysis is to use the geometrically combined overlay as a starting point for more exploratory and inductive tasks.

4. RESULT AND DISCUSSION

A rise in the shallow unconfined groundwater at a site in Addis Ababa is causing water logging of the underground facility and shallow GW are affected by poor planning and management city infrastructural development. Realizing this problem, a study was conducted to identify the source of water that is causing the rise and to develop an implementation and operation plan of the mitigation. Modelling was undertaken using GMS based MODFLOW model, to assess the spatial and temporal groundwater level at the site. The study undertaken incorporates compilation and assessment of available data, including a list of factual information reviewed, development of a conceptual groundwater model for the site was developed.

Aquifers in the study area was open to the atmosphere through a permeable soil cover, and in this condition they are known as unconfined. Unconfined aquifers can receive direct recharge from rainfall infiltrating and percolating through the unsaturated (or vadose) zone down to the water table. These aquifers are also known as water table or phreatic aquifers. The water in them is in direct contact with atmospheric pressure and when these aquifers are pumped, the water table is lowered. To understand and characterize the aquifer in the study area 3D solid model of the aquifer well be analyzed in this section.

4.1 Model Computational Grid

The results of the groundwater model depend on the size of computational grids. In this study, as shown in (Figure 4.1), the grid cell size is 459550 X 965540m in horizontal plane uniformly and the height of each cell is equal to alluvial depth in that point (i.e., the difference between earth's surface and bedrock levels). The modeling grid consists of 251 rows and 214 columns. The total number of grid cells is 107, 428, including 34,146 active cells (all cells inside the aquifer are active) and 73,282 inactive (all cells outside the aquifer are inactive).

The Finite deference 3D grid of the study area as shown blow in (figure 4.1) the most important Step for analyzing and visualizing the aquifer. The grid is interpolated with 30m DEM to create the upper most surface or the topography of the site. As it was visible the ups and downs, the deep river gorges and top of the mountain were shown in the mash. The geologic cractriztion is also created after reefing the finite difference 3D grid.

Table 4.1:- properties of refined 3D model computational grid

Grid type:	Cell Centered	Unit
X origin:	459550	(m)
Y origin:	965540	(m)
Z origin:	1900	(m)
Length in X:	40240	(m)
Length in Y:	47860	(m)
Length in Z:	1400	(m)
Rotation angle:	0	
AHGW X origin:	459550	(m)
AHGW Y origin:	1013400	(m)
AHGW Z origin:	3300	(m)
AHGW Rotation angle:	90	

Minimum scalar:	2026.598	
Maximum scalar:	2689.364	
Num cells i:	251	
Num cells j:	214	
Num cells k:	2	
Number of nodes:	162540	
Number of cells:	107428	
No. Active cells:	34146	
No. Inactive cells:	73282	
Projection:	UTM,	
Zone: 37 (36°E - 42°E - Northern Hemisphere), Adindan, meters		

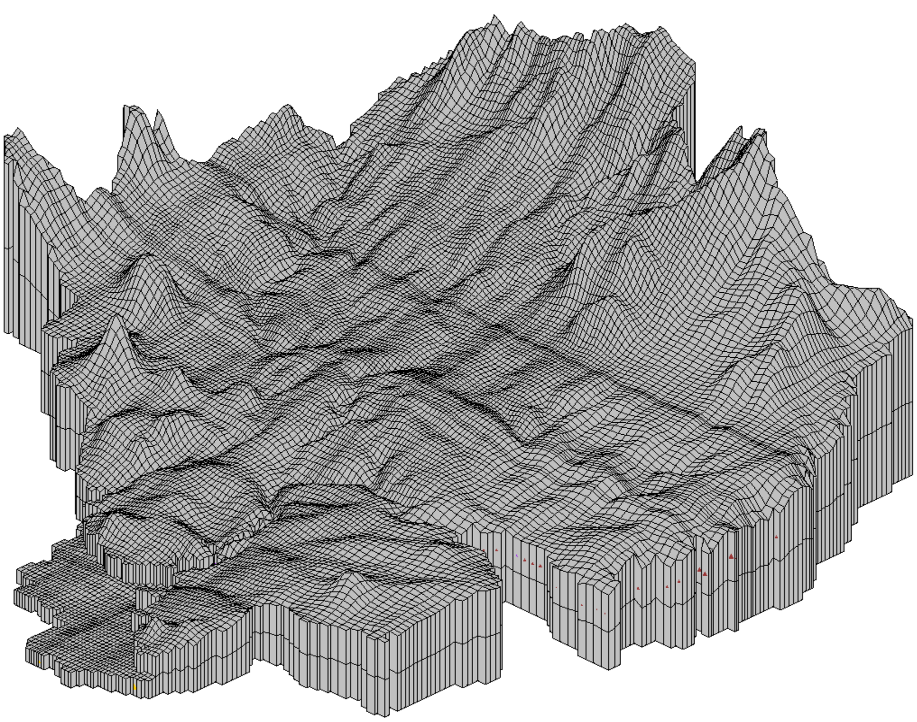


Figure 4.1:- Model computational grid with surface topgrapic enterpolation

4.1.1 Model Layer and aquifer formation

For a site with very complex hydrogeological conditions, model-layer can more accurately represent the groundwater flow and the site lithology conditions, particularly for a site with strong and or variable vertical hydraulic gradients.

The study area shallow GW and character have been done with a model having two-layer thickness having varying thickness from north to south. The maximum thickness of the model helps for the study of shallow groundwater aquifer. The maximum thickness of the model layer is from where the pick of mountain like Entoto, Wochecha and others to bottom of the first layer. The second layer is equivalent all around the study area and have a depth of 50m thick from the first layer. Different colors are the different lithology of the aquifer in the model. Which is interpolated and filled by horizon method from borehole log data. The study area aquifer geology, the model layer and GW hydraulic head result shown below in 3D.

From the solid and cross-section model result shown above Addis Ababa aquifer have different lithological nature. The lithological variation have an impact on the shallow ground water since geology and soil are the main agent for the existence of underground reservoirs or GW. Form the solid model cross-section result shown above (figure 3.12) also 3D layer property show blow in the (figure 4.2) mostly mixed type of lithology were observed at Norther top of Entoto Mountain and northern and northeast Addis Ababa. This study have a limitation on which it may be due to sufficient borehole log data were collected at this area. Solid model result show Trachytes, basalts and pyrocalstics of Entoto Mountain and northern Addis Ababa. There is also Basalts and basaltic builder formation at the central, southern and Eastern highest elevation mountain of Addis Ababa. Trachy-basalts, trachyte, and tuff forming the volcanic mountains of Wechecha, Furi and Yerer.

Some other type of lithology which are shown in the legend were not observed in this model because they cover small area and volume in specific area. Even though they were not observed the model consider in MODFLOW model to assign hydraulic conductivity and obtain hydraulic head. They are assigned to each grid mish as shown above in the (figure 3.13)

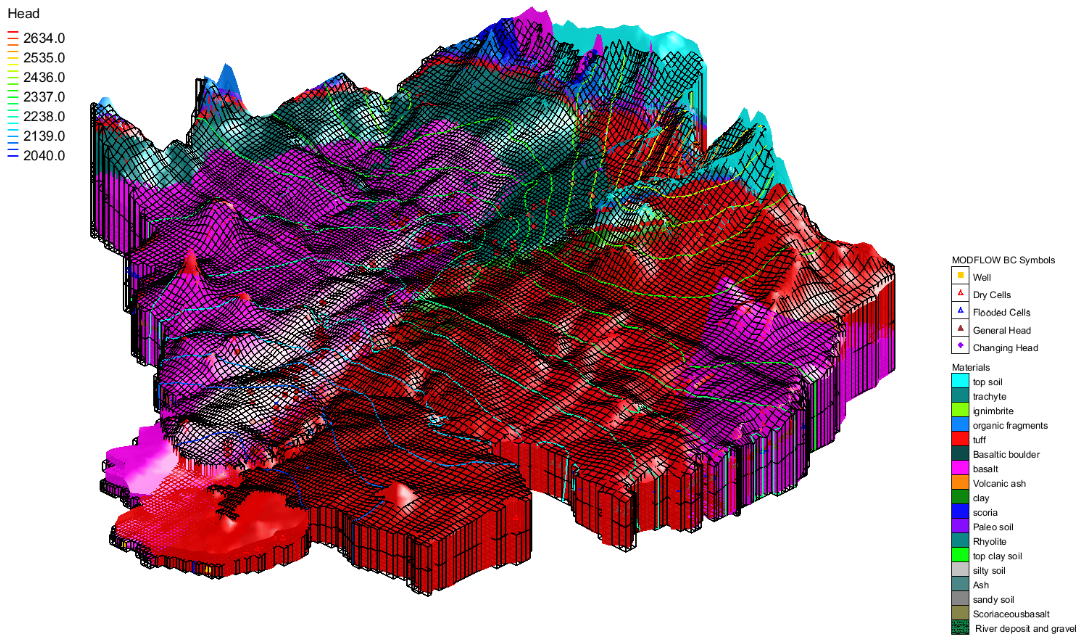


Figure 4.2:- 3-D grid and Model layer created by GMS MODFLOW model

4.2 Shallow Groundwater Aquifer geometry

The study area aquifer is selected in a way that to be bounded by the perennial rivers (Big Akaki, Little Akaki, Kebena River and others) which are present in the study area. For the steady state groundwater modeling the surface nodes near to the perennial rivers is taken as constant-head boundary conditions. The longitudinal profile of the perennial rivers is taken from DEM to represent the surface water level. The bottom nodes of the generated mesh for the study area were also simulated as no flow boundaries.

The Solids module is used to construct three-dimensional stratigraphy of the study area. Once the solids are created, cross sections can be cut anywhere on the model, the volumes of the solids can be computed, and the solid model can be used to define elevation data for numerical models such as MODFLOW. As shown blow in the table for basaltic type of rock aquifer property. The model result will give such property for all 13 type of lithology in the same way.

Table 4.2:- properties, location and volume of Basaltic geology in the study area.

Number Solids:	13	unit
Min x:	460300	(m)
Min y:	976287	(m)
Min z:	1950	(m)
Max x:	489543.6	(m)
Max y:	1005592	(m)
Max z:	3021.154	(m)

Solid name:	basalt 28	unit
Solid material:	basalt	
Begin Layer:	1	
End Layer:	2	
Use top cell bias:	No	
Top cell bias (frac):	0.8	
Target min. cell thickness:	0.1	(m)
Number vertices:	6226	
Number triangles:	11702	
Min x:	467654.5408	(m)
Max x:	489543.6089	(m)
Min y:	467654.5408	(m)
Max y:	489543.6089	(m)
Min z:	2179.608154	(m)
Max z:	2969.749023	(m)
Centroid x:	480005.8821	(m)
Centroid y:	995345.9261	(m)
Centroid z:	2366.20076	(m)
Volume:	642073181.5	(m^3)
Projection:	UTM,	
Zone: 37 (36°E - 42°E - Northern Hemisphere), Adindan, meters		

Table 4.2:- properties, location and volume of Basaltic geology in the study area.

The hydrogeological properties, porosity and permeability, of geological layers and their spatial distribution in Addis Ababa aquifer vary for many reasons, the type of Lithology or sediments, cracks and fissures within the rocks and the depth of burial. The availability of groundwater depends on hydrogeological setting, which may be very variable, even within a single lithology.

Shallow groundwater in the study area are an important source of surface water, particularly base flow, these two water sources, surface and groundwater, and the services they both provide should be considered in an integrated and holistic way within the planning framework of city. Perianal Rivers such as Kebena, big and small Akaki considered in modeling the shallow aquifer are flowing throughout the year due to base flow. Base flow is a water seeping in to the stream and river from shallow GW, which helps keep water to flow in stream during dry season. The hydraulic head section along North to South of the city black space line shown blow (figure 4.3 and x-section figure 4.4) Hydraulic head near the river were at bottom surface of the river shows the base flow line of little Akaki.

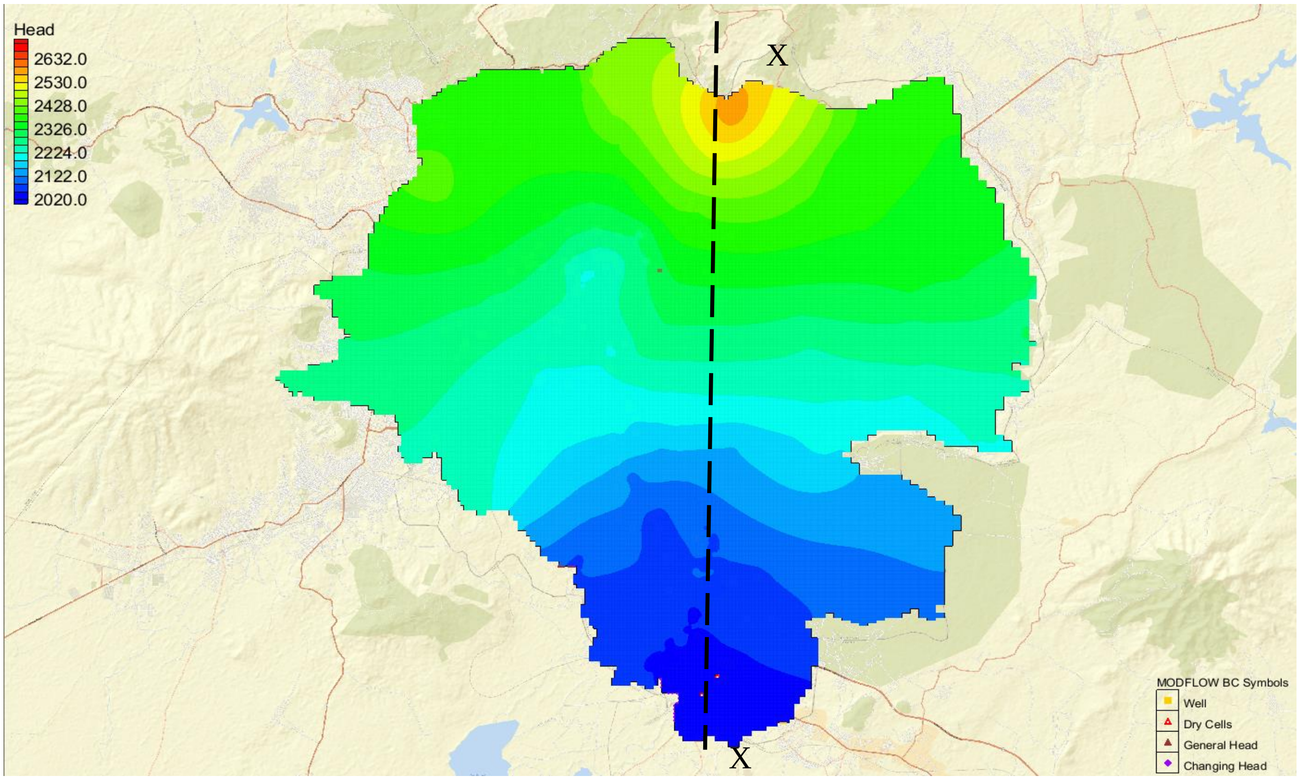


Figure 4.3:-Groundwater head contour map of Addis Ababa

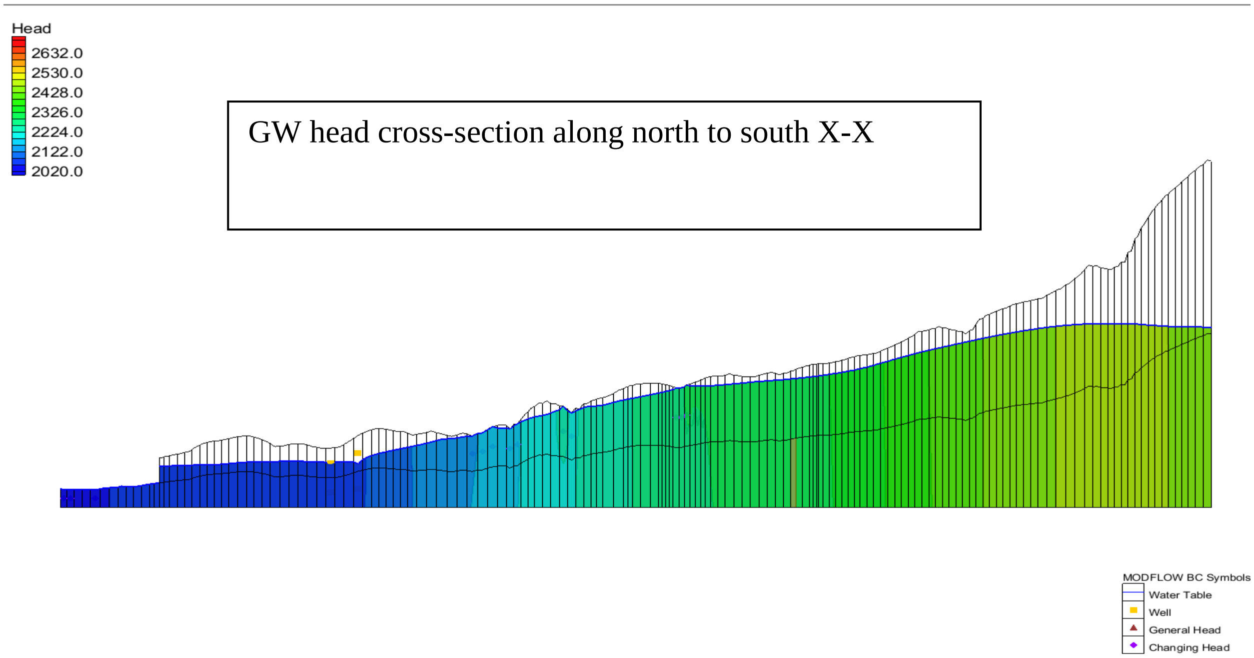


Figure 4.4:-hydraulic head and cross-section from North to south of Addis Ababa

4.3 Hydraulic head and groundwater flow

This study entails us about the simulation of the hydraulic head of the study area at each node under steady state groundwater conditions. To characterize and to estimate the shallow GW of the whole study area by considering the precipitations, recharging river and other as an inflow to the aquifer. The study area hydraulic head is simulated from the actual surface and bottom node elevation of the study area, the element generated from the study area by using the topographic coordinate, the perennial river constant head boundary which is present in the study area, the rainfall which is precipitations, the borehole (the well inventory) data which is drilled for different purpose in the city and the geology of the study area.

The hydraulic head in every node in the mesh generated for this study is simulated by changing the geologic material type (iterative hydraulic conductivity value) and recharge are calibrated and the values are edited to obtain the observation target. Surface node elevation is determined by converting DEM to 2D scattered data interpolated with grid mash using inverse distance weight method and the bottom node elevation is taken by subtracting the model thickness from actual surface node elevation. The total number of node in the generated mesh is one hundred sixty two thousand five hundred forty (162,540).For all the nodes in the study area mesh the hydraulic head is simulated by changing the model sensitive parameters to obtain satisfactory modeling result to achieve the goal of this research.

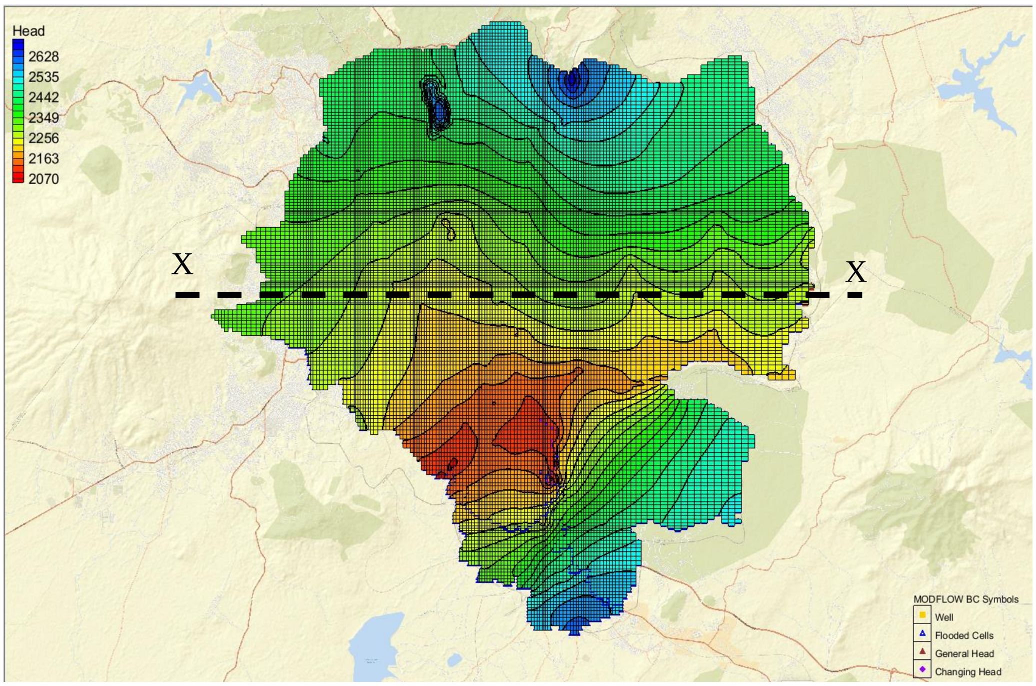


Figure 4.5:- plan view of hydraulic head contour map of study area

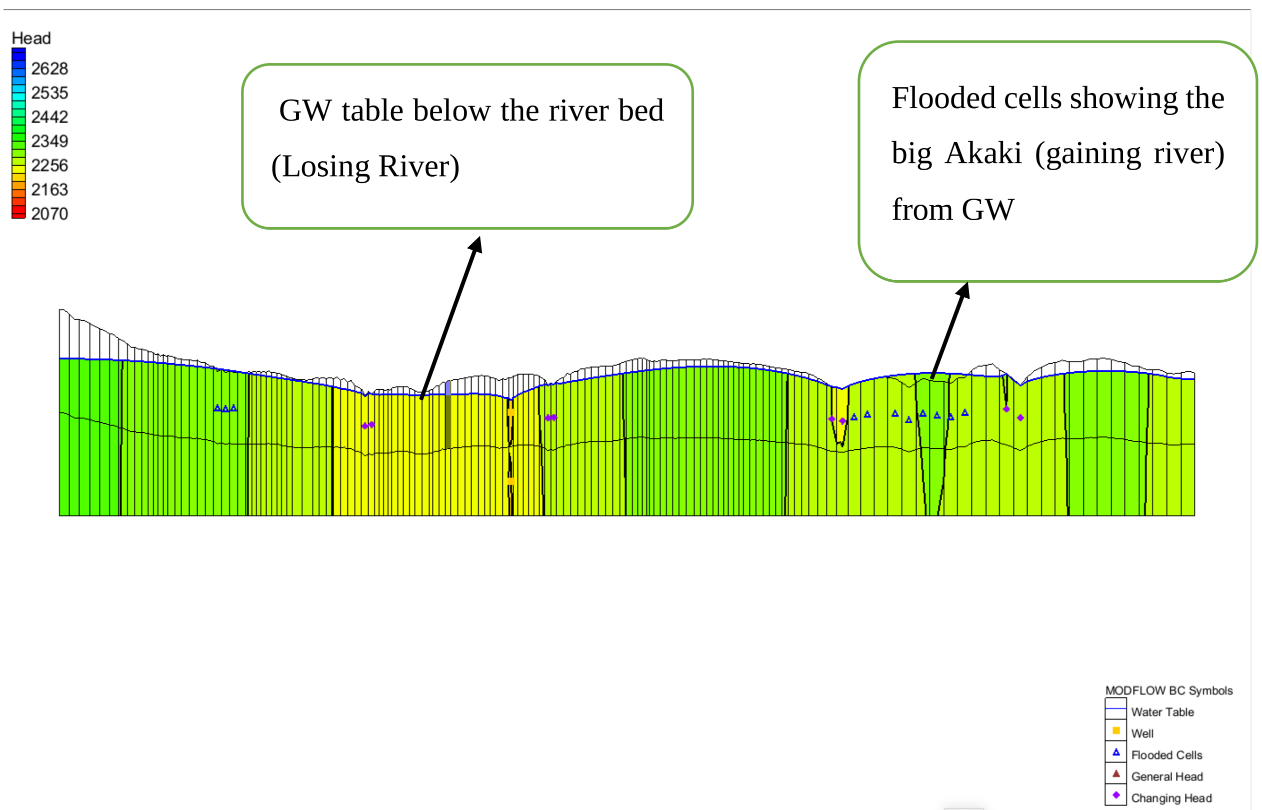


Figure 4.6:- section at X-X of the grid layer and location of water table

The river in the right side of the grid were flooded cells the GW water table is above the river bed such that the river gain groundwater from the aquifer or gaining river. As the result structure and infrastructure built around such kind of gaining river bank become waterlogged, since the water table is near to surface. Before construction of structure around such river bank require further study and detail investigation of the soil nature and the behavior of Bering capacity of the soil to carry and transfer the load of the structure to the ground.

On the other hand on the right side of the grid section show that the river is losing river , since the water table found below the river bed the water seep in to the aquifer as shown above. The saturated aquifer lies below the river bed near the vicinity of the river. The GW table and the hydraulic head shown above is based on study state. The water table may rise above the river bed during the wet summer season and lower during the long dry season this study doesn't consider such transient state of GW situation. This shows that the shallow groundwater have a direct relation and interaction with surface water.

The groundwater flow within the city is variable with a general direction in north south direction. The groundwater head contour show the flow of the GW is the same direction as the surface water or river and stream flow direction. As shown above (figure 4.5) the GW head contour map bends in the direction river channel this entails GW flow from area of high elevation to low elevation like natural surface water flow direction.

4.4 Model calibration and results

For calibration, the hydraulic head data of 115 observation wells or piezometers in the study region is imported to model. Using the trial-and-error approach, attempts are made to minimize the differences between calculated and observed head values. The quality of the calibration is evaluated using some indices including mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) according to the equations

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_0 - h_c)_i$$

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

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

Where n is the number of piezometers; ho and hc show observed/measured and calculated/simulated head values (m), respectively. Calculation of the above mentioned statistic indices is useful in evaluating the merit of the calibration. It should be noted that the GMS software provides ME, MAE, and RMSE values for each model run. Because both positive and negative residuals are used in calculation, ME value should be close to zero for a good calibration. MAE is calculated using the absolute values of the error (only positive values) and is a measure of the average error in the model. The root mean square error (RMSE) or the standard deviation (RMSD) (due to using the steady state results in calibration RMSE and RMSD are equal) is the average of the squared differences in measured and simulated heads. RMSE is less robust to the effects of outlier residuals. Thus, the RMSE is typically larger than the MAE.

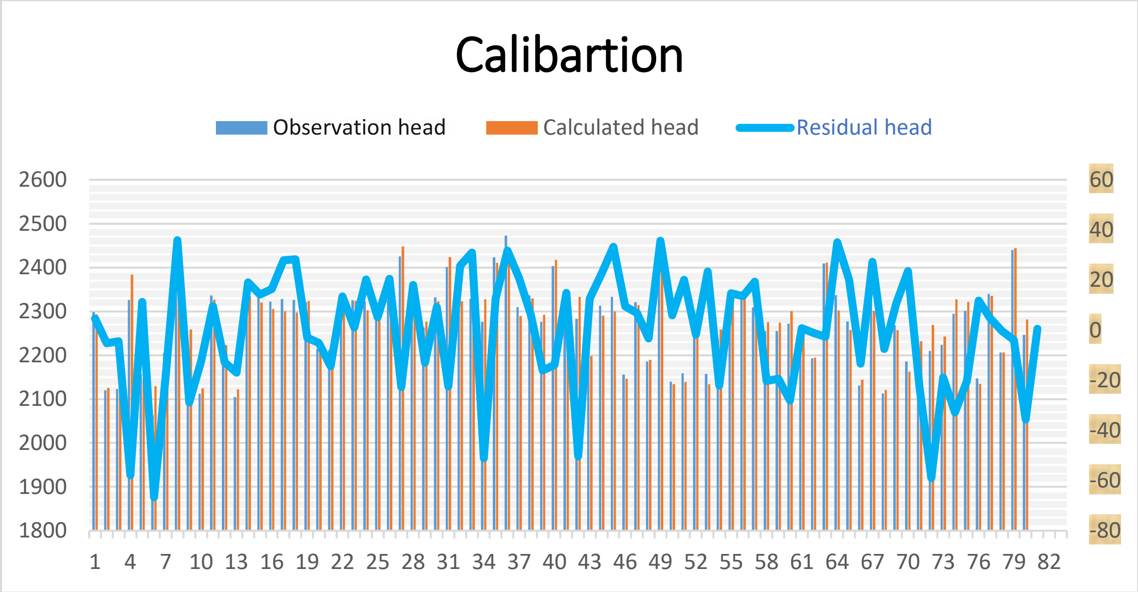


Figure 4.7:-ME, MAE and RMSE of the model result plot

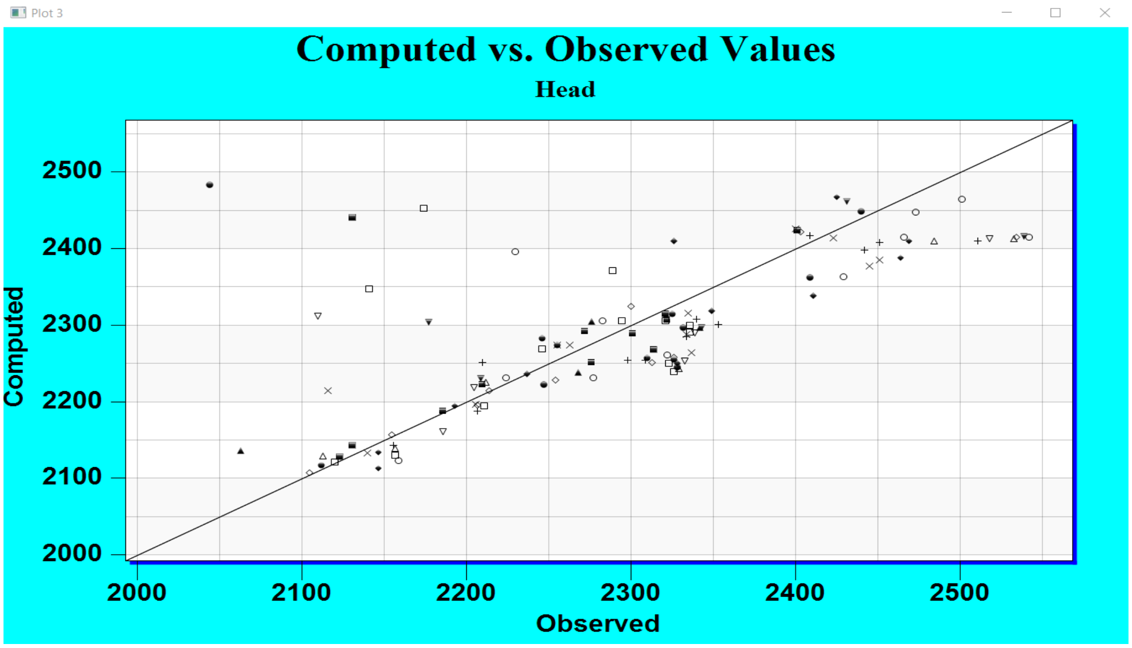


Figure 4.8:- Calibration of computed Vs observed head value

4.4.2 Sensitivity Analysis

In this study the sensitive parameter that affect our result are hydraulic conductivity and recharge. The two parameters are given to the model directly from data obtained from responsible organization. From different soil stratigraphy hydraulic conductivity is derived and from annual rainfall data recharge is calculated by empirical method which is used as an initial input to the model and will be changed after calibration. These two parameters are sensitive to change our result.

4.5 Effect Analysis

The impact of infrastructure development of Addis Ababa city on shallow groundwater response was investigated by using a process-based groundwater model GMS. The groundwater flow model simulation results show that smaller areas in the southern part of the study area become wet at ground surface. The overall study area hydraulic had generated and specific location area selected for further analysis such as Reppi (Kosha) solid waste dumping site , AALRT(Addis Ababa light rail transport) Northern terminal station and Akaki bridge and Akaki low cost condominium houses shown (figure 4.9).

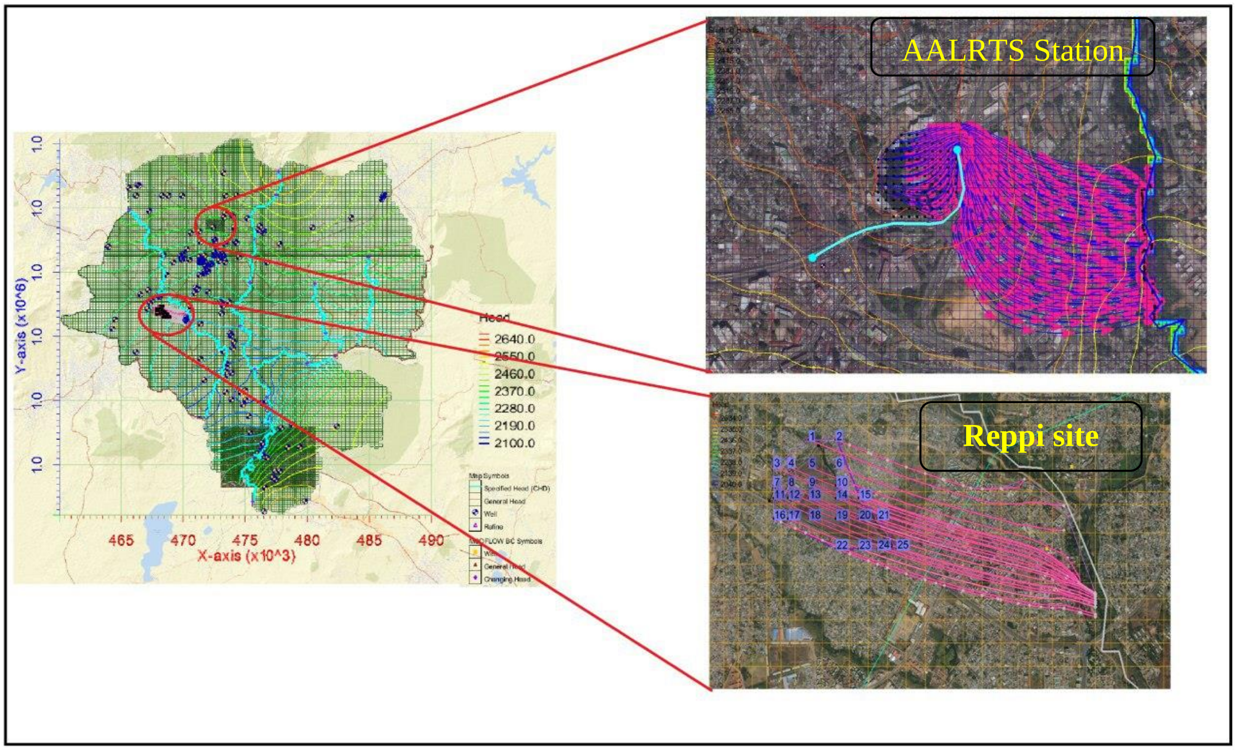


Figure 4.9:-Selected area for effect analysis and the results (Reppi solid west damping site and AALRTS station)

4.5.2 Reppi Solid Waste Dumping Site

There are quality concerns on the very shallow and shallow aquifers. If not well monitored and protected, the concern may also include the deep and very deep aquifers. The vulnerability of groundwater to pollution is a factor of the local subsurface infiltration and the nature of the multi layered aquifers. The subsurface infiltration condition of Addis Ababa area is governed by the thickness and hydraulic conductivity of the unconsolidated sediments overlying on the weathered and fractured volcanic rocks.

The presence of large quantities of mixtures of potentially hazardous chemicals in solid waste dumping sites close to residential area has increasingly caused some significant groundwater and surface water pollution. Concerns have led to conduct this research on groundwater flow path and chemical contaminate flow path associated with solid waste dumping sites. From this study we can conclude that there is an increase in risk to groundwater and surface water such as little akaki river were polluted in near Reppi or local name Koshe solid waste dumping site.

A 3-D groundwater flow model and contaminants transport pathway MODPATH was simulated in the Reppi waste disposal site as shown blow (figure 4.10) as a starting point for GW and contaminate transport. Darcy's law is valid for laminar flow, which is the case for most porous material. Darcy's law is valid for horizontal and vertical flows in the saturated and the unsaturated zone.

The direction of the flow depends on the formation of the geological units, the aquifer systems, hydraulic properties, topography, recharge and the presence of water supplies. The simulation result dictates that the GW and chemical flow from higher gradient of damping site to lower gradient point of little Akaki river. The speed at which groundwater flow depends on the size of the spaces in the soil or rock and how well the spaces are connected. These materials are permeable at damping site because they have large connected spaces that allow water to flow through them, as the result it also have high recharge to percolate the rain fall precipitation to saturated zone of the aquifer.

The leachate from Reppi landfills may leak into groundwater aquifers due to rainfalls, spread in to the adjacent little Akaki river system by groundwater flow and pollute the surrounding environment. However, this process does not stop even after the landfill activities have stopped receiving solid waste. Hence, it is very essential to keep assessing and monitoring the surroundings of decommissioned landfill sites.

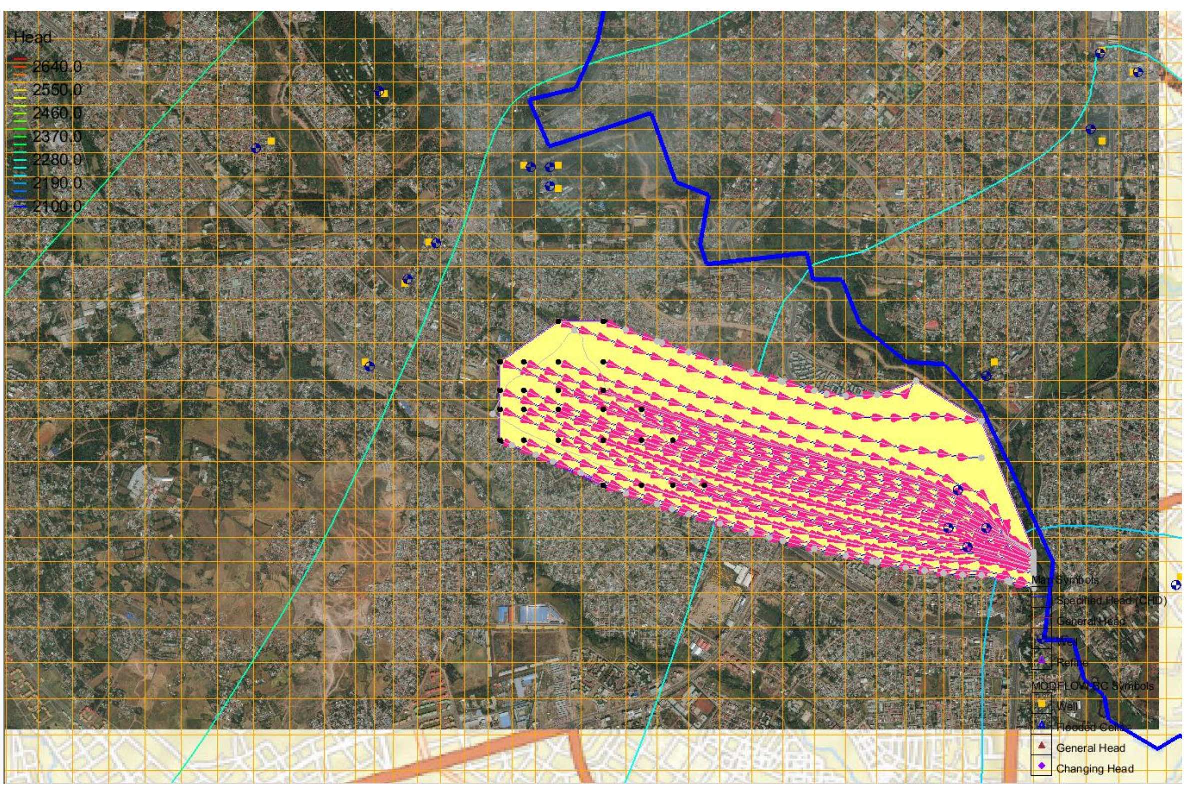


Figure 4.10:- capture zone and particle flow path from solid west damping site

Capture zone of GW was also simulated in the figure (4.10) colored referring specifically to the determination of the flow paths of water from their points of entry into a groundwater system to a discharging little Akaki river and the four wells as shown above. Capture zone also refers to describe both the areal extent and volumetric portion of a groundwater system that contributes discharge to a particular well, including "contributing recharge area," "wellhead protection area," "zone of contribution," and "capture zone. In general capture zone means three-dimensional, volumetric portion of a groundwater flow field that discharges water to a well or rivers.

Path line report was generated for each particle sat name, XYZ coordinate and duration of each particle to reach the discharging point or ending point. Form the figure (4.3) the table blow show the path line report for particle named 1 and 2.

Table 4.3: - Path line report for particle 1 and 2

Particle index	Starting cell	X	Y	Z	Cumulative tracking Time in day	Cell k	Cell J	Cell I
1	80299	468143.75	992387.5117	2110.760254	0	2	125	49
1	80299	468262.5	992343.9902	2108.664063	46092.73828	2	125	50
1	80299	468450.1475	992275.0117	2104.53418	116904.0938	2	126	50
1	80299	468500	992256.916	2098.49585	135055	2	126	51
1	80299	468665	992197.418	2096.685059	194024.0781	2	126	52
1	80299	468830.833	992140.875	2095.314453	251111.2031	2	126	53
1	80299	468996.666	992088.4668	2094.634277	306137.9063	2	126	54
1	80299	469041.7148	992075.0117	2095.561279	320810.2188	2	127	54
1	80299	469162.499	992038.582	2090.531982	359773.875	2	127	55
1	80299	469328.332	991991.0078	2091.166504	412000.4375	2	127	56
1	80299	469387.5674	991975.0117	2091.321777	430207.125	2	128	56

1	80299	469494.165	991946.4141	2090.505615	462897.4688	2	128	57
1	80299	469659.998	991905.584	2095.503906	513300.6875	2	128	58
1	80299	469737.2393	991887.4551	2099.183838	536781.0625	1	128	58
1	80299	469824.998	991881.3379	2105.368652	560880.5625	1	128	59
1	80299	469974.998	991879.5078	2120.01709	600986.8125	1	128	60
1	80299	470074.998	991890.7949	2134.954102	631226.0625	1	128	61
1	80299	470174.998	991889.5938	2149.483154	666871	1	128	62
1	80299	470254.8232	991875.0117	2158.623535	691147.75	1	129	62
1	80299	470274.998	991872.0918	2159.567383	696332.875	1	129	63
1	80299	470374.998	991862.252	2166.321777	719032.9375	1	129	64
2	80300	468381.25	992387.5117	2110.411377	0	2	125	50
2	80300	468500	992344.0273	2108.019775	43949.89453	2	125	51
2	80300	468665	992283.8848	2107.350342	103846.4844	2	125	52
2	80300	468689.7119	992275.0117	2106.960938	112576.3125	2	126	52
2	80300	468830.833	992225.0391	2099.37793	160966.4688	2	126	53
2	80300	468996.666	992170.2676	2098.678711	215993.1563	2	126	54
2	80300	469162.499	992119.8457	2099.73999	269645.4063	2	126	55
2	80300	469313.708	992075.0117	2101.593262	317482.2813	2	127	55
2	80300	469328.332	992070.7109	2097.948975	322037.9688	2	127	56
2	80300	469494.165	992023.1836	2100.738525	372681.4688	2	127	57
2	80300	469558.8604	992006.127	2104.108643	392168.3438	1	127	57
2	80300	469659.998	991996.4922	2109.958984	418562.7188	1	127	58
2	80300	469824.998	992001.2344	2124.229492	461221.0625	1	127	59
2	80300	469974.998	992009.3574	2139.972656	495099.6563	1	127	60
2	80300	470030.0293	992075.0117	2147.849121	508939.7188	1	126	60

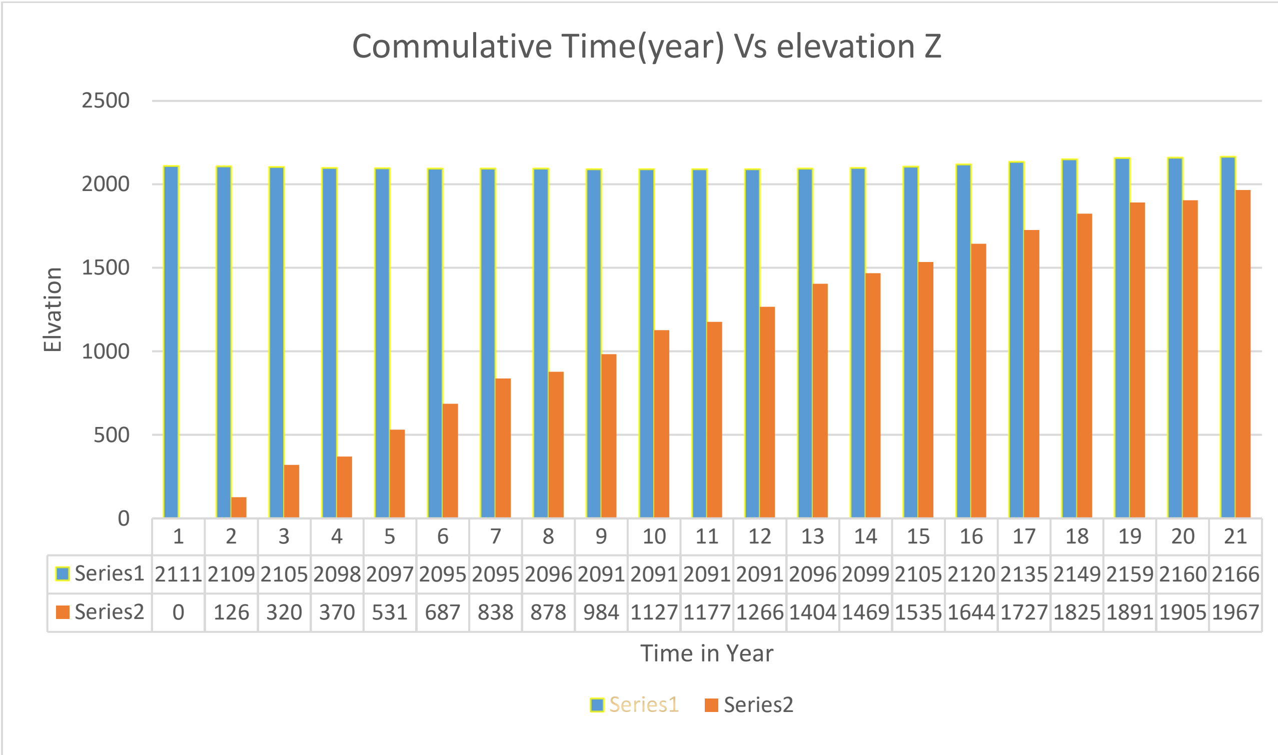


Figure 4.11:- Surface elevation Vs cumulative time taken by the particle 1 to reach end point

4.5.3 Addis Ababa light Rail Transport Terminal at Paisa

The MODFLOW Layers to 2D Scatter Points' conversion is used for regional (Addis Ababa MODFLOW model) to local or (Addis Ababa light rail transport Terminal) model conversion done. Modelling results pointed out a local increasing of the groundwater levels upstream of the railway terminal. Even if the local changes are quite low, they can negatively affect underground structures and buildings because of the superimposition of effects.

Modelling results also show local deformations of the water table as well as the flow direction of the GW nearby the underground structures (railway shear wall) (Figure 4.9). These deformations consist in a rise of the groundwater located upstream of the impermeable elements (with respect to the water flow direction), whereas a groundwater drawdown well occurs downstream.

Structures and infrastructures, acting as impermeable elements, also involve a change in the water flow path: The flow line depicted in the plane (figure 4.9) the flow lines are closely spaced at the end point of the railway shear wall then after the flow line change the direction and join the specified head boundary. Such a sudden change in direction of GW increase may bring about erosive phenomena, especially for the finest soil particles, which in the long term can lead to settlements and instabilities of the structures.

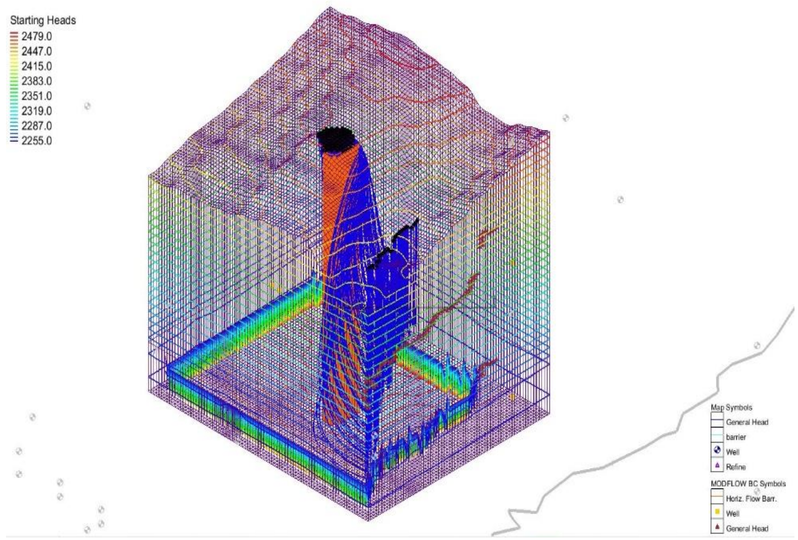


Figure:- 4.12:-3D view water flow direction and the shear wall acting us flow barrier.

4.5.1 Akaki Low-Cost Residential Building and Akaki Bridge

Akaki condominium housing and Akaki brige location as shown blow in the figure located at the lowest elevation of the whole capital city. It is also place where Akaki river delta and the river live the stud area and joining Lake Abasmual.

The hydraulic head contour as shown blow (figure 4.13) that the cells are flooded and head of having 2100 around the area. The shallow water table equal to surface elevation and the ground water table is at surface. Saturated soils are observed throughout the year. The farmer use this opportunity to farm their land produce vegetable products since the soil are wet and swamp nature.

Surface water bodies (rivers Aakai) may interact with groundwater. As concerns for water resources and the environment increase, it is important to consider groundwater and surface water as a single resource. Therefore understanding their interaction is crucial for water resource management in Akaki river basins, even if it is difficult to observe or to measure these exchanges.

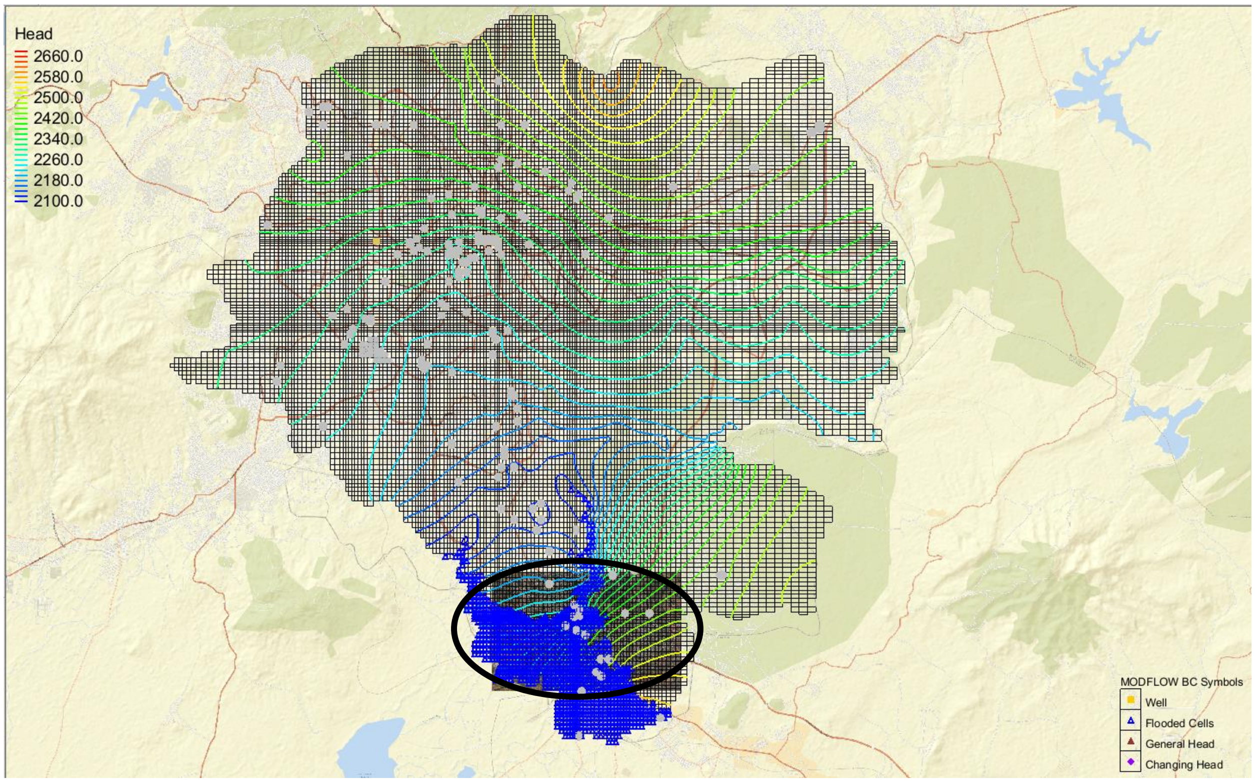


Figure 4.13:-Location of Akaki low-cost residential building and Akaki Bridge

Groundwater in the river environment tends to occur as alluvial deposits associated with the Akaki river channel (Figure 4.14) and this groundwater is usually shallow and easily accessible in the vicinity of the river. Saturated soil aquifers are generally of limited lateral extent and depth to the Akaki River. The farm land below the road (express way to Adam road) as shown blow have limited lateral extent in North to south and a little wider in East to West direction following the river delta. The groundwater flow model simulation results demonstrate that marked area of Akaki Bridge and the surrounding of the study area become wet at ground surface. If there exist high intensity rainfall and surface water leakage to recharge the aquifer, catastrophic flood will occur. It is previously known that many time Akiaki Bridge over flooded by the river mostly in wet summer season. Know there is new bridge under construction. This structure should be designed for the mutual effect of shallow groundwater and surface water interaction effect.

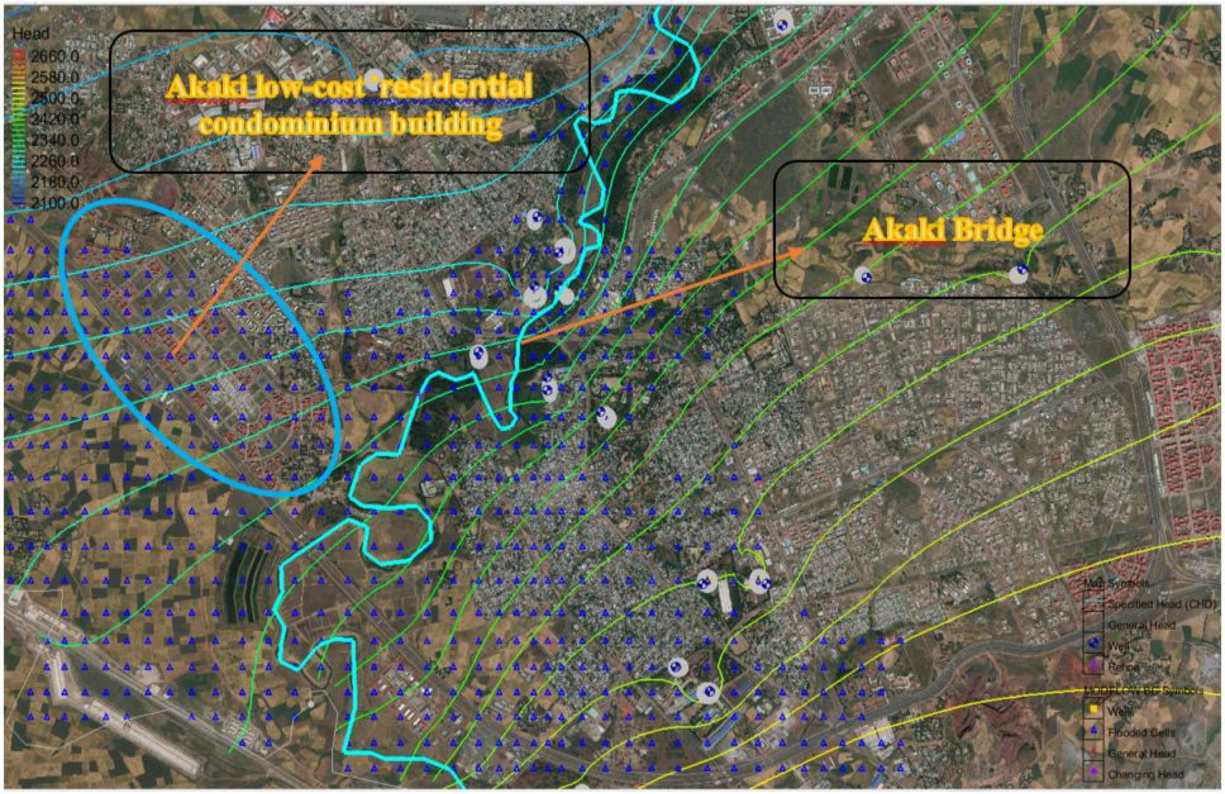


Figure 4.14:-The shallow groundwater head contour and the Big Akaki river

5. CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion this study develop, understand and characterize the aquifer model boundaries or Addis Ababa city shallow groundwater nature in relation with infrastrucral development plane. To do this, a study-state approach of groundwater modeling has been used in order to investigate the aquifer model. Coupling MODFLOW with ArcGIS using GMS powerful software allows us to simulate the shallow groundwater aquifer. This study analyze the above mentioned site (in the result and discussion section) for shallow GW flow model MODFLOW and particle flow path using MODPATH.

In the Reppi solid west damping site Numerical simulation of the ground water flow using the MODFLOW package resulted in hydraulic head contour map and the depth of shallow groundwater table location, which can be considered as reasonable. Moreover, use of the particle-tracking package MODPATH allowed delineation little Akaki river protection zones. These zones are very useful tool in planning future urbanization of the capital city. MODPATH results show that pollutants from point pollution sources (Reppi solid west damping site) to affected regions by the toxic chemicals were marked as capture zone. Since the region out of the capture zone, were considered as zone of degradation of several pollutants.

The part of AALRT have a station with a tunnel which is located at a depth greater than 20 meters below the ground surface, this tunnel is located around paisa St. Gorge church. A leakage of groundwater is observed at the underground facilities within the tunnel and rail. A local GW flow model MODFLOW & MODPATH result shows, the tunnel acts as flow barrier to the shallow GW. This is caused, as a result in the change of the direction of the flow path. This barrier could cause stress and liquefaction and saturation of the soil underneath the foundation of the tunnel the structures around. It also cause draw down in the well downstream of the structure.

Bothe falling groundwater levels and rising groundwater levels bring a host of problems. Rising water levels affect the structural properties of soils and can reduce bearing capacity, cause swelling, and create hydrostatic uplift pressures. Akaki area shallow groundwater table approaches the land surface, a rising water level can intrude on structures and may affect the Akaki Bridge and the surrounding area low cost residential buildings.

5.2 RECOMMENDATION

Because usually groundwater is out of sight, it is sometimes out of mind, but the impacts of city development plan on groundwater systems must be considered in land-use planning, construction, or in regards to water resources to make future urban areas sustainable.

Urban development will not be halted for water considerations. Hence, there is an urgent need to guide urban planners on how to manage urban development with minimal damage to groundwater resources. Sustainable development internalizes into its goals and methods the long range impacts of development on the natural environment and on its utility for human beings in the present and future generations.

Relevant Components of Addis Ababa city infrastructural plan preparation should consider:-

- The Reppi solid waste disposal site has served beyond its design period and has been a source of contamination to shallow groundwater as well as river channel which cause serious damage to the environment and the city population. The site requires sound policy measures and coordinated institutions for the municipal waste management sector.
- African first west to energy transformation plant development near Reppi waste damping site have good transformation, but Aquifer and river water treatment should be done to overcome the contamination. Also the operation of dumping site must be stopped as soon as possible to solve groundwater and public health problems. Modern new damping site outside the city should be constructed.
- The newly started projects such as underground car-parks around maskelflower area, subway and under construction deep foundation buildings should consider the shallow groundwater flow and consider in design and analysis of the structure. Proper and consistent infrastructure planning and management is vitally important, and well thought out asset management is crucial to the daily lives of millions of people. Navigating the planning approval system is not straightforward. It requires relevant and long-standing track record of successfully delivering preeminent and internationally significant infrastructure projects, alongside a portfolio of local, community-based initiatives.

6. REFERENCES

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Appendix and annex

Lithological data for Boreholes model and solid model up to 100m beneath from ground surface of study area for some selected boreholes.

Table 3: KDPW1

Depth interval(m)		Lithological description
From	To	
0	2	top clay soil
2	8	Basaltic boulder
8	26	Highly fractured and decomposed trachyte
26	40	Highly fractured and weathered ignimbrite
40	52	Moderately fractured scoriaceous basalt
52	58	ignimbrite with scoriaceous basalt intercalation
58	78	Gray colored clay/unconsolidated tuff
78	82	Moderately fractured ignimbrite
82	84	Gray colored clay/unconsolidated tuff
84	110	Moderately fractured ignimbrite
110	128	Highly fractured ignimbrite
128	134	Gray colored tuff

Table 4: DCPW1

Depth Interval(m)		
From	To	Lithological description
0	6	Reddish colored
6	34	Slightly weathered basalt
34	42	Moderately fractured basalt
42	66	Volcanic ash
66	70	Scoriaceous basalt
70	74	Highly weathered and slightly fractured basalt

Depth Interval(m)		Lithological description
From	To	
74	76	Scoriaceous basalt
76	84	Highly weathered basalt
84	88	Slightly weathered and slightly fractured basalt
88	98	Moderately fractured and weathered basalt
98	102	Moderately fractured and slightly weathered basalt
102	114	Slightly weathered and moderately fractured basalt

Table 5: DCPW2

Depth Interval(m)		Lithological Description
From	To	
0	9	Reddish colored clay
91	26	Weathered and fractured scoriaceous basalt
26	32	Slightly weathered and fractured ignimbrite
32	80	Clay rich highly decomposed basalt
80	92	Clay with rock fragments
92	112	Moderately fractured and highly weathered scoriaceous basalt
112	124	Moderately to highly fractured and weathered basalt

Table 6: MCPW1

Depth interval(m)		Lithological description
From	To	
0	10	Top soil
10	14	Decomposed basalt
14	24	Moderately weathered and fractured basalt
24	30	Highly weathered and slightly fractured basalt
30	40	Highly weathered scoriaceous basalt
40	42	Highly weathered basalt
42	54	Moderately weathered and slightly weathered basalt

Depth interval(m)		Lithological description
From	To	
54	58	Slightly fractured and highly weathered basalt
58	64	Highly fractured and slightly weathered basalt
64	66	Massive basalt
66	78	Highly weathered scoriaceous basalt
78	86	Moderately fractured and slightly weathered scoriaceous basalt
86	96	Highly weathered scoriaceous basalt
96	98	Highly fractured scoriaceous basalt
98	148	Slightly fractured scoria

Table 7:MKPW1

Well Index	MKPW-1
Well depth, m	357
Static water level ,m	Artesian
Pumping test Pump position, m	179
Pumping test discharge ,l/s	50
Maximum drawdown, m	141.22
Dynamic Water level ,m	141.22
Transmissivity,m^2/day	1.4E+1
Specific capacity, l/s/m	3.54E-1
Safe yield	30
Well Type	Production
Main Aquifer	Fractured decomposed ignimbrite and basalt

Table 4.3: - Path line report for particle 3- 10

Particle index	Starting cell	X	Y	Z	Cumulative tracking Time day	Cell k	Cell J	Cell I
3	80511	467837.5	992175.0117	2115.390381	0	2	126	47
3	80511	467900	992149.5762	2114.413818	25615.60742	2	126	48
3	80511	468025	992099.6953	2110.897949	76122.60938	2	126	49

3	80511	468088.9092	992075.0117	2106.091064	101253.1563	2	127	49
3	80511	468262.5	992008.0527	2102.87793	169114.8125	2	127	50
3	80511	468353.3867	991975.0117	2098.536377	203522.2031	2	128	50
3	80511	468500	991922.5664	2097.143066	258577.1719	2	128	51
3	80511	468642.4551	991875.0117	2090.51001	309515.9688	2	129	51
3	80511	468665	991867.4902	2089.871094	317566.9063	2	129	52
3	80511	468830.833	991814.5098	2083.779785	374561.75	2	129	53
3	80511	468996.666	991764.1074	2080.871094	429894.0625	2	129	54
3	80511	469162.499	991716.6523	2079.933594	484108.375	2	129	55
3	80511	469328.332	991672.582	2078.890625	537058.6875	2	129	56
3	80511	469420.1055	991650.0117	2078.072266	565738.5625	2	130	56
3	80511	469494.165	991631.3809	2075.007813	589081.375	2	130	57
3	80511	469659.998	991592.123	2072.462158	640215.125	2	130	58
3	80511	469824.998	991553.9316	2071.143066	690212.625	2	130	59
3	80511	469974.998	991517.0781	2070.756592	735067.125	2	130	60
3	80511	470074.998	991488.9922	2070.875977	764674.375	2	130	61
3	80511	470174.998	991455.9785	2071.992432	794110.9375	2	130	62
3	80511	470274.998	991406.3125	2075.308105	829239.75	2	130	63
3	80511	470282.4473	991401.0117	2075.195068	832400.8125	2	131	63
3	80511	470374.998	991349.8945	2075.422852	863324.875	2	131	64
3	80511	470512.498	991255.7266	2084.126221	956115.125	2	131	65
3	80511	470514.0752	991251.0117	2083.572021	958887.625	2	132	65
3	80511	470517.8262	991247.3379	2081.464111	960989.25	1	132	65
3	80511	470649.998	991169.7148	2100.38623	987999.125	1	132	66
4	80512	467962.5	992175.0117	2113.636719	0	2	126	48
4	80512	468025	992150.2363	2112.743408	25231.12695	2	126	49
4	80512	468221.1094	992075.0117	2105.733643	102062.1875	2	127	49
4	80512	468262.5	992059.1641	2104.793945	118143.4609	2	127	50
4	80512	468495.8662	991975.0117	2097.962891	205702.1875	2	128	50
4	80512	468500	991973.5449	2098.90332	207241.125	2	128	51
4	80512	468665	991918.3633	2091.842529	266153.7813	2	128	52
4	80512	468801.6191	991875.0117	2088.172607	313203.7188	2	129	52
4	80512	468830.833	991865.7422	2085.326172	323154.3438	2	129	53
4	80512	468996.666	991814.7832	2082.383789	378486.6875	2	129	54
4	80512	469162.499	991766.6426	2081.435547	432701	2	129	55
4	80512	469328.332	991721.8984	2080.380615	485651.3125	2	129	56
4	80512	469494.165	991680.75	2079.318115	537278.9375	2	129	57
4	80512	469626.9541	991650.0117	2079.577881	578052.625	2	130	57
4	80512	469659.998	991642.2031	2076.088867	588191.9375	2	130	58
4	80512	469824.998	991603.834	2074.730713	638189.4375	2	130	59
4	80512	469974.998	991566.6113	2074.332764	683043.9375	2	130	60
4	80512	470074.998	991538.0391	2074.455811	712651.1875	2	130	61
4	80512	470174.998	991504.3672	2075.605225	742087.75	2	130	62

4	80512	470274.998	991454.0957	2079.019287	777216.5625	2	130	63
4	80512	470348.3652	991401.0117	2083.311768	809231.5625	2	131	63
4	80512	470374.998	991386.2188	2082.055176	817993.3125	2	131	64
4	80512	470466.4189	991316.4883	2085.998535	860922.9375	1	131	64
4	80512	470512.498	991253.5879	2091.188721	913465.6875	1	131	65
4	80512	470512.8564	991251.0117	2090.474365	914181.375	1	132	65
4	80512	470649.998	991168.6309	2105.572998	942678	1	132	66
5	80513	468143.75	992175.0117	2109.808594	0	2	126	49
5	80513	468262.5	992129.8887	2107.859619	46317.10156	2	126	50
5	80513	468413.4004	992075.0117	2100.407715	102519.5078	2	127	50
5	80513	468500	992044.0469	2100.505127	134695.25	2	127	51
5	80513	468665	991988.5117	2094.392578	193351.25	2	127	52
5	80513	468706.5889	991975.0117	2094.799561	207919.5781	2	128	52
5	80513	468830.833	991935.1895	2089.917236	250397.0938	2	128	53
5	80513	468996.666	991884.6113	2088.36084	305662.0313	2	128	54
5	80513	469029.5811	991875.0117	2089.012451	316477.1875	2	129	54
5	80513	469162.499	991835.834	2083.776611	359803.9688	2	129	55
5	80513	469328.332	991790.1543	2082.702637	412754.2813	2	129	56
5	80513	469494.165	991748.127	2081.621094	464381.9375	2	129	57
5	80513	469659.998	991709.1445	2082.12085	515294.1563	2	129	58
5	80513	469824.998	991670.8828	2084.372559	565990.0625	2	129	59
5	80513	469906.2695	991650.0117	2087.603516	591515.4375	2	130	59
5	80513	469974.998	991632.7715	2084.293701	612060.375	2	130	60
5	80513	470074.998	991603.5508	2084.426758	641667.625	2	130	61
5	80513	470174.998	991568.998	2085.668213	671104.1875	2	130	62
5	80513	470267.3066	991522.5625	2088.95752	703019.3125	1	130	62
5	80513	470274.998	991519.6484	2089.330811	706043.3125	1	130	63
5	80513	470374.998	991479.793	2095.328857	749112.875	1	130	64
5	80513	470444.083	991401.0117	2099.859863	794087.375	1	131	64
5	80513	470512.498	991290.832	2104.249512	860486.625	1	131	65
5	80513	470518.7363	991251.0117	2104.393311	873232.625	1	132	65
5	80513	470649.998	991172.5254	2115.854492	899976.1875	1	132	66
6	80514	468381.25	992175.0117	2105.047852	0	2	126	50
6	80514	468500	992132.2754	2102.890137	43481.85547	2	126	51
6	80514	468665	992076.0176	2101.025635	102450.9375	2	126	52
6	80514	468668.0244	992075.0117	2102.887451	103519.0859	2	127	52
6	80514	468830.833	992021.457	2096.19873	159610.4375	2	127	53
6	80514	468980.8848	991975.0117	2094.856201	209576.6563	2	128	53
6	80514	468996.666	991970.1602	2091.720703	214750.3906	2	128	54
6	80514	469162.499	991921.127	2091.133301	268586.0313	2	128	55
6	80514	469328.332	991875.582	2090.87207	320921.8125	2	128	56
6	80514	469330.5684	991875.0117	2090.495117	321616.2188	2	129	56
6	80514	469494.165	991832.4746	2086.680176	372541.5625	2	129	57

6	80514	469659.998	991792.6934	2087.199219	423453.7813	2	129	58
6	80514	469824.998	991754.1504	2089.537354	474149.6875	2	129	59
6	80514	469968.9521	991716.8027	2096.191406	519884.75	1	129	59
6	80514	469974.998	991716.0508	2096.482422	521650.0938	1	129	60
6	80514	470074.998	991705.0391	2103.145264	550894.9375	1	129	61
6	80514	470174.998	991689.2715	2111.092529	579953.0625	1	129	62
6	80514	470274.998	991671.541	2120.783936	606936.6875	1	129	63
6	80514	470374.998	991669.2266	2133.944824	629636.75	1	129	64
7	80725	467837.5	992025.0117	2112.968506	0	2	127	47
7	80725	467900	991999.002	2111.946045	25659.85742	2	127	48
7	80725	467958.6084	991975.0117	2110.415283	49495.15234	2	128	48
7	80725	468025	991947.7793	2107.734863	76304.21875	2	128	49
7	80725	468211.3965	991875.0117	2103.660156	150113.5	2	129	49
7	80725	468262.5	991855.2656	2103.848389	170309.7656	2	129	50
7	80725	468500	991769.8691	2096.929199	260481.5313	2	129	51
7	80725	468665	991714.2773	2089.793701	319794.2813	2	129	52
7	80725	468830.833	991661.8496	2083.705566	376789.125	2	129	53
7	80725	468870.5098	991650.0117	2082.546387	390171.8438	2	130	53
7	80725	468996.666	991612.0449	2079.161621	432738.1875	2	130	54
7	80725	469162.499	991564.8691	2077.38623	487683.3125	2	130	55
7	80725	469328.332	991520.6055	2075.615967	541434.375	2	130	56
7	80725	469494.165	991479.3262	2073.592285	593950.3125	2	130	57
7	80725	469659.998	991440.623	2071.075195	645084.0625	2	130	58
7	80725	469824.998	991402.9668	2069.77124	695081.5625	2	130	59
7	80725	469833.1621	991401.0117	2068.648926	697527	2	131	59
7	80725	469974.998	991368.3398	2066.484863	738393.5625	2	131	60
7	80725	470074.998	991344.6367	2064.730713	765772.625	2	131	61
7	80725	470174.998	991321.1973	2064.519043	791540.75	2	131	62
7	80725	470274.998	991295.5313	2065.029053	820612.125	2	131	63
7	80725	470366.0869	991251.0117	2066.337646	851165.0625	2	132	63
7	80725	470374.998	991245.1387	2065.888184	855403.4375	2	132	64
7	80725	470512.498	991206.5801	2081.102783	927989.9375	2	132	65
7	80725	470518.8359	991200.9121	2081.464111	931539.1875	1	132	65
7	80725	470649.998	991142.2773	2100.197021	958253.75	1	132	66
8	80726	467962.5	992025.0117	2112.381348	0	2	127	48
8	80726	468025	991999.5918	2111.370361	25282.66797	2	127	49
8	80726	468087.8594	991975.0117	2107.461426	50132.45703	2	128	49
8	80726	468262.5	991907.3203	2104.884277	118816.5469	2	128	50
8	80726	468351.6748	991875.0117	2100.968506	152799.0313	2	129	50
8	80726	468500	991821.8652	2098.813965	208817.6563	2	129	51
8	80726	468665	991766.3477	2091.586914	268130.4063	2	129	52
8	80726	468830.833	991713.7324	2085.420654	325125.25	2	129	53
8	80726	468996.666	991664.4238	2082.476318	380457.5625	2	129	54

8	80726	469047.7422	991650.0117	2082.949951	397325	2	130	54
8	80726	469162.499	991617.2559	2079.187012	435201.25	2	130	55
8	80726	469328.332	991572.6484	2077.391846	488952.3438	2	130	56
8	80726	469494.165	991531.1348	2075.3396	541468.25	2	130	57
8	80726	469659.998	991492.2422	2072.787109	592602	2	130	58
8	80726	469824.998	991454.4023	2071.4646	642599.5	2	130	59
8	80726	469974.998	991418.2871	2071.077148	687454	2	130	60
8	80726	470038.6055	991401.0117	2070.700195	706281	2	131	60
8	80726	470074.998	991391.916	2068.527832	716117.0625	2	131	61
8	80726	470174.998	991365.1211	2068.309326	741885.1875	2	131	62
8	80726	470274.998	991332.6289	2068.836182	770956.5625	2	131	63
8	80726	470374.998	991281.6836	2070.366699	804429.125	2	131	64
8	80726	470469.5127	991251.0117	2074.171631	849604.875	2	132	64
8	80726	470512.498	991238.4023	2077.751953	873434.6875	2	132	65
8	80726	470526.7061	991224.8828	2081.464111	881435.5625	1	132	65
8	80726	470649.998	991161.248	2098.756592	905921.0625	1	132	66
9	80727	468143.75	992025.0117	2109.573486	0	2	127	49
9	80727	468262.5	991979.2383	2107.48291	46303.67578	2	127	50
9	80727	468274.0723	991975.0117	2104.42749	50706.95703	2	128	50
9	80727	468500	991893.8359	2101.624268	135961.7969	2	128	51
9	80727	468556.124	991875.0117	2096.165039	156146.3125	2	129	51
9	80727	468665	991838.5273	2094.236816	195182.0938	2	129	52
9	80727	468830.833	991785.6504	2087.955566	252176.9375	2	129	53
9	80727	468996.666	991735.5605	2084.956055	307509.25	2	129	54
9	80727	469162.499	991688.4922	2083.989502	361723.5625	2	129	55
9	80727	469308.2197	991650.0117	2083.101807	408323.1875	2	130	55
9	80727	469328.332	991644.6133	2080.352539	414779.5313	2	130	56
9	80727	469494.165	991602.7754	2078.252441	467295.4375	2	130	57
9	80727	469659.998	991563.6211	2075.640625	518429.1875	2	130	58
9	80727	469824.998	991525.5293	2074.287354	568426.6875	2	130	59
9	80727	469974.998	991488.8867	2073.890869	613281.1875	2	130	60
9	80727	470074.998	991461.0762	2074.013428	642888.4375	2	130	61
9	80727	470174.998	991428.4375	2075.158936	672325	2	130	62
9	80727	470234.9707	991401.0117	2076.782227	691804.5625	2	131	62
9	80727	470274.998	991383.4512	2075.46582	704608.5625	2	131	63
9	80727	470374.998	991329.3457	2077.081787	738081.125	2	131	64
9	80727	470509.5967	991251.0117	2085.399658	825984.5625	2	132	64
9	80727	470512.498	991250.1426	2083.657227	827628.8125	2	132	65
9	80727	470512.9131	991249.7363	2081.464111	827860.4375	1	132	65
9	80727	470649.998	991167.9219	2101.32251	856339.8125	1	132	66
10	80728	468381.25	992025.0117	2106.688965	0	2	127	50
10	80728	468500	991982.5371	2104.575684	44210.24609	2	127	51
10	80728	468522.2461	991975.0117	2100.837646	52235.46875	2	128	51

10	80728	468665	991927.3242	2098.215332	103129.2344	2	128	52
10	80728	468830.1182	991875.0117	2093.930664	159828.875	2	129	52
10	80728	468830.833	991874.7852	2091.402832	160071.9531	2	129	53
10	80728	468996.666	991823.7266	2088.328369	215404.2813	2	129	54