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Groundwater potential assessment and characterization of Genale-Dawa River basin

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Groundwater potential Assesment and Characterization of Genale-Dawa river basin

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Civil Engineering (Stream: Hydraulic Engineering)

By

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Abstract

Genale-Dawa River Basin is one of the largest basins in Ethiopia. It is one of the most drought prone regions in Ethiopia. As a result a search for alternative source of water has always been a major issue in the region. This study therefore, aims at characterizing and evaluating the ground water potential resource of Genale-Dawa basin. The results of this research ultimately contribute to development of better water resources potential management.

Delineation of the Genale-Dawa River basin was carried out first in order to define the problem domain of the model. This has resulted in 17860km^2 area of the basin. This area was discretized to form a three dimensional. The discretized region has 19620 nodes, 17862 equilateral triangular elements of varying sizes with a maximum of 5km edge dimension and 2500km model thickness.

The conceptualization of the model was done by grouping the discretized region in to 56 geological classes based on previous geological survey of the basin. The equivalent porous medium modeling approach was used to represent the different geological classes in the basin. Moreover, 23 rain gauge stations were used to determine the areal precipitation over the basin. The model takes perennial rivers as constant head boundaries, the side and bottom geometric boundaries of the model as no flow boundaries and the recharge due to precipitation as specified flow boundary.

After conceptualization of the flow system was complete and numerical model developed, TAGSAC model manual calibration was done by seating hydraulic conductivity and percentage recharge as calibration parameters when calibration is complete. The result was evaluated quantitatively using average indicators (AM, RMS, MAE) and qualitatively by comparison of groundwater contour maps generated with recorded and simulated hydraulic head data.

The calibration model was then used to determine monthly groundwater table fluctuation which eventually enabled the estimation of groundwater recharge potential of the basin. Additionally, base flow separation of perennial rivers was done to determine the monthly excess flux from the aquifer system. By adding these two values the total replenishable groundwater was estimated to be 2.78BMC. Hydro-geological map was also prepared based on hydraulic conductivity values obtained from model calibration. Identification of major groundwater recharge and discharge areas have also been done as an attempt towards basic groundwater flow system characterization.

Key words:

Ethiopia; Genale Dawa River Basin; Numerical Groundwater modeling; Replenishable Groundwater Potential; TAGSAC

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1. Introduction

Groundwater is an important natural resource Worldwide. More than 2 billion people depend on groundwater for their daily supply (Kemper, 2004). It has been estimated that between one third and one half a billion people in Sub-Saharan African countries use both protected and unprotected groundwater for their daily water supply. Provided that the initial cost of well development is in a reasonable order, ground water based water work projects are always preferable. This is because; Ground water is abundant relative to surface water, dependable in the sense of amount and usually smaller cost for treatment plant is needed in case where water is used for domestic supply.

Ethiopia, being one of the most hydrologically blessed countries in east Africa, is believed to have a large ground water potential. Studies show erroneous results of 2.5 BCM by WAPCOS, to 185 BCM by Ayenew and Alemayehu, in 2001 (Moges, 2012). Which can be taken as an indication of how much detailed study and survey is needed to estimate the countries resources with a better precision. This ambiguity in estimation can have a hindering effect on the countries pursuit to utilize its water resources potential to the limit.

The country's water supply coverage was estimated to be 30.9 percent, the rural water supply coverage being 23.1 percent and that of urban being 74.4 percent (Semu, 2012). Unpublished reports indicate that susceptibility to drought is higher in the periphery basins of the country such as Genale-Dawa than the central highlands due to high temporal variations of hydrological trends, making it hard to attain sustainable water supply in the region. Moreover, Master Plan Studies carried out during 1997-2007, indicates that Ethiopia has an estimated total potential irrigable land of 3,798,782 ha out of which 1,074,720 ha or 28.3% of the total irrigable land is in the Genale-Dawa River basin (MOWR, Integrated River Basin Master Plan Studies, carrried out during, 2007)

Therefore, it can be drawn from the discussion above that, exploring sustainable and drought proof water resource is of significant importance. As an attempt to contribute to a suitable solution, this study focuses on evaluating the Genale-Dawa water resource potential and basic characterization of the ground water system. The study employs 3-D numerical ground water model to determine the monthly average groundwater table fluctuation, which then is used to determine the amount of recharge / replenishable ground water potential. The result obtained is then combined with the result of groundwater potential result by base flow separation approach.

1.1. Statement of the problem

Ethiopia has suffered from repeated drought scenarios in the past; especially the peripheries of the country like Genale-Dawa basin are more prone to drought than the interior highlands. At driest seasons even major surface water sources dry up, as a result the available large areas of suitable irrigation land are left uncultivated and in times, standard domestic water supply become scarce. As a result proper management and utilization of water resource is vital in the region. In the past, studies have been done on the region to estimate the water resource potential. However, even though an estimation of groundwater resource was done based on different basic approaches in the region, basin wise groundwater numerical modeling has not been done for the Genale-Dawa catchment. Numerical modeling however is an effective approach to groundwater potential estimation and also reveals basic characteristics of the flow system. This can be of significant importance for the detailed understanding of available water resources and can contribute to the betterment of water resources planning and management. This study therefore attempts to produce a research output that can be useful for sustainable use of available groundwater resource.

1.2. Objective of the study

The main objective of this study is to numerically model the ground water flow system of the study area. There by advance towards detailed understanding of hydro-geological components of the basin, this can eventually lead to:

- Closely approximate the Genale-Dawa river basin ground water potential or replenishable recharge.
- Hydro-geologically characterize the Genale-Dawa Ground water system.

1.2.1. Specific objectives

- Closely approximate the hydraulic conductivity characteristics and percentage recharge of the geological classes by performing model calibration.
- Determine seasonal groundwater table fluctuation that will be used for estimation of groundwater potential
- Determine base flow contribution of the groundwater flow system to nearby rivers by doing the necessary data checks, data fill and performing base flow separation.
- Hydro-geologically classify the aquifer system based on hydraulic conductivity values obtained from calibration.

2. Literature review

2.1. Description of the area

The Genale-Dawa river basin is located in Ethiopia in the southern part of the country adjoining Kenya and Somalia international borders and is bounded by
3° 40’ N and 7° 43‘N latitudes and 37° 04’ E and 43° 28’ E longitudes. It is the third largest basin of the country after Abay and Wabishebele river basins covering an estimated area of about 176705km2 (MOWR, Genale Dawa River basin intigrated resources development master plan study hydrology sector, 2007). It encompasses the western half of Bale (South of Goba) and south-east, south-western and north-eastern parts of Sidamo

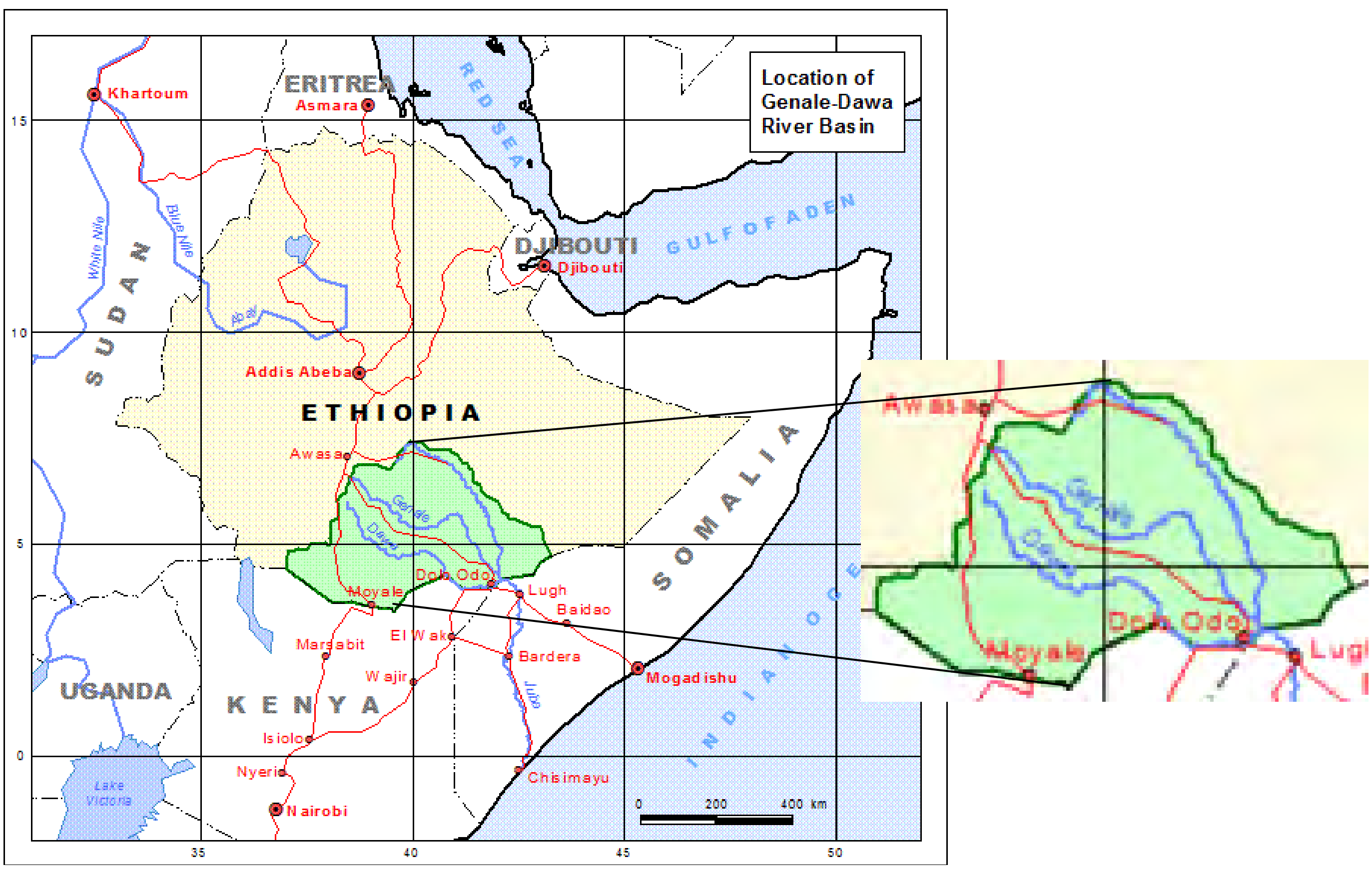


Figure 1 Location of Genale-Dawa river basin (Source Integrated Water Resources Development Master Plan Study)

The catchment constitutes three river systems namely Dawa, Genale and Wabi Gastro. The Genale River is joined by Dawa River to form the Genale – Dawa River at the lower portion of the basin before crossing Ethio-Somali border which drains the western segment of the basin that is aligned with Omo-gibe river basin. Whereas north-eastern part of the basin is drained by the Weyeb -Gastro River that meets the Genale – Dawa River near the Ethio-Somalia border to form the Jubbah River that flows to the Indian ocean (Ethiopian National Meteorological Agency, 2013).

The southern part of the Southeastern Escarpment of the Main Ethiopia Rift Valley, Bale and Borena Highlands mark the main head waters of the Genale-Dawa River basin, that forms the water divide between the Mediterranean and Indian Ocean (Alemayehu, 2006). Altitude decreases from north to south and from west to east, this variation in altitude ranges in elevation from more than 4270m.a.m.s.l on the Bale Highlands to less than 173m.a.m.s.l near the international borders with Somalia and Kenya (south-eastern part of the catchment). Some 20% of the total area lies in the highlands above 1500m and 16% in the lowland plains below 500m (Master plan). The respective sub-basins of the Genale, Dawa and Weyeb Rivers occupy approximately 33%, 28% and 14% of the total Basin area. The remaining 25% is covered by the south and eastern border regions, drained by a number of intermittent streams which do not enter the main river systems (MOWR, Genale Dawa River basin intigrated resources development master plan study hydro-Geology sector, 2007).

It is mentioned in the integrated master plan that the Genale-Dawa basin area, as pre-defined by the MOWR and as shown in the previous figure, does not conform to strict hydrological divisions in the south-west and south-east. This is most apparent on the extreme south-eastern border in which a sizeable area is assigned to the Wabi-Shebele basin which actually drains into the Juba River in Genale Dawa basin. A corrected delineation of the basin is presented on fig. 6 of this study.

2.2. Hydrology and Climate

The basin falls mainly in the arid and semi-arid zone and is generally drought-prone with erratic rainfall of an average monthly rainfall spacial variation ranging from 34mm to 143mm (Ethiopian National Meteorological Agency, 2013).

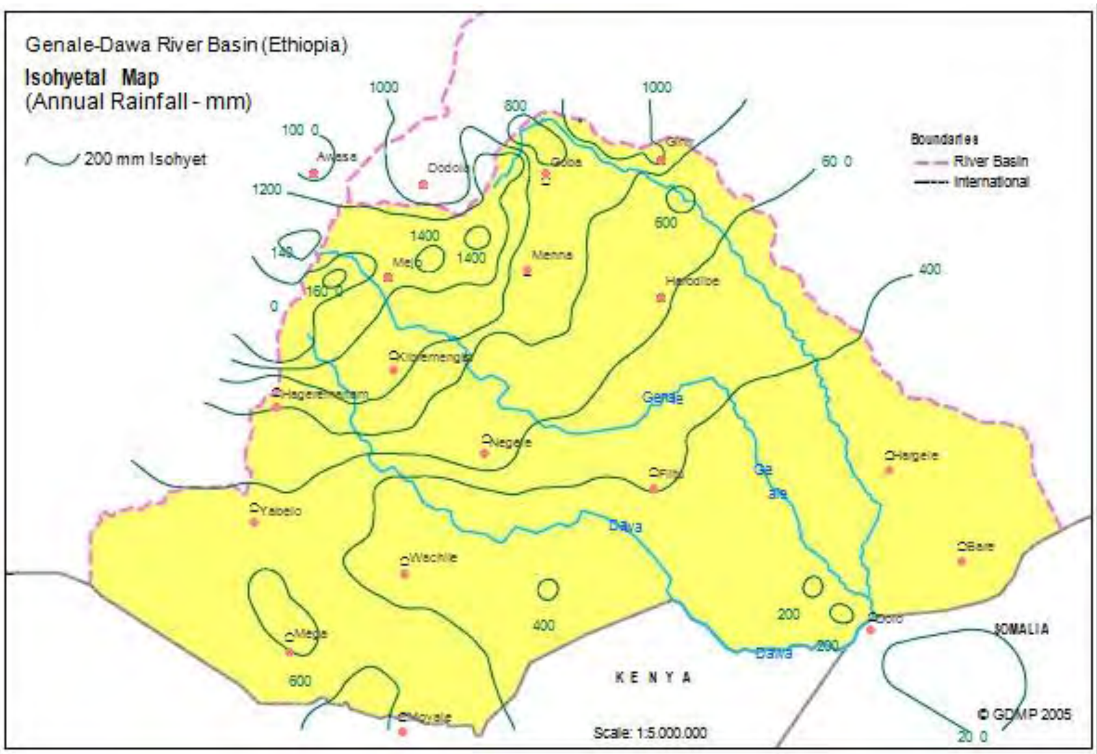


Figure 2 Isohytal map of Genale-Dawa river basin (Source Integrated Resources Development Master Plan Study)

The temporal variation of Hydrologic characteristics can mainly be described in relation with migration of the Inter tropical convergence Zone (ITCZ) as briefly described by Camacho, 1977. A brief review of his work by MOWR master plan describes that seasonal migration of (ITCZ), which is conditioned by the convergence of trade winds of the northern and southern hemisphere and the associated atmospheric circulation. It is also highly influenced, regionally and locally, by the complex topography of the basin, these accounts for the seasonal climatic changes.

Classifications of rainfall regions based on the seasonal variation of monthly cumulative rainfall (rainfall type) is also described as follows

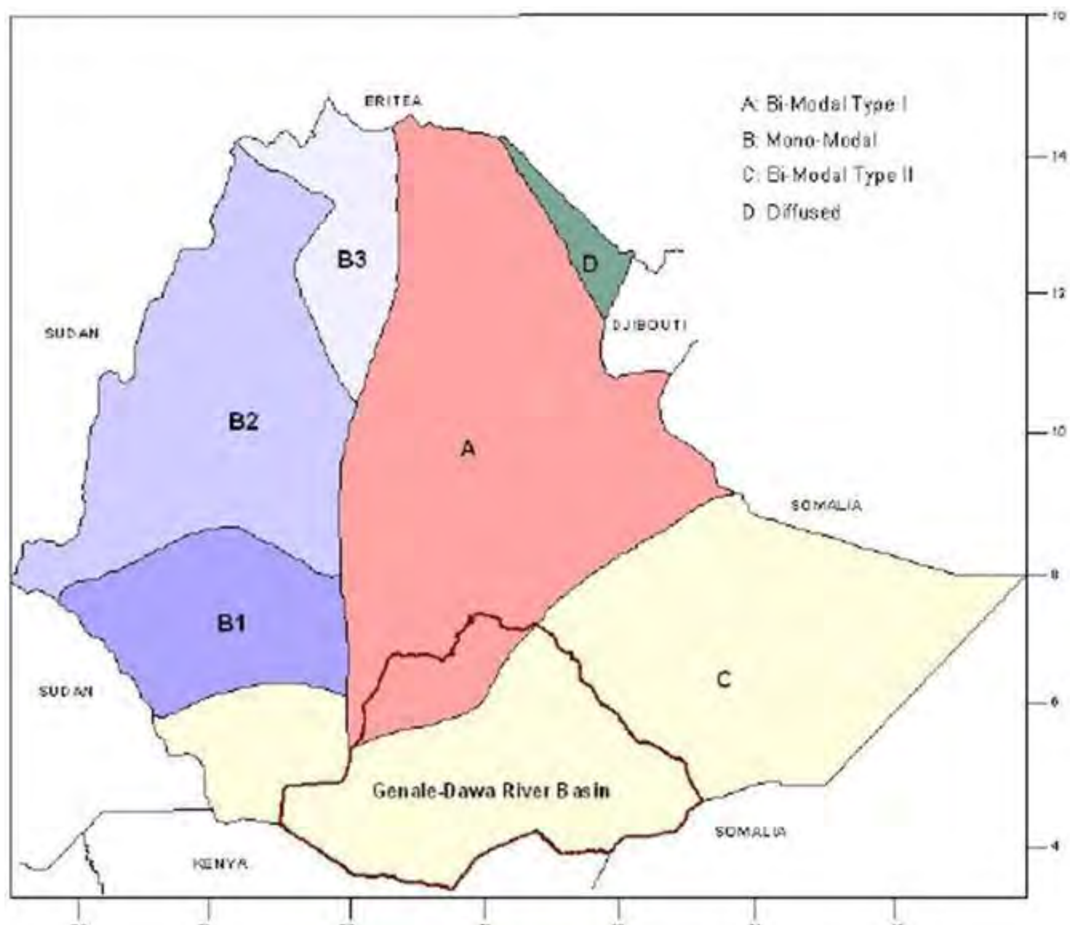


Figure 3 Rain fall types of Genale-Dawa river basin (Source Integrated Resources Development Master Plan Study)

Mono-modal: The area designated as region B on Figure 3. is dominated by a single Peak rainfall pattern in which the relative length of the wet period decrease in a north direction. Three sub-divisions B1, B2 and B3 have been defined according to duration of wet period from February/March to October/November and from June/July to August/September respectively.

Bi-modal Type I: The area designated as region A on Figure 3. is characterised by a quasi-double peak rainfall pattern with a small peak in April and maximum peak in August.

This region is therefore characterised by a semi-bi-modal rainfall pattern.

Bi-modal Type II: The area identified as region C on Figure 3. is dominated by a double peak rainfall pattern with similar peaks during April and October. Generally, the annual rainfall decreases from west to east in the region.

Diffused pattern: The area designated as region D (Danakil region) is characterised by an irregular rainfall pattern. Though erratic rainfall occurs through the period from August/September to January/February, the pattern is diffused and not well-defined (MOWR, Genale Dawa River basin intigrated resources development master plan study, hydrology sector,, 2007).

2.3. Geology

Physiographically the Genale Dawa basin is characterized by low relief tabular plateau made of Mesozoic sediments separated by deep river incisions. The geology of the Genale-Dawa River Basin were categorized into four major divisions. These are: (i) Precambrian crystalline basement, (ii) Late Paleozoic to Mesozoic sedimentary successions, (iii) Tertiary volcanic successions and (iv) Quaternary volcanic rocks and unconsolidated alluvial deposits. These major devisions were further classified and categorized in to 56 geological classes on the bases of geological discontinuities and tectonic bases (MOWR, Genale Dawa River basin intigrated resources development master plan study, Geology sector, 2007).

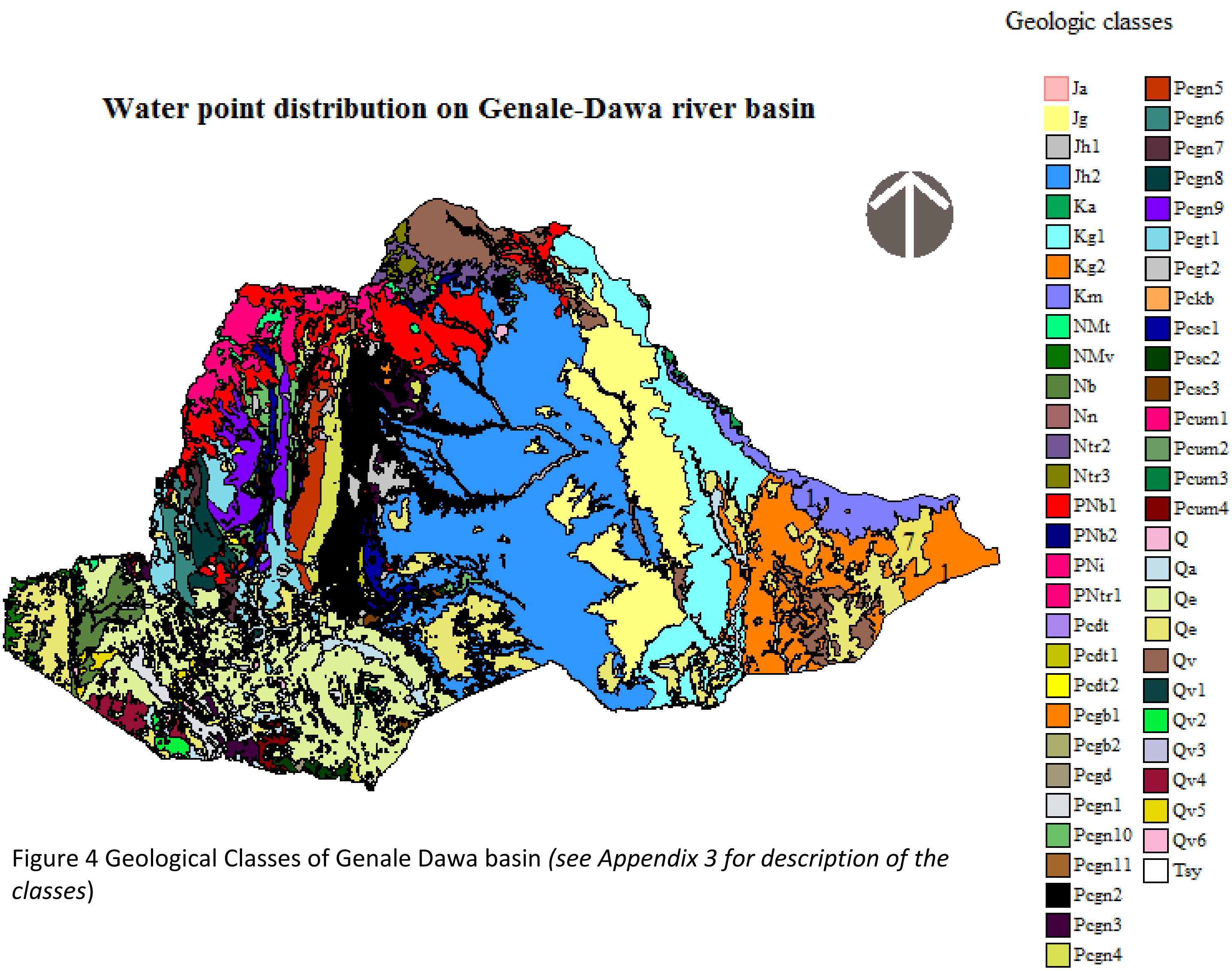


Figure 4 Geological Classes of Genale Dawa basin *(see Appendix 3 for description of the classes)*

2.4. Previous work

Several studies were conducted on parts of the basin to generate the geological and Hydro geological maps on parts of Genale-Dawa basin with different resolution. In parts where detailed study was needed to identify a well field, electrical resistivity method and GIS and remote sensing based techniques were devised.

- Alebachew Beyene, Yetnayet Nigussie and Zenaw Tesema in 1987 Prepared Hydro-geology map of Upper Dawa Basin mainly based on Land seat interpretation with a scale of 1:500,000. (Beyene, Nigussie, & Tesema, 1987)

- Subsequent to the regional hydrogeological mapping, regional and detailed geo-physical surveys were conducted `in the Moyale area by (Hailemariam, 1990). This Survey was also done in the EIGS.

- Regional hydrological and geological works were done in the part at 1:5000000 by ICT Netherlands students as part of an exercise for their advanced diploma. The ICT students conducted their Hydro-geological studies by means of aerial photograph and satellite image interpretation as well as field visits. They have indicated the potential aquifer sites for ground water development options. (MOWR, Genale Dawa River basin intigrated resources development master plan study, 2007)

- Ground water potential mapping of Yabelo, a sub catchment of the Genale-Dawa river basin was carried out to a scale of 1:135000 based on GIS and remote sensing by (Mab consult – consulting hydro-geologists, 2007)

- Genale-Dawa River Basin Integrated Resources Development Master Plan Study (2000) was done by MOWE which is detailed basin wise study that briefly covers the geologic and hydro geologic aspects of the basin at large. This work resulted in generating the hydro-geological mapping of the basing along with classification of aquifer productivity based on hydro-geologic features like transitivity and extent of geologic media, therefore potential water resources development sites were identified ((MOWR, Genale-Dawa River Basin Integrated Resources Development Master Plan Study, 2007)).

- The national water resources master plan employed 3 methods for ground water potential assessment of Genale-Dawa basin namely, Sub surface drainage Approach, Recharge area approach and Base flow approach was used and ground water potential of 1.78 BM3 , 0.43BM3 , 0.5 BM3 were obtained respectively (WAPCOS, 2007).

- Hydro-geophysical surveys were conducted by Aklilu et.al and Hailu et.al around Negele and Filtu towns in 2001. A geophysical method which is VES (Vertical Electrical Sounding) using schlumberger array was employed to acquire the necessary subsurface electrical information with 330m minimum AB/2 separation. Consequently areas which have favorable conditions for groundwater presence were identified around the two towns (Aklilu & Hilu, 2001).

- Geological and hydro-geological maps of Asela sheet which covers part of the Genale-Dawa river basin was prepared by (kiflu, tafa, & mulugeta, 2001) to the scale of 1:250,000 with an accompanying report based on both the geological and hydrogeological information gained during the whole ground water resource assessment. On the basis of this aquifer systems of the area have been defined and characterized.

- Other geological sheets have also been investigated in the Genale-Dawa basin previously. However, Basin wise Numerical models on the Genale-Dawa basin were not encountered for literature review. Most of the previous works conducted on the catchment focus mainly on geological and hydro geological mapping of the area in different scales and resolutions. These can be regarded as a direct approach towards ground water potential assessment. However, this previous studies have contributed in raw data and were basic input for conceptualization of current basin wise model development.

2.5. Groundwater flow Model formulation

A model is a tool designed to represent a simplified version of reality which can be represented either physically or abstract to capture the significant features of a system. Several types of groundwater models have been used to study ground water flow systems. They can be divided into three Broad categories (prickett, 1975): physical models, analog models, including viscous fluid models and electrical models, and mathematical models, including analytical and numerical models.

2.5.1. Physical model

Sand tank is the most common type of physical model. In sand tank model, the actual field dimension was scaled down (three-dimensional) to the laboratory scale and the appropriate aquifer materials are introduced in the box and the model is simulated by incorporating appropriate pumping of water from the model and injection of water in to the model and with appropriate boundary conditions (Thangarajan, Groundwater, Resource Evaluation, Augmentation, Contamination,Restoration, Modeling and Management, 2007). The major drawback of sand tank models is the problem of scaling down a field situation to the dimension of laboratory model. (Herbert F Wang, 1982).

2.5.2. Analog models

An analog model utilizes the similarity of the two physical systems and the one, which is easier to handle, is used as a model of the other. For example mathematical governing equations of the physical processes such as flow of electrical current through resistive media or flow of heat through a solid body are analog physical processes that can be used to model ground water flow. Viscous Fluid Models, Electric Analog Models, Resistance-Capacitance Analog Modeling are some of the common Analog models used for ground water modeling. (Thangarajan, Groundwater, Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management, 2007))

2.5.3. Mathematical models

Mathematical models are abstractions that represent processes as system of equations, physical properties as constants or coefficients in the equations, and measures of state or potential in the system as variables. (Delleur, 1999).

Depending up on the nature of equations involved mathematical models can further be divided in to:

Empirical (experimental): empirical models are derived from experimental data that are fitted to some mathematical function. (a good example is Darcy's law)

Probabilistic: probabilistic models are based on laws of probability and statistics. They can have various forms and complexity starting with a simple probability distribution of a hydro geological property of inters, and ending with complicated stochastic, distribution of a hydro geological property of interest and ending with complicated stochastic, time-dependent models. The main limitations for a wider use of probabilistic models in hydrogeology are: (1) they require large data sets needed for parameter identification and (2) they cannot be used to answer the most common questions from hydro geological point of view

Deterministic: Deterministic models assume that the stage or future reactions of the system studied are predetermined by set of physical laws governing the flow (Anderson & Woessner, 1992).

In the deterministic approach one can see the derivation of groundwater flow governing equation.

2.5.3.1. Governing equations for saturated ground water flow

Consider a unit volume of saturated porous media in Fig4. In fluid mechanics, such a volume is called a control volume. The boundaries of the element are called control surfaces.

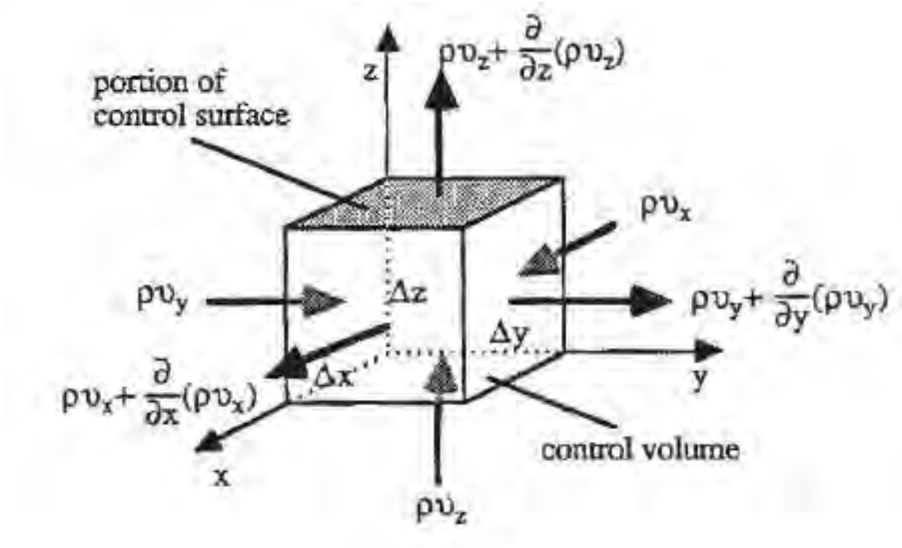


Figure 5 Control volume for groundwater flow through porous media Source (Istok, 1989).

The law of the conservation of mass states that the sum of the gains or losses of mass flow in the X, Y, and Z directions is equal to the loss or gain in mass of the groundwater stored in the elemental control volume Per unit time. For purposes of analysis, consider the rate at which groundwater enters the control volume per unit surface area to consist of three components rυx , rυy and rυz where r is the density of water and υx, υYand υZare the apparent velocities of groundwater flow entering the control volume through control surfaces perpendicular to the x, y, and z coordinate

axes- The dimensions of rυx, rυy, and rυz are ML2/T.

Using a Taylor Series approximation, the rate at which groundwater leaves the control volume in the x direction can be written.

$$\rho\upsilon_x + \frac{\partial \rho\upsilon_x}{\partial x}\Delta x + \frac{\partial^2 \rho\upsilon_x}{\partial x^2}\frac{\Delta x^2}{2!} - \frac{\partial^3 \rho\upsilon_x}{\partial x^3}\frac{\Delta x^3}{3!} + \ldots\ldots$$

If we make the size of the control volume small, we can neglect higher-order terms (i.e, those involving Δx ,Δx^2, Δx^3 etc) and because we have chosen a unit volume $\Delta x = \Delta y$, Δz =1 the net rate of inflow at the x direction is $\rho\upsilon_x + \frac{\partial \rho\upsilon_x}{\partial x}\Delta x$. The net rate of inflow in the x direction is then

Net rate of inflow = rate of inflow in x direction - rate of outflow in x direction

$$= \rho\upsilon_x - [\rho\upsilon_x + \frac{\partial \rho\upsilon_x}{\partial x}\Delta x]$$

$$= - \frac{\partial \rho\upsilon_x}{\partial x}\Delta x$$

And the net rate of inflow in the y and z directions are $- \frac{\partial \rho\upsilon_y}{\partial y}\Delta y$ and $- \frac{\partial \rho\upsilon_z}{\partial z}\Delta z$ respectively. According to law of conservation the net rate of inflow or outflow for the entire control volume must equal to the net change in mass of the control volume.

$$- \frac{\partial \rho\upsilon_x}{\partial x} - \frac{\partial \rho\upsilon_y}{\partial y} - \frac{\partial \rho\upsilon_z}{\partial z} = 0 \ldots\ldots\ldots (1)$$

If we assume that groundwater density, p is constant specially and temporally (i.e., the fluid is incompressible), we can use the product rule of calculus to evaluate a typical term in the above equation

$$- \frac{\partial \rho\upsilon_x}{\partial x} = -[\rho\frac{\partial \upsilon_x}{\partial x} + \upsilon_x\frac{\partial \rho}{\partial x}]$$

$$\text{But}\,\upsilon_x\frac{\partial \rho}{\partial x} = 0$$

Therefore

$$-\frac{\partial \rho \upsilon_x}{\partial x} = -\rho \frac{\partial \upsilon_x}{\partial x}$$

Doing similar simplifications for the time component, y direction and z direction and canceling density that appears outside the derivative (eq. 1) we have

$$-\frac{\partial \upsilon_x}{\partial x} - \frac{\partial \upsilon_y}{\partial y} - \frac{\partial \upsilon_z}{\partial z} = 0$$

Now the apparent groundwater velocities are given by Darcy's Law

$$\upsilon_x = -K_x \frac{\partial h}{\partial x}$$

$$\upsilon_y = -K_y \frac{\partial h}{\partial y}$$

$$\upsilon_z = -K_z \frac{\partial h}{\partial z}$$

WhereK_x, K_y and K_z are the hydraulic conductivities in the x, y, and z directions, respectively and h is the hydraulic head. Substituting equation AI.7 into equation AI.6. and including recharge $\pm$R We arrive at the steady-state, saturated/low equation.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm R = 0$$

If an aquifer parameter is assumed to be homogeneous (at list with in a finite element in case of numerical modeling), then the chain rule can be employed to get a further simplified equation

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} \pm \boldsymbol{R} = 0$$

(Jonathan I stole, 1989)

Aside from heterogeneity, that is, porosity and conductivity variations from point to point, a dependence of hydraulic conductivity on direction is possible. This is the case for the so-called anisotropic porous media, where due to some direction-related properties, as preferential lining of fractures, stratifications, or layering, the conductivity changes depending upon direction. Such situations can be described by an extension of previous equations, where the conductivity becomes a symmetrical matrix (ie. Conductivity tensor), K, with the following components (Jacques W. Delleur, the hand book of ground water engineering)

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

Therefore the most general form of Darcy's law can be written as

$$\begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \end{bmatrix} = - \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \end{bmatrix}$$

In case the 3 coordinate axes coincide with the principal axes of the hydraulic conductivity tensor (the direction of maximum, minimum, and intermediate hydraulic conductivity), K becomes a diagonal tensor and the Darcy's law thus is simplified (Zehang, 2011).

$$\begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \end{bmatrix} = -\begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \end{bmatrix}$$

And the most general form of steady state Laplace's equation in this case can be written In matrix form as:

$$\begin{Bmatrix} \frac{\partial}{\partial \mathrm{x}} \\ \frac{\partial}{\partial \mathrm{y}} \\ \frac{\partial}{\partial \mathrm{z}} \end{Bmatrix} . \left\{ \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial x} \end{bmatrix} \right\} \pm R = 0$$

Assumptions

Some of the simplifying assumptions in steady state groundwater flow equation are made are:

- Aquifer medium is assumed to be incompressible
- Ground completely saturated
- No changes in hydraulic conductivity and piezometric head as a function of time.
- Darcys flow equation is assumed to be valid and flow to be laminar
- Flow is assumed to be slightly compressible under high pressure

Limitations

The major limitations of this study include:

- The model is tailored to isothermal fully saturated fractured porous medium systems (solves the Richard's equation).
- In performing a saturated flow analysis, the study handles only single-phase flow of the liquid (i.e., water) and ignores the flow effects from other potential phases (i.e., air or other non-aqueous phases) which, in some instances, can be significant.

Deterministic mathematical models of ground water flow problems usually involve partial differential equations which need to be solved by either analytical or numerical methods.

2.5.4. Analytical modeling

An analytical model aims at obtaining an exact solution of a mathematical description of a physical process. However, groundwater flow equation, which could be amenable to analytical techniques, requires several simplifying assumptions of the system including the boundary and initial conditions. It also requires large computational resource. This process usually renders the system under study far from being realistic ((Thangarajan, Groundwater, Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management, 2007)). This method is usually difficult to employ for large scale groundwater modeling owing to its need for substantial computational resource

2.5.5. Numerical modeling

Numerical modeling employs approximate methods to solve the partial differential equation (PDE), which describes the flow in porous medium. The emphasis here is not on obtaining an exact solution but on obtaining reasonably approximate solution. (Thangarajan, Groundwater, Resource Evaluation, Augmentation, Contamination,Restoration, Modeling and Management, 2007). Numerical modeling is not subject to many of the restrictive assumptions required for familiar analytical solutions. Numerical solution normally involves approximating continuous (defined at every point) partial differential equations with a set of discrete equations in time (transient model) and space (steady state model). Thus, the region and time period of interest are divided in some fashion, resulting in an equation or set of equations for each sub region and time step. These discrete equations are combined to form a system of algebraic equations that must be solved for specified points in the solution region. Finite-difference and finite-element methods are the major numerical techniques used in ground water applications the two methods are presented as follows (Faust & Mercer, 2006).

2.5.5.1. Finite-difference method (FDM)

The finite difference method consists of discretising the problem area into rectangular elements which are identified with discrete points or nodes ((Essink, 2000)). Various hydro-geological parameters are assigned to each of these nodes. Accordingly, difference operators defining the spatial-temporal relationships between various parameters replace the partial derivatives. A set of finite difference equations, one for each node is, thus, obtained. In order to solve a finite difference equation, one has to start with the initial distribution of heads and compute heads at later time instants ((Thangarajan, Groundwater, Resource Evaluation, Augmentation, Contamination,Restoration, Modeling and Management, 2007)).

The finite difference method is based on the Taylor's series expansion and its most basic discretization approaches can be shown as follows

Taylor's Series

If f(x) is an infinitely differentiable function then the Taylor Series of f(x) about x=x0 is,

$$f(x) = \sum_{n=0}^{\infty} \left(\frac{f^{(n)}(x_o)}{n!} \right) * (x - x_o)^n$$

Where:

$f^{(n)}$ is the nth derivative of the function f.

x_o Known solution point (boundary condition)

X point of interest in the function

Forward in space expansion can be done as follows

If $x = x_o + \Delta x$

$$f(x_o + \Delta x) = \sum_{n=0}^{\infty} \left(\frac{f^{(n)}(x_o)}{n!} \right) * ((x_o + \Delta x) - x_o)^n$$

$$f(x_o + \Delta x) = \sum_{n=0}^{\infty} \left(\frac{f^{(n)}(x_o)}{n!} \right) * (\Delta x)^n$$

$$f(x_o + \Delta x) = f(x_o) + \frac{\partial f(x_o)}{\partial x} \Delta x + \frac{\partial f^2(x_o)}{\partial x^2} \frac{\Delta x^2}{2!} + \frac{\partial f^3(x_o)}{\partial x^3} \frac{\Delta x^3}{3!} + \ldots\ldots$$

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o + \Delta x) - f(x_o)}{\Delta x} - \frac{\partial f^2(x_o)}{\partial x^2}\frac{\Delta x^1}{2!} - \frac{\partial f^3(x_o)}{\partial x^3}\frac{\Delta x^2}{3!} + \ldots\ldots$$

For the sake of simplicity terms containing second order and higher derivatives are truncated.

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o + \Delta x) - f(x_o)}{\Delta x} \ldots\ldots\ldots\ldots\ldots (1)$$

Backward in space

If $x = x_o - \Delta x$

$$f(x_o - \Delta x) = \sum_{n=0}^{\infty} \left(\frac{f^{(n)}(x_o)}{n!}\right) * ((x_o - \Delta x) - x_o)^n$$

$$f(x_o - \Delta x) = \sum_{n=0}^{\infty} \left(\frac{f^{(n)}(x_o)}{n!}\right) * (-\Delta x)^n$$

$$f(x_o - \Delta x) = f(x_o) - \frac{\partial f(x_o)}{\partial x}\Delta x + \frac{\partial f^2(x_o)}{\partial x^2}\frac{\Delta x^2}{2!} - \frac{\partial f^3(x_o)}{\partial x^3}\frac{\Delta x^3}{3!} + \ldots\ldots$$

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o) - f(x_o - \Delta x)}{\Delta x} + \frac{\partial f^2(x_o)}{\partial x^2}\frac{\Delta x^1}{2!} - \frac{\partial f^3(x_o)}{\partial x^3}\frac{\Delta x^2}{3!} + \ldots\ldots$$

Similar to previous one, terms containing second order and higher derivatives are truncated.

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o) - f(x_o - \Delta x)}{\Delta x} \ldots\ldots\ldots\ldots (2)$$

Central in space

$$f(x_o + \Delta x) - f(x_o - \Delta x) = 2\frac{\partial f(x_o)}{\partial x}\Delta x + 2\frac{\partial f^3(x_o)}{\partial x^3}\frac{\Delta x^3}{3!} + \ldots\ldots$$

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o + \Delta x) - f(x_o - \Delta x)}{2\Delta x} - \frac{\partial f^3(x_o)}{\partial x^3}\frac{\Delta x^2}{3!} + \ldots\ldots$$

Terms of third order derivative and higher are truncated.

$$\frac{\partial f(x_o)}{\partial x} = \frac{f(x_o + \Delta x) - f(x_o - \Delta x)}{2\Delta x} \ldots\ldots\ldots\ldots (3)$$

These last expressions in the forward backward and central expansions can be used to approximate a function by forming a system of polynomial equations that can be solved using matrix solution techniques. From the above calculation it can be seen that central in space approximation has smaller truncation error hence a better approximation. The solution of the groundwater problem can be found, by simultaneously solving the sets of algebraic equations of the aquifer at discreet points.

2.5.5.2. Finite-element method (FEM)

The finite element method (FEM) is a very well-known method to solve the governing partial differential equations (Essink, 2000).The basic idea in the finite element method is to find the solution of a complicated problem

by replacing it with a simpler one. The solution region is considered as built up of many small, interconnected sub regions called finite elements. The first step of the finite element analysis involves the discretization of the irregular domain into smaller and regular sub domains, finite elements. This is equivalent to replacing the domain having an infinite number of degrees of freedom by a system having finite number of degrees of freedom. The shapes, sizes, number, and configurations of the elements have to be chosen carefully such that the original body or domain is simulated as closely as possible without increasing the computational effort needed for the solution. Mostly the choice of the type of element is dictated by the geometry of the body and the number of independent coordinates necessary to describe the system (Rao, 2005) for one-dimensional problems, the elements are lines; for two dimensional problems, the elements may be either triangles or quadrilaterals; and for three dimensions, they are tetrahedrons or prisms (Charles R. & Mercer, 2006)In groundwater problems, the polygonal shape of the element is almost always triangular (in two-dimension triangles), whereas occasionally more complex quadrilaterals are used. An irregular polygonal mesh allows the modeler to follow the natural shapes more accurately (Essink, 2000).

Simpler polynomial approximation equations called basis functions are used to determine field variables within a finite element. For the finite element method an integral approach (instead of a differential approach as in the finite difference method) is applied. Two main solution principles of the finite element method can be distinguished (1) the variation principle (using so-called functionals) and (2) the weighted residual technique which mostly preferable for its simplicity. One of the most popular weighted residual techniques for a groundwater problem is the Galerkien's method (Essink, 2000).

Application of the Galarkine's method for the generation of approximating system of equations for a three dimensional finite element method can be demonstrated as follows:

$$L\big(h(x,y,z)\big) - F(x,y,z) = 0 \ldots \ldots..4$$

Where L is the differential operator, h is the field variable (Hydraulic head), and F is a known function. Define an approximate solution h' of the form

$$h^{'}(x,y,z) = \sum_{i=1}^{m} N_i\,(x,y,z)h'$$

Where Ni are interpolation functions, h' are the (unknown) values of the field variable at the nodes, i refers to a particular node and m is the total number of nodes in the mesh. If the approximate solution is substituted back in to the differential operator the equation is no longer satisfied.

$$L\big(h'(x,y,z)\big) - F(x,y,z) = R(x,y,z) \neq 0$$

Where R is the residual or error due to the approximate solution. The residual varies from point-to-point within the problem domain. According to the Garerkine's method the residuals at different points is normalized by weighting it with the interpolation function.

$$\int_{\Omega} \mathrm{W(x,y,z)R(x,y,z)d\Omega} = 0$$

Where Ω represents the problem domain

$$\iiint_{\Omega} W(x,y,z)(L(h'(x,y,z)) - F(x,y,z))d\Omega = 0$$

To evaluate the above equation, we must specify the mathematical form of the approximate solution h' and the weighting function W. In the finite element method h' is defined in a piece - wise fashion over the problem domain.

$$h_i^{(e)} = \sum_{i=1}^{n} N_i^{(e)} h'_i \quad \dots \dots .5$$

'R' represents the error between the true value of hydraulic head and the approximate solution h at that node. The residual at a particular node is the sum of weighted residuals of neighboring nodes.

$$R_i = \sum_{i=1}^{n} R_i^{(e)}$$

The contribution of element e to the residual at node i can be obtained from the integral formulation for that node. Consider one dimensional case in the x direction with two nodes i and j

$$R_i^{(e)} = -\int_{x_i^{(e)}}^{x_j^{(e)}} N_i^{(e)} [k_x^{(e)} \frac{\partial^2 h'^{(e)}}{\partial x^2}] dx$$

Because the second derivation of a linear interpolation function which is common, is undefined; expression of the equation in terms of first derivative$(\frac{\partial h}{\partial x})$ is needed. The Green's theorem can be applied. Negative sign is added for convenience in letter calculation.

$$\int_{x_i^{(e)}}^{x_j^{(e)}} N_i^{(e)} [k_x^{(e)} \frac{\partial^2 h'^{(e)}}{\partial x^2}] dx = -\int_{x_i^{(e)}}^{x_j^{(e)}} N_i^{(e)} [k_x^{(e)} \frac{\partial N_i^{(e)}}{\partial x} \frac{\partial h'^{(e)}}{\partial x}] dx + (N_i^{(e)} k_x^{(e)} \frac{\partial h'^{(e)}}{\partial x} \Big|_{x_i^{(e)}}^{x_j^{(e)}}$$

The second term in the above equation is given a symbol $F_i^{(e)}$ for an element and represents groundwater flow across the element's surface. At the exterior of the mesh this expression represents rates of boundary condition. Where no flows are specified or at impermeable aquifer boundaries, $F_i^{(e)}$ e) will be zero. For elements on the interior of the mesh, the term $F_i^{(e)}$ for adjacent elements will have opposite signs cancelling out the contribution of $F_i^{(e)}$ for the neighboring elements for the node(s) they share. Hence omitting the second term in the right hand side of the equation

$$R_i{}^{(e)} = -\int_{x_i{}^{(e)}}^{x_j{}^{(e)}} N_i^{(e)}[k_x^{(e)}\frac{\partial^2 h'^{(e)}}{\partial x^2}]dx = \int_{x_i{}^{(e)}}^{x_j{}^{(e)}} N_i^{(e)}[k_x^{(e)}\frac{\partial N_i^{(e)}}{\partial x}\frac{\partial h'^{(e)}}{\partial x}]dx$$

Recall groundwater governing equation described in the previous section, it can be written in terms of h'

$$K_x\frac{\partial^2 h'}{\partial x^2} + K_y\frac{\partial^2 h'}{\partial y^2} + K_z\frac{\partial^2 h'}{\partial z^2} \pm q = 0$$

Applying the galarkine's method

$$R_i{}^{(e)} = \iiint_\Omega N_i^{(e)}(K_x{}^{(e)}\frac{\partial N_i^{(e)}}{\partial x}\frac{\partial h'^{(e)}}{\partial x} + K_y{}^{(e)}\frac{\partial N_i^{(e)}}{\partial y}\frac{\partial h'^{(e)}}{\partial y} + K_z{}^{(e)}\frac{\partial N_i^{(e)}}{\partial z}\frac{\partial h'^{(e)}}{\partial z} \pm q)d\Omega$$

To understand the solution approach to this equation lets first consider a one dimensional flow with two nodes. Where, $x_i{}^{(e)}$ and $x_j{}^{(e)}$ represent the two nodal coordinates used to define the element. Because each element had two nodes, it contributed to the residual at two nodes, Rj and Ri. Represent these residuals as separate integral equations and we can write;

$$R_i{}^{(e)} = \int_{x_i{}^{(e)}}^{x_j{}^{(e)}} N_i^{(e)}(K_x{}^{(e)}\frac{\partial N_i^{(e)}}{\partial x}\frac{\partial h'^{(e)}}{\partial x})$$

$$R_j{}^{(e)} = \int_{x_i{}^{(e)}}^{x_j{}^{(e)}} N_j^{(e)}(K_x{}^{(e)}\frac{\partial N_j^{(e)}}{\partial x}\frac{\partial h'^{(e)}}{\partial x})$$

Substitute $\frac{\partial h'^{(e)}}{\partial x} = \frac{\partial N_i^{(e)}}{x}h'_i + \frac{\partial N_j^{(e)}}{x}h'_j$ and rewrite in matrix form the conductance matrix can be written

$$[k^{(e)}] = \int_{x_i{}^{(e)}}^{x_j{}^{(e)}} \begin{bmatrix} K_x{}^{(e)}\frac{\partial N_i^{(e)}}{\partial x}\frac{\partial N_i^{(e)}}{\partial x} & K_x{}^{(e)}\frac{\partial N_i^{(e)}}{\partial x}\frac{\partial N_j^{(e)}}{\partial x} \\ K_x{}^{(e)}\frac{\partial N_j^{(e)}}{\partial x}\frac{\partial N_i^{(e)}}{\partial x} & K_x{}^{(e)}\frac{\partial N_j^{(e)}}{\partial x}\frac{\partial N_j^{(e)}}{\partial x} \end{bmatrix} dx \ldots..6$$

$$= \int_{x_i^{(e)}}^{x_j^{(e)}} \begin{bmatrix} \frac{\partial N_i^{(e)}}{\partial x} \\ \frac{\partial N_j^{(e)}}{\partial x} \end{bmatrix} [k_x] \begin{bmatrix} \frac{\partial N_i^{(e)}}{\partial x} & \frac{\partial N_j^{(e)}}{\partial x} \end{bmatrix}$$

Similarly, for a 3 dimensional equation with n number of nodes we have

$$[K^e] = \iiint_{V^e} \begin{bmatrix} \frac{\partial N_i^{(e)}}{\partial x} & \frac{\partial N_i^{(e)}}{\partial y} & \frac{\partial N_i^{(e)}}{\partial z} \\ \vdots & \vdots & \vdots \\ \frac{\partial N_n^{(e)}}{\partial x} & \frac{\partial N_n^{(e)}}{\partial y} & \frac{\partial N_n^{(e)}}{\partial z} \end{bmatrix} \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \begin{bmatrix} \frac{\partial N_i^{(e)}}{\partial x} & \cdots & \frac{\partial N_n^{(e)}}{\partial x} \\ \frac{\partial N_i^{(e)}}{\partial y} & \cdots & \frac{\partial N_n^{(e)}}{\partial y} \\ \frac{\partial N_i^{(e)}}{\partial z} & \cdots & \frac{\partial N_n^{(e)}}{\partial z} \end{bmatrix} dxdydz \ldots \ldots \ldots 7$$

Conductance matrix is used to write the system of equations for an element

$$\begin{bmatrix} R_i^{(e)} \\ \vdots \\ R_n^{(e)} \end{bmatrix} = [K^e] \begin{bmatrix} h_i \\ \vdots \\ h_n \end{bmatrix}$$

These equations of individual elements are then combined to form the global matrix

$$\begin{bmatrix} R_i \\ \vdots \\ R_n \end{bmatrix} = [K^e]_{global} \begin{bmatrix} h_i \\ \vdots \\ h_n \end{bmatrix}$$

In order to incorporate Boundary conditions, the integration of q (recharge) term from the general ground water flow equation above is considered.

$$\mathrm{F_i^{(e)}} = \iiint_{\mathrm{V^e}} \mathrm{N_i^{(e)} q^{(e)} dxdydz}$$

q (e) represents a specified flow rate along the boundary of element e. And from Grean's theorem, it can also be write as

$$\mathrm{F_i^{(e)}} = \int_{\mathrm{s^{(e)}}} \mathrm{N_i^{(e)} q^{(e)} d\,s} = \int_{\mathrm{s^{(e)}}} \mathrm{N_i^{(e)} k_x^{(e)} \frac{\partial\, h'^{(e)}}{\partial x} dx}$$

Where $s^{(e)}$ is the surface area of element e. The evaluation of these integrals for each node in element e gives the components of the specified flow matrix for element e, $\{F^{(e)}\}$

$$\{F^{(e)}\} = \begin{bmatrix} F_i^{(e)} \\ \vdots \\ F_n^{(e)} \end{bmatrix}$$

And incorporated in the matrix form as follows depending on the hydraulic gradient sign

$$\begin{bmatrix} R_i^{(e)} \\ \vdots \\ R_n^{(e)} \end{bmatrix} = [K^e] \begin{bmatrix} h_i \\ \vdots \\ h_n \end{bmatrix} \pm \begin{bmatrix} F_i^{(e)} \\ \vdots \\ F_n^{(e)} \end{bmatrix}$$

We can combine the $\{F^{(e)}\}$ for each element in the mesh to obtain the global specified flow matrix $\{F\}$

$$\{F\} = \sum_{e=1}^{n} \{F^{(e)}\}$$

The most general form of system of equation that represents the saturated subsurface flow system by setting $R^{(e)} = 0$ can be written as

$$[K]_{global}\{h\} = \mp\{F\}_{global} \dots \dots \dots 8$$

This is usually a sparse matrix and is solved with a matrix iterative solution methods (Istoke, 1989)

3. Methodology

Assessment of ground water potential can be achieved through various methodologies. This chapter focuses on explaining how the FEM modeling approach was adopted for the regional groundwater potential assessment of the current study area.

3.1. Data collection

Various relevant raw data that can reveal an insight of the subsurface reservoir and softwares useful for modeling were collected. These are:

Softwares used for the model development, including;

- Mat lab v.13a: where numerical calculations are carried out and the TAGSAC code is run.
- Global Mapper v.16, Surfer v.10: used for surveying works, delineation, digitization, data manipulation and data pre processing.

Hydrogeologic data

- 1:2000, 000 resolution geological map with 56 geological classes were collected.
- Springs and well inventory data.
- 30×30m resolution Digital elevation model of the region in which Genale-Dawa River basin is located.

Hydrologic data

- Rain fall data records of 23 gauging stations near and on the basin.
- Stream flow data of some gauging station on the basin; this was used to develop an understanding of the overall hydro geological system and also, determine aquifer contribution to the rivers by performing base flow separation.

3.2. Numerical solution technique

Laplace's equation as described in the previous chapter is a general equation that governs groundwater flow system and other analogous systems like conductance of heat with in a solid body. In mathematical modeling of groundwater this equation needs to be solved either analytically or numerically. Analytical solutions can be used to calculate values for the unknown field variable at any point in the problem domain. Whereas, numerical solutions yield values for only a predetermined finite number of points in the problem domain. Considering the complexity of the problem; the numerical method is chosen for this study. And from the two well known numerical methods available the (finite element and finite difference) the finite element is selected considering its computational efficiency. This is due to the following reasons:

1) FEM is more suited to better discretising a given solution region owing to the use of unlimited discretising element shape and size.

2) Because different type and degree of approximation equations can be used, it can better approximate the solution compared to the FDM, which can be considered as a method that uses linear interpolation between two points towards determining field variable at succeeding discrete points. (The Finite Element Method, O.C. Zienkiewicz and R.L. Tylor, 2000, by butterworth-Heinemann, England)

A particular type of FEM based three dimensional computer modeling code called TAGSAC (Three Dimensional Analysis of Groundwater Flow, Saitama University Code) is adopted for modeling the groundwater system. TAGSAC is a model developed for the porous medium. In the TAGSAC approximation procedure, the flow region is first discretized into a network of finite elements, and then trial approximating interpolation functions are generated for individual finite elements using a special type of weighted residual method called Galerkin's method; in which the summation of residuals weighted by interpolation functions is equated to zero. This results in a system of linear interpolation functions. By incorporating boundary conditions and solving, coefficients of interpolation functions are obtained. This system of equations is used to represent the unknown dependent variable (hydraulic head) over the discretized region. A limiting feature of TAGSAC model is that it is bound to use a model thickness not less than half the finite elements dimension used; which otherwise will risk numerical instability. Tagsac Has Proved To Be Applicable In A Number Of Researches Done All Over The Globe (Mohammed, 2010).

3.3. Spatial discretization

The first step of the finite element analysis involves discretization of the irregular domain into smaller and regular sub domains. This is equivalent to replacing the domain having an infinite number of degrees of freedom by a system having finite number of degrees of freedom. The following section is dedicated to describe the discretization processes.

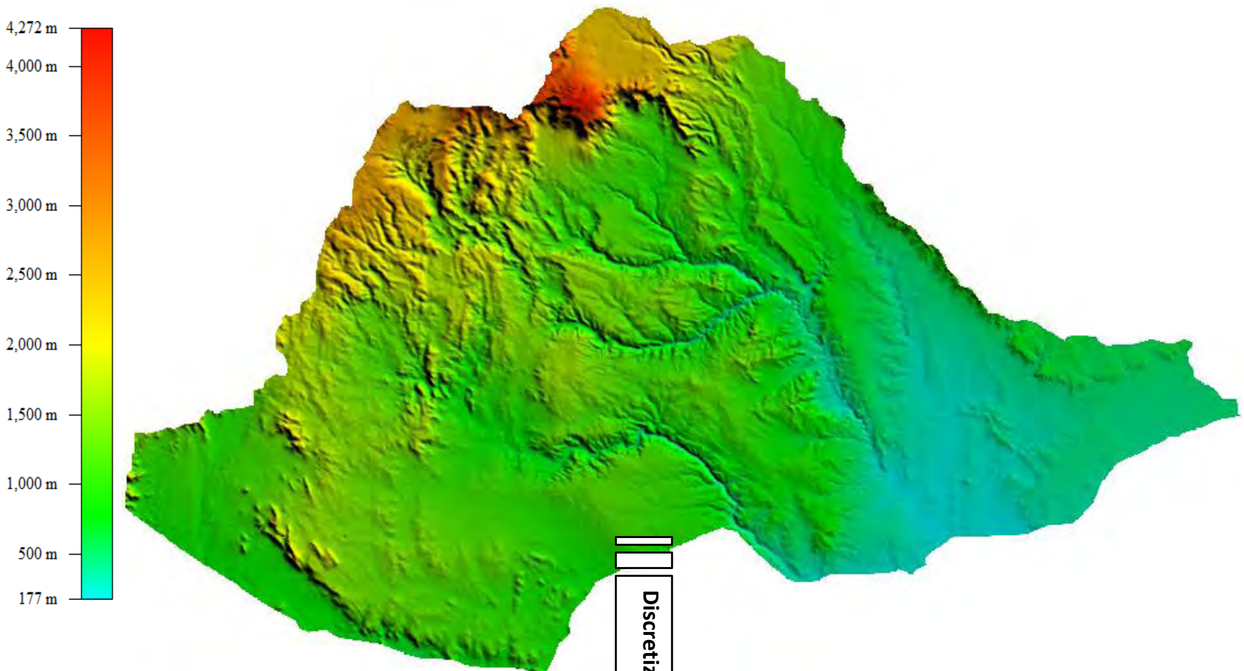
The geometric representation of the system shall first be established for which, Cartesian coordinate system is employed to generate a triangular in plane three dimensional mesh. The x-y plane coincides with plane view of the study area where as z direction point's perpendicularly in the upward direction to the x-y plane, representing elevation.

An initial step taken for discretization was to delineate the Genale-Dawa catchment area which was done using Global Mapper version 16 and using digital elevation model of 30×30m resolution. The result obtained was a little different than the official delineated map of Genale-Dawa basin used by MOWE in that the delineation result obtained and to be used for this study has some additional area on the south-eastern part of the basin with a total of 17860km^2 km2. This, in recent master plan study of the basin was recognized as covered in the literature review part of this paper.

After the delineation x-y coordinates of the catchment boundary are generated and used as problem domain of the model. The discretization elements are made to be non uniform in size to best fit the boundaries of the problem domain where there are Sharpe corners. A maximum of 5km edge dimension for the equilateral triangular finite element is selected. This done considering the available computational capacity and level of details of raw data available. The problem domain of 17860km^2 area is then discretized in to 9810 nodes of known x-y coordinates with consistent and continuous nodal numbering assigned to them. 17862 triangular elements are formed by connecting three neighboring nodes with a line. This geometric discretization of the region is first done on x-y plane and is carried out using automatic discretising Mat lab computer code. The z coordinate of the nodal points of the mesh is tabulated by interpolation from the digital elevation model. After wards this triangular mesh so formed is given a model thickness of 2500m to form the three dimensionally discretized systems. Hence, each triangular two dimensional element was changed in to three dimensional finite element formed with six nodal points in space and becomes a prism that is triangular in plain. Boreholes and springs are represented by 3 nearest surface nodes where as River systems are made to traverse along a series of surface nodes; this is done by moving the nearest surface node to the river at a point using a mat lab code. Relocation of the top layer nodes near a river causes vertical distortion of the prismatic finite elements that can be handled by TAGSAC.

Finally, individual elements and surface nodal points are given codes that designate the material property and rainfall recharge amount respectively to the individual elements and surface nodes. Fig. 6 and Fig 7 Respectively shows the geometrically discretized domain and geologic materials assigned for each discreet triangular element by coloring the element centroid with different classes of colors.

Figure 6 Delineated DEM (Digital Elevation Model) of Genale-Dawa Basin Elevation ranges are shown in color bar



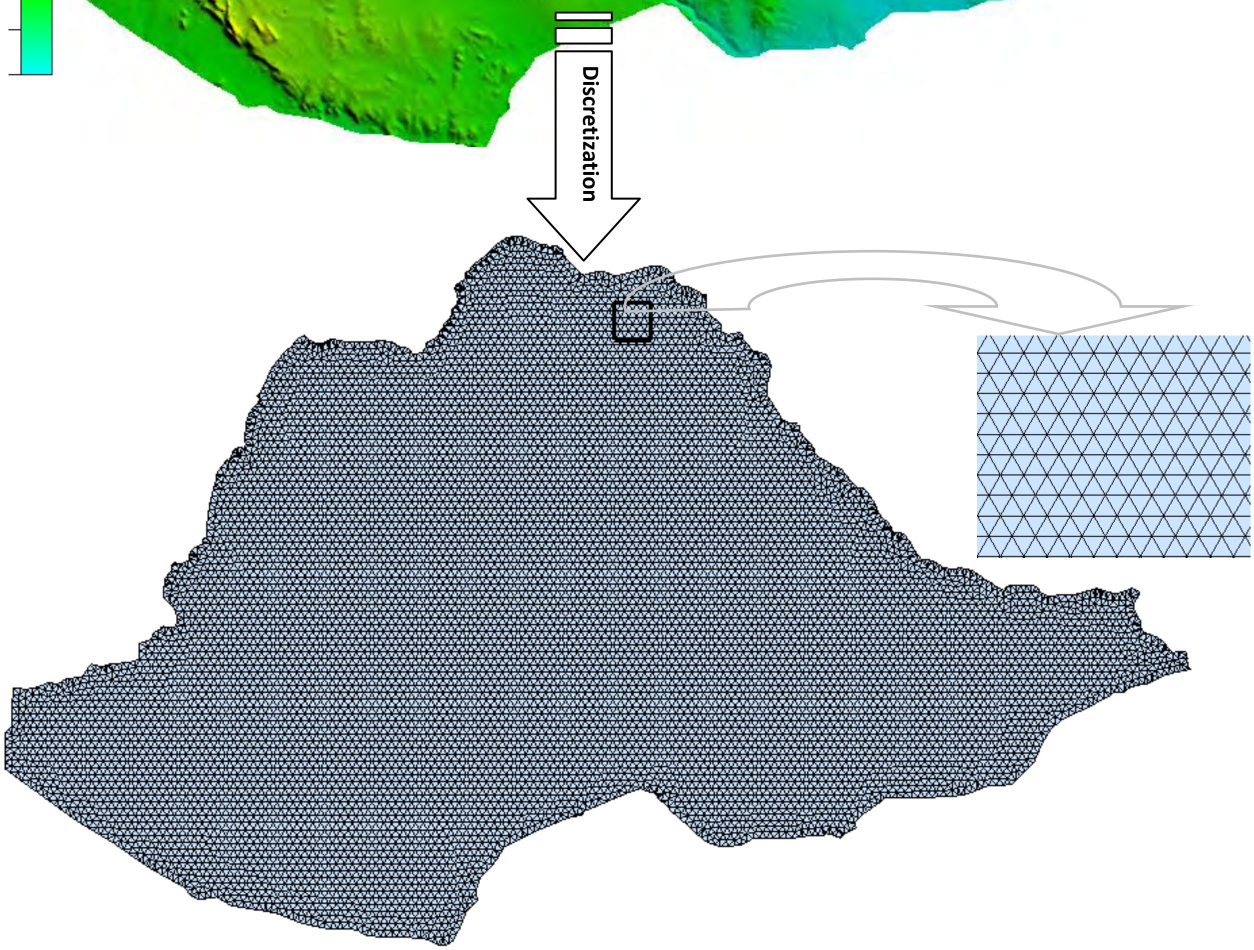


Figure 7 triangularly discretized region of Genale-Dawa River Basin

3.4. Conceptual model

3.4.1. Conceptualization of flow medium

Several conceptual groundwater flow models have be distinguished on the basis of the storage and flow capabilities of the porous medium and fracture. The storage characteristics are associated with porosity, and the flow characteristics are associated with permeability. Three conceptual models have dominated the research: 1) dual continuum, 2) discrete fracture network, and 3) single equivalent continuum. In addition, Explicit discrete fracture, multiple-interacting continua and multi-porosity/multi-permeability conceptual models (Sahimi, 1995) have been introduced in the literature. For the sake of discussion the first 3 are presented below

Discrete Fracture Network

Discrete fracture network (DFN) models describe a class of dual-continuum models in which the porous medium is not represented. Instead, all flow is restricted to the fractures. This idealization reduces computational resource requirements. Fracture "legs" are often represented as lines or planes in two or three dimensions (Sarkar, Toksöz, & Burns). The DF approach is typically applied to fractured media with low primary permeability such as crystalline rock. (Anderson & Woessner, 1992).

Dual-continuum models

Dual-continuum models are based on an idealized flow medium consisting of a primary porosity created by deposition and lithification and a secondary porosity created by fracturing, jointing, or dissolution. The basis of these models is the observation that un-fractured rock masses account for much of the porosity (storage) of the medium, but little of the permeability (flow). Conversely, fractures may have negligible storage, but high permeability (Sarkar, Toksöz, & Burns).

Single Equivalent Continuum Formulation

Fractured material is represented as an equivalent porous medium by replacing the primary and secondary porosity and hydraulic conductivity distributions with a continuous porous medium having so called equivalent hydraulic properties (Anderson & Woessner, 1992). This method is most suited to the condition in which the volume of interest is considered to be large enough that, on average, permeability is a sum of fracture and porous media permeability. This approximation substantially simplifies the flow problem (Diodato, 1994).

This study employs the single equivalent continuum conceptual modeling approach in which the hydraulic parameters are selected so that the; flow pattern in the discretized elements is similar to the flow pattern in the actual fractured system. This formulation methodology is adopted, taking in to account the sizes of the (Representative Elementary Volume) REV considered being large and the moderate availability of computational resources. (Istoke, 1989)

3.4.2. Ground water recharge

Recharge is defined as the downward flow of water reaching the water table forming an addition to the ground water reservoir (Vries & Simmer, 2000). It is also defined as a term used to describe many of the processes involved in the addition of water to the saturated zone (Moore & Wilson, 1998). When the front of infiltrating water reaches the capillary fringe (percolates), it displaces air in the pore spaces and causes the water table to rise along with the capillary fringe (Applied hydrology ground water).

Groundwater recharge rate, as briefly described by (Healy, 2010), is both specially and temporally varied. This variability is due to a number of factors such as; climate, soil cover, geology, surface topography, hydrology and vegetation cover. Therefore, a good recharge estimation for a given study area; requires a clear understanding of the factors in play for the specific site under study. This usually, is not an easy task to achieve because of both financial and techniqueal difficulties faced with. However, some methods such as Chemical tracer methods, Water-budget methods and numerical modeling methods in which Recharge estimates can be obtained through a model calibration process with recharge rate as a calibration parameter (Healy, 2010)can be used to get a close estimation.

Major natural recharge to the unconfined aquifer system in the current study area occurs at elevated regions due to percolation from precipitation along the north, north-eastern and north-western boundary highs of the basin. Whereas recharge from runoff and precipitation on the lower part of the basin also provides a source of groundwater inflow to the area of interest.

This study tries to estimate the replenishable groundwater resource (from hydrological perspective) using the TAGSAC model by seating precipitation to be some portion of the total rainfall in percent and making this percentage a calibration parameter that can be obtained through a series of trial and error procedure.

3.4.3. Model Boundary conditions

It is crucial to define a boundary condition prior to numerical groundwater model development. This is because, the solution of Laplace's equation requires specification of boundary conditions which constrain the problem and make solutions unique (Anderson & Wosner, 1992).Hence, boundary conditions are known solutions at points in the solution domain necessary to obtain solution at unknown points representative of the real system. P.Anderson and W.Wosner have distinguished the different types of boundary condition.

Which are described as follows:

A) head is known for surfaces bounding the flow region (Dirichlet Conditions);
B) flow is known across surfaces bounding the region (Newman condition)
C) a combination of Dirichlet and Newman conditions known as mixed condition

The most common types of boundary conditions are; perennial rivers, springs, lakes and swampy areas known to have ground water reserve underneath, all of which can be taken as Dirichlet boundary conditions after a careful observation of their relation with the aquifer nearby and the hydraulic property of intermediate medium. On the other hand; known amount of inter-aquifer leakage, water wells and springs of known discharge can be taken as Newman's conditions. The determination of which aspects of an actual ground-water system should be incorporated into a computer simulation usually depends, in part, upon the objectives of the study for which the model is being developed (Reilly, 2001) accordingly in constant head constant discharge and specified flow boundary conditions have been identified for the current modeling.

3.4.4. Hydraulic properties

Hydraulic properties important for the three dimensional conceptual model include both horizontal and vertical hydraulic conductivities as well as specific storage coefficient. In order to generate the numerical model of the site, the distribution of these parameters must be specified for each hydro-geological unit. However since the model is based on the principles of equivalent porous medium, Hydraulic properties are assumed to be equivalent or effective values for the 56 individual geological class. These geological classes have been discretized and Equivalent hydraulic properties are obtained by calibration procedure for respective geological classes.

3.4.5. Water points inventory

Water point inventory data is comprehensive data collected about the water points. Inventory data of water points on the basin include data about water wells, hand dug wells and springs. The details of this data include static water level and coordinates of individual water wells and springs. Which is important for the model calibration process, as it is evident information available regarding the regional groundwater condition. The water point inventory data collection on the basin was carried out using dip meters and GPS instruments.

3.5. Model calibration

Model calibration is the process of adjusting the input properties and boundary conditions of a model to achieve a close fit to observed conditions in the real groundwater system. In flow model calibration, simulated heads and discharges are typically compared to their observed counterparts. If a model is well calibrated, there will be some random deviations between simulated and observed data, but there will not be systematic deviations. If there are systematic deviations such as most simulated heads exceeding observed heads, the calibration is poor and adjustments should be made (fitts, 2002).

As discussed by (Kresic, 2009) , there are two methods of calibration:

(1) Trial and error (manual) and

(2) Automated calibration.

In the trial and error approach, the user inputs all the parameters that can be based on physical observation, and provides estimates of the unknown parameters as a first trial. As such, the adjustment of parameters is manual. The model is run and the computed output is compared to the measured output from the model. Most of the time the transmissivities are the least known parameters and thus, they are often modified during the calibration procedure. The comparison is done either by means of visual pattern, or it is based on some mathematical criterion. Based on this comparison, adjustments are made to one or more of the trial parameters to improve the fit between measured and computed output. In an effort to get the best fit between measured and computed output, it helps to go back to the basic principle stated by Darcy $q_x = -\mathrm{k}_x \frac{\Delta h}{\Delta x}$ in which the relationship between h ,k and q can be used as a rule of thumb in calibration. If for example the measured head is larger than the computed. As it can be seen from Darcy's law; reducing the hydraulic conductivity in some proportion would result in larger head to be computed (close to the observed head) by the model and vice versa (fitts, 2002). Hence, a systematic trial and error (manual) calibration can be achieved. These trial runs of the model are repeated until some kind of required accuracy or calibration target is achieved (Essink, 2000). Trial and error calibration was the first technique applied in groundwater modeling and is still preferred by most users (Kresic, 2009). Whereas on the other hand automated calibration method employs a computer program that will automatically calibrate itself and carry out the necessary number of trial runs until the best set of parameters is achieved. The purpose of this program is to minimize an objective function such as to minimize the sum of the square residuals. Though this approach is advantageous for that it gives statistical degree of uncertainty and saves time. It should also be kept in mind that it can also give unstable and unreasonable results. This paper employs the trial and error calibration procedure as described earlier. The protocol followed in the modeling and calibration is shown using a flow diagram described in figure 8.

3.5.1. Calibration Evaluation

The result of the calibration should be evaluated both qualitatively and quantitatively (Anderson & Wosner, 1992)

(a) Qualitatively, by comparison of contour maps of measured and computed parameters, which provides only a qualitative measure of the similarity between the patterns; and

(b) Quantitatively, by a scatter plot of measured and computed parameters, where the deviation of points from the straight line should be randomly distributed (Essink, 2000). In an effort to minimize the error in the calibration, the average deviation is calculated using the mean error (ME), mean absolute error (MAE) and root mean squared error (RMS) indicators, the calibration is continued until these indicators are satisfactorily minimized.

1. The mean error (ME)

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(h_{measured} - h_{computed}\right)_i$$

2. The mean absolute error (MAE)

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(h_{measured} - h_{computed})_i\right|$$

3. The root mean squared error (RMS)

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_{measured} - h_{computed})_i{}^2}$$

The maximum acceptable value of calibration criterion depends on the magnitude of the change in head over the problem domain (Anderson and Woessner, 1992). The scatter diagram generated by model also shows the matching property of the measured simulated head. The scatter plot is usually examined by the position of points scattered in the graph away from the straight line, that is; random distribution of point in the plot shows the deviation between measured and simulated groundwater heads.

3.5.2. Model calibration Target

A calibration target consists of the best estimate of a value of groundwater head or flow rate. Establishment of calibration targets and acceptable residuals or residual statistics depends on the degree of accuracy proposed for a particular model application. This, in turn, depends strongly upon the objectives of the modeling project (ASTEM, 2008). For any particular calibration target, the magnitude of the acceptable residual depends partly upon the magnitude of the error associated with data collection. Head measurements in particular are usually accurate to within a few tenths of a foot. Due to the many approximations employed in modeling and errors associated therewith, it is usually impossible to make a model reproduce all head measurements within the errors of measurement. This incompatibility can be adjusted by taking data collection error in to account and providing a range of acceptable errors for the model output.

As stated by ASTEM (D5981 – 96), the acceptable residual should be a small fraction of the difference between the highest and lowest heads across the site.

3.6. Estimation of Groundwater potential

After the model calibration, monthly water table fluctuation is calculated. This helps determinine the maximum water table, minimum water table and eventually the change in storage of the groundwater system within a year. This amount of water is known as the replenishable groundwater which represents the recharge capacity of the system. But, even though in a given month the aquifer is assumed to have a given amount of groundwater storage with an associated water table it also discharges to the rivers at the same time. Hence, base flow separation is done using digital filter method to account for the water at the discharging end of the system and the cumulative groundwater reserve is calculated for individual months.

Finally based on calibration results hydraulic conductivities of different geologic classes are grouped to generate the different hydro-geologic classes of the region and prepare Hydrogeologic map of the region.

Model protocol

All the discussion made in this chapter applies to the numerical model development of Genale Dawa River Basin. The model protocol followed and work frame adapted to modeling of the basin can be represented with a flow diagram as follows.

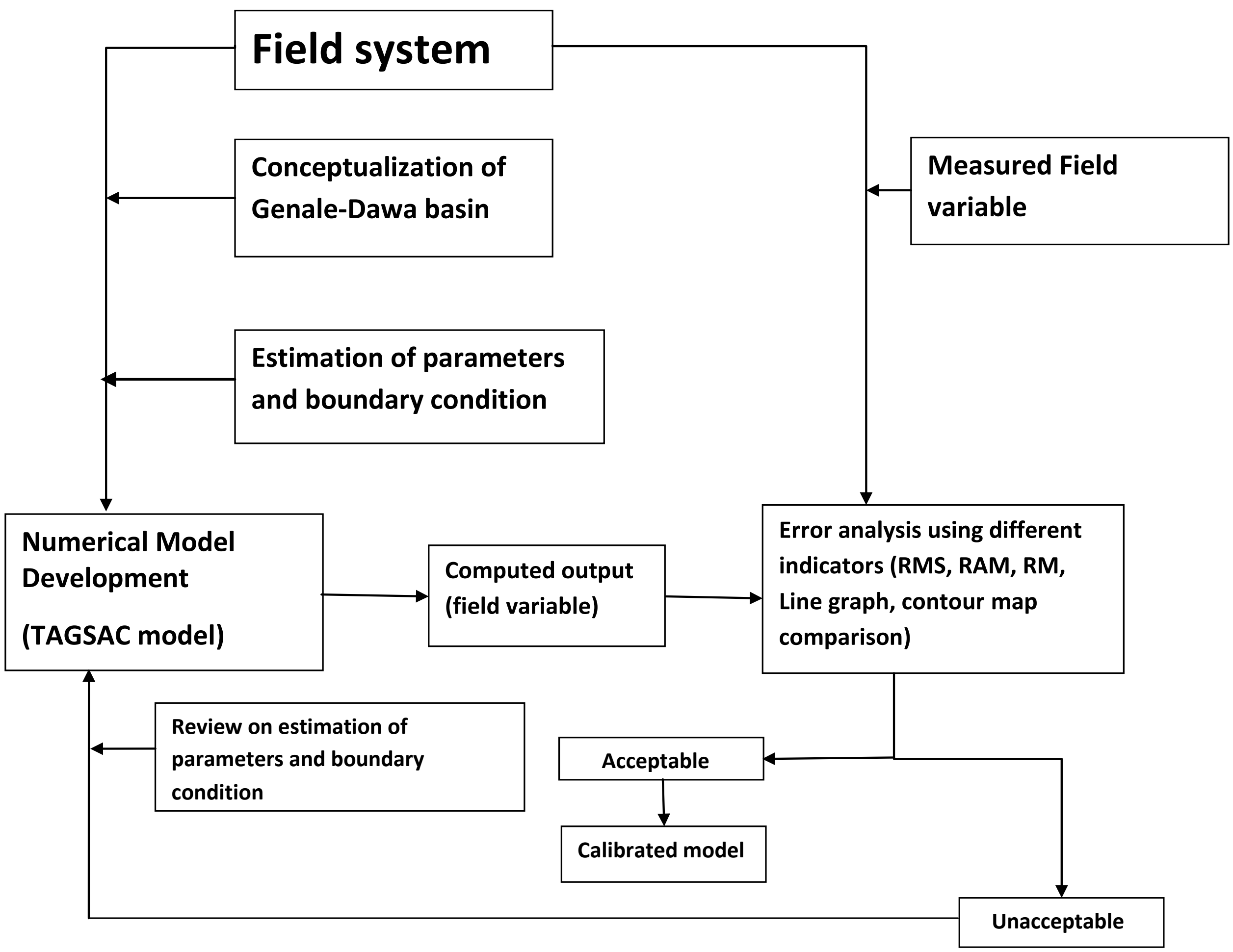


Figure 8 flow diagram representation of model calibration protocol

4. Results and discussion

The methodology described in the previous chapter was employed to develop a three dimensional numerical single layered groundwater model for the evaluation of replenishable groundwater potential. Results and relevant discussions of the model are presented in this chapter in their chronological order.

4.1. Water point inventory data

Water point inventory data relevant for the model calibration was collected from concerned offices. This included; bore hole, hand dug well and spring data of Genale-Dawa River basin. Out of these collected data, some data was omitted for not qualifying to contain either the static water level or coordinate information. A secondary data screening was also done by comparing recorded static water level with expected result from the model. Accordingly, personal judgment was taken to discard where large data inconsistency is observed. After screening 82 Bore holes, 49 hand dug wells and 191 spring data were left to be used as an input for the model.

The distribution of water points used for model calibration is shown in figure 9. From the distribution of this water points it can be seen that more water points are located in the northern north-western and north-eastern parts of the basin which in general are topographically elevated areas. These parts of the basin are also the ones that receive majority of the precipitation and consequently majority of the recharge in the basin. On the other hand it can be seen that there is less concentration in the central and south-western parts of the basin. Therefore, even thought there is uniformity absence in the distribution of water point inventory data for an ideal model calibration use, the fact that the distribution of water well data tends to be concentrated on parts of major recharging areas of the basin is fortunate and has a positive effect in capturing and conceptualizing the main features of the groundwater flow system for recharge potential estimation.

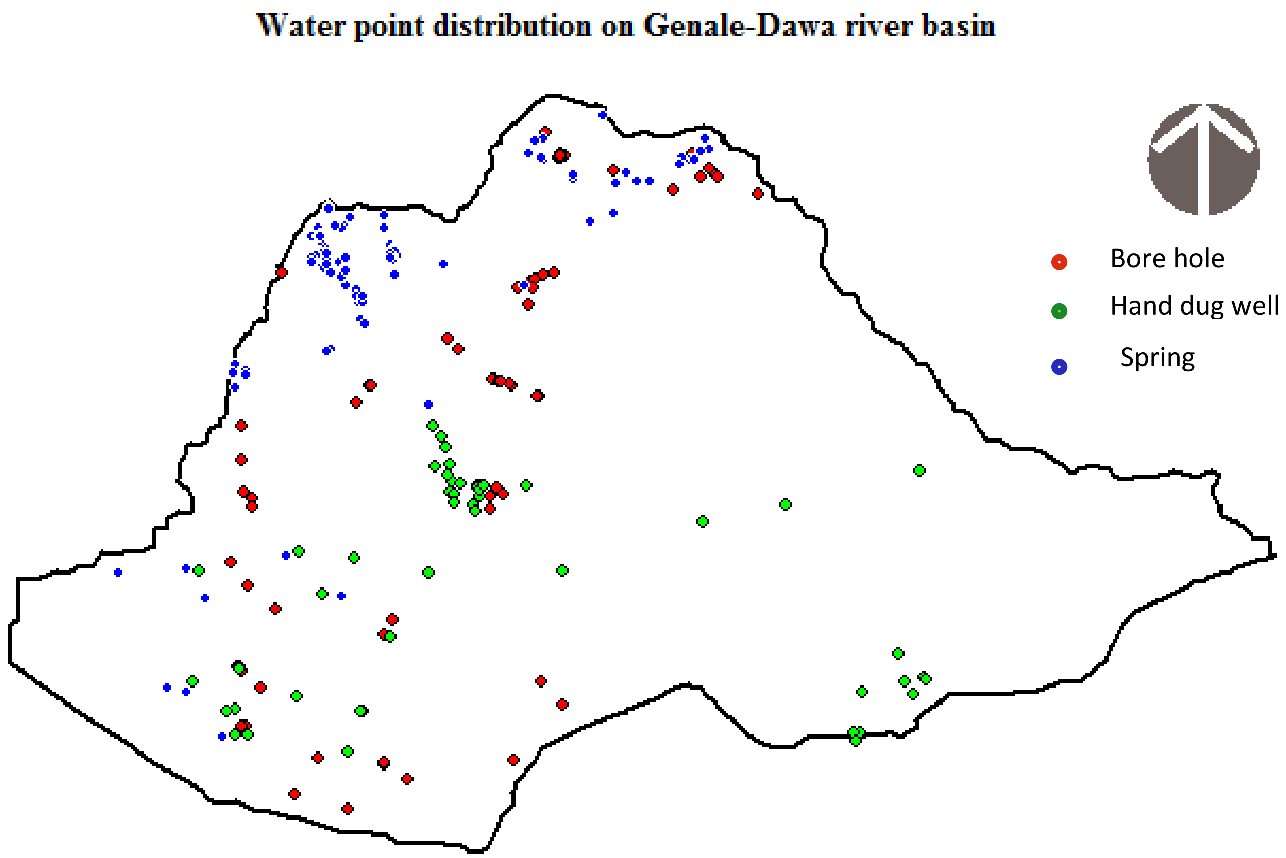


Figure 9 Water point Distribution in Genale Dawa Basin

4.2. Rainfall distribution

Determination of rainfall distribution over the basin is important prior to modeling in the groundwater potential assessment. It is used to approximate the amount of recharge from precipitation. Hence, Precipitation data of the study area was collected from Ethiopian National metrological Agency with a maximum of 15 years and a minimum of 10 years record. Data filling was done where there is missing. This was accomplished using a math lab program that uses the inverse distance method which was developed and coded by the authors of this study. The program is capable of dealing with a large amount of data; the Mat lab code of this program is attached in Appendix 4 for reference. After all fills were done; Point rainfall data is used to determine the spacial rainfall distribution over the entire basin. Thiessen polygon method, where by the influence of each rainfall station is determined and the weighted average rainfall estimated; is selected for this purpose. The Thiessen polygon generated for the

Genale-Dawa River basin on the bases of 23 rain fall stations is presented in Fig10. The area of the Thiessen polygon bounding each station receives the same amount of rainfall as the station.

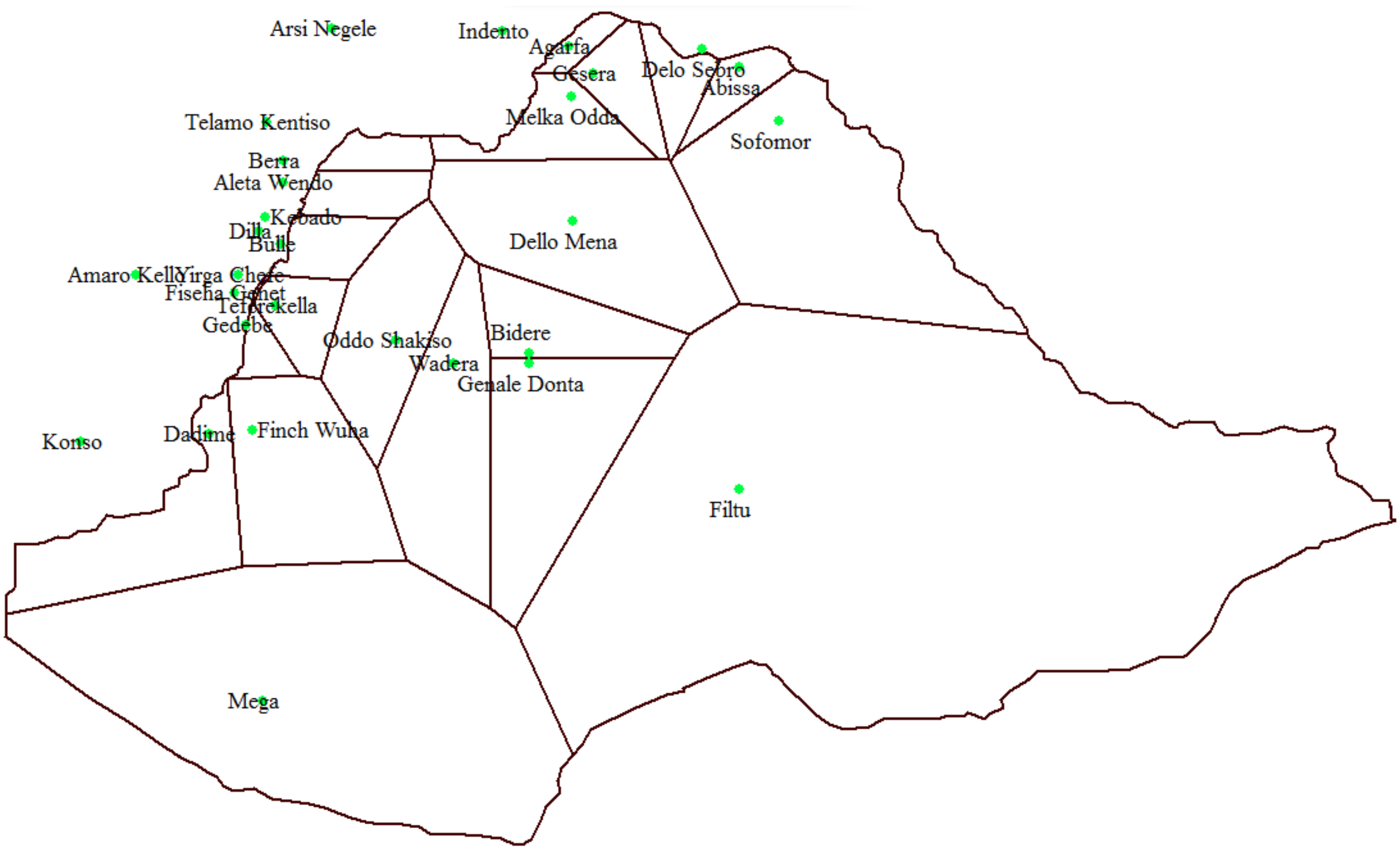


Figure 10 Thiessen polygon diagram generated on Genale-Dawa Basin

The average annual rainfall observed over these stations is shown in Table 1.

Table 1 Location and average precipitation of rainfall gauging stations used for areal rainfall calculation

No.	Met. station	Location (UTM)		Annual cumulative of monthly Mean rainfall
	Station Code	Latitude, N	Longitude, E	(mm)
1	ABISSA (S-21)	70952	403855	747.8054708
2	SOFOUMER (S-20)	65400	405024	585.4909383
3	KEBADO(S-2)	62600	382000	1398.618571
4	FISHA GENET(S-6)	60400	381100	1394.102499
5	YIRGA CHEFE(S-5)	60902	381207	1333.485122
6	FILTU(S-12)	50623	403835	408.485119
7	MEGA(S-11)	40413	381914	615.2595465
8	GENALE DONTA(S-13)	54300	393700	1297.203825
9	DADIME (S-10)	52228	380330	758.3530511
10	FINCH WUHA (S-19)	52335	381611	765.9513511
11	GEDEBE(S-7)	55420	381422	1517.122361
12	BIDER (S-14)	54600	393700	781.2535876
13	WADERA (S-15)	54300	391500	898.3692765
14	ODDO SHAKISO (S-16)	55000	385800	1022.980829
15	TEFERKELA (S-8)	60000	382300	1724.167539
16	BULLE (S-1)	61813	382414	1533.079242
17	ALETA WONDO(S-3)	63614	382505	1582.162685
18	BERRA(S- 4)	64236	382505	1303.217431
19	DELLO MENA (S-17)	62500	395000	1021.439937
20	MELKA ODDA (S-18)	70116	394934	559.8847648
21	AGARFA (S-22)	71600	394900	1086.15793
22	GESERA (S-19)	70800	395600	1007.416663
23	DELLO SIRBO (23)	71500	402800	1023.40185

4.3. Base flow separation

Monthly stream flow data of 12 gauging stations over the basin was collected. The length of data record ranges from 15 to 20 yrs. prior to using these data for the determination of base flow contribution to rivers, data filling and quality check was done using outlier testing as shown below. Data filling was done using single and multiple regression techniques alternatively for different stations. The choice of using either one was depending on the hydrological similarity between the gauging stations. On the other hand quality check was done with outlier testing by seating lower and upper limit using the formulation shown below. After all the necessary data check and fills were done, digital filter method was employed to perform base flow separation of different stations (Appindex1).

$$Y_L = Y_m \pm K_n S_y$$

Where

Y_L is the log of high or low outlier limit,

Y_m is the mean of the log of the sample flows,

S_y is the standard deviation of the logs of the sample flows, and

K_n is the critical deviation

Table 2 Monthly base flow contribution at gauging stations

Month	Station Name												Monthly Total (M^3)
	yadot	welemel	wyib	togona	mormora	mesol	mana	healgo	genale	awata	dimtu	deyou	
jan	4.05	11.73	1.29	0.89	9.19	2.04	0.08	0.65	42.75	8.36	0.02	10.38	2742.50
feb	3.01	9.20	1.60	0.47	6.52	1.55	0.08	0.55	44.14	10.21	0.01	11.15	2654.48
mar	4.38	10.27	2.71	0.33	7.21	1.51	0.10	0.59	57.14	10.38	0.04	11.86	3195.32
apr	5.47	14.51	3.13	0.45	10.33	1.96	0.23	0.80	84.17	11.15	0.05	12.75	4350.28
may	5.89	16.30	2.40	1.08	12.73	2.21	0.27	0.92	138.18	11.86	0.06	14.25	6184.58
jun	6.02	16.56	4.16	1.26	12.71	2.29	0.29	0.82	124.97	12.75	0.09	14.77	5900.45
jul	6.31	18.17	45.49	1.15	13.48	2.49	3.64	9.32	157.15	14.25	0.69	11.74	8516.10
aug	6.63	19.49	6.13	16.31	14.09	30.51	0.45	0.72	206.51	14.77	0.06	6.74	9672.67
sep	6.94	214.22	6.65	1.84	14.76	2.79	0.46	0.65	211.70	11.74	0.07	4.49	14289.19
oct	76.75	22.23	4.00	2.11	162.57	3.00	0.48	0.74	247.42	6.74	0.08	4.17	15909.17
nov	7.87	22.66	2.43	2.29	17.18	3.11	0.34	0.79	826.60	4.49	0.09	8.18	26881.03
dec	6.32	16.85	1.25	1.72	14.33	2.87	0.17	0.69	811.52	4.17	0.04	9.83	26092.85

4.4. Flow system boundary

Based on the previous discussion on conceptualization of flow system boundary, Dirichlet and Newman boundary conditions have been conceptualized in the model as described below.

Rivers as previously discussed are represented in the model with a set of nodal points that collectively make up the river system. Sections of rivers that cut through an aquifer to a considerable length have been identified in the region, they are considered as gaining rivers and in hydrological terms they are named Perennial Rivers; ones that do not dry throughout the season of the year. Some sections of the rivers that displayed such characteristics include Genale, Dawa, Gestro, Mena Weyeb and others small streams as well. These rivers, since they are gaining and are exposed to atmospheric pressure, can be taken as constant head boundaries (Dirichlet condition). Hence, the set of nodes that represent these rivers are set to have known hydraulic head equivalent to atmospheric head.

On the other hand, river sections that lose water to an aquifer are named losing or intermittent rivers. These types of rivers recharge the ground water with a loss rate that is variable spatially and temporally. They can be taken as specified flow boundary if the loss or gain rate of the stream is known spatially and temporally (Reilly, 2001). However, this recharge rate is difficult to determine explicitly. Nevertheless, considering recharge to an aquifer ultimately results from rain fall; recharge from loosing rivers in this study area is implicitly represented with rate of recharge by precipitation.

Moreover, the peripheral physical boundaries of the discretized region lie mostly on topographic highs locking the river basin, the regional groundwater divides are also assumed to align to these topographic conditions. Hence, it is assumed that the boundaries of the basin are no flow boundaries. In addition, the bottom surface of the region which in this study is taken to be 2500km deep is assumed to have an impermeable bed making it a no flow boundary. At the same time, considering recharge due to precipitation is a major source to groundwater in the basin, this study also takes recharge rate into ground-water as a specified flow boundary condition along the top boundary of the groundwater model.

The figure below shows the constant head river boundaries colored light blue and peripheral no flow boundary of the model with dark bold line

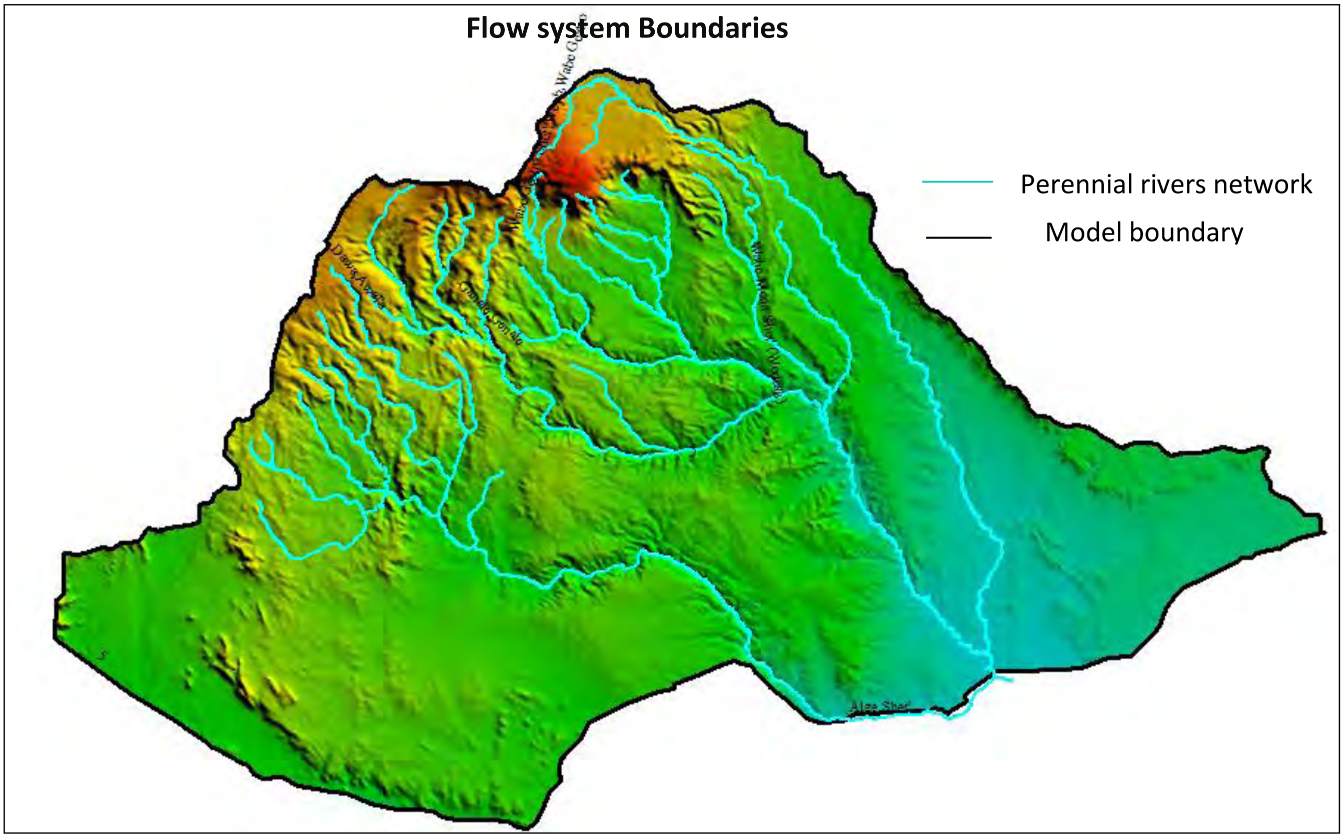


Figure 11 Flow system Boundaries

4.5. Model calibration

As described in the methodology section model calibration in this study is done using manual trial and error approach. Where, values of hydraulic properties are manually tuned in an attempt to make agreement between simulated and recorded field hydraulic head distribution data. Distribution of horizontal and vertical hydraulic conductivities for different geologic classes on the study area are therefore, adjusted as calibration parameters until a satisfactory agreement is made between the measured and simulated field data. When a best fit is achieved the corresponding hydraulic conductivity distribution is assumed to be representative of the study area in the conceptualized region. After many successive trial and error procedures were done, the best agreement made is evaluated quantitatively using a scatter plot between the two set of data.

In the scatter plot graph, ideal fit is expected to have a strictly linear relationship with a value of correlation coefficient , R^2=1 and a randomly scattered plot is an indication of poor fit with a value of R^2=0. The calibration check for the model in this study is shown using a scatter plot.

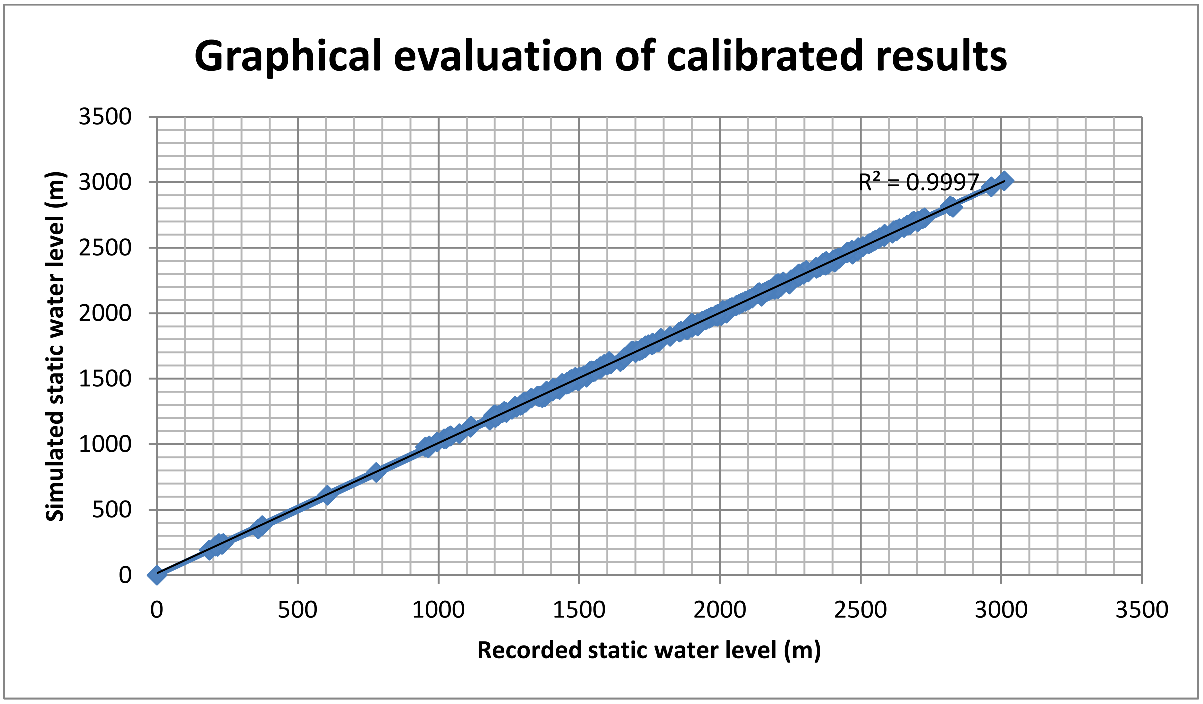


Figure 12 Evaluation of calibration results using scatter plot between hs and hm

Additional quantitative evaluation of model calibration result is also done using average indicators and the following results were obtained

5. The mean error (ME)

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(h_{measured} - h_{computed}\right)_i = 3.91$$

6. The mean absolute error (MAE)

$$AME = \frac{1}{n}\sum_{i=1}^{n}\left|(h_{measured} - h_{computed})_i\right| = 7.46$$

7. The root mean squared error (RMS)

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_{measured} - h_{computed})_i^{\ 2}} = 10.65$$

Qualitative check of calibration results is also done with contour maps generated using simulated and field recorded hydraulic head data. Resemblance between the two contour maps serves as a qualitative check for the model output. Fig 13 and Fig 14 shows the contour maps generated using field recorded and simulated hydraulic head values.

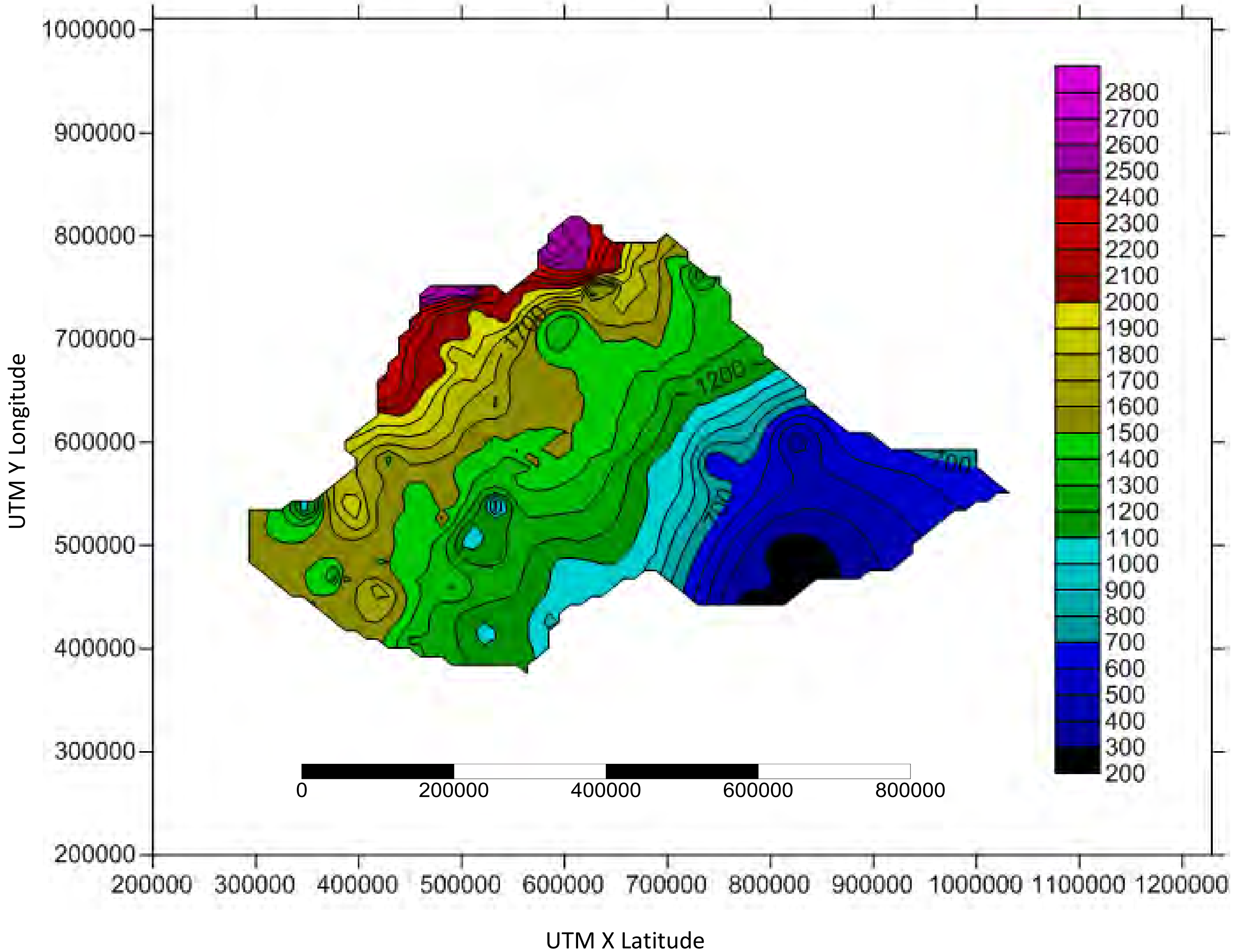


Figure 13 Ground water contour map generated with recorded hydraulic head

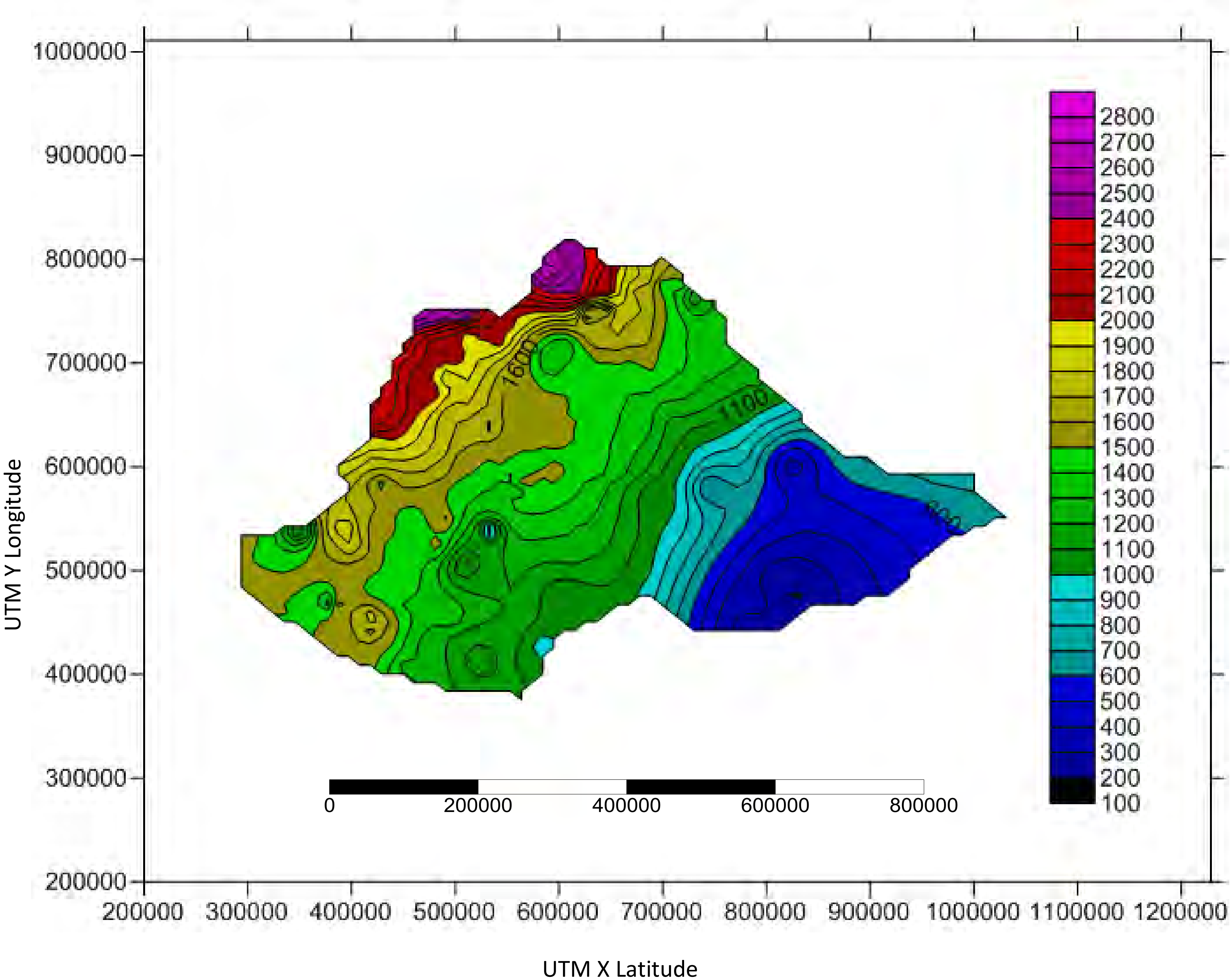


Figure 14 Groundwater contour map generated with simulated head

For the most part, the contour lines generated based on simulated and recorded data seem to agree well. The resemblance between the two contour maps is an indication of how well the model is calibrated and that the model represents the real system. Even thought complete similarity is unachievable, a faire resemblance seems to exist. Considering the resolution of modeling and quality of data used, this result has been taken acceptable.

From the calibrated model, the average recharge percentage of rainfall was estimated to be 10% of the total rainfall received by the catchment. Keeping in mind the arid climate of the basin and morphological setting of the basin that causes sloppy areas; the result obtained is taken acceptable. The resulting horizontal and vertical hydraulic conductivity distribution for individual geologic classes are presented in table

Table 3 Hydraulic conductivity values of different geologic medium on Genale-Dawa Basin (Geologic coding is presented in appendix 3 and is consistent with fig 4)

Geologic class code	Hydraulic Conductivity			
	Kx(m/s)	Ky(m/s)	Kz(m/s)	Keq
Ja	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Jg	1.30E-05	1.30E-05	8.64E-05	1.20E-07
Jh1	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Jh2	1.73E-05	1.73E-05	2.16E-04	2.54E-07
ka	8.64E-05	8.64E-05	8.64E-05	8.03E-07
kg1	8.64E-05	8.64E-06	2.16E-04	4.02E-07
kg2	7.78E-04	7.78E-04	8.56E-04	2.28E-05
km	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Nb	8.64E-04	8.64E-04	8.64E-05	8.03E-06
NMt	8.64E-04	8.64E-05	8.64E-05	2.54E-06
NMv	8.64E-04	8.64E-05	1.73E-04	3.59E-06
Nn	8.64E-04	8.64E-05	1.73E-04	3.59E-06
Ntr2	8.64E-04	8.64E-05	8.64E-05	2.54E-06
Ntr3	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcdt	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcdt1	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcdt2	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcgb1	5.18E-04	5.18E-05	1.30E-04	1.87E-06
Pcgb2	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcgd	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Pcgn1	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcgn2	8.64E-08	8.64E-08	4.32E-07	5.68E-11
Pcgn3	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcgn4	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcgn5	1.73E-07	2.33E-06	1.73E-08	8.35E-11
Pcgn6	8.64E-07	8.64E-09	8.64E-07	8.03E-11
Pcgn7	8.64E-07	8.64E-07	8.64E-08	2.54E-10

Pcgn8	8.64E-07	7.78E-05	4.32E-04	1.70E-07
Pcgn9	4.32E-06	7.78E-07	8.64E-07	1.70E-09
Pcgn10	8.64E-07	8.64E-07	2.16E-06	1.27E-09
Pcgn11	8.73E-07	1.30E-06	8.73E-07	9.94E-10
Pcgt1	4.75E-08	4.75E-08	8.64E-08	1.40E-11
Pcgt2	4.32E-07	4.32E-07	2.16E-07	2.01E-10
Pckb	8.64E-07	8.64E-08	8.64E-08	8.03E-11
Pcs1	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcs2	8.64E-08	8.64E-07	2.16E-07	1.27E-10
Pcs3	8.64E-07	8.64E-07	8.64E-07	8.03E-10
Pcum1	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcum2	8.64E-08	4.32E-07	8.64E-08	5.68E-11
Pcum3	8.64E-08	8.64E-07	8.64E-08	8.03E-11
Pcum4	8.64E-08	8.64E-08	8.64E-07	8.03E-11
PNb1	1.73E-04	1.73E-05	1.73E-05	2.27E-07
PNb2	8.64E-05	8.64E-05	8.64E-05	8.03E-07
PNi	8.64E-05	1.30E-04	1.30E-04	1.20E-06
PNtr1	8.64E-08	8.64E-08	8.64E-07	8.03E-11
Q	2.16E-03	2.16E-03	2.16E-03	1.00E-04
Q6	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Qa	4.34E-03	4.34E-03	4.34E-03	2.86E-04
Qe	1.30E-06	1.73E-06	1.73E-05	6.22E-09
Qv	4.34E-04	4.34E-04	4.34E-04	9.03E-06
Qv1	1.73E-04	1.73E-03	2.16E-03	2.54E-05
Qv2	8.64E-05	8.64E-06	8.64E-05	2.54E-07
Qv3	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Qv4	8.64E-05	8.64E-05	2.16E-05	4.02E-07
Qv5	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Tsy	1.30E-04	8.64E-04	1.30E-04	3.81E-06

The estimated hydraulic conductivity parameter values appear to vary between 8.64E-09 to 4.34E-03 with most of the geologic medium falling in range between 8.03E-07and 2.54E-11. This distribution seem to be reasonable when we consider; that the geology of Genale Dawa River Basin is highly diversified containing Karastic Aquifer characteristics near and around Sofoumer, concentrated geological discontinuities observed on the western parts of the basin and low hydraulic conductivity metamorphic rocks in the northern and central part of the basin.

The geologic map on Fig 4 of the basin shows the configuration of individual geology classes that are listed in the table above.

After the model calibration is complete, groundwater table (pizometric head) of the region is calculated for each month in a year; using the calibrated model at nodal points. Afterwards conditions of possible maximum and possible minimum porosities of individual geologic mediums are taken. For each of these two conditions, monthly storage calculations in individual finite elements are done. The average of these tow conditions is used to determine groundwater table configuration in each month. This monthly groundwater table location showed seasonal fluctuation of the water table as shown in Fig 16. Thereafter, the determination of replenishable groundwater potential of the region is done by quantifying the amount of water that is only temporarily stored in the ground and drains to rivers, springs and lost due to evapotranspiration at latter times. Therefore minimum water table in the seasonal fluctuation is taken as benchmark for zero replenishable ground water storage.

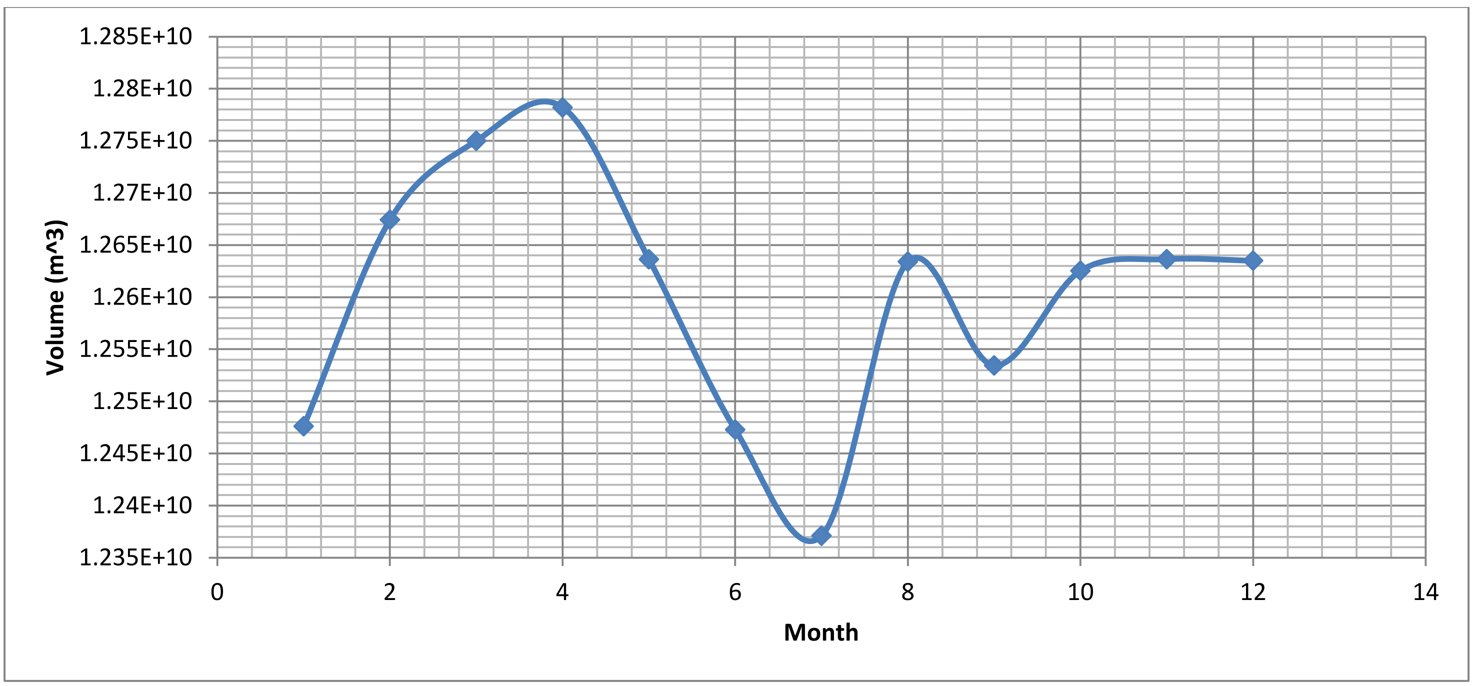


Figure 15 mean monthly water table fluctuation

The Ground water fluctuation trend seems to be comparable with rainfall series of the region for the most part, but near the 9th month it showed erratic behaviour. This could be a cumulative result of a very complex geologic composition of the region and spatially non uniform rainfall pattern in the region.

In order to determine the total replenishable ground water reserve, monthly contribution of groundwater to rivers shall also be taken in to account. Accordingly base flow separation of stream flow data was done using single parameter digital filter approach (Appendix 1) and the result was added to the volume of replenishable ground water obtained from the model. This has resulted in 2.78BM^3 as total replenishable groundwater in Genale Dawa basin; the result is shown in table below.

Table 4 Total Replenishable Ground Water Calculation

Month	**Replenishable Ground Water (M^3)**	**Base flow contribution to rivers(M^3)**	**Total monthly Replenishable Ground Water (M^3)**
jan	1.05E+08	2.74E+03	1.05E+08
Feb	3.03E+08	2.65E+03	3.03E+08
mar	3.79E+08	3.20E+03	3.79E+08
apr	4.11E+08	4.35E+03	4.11E+08
may	2.65E+08	6.18E+03	2.65E+08
jun	1.02E+08	5.90E+03	1.02E+08
jul	0.00E+00	8.52E+03	8.52E+03
aug	2.63E+08	9.67E+03	2.63E+08
sep	1.63E+08	1.43E+04	1.63E+08
oct	2.54E+08	1.59E+04	2.54E+08
nov	2.65E+08	2.69E+04	2.65E+08
dec	2.64E+08	2.61E+04	2.64E+08
Total Replenishable Ground Water			2.78E+09

Hydrogeology of Genale Dawa Basin

From the hydraulic conductivity values obtained from calibration it can be seen that many geological formations have similar hydraulic properties, for instance geologic mediums (1,3,5,8,14,15,16,17,43,47,53,54,55 and 11,12) have the same hydraulic conductivities where as others if not the same they have close similarity. Geologic characteristics of the Genale-Dawa River Basin can therefore be better understood if geologic mediums with similar hydraulic conductivity are grouped together. Accordingly, the following groups have been made

- High hydraulic conductivity geologic medium (>1×10*-4 m/s)
- Moderately high hydraulic conductivity geologic medium (1×10*-4 to 1×10*-5 m/s)
- Moderately low hydraulic conductivity geologic medium (1×10*-5-1×10*-7 m/s)
- Low hydraulic conductivity geologic medium (1×10*-7 to 1×10*-12 m/s)

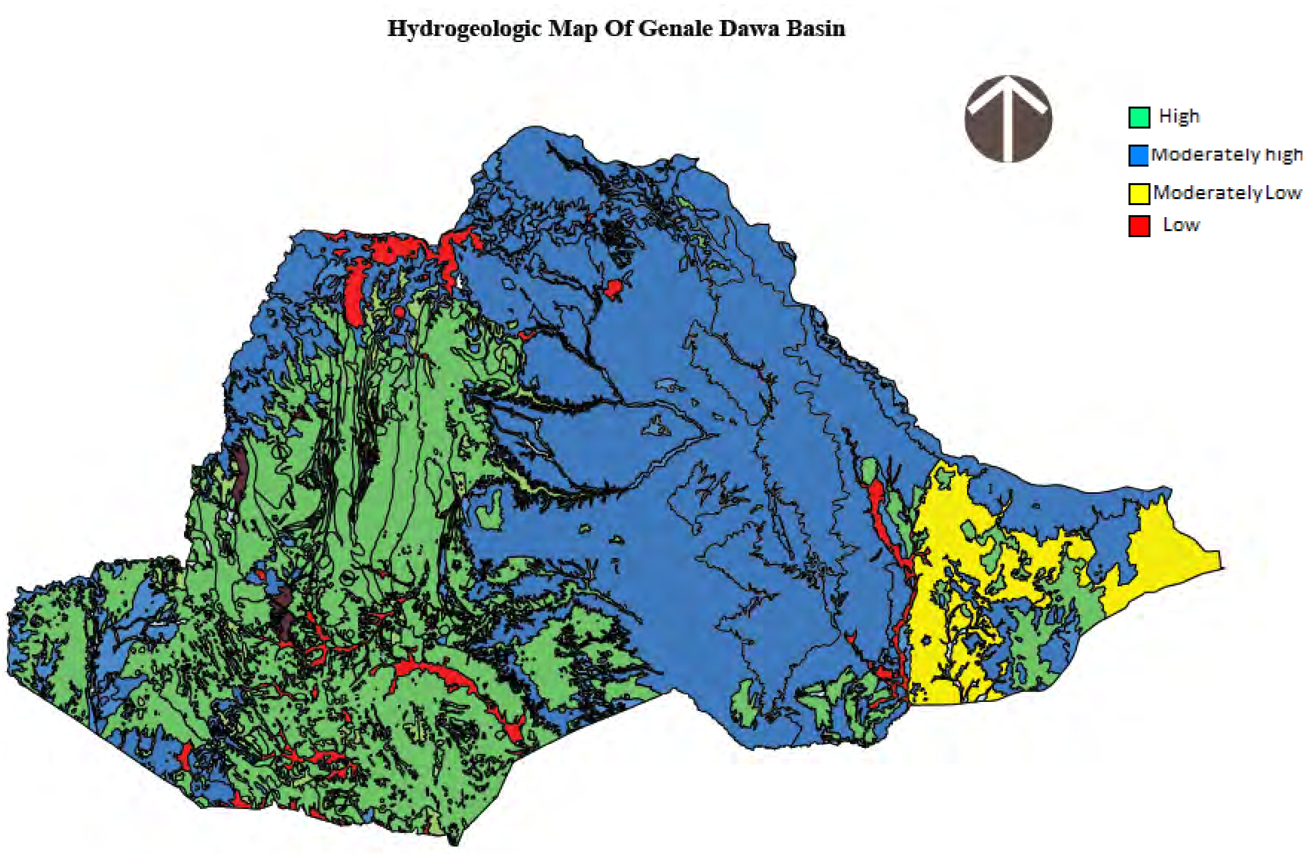


Figure 16 Hydro geologic map of Genale Dawa basin

It is also possible to plot SWL vs. Ground elevation in order to inspect how water table behaves in relation to elevation changes of the ground (terrain) see Fig 18.

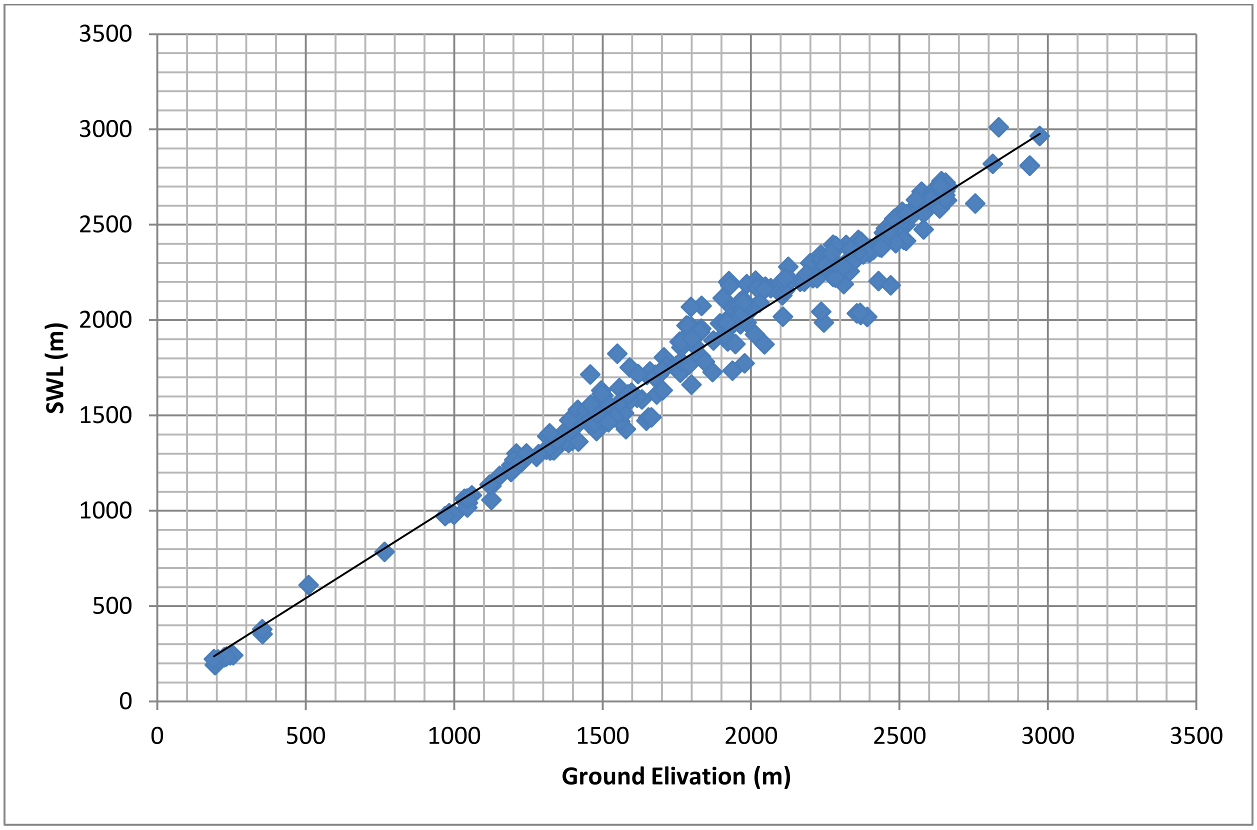


Figure 17 Relationship between elevation of ground surface and water table

It can be seen on the plot that surface terrain and ground water profile are replica of each other. This shows that flow velocity of ground water is parallel ground surface and Ground water system in the region tends to be dominated by an unconfined aquifer system. (Fetter, 2001)

Additionally by looking at the velocity field distribution it is possible to identify major recharging and discharging areas. Circles in read show areas of recharge with dispersing velocity vectors, where as circles in green show areas of discharge with collecting velocity vectors. But it should be noted that identified recharging sites can also be acting as discharging areas at the same time and vice versa. This can be witnessed if we look at the recharging areas at the northern part of the basin; all the velocity vectors are in dispersing position showing a major recharge taking place but at the same time perennial rivers emanate from those areas showing that it is also acting as a discharging site. Moreover it is seen that discharging sites do coincide with river networks showing points at which ground water contributes to rivers. But at points where recharging site is away from rivers, it is possibly an indication that the aquifer is discharging to an underlying strata.

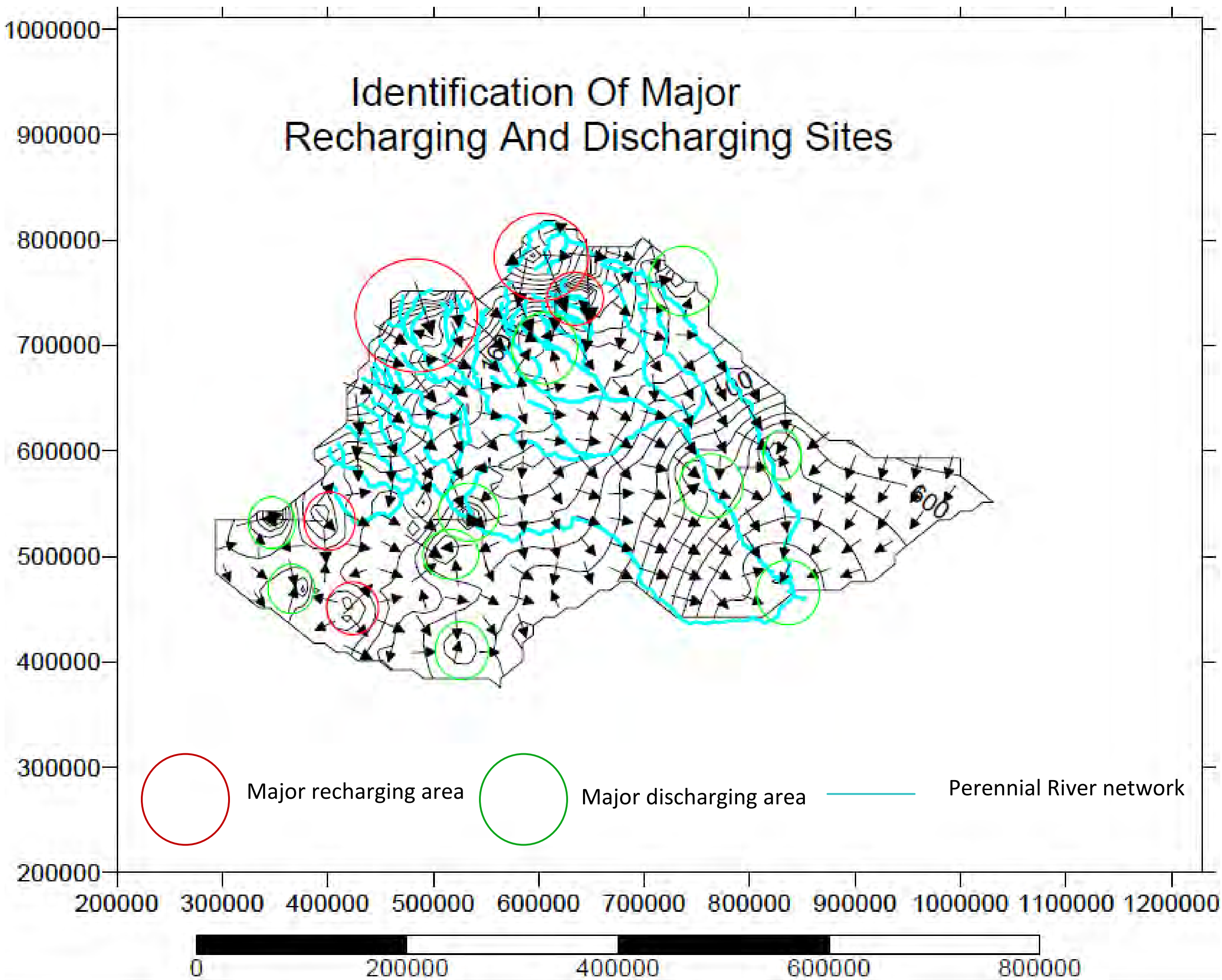


Figure 18 Identification of Recharging and Discharging areas In Genale Dawa Basin

5. Conclusion and Recommendation

5.1. Conclusion

Groundwater modeling has versatile applications in groundwater resources management that can be used for groundwater pollution management and more. This study used finite element based three dimensional groundwater modeling program called TAGSAC to estimate the groundwater recharge potential as described in the previous chapters. The findings of this research showed that the basin has an average recharging potential of 2.78 BCM. This is in order with previous estimations made by WAPCOS in 1990 which was 0.433BCM using recharge area approach. But considering that recent data have also been incorporated in this study and that a different methodology has been employed, the result can be taken as a good estimation. An improved delineation has also been used that helps in making better estimate. However, further study on estimation of extraction factor shall be done. This factor accounts for the sociological, botaniuque and other concerned factors to determine the safest amount of groundwater that can be extracted from the basin. In addition, this study also attempted to characterize the groundwater flow system of the basin by preparing hydro-geological map and contour map, which can be useful in selection of well field in the future.

It should also be noted that this study has faced some challenges due to limitations in computational resources. This has restricted the model not to use finer finite element sizes which would have a positive effect towards better ground water potential estimate. The luck in availability of detailed geological data has also limited the model with a single layer that represents the aquifer system in the vertical extent. With detailed geological investigation an improved model with multiple layers can be developed. Therefore, future studies on the basin can improve on these to get a better estimation.

5.2. Recommendation

Based on the results obtained from the study the following recommendations are forwarded;

- The identified sites of recharge area shall be protected from polluting chemicals to assure quality of the regions groundwater. Forestation of this area can also increase the available groundwater reserve by increasing the amount of infiltration and percolation hence; it is recommended to plane and execute environmental protection projects in these regions.
- Identified discharging areas can be used as well fields after carrying out the necessary detail investigation on the site. Therefore the regional authorities can consider ground water based water supply schemes for domestic and industrial purposes.

- Regular well monitoring shall be planned and executed in the region to gather better quality data and widen our understanding of the basins groundwater flow system which can be used as an input for future study. Concerned authorities shall also provide a framework that can enforce the collection and report of well inventory data including geological log, time log and other standard records at the time of well drillings and completion.

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Appendix 1
Continuous Base flow Separation Method

Digital filter is a frequency analysis method initially developed for signal analysis. Now days it is widely applicable for base flow separation in Hydrology

Approach:

Use a numerical algorithm (a digital filter) to partition the streamflow hydrograph into "high frequency" (direct runoff) and "low frequency" (baseflow) components. One type of digital filter approach is show as follows. (Nathan and McMahon, 1990)

Terms:

Q_k streamflow at time step k

R_k direct runoff at time step k

B_k baseflow at time step k

Parameter:

α base flow filter parameter, it's an attenuation coefficient between 0.9 and 0.995. The bigger the attenuation the stronger the runoff, and the lesser the base flow a value of 0.95 was used for this study.

Algorithm:

At each time step:

$$R_{k+1} = \propto R_k + \frac{(1+\propto)}{2}(Q_{k+1} + Q_k)$$

Check:

If *R_{k+1}<0 then R_k=0*

If R_{k+1}>then R_{k+1}=Q_{k+1}

Compute base Flow:

$B_{k+1}=Q_{k+1}-R_{k+1}$

Appendix 2
Water point calibration data

No.	TYP	SITE_NAME	REGION	ZONE	WEREDA	UTM_X	UTM_Y	SWL
1	BH	Ali Town No 1	OROMIY	BALE	Agarfa	60306	80034	10
2	BH	Ginir	OROMIY	BALE	Ginir	69000	78800	12
3	BH	Melka Oda	OROMIY	BALE	Ginir	69516	77404	8.25
4	BH	Melka Oda	OROMIY	BALE	Ginir	70339	77570	22
5	BH	Melka Oda No. 1	OROMIY	BALE	Ginir	70514	77346	12
6	BH	Tullicha No 3	OROMIY	BALE	Ginir	70022	77915	21
7	BH	Melka Buta	OROMIY	BALE	Goro	67861	76661	8
8	BH	Sinana No 3 State Farm	OROMIY	BALE	Goro	64301	77842	69
9	BH	Abasirba No 1	OROMIY	BALE	Meda	58208	65055	5
10	BH	Abasirba No 2	OROMIY	BALE	Meda	58167	65090	16
11	BH	Bidire BH5	OROMIY	BALE	Meda	57212	65366	15
12	BH	Bidire No 1	OROMIY	BALE	Meda	57252	65448	8
13	BH	Bidire town No 2	OROMIY	BALE	Meda	57180	65432	8
14	BH	Bidire town No 3	OROMIY	BALE	Meda	57075	65401	13
15	BH	Elabidire No 1	OROMIY	BALE	Meda	57448	65279	8
16	BH	Elabidire No 2	OROMIY	BALE	Meda	57609	65223	17
17	BH	Meda No 1	OROMIY	BALE	Meda	59853	64356	6
18	BH	Meda No 2	OROMIY	BALE	Meda	59828	64375	9
19	BH	Oborso No 2	OROMIY	BALE	Meda	54446	67834	21
20	BH	Oda	OROMIY	BALE	Meda	55127	67209	8
21	BH	Burkitu Derara No 1	OROMIY	BALE	Mena	59384	71206	13
22	BH	Chiri Harewa No 1	OROMIY	BALE	Mena	58619	70813	18
23	BH	Chiri Harewa No 2	OROMIY	BALE	Mena	58661	70831	12
24	BH	Dayu Harewa WELL NO 3	OROMIY	BALE	Mena	60751	71750	16
25	BH	Erba No 1	OROMIY	BALE	Mena	59607	71339	12
26	BH	Erba No 2	OROMIY	BALE	Mena	59654	71370	15.3
27	BH	Gomgoma No 1	OROMIY	BALE	Mena	59260	69816	8
28	BH	Mena town BH4	OROMIY	BALE	Mena	59492	70862	6
29	BH	Weltai Gudina No 1	OROMIY	BALE	Mena	60133	71559	14
30	BH	Weltai Gudina No 2	OROMIY	BALE	Mena	60186	71619	13
31	BH	Chelchel No 1	OROMIY	BALE	Rayitu	72918	76358	17
32	BH	Chelchel No 2	OROMIY	BALE	Rayitu	72909	76378	15
33	BH	Bale Robe Airport	OROMIY	BALE	Sinanana	61463	78698	11.2
34	BH	Robe Catholic School	OROMIY	BALE	Sinanana	61082	78497	5

35	BH	Robe No 1	OROMIY	BALE	Sinanana	61104	78492	5
36	BH	Robe No 2	OROMIY	BALE	Sinanana	61116	78557	6
37	BH	Robe No 4	OROMIY	BALE	Sinanana	61113	78680	9
38	BH	Robe No 5 (Kindergarten)	OROMIY	BALE	Sinanana	61125	78734	12
39	BH	Robe Town No 6	OROMIY	BALE	Sinanana	61173	78699	9
40	BH	25 Km South-east of well No. 12	OROMIY	BOREN	Arero	44269	51763	29.5
41	DW	25 Kms south-east Das/village	OROMIY	BOREN	Arero	49260	45682	10
42	DW	27 Kms north of Arero local	OROMIY	BOREN	Arero	48857	54806	1
43	DW	4.5 Kms north-west of Arero/	OROMIY	BOREN	Arero	47020	52701	2
44	BH	Bor-Bor WELL NO	OROMIY	BOREN	Arero	49371	45743	11
45	BH	WACHILE /ETH005	OROMIY	BOREN	Arero	50730	50239	14
46	DW	Wachile HDW	OROMIY	BOREN	Arero	51109	50103	6.1
47	BH	Wachile No. 1	OROMIY	BOREN	Arero	50662	50241	21
48	BH	Wachile No. 3	OROMIY	BOREN	Arero	51201	51116	20
49	BH	Fincha's (Jiges)	OROMIY	BOREN	Bule	42336	58676	3.5
50	BH	Kilenso No. 1	OROMIY	BOREN	Bule	42245	60651	15.9
51	DW	10 Kms Mega-Yabelo	OROMIY	BOREN	Dire	41860	45870	15
52	DW	12 Kms north-west of Mega	OROMIY	BOREN	Dire	41367	45717	6
53	DW	12.5 Kms south-west of Mega/	OROMIY	BOREN	Dire	41841	44254	13
54	DW	16 Kms west of Nomads	OROMIY	BOREN	Dire	45437	46537	15
55	DW	2 Kms south of Mega/Nomads	OROMIY	BOREN	Dire	42588	44370	5
56	DW	40 Kms north-west of Mega /	OROMIY	BOREN	Dire	39272	47423	2.5
57	BH	DUBLUK ETH/025	OROMIY	BOREN	Dire	42012	48293	19
58	BH	Dublick No. 1	OROMIY	BOREN	Dire	42171	48142	22.6
59	BH	Dublick No. 5	OROMIY	BOREN	Dire	42048	48357	19.4
60	DW	Dubluk /Ato Awaticha	OROMIY	BOREN	Dire	42047	48173	19
61	DW	EAGDER DW ETH/007	OROMIY	BOREN	Dire	48555	43326	24
62	BH	EGDER ETH/046	OROMIY	BOREN	Dire	48516	43305	24.5
63	BH	HIDILOLA ETH/036	OROMIY	BOREN	Dire	45328	40813	5
64	BH	MEGA ETH/010	OROMIY	BOREN	Dire	42400	44872	16
65	BH	Mega No. 1	OROMIY	BOREN	Dire	42214	44856	16.8
66	BH	QA GOFA ETH/042	OROMIY	BOREN	Dire	43357	47100	24
67	BH	Site-147 No. 1	OROMIY	BOREN	Dire	46761	42950	17
68	BH	TUKA ETH/013	OROMIY	BOREN	Moyale	48509	39879	6
69	BH	12 Km South-west of well No.	OROMIY	BOREN	Yabelo	42596	53200	33.2
70	DW	3.5 Kms to Teltele-Yabello road	OROMIY	BOREN	Yabelo	39651	53979	5
71	DW	40 Kms north-west of	OROMIY	BOREN	Yabelo	45577	55210	9.2
72	BH	Kedale No. 1	OROMIY	BOREN	Yabelo	41592	54513	12
73	BH	Oda No. 1	OROMIY	BOREN	Yabelo	42874	58381	5
74	BH	Surupa WELL NO 2	OROMIY	BOREN	Yabelo	42858	57782	2
75	BH	Kibre Mengist No. 1	OROMIY	GUJI	Adola	49877	64978	7.72
76	BH	Kibre Mengist high school No. 2	OROMIY	GUJI	Adola	49815	64978	24.5

77	BH	Kibre Mengist town BH9	OROMIY	GUJI	Adola	49884	65062	21
78	BH	Chemeri Bachano No. 1	OROMIY	GUJI	Kercha	42186	62588	53.7
79	DW	Adadi	OROMIY	GUJI	Liben	54557	58687	3.3
80	DW	Bokola	OROMIY	GUJI	Liben	53722	60286	3.1
81	DW	Buledi /Haro/	OROMIY	GUJI	Liben	59135	59135	2.8
82	DW	Buradera	OROMIY	GUJI	Liben	55917	57923	5
83	DW	Buradhera	OROMIY	GUJI	Liben	56125	57628	9.38
84	BH	Debeno	OROMIY	GUJI	Liben	57420	58973	55
85	DW	Dolcha	OROMIY	GUJI	Liben	53536	62669	5.4
86	DW	Gobicha	OROMIY	GUJI	Liben	56289	58917	4
87	DW	Hardot	OROMIY	GUJI	Liben	54871	58617	5
88	DW	Haro /Kobadi/	OROMIY	GUJI	Liben	56429	59133	1.21
89	DW	Harokelo DW6	OROMIY	GUJI	Liben	54329	61371	20
90	DW	Kerero	OROMIY	GUJI	Liben	54685	59303	8.9
91	DW	Kersemele	OROMIY	GUJI	Liben	55193	59197	4.5
92	DW	Mede	OROMIY	GUJI	Liben	54417	59752	5.1
93	DW	Melkaguba	OROMIY	GUJI	Liben	53375	53887	5
94	DW	Mersa	OROMIY	GUJI	Liben	56391	58485	6
95	DW	Mucho	OROMIY	GUJI	Liben	54116	61986	6.62
96	DW	Negele (Kela) DW2	OROMIY	GUJI	Liben	56273	59007	2.5
97	BH	Negele AP No. 2	OROMIY	GUJI	Liben	57802	58535	59.3
98	BH	Negele Army base No. 6	OROMIY	GUJI	Liben	56278	59132	2.5
99	BH	Negele Borena	OROMIY	GUJI	Liben	57017	58396	4
100	BH	Negele No. 6	OROMIY	GUJI	Liben	56294	58810	4
101	DW	Negele Water scheme	OROMIY	GUJI	Liben	56339	58829	1.88
102	DW	Nura humba	OROMIY	GUJI	Liben	54582	60414	2.8
103	BH	Siminto	OROMIY	GUJI	Liben	57001	57657	15.2
104	DW	T. Dhelan	OROMIY	GUJI	Liben	54887	58121	5.28
105	DW	Wofe	OROMIY	GUJI	Liben	56622	59053	4.1
106	BH	Awata No. 1	OROMIY	GUJI	Odo	49062	63965	8.18
107	BH	Arbegona	SNNP	SIDAMA	Arbegon	46891	73975	6
108	BH	Bensa Daye	SNNP	SIDAMA	Bensa	48200	72000	13.5
109	BH	Hagere Selam BH16	SNNP	SIDAMA	Hula	44657	71671	100
110	DW	Chereti	SOMALI	AFDER	Chereti	82500	60000	1.2
111	DW	Bur amino	SOMALI	AFDER	Dolo Bay	82715	47666	4.3
112	DW	Biyoole	SOMALI	LIBEN	Dolo Odo	79099	46812	2.5
113	DW	Dipi (near Dolo) DW4	SOMALI	LIBEN	Dolo Odo	82188	46688	5
114	DW	Dytuli	SOMALI	LIBEN	Dolo Odo	78991	44446	15.2
115	DW	Geled	SOMALI	LIBEN	Dolo Odo	78569	44403	5
116	DW	Golome	SOMALI	LIBEN	Dolo Odo	82865	47582	7.5
117	DW	Kole	SOMALI	LIBEN	Dolo Odo	81203	49054	4.6
118	DW	Niman	SOMALI	LIBEN	Dolo Odo	78669	43974	4

119	DW	Shambel	SOMALI	LIBEN	Dolo Odo	81681	47502	7.2
120	DW	Mesajid-1	SOMALI	LIBEN	Filtu	69651	56937	20
121	DW	Mesajid-2	SOMALI	LIBEN	Filtu	69649	56939	17.5
122	DW	Rideb	SOMALI	LIBEN	Filtu	74570	57987	4.5
123	DW	Sirba	SOMALI	LIBEN	Filtu	61230	53982	2.86
124	BH	Chilango No. 1	SOMALI	LIBEN	Moyale	61330	46125	21
125	BH	Dawa South 1	SOMALI	LIBEN	Moyale	60000	47500	21
126	BH	El Der No. 1	SOMALI	LIBEN	Moyale	58419	42769	24.4
127	BH	El Gof	SOMALI	LIBEN	Moyale	50621	42588	19.5
128	BH	El Gof	SOMALI	LIBEN	Moyale	50675	42650	20.7
129	BH	El Kalu	SOMALI	LIBEN	Moyale	52077	41694	19.3
130	BH	El Kalu No. 1	SOMALI	LIBEN	Moyale	52035	41630	19
131	BH	El Leh	SOMALI	LIBEN	Moyale	52054	41654	20
132	SP	Elabidu Spring	OROMIY	BALE	Agarfa	60154	79664	0
133	SP	Kasowara	OROMIY	BALE	Agarfa	59701	79612	0
134	SP	Burkitu (Cheketa Urene)	OROMIY	BALE	Berbere	64300	75307	0
135	SP	Haro Dumal	OROMIY	BALE	Berbere	62958	74719	0
136	SP	Amigna Shirar Spring No 1	OROMIY	BALE	Gasera	63719	81104	0
137	SP	Amigna Shirar Spring No 2	OROMIY	BALE	Gasera	63731	81093	0
138	SP	Amigna Shirar Spring No 3	OROMIY	BALE	Gasera	63734	81093	0
139	SP	Ashute Gaguro No 1	OROMIY	BALE	Ginir	68913	78407	0
140	SP	Ashute Gaguro No 2	OROMIY	BALE	Ginir	68910	78407	0
141	SP	Ashute Gaguro No 3	OROMIY	BALE	Ginir	68907	78407	0
142	SP	Chancho Ardaterie	OROMIY	BALE	Ginir	69146	78364	0
143	SP	Doyo	OROMIY	BALE	Ginir	68349	78571	0
144	SP	Elani Abiyu	OROMIY	BALE	Ginir	68244	78120	0
145	SP	Ginir (9km NE) SP1	OROMIY	BALE	Ginir	69750	79740	0
146	SP	Keteti No 1	OROMIY	BALE	Ginir	69965	78993	0
147	SP	Keteti No 2	OROMIY	BALE	Ginir	69958	78996	0
148	SP	Oda Roba	OROMIY	BALE	Ginir	69510	78885	0
149	SP	Elasa Iteya	OROMIY	BALE	Goba	61869	77245	0
150	SP	Misira Spring	OROMIY	BALE	Goba	61955	77538	0
151	SP	Addis Alemana Water Supply	OROMIY	BALE	Goro	65047	77686	0
152	SP	Awugiegesh Spring	OROMIY	BALE	Goro	64426	77033	0
153	SP	Burkitu No 1	OROMIY	BALE	Goro	66632	77099	0
154	SP	Burkitu No 2	OROMIY	BALE	Goro	66632	77097	0
155	SP	Dodimol	OROMIY	BALE	Goro	65750	77093	0
156	SP	Goro (Dadimos)	OROMIY	BALE	Goro	66570	77210	0
157	SP	Weltai Chefa	OROMIY	BALE	Goro	66470	77178	0
158	SP	Chali Spring No 1	OROMIY	BALE	Kokosa	48230	74455	0
159	SP	Chali Spring No 2	OROMIY	BALE	Kokosa	48231	74456	0
160	SP	Churisa No 2	OROMIY	BALE	Kokosa	47380	75615	0

161	SP	Churisa Spring No 1	OROMIY	BALE	Kokosa	47420	75501	0
162	SP	Diki Liemeni Spring	OROMIY	BALE	Kokosa	48139	74399	0
163	SP	Ebicha Spring	OROMIY	BALE	Kokosa	48622	74995	0
164	SP	Halila Spring	OROMIY	BALE	Kokosa	47755	74515	0
165	SP	Rera	OROMIY	BALE	Mena	54238	72211	0
166	SP	Wabero Spring	OROMIY	BALE	Mena	58963	71024	0
167	SP	Antokia Spring	OROMIY	BALE	Nensebo	51217	72721	0
168	SP	Bochesa	OROMIY	BALE	Nensebo	51327	71642	0
169	SP	Bulga	OROMIY	BALE	Nensebo	51374	72770	0
170	SP	Burka Mena Beromsa	OROMIY	BALE	Nensebo	50622	74330	0
171	SP	Burkitu Jeldo Spring	OROMIY	BALE	Nensebo	50681	74333	0
172	SP	Burkitu Spring	OROMIY	BALE	Nensebo	51213	72883	0
173	SP	Giorgis Spring No 1	OROMIY	BALE	Nensebo	51233	72775	0
174	SP	Giorgis Spring No 2	OROMIY	BALE	Nensebo	51235	72783	0
175	SP	Huro	OROMIY	BALE	Nensebo	51044	73307	0
176	SP	Ketena No 1 Spring	OROMIY	BALE	Nensebo	51221	72736	0
177	SP	Ketena No 3 Spring	OROMIY	BALE	Nensebo	51167	72888	0
178	SP	Korema	OROMIY	BALE	Nensebo	51224	72499	0
179	SP	Koro Doyo Spring	OROMIY	BALE	Nensebo	50648	75145	0
180	SP	Mewa	OROMIY	BALE	Nensebo	51267	73218	0
181	SP	Solena	OROMIY	BALE	Nensebo	51363	73098	0
182	SP	Werka Health Center	OROMIY	BALE	Nensebo	51191	72862	0
183	SP	Werka Town (Tebel Spring No 1)	OROMIY	BALE	Nensebo	51251	72926	0
184	SP	Werka Town (Tebel Spring No 2)	OROMIY	BALE	Nensebo	51250	72924	0
185	SP	Abakarazalo Spring No 1	OROMIY	BALE	Sinanana	59295	78784	0
186	SP	Abakarazalo Spring No 2	OROMIY	BALE	Sinanana	59294	78785	0
187	SP	Chelo Robe Meliyu	OROMIY	BALE	Sinanana	60120	78364	0
188	SP	Robe Oda Robe Meliyu	OROMIY	BALE	Sinanana	59955	78587	0
189	SP	Werabo Robe Meliyu	OROMIY	BALE	Sinanana	59969	78527	0
190	SP	1.5 Kms north-east of Arero /	OROMIY	BOREN	Arero	48185	52521	0
191	SP	2 Kms south-west of Dekole	OROMIY	BOREN	Dire	37792	47072	0
192	SP	40 Kms north-west of Mega	OROMIY	BOREN	Dire	38924	46858	0
193	SP	About 20 Kms south-west of	OROMIY	BOREN	Dire	41075	44238	0
194	SP	Yabelo-Teltele Areri	OROMIY	BOREN	Teltele	34937	53894	0
195	SP	15 Kms West of Yabelo / Gnaro	OROMIY	BOREN	Yabelo	38973	54164	0
196	SP	20 Kms South of Yabelo Deritu	OROMIY	BOREN	Yabelo	40041	52429	0
197	SP	About 60 Kms west of Yabelo /	OROMIY	BOREN	Yabelo	44836	54915	0
198	SP	Bambua Wuha SP4	OROMIY	GUJI	Bore	47496	67193	0
199	SP	Bensa (Tsebel)	OROMIY	GUJI	Bore	47233	67051	0
200	SP	Benti SP3	OROMIY	GUJI	Wadera	53377	63832	0
201	SP	Banti Bodo	SNNP	GEDEO	Kochere	42425	65725	0
202	SP	Bedessa	SNNP	GEDEO	Kochere	41857	65893	0

203	SP	Bonsho	SNNP	GEDEO	Kochere	41829	64936	0
204	SP	Bule	SNNP	GEDEO	Kochere	41877	65939	0
205	SP	Bule	SNNP	GEDEO	Kochere	41813	66004	0
206	SP	Bule	SNNP	GEDEO	Kochere	41822	65967	0
207	SP	Chelbsa	SNNP	GEDEO	Kochere	42438	65894	0
208	SP	Sakarro	SNNP	GEDEO	Kochere	42457	65705	0
209	SP	Sakarro	SNNP	GEDEO	Kochere	41797	65856	0
210	SP	Shayssa	SNNP	GEDEO	Kochere	41769	66193	0
211	SP	Shayssa	SNNP	GEDEO	Kochere	41793	66232	0
212	SP	01 kebele	SNNP	SIDAMA	Arbegon	46773	72215	0
213	SP	01 kebele	SNNP	SIDAMA	Arbegon	46843	72149	0
214	SP	01 kebele	SNNP	SIDAMA	Arbegon	46772	72226	0
215	SP	01 kebele	SNNP	SIDAMA	Arbegon	46777	72176	0
216	SP	Aalawa	SNNP	SIDAMA	Arbegon	47027	72626	0
217	SP	Ajerssa	SNNP	SIDAMA	Arbegon	47106	73094	0
218	SP	Awokiro	SNNP	SIDAMA	Arbegon	47099	72708	0
219	SP	Babo	SNNP	SIDAMA	Arbegon	47016	72548	0
220	SP	Bakito	SNNP	SIDAMA	Arbegon	47052	73168	0
221	SP	Beto eemcy comp.health.	SNNP	SIDAMA	Arbegon	47018	73540	0
222	SP	Bobilicho	SNNP	SIDAMA	Arbegon	47042	72515	0
223	SP	Borata	SNNP	SIDAMA	Arbegon	47084	72623	0
224	SP	Bukie	SNNP	SIDAMA	Arbegon	47090	72302	0
225	SP	Burchano	SNNP	SIDAMA	Arbegon	46853	73795	0
226	SP	Butura sine	SNNP	SIDAMA	Arbegon	46656	74029	0
227	SP	Chancho	SNNP	SIDAMA	Arbegon	47178	72278	0
228	SP	Deguba	SNNP	SIDAMA	Arbegon	47218	72353	0
229	SP	Demka	SNNP	SIDAMA	Arbegon	46670	72525	0
230	SP	Dentano	SNNP	SIDAMA	Arbegon	47281	72591	0
231	SP	Derasha	SNNP	SIDAMA	Arbegon	46866	74349	0
232	SP	Dillagenet	SNNP	SIDAMA	Arbegon	47070	72639	0
233	SP	Diranto	SNNP	SIDAMA	Arbegon	46422	72481	0
234	SP	Diranto	SNNP	SIDAMA	Arbegon	46416	72453	0
235	SP	Dobancho	SNNP	SIDAMA	Arbegon	47132	72816	0
236	SP	EECMY comp.	SNNP	SIDAMA	Arbegon	47173	73055	0
237	SP	Gassie	SNNP	SIDAMA	Arbegon	46414	73978	0
238	SP	Gedana 01 kebele	SNNP	SIDAMA	Arbegon	46688	72324	0
239	SP	Gerha	SNNP	SIDAMA	Arbegon	46475	74111	0
240	SP	Giranto	SNNP	SIDAMA	Arbegon	46430	72522	0
241	SP	Gobacho	SNNP	SIDAMA	Arbegon	47286	72503	0
242	SP	Golana river	SNNP	SIDAMA	Arbegon	47080	72037	0
243	SP	Golga	SNNP	SIDAMA	Arbegon	47023	73248	0
244	SP	Golga	SNNP	SIDAMA	Arbegon	47007	73246	0

245	SP	Goto	SNNP	SIDAMA	Arbegon	46885	73751	0
246	SP	Gubacho	SNNP	SIDAMA	Arbegon	46564	72714	0
247	SP	Gubacho	SNNP	SIDAMA	Arbegon	46584	72724	0
248	SP	Guderanto 01	SNNP	SIDAMA	Arbegon	46397	72630	0
249	SP	Hadero	SNNP	SIDAMA	Arbegon	46505	72489	0
250	SP	Harake	SNNP	SIDAMA	Arbegon	47123	72371	0
251	SP	Health Kella	SNNP	SIDAMA	Arbegon	46368	73948	0
252	SP	Heyo	SNNP	SIDAMA	Arbegon	47049	73539	0
253	SP	Heyo	SNNP	SIDAMA	Arbegon	46663	73948	0
254	SP	Hodamo	SNNP	SIDAMA	Arbegon	47098	73237	0
255	SP	Honcho	SNNP	SIDAMA	Arbegon	47130	73392	0
256	SP	Honcho	SNNP	SIDAMA	Arbegon	47194	73411	0
257	SP	Loke	SNNP	SIDAMA	Arbegon	46985	73617	0
258	SP	Malako	SNNP	SIDAMA	Arbegon	47195	72949	0
259	SP	Mansuro	SNNP	SIDAMA	Arbegon	46677	72536	0
260	SP	Mayka	SNNP	SIDAMA	Arbegon	46528	74087	0
261	SP	Melga	SNNP	SIDAMA	Arbegon	46483	72717	0
262	SP	Nameto	SNNP	SIDAMA	Arbegon	46863	74249	0
263	SP	Primary school	SNNP	SIDAMA	Arbegon	46367	73913	0
264	SP	Shasho	SNNP	SIDAMA	Arbegon	46812	74326	0
265	SP	Shedama	SNNP	SIDAMA	Arbegon	46962	73543	0
266	SP	Soyamo	SNNP	SIDAMA	Arbegon	46610	72608	0
267	SP	Terchicha	SNNP	SIDAMA	Arbegon	47305	72904	0
268	SP	Tulasene	SNNP	SIDAMA	Arbegon	46572	72754	0
269	SP	Urago	SNNP	SIDAMA	Arbegon	46836	73594	0
270	SP	Welaku	SNNP	SIDAMA	Arbegon	46775	73917	0
271	SP	Worancha	SNNP	SIDAMA	Arbegon	47051	72091	0
272	SP	Worancha	SNNP	SIDAMA	Arbegon	47144	71975	0
273	SP	Worancha pri. sch.	SNNP	SIDAMA	Arbegon	47131	72001	0
274	SP	Wotito	SNNP	SIDAMA	Arbegon	46382	72626	0
275	SP	Yeye kebe. 01	SNNP	SIDAMA	Arbegon	46874	74005	0
276	SP	Yeye kebe. 01	SNNP	SIDAMA	Arbegon	46814	73883	0
277	SP	Yeye kebe. 01	SNNP	SIDAMA	Arbegon	46888	73900	0
278	SP	Amello	SNNP	SIDAMA	Aroresa	49148	69904	0
279	SP	Cheffa	SNNP	SIDAMA	Aroresa	48955	70720	0
280	SP	Chiro	SNNP	SIDAMA	Aroresa	49100	70360	0
281	SP	Dikogora	SNNP	SIDAMA	Aroresa	49059	70402	0
282	SP	Fechena	SNNP	SIDAMA	Aroresa	49156	70316	0
283	SP	Fenchena	SNNP	SIDAMA	Aroresa	49079	70313	0
284	SP	Gerbicho	SNNP	SIDAMA	Aroresa	49432	69974	0
285	SP	Merkata	SNNP	SIDAMA	Aroresa	48945	70723	0
286	SP	Muremura	SNNP	SIDAMA	Aroresa	49327	68966	0

287	SP	Muyedo	SNNP	SIDAMA	Aroresa	49167	69959	0
288	SP	Nemero	SNNP	SIDAMA	Aroresa	49530	68666	0
289	SP	Sericho	SNNP	SIDAMA	Aroresa	49479	70209	0
290	SP	Suduwo	SNNP	SIDAMA	Aroresa	48983	70695	0
291	SP	Tulanto	SNNP	SIDAMA	Aroresa	49033	70321	0
292	SP	Wachota	SNNP	SIDAMA	Aroresa	49411	70064	0
293	SP	Wajito	SNNP	SIDAMA	Aroresa	49412	69982	0
294	SP	Ware	SNNP	SIDAMA	Aroresa	49406	69984	0
295	SP	Weyera	SNNP	SIDAMA	Aroresa	49403	70394	0
296	SP	Bello	SNNP	SIDAMA	Bensa	51047	72867	0
297	SP	Bensha	SNNP	SIDAMA	Bensa	47947	72242	0
298	SP	Burka	SNNP	SIDAMA	Bensa	48226	72002	0
299	SP	Chabie	SNNP	SIDAMA	Bensa	48439	71003	0
300	SP	Damilie	SNNP	SIDAMA	Bensa	48421	71856	0
301	SP	Gado	SNNP	SIDAMA	Bensa	47279	72274	0
302	SP	Gidibu	SNNP	SIDAMA	Bensa	48211	71427	0
303	SP	Godicho	SNNP	SIDAMA	Bensa	48452	72648	0
304	SP	Gomora	SNNP	SIDAMA	Bensa	47906	72176	0
305	SP	Gormora	SNNP	SIDAMA	Bensa	47958	72143	0
306	SP	Haqansa	SNNP	SIDAMA	Bensa	48221	71606	0
307	SP	Harepha	SNNP	SIDAMA	Bensa	47505	71765	0
308	SP	Heacho	SNNP	SIDAMA	Bensa	48396	71864	0
309	SP	Hodamo	SNNP	SIDAMA	Bensa	48016	72265	0
310	SP	Holo	SNNP	SIDAMA	Bensa	48416	71906	0
311	SP	Horawa	SNNP	SIDAMA	Bensa	47981	72300	0
312	SP	Kore	SNNP	SIDAMA	Bensa	51112	72634	0
313	SP	Kurmnie	SNNP	SIDAMA	Bensa	48213	71993	0
314	SP	Mirado	SNNP	SIDAMA	Bensa	48403	72002	0
315	SP	Motorie	SNNP	SIDAMA	Bensa	48353	72546	0
316	SP	Saga	SNNP	SIDAMA	Bensa	48112	71483	0
317	SP	Sasinga	SNNP	SIDAMA	Bensa	48420	71854	0
318	SP	Wania	SNNP	SIDAMA	Bensa	48368	72609	0
319	SP	Kebelanka	SNNP	SIDAMA	Hula	46314	72394	0
320	SP	Oudo	SNNP	GEDEO	Kochere	41683	65746	0
321	SP	Oudo	SNNP	GEDEO	Kochere	41744	65647	0
322	SP	Oudo sukaro	SNNP	GEDEO	Kochere	41723	65728	0

SWL- Static water level

BH- Bore hole

Sp- Spring

Dw- Dug well

Appendix 3
Geological coding

(Adopted form integrated water resource development master plan study: Geology sector)

No.	Code	Description of Geologic class
		Quaternary Volcanics and Sediments
1	Q	Undivided alluvium, eluvium and lacustrine sediments
2	Qa	Alluial deposits: gravel,sand silt and clay
3	Qe	Eluvium: Red to reddish brown sandy soil black cotton soil calcrite, minor ferricrite, silt clay
4	Qv6	Augite-olivine-phyric basalt, scoraceous-vesicular with xenoliths of mantle nodules
5	Qv5	pyroclastic surge deposits: Lapilli tuff
6	Qv4	Olivine-phyric-basalt
7	Qv3	pyrocalistic surge deposits: lapilli tuff
8	Qv2	augite-abradorite-lapilli tuff
9	Qv1	pyrcasitic surge deposits: mainly bedded fall deposits scoria, rock fragments
10	Qv	scoraceous-vesicular-oilivine-phyric basalt
		Tertiary Volcanic Sucessions
11	Nn	Nazeret Group: stratoid silics-ignimbites, tuffs, ash, rhyolites, trachye, minor basalt
12	Ntr3	Alkal trachyte flows
13	Ntr2	Alkali trachyte and basalt flows
14	Nb	Bulal Basalt flows
15	NMv	Upper basal flows
16	PNtr1	Alkali trachyte and basalt flows, rhyolitic ignimbrite, minor tuff and bassal flows
17	NMt	Teltele basalt flows
18	PNi	Ignimbrite, minore tuff and bassalt
19	PNb2	Ankaramite and minor divine-phyric basalt
20	PNb1	Lower flood basalts
21	Tsy	Hornblende-Alkali syenite, minor hornblende-nepheline syenite
		Mesozoic Sedimentary Successions
22	Ka	Amba Aradam Formation: varicoloured sandstones with inter beddding
23	Km	Mustahil Formation: limestones inerbedded with shales and marls
24	Kg2	dominantly gypsum and anhydraites with beds of limestones, shales, marl and iron carbonate rock
25	Kg1	Korahe Formation: Lower unit dominantly sandstones with bes of dolomites, limestones marl, shale, gypsum and anhydrites
26	Jg	Gabredarre Formation: micritic to microcrysaline and oolitic limestones

27	Jh2	Hamanlei Formation: micritic locally oolitic (grainstone) peletic limestones
28	Jh1	Hamanlei Formation: less fossiliferous limestones with beds of calcareous sandstone
29	Ja	Adigrat formation: variegated quatzos sanstones, intercalations of siltstones, shales and intrafomational conglomerates
Precambrean- Early paleozoic Basement Cmplexes		
30	pcgt2	Blotite and homblende granites
31	pcdt	Meta-quartz diorite plutonic bodies
32	pcgb1	Metagabbro
33	pcgd	Metagranodiorite
34	pcgt1	Biotite metagranite
35	pcdt2	Quartz metadiorite
36	pcdt1	Melka Guga diorite gneiss
Mafic-Ultramafic-Volcano-Sedimentary Assemblages		
37	pckb	Kajimiti Beds: Metasandstone and metaconglomerate
38	pcsc3	Metasediments: philite, metasiltstone melasandstone,micaschists, quartz-graphite-muscovite, kyanite-muscovit schists
39	pcsc2	Metavolcanics: Amhibotite and plagioclase-chlorite-actinitit schist
40	pcsc1	Subvolcanic amphibolite
41	pcum2	Metaomblendite
42	pcgb2	metagabbro
43	pcum4	Talc, tremolite-Chiorite-talc, chlorite, chlorite-actindite and actinolite schists
44	pcum3	Serpentinite
45	pcum1	Undeferentiated metaltramafics
Gneissic and Migmataitic Complexes		
46	pcgn11	Quartz-graphite schist,minor marble and quartz-sericite schist
47	pcgn10	Biotite-microline-quartz and gamet-staurolite -gneises and amphibolite
48	pcgn9	Biotite-quartz - oligoiase gneiss, amphibolite and digoclase-quartz-microcline gneiss
49	pcgn8	strongly migmatized-bioite-quartz-felspar gneiss(paragneisses)
50	pcgn7	Oligoclase-hornblende-biotite-quartz, biotite-hornblende, biotite and calcsilicate
51	pcgn6	Quartzofeldspathic gneiss, minor biotitie-feldspar-quartz gneiss and biotite granite pods
52	pcgn5	Magetite-quartzofeldspathic gneiss
53	pcgn4	wadera mylonite and mylonitic gneiss
54	pcgn3	Hornblende-biotite-quartz-feldspar and biotite-quartz-feldspar gneisses
55	pcgn2	Biotite-hornblende gneiss
56	pcgn1	Granulite-quartzofeldspathic gneiss

Appendix 4
Mat lab Code for filling missing rainfall data

(Using inverse distance method)

```
clear
clc
dims(:,:,1)=load('Abissa.dat');
dims(:,:,2)=load('Agafara.dat');
dims(:,:,3)=load('Aleta Wendo.dat');
dims(:,:,4)=load('Amaro Kello.dat');
dims(:,:,5)=load('Arsi Negele.dat');
dims(:,:,6)=load('Asahara.dat');
dims(:,:,7)=load('Berra.dat');
dims(:,:,8)=load('Bidere.dat');
dims(:,:,9)=load('Bulbula.dat');
dims(:,:,10)=load('Bulle.dat');
dims(:,:,11)=load('Dadime.dat');
dims(:,:,12)=load('Dello Mena.dat');
dims(:,:,13)=load('Delo Sebro.dat');
dims(:,:,14)=load('Dilla.dat');
dims(:,:,15)=load('Edo_Dodola.dat');
dims(:,:,16)=load('Filtu2.dat');
dims(:,:,17)=load('Finch Wuha.dat');
dims(:,:,18)=load('Fiseha Genet.dat');
dims(:,:,19)=load('Gedebe.dat');
dims(:,:,20)=load('Genale Donta.dat');
dims(:,:,21)=load('Gesera.dat');
dims(:,:,22)=load('Gobessa III.dat');
dims(:,:,23)=load('Indento.dat');
dims(:,:,24)=load('Kebado.dat');
dims(:,:,25)=load('Konso.dat');
dims(:,:,26)=load('Mega.dat');
dims(:,:,27)=load('Melka Odda1.dat');
dims(:,:,28)=load('Oddo Shakiso.dat');
dims(:,:,29)=load('Sofomor.dat');
dims(:,:,30)=load('Teferekella.dat');
dims(:,:,31)=load('Telamo Kentiso.dat');
dims(:,:,32)=load('Ticho.dat');
dims(:,:,33)=load('Tuka.dat');
dims(:,:,34)=load('Wadera.dat');
dims(:,:,35)=load('Yirga Chefe.dat');

format longG
n=size(dims,1);
m=size(dims,2);
q=size(dims,3);
```

```
los=0;

for j=1:n;
   for p=1:q;
%    for p=16;
    for k=1:m;
    if dims(j,k,p)==999;
%         4 is a random point for the selection of coordinate points x and
%         y
% u is coordinate of neigboring station and v is missed station
        u(:,:)=dims(4,[1,2],:);
        v=dims(4,[1,2],p);
        w=setdiff(u',v,'rows');
        nd=3;
      [Neighbors,distance] = kNearestNeighbors(w,v,nd);
%      obtaining indexes
       x=Neighbors(1,1);
       y=Neighbors(1,2);
       z=Neighbors(1,3);
%      using the layers select the layer to work on
       lx=dims(:,:,x);
       ly=dims(:,:,y);
       lz=dims(:,:,z);
%      extract index corrosponding to missing data

      [x1,x2]=ind2sub(n,find((lx(1:n,4)==dims(j,4,p))));
      [xd,xd2]=ind2sub(n,find((lx(1:n,5)==dims(j,5,p))));
      xf=intersect(x1,xd);

      [y1,y2]=ind2sub(300,find((ly(1:n,4)==dims(j,4,p))));
      [yd,yd2]=ind2sub(300,find((ly(1:n,5)==dims(j,5,p))));
      yf=intersect(y1,yd);


      [z1,z2]=ind2sub(300,find((lz(1:n,4)==dims(j,4,p))));
      [zd,zd2]=ind2sub(300,find((lz(1:n,5)==dims(j,5,p))));
      zf=intersect(z1,zd);
% looging for other neareast stations with desired record
      loop1=0;

   ys =[];
   xs =[];

      while isempty(xf)||dims(xf,k,x)==999;
          lop1=0;
         u1=dims(4,[1,2],x);
         u2=dims(4,[1,2],y);
         u3=dims(4,[1,2],z);
         v1(:,:)=dims(4,[1,2],p);
         u10=cat(1,u1,u2,u3,v1);
%        u4=union(u10,u2,'rows');
         u30(:,:)=dims(4,[1,2],:);
         w1=setdiff(u30',u10,'rows');
```

```
      while isempty(xf)||dims(xf,k,x)==999;

        v5=setdiff(w1,u10,'rows');

        [Neighbors(1,1),distance(1,1)] = kNearestNeighbors(v5,v1,1);
        x=Neighbors(1,1);
       u100=u30';
%         lx=v5(x,[1,2])==u100(:,:);

        [xs1,xs2]=ind2sub(300,find(u100(1:size(u100),1)==v5(x,1)));
        [xc,xc2]=ind2sub(300,find(u100(1:size(u100),2)==v5(x,2)));
        xs=intersect(xs1,xc);
        lx=dims(:,:,xs);

        [x1,x2]=ind2sub(300,find((lx(1:n,4)==dims(j,4,p))));
        [xd,xd2]=ind2sub(300,find((lx(1:n,5)==dims(j,5,p))));
%       [xe,xde2]=ind2sub(300,find((lx(1:n,[1,2])==dims(4,[1,2],:))));

      xf=intersect(x1,xd);
      u10=cat(1,u10,dims(4,[1,2],xs));
     x=xs;
      lop1= lop1+1;
%       u4=union(u4,(dims(4,[1,2],x)),'rows');
      if lop1==(q-5),break,end
      end
      loop1= loop1+1;
      if loop1==1,break,end
      end




       lop2=0;

      while isempty(yf)||dims(yf,k,y)==999;

          loop2=0;
         u4=dims(4,[1,2],x);
         u5=dims(4,[1,2],y);
         u6=dims(4,[1,2],z);
         v2(:,:)=dims(4,[1,2],p);
%        xxs=dims(4,[1,2],xs);
         if isempty (xs)
     u11=cat(1,u4,u5,u6,v2);
         else
    u11=cat(1,u4,u5,u6,v2,dims(4,[1,2],xs));
        end
%          u11=cat(1,u4,u5,u6,v2,dims(4,[1,2],xf));
         u31(:,:)=dims(4,[1,2],:);
         w2=setdiff(u31',u11,'rows');
%        v2(:,:)=dims(4,[1,2],p);
```

```
      while isempty(yf)||dims(yf,k,y)==999;

        v3=setdiff(w2,u11,'rows');

        [Neighbors(1,2),distance(1,2)] = kNearestNeighbors(v3,v2,1);
        Y=Neighbors(1,2);
%         ly=dims(:,:,y);

        u101=u31';

        [Ys1,Ys2]=ind2sub(300,find(u101(1:size(u101),1)==v3(Y,1)));
        [Yc,Yc2]=ind2sub(300,find(u101(1:size(u101),2)==v3(Y,2)));

        ys=intersect(Ys1,Yc);
        ly=dims(:,:,ys);

      y=ys;
          [y1,y2]=ind2sub(300,find((ly(1:n,4)==dims(j,4,p))));
          [yd,yd2]=ind2sub(300,find((ly(1:n,5)==dims(j,5,p))));
          yf=intersect(y1,yd);

        loop2= loop2+1;
         u11=cat(1,u11,(dims(4,[1,2],ys)));
        if loop2==(q-5),break,end

      end
      lop2= lop2+1;
      if lop2==1,break,end
      end



       lop3=0;
     while isempty(zf)||dims(zf,k,z)==999;
           loop3=0;

         u7=dims(4,[1,2],x);
         u8=dims(4,[1,2],y);
         u9=dims(4,[1,2],z);
         v4(:,:)=dims(4,[1,2],p);

         if isempty(ys) && isempty (xs);
             u12=cat(1,u7,u8,u9,v4);
         elseif isempty (ys);
             u12=cat(1,u7,u8,u9,v4,dims(4,[1,2],xs));
         elseif isempty(xs);
             u12=cat(1,u7,u8,u9,v4,dims(4,[1,2],ys));
         elseif   ~isempty(ys) && ~isempty (xs);
             u12=cat(1,u7,u8,u9,v4,dims(4,[1,2],xs),dims(4,[1,2],ys));
         end
%          u12=cat(1,u7,u8,u9,v4,dims(4,[1,2],xf),dims(4,[1,2],yf));
%          dims(4,[1,2],xs),dims(4,[1,2],Ys)
         u32(:,:)=dims(4,[1,2],:);
```

```
         w3=setdiff(u32',u12,'rows');
%          v7(:,:)=dims(4,[1,2],p);


      while isempty(zf)||dims(zf,k,z)==999;
%          u1(:,:)=dims(4,[1,2],:);
%          w3=setdiff(u1',u2,'rows');
%          v7(:,:)=dims(4,[1,2],p);
         v7=setdiff(w3,u12,'rows');

        [Neighbors(1,3),distance(1,3)] = kNearestNeighbors(v7,v4,1);
        z=Neighbors(1,3);

         u102=u32';

        [zs1,zs2]=ind2sub(300,find(u102(1:size(u102),1)==v7(z,1)));
        [zc,zc2]=ind2sub(300,find(u102(1:size(u102),2)==v7(z,2)));

        zs=intersect(zs1,zc);

        lz=dims(:,:,zs);

          [z1,z2]=ind2sub(300,find((lz(1:n,4)==dims(j,4,p))));
          [zd,zd2]=ind2sub(300,find((lz(1:n,5)==dims(j,5,p))));
          zf=intersect(z1,zd);
          u12=cat(1,u12,dims(4,[1,2],zs));
           z=zs;
     loop3= loop3+1;
%      u12=union(u12,(dims(4,[1,2],zs)),'rows');
     if loop3==(q-5),break,end

      end
      lop3= lop3+1;
      if lop3==1,break,end
     end


%      Calculation by linear inverse distance for the respective conditions
                         if isempty(xf)&&(~isempty(zf)&&~isempty(yf));
                                 if(((dims(zf,k,z)==999 || dims(yf,k,y)==999)));
                                                 if dims(zf,k,z)==999
                                                    dims(j,k,p)=dims(yf,k,y);
                                                 elseif dims(yf,k,y)==999
                                                    dims(j,k,p)=dims(zf,k,z);
                                                 end
                                 elseif(((dims(zf,k,z)==999 && dims(yf,k,y)==999)));
                                     dims(j,k,p)=999;
                                 elseif(((dims(zf,k,z)~=999 && dims(yf,k,y)~=999)));

dims(j,k,p)=1/(1/distance(1,2)+1/distance(1,3))*((dims(zf,k,z)/distance(1,3)) +
(dims(yf,k,y)/distance(1,2)));
                                 end
                         elseif isempty(yf)&&(~isempty(zf)&&~isempty(xf));
```

```
                                 if(((dims(xf,k,x)==999 || dims(zf,k,z)==999)));
                                                  if dims(xf,k,x)==999
                                                     dims(j,k,p)=dims(zf,k,z);
                                                  elseif dims(zf,k,z)==999
                                                     dims(j,k,p)=dims(xf,k,x);
                                                  end
                                 elseif(((dims(xf,k,x)==999 && dims(zf,k,z)==999)))
                                     dims(j,k,p)=999;
                                 elseif(((dims(xf,k,x)~=999 && dims(zf,k,z)~=999)));

dims(j,k,p)=1/(1/distance(1,3)+1/distance(1,1))*((dims(xf,k,x)/distance(1,1)) +
(dims(zf,k,z)/distance(1,3)));
                                 end
                         elseif isempty(zf)&&(~isempty(xf)&&~isempty(yf));
                                 if(((dims(xf,k,x)==999 || dims(yf,k,y)==999)));
                                                  if dims(xf,k,x)==999
                                                     dims(j,k,p)=dims(yf,k,y);
                                                  elseif dims(yf,k,y)==999
                                                     dims(j,k,p)=dims(xf,k,x);
                                                  end
                                 elseif(((dims(xf,k,x)==999 && dims(yf,k,y)==999)));
                                     dims(j,k,p)=999;
                                 elseif(((dims(xf,k,x)~=999 && dims(yf,k,y)~=999)));

dims(j,k,p)=1/(1/distance(1,2)+1/distance(1,1))*((dims(xf,k,x)/distance(1,1)) +
(dims(yf,k,y)/distance(1,2)));
                                 end
                         elseif ((isempty(xf) && isempty(zf))&& isempty(yf));
                             dims(j,k,p)=999;
                         elseif ((isempty(xf) && isempty(zf))||(isempty(xf) &&
isempty(yf))||(isempty(zf) && isempty(yf)));
                             if(isempty(xf) && isempty(zf));
                                 dims(j,k,p)=dims(yf,k,y);
                             elseif (isempty(xf) && isempty(yf));
                                 dims(j,k,p)=dims(zf,k,z);
                             else
                                 dims(j,k,p)=dims(xf,k,x);
                             end
                         else
                                     if dims(zf,k,z)==999 && (dims(xf,k,x)~=999 &&
dims(yf,k,y)~=999)

dims(j,k,p)=1/(1/distance(1,1)+1/distance(1,2))*((dims(xf,k,x)/distance(1,1)) +
(dims(yf,k,y)/distance(1,2)));

                                     elseif dims(xf,k,x)==999 && (dims(zf,k,z)~=999 &&
dims(yf,k,y)~=999)

dims(j,k,p)=1/(1/distance(1,2)+1/distance(1,3))*((dims(yf,k,y)/distance(1,2))+
(dims(zf,k,z)/distance(1,3)));

                                     elseif dims(yf,k,y)==999 && (dims(zf,k,z)~=999 &&
dims(xf,k,x)~=999)
```

```
dims(j,k,p)=1/(1/distance(1,1)+1/distance(1,3))*((dims(xf,k,x)/distance(1,1))
+(dims(zf,k,z)/distance(1,3)));

                                    elseif (dims(zf,k,z)==999 &&
dims(xf,k,x)==999)||(dims(zf,k,z)==999 && dims(yf,k,y)==999)||(dims(yf,k,y)==999 &&
dims(xf,k,x)==999)
                                         dims(j,k,p)=((dims(xf,k,x)+dims(yf,k,y)+dims(zf,k,z))-
(2*999));
                                    elseif dims(zf,k,z)~=999 && (dims(xf,k,x)~=999 &&
dims(yf,k,y)~=999)

dims(j,k,p)=1/(1/distance(1,1)+1/distance(1,2)+1/distance(1,3))*((dims(xf,k,x)/distance(1,1))+(di
ms(yf,k,y)/distance(1,2)) +(dims(zf,k,z)/distance(1,3)));
                                    else

dims(j,k,p)=1/(1/distance(1,1)+1/distance(1,2)+1/distance(1,3))*((dims(xf,k,x)/distance(1,1))+(di
ms(yf,k,y)/distance(1,2)) +(dims(zf,k,z)/distance(1,3)));
                                    end

                        end

    else
     dims(j,k,p)= dims(j,k,p);
    end
    end
    end

end
% los=los+1;
% if los==2,break,end
% end
%   store the matrix in diffrent variables
Abissa=dims(:,:,1);
Agafara=dims(:,:,2);
AletaWendo=dims(:,:,3);
AmaroKello=dims(:,:,4);
ArsiNegele=dims(:,:,5);
Asahara=dims(:,:,6);
Berra=dims(:,:,7);
Bidere=dims(:,:,8);
Bulbula=dims(:,:,9);
Bulle=dims(:,:,10);
Dadime=dims(:,:,11);
DelloMena=dims(:,:,12);
DeloSebro=dims(:,:,13);
Dilla=dims(:,:,14);
Edo_Dodola=dims(:,:,15);
Filtu=dims(:,:,16);
FinchWuha=dims(:,:,17);
FisehaGenet=dims(:,:,18);
Gedebe=dims(:,:,19);
GenaleDonta=dims(:,:,20);
```

```
Gesera=dims(:,:,21);
GobessaIII=dims(:,:,22);
Indento=dims(:,:,23);
Kebado=dims(:,:,24);
Konso=dims(:,:,25);
Mega=dims(:,:,26);
MelkaOdda=dims(:,:,27);
OddoShakiso=dims(:,:,28);
Sofomor=dims(:,:,29);
Teferekella=dims(:,:,30);
TelamoKentiso=dims(:,:,31);
Ticho=dims(:,:,32);
Tuka=dims(:,:,33);
Wadera=dims(:,:,34);
YirgaChefe=dims(:,:,35);

%    save data in separate sheet

   save Abissa1.dat Abissa -ascii
   save Agafara1.dat Agafara -ascii
   save AletaWendo1.dat AletaWendo -ascii
   save AmaroKello1.dat AmaroKello -ascii
   save ArsiNegele1.dat ArsiNegele -ascii
   save Asahara1.dat Asahara -ascii
   save Berra1.dat Berra -ascii
   save Bidere1.dat Bidere -ascii
   save Bulbula1.dat Bulbula -ascii
   save Bulle1.dat Bulle -ascii
   save Dadime1.dat Dadime -ascii
   save DelloMena1.dat DelloMena -ascii
   save DeloSebro1.dat DeloSebro -ascii
   save Dilla1.dat Dilla -ascii
   save Edo_Dodola1.dat Edo_Dodola -ascii
   save Filtu1.dat Filtu -ascii
   save FinchWuha1.dat FinchWuha -ascii
   save FisehaGenet1.dat FisehaGenet -ascii
   save Gedebe1.dat Gedebe -ascii
   save GenaleDonta1.dat GenaleDonta -ascii
   save Gesera1.dat Gesera -ascii
   save GobessaIII1.dat GobessaIII -ascii
   save Indento1.dat Indento -ascii
   save Kebado1.dat Kebado -ascii
   save Konso1.dat Konso -ascii
   save Mega1.dat Mega -ascii
   save MelkaOdda11.dat MelkaOdda -ascii
   save OddoShakiso1.dat OddoShakiso -ascii
   save Sofomor1.dat Sofomor -ascii
   save Teferekella1.dat Teferekella -ascii
   save TelamoKentiso1.dat TelamoKentiso -ascii
   save Ticho1.dat Ticho -ascii
   save Tuka1.dat Tuka -ascii
   save Wadera1.dat Wadera -ascii
   save YirgaChefe1.dat YirgaChefe -ascii
```