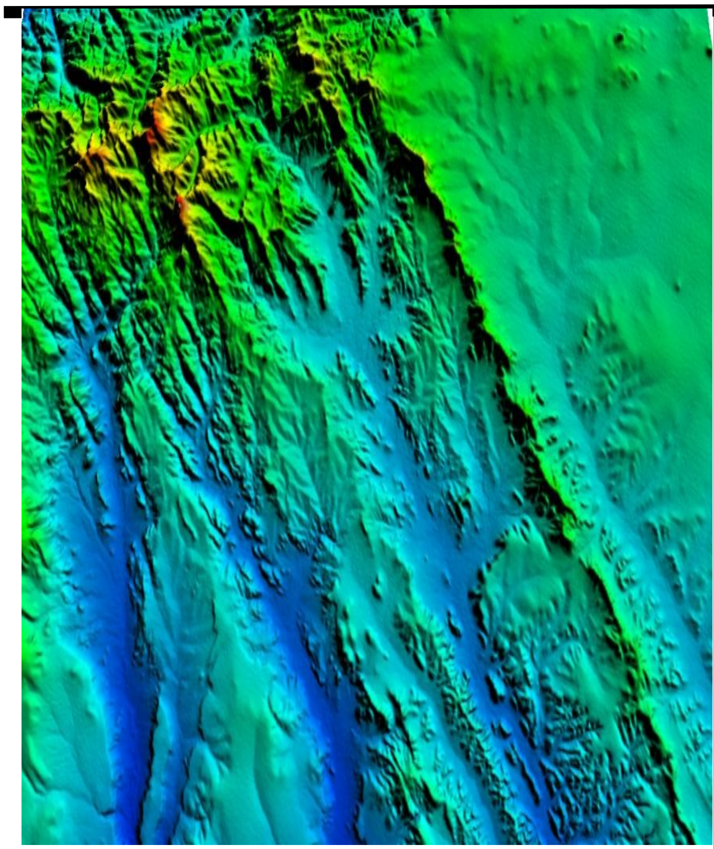
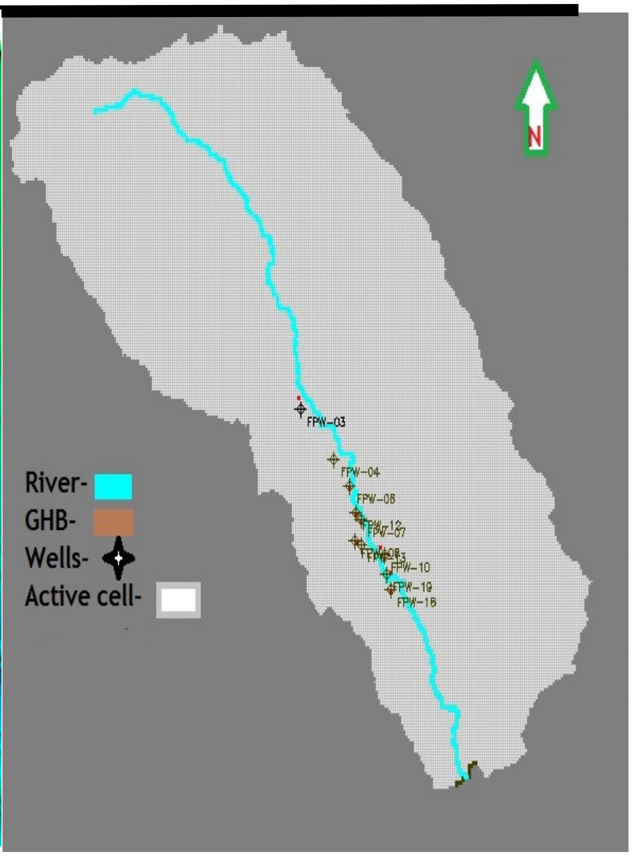
Groundwater Flow Modeling of Upper Fafan Sub Basin For Managed Groundwater System

Sintayehu Mulu

A Thesis Submitted to the
School of Earth Sciences





Advisor Prof. Tenalem Ayenew

Presented in Partial Fulfillment of the Requirements
for the Master of Science (Hydrogeology)

Addis Ababa University

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STATEMENT OF THE AUTHOR

By my signature below, I state and confirm that this thesis is my own work. I have followed all ethical and technical principles of research in the data preparation, collection, analysis and compilation of this thesis. Any scholarly matter that is included in the thesis has been given acknowledgment through reference.

Sintayehu Mulu Signature: ------------------------

Date: June, 2017

SIGNATURE OF APPROVAL

Addis Ababa University

School of Graduate Studies

This is to certify that the thesis prepared by **Sintayehu Mulu**, entitled: Groundwater Flow Modeling of Upper Fafan Sub Basin for Managed Groundwater System and submitted in partial fulfillment of the requirements for the Degree of Master of Science (Hydrogeology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Committee:

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ABSTRACT

Upper Fafan River valley is a sub catchment of Fafan drainage basin with an approximate surface area of around 1380km^2, boundary length of 255.58km and it lies at the northwester edge of the Ogaden basin. The Fafan town and other smaller village are found in this catchment. The catchment is covered with Mesozoic and Precambrian rocks of various ages that correspond to different stratigraphic units. The rocks were subjected to rift tectonics that is manifested by a number of fault systems having a general trend of the rift system (NW – SE). In this study, local groundwater flow model was established. The major purpose of this study was to determine the groundwater elevations decline of the sub basin using a numerical model under different groundwater abstraction. The Model was run as three dimensional (3D) and steady-state conditions by considering unconfined aquifer. The model inputs were obtained from field work results and from the previous works done in the area. The horizontal hydraulic conductivity from 0.5 m/day to 40 m/day and groundwater recharge 27mm/year, which constitute the key model parameters were considered as calibration parameters. The SWAT model was used to calculate the recharge rate for the zone representing the Upper Fafan River sub basin. The measured water table elevations in average 5m from the surface were used as targets in the calibration and verification of the model. The model was run for 2 pumping scenarios and 12 sensitivity analysis conditions; the model is found to be highly sensitive for hydraulic conductivity parameter. Groundwater elevation and flow direction maps were produced based on modeling results. Model calibration was carried out by trial and error calibration method using groundwater contours constructed from heads collected in 10 observation points. The calibration showed that about 98.9% of simulated heads were within the calibration target and the overall RMSE for simulated hydraulic heads is about 8.42m. Model sensitivity analysis was conducted by taking hydraulic conductivity and river leakage as the model is most sensitive to them. A change in hydraulic conductivity -50%, -75%, 50% and 75% resulted in RMS head changes from the calibrated value by 380.68%, 40.55%, 21.78% and 26.13% respectively. Identical changes in recharge and river leakage (in the order mentioned for hydraulic conductivity recharge) resulted in RMS head changes from calibrated value by 0.34%, 0.51%, 0.18% and 0.36%, for the river package 15.61%, 20.77%, 86.21% and 35.51% respectively. The results of the numerical simulations showed that increased well withdrawals by 50% and 100% resulted in RMS head changes of 6cm, and 10cm, respectively. Water budget results of the model revealed that groundwater recharge comprised 0.2% and 99.8% by river leakage of the total water input for the entire study area. The spatial distribution of the groundwater decline was limited towards the river. Furthermore, it can be noted that there is a hydraulic connection between the alluvial valley aquifer and the Fafan river.

Key Words: Calibration, Ethiopia, Modeling, Unconfined Alluvial Aquifer, Upper Fafan (Ethiopian-Somali)

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ABBREVIATION

DD	Drawdown
DEM	Digital Elevation Model
DWL	Dynamic Water Level
EAO	East African Orogen
EIGS	Ethiopian Institute of Geological Survey
ETa	Actual Evapotranspiration (mm)
ETo	Potential Evapotranspiration(mm)
GIS	Geographic Information System
GPS	Global Positioning System
Hm	Measured head
Hs	Simulated head
MER	Main Ethiopian Rift
m.a.s.l	Meter above sea level
MAE	Mean absolute error
ME	Mean error
MCM	Million Cubic Meters
RMSE	Root mean square error
SWAT	Soil Water Assessment Tool
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topographic Mission
SWL	Static Water Level
U.S.G.S	United State Geological Survey

CHAPTER ONE

INTRODUCTION

1.1 Background

Groundwater is among the peak valued natural resources, which sustenance human welfare, facilities development, and equilibrates the natural environment. In line for the number of indispensable qualities (e.g., steady temperature, wide and persistent accessibility, exceptional natural quality, limited susceptibility for pollution, low development cost, drought reliability), it turns out to be significant and trustworthy source of water supplies in all over the weather regions including both municipal and country side areas of urbanized and unindustrialized countries (Todd, 2005). Approaches for doable growth and integrated groundwater treasure management must be developed and instigated to pledge the right use of the limited water wealth for the upcoming children. Groundwater reserve management of an aquifer scheme encompasses developing a measureable sensitive of the flow behaviors that function inside the aquifer. Three key futures that must be give high consideration: how water comes into the aquifer scheme; how water travel through the water bearing zones and how water flow out of the aquifer. The paramount device accessible to support groundwater hydrologists to articulate theoretically complete ground water wealth administration is usually a groundwater flow model. Groundwater models have been practice as explanation device for scrutinizing groundwater system dynamics, calculation tools for weighing recharge and computation of viable yield (Anderson and Woessner, 1992).

In water management, models have turn out to be a key tool of the modern globe. They are fulfilling the essential works of water management, used broadly and show a significant assisting job, in strategy preparation, operative water management and research, and in the assembly of fundamental data (monitoring), among other things. In a groundwater system, management resolutions possibly will be associated to amounts and locality of pumping boreholes, changes in water quality, place and proportions of pumping in extravagance operations, etc. Management's objective function should be to appraise the time and price necessary to attain remediation targets. Management decisions are aimed at reducing the charge while take full enhancement of the paybacks to be deduced from operative system. In the administration of a ground-water system in which resolutions must be prepared with respect to water quality and water quantity, a device is needed to deliver facts about the future response of the system to the effects of management decisions. Depending on the nature of the supervision problem, decision variables, objective functions, and limitations, the response may take the form of future areal distributions of contaminant concentrations, water levels, etc. This is the work of a model.

The groundwater intensifies crop harvests and quality in semi-arid zones like Fafan, Eastern Part of Ethiopian Somali Region. It is crucial especially during periods of inconsistent rain fall and scarcity. From the time when there is a no surface water flow, the main sources for irrigation, industrial and municipal in the study area are groundwater. The groundwater productivity has to be enhanced as much as possible. The investigated area mainly focuses on the Upper sub-basin of Fafan valley located in Eastern Ethiopia. This sub-basin has a high groundwater prospective and also recognized by having little or no rainfall. As of low and inconsistent annual rainfall, groundwater is used to overcome draught problem in the area but there is low attention given to groundwater resource management.

As perceived from the field work stopover, history of wells is not recorded properly, no surface water gauging stations over the area and along the main rivers and no weather stations. However, for regularity of groundwater resource, there should be safe abstraction and proper management. In this thesis, numerical groundwater flow modelling of upper Fafan Sub basin using MODFLOW-version 8 for steady state situation has given greater priority. Therefore, clear understanding of the response of the aquifer is vital for better management of groundwater resources.

1.2 Modeling Groundwater Flow

“A groundwater model may be defined as a simplified version of the real groundwater system that approximately simulates the excitation- response relations of the groundwater system. The real system is very complicated and difficult to use it directly for the purpose of planning and making management decisions. The simplification is introduced in the form of a set of assumptions that express our understanding of the nature of the system and its behavior. These assumptions will tend to smooth out the effect of various heterogeneities. Because the model is a simplified version of the real system, there exists no unique model for a given groundwater system" (Bear, 1979). According to Anderson and Woessner, 1992, there are numerous ways to group groundwater flow models, models can be transient or steady state and one, two, or three spatial dimensions. Steady state flow occurs when at any point in a flow field the scale and direction of the flow are independent with time.

Examples of potential model applications include:

- Design and/or evaluation of pump-and-treat systems and hydraulic containment systems
- Evaluation of physical containment systems (e.g., slurry walls)
- Analysis of "no action" alternatives
- Evaluation of past migration patterns of contaminants and assessment of attenuation/transformation processes
- Evaluation of the impact of non-aqueous phase liquids (NAPL) on remediation activities (dissolution studies)

1.3 Types of Groundwater Models

1.3.1 Conceptual Model

- ❖ The assumptions that constitute a conceptual model should relate to such items as:
- ❖ The dimension of the boundaries of the inspected aquifer province;
- ❖ The kind of solid matrix comprising the aquifer;
- ❖ The kind of flow in the aquifer (e.g., 1D, 2D horizontal, or 3D);
- ❖ The flow system (laminar or non-laminar);
- ❖ The properties of the water (with reference to its homogeneity, compressibility, effect of dissolved solids and/or temperature on density and viscosity, etc.);
- ❖ The presence of assumed sharp fluid-fluid boundaries, such as a phreatic surface;

- The relevant state variables and the area, or volume over which the averages of such variables are taken;
- Sources and sinks of water and of relevant contaminants, within the domain and on its boundaries;
- Initial conditions within the considered domain; and
- The conditions on the boundaries of the considered domain that express the interactions with its surrounding environment.

1.3.1 Analytical Models

During the early phase of a ground-water contamination study, analytical models offer an inexpensive way to evaluate the physical characteristics of a ground-water system. Such models enable investigators to conduct a rapid preliminary analysis of ground-water contamination and to perform sensitivity analysis. A number of simplifying assumptions regarding the ground-water system are necessary to obtain an analytical solution. Although these assumptions do not necessarily dictate that analytical models cannot be used in “real-life” situations, they do require sound professional judgment and experience in their application to field situations. Nonetheless, it is also true that in many field situations few data are available; hence, complex numerical models are often of limited use. When sufficient data have been collected, however, numerical models may be used for predictive evaluation and decision assessment. This can be done during the later phase of the study. Analytical models should be viewed as a useful complement to numerical models.

1.3.2 Numerical Models

Once the conceptual model is translated into a mathematical model in the form of governing equations, with associated boundary and initial conditions, a solution can be obtained by transforming it into a numerical model and writing a computer program (code) for solving it using a digital computer. The main features of the various numerical models are:

1) The solution is sought for the numerical values of state variables only at specified points in the space and time domains defined for the problem (rather than their continuous variations in these domains).
2) The partial differential equations that represent balances of the considered extensive quantities are replaced by a set of algebraic equations (written in terms of the sought, discrete values of the state variables at the discrete points in space and time).
3) The solution is obtained for a specified set of numerical values of the various model coefficients (rather than as general relationships in terms of these coefficients).
4) Because of the large number of equations that must be solved simultaneously, a computer program is prepared.

1.4 Problem Identification

Being it is lowland area it has low rainfall therefore, due to intermittency of rainfall distribution in the area, the pastoralist often fails to fulfill the required soil moisture conditions for growing crops and cattle's. Consequently, the area was affected by drought for a long period of time. However, now a day, groundwater usage is growing persistently and gradually as a main source of water for cultivation. On the other hand, there is no mechanism for management of groundwater resources, therefore preparing groundwater model is essential.

1.5 Objectives of the Study

The central target of this research was to formulate and implement a numerical groundwater flow model for the upper Fafan River sub basin. The key purpose of the model was to pinpoint the decline of the groundwater table at different circumstance including various hydrological and hydrogeological conditions. Correspondingly, the groundwater flux was predicted using the model. The established model can also be used for a succeeding contaminant transport modeling study, where the output of the groundwater flow model is used as contribution to the transport model. A groundwater flow model of the area may also prove useful for the assessment of climate alteration influence scenarios. It is therefore an essential discoverer for any kind of Geo-hydrological study.

The overall aim of the project was threefold;

1. Identify the capture zones of the productions wells in upper Fafan
2. Use the parameter estimation technique in order to calibrate the model
3. To understand and predict the groundwater flow system in the watershed.

Question of the Research is:

- What are the influences of under different well operation circumstances on groundwater level?

1.6 Scope of the Study

The main scope of the research is to develop local groundwater flow model for the Upper Fafan sub basin in Ethiopian Somali region. The study covered of two main works; the first job was to collect necessary data, from existing databases and previous studies, and during field trips. The second mission was the preparation of conceptual and applied groundwater flow model for the watershed. Field trips were planned to determine the study area and consider promising groundwater monitoring well locations and to consequently measure groundwater levels. A geographic information system (GIS) was engaged for organizing and handling of various data and for map production and illustration of modeling outputs. After the mathematical groundwater flow model was framed up, the model was calibrated and also verified using one time measured static level data. Calibration, statistics and other marks of model performance were calculated for both the calibrated and confirmed models to accurately assess the validity of the groundwater flow model. Hydraulic head contour maps and maps showing groundwater flow directions were generated and interpreted with respect to local hydrogeology, groundwater abstractions and the groundwater flux within the sub basin. Finally, the spatial distribution of groundwater decline was determined using the developed model.

1.7 Methodology

Even though there are few hydrogeological studies conducted in the study area, the available data are enough to build numerical ground water model to asses and try to supplement the upcoming groundwater exploration and evaluation in the sub basin.

The techniques used in this research embrace paper review, field survey and data inspection using different software. Satellite image and topographic maps at a scale of 1:50,000 were logically studied. The satellite imageries were used to distinguish the geomorphological structures and plotted them on to the topographic sheet of 1:50,000 scale. The topo-sheet was used as base map to mark the litho-hydrogeoloical contacts and trends.

Hydrogeological investigation was concentrated more on differentiating the rock units of groundwater significance and in collecting hydrogeological information, i.e., locating of water points, collection of water samples, and measurement of discharge of wells. For defining the productivity of the water bearing formations within the catchment; constant pumping test data from ten boreholes drilled through the alluvial up to weathered basement aquifer were used. In the sub basin, due to the absence of the piezometer, the evaluation has been performed for constant rate pumping test by using the pumping test borehole data. The drawdown data of all boreholes have been analyzed using Theis method.

The basic methodology for the groundwater flow modeling of upper Fafan sub basin uses and follow the conventional work flow of the modeling protocol which is shown in the figure 1.1. In order to accomplish the objectives of the research project, the followings methods and materials were used:

- Review of inventory of wells in the watersheds
- Water level collection
- Construction of a conceptual model to simplify field problem and organize field data so as to analyze the system so readily.
- Groundwater flow modeling software, MODFLOW 1996 (McDonald and Harbaugh, 1988 as developed by USGS) was used to simulate numerical groundwater flow system in the area under study.
- Comparison of simulated head water level obtained in the field during model calibration.

1.8 Limitations

The study was only aimed to identify capture area and flow pattern for which the flow conditions were unchanged from today. The model was spatially limited to the upper part of the watershed where no data is available and the aquifer was simulated with steady state hydraulic conditions. No prior information was supplied for the parameters and no flow observations were used in the parameter estimation process.

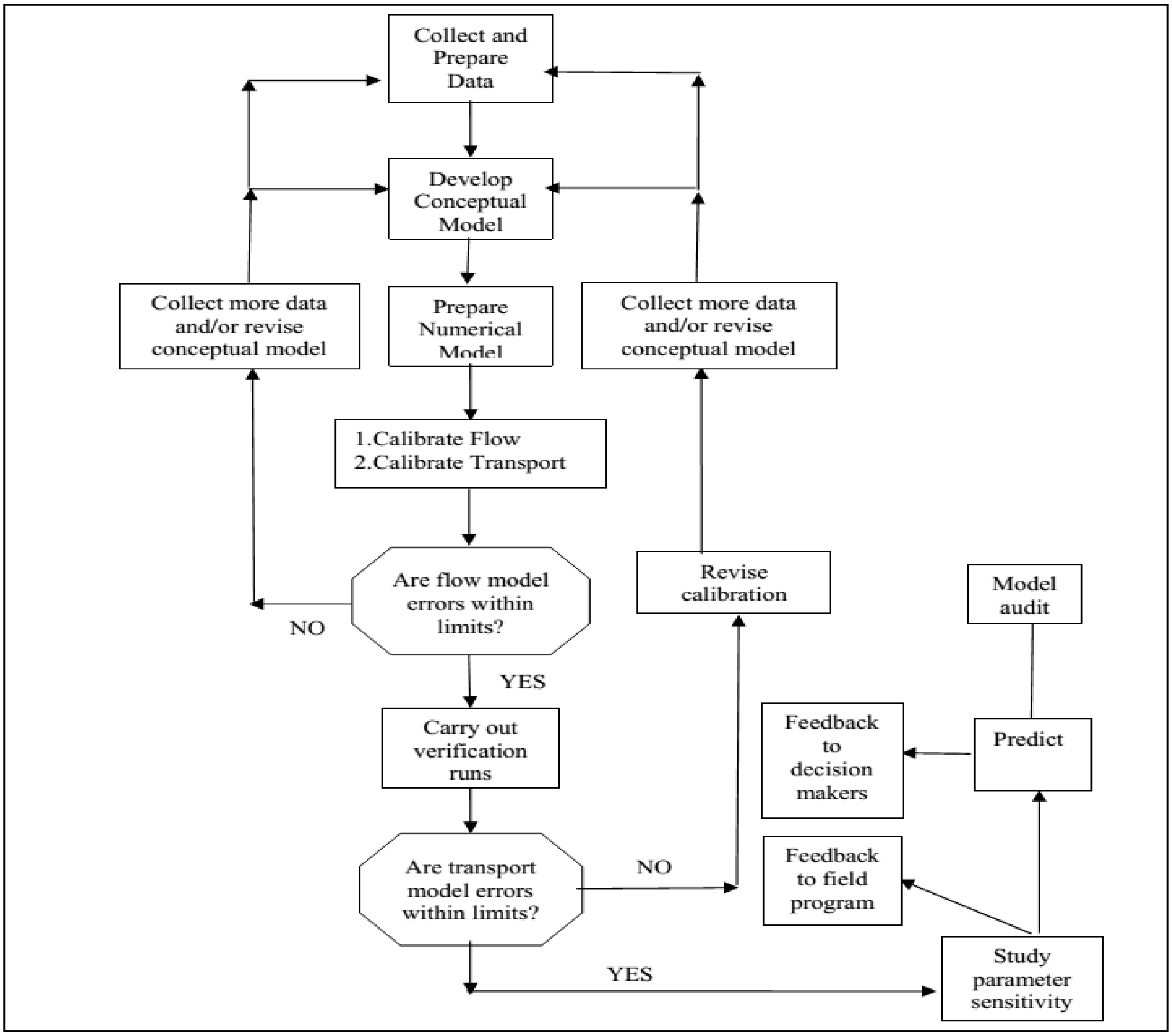


Figure 1.1 The Groundwater Flow Modeling Protocol (Adopted from Anderson & Woessner, 1990)

CHAPTER TWO

LITERATURE REVIEW

There are so many groundwater modeling works done in previous time and to mention and review some of them; Ayenew, Demlie & Wohnlich (2007) conducted a numerical modeling study for the groundwater system in the Akaki catchment of central Ethiopia. A 3-D steady state finite-difference groundwater flow model was developed to quantify the groundwater fluxes and analyze the subsurface hydrodynamics in the Akaki catchment by giving particular emphasis to the well field that supplies water to the city of Addis Ababa. The model was calibrated using head observations from 131 wells. The simulation was made in a two-layer unconfined aquifer with spatially variable recharge and hydraulic conductivities under well-defined boundary condition. The result indicated that the groundwater flows regionally to the south converging to the major well field.

Juckem, Hunt & Anderson (2006) provided extensive data that scale effects of hydrostratigraphy and recharge zone on base flow. This study's objective was to present a methodology for estimating a critical basin size, above which base flows appear to be relatively less sensitive to the spatial distribution of recharge and hydraulic conductivity. Influence of recharge zonation and hydrostratigraphic 17 layering on base flow was determined using MODFLOW for the Coon Creek Watershed, which is located in the Wisconsin, USA. This model was set up as three dimensional and for steady-state conditions. The results showed that there is a scale effect that influences the relative importance of recharge and hydraulic conductivity such that at some scale, the influence of spatial parameter variability on base flow diminishes and can be approximated using a simplified representation.

There are some available hydrogeological studies which can be categorized in three parts and presented as: Hydrogeological studies conducted for water supplies of major towns and villages in the area, various well completion reports and regional hydrogeological study. Most of the works done are only investigation and water supply works and they didn't adequately infer the available amount of water in the sub basin. Therefore, this thesis is going to fulfill this gap. The reviews of these reports are summaries in the next paragraphs.

Water supply source study of Jijiga, Warder and Filtu zonal administration towns; the main objective of this study was to evaluate the existing groundwater supply condition of Jijiga, Warder and Filtu towns. According to the report, the groundwater resource condition of Jijiga town was evaluated by the groundwater data mainly collected from hydrogeological and geophysical report of C. Lotti Cloti and also from Somali National Water Mines and Energy Development Bureau. For the study a total of 48 boreholes were inventoried out of which only 19 of them were relevant to assess the existing water supply condition and to estimate the hydraulic parameters and well yields. The report also stated that the hydrolithological condition of Jijiga is characterized by alluvial cover of shallow thickness with low permeability, underlain by Mesozoic sedimentary of moderate permeability and pre- Cambrian basement rocks (Granite, gneiss and Mica schist).

For convenience to the hydrogeological study of the town and its surrounding, four well fields were selected with reference to Jijiga Town; the northern well field, the central well field, the southern well field and the eastern well field. In May 2002 group and single well pumping test was conducted in 6 wells found in the four well fields. The groundwater in the surrounding of Jijiga town is generally unconfined and is controlled by fractures and weathered horizons.

SHAAC, Engineering Consulting plc also conducted Hydrogeological investigation of 19 sites in Gode, Afder, Liban Dhagahbur, Korahe, and Warder zones, SRS of Ethiopia. This report comprises of hydrogeological properties of the different formations present in all the five zones of the Somali Regional State (SRS). As per the report, even though groundwater is present at greater depth in Urandeb formation, the presence of gypsum deteriorates the quality of the groundwater. The absence of retaining impervious layer at shallower depth makes the recharging water in Jessoma sandstone, to percolate deep down to the ground until it is retained by the underlying impervious limestone or clay horizons of the upper Cretaceous formation, increasing the cost of groundwater exploitation. The report stated that the aquifer of the Jessoma sandstone is spatially varies between depths of 300 m to 450m below the surface of the earth.

In support to the hydro geological investigation about 54 Vertical Electrical Soundings (VES) were carried out. Despite the quality and quantity, the analysis shows that groundwater is generally found at greater depth; for instance, 200m to 300m depth in Auradu limestone and 450m to 500m depth in Jessoma sandstone. In Urandeb formation the quality of water becomes super saline with increasing depth even at shallower depth below 35 m the groundwater quality is highly deteriorated. A relatively fresh groundwater is only obtained at shallower depth in weathered basalt around Baareey area.

The drilling report of Hadow and Fafan (GoloAjo) boreholes account to drilling history of three boreholes; one borehole drilled 13km west of Jijiga town in the village called Hadow. The borehole was drilled to a depth of 80m, yet, because of its low yield it was left abandoned. The lithologic log deciphers that the basement is reached at 20m. The other two boreholes drilled for the Golo-Ajo cattle and sheep research center located20km north of the Fafan village. The boreholes were drilled up to a depth of 44m and 43m, where the basement starts from this depth. Step drawdown, constant and recovery tests were carried out. The constant tests were done at a discharge of 7.2l/s and 7.5l/s attaining a drawdown of 8.46 m and 16.93respectively after pumping for 24 hours. The constant test analysis by Jacob method showed that the wells have a transmissivity value of 46.3m^2/day 14.06m^2/day.

Fafan Integrated Development Project well completion report final of 4 boreholes in Kobijara. This report comprises of partly or fully completed well completion report of the four boreholes drilled in Kobijaro village located, 35km southwest of Jijiga town to a village called Fafan and then another 20km north of the Fafan valley. The lithological log obtained from the four boreholes shows that the alluvial thickness varies from 40 to 46m and the static water level depth ranges between 8.8m to 9.4m. Step drawdown, constant and recovery tests were carried out in two of the boreholes and the water level after pumping constantly for 24 hours with a discharge of 13.6l/s resulted in a drawdown of 5.82m in one of the borehole and 17.54m in the other borehole.

A total of 16 Pilot and test wells were drilled under Fafan-Jerer Sub Basins and Adjacent Eastern Areas Groundwater Potential Assessment and Supervision of Pilot and Test Wells Drilling Project. The project evaluates the groundwater resources potential by a total of 10 pilot and test wells, 3 commissioning wells and 3 test wells were drilled in Fafan valley, Jerer valley and Adjacent Easter Escarpment areas of Somali region respectively (See Annex 1).

CHAPTER THREE

GENERAL OVERVIEW OF THE STUDY AREA

3.1 Location and Accessibility

The study area is located in the Jigjiga zones of the Somali National Regional State. The Upper Fafan sub basin is situated in Eastern Ethiopia, in the Ethiopian Somali National Regional State, Jigjiga Zone, Fafan Woreda; about 40 km south west of Jigjiga town and 590 km from Addis Ababa. Jijiga town which is the capital of Somali National Regional State is situated east of Addis Ababa at about 630kms asphalt road running from Addis Ababa through Harar to Jijiga. The study area is accessed by the Addis Ababa via Harar to Jigjiga asphaltic road. The specific places inside the site can be accessed by weathered gravel roads from Fafan village towards North-West and South-East to reach Halahago and Tikedem villages respectively.

3.1.1 Geomorphology and Land Use Land Cover

Mapping regional geomorphological features and understanding their mode of formations may have a significant importance for water resources (groundwater/surface water) assessment and investigations. Geomorphic features reflect interaction of different processes such as the underlying lithologies, geologic structures, surface processes, and the geologic time required for their development. Landforms develop on various types, namely igneous rocks (extrusive and intrusive varieties with varying compositions), alluvial deposit (e.g., sand, gravel and clay), metamorphic rocks (e.g., gneisses, schists and granitites), are remarkably different. Moreover, primary and tectonic structures present in the rocks combined with surface processes such as climatic conditions, weathering, erosion, depositions, fluvial/lake actions and time span during which the processes were in operation also have impact on geomorphic features. Recognition and understanding of landforms/geomorphic features are useful to make a reasonable deduction about the processes responsible for their formation and development. The geomorphology of the study area is dominated by type of the underlying lithologies, fluvial actions, tectonic structures (faults and fractures) mainly associated with uplift of the Horn of Africa and formation of the Main Ethiopian rift and the Gulf of Aden, and volcanic landscapes. Moreover, presence of basement mounts, upper Paleozoic grabens and horsts, may also have contributed to the present geomorphic features in the study area.

3.1.2 Drainage

The major drainage system is associated with valley plains. The rivers in the valley originate from the mountains of Guressa and Funnya. The streams drain in to the Fafan valley. The Fafan valley can be classified in to seven minor watersheds namely, Hariro-Godene, GiriKoche-China Hasen, Gursum-Goro-Obele-Hilmo, Shebelle, Thikdeme, Hado, and Fafan-Halhago-Gori.

3.1.3 Physiography and Climate

Elevation in the study area varies from about 3000m amsl in the upper most catchment of sub basin to about 1380 m amsl at the lower most parts of the study area at the southeastern limit. The study area is bounded in the longitude ranges 42° 18' 18.730" E to 42° 42' 20.601"E and latitudes ranges 9° 9' 18.730" N to 9° 33' 42.879"N. Fafan river basin is extended towards NW-SE direction of about 250km length and the whole sub basin study area has an area of about 1380km^2. The mean annual rainfall and mean annual temperature vary respectively from 321mm to over 550 mm and 10°c to over 30°c.

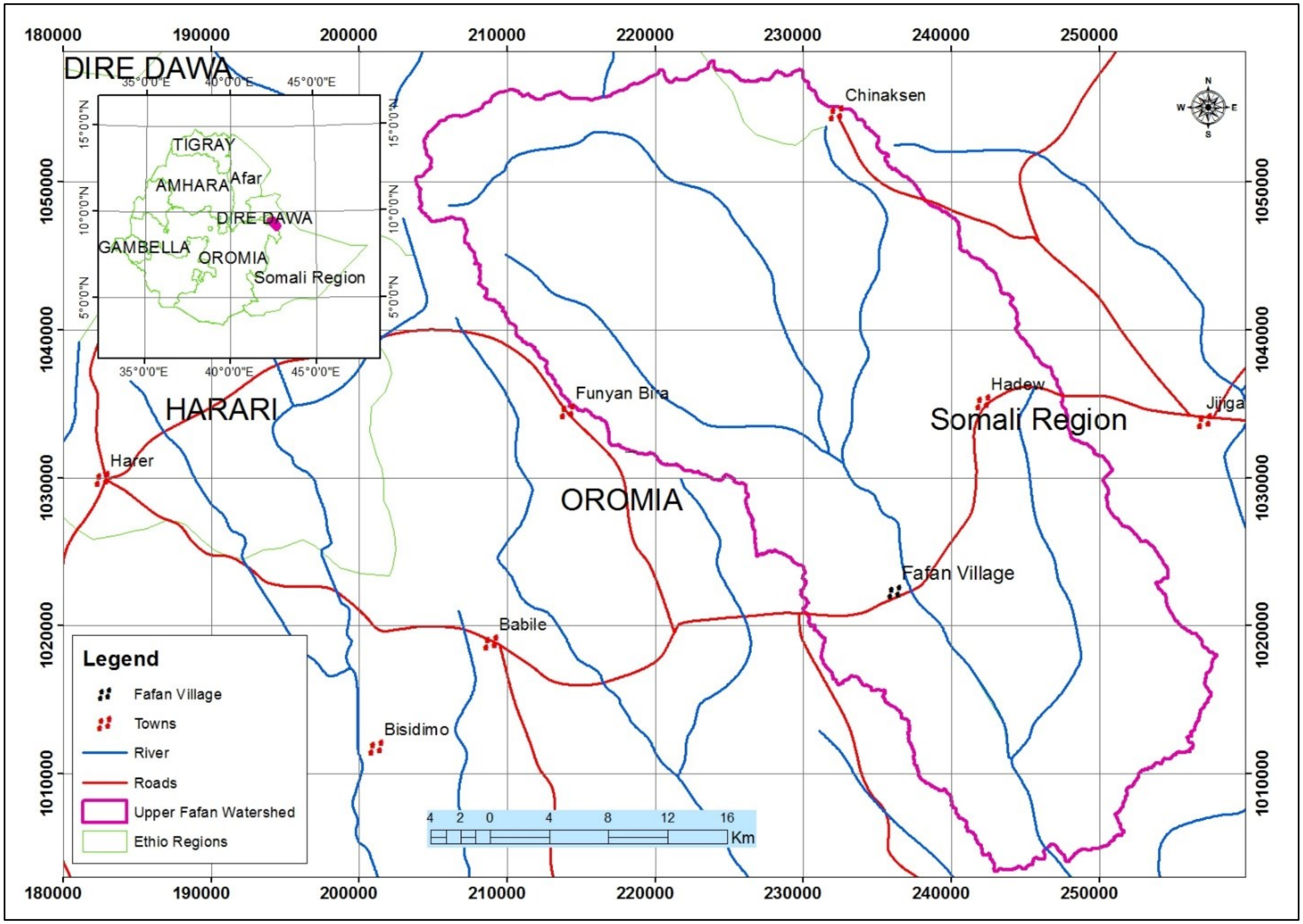


Figure 3.1 Location Map of the Study Area

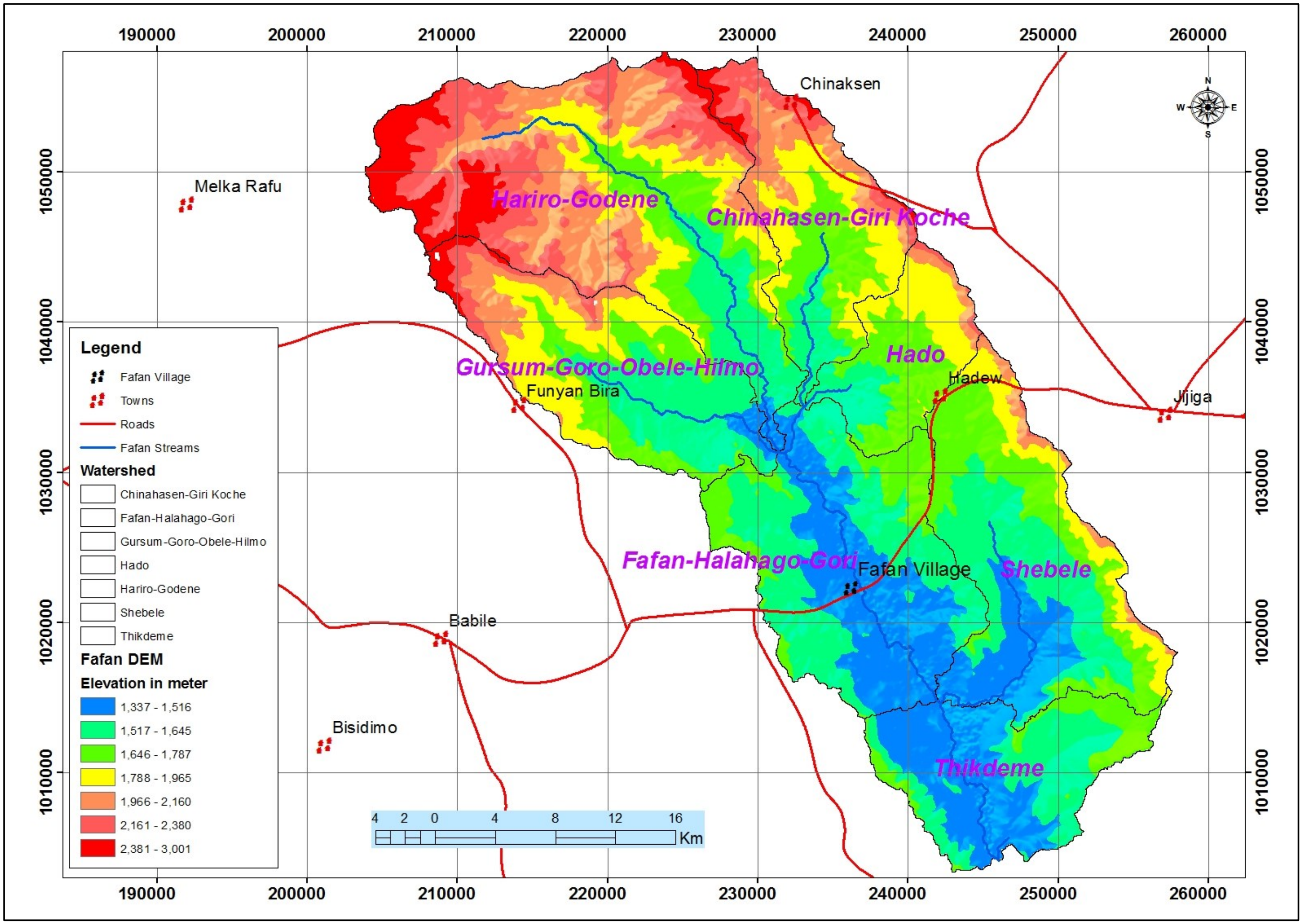


Figure 3.2 Watersheds of the study area

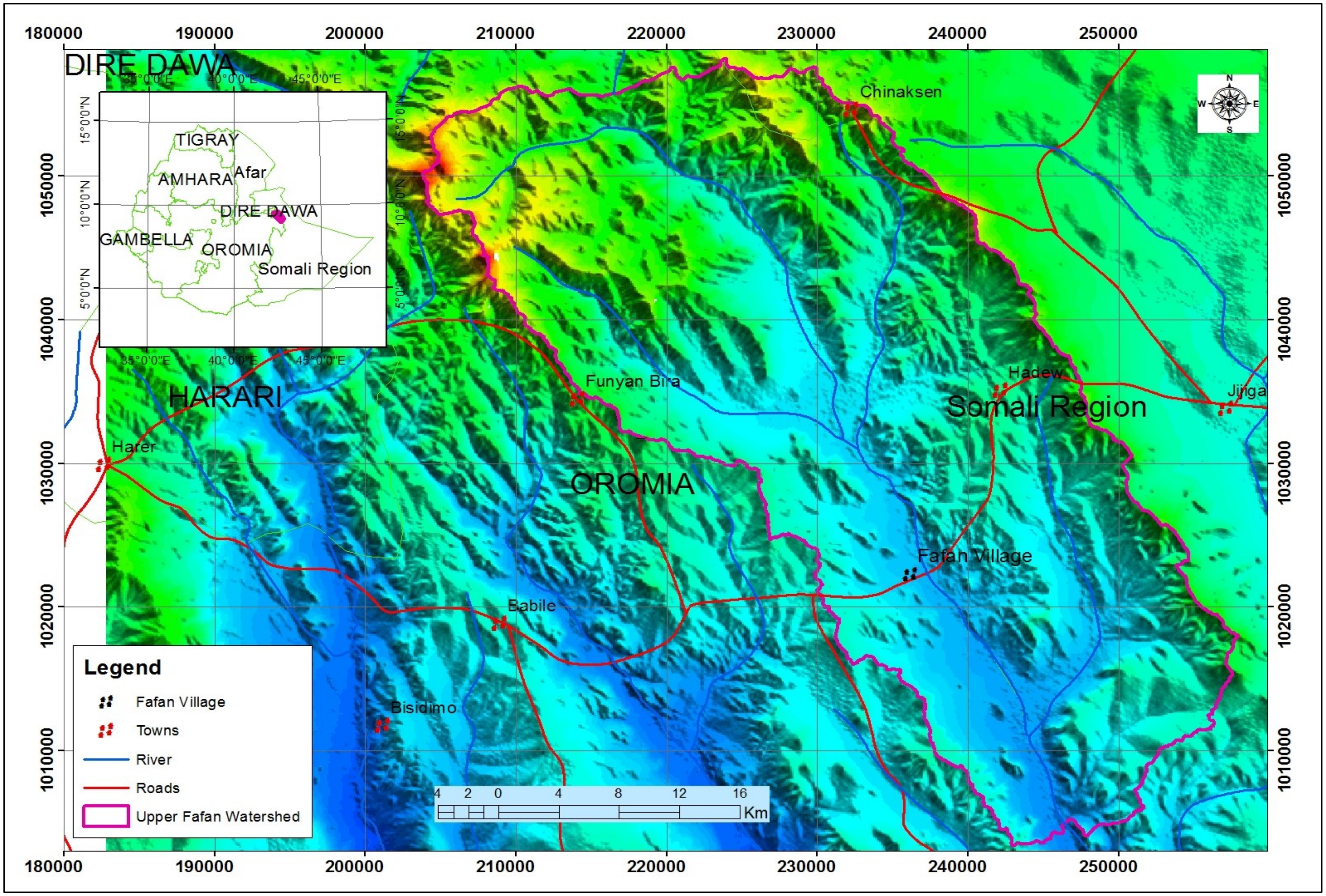


Figure 3.3 Physiography of the study Area

3.2 Meteorological Data Analysis of Global Weather Data for SWAT

Due to the non-availability of accurate and full data of the conventional metrological station in the sub basin the Global weather data was used instead. Four station which can represent the study area were selected and analyzed for all metrological parameters.

The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) was accomplished over the 36-year dated from 1979 through 2014. The CFSR was planned and performed as a worldwide, high resolution, joined atmosphere-ocean-land surface-sea ice system to deliver the best estimate of the state of these coupled domains over this period. The present CFSR will be stretched as a functioning, real time product into the future. This website allows to download daily CFSR data (precipitation, wind, relative humidity, and solar) in SWAT file format for a given location and time period. For the current study area four hydro metrological stations data has been extracted for a total of 21 years from 1993 up to 2013.

3.2.1 Rainfall

Rainfall is the main water source of the sub basin. The precipitation data is download from global weather data for 20 years starting from 1993 up to 2013. Even though the total amount of the rainfall is very small, the analyses show that the mean annual precipitation has a bimodal distribution with most of the rainfall occur during the south east monsoon season from March to May and a few rainfalls recorded from mid-September to November. From the analysis of SWAT, the average annual precipitation is 336 mm/year.

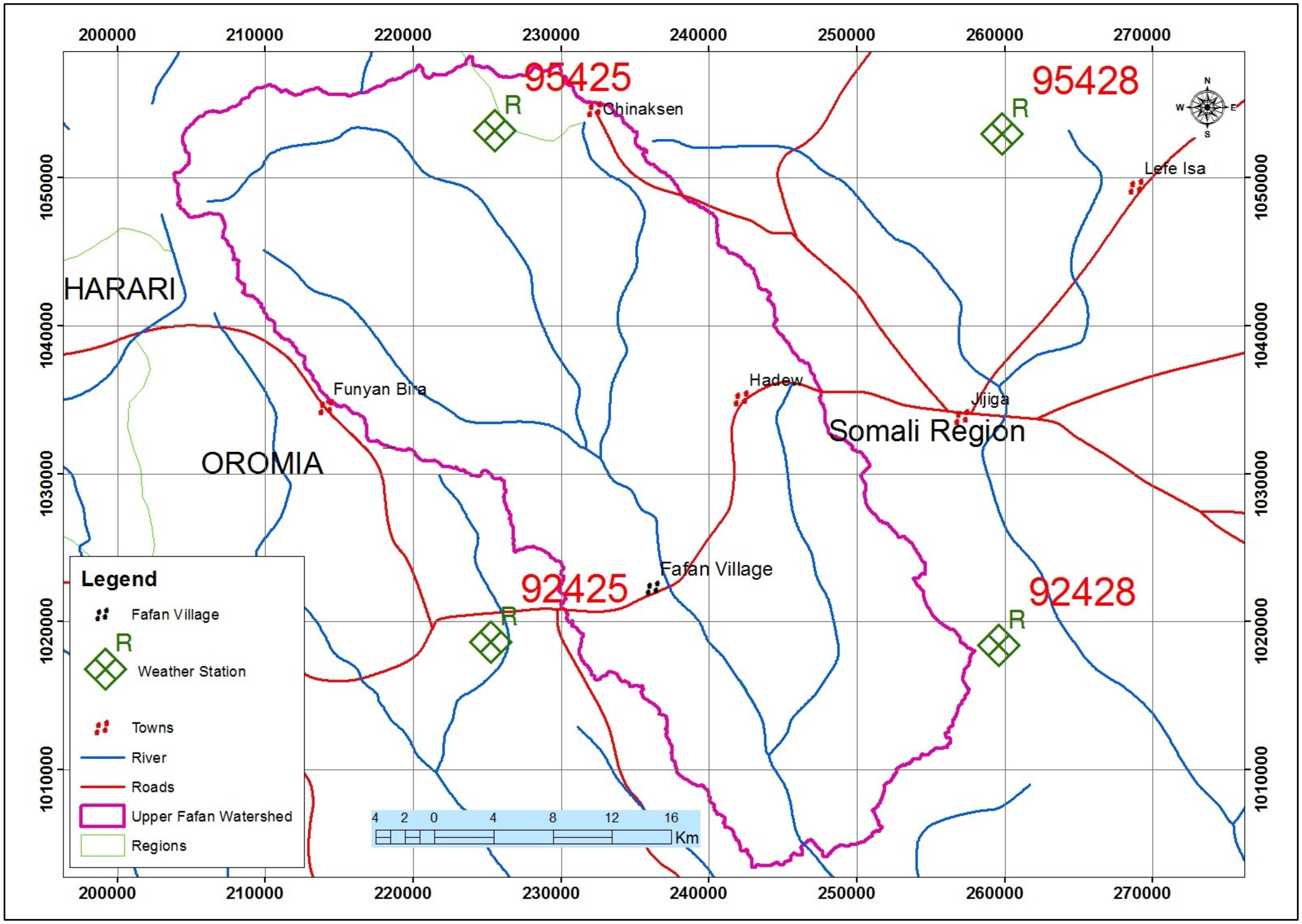


Figure 3.4 Weather Stations From Global Data of the sub basin

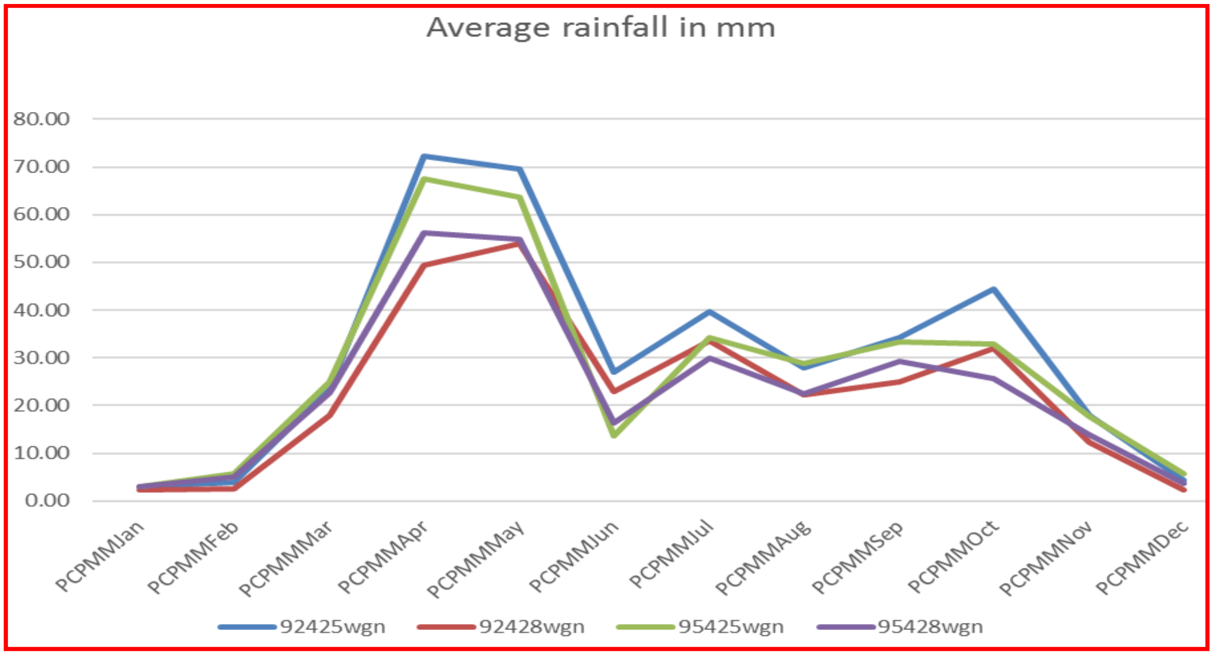


Figure 3.5 Average Rainfall representation of the sub basin

3.2.2 Maximum and Minimum Temperature of the sub basin

The mean annual temperature of the study area is about 27°C and with a fluctuation of 3°C. The highest temperature is recorded during the month of May with 30°C while the lowest recorded on December with 10°C. The mean monthly temperature variation at all station is shown in graph on the figure below.

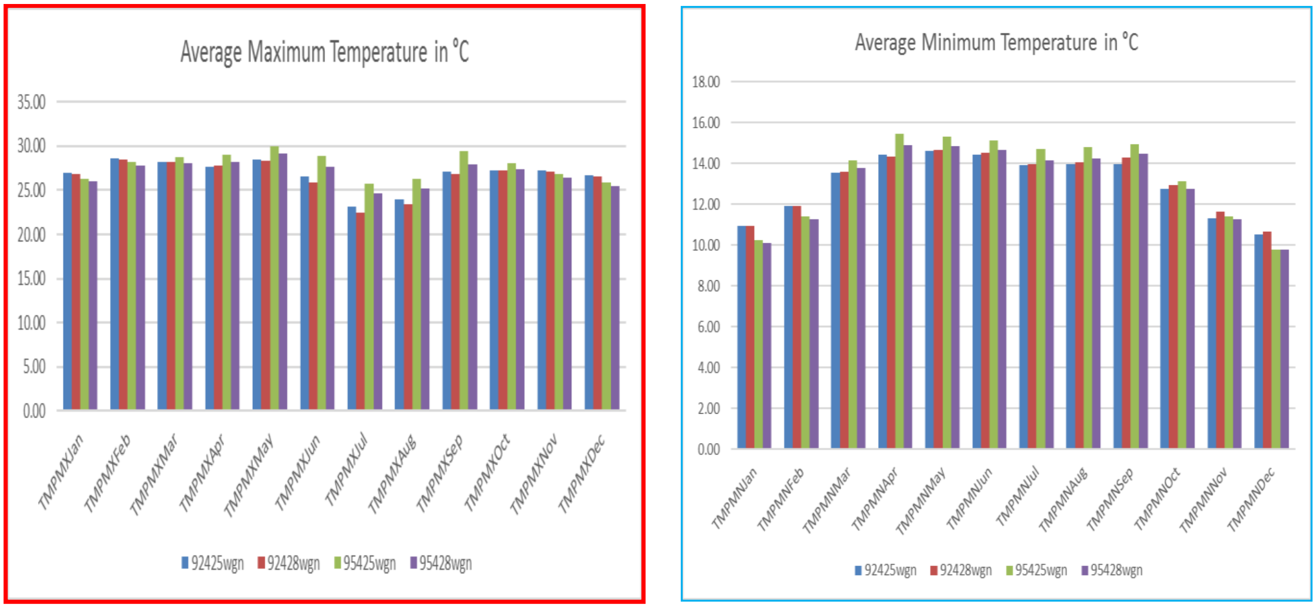


Figure 3.6 Average Monthly Maximum and Minimum temperature in °C representation of the sub basin

3.2.3 Wind speed and Solar Radiation of the study area

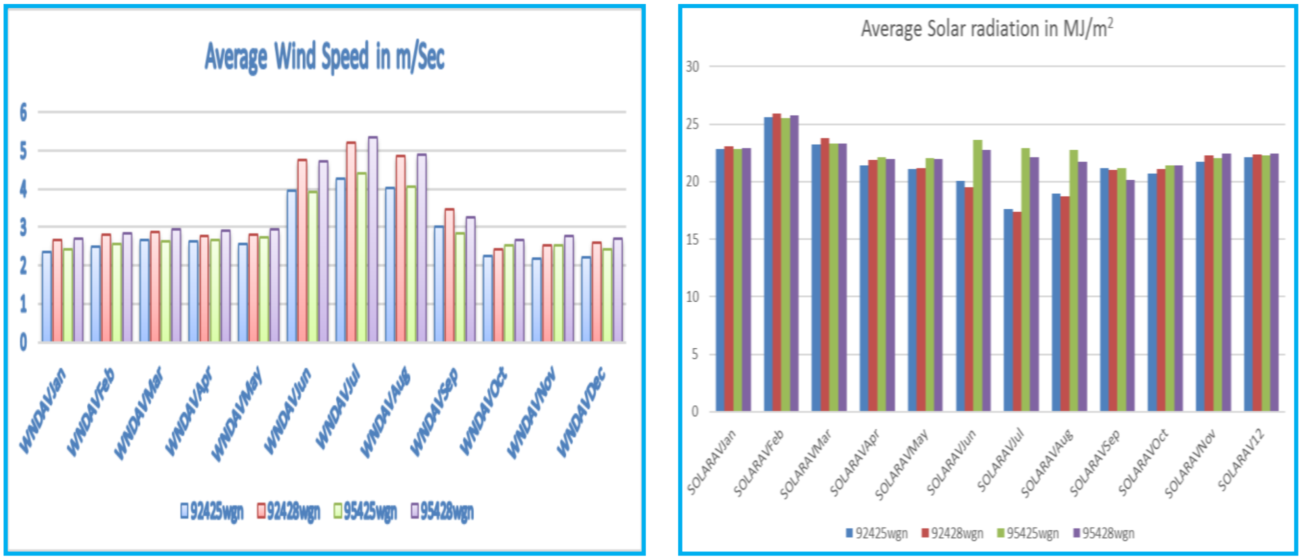


Figure 3.7 Average Monthly Wind Speed and Solar radiations in representation of the sub basin

3.2.4 Evapotranspiration (Eta) and Potential Evapotranspiration (Eto)

Evapotranspiration of the area can be analyzed in two ways as potential evapotranspiration and actual evapotranspiration. Potential evapotranspiration describes the water losses that will occur under a given climatic condition with no deficiency of water for vegetation. Since the actual evapotranspiration account the field condition, it depends on the availability of water.

Generally, the watershed has high rate of potential evapotranspiration mainly around the valley and relatively lower near and around the mountainous area. The figure 3.7shows the magnitude of the potential evapotranspiration of the sub upper Fafan sub basin.

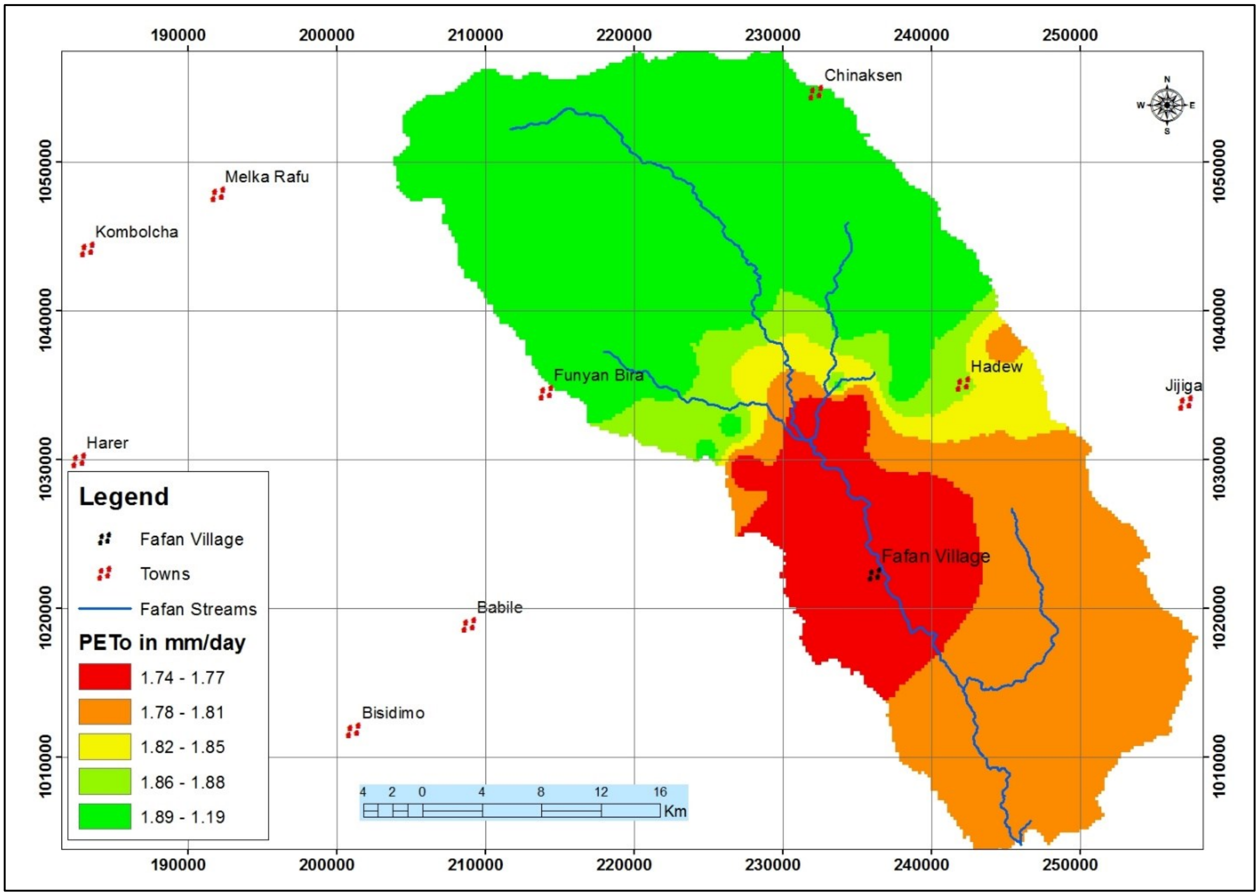


Figure 3.8 Potential Evapotranspiration

Numerous methods have been developed to estimate the potential evapotranspiration, from point measured data. Among them Penman Monteith method was used to estimate the potential evapotranspiration of the catchment because the method incorporates the effect of factors such as altitude, aerodynamics, geographic location, solar radiation for the evaluation.

SWAT estimates the surface runoff volume from HRUs using the SCS curve number method (USDA-SCS, 1972) or the Green and Ampt infiltration method (Green and Ampt, 1911). In this study, the SCS curve number method was used, which is a function of the soil's permeability, land use, and antecedent soil water conditions as defined in SWAT. SCS defines three antecedent moisture conditions: dry (wilting point), average moisture, and wet (field capacity). SWAT calculates the peak runoff rate with a modified rational method. The model offers three options for estimating potential evapotranspiration: The Hargreaves method (Hargreaves et al., 1985), the Priestley-Taylor method (Priestley and Taylor, 1972), and Penman-Monteith method (Monteith, 1965). The Penman-Monteith method has been used in this study to estimate evaporation. SWAT uses Manning's equation to define flow rate and velocity. Water is routed through the channel's network using the variable storage routing method developed by Williams (1969) or the Muskingum routing methods, which are variations of the kinematic wave model. For this study, the variable storage routing method was used.

Estimation was carried out for 20 years' period, from year 1993 to 2013.Although the Penman Monteith method used for the calculation by the SWAT tool, consider the climatic and physiographic factors of the catchment, it does not take into account correction factors for the effect of humidity, wind speed and radiation for day and night weather conditions, results may be effected by overestimate or under estimate during the day and night respectively.

The catchment is experiencing long dry period with more sunshine over the year. Relative humidity temperature and wind speed also comparatively high during this period. Because of that the average annual evaporation of the catchment, which is estimated as 270 mm/year is also relatively high.

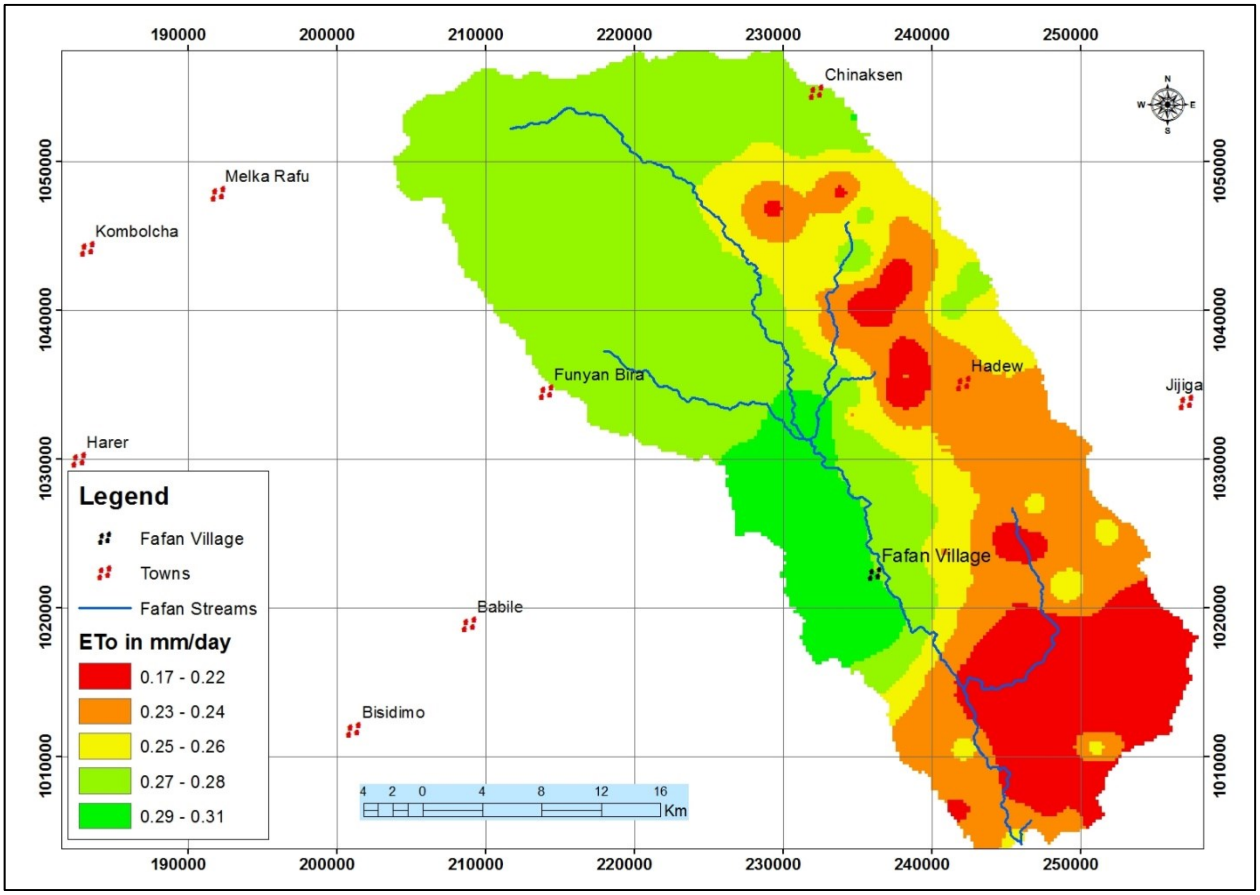


Figure 3.9 Evapotranspiration of the study area

3.2.5 Water balance of the Study area using SWAT

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) was developed to predict the effects of different management practices on water quality, sediment yield and pollution loading in watersheds. Arnold et al. (2000) applied SWAT with the addition of a streamflow filter and recession methods for regional estimation of base flow and groundwater recharge in the upper Mississippi River basin. The results showed a general tendency for SWAT to under predict spring peaks and to miscalculate autumn streamflow compared to measured monthly data during both calibration and validation episodes. According to son & Shoemaker (2004) reported application of the SWAT2000 model to Cannons Ville Reservoir, a New York City water supply reservoir, and found it was an appreciated tool that could be used to help categorize and quantitatively estimate the enduring effects of various phosphorus management options for alleviating loading to the reservoir. As cited in Abbaspour et al. (2007) used the SWAT model to simulate all related processes affecting water quantity, sediment and nutrient loads in the Thur watershed in Switzerland. Their study indicated excellent results for discharge and nitrate, and quite good results for sediment and total phosphorusThe quantitative statement of the balance between water gains to the catchment and water losses from the catchment during a specified period is known as water budget. Two type of waterbudgets can be considered in a catchment; hydrologic budget which include the whole component of the catchment and groundwater budget which is restricted to the balance of groundwater, what ever the sources might be. Macro water balance was carried out over the entire catchment based on the following convetional equation, assuming changing storage equal to zero under steady state condition.

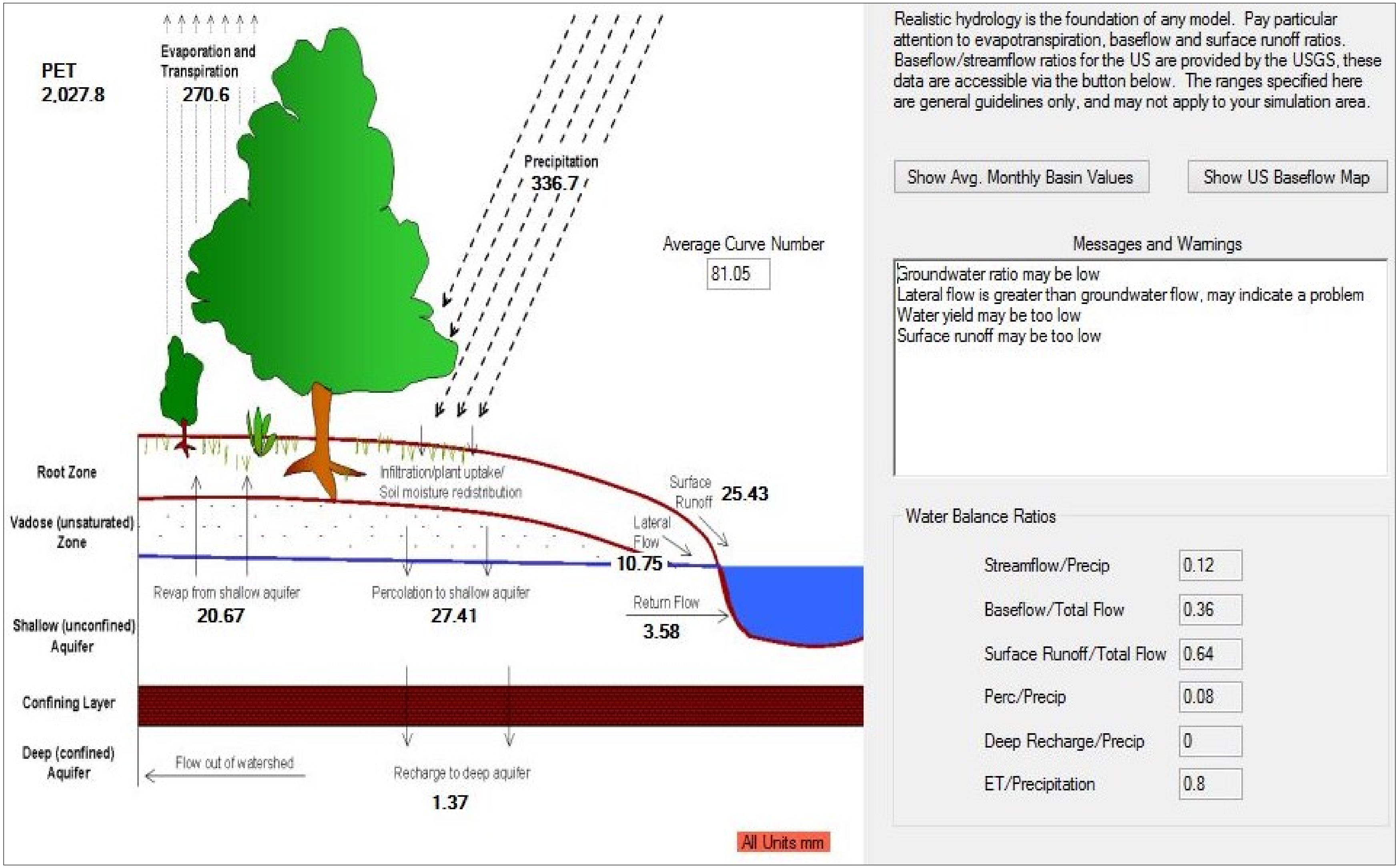
Precipitation = Evapotranspiration + Groundwater out flow +Surface out flow

Long term average precipitation of the catchment was calculated as 336mm and the long term evapotranspiration was 270.6 mm. The surface runoff of the catchment was reported as 25.43mm. The application of steady state hydrologic water balance provides crude approach of the gaining and losses of the catchment; and it has its own limitation especially in the method of estimation. As it is lumped parameter approach it does not represent either spatial variation or time dependent effects of precipitation, evapotranspiration, recharge and discharge. For the better accuracy of the water balance, it is necessary to have long term data of the coentional stations and to recalculate the waterbalance using the classical methods.

Water balance of the study area can be calculated from :

Inflow - Outflow = ± Change in aquifer storage

Inflow = 336.5 mm/yr and Out flow = 359.81 mm/yr therfore, the change in storage will be negative (-) 23.31 mm/yr. The whole result is displayed on the folowing figure below.



Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

Average Curve Number: 81.05

Messages and Warnings

Groundwater ratio may be low
Lateral flow is greater than groundwater flow, may indicate a problem
Water yield may be too low
Surface runoff may be too low

Water Balance Ratios

Streamflow/Precip	0.12
Baseflow/Total Flow	0.36
Surface Runoff/Total Flow	0.64
Perc/Precip	0.08
Deep Recharge/Precip	0
ET/Precipitation	0.8

Figure 3.10 SWAT Modeled Output Hydrological water balance representation of the sub basin

3.3 Geological and Hydrogeological Setting

3.3.1. Regional Geological and Tectonic Setting

3.3.1.1 Geological Setting

The Fafan area is situated in Ogaden Basin where Precambrian crystalline basement rocks, Mesozoic sedimentary rock succession, and Tertiary volcanic and sedimentary rock successions occur.

Geochronological studies carried out by Teklay et al. (1998) on Precambrian basement rocks of eastern Ethiopia around Harar and Hirna not far from the study area indicated Archean to Paleoproterozoic ages. As such the Precambrian basement rocks of eastern Ethiopia are classified in to three groups viz. Lower, Middle and Upper Complexes and presumed to contain rock components older than all other Precambrian basement occurrences in southern, southwestern, western and northern parts of Ethiopia.

As also shown in the geological map of the study area the Precambrian basement exposures are found to occur in the upper reaches of Fafan and Jerer sub-basins close to the rift margin which suggest considerable upliftment. These rocks are comparable to Precambrian basement rocks of Borama area in northern Somalia and Yemen as well.

The Mesozoic sedimentary successions including mainly the basal Adigrat sandstone and limestone formations unconformably overlie the Precambrian basement that forms the floor of the Ogaden Basin.

The Mesozoic sedimentary successions mainly occur to the west of NW – SE trending Marda fault which extends from rift margin in the north to the margin of Indian Ocean in the south. Furthermore, the eastern half of the study area to the east of Marda fault zone is largely underlain by the inhomogeneous variegated Jessoma sandstone formation. Inter-layering of similar sandstone with Tertiary volcanic rocks in Karamara mountain range suggests Tertiary age of the Jessoma sandstone. The Tertiary rocks cap both the Precambrian basement and Mesozoic – Cenozoic sedimentary successions along the Karamara mountain range in the northern part of the study area close to the southeastern margin of the Main Ethiopian Rift (MER) margin.

Table 3. 1Summary of Sedimentary Rock Formations in SE Ethiopia (after Tefera et al., 1996, Geleta 1998, and references therein)

Lithostratigraphy	Age	Lithologic Description	Depositional Environmental
Karkar Formation	Tertiary	Limestone with intercalation of marls, shale, and chalky limestone	
Taleh Formation		Evaporitic unit containing, anhydrite, gypsum, dolomite, and clays	
Auradu Formation		Biogenic limestone alternating with beds of chalky or gypsiferous limestone alternating with green to brown shale	
Jessoma Formation		Fine to coarse grained sandstone and marls	Fluvial – shallow marine
BeletUen Formation	Cretaceous	Fossiliferous, sandy and cherty limestone with shale & gypsum. Marls, sandstone, &gypsiferous limestone also occur	Reefal
Ferfer Gypsum (Faf)		Grayish brown dolomite, shale, anhydrite, marl, interbeds limestone (equivalent to AmbaAradom Formation).	Supra-tidal – inner shelf
Mustahil Formation		Limestone inter-bedded with shale and marls	Reefal
Gorahi Formation		Thickly bedded gypsum alternating with dolomite and thin limestone. It is also known as Main Gypsum Formation	Inner shelf
Gabredarre Formation		Light colored oolitic limestone, marls, &shaly limestone	Outer – inner shelf
Urandab Formation	Jurassic	Sequence of dark shale, marl and gypsiferous limestone (equivalent to Agula Shale).	Basinal – outer shelf
Upper Hamanlei		Cryptocrystalline limestone, grey to white and is fine grained	Inner – outer shelf
Middle Hamanlei		Mainly evaporites, like grey anhydrite and dark grey dolomite (equivalent to Antalo limestone)	Supratidal – inner shelf
Lower Hamanlei		Densely cemented, bottom part fossiliferous, fine grained, grey to dark grey rock (equivalent to Antalo limestone).	Inner shelf
Adigrat sandstone	Upper Triassic	Fine to medium grained, sorted or non-sorted at places cross-bedded, yellow, reddish brown to white sandstone	Fluvial – marginal marine
Gumburo Sandstone	Paleozoic	Sandstone with overbank sediments	Fluvial
Bohk Shale		Lacustrine shale, siltstone and minor sandstone	Lacustrine with marine influence
Calub Sandstone		Arkosic sandstone and lithic conglomerate and sandstone	Fluvial with glacial influence
Basement Rocks	Precambrian	Various basement rocks	

Note: For better appreciation the locations of the type localities of the Sedimentary Formations used in the description of regional geology are shown in Figure 3.10.

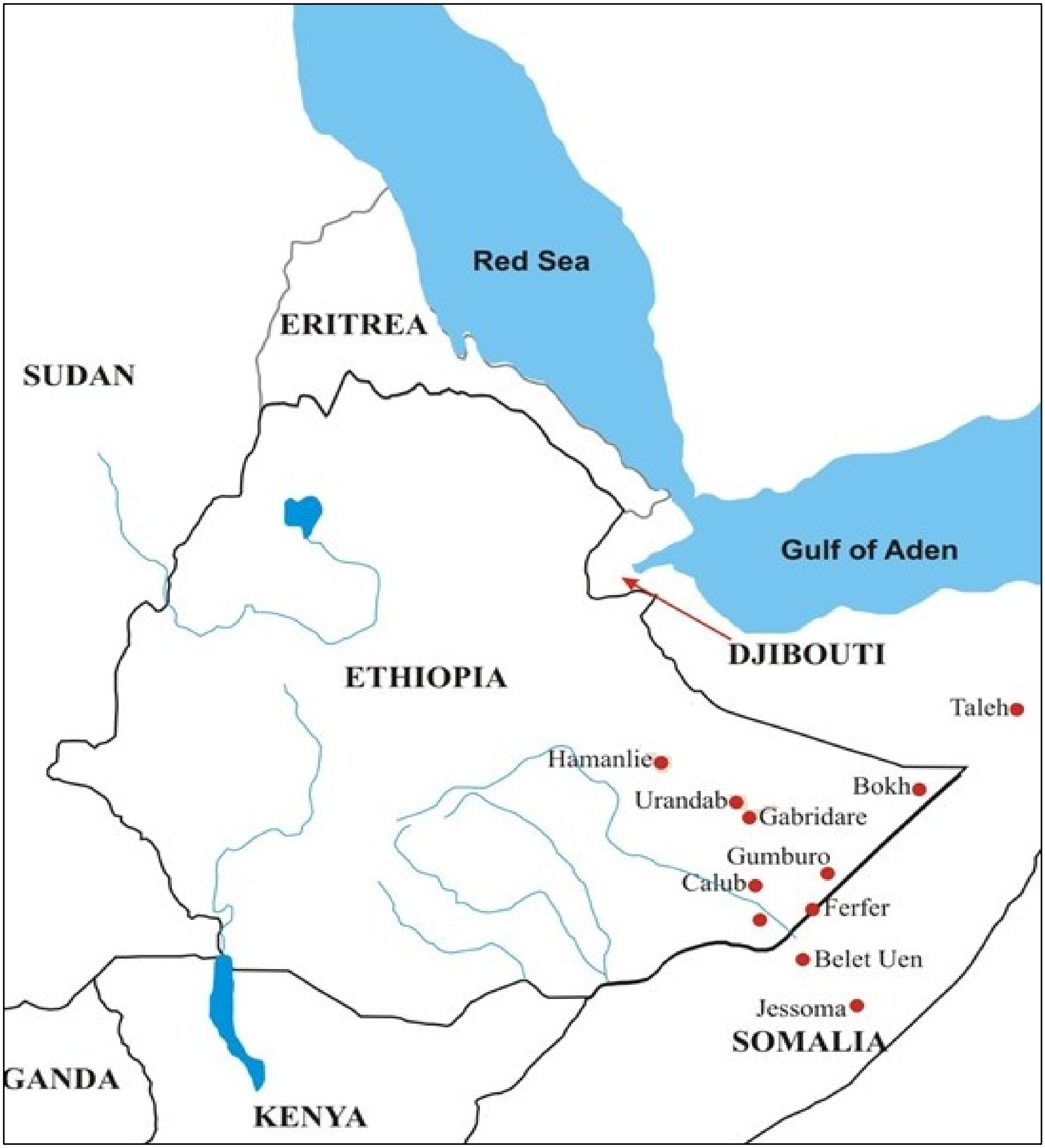


Figure 3.11Location map of important locality names used in regional geology of the area (modified from Geleta, 1998)

3.3.1.2 Tectonic Setting

The study area is entirely located in the Ogaden sedimentary basin situated in Eastern Africa where the Proterozoic East African Orogen (EAO), Paleozoic to Mesozoic sedimentary basins and Tertiary rifting tectonic history were recorded in Precambrian basement, Paleozoic to Mesozoic sedimentary succession, Tertiary volcanic and sedimentary rocks, respectively. The basement rocks were formed during the EAO in at the end of Proterozoic time as a result of collision between East and West Gondwana to form the supercontinent *Greater Gondwana* (Stern, 1994).

The EAO marks the disappearance of a major ocean basin known as the *Mozambique Ocean*, the formation of a vast tract of juvenile Neoproterozoic continental crust and where East and West Gondwana joined (Stern, 2002 and references there in). The great rifts of Africa, the Red Sea, and the Indian Ocean itself were believed to be initiated along the EAO.

After the EAO the major pre-Jurassic geologic structures are the rift grabens, in the Precambrian basements, containing Permo – Triassic clastic sediments (see also Geleta, 1998). The rift grabens where formed by extensional tectonics that resulted in the breakup of the Gondwana. The Karoo rift extends in northeast direction from Kenya to Calub locality in Ogaden Basin from where it stretches east to Somalia border and join Blue Nile rift in Ogaden to form a triple junction. These structures which repeatedly down warped this part of Eastern Africa resulted in formation of thick succession of Mesozoic sedimentary rocks that also cover considerable part of the study area. This succession is believed to be linked to the sedimentary rocks deposited in the Blue Nile rift before the break up by the Main Ethiopian Rift which is part of the East African rift system. However, the Paleozoic – Mesozoic basins were bordered by structural highs of Precambrian basement rocks of Somalia in the south and Harer area in the north.

In the study area generally the Marda fault separates the Mesozoic sedimentary sequence from the Jessoma sandstone formation. This fault runs in northwest to southeast direction for about 900 km from southeastern margin of the MER to Somalia. The age of Marda fault is controversial as Black et al. (1974) and Purcell (1986) consider as Tertiary and Precambrian age, respectively. Whatever its age maybe the effect of Marda fault in the rocks at and around Karamara area is remarkable.

The influence of the rift structures in the study area is negligible except the northern part where nearly east to west trending structures are common. As such the tectonic evolution of the MER will not be discussed further here.

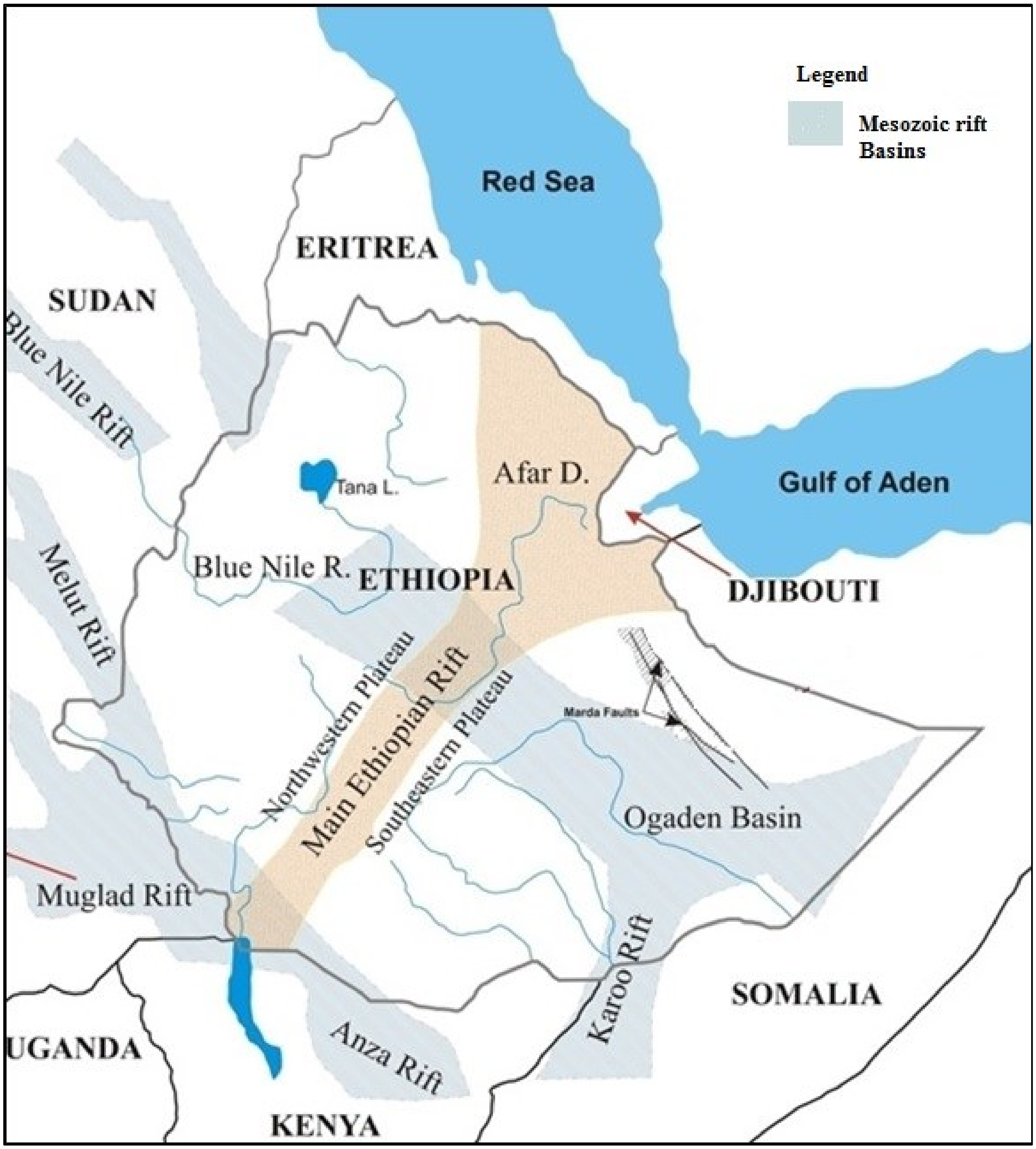


Figure 3.12 Mesozoic rift basins in and around Ethiopia and Main Ethiopian Rift (MER) [modified from Gani et al. 2008 and references there in].

3.3.2. Local Geology and Structure of the Study Area

Field visits to the study area and geological data collection mainly along road cuts, quarry sites and selected traverses, wherever possible, were taken to have a glimpse of various lithological units such as Precambrian basement rocks, Mesozoic to Tertiary sedimentary rock successions, limited Tertiary volcanic rocks and superficial deposits; as well as primary and tectonic geologic structures so as to assess geological conditions for groundwater potential assessment of the study area. The lithostratigraphic units mapped in the study area are described as follows.

3.3.2.1 Lithology and Stratigraphy

3.3.2.1.1 Precambrian Basement Rocks

The Precambrian basement rocks are exposed in the northwestern part of the study area mainly in the upper reach of Fafan River excepting some hilly areas capped by Mesozoic rocks and/or Tertiary basaltic rocks; and northeast to northwest of Jijiga town. The basement rocks exposed in the area include granodiorites with associated gabbroic bodies, granitic gneisses, granodiorites and different generations of granites.

Figure 3.13 Highly fractured basement rock found to occur at the eastern foothill of Karamara mountain range.

3.3.2.1.2 Mesozoic Sedimentary Successions

The Mesozoic sedimentary rock successions unconformably overlie the Precambrian basement rocks in the northwestern part of the study area in the valleys of Fafan and Jerer as well as their major tributaries. These rocks comprise mainly the Lower Sandstone and Hamanlei Limestone. The younger successions, mainly Urandab and Gabredarre formations, are found to occur on flanks of Karamara mountain range and further downstream on ridges separating tributary rivers entering Fafan and Jerer and in Fafan valley itself.

3.3.2.1.3 Adigrat Sandstone

This sandstone unit is mainly exposed in the northwestern part of the study area in upper part of Fafan and Jerer River valleys and at the foot of Karamara mountain range. This sandstone formation is the oldest Mesozoic sedimentary succession in the study area and is found to occur unconformably overlying the Precambrian basement rocks.

The sandstone is generally massive with inter-layering of horizontally bedded shale and mudstone. The prominent ridges and hills at and around Funyan Bira & Buchmen are underlain by Adigrat sandstone and sandy limestone that is bottom part of Hamanlei Formation. The sandstones exposed at these areas are fine to medium grained with occasional conglomeratic variety containing of quartz pebbles.

The lithological contact between the Lower/Adigrat sandstone and the underlying Precambrian high-grade gneissic and plutonic basement rocks wherever exposed is marked by unconformable relationship. At lithologic contact zones the underlying basement rocks are represented by deeply weathered, decomposed and friable basement rock materials. On the contrary the lithological contact between the Adigrat and overlying limestone is gradational as marked by gradation from sandstone – calcareous sandstone – sandy limestone – limestone; such relationship is observed not far from Jijiga at Sheik Algure area. This actually signify changes of sedimentary depositional environment, i.e. gradual deepening of the basin.

Similar sandstone with variegated colors (grey, pinkish, reddish brown and yellowish) is found to occur inter-bedded with mudstone and siltstone which are poorly consolidated (Fig. 13). The sandstone is extensive and often conglomeratic. Depositional break or discontinuities are observed by presence of lag deposits and ferruginized/lateritic zones. Overall the rock is poorly consolidated and friable. In this area lithologic contact between the sandstone and underlying Precambrian basement rock is observed to be unconformable.

3.3.2.1.4 Hamanlei Limestone

Hamanlei Formation represents fossiliferous limestone of Jurassic age exposed in southeastern Ethiopia mainly Ogaden region (e.g. Tefera et al. 1996 and references therein). The formation gets its name from Hamanlei locality situated between lower reache of Fafan valley. Hence, in the study area Hamanlei formation is found to occur at its type locality; upper Fafan valley, around Karamara mountain range. As observed in the Karamara mountain range, upper Fafan valley south of Jijiga town the Hamanlei formation conformably overlies the Adigrat/Lower sandstone formation. The nature of the lithological contact between Hamanlei and Adigrat formation is gradational from sandstone – calcareous sandstone/fine sandstone or siltstone – shale and to sandy limestone – fossiliferous limestone. The thickness of the Hamanlei limestone is thin at places, particularly in the upper reache of Fafan rivers where interplay of tectonic upliftment, mass-wasting, weathering and erosional activities removed the overlying succession and upper portion of the unit. Even at places the Mesozoic sedimentary succession is uplifted and completely weathered and eroded to expose the Precambrian basement rocks. However, where overlain by the Urandab formation the thickness of Hamanlei is estimated to be more than 250 – 300 m.

Figure 3.14 Hamanlei limestone containing abundant macro-fossils exposed (a) along Harer – Jijiga road cut, (b) north of jijiga Teferi Ber road

3.3.2.1.5 Tertiary Volcanic and Sedimentary Rocks

The Tertiary volcanic and sedimentary rocks in the study area are represented mainly by basaltic rocks exposed along the prominent Karamara mountain range and Jessoma sandstone underlying the flat-lying plain areas situated to the east of the Jerer valley, respectively. These map units are described as follows.

3.3.2.1.5.1 Karamara Basaltic Volcanic Rocks

Karamara basaltic volcanic rock occupies the top part of the Karamara mountain range which occurs between the upper to middle reaches of the Fafan and Jerer rivers. The linearly arranged outcrops of Karamara basalt trends in NW – SE direction paralleling the Marda fault zone. It is presumed to be channeled and erupted through the Marda faults capping the Mesozoic sedimentary succession. This rock is at places bounded by regional fault/fractures trending in NW – SE orientations.The Karamara basalt is generally aphanitic in texture exhibiting crude/broad and less developed columnar joints. The joints range from about less than 10 cm to about 30 – 40 cm and the rock is commonly used as quarry sites for construction materials.

At places the spheroidally weathered aphanitic basaltic outcrop is found to occur at lower elevation suggesting flow of basaltic lava on irregular surface paleo-geography. Inter-layering and intermingling of basalt and sandstone where the Harer – Jijiga highway crosses the Karamara mountain range.

Figure 3.15 Aphanitic basalt outcrop forming outstanding hillock and showing less regular columnar jointing at Karamara mountain range

3.3.2.1.6 Superficial Deposits

3.3.2.1.6.1 Alluvial Deposits

The upper Fafan valley, particularly along its main course, deposits considerable alluvial deposits, which range from silty clay overbank floodplain sediments and fine-coarse sand channel deposits. The thicknesses of the alluvial deposits vary from place to place. Results of previous well drilling in the valley indicated the maximum thicknesses of the alluvial deposits range from ~40 m to ~70 m. As the major source of the alluvial deposits are the basement rocks in the upper Fafan, the size distributions of the alluvial sediments gradually decrease downstream suggesting dominance of silty clay or clayey silt in middle and lower Fafan valley.

3.3.3. Geologic Structures

In the study area a number of mapping units categorized into Precambrian basement, Mesozoic sedimentary succession, and Tertiary sedimentary & volcanic rocks subject to diverse geological and structural evolution are documented and shown in the geological map of the study area. The road cuts, quarry sites and river/stream banks present fresh rock exposures where meso-scale structures could be observed.

Therefore, the lineaments are categorized in domains based on underlying major rock types, namely Precambrian basements, Mesozoic sedimentary succession, and Tertiary sedimentary/volcanic rocks so as to clearly characterize the orientations of dominant faults/fractures in the study area. On the other hand, the density analyses of the lineaments clearly indicate zones of high fracture concentration and cross-cutting relationships and this would have significance for regional groundwater assessment potential.

Some of the major structures observed in the Precambrian crystalline basements, Mesozoic sedimentary strata, and Tertiary sedimentary/volcanic, e.g. Jessoma sandstone and Karamara basalts as well as other volcanic rocks, are briefly described as follows.

3.3.3.1 Precambrian Basement Structures

Strongly deformed and sheared Precambrian basement rocks showing strong alignment of structural fabrics are observed in the upper reach of Fafan River valley and underlying the Adigrat sandstone on eastern flank of the Karamara mountain range. The pervasive structural elements (mainly shear fabrics) trends N50W and dipping 86º/220º, 65º/228º and 75º/210º suggesting slight swinging. At places the foliation partings are filled with quartz veins and carbonate precipitates. Due to strong shear deformation the rock can be termed as phyllonite. The northwest trending shear zone is cross-cut by a northeast trending structure dipping 63º/114º. A third set of fractures trending NE and dipping 8º – 10º/110º is encountered in the basement rocks as well.

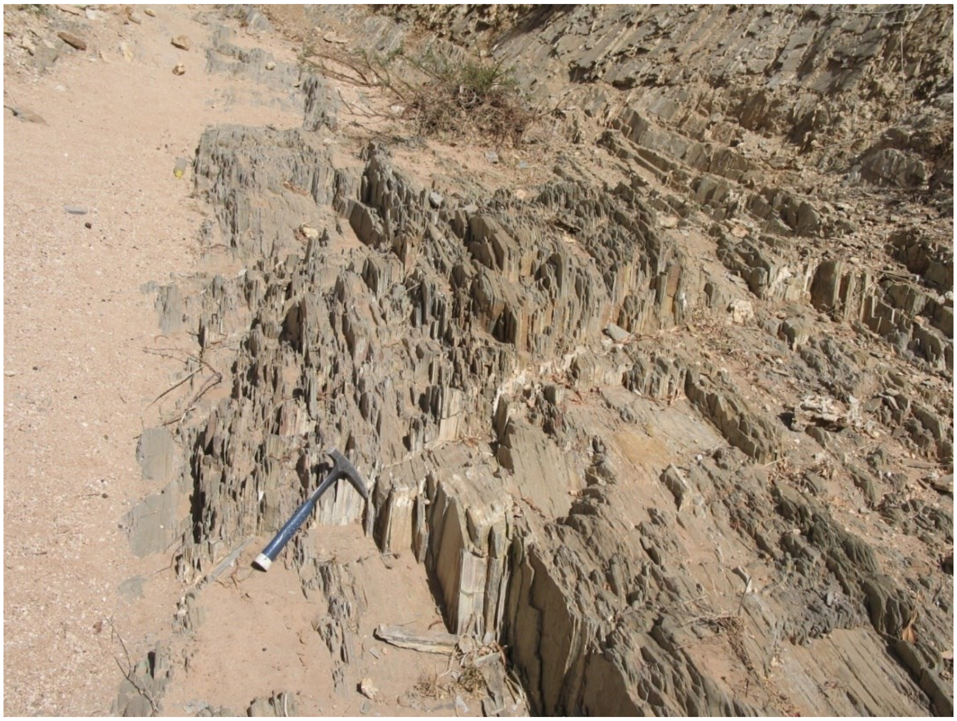


Figure 3.16Precambrian basement rocks immediately underlying the Mesozoic sedimentary succession, eastern side of Karamara mountain range

Figure 3.17Strongly sheared amphibole biotite gneiss with stringers of leucocratic granitic gneissic materials exposed in upper Fafan valley.

Generally, as the basement rocks experienced ductile deformation at great depth the fresh rock outcrops exhibit tight shear zones without open fractures. On the contrary, the open fractures are recognized in the basement rocks towards the top parts which were affected by surface weathering actions and/or where affected by Paleozoic – Mesozoic and Tertiary rift tectonics.

3.3.3.2 Structures in Mesozoic Sedimentary Rocks

The middle and lower Fafan valley is mainly underlain by Mesozoic sedimentary rocks, namely Adigrat/Lower sandstone and the overlying limestone formations, i.e. Hamanlei, Urandab, and Gabredarre Formations. Hamanlei and Urandab are at places bioclastic containing numerous macro-fossil fragments.

At the lithologic contact between the lower sandstone (Adigrat Sandstone Formation) and the overlying Hamanlei Limestone Formation frequent intercalations or lamination of fine-sandstone, siltstone, shale and marly limestones are encountered during the field visit at the foot of Karamara mountain range and North to northeast of Fafan Town.

The Mesozoic sedimentary rocks exhibit horizontal bedding and laminations often intercepted by joints and fractures. Such vertical to sub-vertical fractures/joints are commonly observed in the Mesozoic sedimentary succession. At places the sedimentary rocks are displaced/off set by meso-scale faults. These faults trend parallel to the Marda Fault zone.

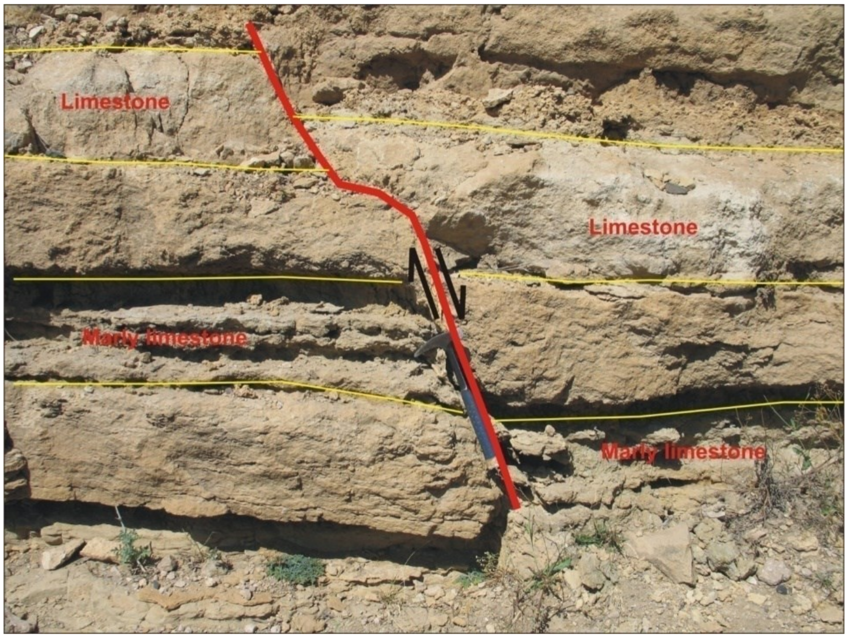


Figure 3.18 Normal fault as observed in the Mesozoic sedimentary rocks, at the foot of Karamara range in the Harer – Jijiga road near Hado village.

The Mesozoic sedimentary strata exhibit high density of lineaments indicating occurrence of frequent jointing and fracturing as well as faulting particularly related to Marda Fault Zone.

3.3.3.3 Structures in Tertiary Sedimentary and Volcanic Rocks

Tertiary sedimentary (Jessoma sandstone) and volcanic rocks underlie large part of the groundwater potential assessment study area and occupy almost the top part of the Karamara mountain range.

Volcanic rock exposures are present covering the top part of hills and ridges in the far north of Fafan sub-basin, on peaks of ridges dividing Fafan and Daketa sub-basins around Babile.

Lineament analysis of the areas underlain by Jessoma sandstone and Tertiary volcanic rocks exhibit less fracture density as compared to areas underlain by Precambrian basement rocks and Mesozoic sedimentary strata. However, this doesn’t necessarily imply that the rocks are less fractured or affected by tectonic movement. Area underlain by Jessoma sandstone as well as Adigrat sandstone and Hamanlei limestone, exposed north to southwest of Jijiga are often covered by calcrete and elluvial deposits which hinder the occurrence of faults/fractures. At places hardpans are well formed and such features may hinder recharge of groundwater.

3.3.3.4 Marda Fault Zone and Other Major Structures

The NW–SE trending Marda Fault Zone was first recognized in the Karamara mountain range and is down thrown to the NE and possibly extending more than 900 km from southeast of Afar Depression to the Indian Ocean (Purcell, 1976). The Marda Fault zone is recognized as a major structural element in the Horn of Africa. The Marda Fault striking northwest – southeast and practically delineates Jessoma sandstone formation to the west from the Mesozoic sedimentary succession. Despite the fact that the age of Marda Fault zone is controversial, it is a major structure which requires detailed study and analysis for the groundwater study underway.

The structure extends for about 900 km from around northern part of the study area to Somalia across Ethiopian border. It is presumed to cut across or truncate against the structural high (Mirio Uplift) located south of the study area.

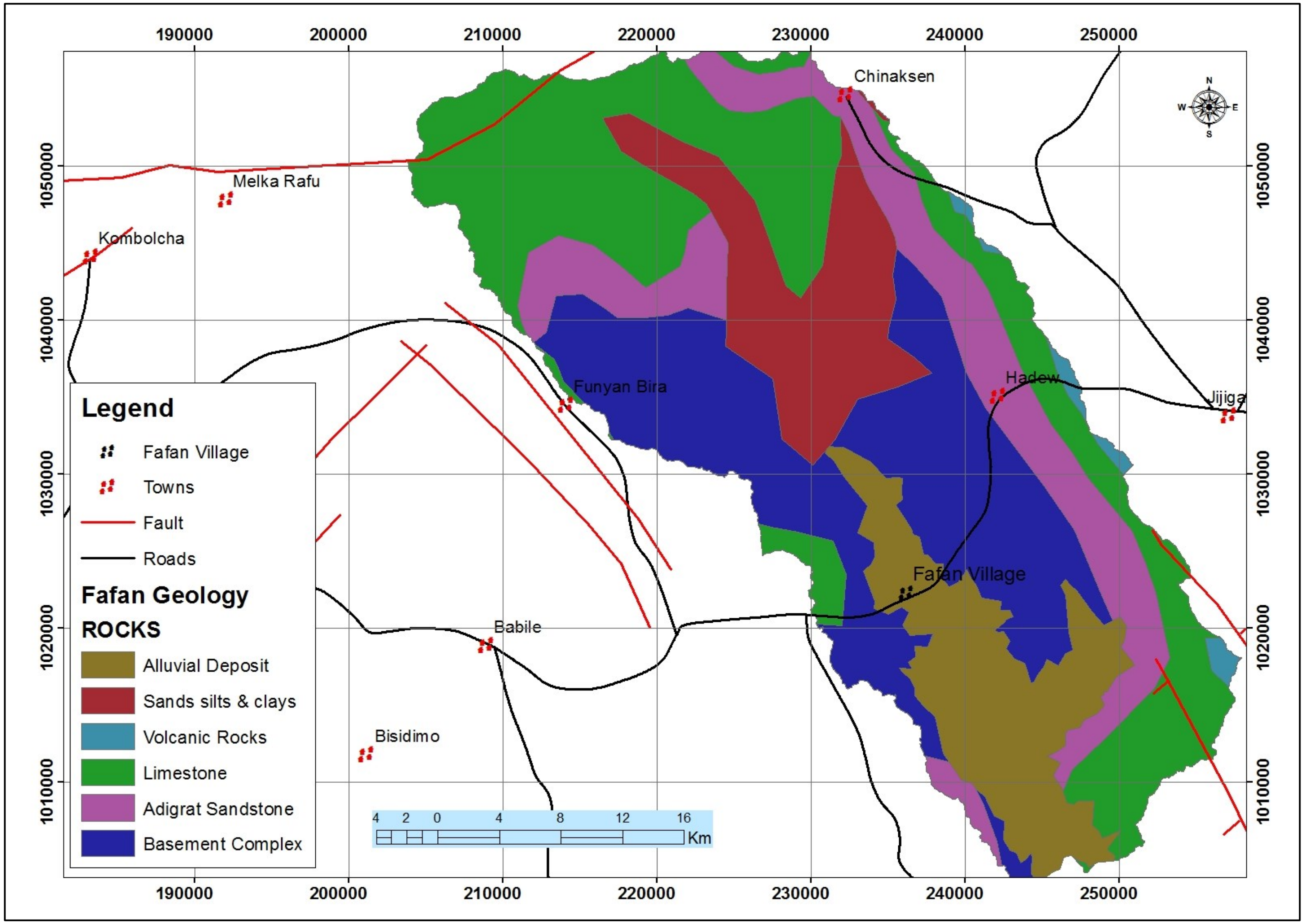


Figure 3.19 Extract from the 1:2,000,000 scale Geological Map of Ethiopia (Tefera et.al 1996)

3.3.4. Hydrogeology

3.3.4.1 Evaluation of Aquifer Properties

Evaluation of aquifer properties is based on the pumping test analysis, as it is useful to determine aquifer interaction, the hydraulic properties of the aquifer such as transmissivity, permeability and storativity and the performance characteristics of wells. These properties determine how easily water moves through the aquifer, how much water is stored, and how efficiently the well produces water. Pump tests can allow predicting the effect on water levels of different pumping rates, or the addition of one or more pumping wells.

Aquifer pump test data were collected during the field work. Since the tests were used to determine the safe yield, majority of the tests were carried out under constant discharge rate for short time durations. The majority of the available data were not completed. Wells which have complete data were selected for the analysis and all the analysis are carried out using AQUITEST 3.5 (Waterloo 2002). Generally, all these analytical methods assumed the aquifer is homogeneous and isotropic, flow is radial towards the well, groundwater flow is horizontal and Darcy's law is valid, groundwater has constant viscosity and density, pumping wells are fully penetrating to the aquifer, geologic formations are horizontal and have infinite horizontal extent.

3.3.4.2 Constant Discharge Pumping Test Analysis

Analyses of constant discharge tests were obtained as mathematical solutions of Theis, Cooper Jacob straight line and recovery methods. Pumping test analysis results shows two types of aquifers with high variation of transmissivity within the range of 36.3-2180 m^2/d. Almost all the high transmissivity values were obtained from the wells which are near to the river while the low values are restricted to the wells which are located far from the river and up stream of the watershed. Since the aquifer depth of the wells located in the upper most part of the watershed is not available, hydraulic conductivity was calculated assuming the length of the screens is equal to the thickness of the aquifer. Maximum calculated hydraulic conductivity of the study area is 75.5 m/d, and the minimum is 0.189 m/d (see annex).

Drawdown takes place due to aquifer losses and well losses which are related to well inefficiency and turbulent flow. Further measuring drawdown convergent vertical radial flow and recovery measuring with recovery data is the filling of a previously created cone and no vertical convergence. This may be the reason for the deviation shown from the transmissivity calculated based drawdown data to the recovery data. Since the available pumping test data points are not sufficient to get a better understanding on the aquifer properties of the study area relationship of the specific capacity with the transmissivity was studied.

3.3.4.3 Specific Capacity and Transmissivity

Transmissivity of an aquifer is determined from pumping test analysis, but due to the difficulty of performing such tests as well as the relatively high cost of these tests, it is often estimated aquifer properties from specific capacity data (Freeze and Cherry, 1979). The linear regression functions have been performed and it is found that the power model predicting transmissivity from specific capacity data has a linear correlation of R^2=0.96. (Figure 3.19)

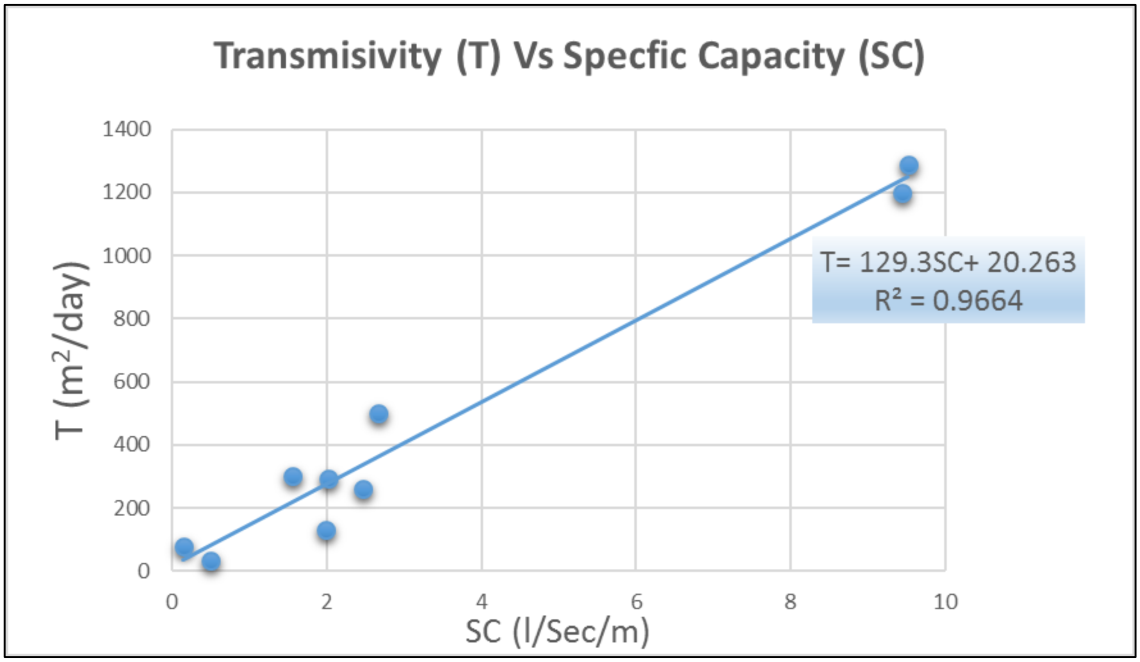


Figure 3.20 Correlation of transmissivity versus Specific Capacity of Wells in the Upper Fafan

3.3.4.4 Aquifer Type

Only one lumped aquifer type is distributed with in this groundwater flow model assessment, namely the alluvial formation, unconfined aquifer. The unconsolidated formation is the topographically dominated unit, building most of the low land ranges, and is hydrogeologically most important in that is has the widest extent in the areas of maximum thickness and recharge potential and the greatest subsurface volume of permeable material. The permeability of unconsolidated deposit is an important factor for the capacity of the aquifer to store water, while the occurrence of pore spaces, thickness and uniformity in composition are necessary to transmit the stored water in a sufficient amount to the borehole or another abstracting system. From the pumping test analysis of the available borehole data, the hydraulic conductivity values vary greatly from 0.2 m/day and up to 70 m/day for boreholes near the river valley. The alluvial aquifer of the upper Fafan watershed is composed of thin clay, fine to coarse sand and gravel in varying degree of sorting and thickness.

3.3.4.5 Phreatic Surface

The spatial variation of groundwater level was studied by analyzing the available average hydraulic head data. It was found that hydraulic head ranges from couple of meters near the river to around 18m in the mountainous foothills. Available hydraulic head data of the area were used as initial prescribed head of the model simulation.

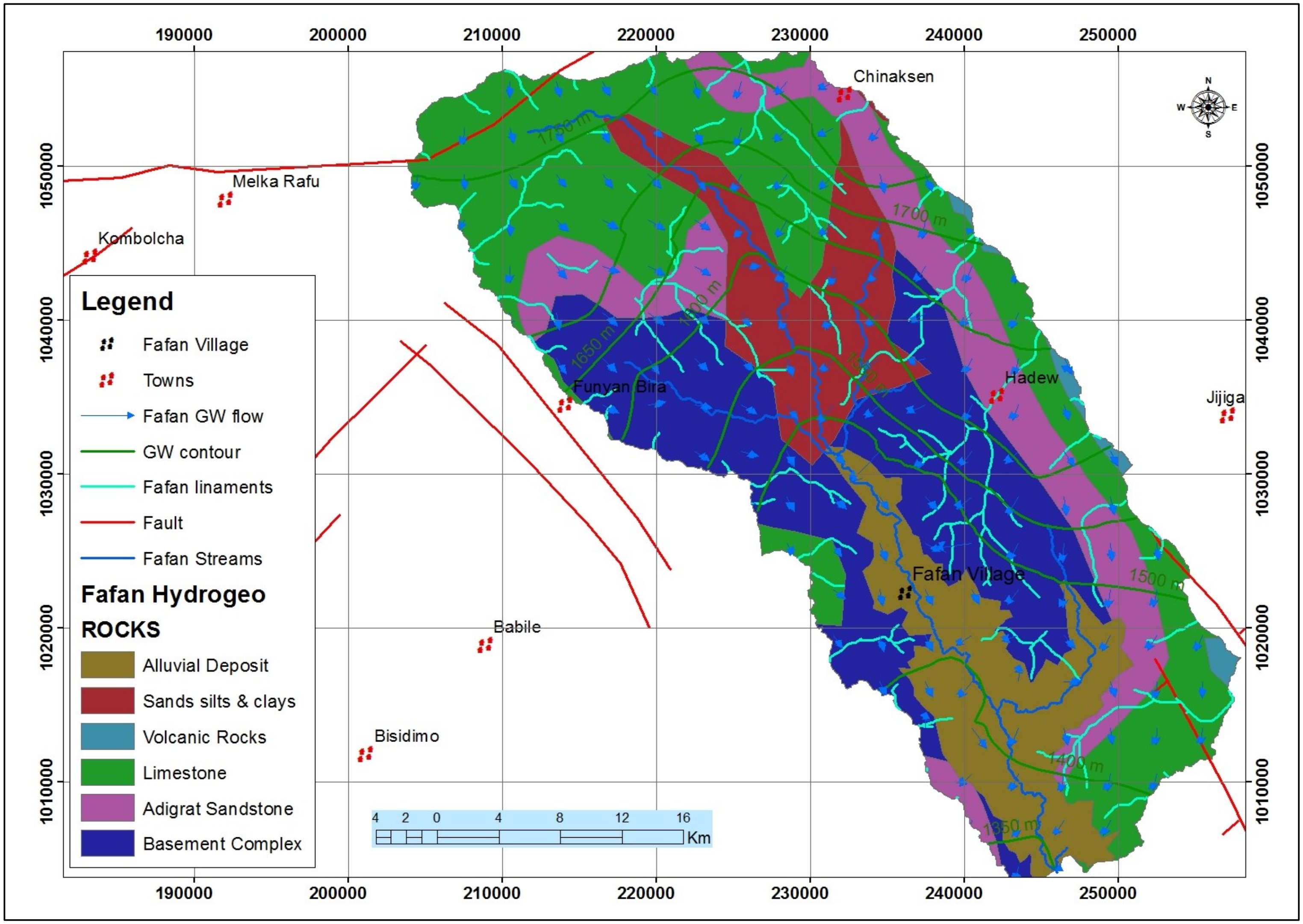


Figure 3.21 Hydrogeological map of the Upper Fafan Sub basin

CHAPTER FOUR

CONCEPTUAL MODEL DEVELOPMENT AND MODEL INPUT DATA PREPARTION

4.1 Introduction

A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross-section (Anderson and Woessner, 1992). Ground water flow models attempt to represent an actual ground water system with a mathematical counterpart, and the dimensions of the numerical model and the grid design depend on the nature of the conceptual model. The development of a conceptual model is the most important stage in ground water flow modeling work as it simplifies the field problem and makes the organization of the associated field data easier so that one can readily analyze the system. The initial stage of formulating a conceptual model is to define the study area (boundaries of the model) and the conceptual model should be a valid representation of the important hydrogeologic conditions. It is worth mentioning that before making any attempt of ground water flow modeling, the system should be conceptualized and all important data for the modeling work should be assembled in to the conceptual model. Significant steps in building a conceptual model include:

- defining hydrostratigraphic units
- preparing a water budget (from stresses)
- defining a flow system
- boundary conditions

To define hydrostratigraphic units it is good to rely on hydrogeologic information. Site specific information on stratigraphy and hydraulic conductivity data is required to synthesize hydrogeologic information that is used to identify different hydrostratigraphic units.

Moreover, a conceptual model should consist of the source of water as well as the expected flow directions and out flows. From the total inflows (recharge) and outflows (sub surface outflow, well withdrawal, spring discharge and base flow) in the system, a water budget should be prepared to summarize the magnitudes of different flows and change in storage (in this case zero).

As discussed in chapter one section 1.3.1, to conceptualize the movement of groundwater through the system, hydrologic information on precipitation, recharge, water level head, base flow, subsurface outflow and geochemical information were employed for the purpose of this study. Water level measurements are used to estimate flow direction and show connections between aquifers and surface waters.

4.2 Hydrogeology of Fafan River Valley

As previously been discussed, the area is covered with Precambrian crystalline basement rocks, Mesozoic sedimentary rock succession, Tertiary volcanic and sedimentary rock successions occur and have variable hydraulic characteristics that cover the full range of possible values found in natural systems. Basically, hydrogeology deals with the behavior of geological materials towards the interaction with, storage and transmissions of ground water. Based on their degree of storage and transmissions of ground water, geologic materials can be classified into three: geologic materials that store and transmit water are aquifers, those that can store but don't transmit water are aquicludes and those which can neither store nor transmit water are aquifuges. For a rock to yield sufficient quantity of water, in addition to its high permeability, it should be underlain by a geologic material of low or nil permeability on which water accumulates. As discussed in the preceding sections, it is clear that basic surface and subsurface geology and knowledge of local and regional structures of an area are decisive elements to the understanding of hydrogeology of an area.

Hydrogeologically, the study area is grouped into valley field with unconsolidated alluvial aquifer. Different aquifers have different hydrogeological characteristics, that is, lithologically different rocks with similar hydrogeological behavior can be grouped into one class or lithologically similar rocks of different hydrogeological characteristics can be considered different in relation to their water yielding capacity. Previous works show that the Fafan river valley is composed of primary porosity; alluvial sediments aquifers. The hydrogeology of the watersheds was classified in to aquicludes and aquifers categories based on their productivity.

Accordingly, Major aquifers are alluvial field aquifer sequences excluding the mountain ranges, moderate aquifer of the sands and silts in which most of the hand dug wells located. Boreholes of variable discharges have been drilled in these aquifers and in most cases the yield is over 5 l/sec. The transmissivities of these aquifers vary between mean minimum value of 36.3 m^2/day and mean maximum of about 2180 m^2/day.

Poor aquifers are the mountain ranges of Karamara are no aquifers because are generally not considered as ground water containing materials in exploitable quantities.

Previous works show that unconfined aquifers are found in the catchment, but most of the aquifers are hydraulically interconnected which is justified by continuous piezometric surface that follows approximately the topographic surface. The ground water level in the catchment ranges from 2m to more than 18m below ground level.

The Upper Fafan River valley is part of Fafan sub basin in which a large number of hand dug wells were drilled by different individuals for various purposes at different times. Despite of this fact, most of the wells do not have a well data that is to its standard and those that have a well data are aligned with the stream of Fafan. This data scarcity has resulted in problem in mapping one of the model input parameter, hydraulic conductivity. In addition, there is no access to take ground water level measurements as the wells do not have observation pipes in most cases.

As the aquifer was considered as a homogeneous, isotropic and single layer, its properties were not expected to vary vertically with in the considered thickness, but there is lateral variation from north to south. The thickness of this aquifer is roughly approximated to be 40-90m by using drilling depths and this value might be modified during model calibration.

4.3 Hydraulic conductivity

Hydraulic conductivity is a measure of the ability of a fluid to move through interconnected void spaces in sediments or rocks. It is a function of both the fluid and the medium. The higher the hydraulic conductivity of a rock/sediment, the higher the water yielding capacity of the rock is. The hydraulic conductivity of fractured rocks depends largely on the density of the fractures and width of their apertures.

Since the groundwater flow model was single-layered, only horizontal (lateral) hydraulic conductivities were relevant. The hydraulic conductivity is calculated from the pumping test analysis of available borehole data and interpolated on ARCGIS environment. The horizontal hydraulic conductivity of the upper Fafan sub basin varies entirely from the middle of the river towards the hills of Chinagsen Norther part. The variations of these hydraulic conductive values are due to the difference in the thickness of the alluvial aquifer. Accordingly, most of the wells and hand dug are concentrated near and along the river peripheries.

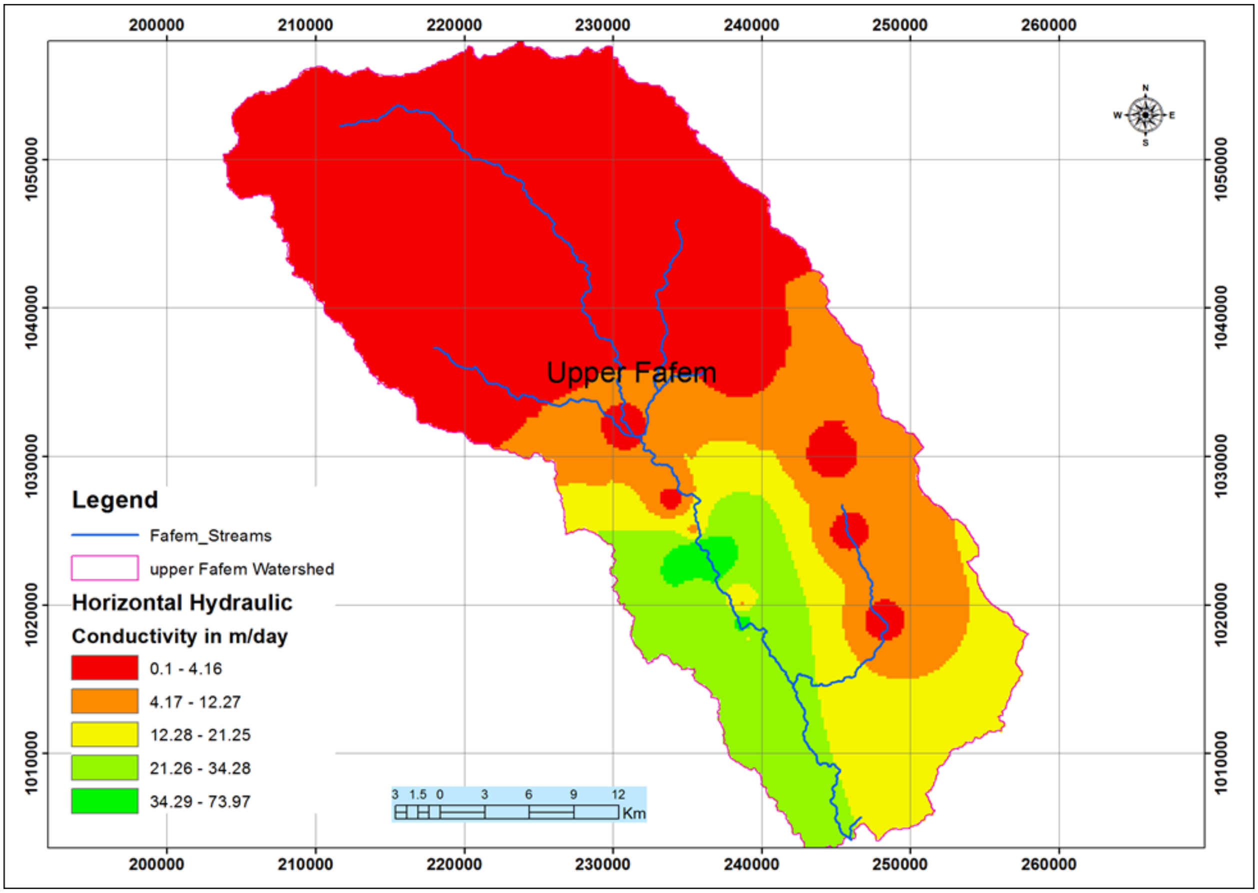


Figure 4.1 Horizontal Hydraulic conductivity of the Upper Fafan sub basin

4.4 Groundwater recharge estimation

Data in the physical structure explain the geometry of the system including thickness and areal extent of each hydro stratigraphic unit. Data within the hydrologic frame work include information on head sand fluxes, which are needed to formulate the conceptual model and check model calibration. Hydrogeologic data also define aquifer properties and hydrologics tresses. They include pumping, recharge and evapotranspiration. Recharge is the one of the most difficult parameters to estimate (Anderson & Woessner, 1990).

Groundwater recharge is defined as the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone (Freeze and Cherry 1979). Quantitative assessment of groundwater recharge is an important issue in groundwater development. Estimation of groundwater recharge requires proper understanding of the recharge and discharge process and their interrelationship with geological, geomorphological, soil, land use and climatic factors. The aquifer is recharged naturally by rainfall and also indirect recharge is taking place due to the excessive irrigation. There are various methods in use for the quantitative evaluation of groundwater recharge.

Groundwater recharge is one of the key parameters of a groundwater flow model. Different methods exist to estimate groundwater recharge. These methods can be divided into physical, chemical (tracer) and numerical modeling approaches. The numerical model is useful and robust tools to quantify recharge. SWAT modeling or sometimes referred to as watershed modeling is a surface-water focused approach, which generally yield groundwater recharge estimates as a residual term in the water budget equation (Wanke, Dünkeloh & Udluft, 2008).

In this study, the estimated recharge was considered as net recharge, i.e. the actual portion of water reaching the water table after being withdrawn by plants in the root zone, thereby excluding the need for the evapotranspiration parameter. Recharge rates were greater for higher altitude areas, and less for the rest low land areas of the model. Zone located in the lower part contributes low recharge and it is increasing to the upper part of the catchment. Irrigation return flow is water that is applied as irrigation but not taken up by the crops and returns to the aquifer, which may occur in the irrigated areas where row watering is used. For this study it is assumed that return flow from irrigation system is insignificant due to the unavailability of reliable data. Hence irrigation return flow will not be accounted for in the model directly. However, the calibration process will automatically offer an indirect way to account for this recharge. But for this study, it is assumed that return flow from irrigation systems is insignificant.

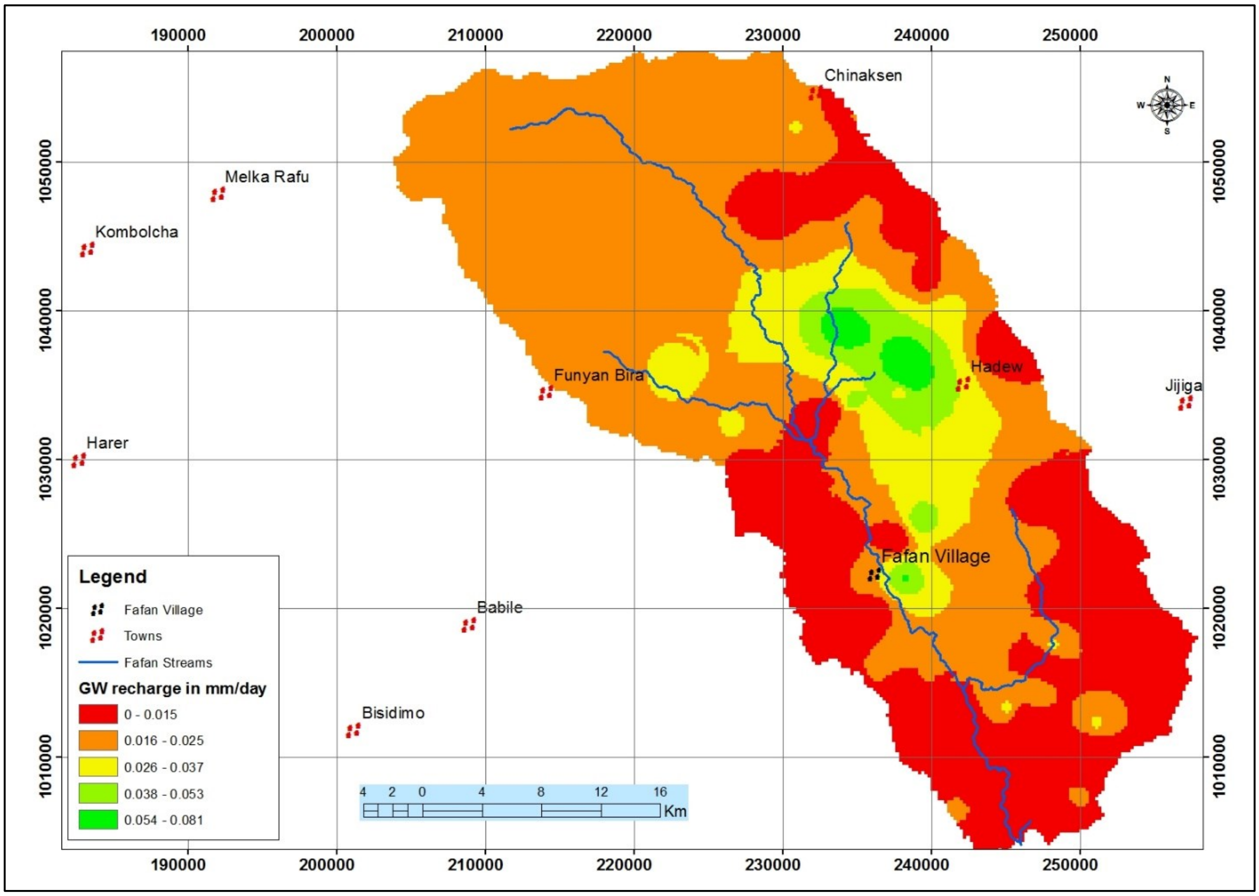


Figure4.2 Groundwater Recharge of the study area

4.5 Pumping and Observation Wells

Groundwater is extract from the aquifer by means of drilled boreholes and dug wells. Dug wells are used for domestic purposes where there are no water supply schemes. These wells are usually shallow and water is withdrawn by human power. Volume extracted them are relatively low compare to the volume extracted by deep boreholes using hand pumps and electrical pumps for small scale irrigation and water supply schemes.

Water abstraction wells within the study area that are used for drinking, industrial and irrigation water supply were determined and major wells that withdraw groundwater more than 2 L/s were shortlisted to use as groundwater sinks in the model. A total of 19 individual water supply wells and wellfields were considered in the model. The locations of these wells are shown in figure4.5. This are the well that have record of the measurement of the groundwater level data for the preparation of the calibration and verification model output hydraulic head.

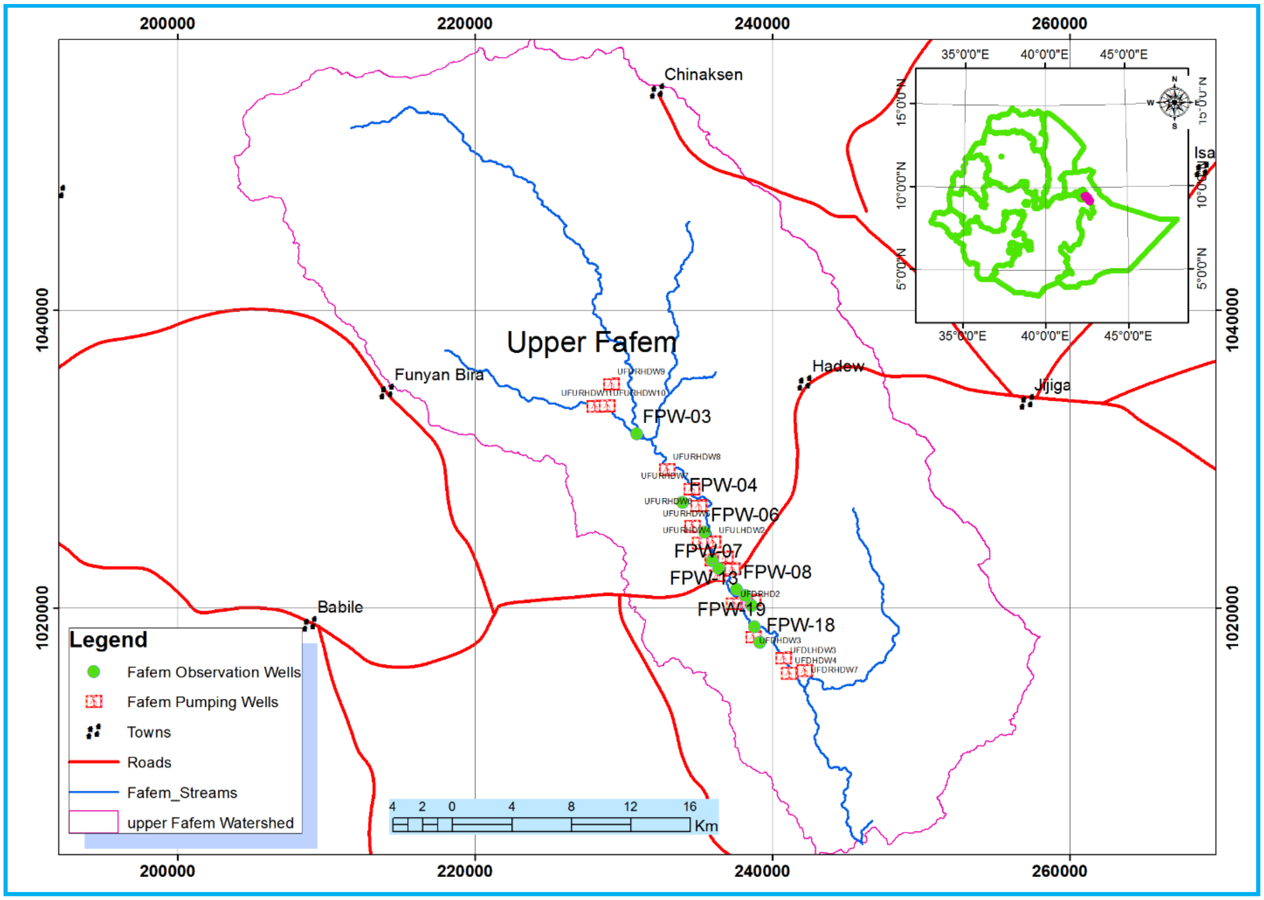


Figure4.3 Observation and pumping Boreholes in the watershed

4.6 Conceptual Model

The size of the modeling domain was taken as the same as the extent of the study area watershed in figure 4.4. The boundaries of the model were determined such that it comprises the entire area of interest and coincides with hydrological boundaries. The modeling domain was divided up (discretized) into equal-sized 200×200 m finite-difference grid cells. Furthermore, more than 10 borehole logs were processed to determine the depth to the impermeable layers, which were subsequently interpolated to achieve the surface representing the bottom surface of the model layer. The top surface of the model was picked up from 30m-resolution DEM data (NASA' Digital Elevation Model). The unconfined aquifer with the study area boundaries was modeled as one layer, with the MODFLOW setting 'LAYCON=1, unconfined'.

4.7 Stratigraphic Units and Aquifer Geometry

Identification of hydrostratigraphic units is crucial in determining the number of layers controlling groundwater flow within the system. A hydrostratigraphic unit is comprised of geological units of similar hydro geological properties. Numerous geological units may be grouped together or a single formation may be subdivided into different aquifers and aquitards (Anderson and Woessner, 1992).

From the drilling lithological description and well logs the stratigraphic units are lumped in to two that is alluvial valley field and basement complexes'. The alluvial section is mainly taken as the main aquifer of the watershed with a depth up to 90m from the surface and with a composite of no or a few clay cover, fine to coarse sand and gravel underlain by slightly weathered undifferentiated basement complexes. The well log picture in annex illustrates a more descriptive image of the stratigraphy.

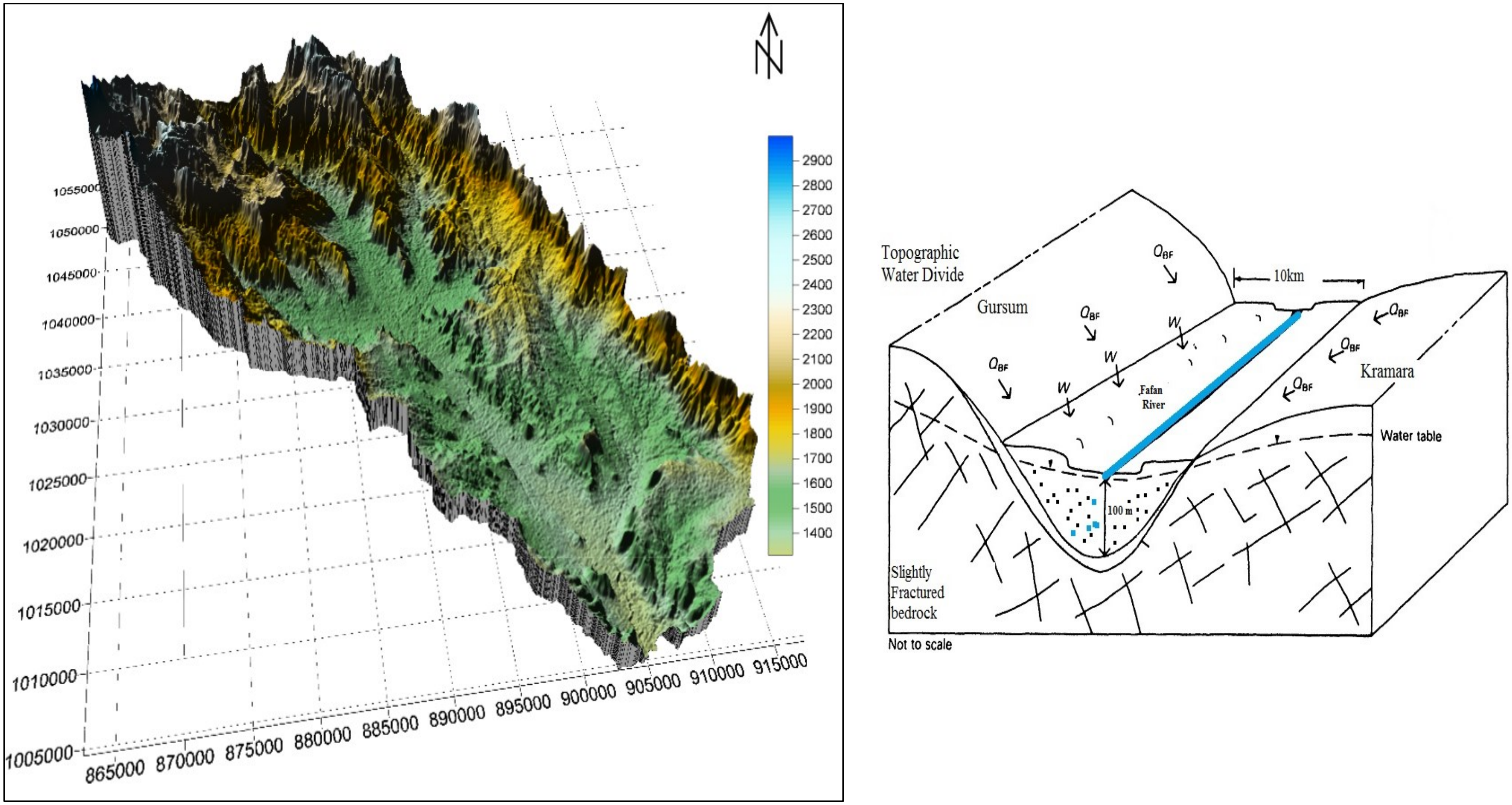


Figure4.4 Conceptual model development of Fafan River Valley

CHAPTER FIVE

NUMERICAL GROUNDWATER FLOW MODELING OF UPPER FAFAN SUB BASIN

5.1 Introduction

The groundwater flow equations that comprise the groundwater flow model of this study were solved using the model code MODFLOW-2000 that is based on the finite-difference method. The groundwater flow model was set up as a one-layered, local and steady-state condition. The purpose of the model was to simulate groundwater flow of the unconfined aquifer, and thereby calculate the distribution of water table elevations and groundwater fluxes to manage the groundwater system in the sub basin.

5.2 Top of layer

It is the top elevation of the aquifer layer under consideration. In this study, the aquifer was considered to be single layer and unconfined. Generally, the top layer elevation was considered to be the elevation of ground surface and in this case nodal values of ground surface elevation were interpolated from USGS digital elevation data. The interpolation was done at a resolution of 200m by 200m and then loaded into MODFLOW top elevation array.

5.3 Bottom of layer

It is the bottom elevation of aquifer layer being modeled. In this study, the aquifer thickness lie down within the range of 40-90m in most parts of the watershed except along the boundaries where ridges with high elevation are found. Higher altitude zones were simulated by assigning relatively higher depths at the cells in order to escape drying of cells during simulations. Therefore, bottom layer was acquired by subtracting a range of 50-90m from elevation top in most parts of the sub basin. In fact, the thicknesses of the aquifers are very irregular as it has not yet been determined exactly for the aquifers and was modified a bit in few areas during model calibration process.

5.4 Initial and Prescribed Hydraulic Head

It is the initial stage at which ground water level stood in aquifer system. Processing MODFLOW pro needs this initial heads to start simulation. For this simulation, it was obtained by subtracting a constant (that approximates static water levels) over a large area from the layer top elevation. Based on this, the catchment was sub divided broadly into two: the northern part of the catchment where water that recharges to aquifer comes to the ground as local flow systems, the initial hydraulic head was approximated to be equal to or less than the topographic elevation in few meters. In the central and southern part of the catchment the initial hydraulic head was approximated to be 5m below the ground elevation. The real value of water level elevation was given as initial heads in active cells.

5.5 Boundary Conditions

Boundaries of the groundwater flow model were defined as geological and hydrological features that influence the pattern of groundwater flow such as topographic divide, water table divides, watershed boundaries, faults, surface water features and outcrops. The model boundaries and the types of boundary conditions the study domain are shown in figure 5.1. The boundaries of the model coincided mostly with the topographic water divide of the Upper Fafan river basin. Only the two types of boundary conditions, namely defined flux (no-flow) and mixed-type (Cauchy), were functional in this study. Boundary conditions used in the model are discussed in the following subdivisions.

5.5.1 No-Flow Boundaries

Model boundaries that overlap with watershed boundaries were defined as no flow boundaries. For example, the no-flow boundaries in the west of the model domain coincide with Western boundaries of the Babile watershed boundaries. Correspondingly, the no-flow boundary in the East overlaps with the Jerer sub basin boundary. The boundary in the North of the model province is based on the topographical divide of the Karamara Mountain range and Chinaksen hills, with the postulation that the groundwater divide coincides with this topographical divide.

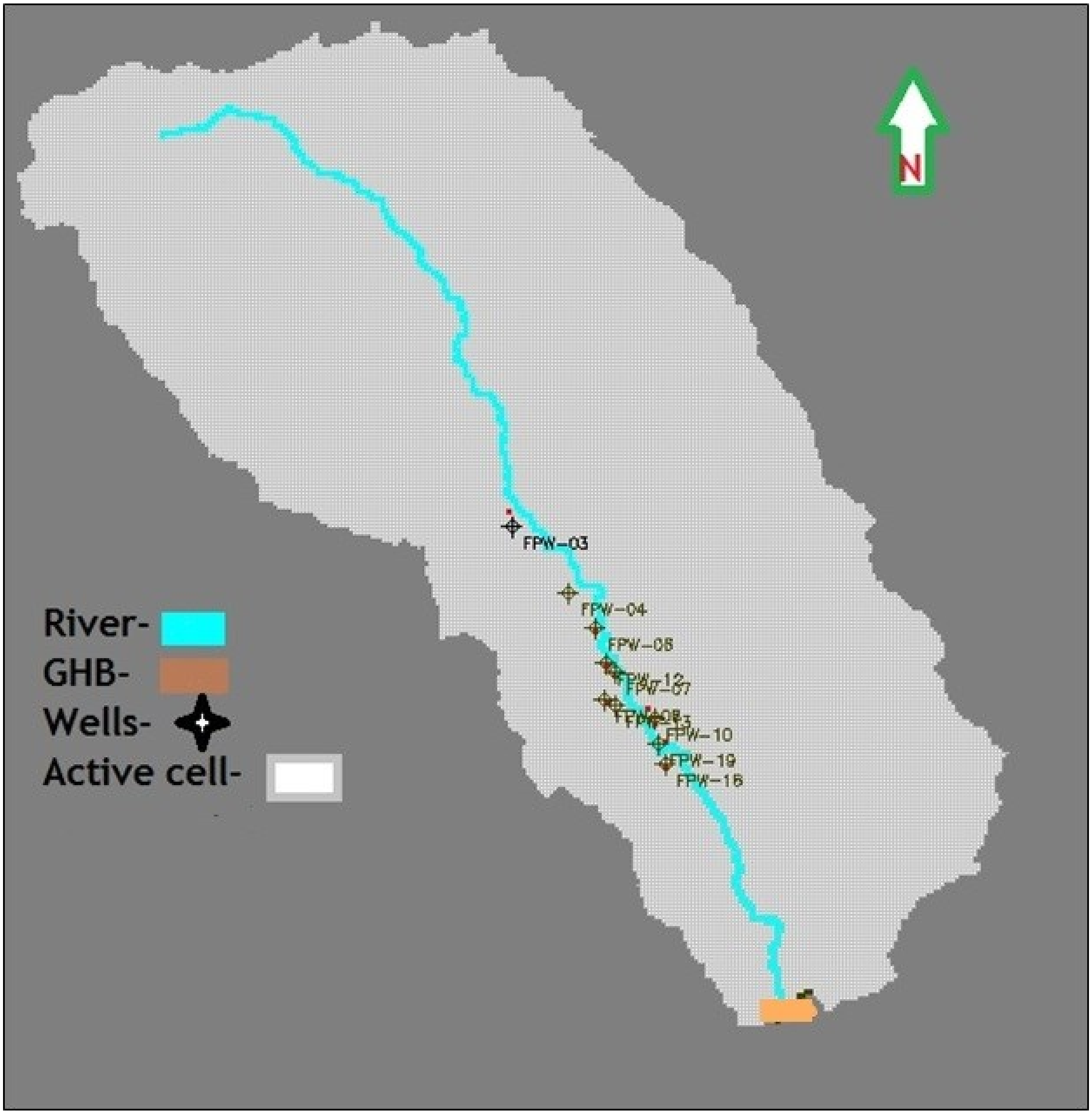


Figure 5.1 Boundary conditions of the study area

5.5.2 General-Head Boundaries (GHB)

General-head boundaries (GHB) are third-type boundary conditions, which are basically head-dependent. The water flux at the boundary is fundamentally a function of the lateral head gradient and a given conductance, similar to the hypothetic of the river package in MODFLOW, only that the GHBs disturb groundwater flux in the lateral direction. Boundaries of the model that could neither are assigned as no-flow or constant head were defined as GHBs, which permitted groundwater flux interactions with neighboring aquifers. GHBs require the assignment of two parameters; a conductance value and head value representing a distant constant-head boundary. In this model simulation, Conductance values in the order of magnitude of $10^3 m^2/d$ were used and varied during the manual pre-calibration process. The GHB head values were initially anticipated using head values that were measured in neighboring monitoring wells. They were also varied during the pre-calibration process. However, for the verification run of the model the GHB head values were reduced to accommodate dry summer conditions.

The General-Head Boundary Package requires the following information for each General-Head grid cell:

Boundary Head: This is the head of the external source/sink. This head may be physically based, such as a large lake, or may be obtained through model calibration.

Conductance: The conductance is a numerical parameter that represents the resistance to flow between the boundary head and the model domain. In contrast to the River, Drain, and ET Packages, the GHB Package provides no limiting value of head to bind the linear function in either direction. Therefore, as the head difference between a model cell and the boundary head increases/decreases, flow into or out of the cell continues to increase without limit.

Consequently, care must be used to guarantee that impractical flows into or out of the system do not develop during the simulation. The conductance value may be actually based; representing the conductance connected with an aquifer between the model area and a large lake, or may be obtained through model calibration.

The Conductance value (C) for the scenarios illustrated in the preceding figure may be calculated using the following formula:

$$C = \frac{(L \times W) \times K}{D}$$

Whereas, (LxW) is the surface area of the grid cell face exchanging flow with the external source/sink, K is the average hydraulic conductivity of the aquifer material separating the external source/sink from the model grid, D is the distance from the external source/sink to the model grid

5.5.3 River Package

The River Package is used to simulate the flow of water between an aquifer and an overlying (or underlying) source reservoir which is usually a river or lake. The code described by McDonald and Harbaugh (1988) contains the RIV package. It allows water to flow from the aquifer to the source reservoir, thereby removing water from the model by seepage to gaining stream reaches. Water can also flow out of the stream into the aquifer but the seepage out of the stream is independent of the stream discharge. Thus, a losing reach of stream could recharge the aquifer with more water than is being carried in the stream. No adjustment is made in stream stage. Even with these limitations, the RIV package adequately represents most surface groundwater systems.

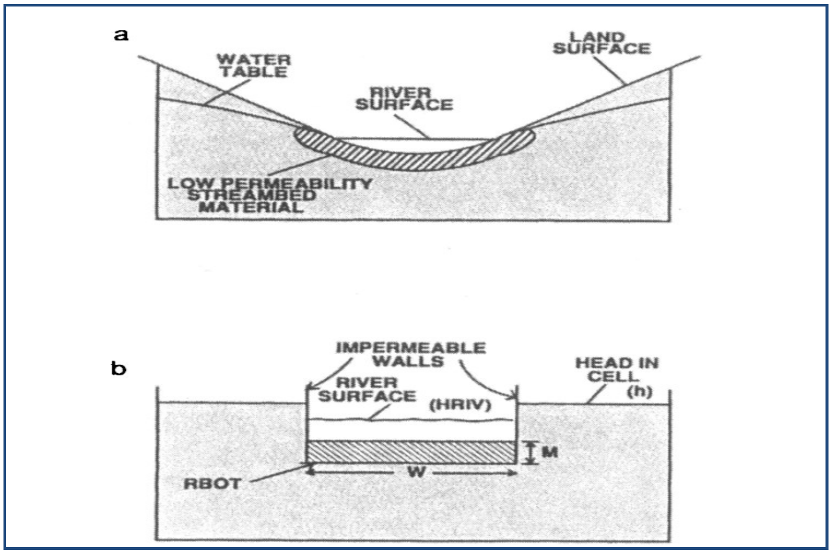


Figure 5.2 (a) Stream- Aquifer System (b) Representation of the stream-aquifer system in the RIV Package (Adapted from Visual Modflow software help file)

The RIV package uses the river bed conductance (CRIV) to account for the length (L) and width (W) of the river channel in the cell, the thickness of the river bed sediments (M), and their vertical hydraulic conductivity (Kr)

Whereas, $CRIV = Kr\,LW/M$ (1a)

The rate of leakage between the river and the aquifer (QRIV) is calculated from (2a)

$QRIV = CRIV\,(HRIV - h) \quad h > RBOT$ (2a)

Where HRIV is the head in the source reservoir and

h is the head in the aquifer directly below the source reservoir (Fig.5.2b).

When the water table falls below the bottom of the stream bed (RBOT), leakage stabilizes and QRIV is calculated from

$QRIV = CRIV\,(HRIV - RBOT) \quad h < RBOT$ (2b)

When the RIV package is used to simulate a leaky confined aquifer,

CRIV is the leakance parameter of the confining bed and

HRIV is the head in the overlying (or underlying) source bed.

5.6 Groundwater Flow Model Setup and Execution

5.6.1 Numerical Model

Numerical model development allows for a detailed analysis of the movement of water through the hydrologic units that constitute the groundwater flow system. The groundwater flow in the unconsolidated deposit of the Upper Fafan valley was simulated using the U.S. Geological Survey modular three – dimensional finite- difference groundwater flow model, MODFLOW (McDonald and Harbaugh, 1988). This numerical modelling was performed using the interface of Processing Modflow Pro (PMWIN Pro), Version 8.0 (Chiang and Kinzelbach, 2001) as code environments for the data input and output management. PMWIN Pro supports MODFLOW- 2000, PEST-ASP, different packages, and models/programs. It is founded on the physical theory of groundwater movement: Darcy’s law and the continuity equation. The steady- state groundwater flow is simulated based on the following governing differential equation under three dimensional aerial view (Anderson and Woessner, 1992).

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

Where: Kx, Ky and Kz are Components of the hydraulic conductivities along x, y &z axes [LT^{-1}]

h = Hydraulic head [L]

Basic Assumption

1) The lateral boundaries of the aquifer are impermeable (no flow is allowed).
2) The rocks underneath the aquifer are impermeable.
3) The river penetrates partially the aquifer and has vertical banks.
4) The river is not separated from the aquifer by any confining material.
5) The aquifer is unconfined and Darcy's Law is valid.
6) The flow of groundwater is horizontal.
7) The groundwater level in the river bed is constant along its length and with time.
8) The infiltration of recharge to the aquifer is instantaneous (the assumption is no delay between the time precipitation infiltrates the surface until it reaches the water table which means the effect of vadose zone is negligible).

5.6.2 Model execution and Calibration

Calibration verifies that the simulation is reproducing field measured heads and flows (Anderson and Woessner1992). It engages regulation and modification of parameter structure and values to provide the best match between measured and calculated hydraulic heads and flows. Steady-state calibration was made using static water level observations of 10 wells. In the course of calibration adjustments on aquifer thickness and hydraulic conductivity were made within sensible ranges based on field hydrogeological observations and pumping test data.

According to Anderson and Woessner, "calibration can be accomplished in two method using forward and inverse problem solutions. In an inverse solution method one establish values for a given parameter structure and hydrologic stress using a mathematical technique, such as non-linear regression from information about head distribution (Anderson and Woessner1992)". This method is on occasion called parameter estimation and it finds the set of parameter values that minimize the difference between simulated and measured quantities such as hydraulic heads and flows. The forward problem calibrated parameters, such as hydraulic conductivity and hydrologic stresses, are specified and the model calculates the head distribution.

In this study, the parameter estimation was used by a trial and error method in which model parameters were step manually within practical limits of the existing data and field hydrogeological observations to achieve the best fit. The effectiveness of calibration was evaluated by comparing measured heads with simulated heads for all observation wells used. Two calibration criteria were used: visual matching of simulated contours to those of observed contours and matching simulated hydraulic heads at 90% of the points to within 5 m of the observed hydraulic heads. The model was assumed to be calibrated when the fit between observed and calibrated heads was within this criteria and simulated groundwater contours (Fig.5.4). The correlation coefficient was found to be 0.99 after calibration (Fig. 5.3).

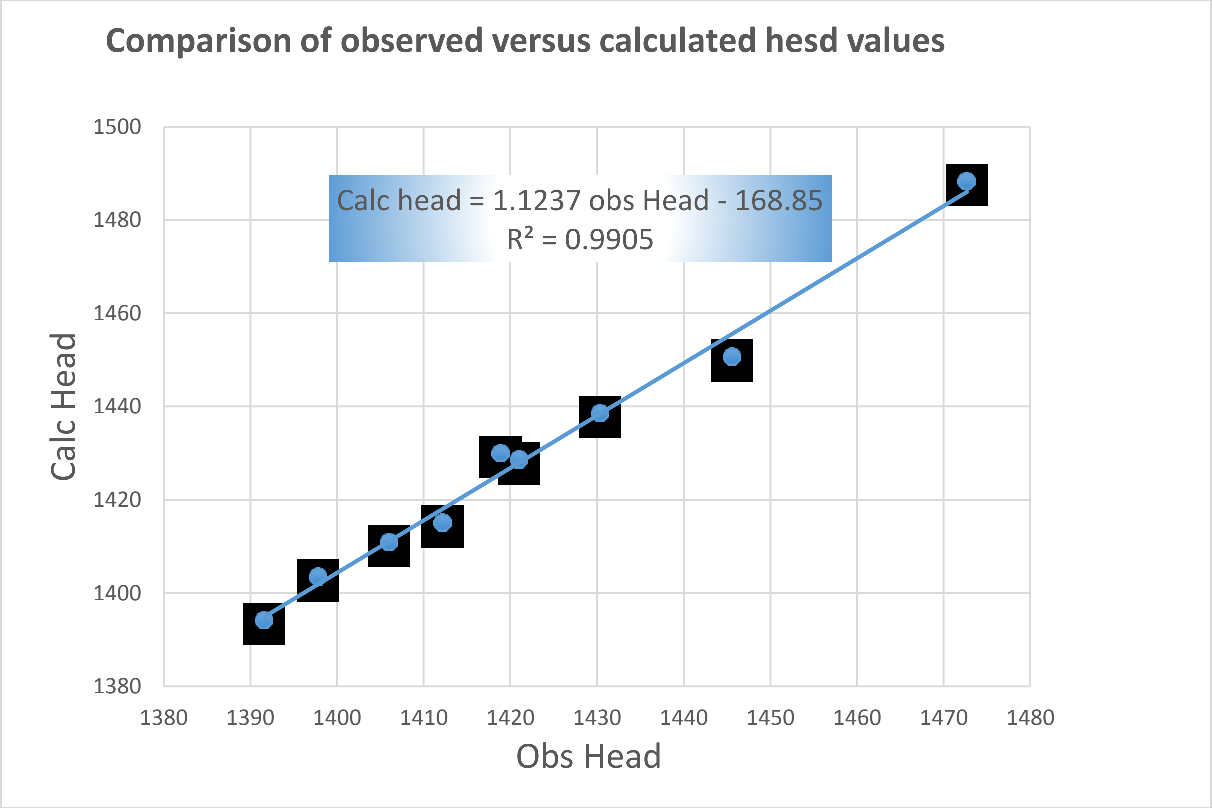


Figure 5.3 Comparison of Calculated and Observed heads

5.7 Model Calibration Verification and Uncertainty

5.7.1 Trial and Error Calibration

These model parameters were handled as calibration parameters, which were varied within a plausible range of values during the calibration process. Calibration of the model was performed automatically using the parameter estimation code PEST (Doherty, 2004). The purpose of the calibration process was to correct the calibration parameters in an organized manner in order to obtain a reasonable match between measured water table elevations and the calculated values by the model. The model was pre-calibrated manually on a trial-and-error basis before the automatic calibration procedure with PEST was initiated. Thereby, a best possible starting point was achieved for the automatic calibration, which resulted in a more robust performance of the parameter estimation process with PEST.

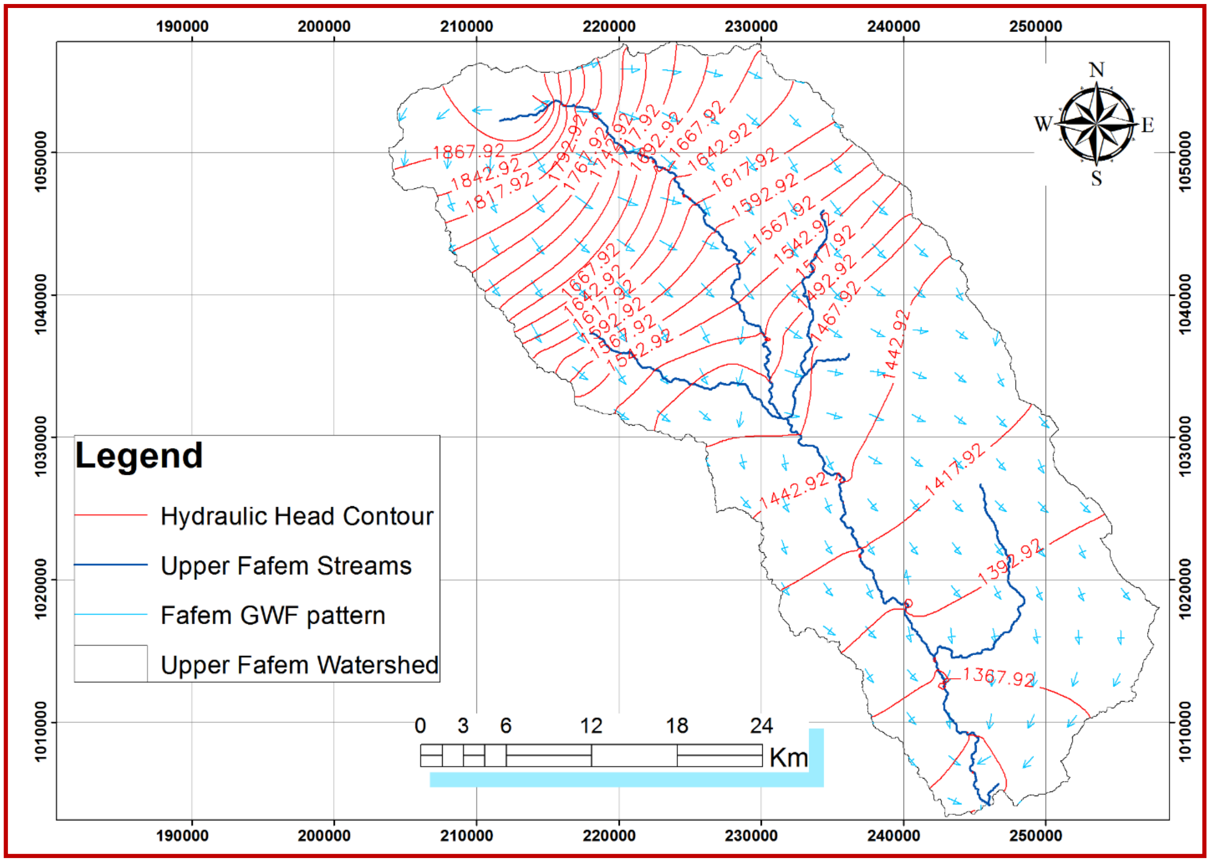


Figure 5.4 Calibrated Groundwater flow pattern with Hydraulic head of the model output of the watershed

5.7.2 Evaluation of calibration

5.7.2.1 Root Mean Squared Error (RMSE)

The Root Mean Square Error (**RMSE**) (also called the root mean square deviation, RMSD) is a regularly used to measure the difference between values predicted by a model and the values actually observed from the field data that is being modelled. The use of RMSE is very common and it makes an excellent general purpose error metric for numerical predictions. Compared to the similar Mean Absolute Error, RMSE amplifies and severely punishes large errors. Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. Root mean square error is commonly used in climatology, forecasting, and regression analysis to verify experimental results.

- The RMSE of a model prediction with respect to the estimated variable X_{model} is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

Where X_{obs} is observed values and X_{model} is modeled values at time/place i.

The RMSE values can be used to distinguish model performance in a calibration period with that of a validation period as well as to compare the individual model performance to that of other predictive models. When standardized observations and forecasts are used as RMSE inputs, there is a direct relationship with the correlation coefficient.

Table 5. 1 Statistics for the calibrated model

Measures	Calibrated
Residual Mean (m)	7.01
Root mean square error (RMSE) (m)	8.42
Sum of residual squares (m2)	638.29
Min. Residual (m)	2.58
Max. Residual (m)	15.63
Range in Target Values (m)	13.05
Standard Deviation	4.17
Std. Dev./Range of observed values (%)	4.23

CHAPTER SIX

RESULTS AND DISCUSSIONS

6.1 Water Budget of the model domain

The water budget for steady-state simulation is balanced with a percent of discrepancy of [%] 0.01. In the model area, the inflow term includes the recharge and head dependent boundary whereas, the outflow term includes wells, river leakage and head dependent boundary. The model result shows both inflow and outflow are in balance which is consistent with the steady-state modelling theory.

Based on the modeling results a strong inflow of groundwater toward the watershed was observed at the foothills of the Karamara Mountain, in the northeast of the study area. The flow directions towards the river varied significantly, influenced mainly by stream-aquifer interactions and groundwater withdrawals. Water budget results of the model, shown in Table 6.1, revealed that groundwater recharge comprised about 0.2% of the total water input for the entire study area. Recharge was the second largest component in the budget after leakage from river into the subsurface. It is also observed that there is a significant amount of ground water influx towards the river, when ground water flow directions in the surrounding area of the river are examined.

The water budget of the model domain is used to quantify and identify all flows in and out of the aquifer structure. This water budget of the model area quantitatively evaluates the amount of groundwater through an aquifer system. Even though, the in-flow and outflow components of groundwater system are the most difficult to calculate directly, both components were computed by the model.

Model calibration was achieved through trial and error approach until the simulated head fit the observed head values to a satisfactory degree. The calibration result indicated a reasonably match between simulated and observed heads with RMS error of 8.42m. From the contour map of simulated heads, it was noted that a flow direction is in agreement with the flow of conceptual model. Therefore, the calibrated groundwater flow for this study area especially the sub-basin was able to simulate the measured head.

The hydraulic conductivity values for the Fafan valley aquifer were taken from pump test data analysis. The main target of this test was to evaluate well properties rather than aquifer properties and the values may be in accurate to represent the whole model area. This may increase the uncertainty in the distribution of the parameter. Even though, the hydraulic valve obtained from pump test data analysis indicated high spatial variation, possible effort was tried to optimize the hydraulic properties during calibration process by considering the reasonable range of valves from pump test data analysis. The hydraulic conductivity obtained from pump test data analysis ranges from 1 to73 m/d, on the other hand, model calibrated values mostly ranges 0.1 to 40 m/d.

Table 6. 1Water budget of the calibrated model

	WATER BUGET WITHOUT WELL ABSTRUCTION			WATER BUGET WITH WELL ABSTRUCTION			WATER BUGET WITHOUT WELL ABSTRUCTION			WATER BUGET WITHOUT WELL ABSTRUCTION		
FLOW TERM [L^3/T]	IN	OUT	IN-OUT	IN	OUT	IN-OUT	IN	OUT	IN-OUT	IN	OUT	IN-OUT
WELLS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.72E+04	-2.72E+04	0.00E+00	4.08E+04	-4.08E+04	0.00E+00	5.44E+04	-5.44E+04
RECHARGE	1.77E+03	0.00E+00	1.77E+03	1.77E+03	0.00E+00	1.77E+03	1.77E+03	0.00E+00	1.77E+03	1.77E+03	0.00E+00	1.77E+03
RIVER LEAKAGE	2.48E+06	2.45E+06	3.22E+04	2.49E+06	2.43E+06	5.94E+04	2.50E+06	2.43E+06	7.30E+04	2.50E+06	2.42E+06	8.66E+04
HEAD DEP BOUNDS	1.01E+04	4.39E+04	-3.38E+04	1.01E+04	4.39E+04	-3.38E+04	1.01E+04	4.39E+04	-3.38E+04	1.01E+04	4.39E+04	-3.38E+04
SUM	2.49E+06	2.49E+06	2.06E+02	2.50E+06	2.50E+06	1.80E+02	2.51E+06	2.51E+06	1.99E+02	2.52E+06	2.52E+06	1.86E+02
DISCREPANCY [%]	1.00E-02			1.00E-02			1.00E-02			1.00E-02		

6.2 Sensitivity Analysis

Sensitivity analysis is the measure of uncertainty in the calibrated model caused by uncertainty in aquifer parameters and boundary conditions. The Sensitivity analysis was performed by systematically changing the calibrated values of conditions (Anderson and Woessner, 1992).

Therefore, main objective of a sensitivity analysis is to recognize the influence of various model input parameters and hydrological stresses on the aquifer system and to identify the most sensible parameter(s), which will need a special attention in future studies.

As a result, by running the calibrated model for the respective changed values of the input parameter and comparing the result with the calibrated head, the parameter(s) sensitive to the model was established. The parameter values were varied within a reasonable range. Thus, it is important step in modelling studies.

Accordingly, the model in this studied area was highly sensitive with decrease of the calibrated recharge and hydraulic conductivity values and relatively less sensitive with increasing these values which result in lower RMS error. Sensitivity analysis was carried out, in this study, to understand uncertainty in the calibrated model caused by uncertainties in the estimates of aquifer parameters and stresses.

Groundwater models are sensitive to different model input parameters variably and parameters for which the model is most sensitive, small changes in those parameters will result in large differences in simulated heads or fluxes. The response of the calibrated numerical model to changes in model parameters like hydraulic conductivity and recharge was examined. During simulation when the effect of one parameter was being tested, the other parameters were kept to the steady state calibrated value and each parameter was changed uniformly over the whole area. The magnitude of changes in heads or fluxes from the calibrated solution was used as a measure of the sensitivity of the model to that particular parameter. Sensitivity analysis test was done using recharge and hydraulic conductivities as the model was most sensitive to them.

The calibrated values of river leakage, recharge and hydraulic conductivity were varied by ±50% and ±75% at different times to test the sensitivity of the model to the parameters. A total of twelve model runs have been made by changing the hydraulic conductivity only, by the specified percent and the respective root mean squared head changes in percent from the calibrated value are shown in table 6.2.

In all simulations, it was observed that the model was highly sensitive to Hydraulic Conductivity parameter changes meanwhile it is moderately and less sensitive for changes in River Leakage and recharge parameter respectively.

Table 6. 2 Sensitivity head observation of the calibrated model with varied Hydraulic conductivity

	Percent change in sensitivity parameter from the calibrated value	**Percent respective RMS head change from the calibrated value**
1	Hydraulic conductivity (HK) decreased by 50 and 75	380.68 and 104.55
2	Hydraulic conductivity(HK) increased by 50 and 75	21.78 and 26.13

3	Recharge increased by 50 and 75	0.34 and 0.51
4	Recharge decreased by 50 and 75	0.18 and 0.36
5	River leakage increased by 50 and 75	15.61 and 20.77
6	River leakage decreased by 50 and 75	86.21 and 35.51

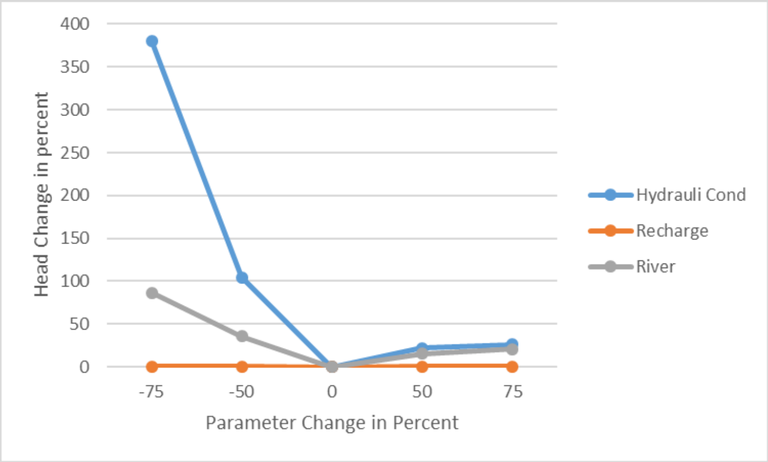


Figure 6. 1 Sensitivity Analysis Test on Heads Vs Hydraulic Conductivity

6.3 Pumping Scenario

In order to evaluate the response of the groundwater system under different groundwater abstraction rates, pumping scenario analysis were computed. The groundwater system response was compared with resulting changes in water level (drawdown) and groundwater outflow from the model domain. Even though, there was limitation in recording data how the groundwater has been abstracted currently, some estimation was done based on the information gained from project area.

In this study, the model was run for two pumping scenarios besides the current situation and the result was interpreted for each condition. In current condition, a total of 27200m^3/d was abstracted resulting in an average decline of groundwater level at the pumping well about 7.59m. Correspondingly, a total of 40800 m^3/d and 54400 m^3/d abstracted water resulted in an average decline of groundwater level at the pumping well by 7.65m and 7.69m in simulation one and simulation two respectively. The groundwater level decline is further observed where the wells are located very far from the streams for the wells FPW-04 and FPW-18 and at the upper part of the watershed for the well FPW-03. This indicates that the river bed has high capacity of hydraulic conductance.

6.4 Groundwater reserve and allowable exploitation

The total subsurface water reserve is a function of saturated thickness and storage coefficient/specific yield. The aquifer system is generalized into water table aquifer of the sediment. The average saturated thickness is 60 m in the whole sub basins. The groundwater reserve is computed applying the following formula.

$$\mathbf{V = Sy * A * H}$$

Whereas, **V**= Reserve (m^3)

Sy = Specific yield (0.1 for Fafan valley taken from pump test data)

A = surface area of the aquifer (m^2)

H = saturated thickness (m)

Total surface area of the Upper Fafan river valley aquifer is calculated to be 1400Km^2 and the saturated thickness of the unconsolidated sediment id to be 35m the total groundwater reserve of the Fafan river valley was calculated as 4900MCM for the whole sub-basin. By taking the allowable extraction of groundwater is to be 30% of the saturated thickness of the alluvial aquifer, the upper Fafan sub-basin have exploitable amount of water about 1470 MCM. Considering availability of exploitable groundwater amount and some basic assumptions such as the minimum radius of influence is 250m and a distance between wells is to be 500m in order to locate and propose additional 50 wells to be drilled and installed.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATION

7.1 General Discussion and Shortcomings

Ground water is the primary source of water supply of the towns and village in upper Fafan Sub basin as parts of the. As a result, the prospective of this precious resource should be properly assessed and managed through different hydrogeological investigation methods like flow models.

The upper Fafan river valley watershed is found in the North eastern Ogaden basin. The modeled area is part of Fafan river that is found at upstream of Fafan town and with an area of 1386km^2.

In this study, a homogeneous, an isotropic and a single layer aquifer was considered. Water level data was collected from 10 wells and the measured water levels in wells used for observation was about 5m. Ground water contours and flow directions were determined based on these observed heads. The general trend of groundwater flow direction was determined to be from northwest to southeast, with some local variations.

Ground water recharge is from precipitation and the amount is higher for the northeastern part relative to southern or central zones of the catchment. Discharges from the ground water system include well withdrawal, subsurface outflow and base flow to rivers. The inflow and outflow values agreed with in reasonable limits given the limitations in estimating the different flow components.

Numerical groundwater flow was used to study the response of the upper Fafan River valley groundwater system to different scenarios. As numerical groundwater flow models represent the simplification of complex natural systems, different parameters were input into the conceptual model to represent the system in a simplified form. The numerical groundwater flow model was simulated using MODFLOW, 1996 (McDonald and Harbaugh, 1988). The area was denoted by each cell size of 200m by 200m, arranged in 300 rows and 300 columns. A three dimensional profile model under steady state condition was developed to study the response of the system to different scenarios.

The model was calibrated using contours constructed from heads measured in 10 observation points. Recharge, hydraulic conductivity and river bed conductance were varied within reasonable limits during model calibration. Model calibration was considered sufficient when observed heads and simulated heads were within the calibration criteria set during to calibration, which includes visual comparison of simulated heads to calculated heads and fitting 98% simulated heads to calculated heads within a maximum difference of about 8m. Large differences between calibrated and observed heads at some places was due to the degree of accuracy of model input parameters, overall limitations of the model design like coarser grid size, or due to error in observed heads, etc. The simulated inflows and outflows in the steady state model were within reasonable limits of the observed inflows and outflows. The difference, especially lower observed inflow, was due to under estimation of recharge or exaggerated estimates in one of the outflows component.

Model simulated heads were found to be highly sensitive to hydraulic conductivity, but the degree varied from northern to southern part of the catchment. The northern part is more sensitive to changes in these parameter than the southern part. In general, if a model is more sensitive to one parameter than the others, the degree of uncertainty of that parameter will have a greater effect on the model results than the other parameters. So, care has been taken during the calibration of such a parameter to which the model was most sensitive.

As the model was intended to study the response of the hydrologic system, two scenarios of increased withdrawals were used to study the system. The effects of the scenarios were evaluated with respect to changes induced on stream leakage, subsurface outflow and groundwater heads compared to the steady state simulated values.

Accordingly, an increase in well withdrawal by 50% and 100% over the whole catchment resulted in an average decline of the steady state water level by 6cm and 10 cm, respectively and caused the steady state stream leakage to be reduced by about 2.92% and 3.46% respectively.

Generally, as extraction rate is increased initially it induces decline in water level but eventually, if the stress continues, the increasing groundwater pumping will begin to reduce natural discharge of groundwater. As seen from the simulation results, this was manifested by reduced river leakages or reduction in other discharge mechanisms.

The overall accuracy of the results of these simulations depends on future land use/ cover and hydrologic stress conditions. In addition, such scenario results will be applied for practical purposes if and only if the assumptions on which the simulations were based are valid, therefore the results should not be interpreted as perfect predictions, rather as system response projections. Moreover, the results should be interpreted and applied by considering all the limitations and drawbacks associated with the numerical model and knowledge gap of the modeler. Some of the inadequacies and restrictions of the developed groundwater flow model are discussed in the following below

1. Simulation of the ground water system was based on various assumptions regarding the real natural system being modeled. In this study, some of these assumptions were that the system was represented as single layer, the aquifer is unconfined and simulation was made assuming that the system is under steady state condition, which can never be known in the absence of long term water level data.
2. Trial and error calibration techniques, as surveyed in this study, don’t produce unique solutions and are expected to introduce uncertainties in model results.

3. The whole study area was discretized in to a number of cells of equal size (200m by 200m) and input into the numerical model for simulation. The level of discretization used was too coarse to include the effects at local scale, like the effects of structures. Moreover, the grid size used was not compatible with well diameters or river channel widths that are represented to have homogeneous properties in a cell. Their exact locations were approximated by the centers of the cells in which they occur.

4. It is conceivable that the well measurements did not reflect the true depth to the water table due to the fact that the monitoring wells were actually have very long well screens; mostly about 30 m. It is likely that this fact affected the performance of the model (see annex 2).

5. Connected to the previous point; the monitoring wells were screened over several aquifer units and sometimes over units with different properties. Therefore, the representativeness of the well measurements is somewhat questionable. However, conceptually the groundwater flow model would not be different if perfect measurements would be available, only the accuracy of the model would be better.

6. Monitoring wells are sparse in most parts of the study area. Accessible monitoring wells were unavailable in particular in mountainous parts of the study area or in areas where groundwater was either deep or not available.

7. The amount of groundwater withdrawal in the study area could only be grossly estimated. The actual amount is unknown and hard to quantify since numerous irrigation wells exist in the valley. Many wells are not licensed and are not accounted for by the water authorities. It is possible to enhance the groundwater flow model through more additions of pumping wells in the study area.

7.2 Recommendations

The presented groundwater flow model and the SWAT model can be undoubtedly improved. Also, the purpose and thereby the application of the model can be re-defined. Recommendations for future studies can be listed as follows:

1. Recharge rates used in the model can be modified to accommodate climate change scenarios to eventually assess the effects of climate change on water resources in the study area
2. Investigate more monitoring wells to improve the calibration of the model

3. Obtain more sets of monitoring data to improve the overall reliability and usability of the model
4. Inclusion of more pumping wells to account for a more accurate groundwater withdrawal
5. The model grids can be refined for more accuracy
6. Revisit the parameters and formulations of the SAWT model for higher model accuracy
7. Conduct particle-tracking simulation to support the interpretation of modeling result
8. The model results can be used as input for contaminant transport modeling studies in order to evaluate the effects of different land-use practices or diffuse pollution scenarios.
9. Geological and hydrogeological study of the valley should be further studied through widespread data collection in the future since the main focus for the development of groundwater resource is the unconsolidated alluvial fill which is likely to be the principal reservoir of sub-surface water in the sub basin.
10. Groundwater abstraction from irrigation as well as from water supply boreholes should be reported and recorded in data base periodically in order to evaluate seasonal and annual variations.
11. To represent the system in a more realistic condition, it is important to divide the aquifer system into different layers and estimate their respective hydraulic parameters.

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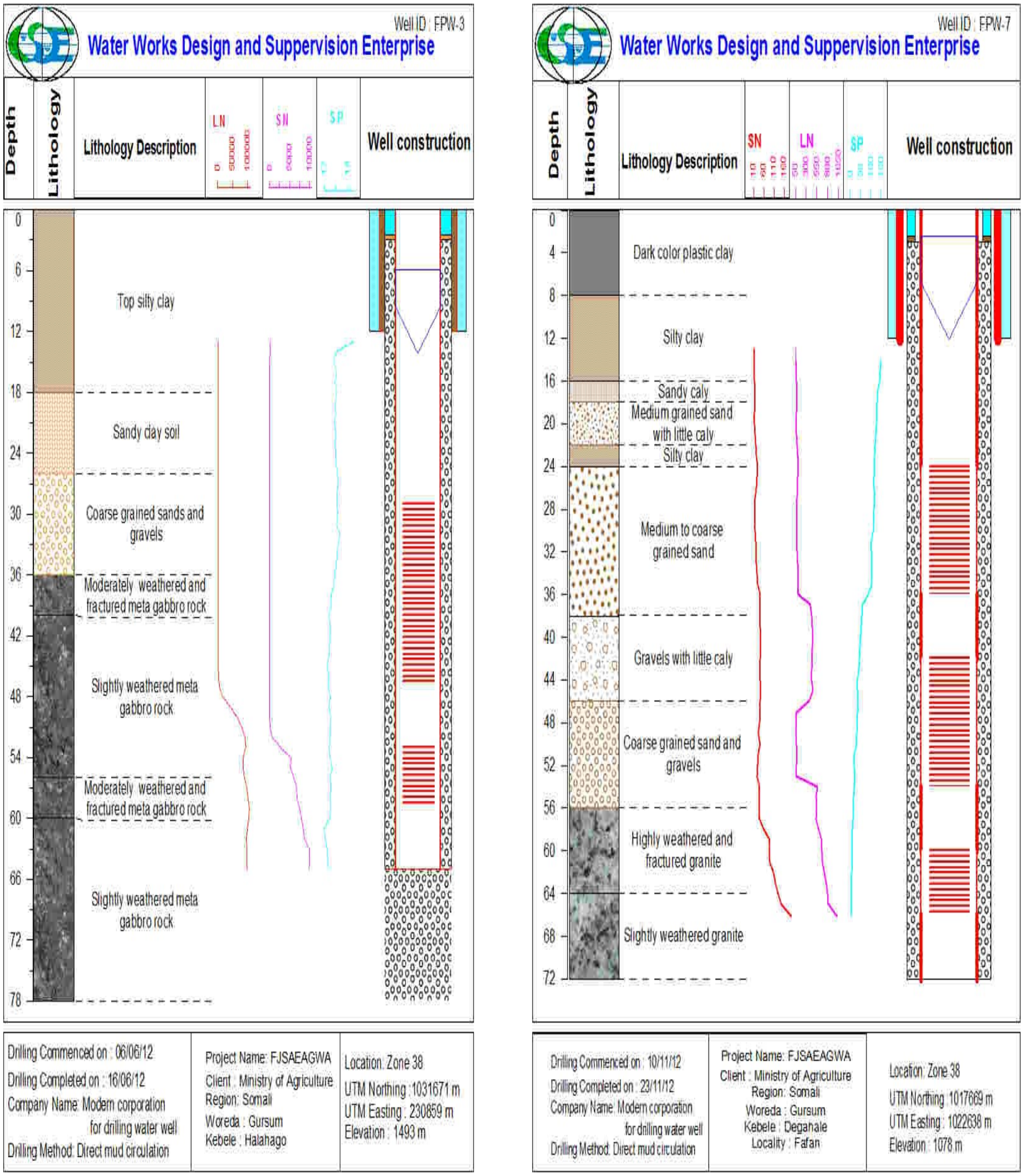
ANNEXES

Annex 1 The complete Well Data of the upper Fafan Sub basin

Well ID	Locality	X	Y	Z	Depth	SWL	Q (L/Sec)	DD	Specific Cap	T	Q (m3/d)	GWE	K Cons. (m/day)	K Rec. (m/day)	DDE
FPW-03	Halhago	230859	1031666	1493	65	4.68	13	25.8	0.5	36.3	1123.2	1488.32	1.56	2.07	1462.48
FPW-04	Halhago	233964	1027059	1469	99	18.31	4.9	34.6	0.14	77.5	423.36	1450.69	0.189	0.534	1416.05
FPW-06	Halhago	235430	1025082	1444	75	5.51	19.6	7.98	2.46	263	1693.44	1438.49	14.6	5.87	1430.51
FPW-12	Degahale	235950	1023167	1433	53	4.35	19.6	2.77	7.08	2180	1693.44	1428.65	75.5	73.9	1425.88
FPW-07	Degahale	236396	1022638	1432	72	1.37	33.7	3.54	9.52	1290	2911.68	1430.63	51.9	42.8	1427.09
FPW-13	Batey	238182	1020820	1418	58.5	2.89	15.5	10	1.55	304	1339.2	1415.11	22.9	13	1405.08
FPW-08	Degahale	238613	1020135	1420	59.7	2.6	15.1	7.4	2.02	295	1304.64	1417.4	42.1	13.2	1410
FPW-10	Batey	238613	1020135	1416	52.5	5.04	10	19.4	1.98	132	864	1410.96	15.9	7.76	1391.56
FPW-19	Tohadakesis	238777	1018737	1409	76.5	5.45	25.88	2.74	9.45	1200	2236.03	1403.55	42.6	39.8	1400.81
FPW-18	Dufeyis	239157	1017669	1401	82.5	6.8	27.86	10.4	2.67	501	2407.1	1394.2	37.3	4.88	1383.78

Annex 2Well log of FPW 03 and FPW 07 Adapted from FJAESB well accomplishment report



Drilling Commenced on : 06/06/12
Drilling Completed on : 16/06/12
Company Name: Modern corporation for drilling water well
Drilling Method: Direct mud circulation

Project Name: FJSAEAGWA
Client : Ministry of Agriculture
Region: Somali
Woreda : Gursum
Kebele : Halahago

Location: Zone 38
UTM Northing :1031671 m
UTM Easting : 230859 m
Elevation : 1493 m

Drilling Commenced on : 10/11/12
Drilling Completed on : 23/11/12
Company Name: Modern corporation for drilling water well
Drilling Method: Direct mud circulation

Project Name: FJSAEAGWA
Client : Ministry of Agriculture
Region: Somali
Woreda : Gursum
Kebele : Deganale
Locality : Fafan

Location: Zone 38
UTM Northing :1017669 m
UTM Easting : 1022638 m
Elevation : 1078 m

Annex 3 Simulation output of hydraulic head

Obs. Name	Observed Head	Calculated head	Residual
FPW-07	1430	1418.906	11.094
FPW-19	1403.55	1397.862	5.688
FPW-03	1488.32	1472.692	15.628
FPW-06	1438.49	1430.392	8.098
FPW-10	1410.96	1406.026	4.934
FPW-13	1415.11	1412.212	2.898
FPW-18	1394.2	1391.622	2.578
FPW-12	1428.65	1421.026	7.624
FPW-04	1450.69	1445.631	5.059

Annex 4 Parameter Sensitivities

PARAMETER SENSITIVITIES:CASE pestctl			
OPTIMISATION ITERATION NO.1 ----->			
Parameter	name Group	Current value	Sensitivity
hk_1	g1	3.34276	0.590104
rch_3	g1	1.27E-06	3.62E-02
riv_4	g1	14002.2	0.593423
ghb_2	g1	3.75175	0
COMPLETION OF OPTIMISATION PROCESS			
Composite sensitivities for all observations/prior info ----->			
Number of observations with non-zero weight =9			
Parameter	name Group	Current value	Sensitivity
hk_1g1	g1	3.34276	0.590104
rch_3g1	g1	1.27E-06	3.62E-02
riv_4g1	g1	14002.2	0.593423
ghb_2g1	g1	3.75175	0

Annex 5 Simulation output of head calibrated model

Obs_point	Obs head	calcu head 1	DD 1	DD 1 Square
FPW-07	1430	1419.107	10.893	118.657449
FPW-19	1403.55	1396.333	7.217	52.085089
FPW-03	1488.32	1469.776	18.544	343.879936
FPW-06	1438.49	1430.954	7.536	56.791296
FPW-10	1410.96	1403.832	7.128	50.808384
FPW-13	1415.11	1414.267	0.843	0.710649
FPW-18	1394.2	1390.829	3.371	11.363641
FPW-12	1428.65	1421.573	7.077	50.083929
FPW-04	1450.69	1444.978	5.712	32.626944
		ME	7.591222222	79.66747967
			RMSE	8.93