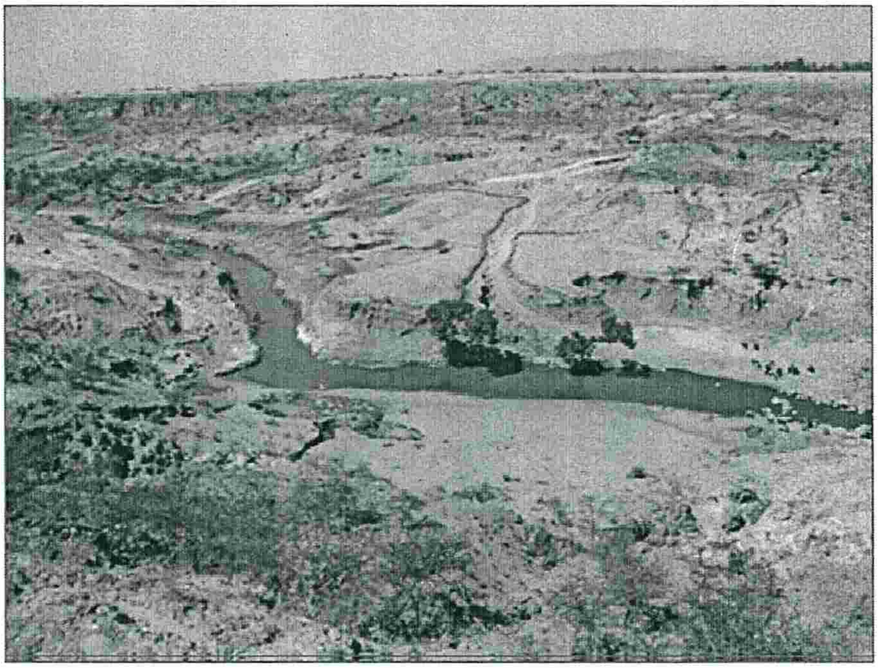
APPLICATION OF NUMERICAL MODEL FOR GROUNDWATER FLOW SYSTEM ASSESSMENT IN UPPER AWASH RIVER BASIN (CASE STUDY MOJO RIVER CATCHMENT)



By

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ATHESIS SUBMITTED TO THE SCHOOL OF GRADUATESTUDIESIN PARTIAL FULFILLMENTS OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROLOGY AND WATER RESOURCES MANAGEMENT

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TABLE OF CONTENTS

LIST OF FIGURES

List of Table

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ABSTRACT

The project area, Mojo Catchment, is located 40k.m southeast of Addis Ababa in Oromiya Regional State. Its geographical location is between $38^0 49'$ and $39^0 17'$ longitude and $8^0 25'$and $9^0 05'$ latitude. It covers an area of about 2104.5 km^{2}.

The study targeted numerical simulation of the groundwater flow system of the Mojo River Catchment there by to evaluate the response of the hydrologic system to different scenarios so that the resulting consequence on the system might be projected.

The modeling process was accomplished using groundwater flow modeling software, MODFLOW 1996 (McDonald and Harbaugh, 1988)

The water budget of the whole model domain was calculated with a percent discrepancy of 0.12. We found the total inflow is 1051.83MCM per year ($2.88X10^6 m^3$/day) and the total outflow is 1050.53 MCM per year ($2.88x10^6 m^3$/day)

This study sheds light, on the nature of the recharge water, on the subsequent ground water movement through the storage aquifer; it also produced a calibrated ground water-flow model that can be used in predicting the effects of future recharge and ground water extraction operations in the Mojo River Catchment aquifer.

The results of sensitivity analysis show that small errors in the values of the aquifer properties to which the model is most sensitive which in this case recharge and hydraulic conductivity can have significant effect on model simulation. However, other properties such as pumpage and river bed conductance can be varied in magnitude with little effect on the result. The system respond in such a way that the water level and base flow decrease upon the increment of water withdrawal beyond 25 percent.

DECLARATION

I here by declare that the dissertation entitled "*APPLICATION OF NUMERICAL MODEL FOR GROUNDWATER FLOW SYSTEM ASSESSMENT IN UPPER AWASH RIVER BASIN (CASE STUDY MOJO RIVER CATCHMENT)*" is my own work and has been carried out by me under the supervision of Dr. Tenalem Ayenew, Department of Earth Sciences, Addis Ababa University. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Place: Arbaminch

Date: November, 2008

Tsegaye Telila Beji

CERTIFICATION

The undersigned certify that they have read the thesis: *"APPLICATION OF NUMERICAL MODEL FOR GROUNDWATER FLOW SYSTEM ASSESSMENT IN UPPER AWASH RIVER BASIN (CASE STUDY MOJO RIVER CATCHMENT)"* and hereby recommended for the acceptance by the Arba Minch University in partial fulfillment of the requirements for the degree of Master of Science in Hydrology and Water Resources Management.

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(Supervisor)

Date _________________________

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(External Examiner)

Date _________________________

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(Co-supervisor)

Date _________________________

M. RAMESH BABU

(Internal Examiner)

Date 21/11/08

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Water is essential for life and plays a vital role in the proper functioning of the Earth's ecosystems. Ethiopia has extensive groundwater and surface water resources. Groundwater which is a vital component of hydrologic cycle is the most important fresh water resources on the Earth. Besides being vital drinking water resources, it supports terrestrial and aquatic system. Its vitality, however, has been endangered due to contamination and over exploitation. Its rehabilitation and utilization requires prudent management. Ground water management needs knowledge on local water balance and water resources as well as on the flow system. One tool that is employed in acquiring this information is groundwater modeling. These days groundwater modeling has received great attention worldwide not only for groundwater resource assessment or management, but also for selecting sites for hazardous waste disposals and to study contaminant transport behavior in groundwater. In forward modeling, Physical or mathematical models are used to find the distribution of state variables (heads, concentration, etc) of the ground water system in accordance with a given aquifer parameters and boundary conditions.

In inverse modeling, distributed aquifer parameters or boundary conditions are determined from given state variables. The natural way to get these parameters is through measurements. Because aquifer system is highly heterogeneous, the method requires a large set of data obtained from field tests. As this incurs high cost of measurement, the amount of data available is not sufficient. Hence model calibration is very often necessary.

Mojo catchment is a part of Upper Awash Basin which has a relatively a better groundwater data. Groundwater is an important resource in this catchment. It replenishes the streams, rivers, habitats and also provides fresh water for irrigation, industry, and communities. To meet the increasing demand of pure and adequate water in the area, several investigation works have been carried out in this catchment to obtain groundwater. This study intends to add some more knowledge to system dynamics of the stated Catchment applying the full capability of groundwater modeling.

1.2 STATEMENT OF THE PROBLEM

In the Mojo River Catchment groundwater is exploited by different industries and institutions, and irrigation schemes in addition to wells that are used for public services, the population growth are at an alarming rate. A number of flower cultural and horticultural investment activities which are considered to be large potential consumers of water are also growing in a rapid rate since the last ten years. Several small scale factories and industries are being established within the area. All towns within the study area are utilizing groundwater for their water supply. Lack of adequate water management that may serve for drinking as well as for agricultural activities inhibits the progress of developing countries and could be the cause of considerable hardship. As a result groundwater resources investigation in general is receiving great attention due to its multidimensional importance from economic and environmental point of view.

In long terms, extended and uncontrolled withdrawal may result in water level declines, which causes imbalance among hydrologic stresses. Most surveys for selection of well sites for groundwater supply mainly rely on traditional field studies using existing water point sites as well as ground information that are gathered as guidelines. In general a systematic approach to groundwater management is lacking. The flow system and aquifer properties in areas of the catchment without water points are not known. As a result of this the response of the system for different scenarios of groundwater exploitation is far from being known.

So, this groundwater flow model simulation may project the risk of such uncontrolled withdrawal on the hydrologic system, based on which necessary actions to be taken would be proposed to alleviate such a problem. This research work, hence, is intended to incorporate and contribute towards the effort to understand and conceptualize the groundwater system Mojo catchment

1.3 LITERATURE REVIEW

Groundwater is essentially a subsurface phenomenon and besides being vital drinking water resources, it supports terrestrial and aquatic system. Its sustainability and proper functioning in the hydrologic cycle, however, requires prudent management. Groundwater modeling has become an increasingly valuable tool not only for groundwater resource assessment or management, but also for selecting sites for hazardous waste disposals and to study contaminant transport behavior

Groundwater modeling is a result of careful understanding of hydrology, hydrogeology and dynamics of groundwater flow in and around the area (Anderson et.al., 1992)

The general method for assessing regional groundwater resources, which starts with conceptualization of the hydrogeology consists building-up of the three dimensional hydrogeological setting based on surface and subsurface geology followed by estimation of the regional groundwater surface (Schultz, 2000, Engman, 2000). Availability in any terrain is largely controlled by the prevalence and orientation of primary and secondary porosity (Semere, 2003)

In Debra Zeit the majority of water used for domestic purposes comes from groundwater sources. Several groundwater related studies have been conducted in Debra Zeit which includes the whole Ada'a plain. Tamiru and Antonio (1995) have used all possible geological and hydrogeological methods for the evaluation of groundwater potentiality together with chemical characteristics and their interactions with the country rocks. They have also explained that the area is part of the Ethiopian rift system that is characterized by a Plio-Quaternary volcanism which gave rise to trachitic domes, rhyolitic lava flows and rhyolitic ignimbrites in the upper part of the area and successive olivine basaltic lava flows, surge deposits and alluvial deposits. In their result of investigation the basaltic lava flows, occurring as alternative layers of amygdaloidal, fractured, vesicular and scoraceous basalts are found to be the best and the most productive aquifers in the area. In addition, they pointed out that groundwater occurs within the basaltic layers under unconfined; semi confined or confined conditions, where the thick clayey and pyroclastic layers play an important role of aquitards. In their analysis of lake level fluctuation, they have shown that there is a good hydraulic connection between the explosion crater lakes and the groundwater circulation.

Alem Tiruneh (2006) carried out Hydrogeology of Modo River, in his Msc thesis. In his research he has carried out conventional hydrogeological investigation in order to define the basic hydrogeological factors controlling the occurrence, movement and storage of groundwater in the Mojo river basin. In his research result he pointed out that alluvial deposits, basaltic flows and domes are important permeable units, while fractured ignimbrite and rhyolitic ignimbrite are considered as medium permeability group and are also good water bearing units. The rest of geological units such as massive ignimbrites and lacustrine deposits are considered to be low permeable units.

Studies about Surface Water and Groundwater Pollution Problems in The Upper Awash River Basin, Ethiopia carried out by Adane (1999) show that the scoracious and vesicular basalts that out crop in the vicinity of Debra Zeit and Akaki are highly permeable due to interconnection of pore space and high fracture system.

Abebe et al. (1998) stated that Mojo river catchment represents a transition zone between the Ethiopian Plateau and the Main Ethiopian Rift (MER). In this area the rift escarpment is not well defined.

Sissy Libase (2007) in this MSC thesis on “Application of Remote Sensing and GIS for Groundwater Potential Zone Mapping in Northern Ado’s Plain (Moro Catchments)” indicated that the groundwater potential of the study area is related mainly to geology, geomorphology and lineaments. He emphasized spatially the very good and good categories are distributed along areas near to lineaments and less drainage density and where the lithology is affected by secondary structure and having interconnected pore spaces. Areas with moderate groundwater prospects are attributed to contributions from combinations of the land use/cover, lithology, slope, landform and soil. The low to poor categories of groundwater potential zones are spatially distributed mainly along ridges where slope class is very high, the lithology is compact/massive, clay soil composition and far from lineaments.

Lake Koka is the discharge area for the local and regional groundwater in the area (Silesh Mamo, 1999).

Tesfaye Cherinet (1982) pointed out that jointed ignimbrites and lacustrine sediments are the major aquifers in the Lake’s region.

Tilahun Azagegn (2008) disclosed that there are crater lakes which have hydraulic interconnection with the groundwater. Due to intensive faulting and highly pervious scoria cones in the area, the recharge from lakes water influences the chemistry of the groundwater downstream and southeast and southwest of the Bishoftu lakes region. Groundwater east of the Mojo River shows very low salinity which may be due to the influence of the recharge from the river.

1.4 OBJECTIVES

The general objective of this study is numerical simulation of the groundwater flow system of the Mojo River Catchment there by to evaluate the response of the hydrologic system to different scenarios so that the resulting consequence on the system might be projected; requires calibration. Different scenarios of increased withdrawals, hydraulic conductivity and decreased recharge were simulated using Processing MODFLOW, 2000 to study system response, the result of which can be used as a tool to understand the future risk of over exploitation of groundwater.

The specific objects are to:

☞ Identify the study area boundary and conceptualize the boundary conditions.

☞ Construct water balance of the study area.

☞ Organize field data and formulating ideas about system dynamics.

☞ Build a conceptual model of the hydro geological model of the Mojo River Catchment.

☞ Produce groundwater table map.

☞ Address the relation between base flow and pumping wells.

1.5 METHODOLOGY

In order to achieve the objectives of the research, the followings methods and materials were used:

☞Systematic hydro-meteorological data analysis

☞ Recharge estimation using WATBAL software (soil-water balance) method

☞Groundwater modeling using groundwater flow modeling software, MODFLOW 1996 (McDonald and Harbaugh, 1988)

☞Construction of conceptual model to simplify field problem and organize field data so as to analyze the system so readily.

☞Review of inventory of wells and springs in the catchment

☞ Integrating hydrogeologic information into a conceptual model,

☞ Water level collection

The general methodology followed during data assembly and the simulation process in this work is given in Figure 1.1

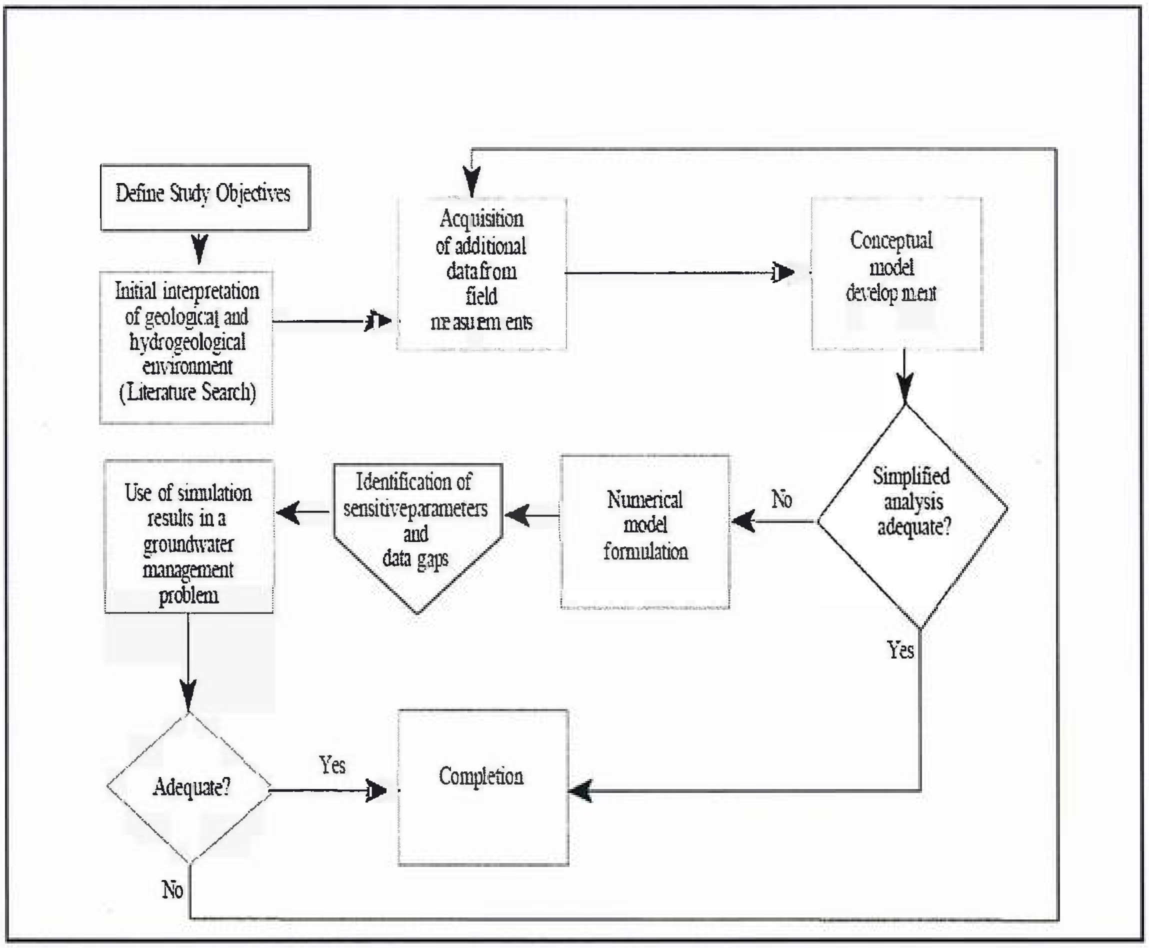


Figure 1.1 General flow diagram for characterizing groundwater flow System (adopted after Eaba, 2006)

CHAPTER TWO

2. GENERAL OVERVIEW OF THE STUDY AREA

2.1 LOCATION

The project area, Mojo Catchment, is located 40k.m southeast of Addis Ababa in Oromiya Regional State (Fig2.1). Its geographical location is between $38^0 49'$ and $39^0 17'$ longitude and $8^0 25'$and $9^0 05'$ latitude. It covers an area of about 2104.5 km$^{2.}$ The area is bordered with Yerer mountain and water divide with Kesem river in the north and mountain Zikuala in the south. Mojo River that flows from northeast to southwest is the main stream draining the area. The area is traversed by the main high way from Addis Ababa to Djibouti. Most parts of the area are accessible from all directions by a number of all weathered roads, dry season roads and footpaths as well asphalt road.

2.2 GEOMORPHOLOGY

The project area is generally characterized by flat topography mostly underlain by diverse volcanic products of the Quaternary rift volcanics (Tamiru and Antonio, 1995), and sediments. The general smooth morphology of the central area is interrupted by the two central volcanoes Yerer and Zikwala that rise more than 1000 m above the plain. The main river is Mojo, and it runs from north to south.

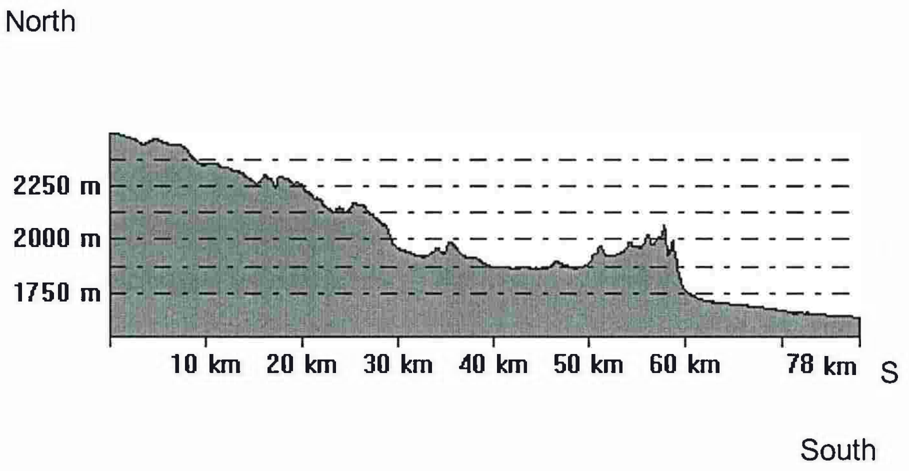


Figure 2.1 profile showing elevation drop from Chefe Donsa to koka Lake. The elevation difference is about 750m within about 80km.

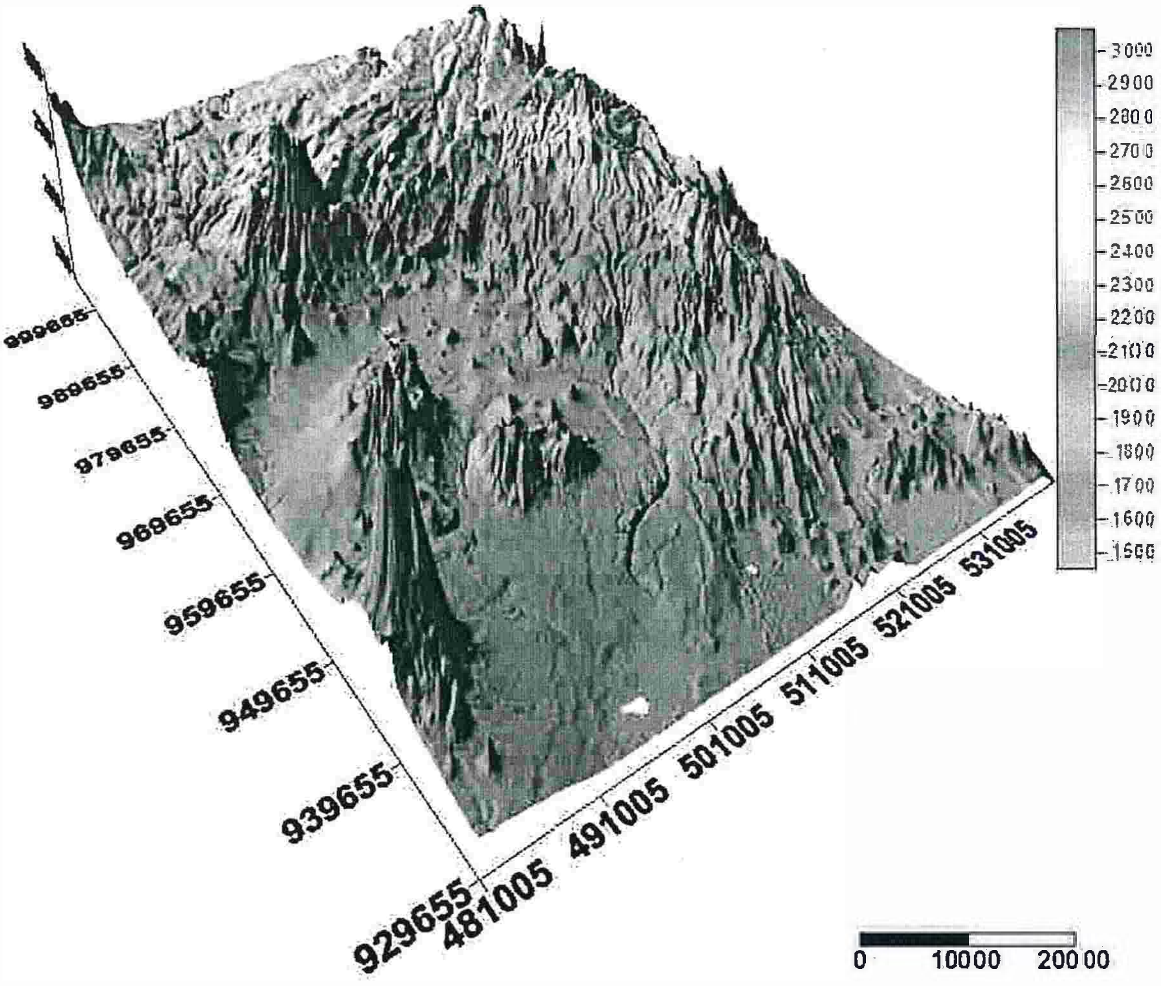


Figure 2.2 Geomorphology of the study area

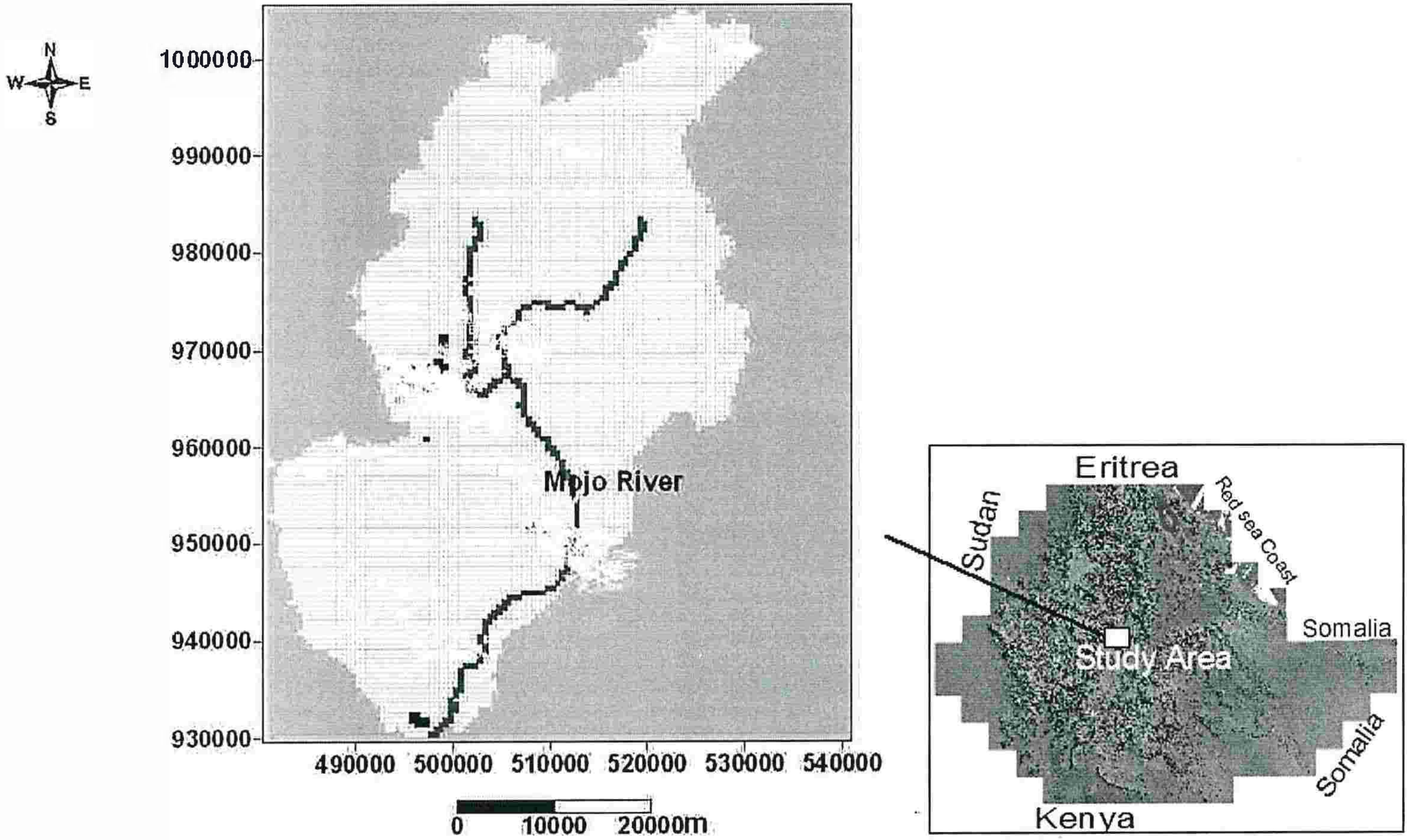


Figure 2.3 Location Map of the Study Area

The topographic elevation of the study area ranges from 1500m to 3000m above mean sea level

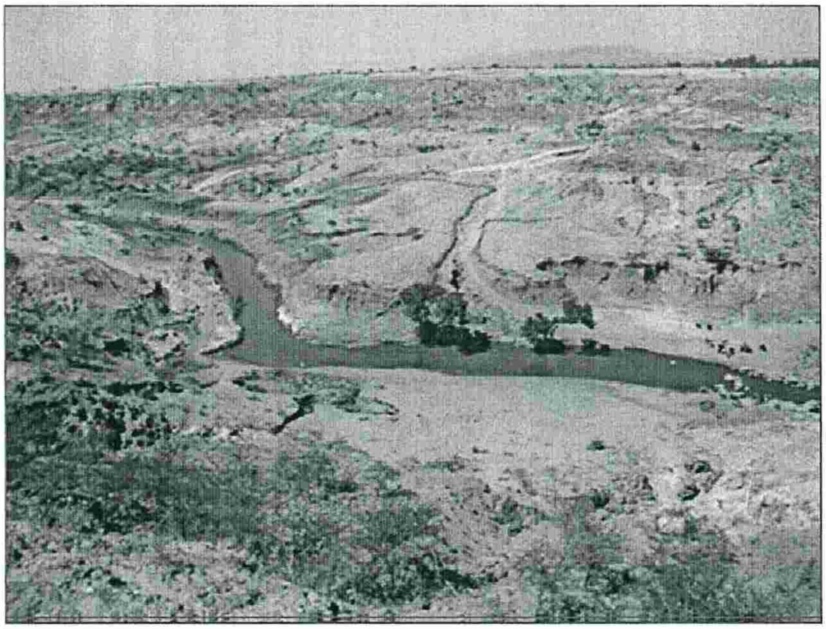


Figure 2.4 Mojo River, the principal drainage system,southern part

2. 3 CLIMATE

The area experiences heavy rainfall in June and July. Rainfall data from NMSA (National Meteorological Service Agency) the mean annual rainfall in the Mojo River catchment ranges from 870mm at southeastern end to over 930mm to southwestern. The annual amount of the rainfall is sufficient for the crop production even when it is low. But there is large spatial and temporal variability of rainfall.

The rainfall of the study area was taken to from five different stations (Mojo, Chefe Donsa, Dertu Liben, Bushofitu, and Adama) of which four areas located in the study area except Adama Station. The data was collected from the last 37 years records (1968-2005) and the mean is tabulated and presented in the table 2.1.

Accordingly the mean annual rainfall of the study area is 900mm.

MONTHS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly RF(mm)	15	32	53	63	54	93	224	224	106	27	7	5
M.M.MAX.TEMP	10	13	17	17	17	22	34	38	23	12	8	7
M.M.MIN.TEMP	10	13	17	17	17	22	34	38	23	12	8	7
M.M.TEMP	10	13	17	17	17	22	34	38	23	12	8	7
WIND SPEED	9	9	8	8	9	8	6	7	8	9	10	10
RELATIVE HUM.	53	48	54	53	51	59	71	73	69	56	51	52

Table 2.1 Mean Monthly Values of Meteorological Data

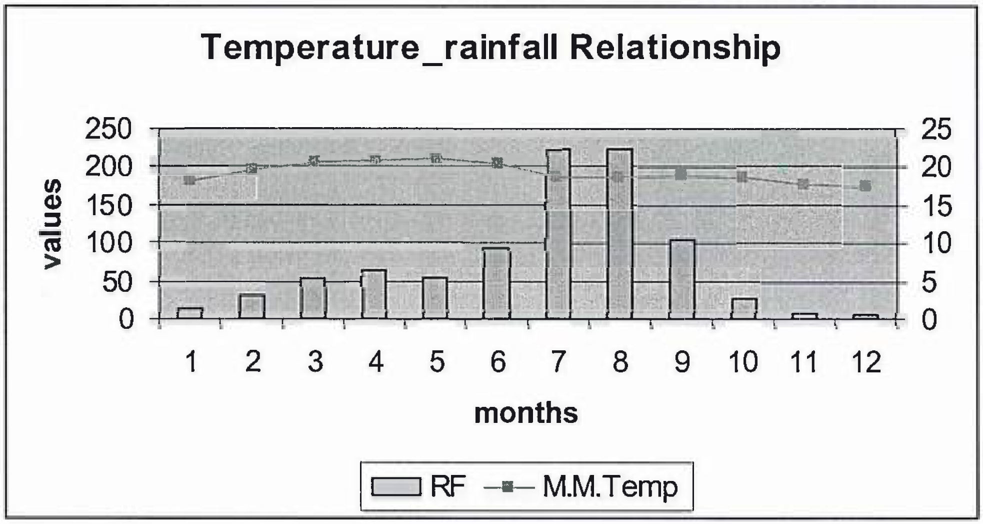


Figure 2.5 Rainfall and Temperature Relationship

Temperature

In Ethiopia the sun is always high, making the solar radiation intense. The variation of daily solar radiation is small throughout the year. Temperature is high during the day and is considerably reduced at night causing the daily range of the temperature to be large. But in the case of monthly average, variation is minimal and the annual range of temperature is small. The temperature data were taken from stations within the study area for the year (1968-2005). Since the target area and the stations are not far away extrapolation by increment for depression and temperature drops per given altitude is not necessary.

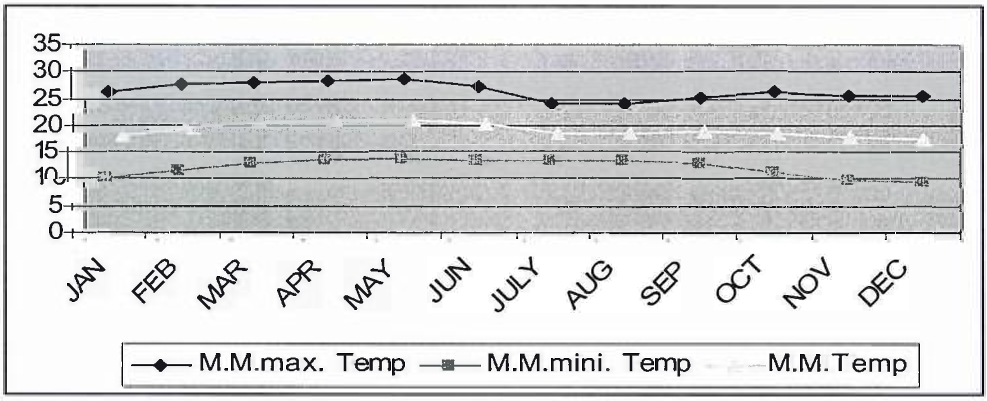


Figure 2.6 mean monthly value of temperature of the study area

The above figure shows the temperature and rainfall relations over the period (1968-2007) for the catchments. The maximum Temperature is observed in May and it is low during December. The temperature shows a tendency of decreasing during the maximum rainfall.

Wind speed

The mean monthly wind speed variation is in the range of 6-10 m/s as measured 2m above ground surface. Wind data was taken from Bushofitu and Adama stations. The data was fifteen years record from 1990to 2005 .The maximum and minimum were computed and presented in the table 2.1

Humidity

The monthly relative humidity ranges from 51 to 73% .August has the highest relative humidity and November has the minimum. As it is observed below the highest humidity values are found in the rainy months where as the lowest values are in the dry months.

2.4 HYDROLOGY

2.4.1 LAND USE/LAND COVER

Most catchment issues that require a greater understanding of groundwater behavior for evaluating management options and determining appropriate solutions, relate to either rising or falling water tables. These fluctuations are commonly related to river regulation, flooding, irrigation development and associated changes to surface water regimes, groundwater recharge changes due to changing land use, or groundwater pumping.

In the past few decades there was a great change in Mojo River Catchment. Many of these changes have been induced by changes in the hydrology and hydrogeology of catchment and are today reflected in stressed rivers and groundwater systems. For groundwater systems, these stresses are reflected in water level declines (and associated issues such as water quality impacts) which are impacting the productivity and environmental sustainability of catchment.

In this regard, groundwater models provide a relevant and useful scientific and predictive tool for predicting impacts and developing management plans. Groundwater models should be seen as an integral part of the water resource management process. This is so because models are increasingly being used to demonstrate the effects of proposed developments and alternative policies to stakeholders and communities, for the purposes of gaining consensus on improved allocation distributions and management plans. But Groundwater modeling is only one management tool available to catchment managers for developing solutions to complex catchment issues and is often linked to other socio-economic models and extensive community consultation initiatives. Modeling can be a very powerful tool when used in the right circumstances and when models are properly constructed.

Models provide one of the best tools for determining the most appropriate land/water management options or strategies to adopt.

One of the parameters that influence the occurrence of sub-surface groundwater occurrence is the present condition of land cover and land use of the area. The effect of land use / cover is manifested either by reducing runoff and facilitating, or by trapping water on their leaf. Water droplets trapped in this way go down to recharge groundwater. Land use/cover may also affect groundwater negatively by evapotranspiration, assuming interception to be constant.

Misuse of water resources and poor water management practices have often resulted in depleted supplies, falling water tables, shrinking inland lakes, and stream flows diminished to ecologically unsafe levels. Water pollution, originating mostly from human activities, occurs even more frequently and in a widespread manner, thus causing decreases in the amount of water suitable to many uses.

Under these circumstances, the need for improved, more efficient management of water resources is obvious. So far, water has been managed in a fragmented way. Surface water and groundwater are considered separately in development activities without due recognition of their interdependence. Water resources are not managed in conjunction with land resources.

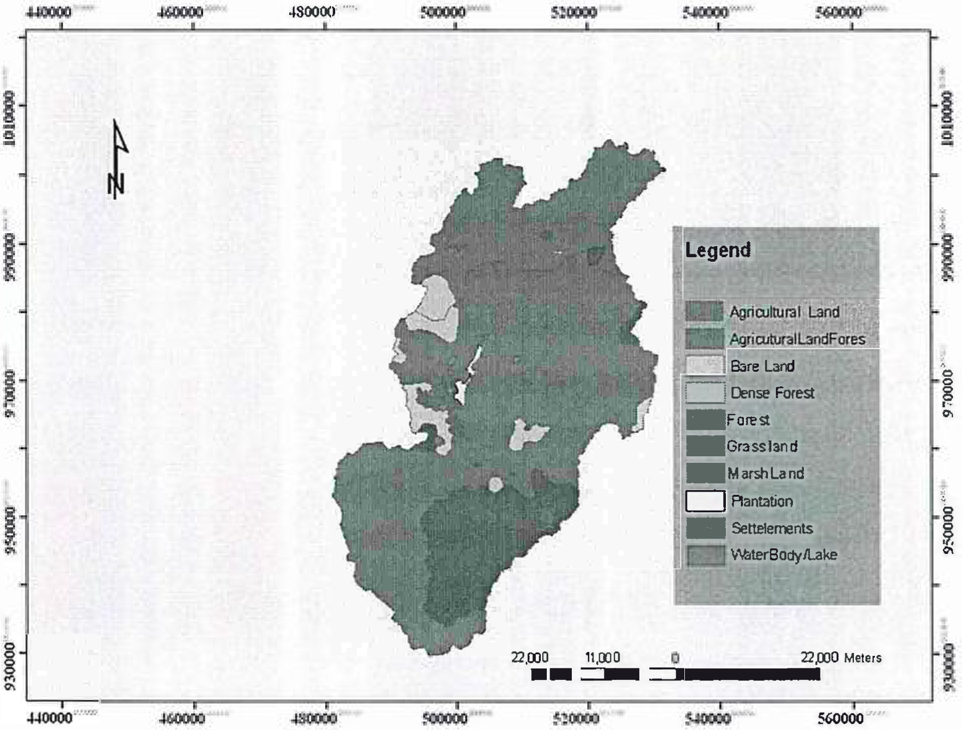


Figure 2.7 Land Use/ Land Cover Map

CHAPTER THREE

3. GEOLOGY AND HYDROGEOLOGY

3.1 GEOLOGY

3.1.1 GEOLOGICAL SETTING.

In Ethiopian volcanic province is broadly classified in to Trap and Aden Series (Mohr, 1963) based on the eruption that took place prior to or after East Africa rift formation. In Mojo river basin, Central Ethiopia, both series are exposed. Pre-rift volcanic sequences occur on the plateau while Aden series occur on the escarpment and on the rift floor. The latter is extensively exposed in the study area. The Mojo river drainage basin is underlain by a variety of volcanic rocks that depict a geologic history from Miocene to recent. They comprises of Nazreth series/Nazreth group basalt, Chilalo formation, Mursi & Bofa basalt, Bishoftu formation, Dino formation/Wonji Group, Rhyolite volcanic complex and Alkaline basalt (Kazmine et al., 1980, 1979, Zanettin& Justin-Visentin 1974, Mayer et al., 1975 Mengesh et al., 1996, Cherent et al., 1999).

Nazreth Series rocks which consist welded ignimbrite, pumice, ash and rhyolite flow and dome with rare interaction of basaltic flows occur in Main Ethiopian Rift (MER) and rift margin especially, north and east of Mojo town (Kazmin and Berhe, 1978). On the plateau margins, their thickness varies from 1 to 30 meters where as within the rift group attains a maximum thickness of up to 250 m. Ignimbrites of the Nazreth series are of the fall type and are considered to be products of explosive eruptions, mainly on marginal faults of the Rift (Morbideilli et al., 1973). Many widely distributed rhyolitic domes have been observed indicating that central type explosive eruptions played a significant role in the formation of the Nazreth volcanics.

Chilalo formation is found along the margin of the MER and is constituted of strongly porphritic dark trachyte with sanedene phenocryst, trachy basalt and ignimbrite as subordinate. This formation exhibits ages ranging from 8 to 4Ma (Kazmin et al., 1980b; Cherent et al., 1999).

Bofa basalt is represented by flood basalt volcanism comprising aphyric locally vesicular basalt with predominantly transitional to alkaline nature. These basaltic units form a wage between Nazerth series and Dino formation. Existing ages on samples collected from the study area range between 4 and 1.6Ma (Kazmin et al., 1980b).

Basalt flow with well preserved scoria cones with affinity to alkaline form Bishoftu formation. The volcano is placed on tectonic lines transversal to the axial and shows ages ranging from 2 to 2.8 Ma (Zanettin&Justin-Visentin., 1974; Kazmin et al., 1980).

Wonji series constitute the latest constitute volcanism that is after the last major episode of rifting and is also related to its axial extension zone which is known as the Wonji fault belt. It comprises green & grey fiamme ignimbrites associated with unwelded pyroclastics with intercalated lacustrine beds aphyric basalt. Dino ignimbrite is the oldest of the group followed by pantelleritic volcanic centers, and finally by recent fissural basalts. The oldest unit of the group is dated to be 1.5Ma. The majority of pantelleritic volcanic centers exhibit alignment along segments of Wonji Fault Belt. The main components of these centers are rhyolites, trachytes, obsidian, and recent fissural basalts (Kazmin et al., 1979).

The age of the lacustrine rift sediments is contemporaneous with the Wonji volcanics. They are mainly of volcanoclastic sediments and tuffs with silts, clays and diatomites; silts and clays are the dominant ones. Alluvial deposits are also common in the rift, associated with flood plains and at some places mixed with volcano clastic sediments.

Detailed geological mapping in Debrezite area has classified the underlain volcanic rocks into three non-formal litho-stratigraphic complexes; viz, Western rift margin complex consisting of Addis Ababa basalt unit, central volcano unit and Akaki units; intra rift complex comprising nazret unit, Tulu rie basalt unit and Chefe donsa unit, and rift axis complex that comprises Zikwala Volcano unit, Bede Gebabe volcano unit, Bishoftu volcanic unit and lacustrine deposit (F.Mazzarini et al., 1999).

The Nazreth group consists of thick succession of ignimbrites, unwelded tuffs, ash-flows, rhyolite and trachyte flows. On the plateau margins, they are from 1 to 30 meters thick where as the group attains a maximum thickness of up to 250m in the Rift. Ignimbrites of the Nazreth group are of the stratoid type and are considered to be products of fissure eruptions, mainly on marginal faults of the Rift (Morbideilli et al. 1973). Many widely distributed rhyolitic domes have been observed and indicate that central type explosive eruptions played a significant role in the formation of the Nazreth volcanics. According to Kazmin and Seifemichael Berhe (1978), the age of Nazreth group is between 9.5 and 3Ma.

3.1.2 GEOLOGIC STRUCTURE

The Main Ethiopian Rift is a structurally characterized by several step faults. The NE-SW fault system runs parallel to the principal system of fissures in rift floor north east of Debrezeit and Mojo extending to Nazareth. This fault system densely affected the volcanic rocks and served as a conduit to younger eruption (Tulu Rie basalt). The fault system of the rift margin exhibit step like block faults; WWDSE (2008).The NS fault system is the recent fault system, which serves as a conduit for young volcanic (Addis Ababa basalt).

Nazreth Series rocks' (constituting welded ignimbrite, pumice, ash and rhyolite flow and dome with rare interaction of basaltic flows) occur in MER and rift marigin especially north and east of Modjo town (Kazmin, and Berhe, 1978). Mojo, like the other Rift Valley areas was subjected to tectonic activities and intense volcanism. The Wonji fault belts are the prominent MER structures characterized by NNE-SSW system forming minor graben and horst structures as depicted in Mojo (Modjo graben) and Nazreth (Adama graben, Kimbibit and Delocha horest to the west and east of the town itself) areas (Tsegaye Abebe, et al., 1999).

Some faults have been observed in Mojo area (eastern, southern, southwestern parts) forming minor fault escarpment. The river channels, large gullies seem to outline and follow the hidden and an exposed fault line. In the MER, faults, joints, fractures, volcanic flows and layering and flow folding, which are associated with silicic lava flows, are main geologic structures. The presence of thick fluvo-lacustrine deposits and active erosional or denudation processes in the MER during pluvial period of the Quaternary mask the probable existence of fault/lineaments.

Brittle deformation consisting of fractures, joints and faults are dominant in the area

Structures are extensional and affect chiefly the rocks of the Intra Rift Complex and partially those of the Western Rift Margin Complex. These structures are grouped into four main fracture systems consisting mainly of joint sets and some faults. (Abebe et al.1999). Those are the N-S/NNE-SSW fracture system which is analogous to Wonji

Fault Belt, constitutes normal faults with steeply dipping joints dip angle of >85°. The next one is NE-SW fracture system that parallels the regional trend of the MER, and has normal fault of about 1m thrown and dip angle >85°. It is widespread especially in the Nazreth unit where the most important physiographic features are NE trending ridges and escarpments.

The third one is E-W fracture system mainly concentrated in zones close to the Yerer Volcano or just east of Addis Ababa. It parallels the trend of the Yerer-Tullu Wellel Volcanic Lineament (YTVL) structure. It consists of sub vertical to vertical joints with dip angle >85°.

The last one is the NW-SE fracture system. Few high angle normal faults have been observed with high morphologic evidence (escarpments). This system affects mainly the oldest units of western Rift margin.

The geology of the area is strongly conditioned by the interaction between the left-lateral oblique rifting of the MER (Boccalitti et al., 1999) and right lateral transtensional Yerer-Tullu Wellel Volcanic Lineament structure (Tsegaye Abebe et al., 1998). Thus, the interference between the MER and YTVL structures would be the first order cause of features like gradual transition between the rift floor and the West Rift shoulder.

3.1.3 Geology of the Study Area

The geology of the study, Tertiary age groups of acidic and basic volcanic rocks, Quaternary age groups of acidic and basic volcanic rocks and lacustrine and alluvial deposits. Major part of study area comprises of lava plateau at northern extreme of the area.

The quaternary volcanic rocks comprise of tuff, pumices, ignimbrite, pyroclastic flows and different volcanic fragments, scoria and basaltic flows. In the single pile of the volcanic tuff deposits two of three different eruption episodes could be easily identified that are separated by development of paleosoil.

Scoria cone and basalt flows, which are exposed in the northern and southern section of the town, are probably related to the Bishoftu volcanic activity. The scoria unit has reddish and reddish yellow, layered flow inclined towards north. It is main source of road surfacing material in the town.

A detailed geological mapping of the Debre Zeit and Mojo area allowed the recognition of ten volcanic units that were grouped into four volcanic complexes. (Tsegaye Abebe et al.,1999).

Stratigraphic relationships between the recognized units have been further constrained by new K-Ar measurements. The volcanic complexes define three main structural sectors: the western rift margin, the main rift floor and intra-rift depression, respectively.

a) Tertiary Volcanic Rocks

Addis Ababa Ignimbrite (AAI)

This unit is included in western Rift margin complex and an exposure of this unit is found in the study area. But it is mainly found close to Addis Ababa; along Akaki and Kebena rivers. It rests on the Addis Ababa basalt and locally covers the products of the composite central volcanoes of Wechacha and Furi. The sequence is constituted by different flow units. It is composed of welded tuff (ignimbrite) and non welded pyroclastics fall (Ash and tuff). It is grayish to white color and when welded it exhibits fiamme textures, elongated rock fragments of various color.

Nazareth Unit *(NZ)*

It forms rift floor. It consists of a sequence of welded per alkaline rhyolitic ignimbrite. The unit comprises numerous rhyolitic and trachytic domes. The ignimbrites generally show eutaxitic texture with oblate glassy fragments. Rock fragments and crystals, generally broken, are abundant; alkali feldspars, quartz, and amphiboles are the most common crystals. Maximum numbers of observed flow unints are four with thickness variable from 5 to 15m

This unit is a basal unit grouped under the intra Rift complex and may constitute the upper part of Nazreth Group of Kazmin and Seifemichael Berhe (1978) with respect to age constraints. Nazreth unit is only exposed in the eastern part of the study area in association with the NE-SW trending lineaments. The NZ activity lasted about 2Ma, from 5.4 to 3.1Ma. (Tsegaye Abebe 1999)

b) Central Volcano

Wecheca, Furi and Yerer Trachyte *(NcvTy)*

These are mainly trachytic lavas exposed at Wechecha, Furi, Yerer. The Western and Southwestern ridges of the study area are forming mountain picks. These units belong to the western Rift margin complex and include the Yerer volcano and the products of the composite volcanoes of Wechacha and Furi. Among them it is Yerer volcano unit, which outcrops in the study area. Yerer is located on the northwestern corner of the study area that represents the largest volcanic edifice of the region, with a relief of 1000m from the plain. It is 14kms wide along the E-W direction. Ridges and domes are NE-SW aligned. These products consist of mainly lavas, even if pyroclastics are wide spread mainly in the central and eastern sector. Overall the volcano is strongly eroded, especially at the southern slope, where 200m high escarpments occur.

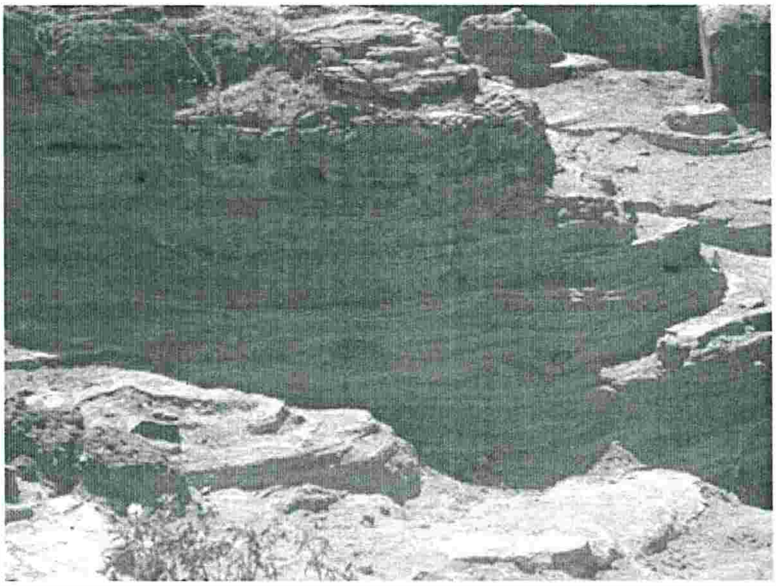


Figure 3.1 Pyroclastic Deposit Exposed in Erob Gebeya

The highest part of the Yerer volcano was affected also by a more recent volcanic activity that produced spatter cones and associated basaltic lavas, ascribed to the Akaki unit. The petrographic study showed the lavas mainly porphyritic trachytes.

Fresh ignimbrite rock along the banks and floor of Mojo River is interblended with lacustrine deposit. Each ignimbrite layer has a thickness of about 2 meters. This unit includes various welded and often jointed columnar ignimbrites. Basically two types of ignimbrites have been identified: the slightly welded ignimbrite (top) and intermediately welded ignimbrite (bottom), separated by paleosoil and lacustrine deposits. Lithic fragments, mainly of basaltic (often scoriaceous) and silicic nature were abundantly present in the former. The color of the ignimbrite rock varies from dull gray, greenish gray to yellowish gray. Layered ash deposit is found around Mojo Town. It's observed highly weathered and highly fractured. The layering is a result of small time gap between successive volcanic eruptions.

Tulu Rie Basalt (TRB)

Tulu Rie Basalt crops out in the eastern and northern section of the study area. The unit belongs to intra Rift complex where it covers the Nazeret unit and forms the upper part of NE trending escarpments. Lavas have mainly olivine basaltic composition, rare plagioclase–rich basaltic andesites are also found. The basalts show porphyritic or subaphyric texture, the phenocrysts are generally constituted by olivine.

An exposure at Tulu Rie basaltic ridge covered with shattered blocks of basaltic boulders. The unit is weathered and shows fracturing that line up with regional structures.

Chefe Donsa unit (CD)

This unit belongs to intra rift complex. The volcanic rocks of CD unit are exposed mainly along the border of the central plain. They consist of all deposits and poorly welded ignimbrites of rhyolitic composition. They are fairly distributed in the Mojo river catchments. It covers the Nazreth, TRB and Yerer products. Fission track analysis applied to juvenile material (obsidian fragments) from the upper pumice falls in a section close to Chefe Donsa village yielded on age of 2.2My (Tsegaye Abebe 1999). Observed total thickness of the unit varies from few meters up to 40m close to Chefe Donsa village, where the most complete section is exposed. It consists of four fall deposits each separated by paleosoils up to one meter thick. In the eastern most section of the study area the Chefe Donsa unit is made up of pyroclastic fall with a thickness of about 12m. These pyroclastics have been interpreted as stratigraphically equivalent to Boku Tede unit of Boccaletti et al., (1999)

Bishoftu volcanics (BV)

This unit is included in the rift axis complex and forms a NNE trending belt outcropping mainly in the central flat area of Modjo River catchment. The term Bishoftu volcanics is utilized to indicate the most recent basic products of the Debrezeit area, (Tsegaye Abebe. et al., 1999) which coincides with the name younger volcanics by Grasparon et al., (1993).

In the BV there are two groups represented by spatter and cinder cones with associated tabular lavas and phreatomagmatic deposits, respectively. These latter, consisting mainly of surges and highly fragmented deposits are associated with maars are chiefly concentrated in the central part of the central section where the highest thickness of the lacustrine sediments frequently intercalated with the phreatomagmatic products. The composition of lavas and juvenile glass ranges from alkali basalts to olivine basalts to trachyandesites. (Tsegaye Abebe, 1999)

Vesicular basalt (probably related to Bofa Basalt) is found associated with and or sandwiched between pyroclastic and lacustrine deposit and covering the volcanic tuff in some parts of the area. It is dark gray in color, vesicular, massive and sometimes scoriaceous and at places secondary precipitates, dominantly zeolites and calcite fill the vesicles.

C) Lacustrine deposits and alluvial cover

The Quaternary sediments are composed of fluvo-lacustrine deposits of alluvium, colluvium, elluvium, coarse sand, silty sand and siltstone. Mojo and its surrounding areas are supposed to have been covered by ancestral lake during the pluvial period of the Quaternary. The lacustrine sedimentations are the results of deposition in this large ancestral lake (Mohr, 1967 and Abebe, et al., 1999). Accordingly, borehole data indicate there is shallow marine deposition of limestone and diatomite. The lacustrine beds are interbedded with Pliocene-Pleistocene ignimbrite in lakes region and on the rift shoulders in general and in Mojo and its surroundings in particular (Mohr, 1966). They are mostly redeposited volcanic sands, siltstone, sandstone, calcareous materials and diatomite with intercalation of water-laid tuffs.

The sandy and silty sand deposits are layered horizontally with graded bedding and cross lamination. They are very friable, less compact and hammered very easily. Diatomite lenses are 0-10cm thick and are commonly intercalated with the fine lacustrine deposition. These Late Quaternary sedimentary rocks were deposited alternating with the volcanic tuff and pumice. The redeposited volcanic sands and associated sedimentary rocks are fine grained and or cemented by fine-grained materials.

The deposits represent about 28% of the exposed rocks and are developed on relative, NE elongated depression in the central section of the area. These fine-grained deposits are generally brown-yellowish, thinly stratified and often contain abundant volcanic matrix. Their thickness ranges from less than 5m up to 8m. In these successions, volcanic layers are frequent and become predominant and coarse grained in the neighboring of the mars. Lacustrine environment started after the Bede Gebabe volcano unit and continued during the eruptive activity of Bishoftu volcnaics.

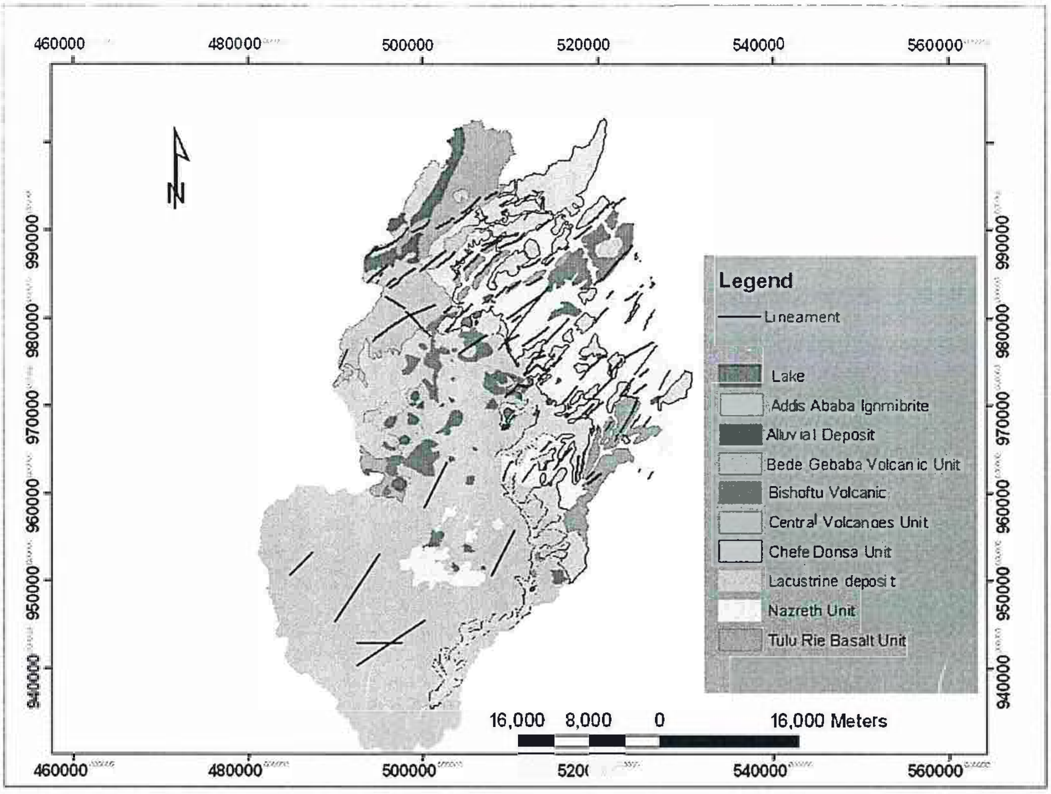


Figure 3.2 Geological Map of Mojo River Catchment

3.2. HYDROGEOLOGY

3.2.1 Hydrogeology of Mojo River Catchment

The current available data shows the Mojo River catchment has different aquifers, which are replenished from Mojo River and the large volcanic escarpment from norththeast fractured and faulted to be the main recharge zone as subsurface flow to the plain and generator of runoff, which recharge at the upper part of the catchment.

The Mojo Catchment aquifer consists of alluvium deposits, up to 120 meter below the surface, particularly near the Mojo town overlying an ignimbrite and fine – grain ash materials intercalated with well compacted lacustrine deposits unit. Alluvial deposits, basaltic flows and domes are important permeable units, while fractured ignimbrite and rhyolitic ignimbrite are considered as medium permeability group and are also good water bearing units. Aquifers of good categories are distributed along areas near to lineaments and less drainage density and where the litho logy is affected by secondary structure and having interconnected pore spaces.

Discontinuity in impervious clay layers exposes the aquifer to infiltration of water from the surface and as a result the aquifer is generally considered unconfined. Consequently a single layer approach has been used. The water levels in shallow and deep bores were found to be correlated indicating vertical hydraulic connectivity. The water levels in these bores are also correlated with rainfall and recharge through the unsaturated zone is found to be rapid.

A lot of works have been done on the geology of the whole catchment or on some zone of the catchment. All the works show that the area is totally covered with volcanic materials of various ages that correspond to different stratigraphic units. The geology, including the mineral composition, grain size, grain packing and roundness of grains, is the main factor in determining the physical variation in aquifer properties.

The stratigraphy describes the geometrical and age relations between the various formations in the geologic systems, providing some frame work for the stacking of the various units and their hydrologic properties. Structural features, such as, fractures, joints & faults and the geometrical properties of the geologic system produced by deformation or crystallization (Freeze, 1979), may provide secondary hydrological properties to the various rock bodies.

Generally, volcanic rocks are very diverse and play an important role in allowing ground water movement or in impeding it based on the primary and secondary characteristics of the formations.

When dealing with flow of water in aquifers, one should consider how water enters the aquifer, how it passes through the aquifer and leaves it. In volcanic rocks in which extreme contrasts in permeability exist, it would be correct to consider them as different aquifers with a certain degree of connection along their boundaries; and such contrasts play a predominant role in flow distribution. Permanent springs may crop out in areas where younger volcanic cover thins out and is no longer able to transmit all the ground water flowing inside it.

Having the geology of the area and the general characteristics of volcanic rocks, it is possible to outline the general hydrogeology of the area. 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.

Previous works show that the Mojo river catchment is made up of both inter - granular and fracture type aquifers. Alluvial sediments and pyroclastic rocks are inter- granular porosity aquifers, and volcanic rocks such as weathered/ fractured basalts, ignimbrites, trachytes, welded tuffs and rhyolites are fractured aquifer types. Accordingly, Major aquifers are fractured and intergranular aquifers of young volcanic sequences excluding the mountain ranges. Boreholes of variable discharges have been drilled in these aquifers and in most cases the yield is over 10 l/sec. Scoria deposits, among the major aquifers are the most important unit from hydrological point of view. The interconnection of the pore space has resulted in high permeability for these deposits.

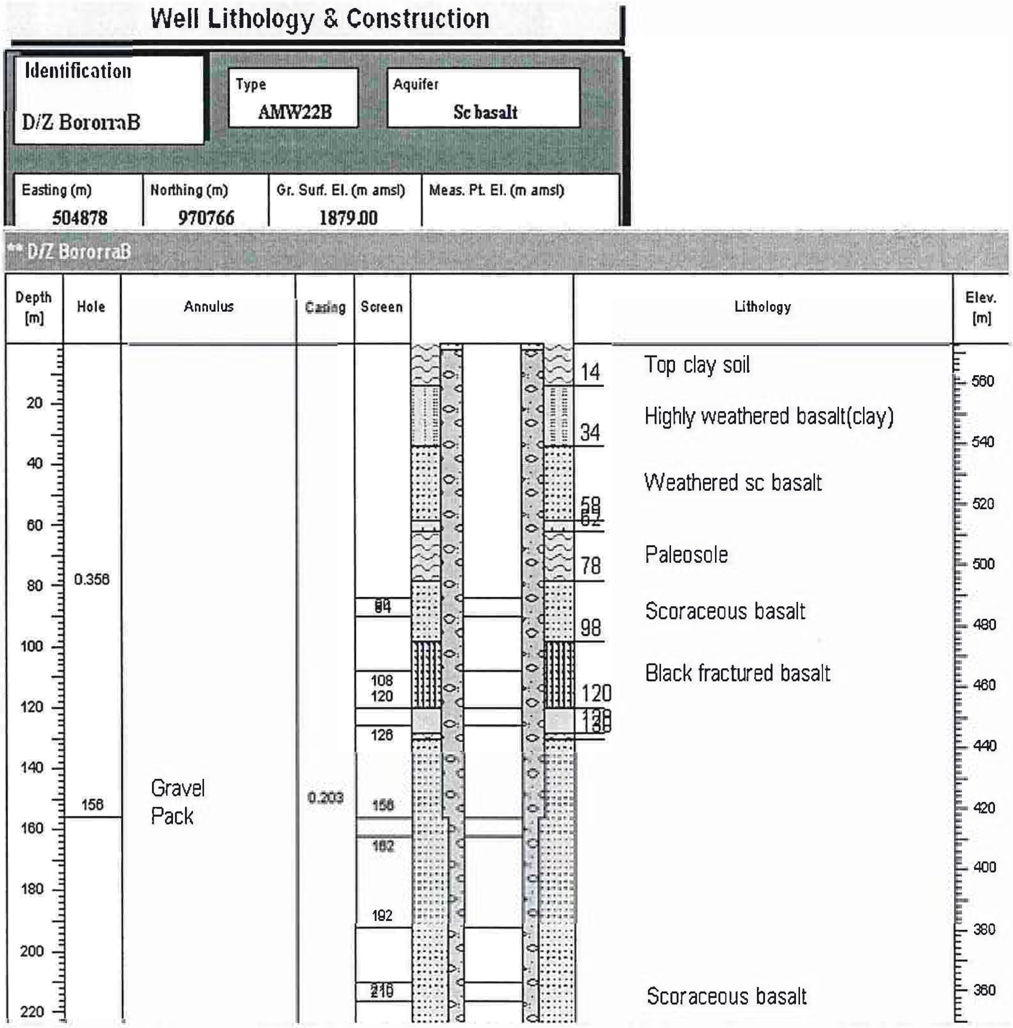
Most of the aquifers are hydraulically interconnected which is justified by continuous piezometric surface that follows approximately the topographic surface.

The catchment consists of complex aquifer systems, for the purpose of groundwater flow simulation modeling, in this study, a single layer of shallow unconfined aquifer system was considered. The aquifer properties were not expected to vary vertically within the considered thickness, but there is lateral variation from north to south. The thickness of this aquifer is roughly approximated to be 150-250m by using screen lengths and this value might be modified during model calibration.

According to report WWDSE (2008) the major hydrogeolgeologic characteristics of the study area is indicated below.

- ✓ The hydrogeological condition of the study area is a function of geomorphology, tectonics and lithostratigraphy of the volcanic rocks of Tertiary to Quaternary succession
- ✓ Regional groundwater flow direction; which is generally North-South towards northern part of Koka Lake area;
- ✓ Three regional aquifer systems were identified in the study area. These are alluvial and lacustrine aquifer, upper basal and lower basalt aquifer.

Figure 3.3 Borehole Log at Bororra, near Bushofitu Town



CHAPTER FOUR

4. GROUNDWATER MODELING

4.1 Introduction

A groundwater model is a computer-based representation of the essential features of a natural hydrogeological system that uses the laws of science and mathematics. Its two key components are a conceptual model and a mathematical model. The conceptual model is an idealized representation (i.e. a picture) of our hydro geological understanding of the key flow processes of the system. A mathematical model is a set of equations, which, subject to certain assumptions, quantifies the physical processes active in the aquifer system(s) being modeled. While the model itself obviously lacks the detailed reality of the groundwater system, the behavior of a valid model approximates that of the aquifer(s). It is not possible to see into the sub-surface, and observe the geological structure and the groundwater flow processes. The best we can do is to construct bores, use them for pumping and monitoring, and measure the effects on water levels and other physical aspects of the system. It is for this reason that groundwater flow models have been, and will continue to be, used to investigate the important features of groundwater systems, and to predict their behavior under particular conditions.

A groundwater model provides a scientific means to draw together the available data into a numerical characterization of a groundwater system. It provides a scientific and predictive tool for determining appropriate solutions to water allocation, surface water – groundwater interaction, landscape management or impact of new development scenarios. That is the model represents the groundwater system to an adequate level of detail, and provides a predictive scientific tool to quantify the impacts on the system of specified hydrological, pumping or irrigation stresses.

Typical model purposes include:

- ✓ improving hydrogeological understanding (synthesis of data);
- ✓ Aquifer simulation (evaluation of aquifer behavior);
- ✓ Designing practical solutions to meet specified goals (engineering design);

- ✓ Optimizing designs for economic efficiency and account for environmental effects (optimization);
- ✓ Evaluating recharge, discharge and aquifer storage processes (water resources assessment);
- ✓ Predicting impacts of alternative hydrological or development scenarios (to assist decision-making);
- ✓ Quantifying the sustainable yield (economically and environmentally sound allocation policies);
- ✓ Resource management (assessment of alternative policies);Sensitivity and uncertainty analysis (to guide data collection and risk-based decision-making);
- ✓ Visualization (to communicate aquifer behavior).

4. 2 Conceptual Model Development

Prior to simulating the ground-water system, conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all of the complexities of the natural system into a computer model is not feasible given the existing knowledge of the subsurface and current computer capabilities. Therefore, the hydrogeologic conceptual model (HCM) is a simplified representation of the groundwater flow system, frequently in pictorial form that defines the hydrostratigraphic units of interest and all system boundaries. The HCM involves delineation of groundwater sources and sinks, expected flow directions, model discretization (in terms of space and time), and selection of appropriate computer code(s) (Anderson and Woessner, 1992).

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. It is critical that the conceptual model be valid representation of the important hydrogeologic conditions;

failure of numerical models to make accurate prediction can often be attributed to errors in the conceptual model. 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.

Features often described in conceptual models include the following:

(a) Relationship and extent of hydrogeologic units (hydrostratigraphy, hydrofacies).

(b) Aquifer material properties (porosity, hydraulic conductivity, storativity, isotropy).

(c) Potentiometric surfaces.

(d) Water budget (inflows and outflows such as: surface infiltration, lateral boundary flux, leakage through confining units, withdrawals and injections).

(e) Boundary locations (depth to bedrock, impermeable layer boundaries, etc.).

(f) Boundary conditions (fluxes, heads, natural water bodies).

(g) System stresses (withdrawal wells, infiltration trenches, etc.).

(h) Hydraulic property of the aquifer.

(i) Water chemistry (varies with purpose; drinking, irrigation, pumping, etc.).

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. But due to lack of such detailed information in the case of Mojo River Catchment groundwater numerical simulation, a single aquifer system of an unconfined type was considered and this simplifies the complex natural aquifer system of the area.

In addition, a conceptual model should consist of the source of water as well as the expected flow directions and exit points. From the total inflows (recharge) and outflows (well withdrawal, sub surface outflow, 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).

To conceptualize the movement of groundwater through the system, hydrologic information on precipitation, recharge, water level head, base flow, and subsurface outflow 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.

In general, as careful conceptualization of hydrologic system under study and a conscious representation of the physical features that are hydrologic boundaries is a key to the development of reasonably accurate simulations, care has been taken to estimate each parameter in this study. Overall, the closer the conceptual model approximates the field situation the more accurate the model result will be.

In the following sections all these parameters are discussed in detail in relation to realities in the Mojo River Catchment as input into the model.

4.3 HYDRAULIC PROPERTIES OF THE AQUIFER

Initial estimates of hydraulic conductivity, recharge, and streambed leakance for the two-dimensional ground-water-flow models were based on existing and on new geologic and hydrologic data. Knowledge of aquifer parameters is essential for the modeling of groundwater resources. Conventionally, these parameters are estimated through pumping tests carried. Few boreholes may be available and carrying out pumping tests at a number of sites may be costly and time consuming. Hence geostatistical methods may be employed to distribute the properties to all nodes based on the data known at only a few nodes. However, geostatistics provides a systematic method for distributing the properties and does not account for site geological conditions.

The hydraulic conductivity of a given medium is a function of the properties of the medium and the properties of the fluid. Using empirically derived proportionality relationships and dimensional analysis, the hydraulic conductivity of a given medium transmitting a given fluid is given as:

$$K = \frac{k\rho g}{\mu} \qquad \text{(4.1)}$$

where

k = intrinsic permeability of porous medium $\left[L^2\right]$

ρ = fluid density $\left[ML^{-3}\right]$

μ = dynamic viscosity of fluid $\left[ML^{-1}T^{-1}\right]$

g = acceleration of gravity $\left[LT^{-2}\right]$

The intrinsic permeability of a medium is a function of the shape and diameter of the pore spaces.

In groundwater modeling hydraulic conductivity property is used as an input for the conceptual modeling. Hydraulic conductivities for the first run of the model were obtained from existing data, fieldwork, qualitative and quantitative approaches by direct and indirect methods. The characterization of hydraulic conductivity of Mojo River Catchment involved the use of existing pump test data, geological map, hydrogeological map, borehole logs, aquifer thickness, static water level, geological structures, surface and subsurface features.

Hydraulic properties of the Mojo catchment aquifer vary due to the heterogeneity of the aquifer the thickness and hydraulic properties of the sediments comprising the aquifer system. Previous studies made in the area used as background information for this research work.

The Mojo River catchment is made up of different rocks having different hydrogeological characteristics. Previous works in the catchment show that all aquifer types exist is the area, but as this study considered a single layer of an unconfined aquifer system the hydraulic conductivity is expected to vary laterally, not vertically.

Evaluation of several contaminated sites existing in Mojo area on the aquifer using ground water flow and transport models depends on availability of measured hydrogeologic data (e.g., hydraulic conductivity, for parameterization of the modeling runs. However, field measurements of such critical data have inadequate spatial density, and their locations are often clustered around Mojo Town and Debre Zeit area. Heterogeneity among geological formations is the basis for different hydraulic conductivity demonstrated on pumping test data analysis. The genesis of the rocks and the geological process that they happened to pass through is responsible for the opening and interconnection between them. Analysis of the test is built upon Neumann's approximate solution because the aquifer is assumed as an unconfined. But field measurements of such critical data have inadequate spatial density, and their locations are often clustered.These solutions assume aquifer homogeneity and uniform thickness despite the fact that aquifers are inherently heterogeneous and their thicknesses may vary significantly.

The specific yield and transmissivity data should be available at sufficient number of points to account for the variation of these parameters within the area. Spatial interpolation of horizontal hydraulic conductivity measurements was performed using kriging method. Structurally affected area has a dominant secondary porosity because of discontinuities such as fractures, joints, and faults. These discontinuities in the rock, collectively referred to as fractures, transmit water more readily than the surrounding solid rock. The fractures represent channels or avenues of high permeability relative to the low permeability matrix. They have the ability to transport fluid and contaminants over relatively large distances very rapidly, which could result in extensive contamination of ground water and surface water.

LOCAL_NAME	WATER_POINT	UTME	UTMN	ELV	RWL	T(m^2/day)	K(m/day)
Koka	AdBh0030	506728	937459	1659.3	1606.03		
Modjo Abu	AdBh0031	512159	946729	1769.7	1697.18		
D/Z-Dombo	AdBh0039	496479	965700	1904.3	1847.74		
Tede	AdBh0040	518458	946916	1854.9	1854.9		
Tede Dild	AdBh0041	521116	948053	1906.2	1906.2		
Modj-Golg	AdBh0042	521269	949730	1898.3	1690.7		
Modjo Tan	AdBh0043	512640	951316	1774.3	1774.3		
D/Z-Sunsh	AdBh0044	493545	968537	1915.8	1849.12		
RMI Steel	AdBh0052	494320	965101	1981	1870.56		
D/Z-Genes	AdBh0053	495447	968060	1912.8	1864.5		
D/Z-Draga	AdBh0054	494054	968452	1924	1857.89		

Shimbra M	AdBh0061	500885	973803	1895.4	1895.4		
Shimbra M	AdBh0062	501422	973727	1896	1871.9		
Shimbira	AdBh0063	500766	973335	1893.9	1871.26		
Shimbira	AdBh0064	500494	974376	1902.1	1877.23		
Shimbira	AdBh0065	500424	974376	1902.9	1872.3		
Shimbira	AdBh0066	500997	974272	1900.9	1900.9		
D/Z-Airfo	AdBh0067	500204	963672	1890.6	1859.1		
D/Z-Airfo	AdBh0068	499131	965767	1896.9	1869.1		
D/Z-Airfo	AdBh0069	499228	964796	1899.5	1856.43		
D/Z-Airf	AdBh0070	500909	964676	1886.4	1862.27		
D/Z-Airfo	AdBh0071	499148	965330	1901.1	1866.85		
Gafat#1	AdBh0072	507491	952694	1827.1	1787		
Gafat#2	AdBh0073	508079	952013	1819.5	1811.6		
Gafat#4	AdBh0075	508995	951614	1805.2	1773.94	13.68	0.34
Gafat#7	AdBh0078	509385	950325	1793.3	1767.22	27.36	0.41
Gafat#8	AdBh0079	509020	950736	1796.4	1767.5	9.75	0.15
Gafat#9	AdBh0080	508684	951058	1802.1	1778.19	15.41	0.23
Gafat#10	AdBh0081	507950	951364	1815.5	1789.95	1.45	0.34
Ude Villa	AdBh0082	503886	958637	1889.6	1859.6		
Modjo-Biy	AdBh0084	507722	955887	1849.7	1817.7		
Modjo-Biy	AdBh0085	507714	955875	1849.3	1817.7		
Shera Dib	AdBh0086	510619	952016	1810.9	1810.9		
Modjo Lum	AdBh0087	512957	947774	1771	1734.3		
Modjo kok	AdBh0089	512602	947821	1760.2	1721.1		
Modjo#4	AdBh0090	511927	948292	1761.1	1752.8		
Modjo#2	AdBh0091	511976	948671	1769.6	1734.26	30.67	0.04
Modjo#3	AdBh0092	512408	948682	1772.6	1738.46	17.28	0.77
Modjo#1	AdBh0093	512011	949196	1765.6	1733.83	1.45	0.04
Modjo Bek	AdBh0094	513423	948940	1777.1	1739.9		
Modjo Eth	AdBh0095	513773	949998	1786.7	1747.18		

Wonji Gef	AdBh0127	523531	936474	1549.2	1538.19
D/Z-Healt	AdBh0261	497100	968198	1896.2	1859.8
Modjo-Alm	AdBh0292A	517022	947564	1809.3	1699.3
D/Z-Assem	AdBh0293A	496646	967481	1893.2	1872.8
Modjo Han	AdBh0295	509969	952000	1798.8	1783.7
D/Z-Dugda	Adbh0349	502364	970907	1884.8	1861.02
Modjo Dai	Adbh0351	512282	951356	1773.3	1766.2
Modjo lum	AdBh0352	512282	951356	1773.3	1765.96
Modjo Lum	AdBh0353	512355	951516	1777.4	1768.15
SUN Tanne	AdBh0354	512356	947895	1750.7	1725
Liben Gar	AdBh0378	496234	939700	1658.8	1652.8
Kusaye	AdBh0379	498233	939885	1645.7	1640.7
Modjo Exp	AdBh0380	511848	948993	1763.2	1763.2
D/Z-Green	AdBh0386	494598	967157	1926.6	1859.82
Malmalle	AdBh0417	515109	943100	1737.5	1669.92
Buti peas	AdBh0831	496697	974436	1921.2	1921.2
D/Z-Flour	AdBh0835	496147	967674	1895	1854.7
D/Z-steel	AdBh0849	496159	966870	1901.3	1860.8
D/Z-Genes	AdBh0949	495447	968068	1912.7	1863.02
D/Z-Elfor	AdBh0987	494145	966864	1939.4	1939.4
D/Z-Airfo	AdBh1006	499500	964500	1898.8	1868.3
D/Z-IAR N	AdBh1010	500260	969015	1880	1880
D/Z-IAR N	AdBh1011	500180	969240	1878.9	1878.9
D/Z-IAR N	AdBh1012	500524	969317	1879.7	1879.7
D/Z-Jegno	AdBh1016	499500	967700	1889.8	1889.8
D/Z-Jegno	AdBh1017	499500	967700	1889.8	1889.8
D/Z-Sahil	AdBh1020	494829	967088	1917.3	1853.2
D/Z-Girma	AdBh1022	495561	968574	1906	1856.1
D/Z-Almaz	AdBh1023	499320	970175	1889.5	1870.6
D/Z-Blue	AdBh1024	495765	966397	1906.1	1859.5

D/Z-Hora	AdBh1026	498633	970028	1889.2	1855.1		
D/Z-Veter	AdBh1027	500078	968505	1907.1	1892.6		
Mekaneyes	AdBh1029	499445	967905	1872.6	1872.6		
Koka-CGC	AdBH1149	520353	939385	1651.2	1562.2		
Modjo Ude	AMW21	506765	957179	1856.1	1837.1		
Borora	AMW22A	505014	970969	1883.9	1863.4		
Borora	AMW22B	504878	970766	1882.4	1861.95	153	
Modjo Mud	AMW25	506464	941989	1698.9	1613.9		
Modjo Ude	AMW21	506765	957179	1836	1817	96.31	1.61
Borora	AMW22B	504878	970766	1879	1858.55		
Modjo Muda	AMW25	506464	941989	1697	1612		
Kersa Rig	AdBh0382	519810	1002644	2499.4	2499.4		
Manginso	AdBh0383	508639	993924	2481	2481		
Bekie-Are	AdBh0384	527037	1002037	2487.7	2487.7		
Oda suftu		510393	991274	2390	2363	104.11	5.34
Rafiki well		954008	511760			43.49	0.87
Arosa hotel		506506	956871	1862		11.44	6.97
Kolba Tunnery		512733	947675	1760		21.85	0.32
Gafat 5							0.26

Table 4.1 Hydraulic Characteristics of Wells in the Study Area

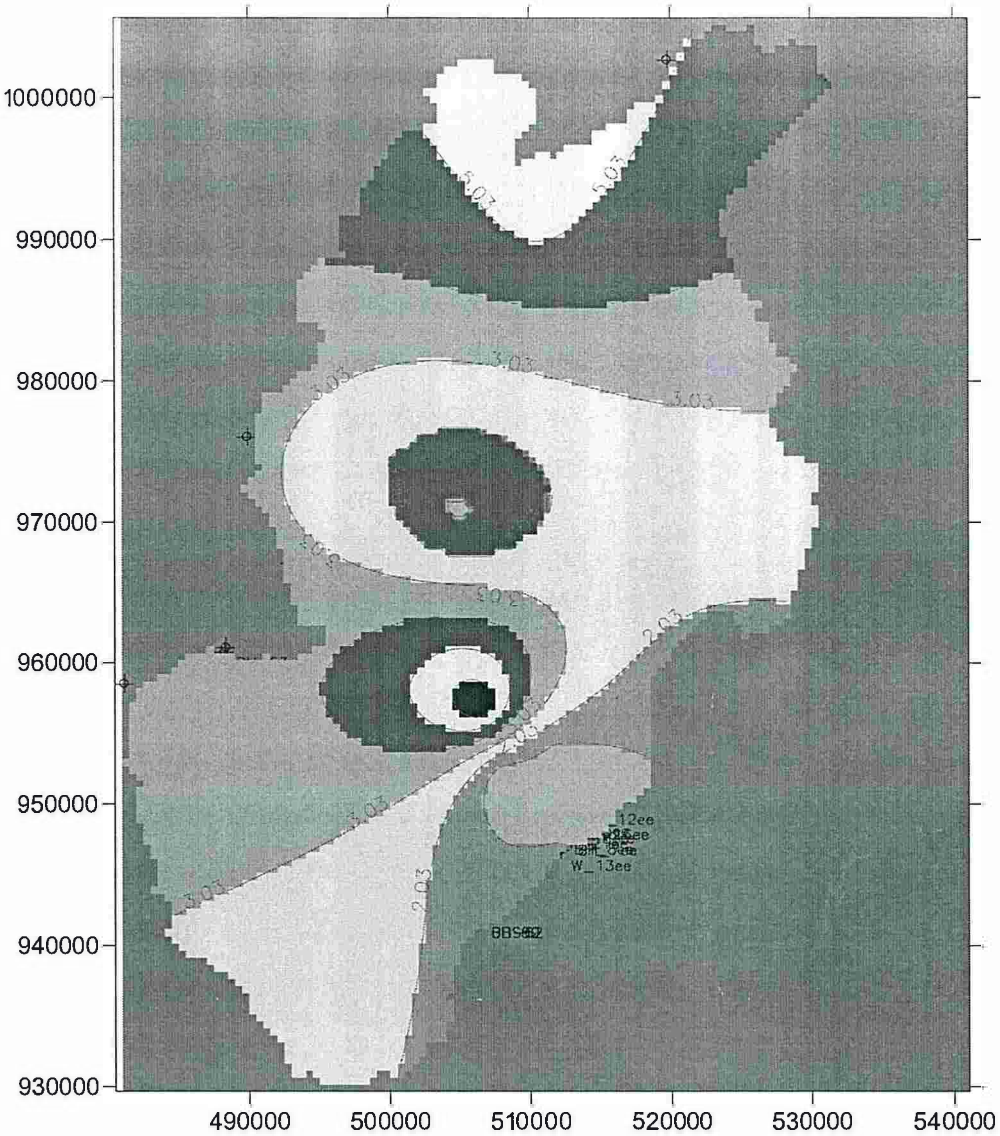


Figure 4.1 Interpolated Initial Horizontal Hydraulic Conductivity Map of the Study Area

4.4 BOUNDARY CONDITIONS.

Boundary conditions are constraints imposed on the model grid to represent the interface between the model calculation domain and the surrounding environment. There are three major types of boundary conditions, all of which may vary with time.

They are mathematical statements specifying the dependent variable (head) or derivative of the dependent variable (flux) at the boundaries of the problem domain

(Anderson and Woessner, 1992). Boundary conditions are constraints imposed on the model grid that express the nature of the physical boundaries of the aquifer being modeled. Correct selection of boundary conditions is a critical step in model design.

Specified head: the head value is specified and the model calculates the flow across the boundary to or from the model domain (Rivers, coastlines, lakes, groundwater divides, known pumping water levels in bores, dewatering targets.). A specified head boundary can be used when expressing the constraints imposed by a lake, a reservoir, or a known phreatic surface. Easiest to solve, but constrains solution to greatest degree (can artificially constrain solution too greatly). Commonly used because head data can be measured much easier than flow data. A specified head allows an inexhaustible amount of water flow (calculated by the model) into or out of a model.

Specified flux: a specified flux boundary expresses the effects of a feature that constrains flow into or out of a boundary or a location where the flux can be estimated. Examples include: zero flux from a subsurface barrier, surface infiltration, leakage across a confining layer, or a "no-flow" boundary chosen to coincide with a groundwater divide or a groundwater flow line so that lateral flux is negligible. Caution should be used in the latter case because natural groundwater divides and "no-flow" lines can move when the aquifer is stressed. The type of boundary chosen should be fully consistent with the water budget and boundary conditions identified in the conceptual model

The type of boundary selected should be consistent with the conceptual model and the water budget, and should be located and oriented consistent with the physical features it represents. In particular, model domain boundaries should be set far from the area of interest (e.g. a water supply bore field) so that imposed stresses on the grid interior do not reach the boundaries. Alternatively, the boundary needs to be configured such that the simulated boundary effect is realistic (e.g. using a head-dependent flow boundary at a groundwater divide or a surface-groundwater interaction feature).

Boundary conditions should be designed to take advantage of physical or hydraulic boundaries. Physical boundaries usually relate to the physical presence of an impermeable geological formation or a large body of surface water. An impermeable boundary typically forms the lower and/or lateral boundaries of modeled systems, and may be justified provided there is at least a two order of magnitude contrast in hydraulic conductivity between the two units (Anderson and Woessner, 1992). Hydraulic boundaries form as a result of hydrologic conditions, notably at groundwater divides and streamlines, although these features are not permanent, and may shift their location or magnitude (of flux or head). Care must be taken in specifying hydraulic boundary conditions, whereas physical boundaries are more easily handled.

Head-dependent Flow: the model calculates the flow for the given head, Leaky Rivers, drains, flow to or from adjacent aquifers, basement leakage, and springs. Most difficult to solve, and involves least constraints on solution. It can form a very complex and sensitive boundary condition. Cases, as the model calculated flow is subject to a conductance parameter, which may need to vary with time, and this may violate some calibration assumptions.

The type of boundary chosen should be fully consistent with the water budget and boundary conditions identified in the conceptual model.

Two of the boundaries, Specified head and Specified flux Flow, were used to define groundwater flow system of the Mojo River Catchment. The boundary approximately corresponds with natural hydrologic boundaries across which groundwater flow was assumed to be negligible. On all sides, major topographic divides were assumed to coincide with groundwater divides.

Groundwater on either side of the divide flows away from the divide and not across it, the divide itself acts as a no flow boundary. It is worth noting that the position of such a boundary changes based on stress applied to the system. The location and magnitude of stresses applied to the model affect the appropriate choice of boundary conditions. For example, if a groundwater divide is chosen as a zero-flux boundary condition, the natural boundary and the model boundary may match closely in an unstressed steady state. If, however, an extraction well is placed near this boundary in the computer simulation, the original flow system is no longer being modeled and the original boundary condition and its alignment may need to change. A rule of thumb is to avoid placing boundaries close to where stresses will be applied.

In the case of Mojo River catchment it was assumed that the effect of the stress applied does not go beyond the groundwater divides so that the divides might be consider as boundaries.

In addition, the upper boundary of the modeled catchment was assumed to be the water table and recharge was used to represent the boundary flux. Although not known to exact, the lower boundary was considered as a no flow because the aquifer was assumed to be underlain with an impermeable rock body.

In general, the boundary systems used for the purpose of this modeling work are selected to coincide with groundwater divide features in the actual systems.

4.5. FLUXES AND STRESSES

4.5.1 GROUND WATER RECHARGE

The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the ground water recharge. Thus, a quantitative evaluation of spatial and temporal distribution of ground water recharge is a pre-requisite for operating ground water resources system in an optimal manner.

Rainfall is the principal source for replenishment of moisture in the soil water system and recharge to ground water. Moisture movement in the unsaturated zone is controlled by suction pressure, moisture content and hydraulic conductivity relationships. The amount of moisture that will eventually reach the water table is defined as natural ground water recharge. The amount of this recharge depends upon the rate and duration of rainfall, the subsequent conditions at the upper boundary, the antecedent soil moisture conditions, the water table depth and the soil type.

Estimating the rate of aquifer replenishment is probably the most difficult of all measures in the evaluation of ground water resources. Estimates are normally and almost inevitably subject to large errors. No single comprehensive estimation technique can yet be identified from the spectrum of those available, which gives reliable results. Recharge estimation can be based on a wide variety of models which are designed to represent the actual physical processes. The methods, commonly in use for estimation of natural ground water recharge, include ground water balance method, soil water balance method, zero flux plane method, one-dimensional soil water flow model, inverse modeling technique, and isotope and solute profile techniques. Part of the rain water that falls on the ground is infiltrated into the soil. This infiltrated water is utilized partly in filling the soil moisture deficiency and part of it is percolated down reaching the water table. This water reaching the water table is known as the recharge from rainfall to the aquifer. Recharge due to rainfall depends on various hydro meteorological and topographic factors, soil characteristics and depth to water table.

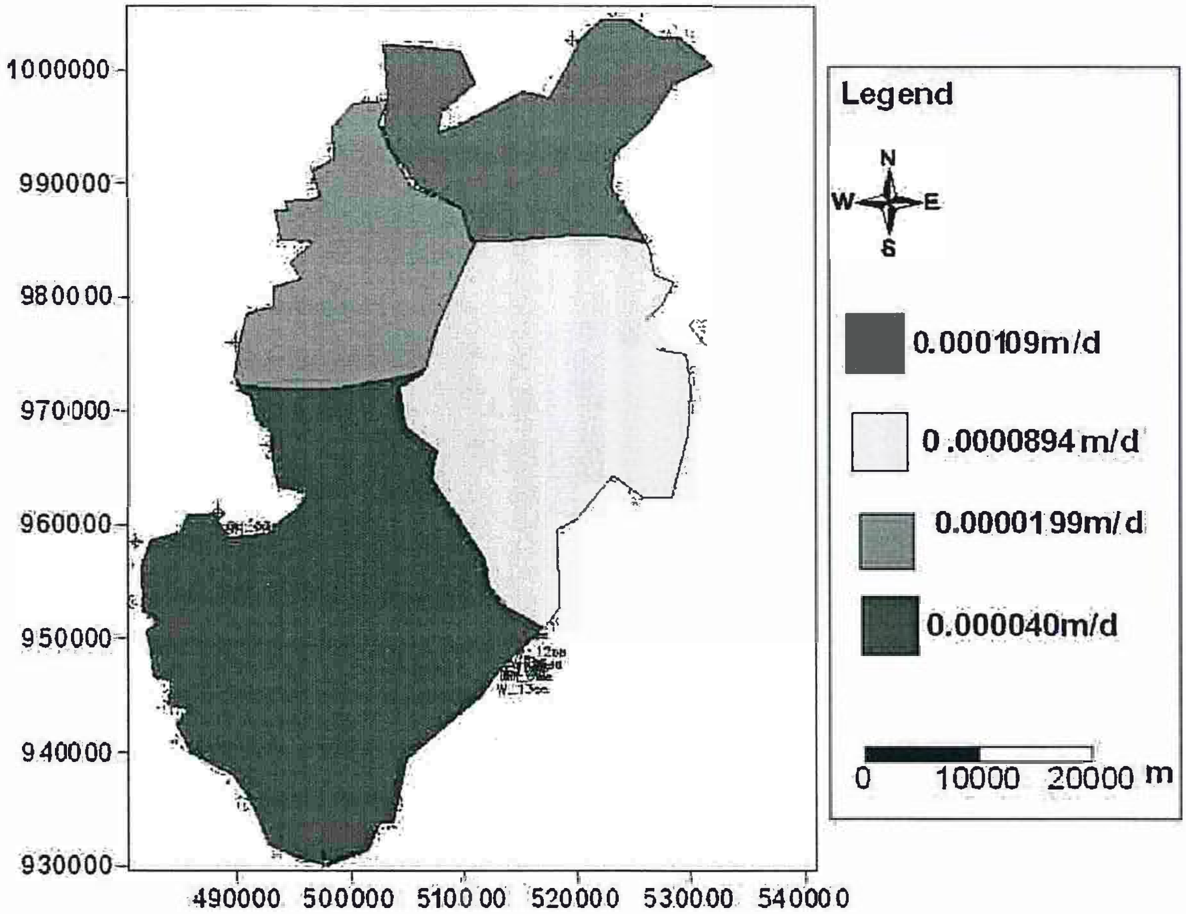


Figure 4.2 Recharge Zones of the Study Area

Accordingly, the study area was classified in to different zones, as shown in figure above. The zonation and the assumptions behind the classification are outlined as follows.

- ✓ The northern part of the study area is assumed to have maximum recharge values relative to other zones. These areas are covered with agricultural land

and forests lying over Chefe Donsa unit. A recharge amount of 0.00604167 cm/day has been assigned to this elevated zone.

- ✓ The next large recharge zones are areas covered with highly fractured Nazerth unit with land use/cover of agriculture or open field. The value is approximated to be 0.00302084cm/day.
- ✓ The Third zone that is approximated to receive a relatively higher recharge, next to the second zone, is the North Western Part of the study area. For this zone the recharge is roughly approximated to be 0.0018125 cm/day.
- ✓ In zones at the southern and southeastern tips of the catchment, where the elevation drops and the slope favors the formation of thick clay cover, it is assumed to receive an average recharge value of 0.00120833 cm/day

4.5.2. DISCHARGES

Currently groundwater is removed from aquifers in the Mojo River Catchment by withdrawal through wells for human consumption or industrial activities, spring discharge and base flow to rivers. The evapotranspiration loss from aquifers was considered to be negligible.

Most of boreholes in Mojo River catchment have a capacity greater than 2 l/s on minimum and up to 6-8l/s on maximum. The availability of productive boreholes in the catchment is attributed to the presence of fractured volcanic rocks that encompasses the Mojo Town and Part of Debrezeit Town where large population live and different institutions/factories are found in the area, there is enormous number of wells drilled for various uses. Currently there is high encroachment of Flower plantation farm in the area. Therefore, the rate of abstraction varies from well to well, according to the use for which they are purpose they being developed.

Most of the wells that are owned at household levels have a lower withdrawal rate that is suffice to meet the demand of one or two households per day and the abstraction rate from most of such wells was very low. In general, withdrawal from these groups of wells is very small.

Wells that have relatively higher abstraction rates are those wells that are owned by big hotels and different industries that use water for processing their products. The withdrawal from these wells has been approximated for the purpose of this study based on minimum pumping hours and calibrated to a reasonable value. Other public wells in smaller towns and hand operated wells in large rural villages were also incorporated into the conceptual model.

No	Name	Location		Abstraction(m3/day)
		X	Y	
1	Koka	506728	937459	345.6
2	Modjo Abu	512159	946729	691.2
3	Modj-Golg	521269	949730	345.6
4	RMI Steel	494320	965101	1209.6
5	Shimbra M	501422	973727	1036.8
6	Shimbira	500766	973335	604.8
7	Shimbira	500494	974376	1468.8
8	Shimbira	500424	974376	604.8
9	Shimbira	500997	974272	1209.6
10	D/Z-Airfo	499228	964796	691.2
11	D/Z-Airf	500909	964676	518.4
12	Gafat#1	507491	952694	518.4
13	Gafat#2	508079	952013	432
14	Gafat#4	508995	951614	432
15	Gafat#7	509385	950325	345.6
16	Gafat#8	509020	950736	345.6
17	Gafat#9	508684	951058	345.6
18	Gafat#10	507950	951364	345.6
19	Modjo Lum	512957	947774	777.6
20	Modjo#4	511927	948292	432
21	Modjo#2	511976	948671	1123.2
22	Modjo#3	512408	948682	432

23	Modjo#1	512011	949196	432
24	Modjo Bek	513423	948940	518.4
25	Modjo Eth	513773	949998	432
26	Wonji Gef	523531	936474	259.2
27	D/Z-Healt	497100	968198	864
28	Modjo-Alm	517022	947564	86.4
29	D/Z-Dugda	502364	970907	2073.6
30	Modjo lum	512282	951356	691.2
31	Modjo Lum	512355	951516	691.2
32	D/Z-Green	494598	967157	604.8
33	Malmalle	515109	943100	518.4
34	D/Z-Flour	496147	967674	345.6
35	D/Z-steel	496159	966870	1728
36	D/Z-Genes	495447	968068	1468.8
37	D/Z-Airfo	499500	964500	432
38	D/Z-Sahil	494829	967088	259.2
39	D/Z-Girma	495561	968574	172.8
40	D/Z-Almaz	499320	970175	518.4
41	D/Z-Blue	495765	966397	432
42	D/Z-Hora	498633	970028	864
43	D/Z-Veter	500078	968505	1296
44	Borora	504878	970766	3110.4

Table 4.2 Groundwater Abstraction of Some Public Wells

4.5.3 Base Flow to Rivers

Rivers are surface features that commonly form an interface of a saturated groundwater flow system. Streams are important boundaries of groundwater systems because they influence the heads and flows of the groundwater system with which they interact.

In this study, only perennial streams that were expected to have an interaction with groundwater systems were considered and these streams gain water from aquifers at most reaches. The rivers were considered simply as sinks and were simulated using the River Package of MODFLOW. The rate of leakage between the aquifer and the rivers is calculated by MODFLOW based on the following relations:

$Q_{Riv} = C_{Riv} (H_{Riv} - h)$, when $h > R_{Bot}$ .... (4.2)

$Q_{Riv} = C_{Riv} (H_{Riv} - R_{Bot})$, when $h < R_{Bot}$ .... (4.3)

Where Q_{Ri} : the rate of leakage through the river bed

H_{Riv}: head in the river

h: head in the aquifer

R_{Bot}: elevation of bottom of the river bed

C_{Riv} : river bed hydraulic conductance

The River Package simulates the effect of loss from aquifer to rivers or from river to aquifers and uses stream bed conductance to calculate the flux. Some stream beds consist of material of low hydraulic conductivity that can cause a large head difference between the stream and the aquifer, while other streams may be well connected to the aquifer system through permeable material of high hydraulic conductivity.

Hydraulic conductance, head in the river and bottom elevations of river bed were approximated for river segments. Hydraulic conductance is incorporated into river package to account for the length (L) and width (W) of the river channel in a cell, the thickness of the river bed sediment (M) and the hydraulic conductivity of the river bed sediments (K). It can be expressed as:

$C_{Riv} = KLW/M$ .... (4.4)

In this study, all these parameters were estimated for river segments that comprises a large number of cells as measurement of each parameter for each cell is very difficult in the field. The values were re-approximated for each single cell and entered into the

River Package of MODFLOW during simulation. Model cells were designated as river cells along perennial rivers and their tributaries

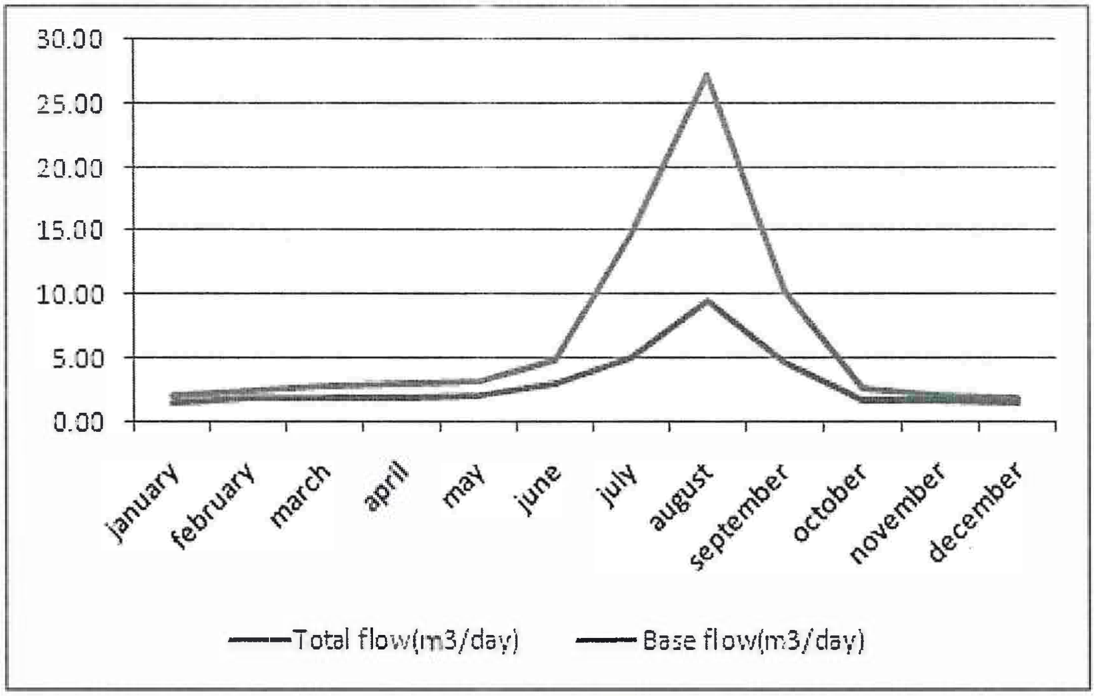


Figure 4.3 Base flow Separation Hydrograph

Month	Total flow(m^3/day)	Base flow(m^3/day)
january	2.00	1.59
february	2.50	1.90
march	2.76	1.95
april	3.04	1.98
may	3.19	2.21
june	4.84	2.99
july	14.82	5.16
august	27.29	9.49
september	10.29	4.75
october	2.62	1.71
november	1.99	1.74
december	1.88	1.64

Table 4.3 Summary of total stream flow and base flow

4.5.4 SPRING

Many people are fascinated by springs. The very word seems to have some magic. If you are faced with the challenge of giving a talk about ground water, a discussion of springs could be a good topic to include in your presentation.

Ground water that flows naturally from the ground at the surface is called a spring, and where the flow is diffuse, it may be called a seep or seepage. Many rivers receive water from diffuse seepage. The occurrence of most springs is controlled by the structure of the rock formations. The flow rate from a spring may depend on ground water recharge conditions, the season, and the water demands of vegetation. A spring can occur if impermeable bedrock prevents downward flow. The size of upslope area, the soil thickness, and the frequency of precipitation will determine whether the spring flows year-round.

In situations where rocks are fractured along the line of a geologic fault, it may result in a spring supplied from an aquifer in contact with the fault. Depending on the topography of the land surface there could be a line of springs related to the same fault.

There are a number of variable discharge springs in the interior of the study area. Most of these springs have low discharges and they simply flow to rivers or infiltrate to soil along flow paths. Few have higher discharge rates and were simulated using the Well Package, considering that the yield does not vary with the head in the aquifer. One of such springs considered in the simulation is Gimbichu Fentale, has a discharge rate of 35 l/sec and is used for Chefe Donsa town water supply.

Once ground water flows as a spring it loses the natural protection provided by the overlying rock layers and is more vulnerable to contamination threats from surface and atmospheric conditions. Many homes, farms and cabins use spring water as a drinking source by constructing a protective hut or “spring-box” that keeps critters out of the source water. However, compared with water from drilled wells, there is a greater risk of bacteria or protozoa occurring in springs, and some form of disinfection in addition to regular water quality testing is recommended.

4.6 SOIL WATER BALANCE

Water balance techniques have been extensively used to make quantitative estimates of water resources and the impact of man's activities on the hydrologic cycle. On the basis of the water balance approach, it is possible to make a quantitative evaluation of water resources and its dynamic behavior under the influence of man's activities. The study of water balance is defined as the systematic presentation of data on the supply and use of water within a geographic region for a specified period. With water balance approach, it is possible to evaluate quantitatively individual contribution of sources of water in the system, over different time periods, and to establish the degree of variation in water regime due to changes in components of the system.

A steady state water balance:

Input to the system - outflow from the system= change in storage of the system (over a period of time).

The general Relation of groundwater Recharge Estimation

$Ri = P - Ea + \Delta S - Ro$ .... (4.5)

Where

Ri= recharge

P= precipitation

Ea= actual Evapotranspiration

ΔS= Change in soil water moisture

Ro= Runoff

Under predevelopment condition the groundwater system is in long term equilibrium. Predevelopment equation of groundwater budget can be written as:

Inflow=outflow

$Ri = P - Ea + \Delta S - Ro$

Equation (4.5) represents the water balance of Mojo River catchment used to quantify Recharge

P= 910.48mm per year

Ro= 77mm per year

Ea= 790mm per year

ΔS= Change in soil water moisture

Ri= P-Ea-Ro= **254293.75** m^3/day

Change in soil water moisture on yearly base is zero. In a steady state model simulations, inflows to and outflows from surface water –groundwater system should be known and quantified on an average annual basis. The steady state water balance for Mojo River catchment aquifer system, as described in this work, include only the components simulated in the flow model. As described in preceding sections, inflow includes areal recharge from precipitation that infiltrates into soil, passes through the soil and reaches the water table; and is equal to total precipitation minus direct runoff and evapotranspiration at or near land surface. Outflows include base flow to rivers, well withdrawal, springs discharge

Under steady state conditions, inflow to groundwater system should be equal to outflow from the system as changes in storage on annual basis is considered to be negligible.

The groundwater inflow to the aquifer is 93MCM per year and the total groundwater outflow is 86 MCM per year. The remaining 7 MCM could be part of groundwater outflow from the catchment to the adjacent catchments through deeper routes or faults that it is difficult to quantify. The base flow is 4% of the precipitation recharge rate.

Groundwater discharge to wetlands that in turn is lost through evapotranspiration may also contribute to the differences to some extent. Still there is a large amount of water withdrawn by hand pumps and dug wells that were not included in the balance. In addition as the recharge value is an approximation, this may also contribute to the resulting differences.

Water balance equation therefore usually does not balance, even if all its components are computed by independent methods. The discrepancy of water balance is given as a residual term of the water balance equation.

No	Water Balance Component	Inflow (m3/day)	Outflow (m^3/day)
1	Recharge	**254294**	
2	Well Withdrawal		14511
	Base flow		216857.62
3	Springs		3024
	Total	254294	234392.6

Table 4.3 Estimated Average Conceptual Groundwater Balance of the Study Area

4.7 NUMERICAL GROUNDWATER FLOW MODELING

MODFLOW is a groundwater model that simulates groundwater flow in confined and unconfined aquifers in three dimensions. Mojo River Catchment is considered as unconfined aquifer and groundwater modeling is accomplished using It is the most widely used and accepted groundwater model internationally. The model utilizes distributed input and variables such as hydraulic conductivity, storativity, recharge and evaporation to simulate groundwater flow using a range of Finite Difference solvers. Being a modular model, additional packages can be easily incorporated to enhance its capability. The attraction of groundwater modeling is that it combines the subtlety of human judgment with the power of a digital computer Although groundwater models are time consuming to design and therefore expensive in terms of labor time, it is also true that the use of groundwater model is the best way to make an informed analysis or prediction about the consequences of the proposed action.

Numerical ground water flow modeling helps to have a good understanding of the current or to predict the long term tendencies of a hydro geological system and it allows a detailed analysis of the movement of water through a hydro geologic unit that constitute the groundwater flow system.

It is mandatory to have good initial data on boundary conditions, fluxes and aquifer hydraulic parameters for a model to give simulation output that approaches the real situation. In other words, models can only be good if the input data is good enough. Especially, input parameters that have the most control on the model output have to be carefully investigated and correctly estimated. In this study, a shortage of well organized standard hydro geological data has been encountered in most parts of the catchment to have good estimates of these parameters but collection and assemblage of relevant hydro geological data in the conceptual model has been carefully made.

In recent years ground water modeling has become a major part of projects dealing with ground water exploitation, protection, remediation and it is the most useful tool to study the response of a hydrogeologic system to any hypothetical scenario or to predict system response.

Numeric models describe the entire flow field of interest at the same time providing solutions for as many data points as specified by the user. The area of interest is subdivided into many small areas (usually referred to as cells or elements) and a basic ground water flow equation is selected to solve for each cell. The solution of a numeric model is the distribution of hydraulic heads at points representing individual cells.

Similar to most numerical ground water flow models, the Mojo River catchment ground water flow model developed in this thesis was simulated to study the response of the system to different hypothetical scenarios of pumpage, recharge or any other parameter under a steady state condition.

The approach followed to develop this numerical model includes definition of system boundaries, estimation of well withdrawal, estimation of base flow and subsurface outflow, compilation and examination of previously estimated recharge and hydraulic conductivities, compilation of water level data, groundwater level contouring, selection of an appropriate computer code/governing equation for simulation, calibration of calculated heads/fluxes to field observed heads/fluxes and simulation under different scenarios to understand the response of the system. The underlying concept of the approach used is that an understanding of related basic principles and an accurate description of the specific system under study will enable an accurate quantitative understanding of the cause and effect relationship. This quantitative understanding of the relationships allows one to understand the response of the system under consideration to any proposed scenario or to make predictions for any defined set of conditions.

4.7.1 GOVERNING EQUATION

In an unconfined aquifer, the saturated thickness of the aquifer changes with time as the hydraulic head changes. Therefore, the ability of the aquifer to transmit water (the transmissivity) is not constant:

$$\frac{\partial}{\partial x}\left(K_x h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y h\frac{\partial h}{\partial y}\right)+\left(\frac{\partial}{\partial z}h\frac{\partial h}{\partial z}\right)=S_y\frac{\partial h}{\partial t} \quad\text{.. (4.6)}$$

Where

S_y= specific yield [dimensionless]

For a homogeneous, isotropic aquifer, the general equation governing unconfined flow is known as the *Boussinesq equation* and is given by:

$$\frac{\partial}{\partial x}\left(K_x h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y h\frac{\partial h}{\partial y}\right)+\left(\frac{\partial}{\partial z}h\frac{\partial h}{\partial z}\right)=\frac{S_y}{K}\frac{\partial h}{\partial t} \quad\text{.. (4.7)}$$

If the change in the elevation of the water table is small in comparison to the saturated thickness of the aquifer, the variable thickness *h* can be replaced with an average thickness *b* that is assumed to be constant over the aquifer. Equation 4.7 can then be linearized to the form:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S_y \partial h}{K b \partial t} \qquad (4.8)$$

The assumption for the flow in this model is two dimensional steady state flows and the governing differential equation used is therefore:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \qquad (4.9)$$

4.7.2 MODEL DESIGN AND DISCRITIZATION

Grids define the spatial area of the numerical model domain in terms of finite differences or finite elements, (grids are not required for analytical models). Finite differences divide the aquifer into a rectangular grid of nodes that define the corners or the centers of model cells. Most finite difference grids are "block-centered", where nodes lie in the centre of cells, but they can be mesh-centered, where the nodes lie at the intersections of the grid lines and define the corners of the cell. For block-centered grids, flux boundaries need to fall on the edge of cells, and head boundaries need to fall on the node in the centre of the cell. The boundary condition location must be consistent with the adopted grid design. To design the model, it is necessary to specify the model type (i.e., 1D, 2D, or 3D) that bests suits the objectives of modeling, the data set available, the model domain and the conditions encountered at the site. Once the model type has been specified, it is possible to discretize the model domain in time and space. One goal of model design is to simplify the system so it can be analyzed by reasonable means.

The spatial discretisation of the grid should be fine in areas of interest or areas of stress, but may be coarse away from these areas, or where data are sparse. The size of the nodal spacing is dependent on the expected curvature of the water table or potentiometric surface, with fine spacing required to accurately define highly curved surfaces (e.g. around pumping wells or near rivers, etc.) or steep hydraulic gradients in the horizontal or vertical directions. Nodes may be regularly spaced, or the spacing may be increased as the grid is expanded towards regional boundaries. For finite difference grids, the grid expansion factor (ratio of larger to smaller adjacent nodal spacing) should not exceed 1.5. The aspect ratio (ratio of maximum to minimum cell dimensions) should ideally be close to unity, and should not exceed 10 for finite difference grids, or a value of 5.0 for finite element meshes (Anderson and Woessner, 1992).

The external boundaries of the model domain should be oriented parallel to the primary groundwater flow direction if possible. Often, particularly for regional models with variable flow direction, it is more convenient to align a model grid with cardinal directions.

In this study two dimensional finite-difference ground-water-flow model covering a 76-by 60-Km area (fig.4.4) that is subdivided into 18240 nodes (152rows, 120 columns, and 1 layer) is used. The row and column dimension of each node is uniform throughout the model area, with each node measuring 500m on a side. This uniformly spaced grid was used to simulate all parts of the flow system. There is a high variation in the thickness of the aquifer similar to the lithology. From previous and well logs thickness of the aquifer is in the range of 30 to 160m.Taking the average of Borehole depth in the study area the model thickness is considered to be 230m. The boundaries of the basin are simulated using no-flow boundary conditions. The recharge option is used to enter recharge rates at the edge of the basin. Layer types are defined in the BCF package (under MODFLOW). MODFLOW will calculate layer transmissivities given the top and bottom layer elevations and the hydraulic conductivities for the layer. The layer has a variable bottom, which is entered into the bottom option.

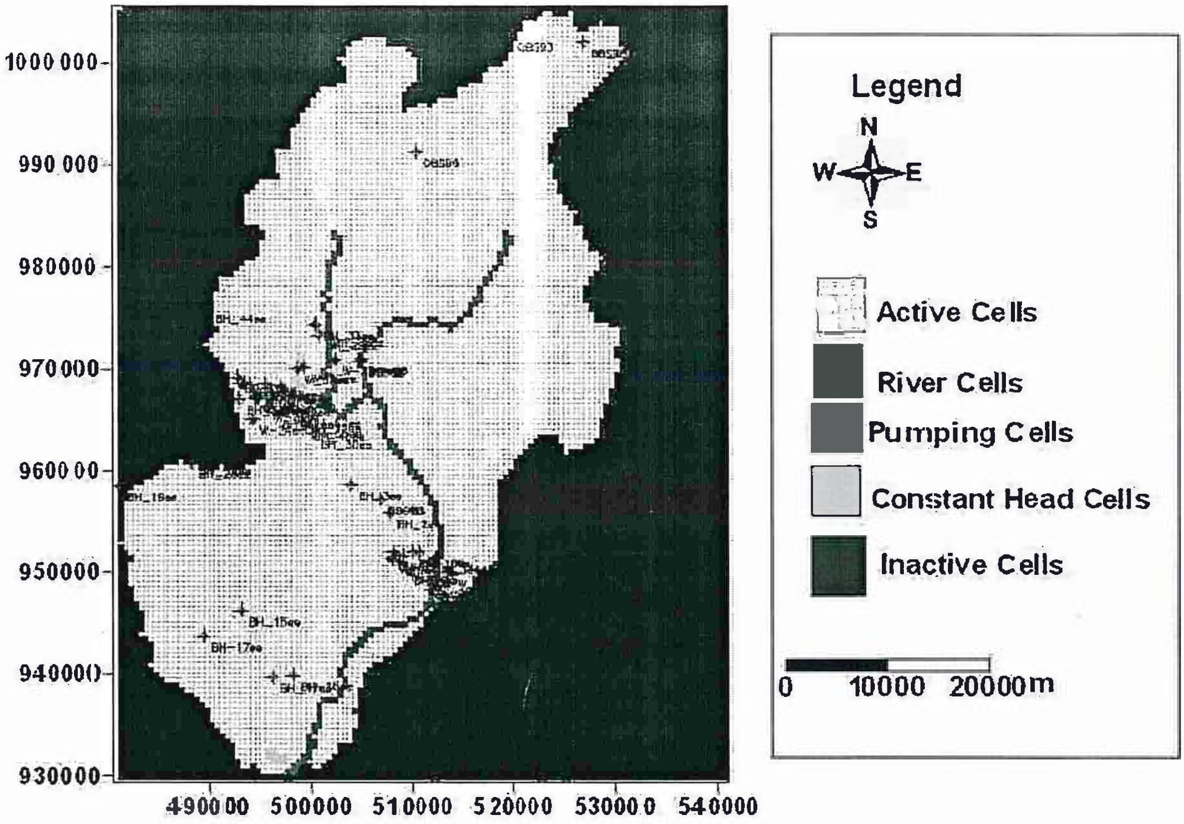


Figure 4.4 Model Design and Boundary Condition

4.7.3 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 Shuttle Radar Terrain Mission (SRTM). The interpolation was done at a resolution of 500m by 500m and then loaded into MODFLOW top elevation array. At points like lakes/reservoirs where elevation value misses in the SRTM, the elevation of the points were patched based on the values of nearby points.

4.7.4 BOTTOM OF LAYER

It is the bottom elevation of aquifer layer being modeled. In this study, the aquifer thickness is approximated to be about 120-260m in most parts of the catchment except along the boundaries where ridges with high elevation are found. Elevated zones were simulated by giving relatively higher thicknesses at the cells in order to avoid drying cells during simulations. Hence bottom elevation was obtained by subtracting 230m which is an average of depth of all boreholes from elevation top in most parts of the catchment. In fact, the thickness of the aquifer is very rough as it has not yet been determined exactly for the aquifers and was modified a bit in few areas during model calibration process.

CHAPTER FIVE

5 CALIBRATIONS AND SENSITIVITY ANALYSIS

5.1 MODEL CALIBRATION.

Calibration of a flow model refers to a demonstration that the model is capable of producing field measured heads and flows which are the calibration values (Anderson and Woessner, 1992). It involves adjustment and refinement of parameter structure and parameter values to provide the best match between measured and simulated values of hydraulic heads and flows. Calibration is carried out to demonstrate that the calibrated model can reproduce measured heads or fluxes and groundwater flow modeling is usually intended to produce a model that can accurately simulate future condition for which no head data are available. Therefore to make good projections and to understand system dynamics, model calibrations was done to acceptable error range by taking realities in the area in to considerations.

Basically, calibration can be achieved in two ways. That are, the forward and inverse problem solutions. In an inverse solution method one determines values for a given parameter structure and hydrologic stress using a mathematical technique, such as nonlinear regression (Cooley & Naff, 1990; Hill, 1992, 1998) from information about head distribution (Anderson and Woessner, 1992). This technique is sometimes called parameter estimation & it finds the set of parameter values that minimize the difference between simulated and measured quantities such as hydraulic heads and flows; where as in the forward problem system parameters such as hydraulic conductivity and hydrologic stresses are specified and the model calculates the head distribution. In this study, the forward solution method was used & calibration was performed by the traditional trial and error process in which model parameters were adjusted manually within reasonable limits of the existing data and field hydro geological observations to achieve the best model fit. In addition, available point hydraulic conductivity data of wells was used as a control during calibration of hydraulic conductivity. Model fit was evaluated by visual comparison of simulated and measured heads, and by comparing root mean errors of heads between simulations.

5.1.2 Calibration Data

The Mojo River catchment ground water model was calibrated to steady state condition of average head collected at different times in different parts of the catchment. Head observations for calibration of Mojo River Catchment groundwater flow model consisted of water level measurements data from 136 wells. Observations points were not evenly distributed throughout the model domain but clustered geographically in Mojo Town and Debrezeit Town. In this study an attempt has been made to collect water level in areas where available data was scarce. The calibration was done using heads measured at different times. This was done due to the fact that obtaining water level measurements in some wells (e.g. private wells and other sealed wells) during this work was not possible. In some cases water levels measured during pumping test were used. This seems to cause some discrepancy but it can be accepted hydrologic ally because time series water level fluctuations in wells in the catchment can be assumed to be negligible. Moreover, it is logical to assume that error introduced into the result due to heads measured at different times is lower than error due to uncertainties in recharge, hydraulic conductivity or other model input parameters.

Ground water head contours were constructed from these water levels and matching field contours with calculated contours was made in calibration. During the longer calibration process, initial estimates of model input parameters; especially recharge, hydraulic conductivity, stream bed and general head boundary interface conductance were adjusted within reasonable limits to get satisfactory fit. Initially adopted recharge values and zones were modified with in plausible ranges based on land use, elevation, rocks types and precipitation amounts. Accordingly, recharge to the elevated western and northern areas covered with forest was increased from 0.001813 cm/day to 0.006042 cm/day.

Horizontal hydraulic conductivity was adjusted manually to get best fit between observed and calculated heads. Initial zones were modified to obtain better fit of heads by adding separate zones, widening /narrowing of initial hydraulic conductivity zones and changing the initial hydraulic conductivity values within zones. The final calibrated hydraulic conductivity values ranged from 0.02m/d to 200m/d. The lowest value is to the north central part of the study area and the value increases to south attaining maximum (200m/d) in the Koka lake areas.

In addition, streambed conductance was adjusted to make the match between calculated and observed heads or flows better.

5.1.3 Calibration Results

The calibration of groundwater flow model is the process of adjusting hydraulic parameters, boundary conditions and initial conditions within reasonable ranges to obtain a match between observed and simulated potentials, flow rates, and other calibration targets. The range over which model parameters and boundary conditions may be varied is determined by data presented in the conceptual model. In the case where parameters are well characterized by field measurements, the range over which that parameter is varied in the model should be consistent with the range observed in the field. The degree of fit between model simulations and field measurements can be quantified by statistical means. The following paragraphs describe the steps to be taken for calibration of the model.

Prior to calibration of the groundwater flow model appropriate calibration targets are selected from the available head data or other field data. The calibration criteria are then defined, providing the rationale for establishing when a model is calibrated and when calibration efforts should be terminated. The appropriate rationale for establishing acceptable quantitative calibration target residuals and residual statistics for analyzing model error (how well the model simulates the physical system) depends on several factors: the degree of natural heterogeneity or complexity of boundary conditions; location, number and accuracy of water level measurements; and the model purpose. The acceptable residual should be a small fraction of the difference between the highest and lowest heads across the site and be based on:

- ✓ The magnitude of the change in heads over the problem domain in the specific area(s) of interest;
- ✓ The ratio of the Root Mean Squared (RMS) error to the total head loss should be small;

- ✓ Head differential of <5% for the residual mean and standard deviation, and <10% for the ratio of the standard deviation to total head change.

The effectiveness of the calibration conducted was evaluated by comparing measured heads with simulated heads for each observation well used. The calibration criteria set for this calibration process were: first, generally matching the simulated potentiometric surfaces to those of observed potentiometric surfaces. As can be seen in figure 5.2, the observed and simulated potentiometric surfaces are generally similar in shape, the two curves run parallel to each other or gradients in most cases and this satisfied the calibration criterion. Actually, this reasonable fit between the simulated and observed heads has been achieved after many trial simulations in long period.

The second, technique is the regression coefficient (R$^{2)}$ is the square of the Pearson product–moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. The closer the value of R^2 to 1, the higher is the agreement between the simulated and the measured flows and calculated as:

$$r= \frac{\sum_{i=1}^{n}(hi-\overline{h})(HI-\overline{H})}{\sqrt{\sum_{i=1}^{n}(hi-\overline{h})^2}\sqrt{\sum_{i=1}^{n}(Hi-H)^2}} \dots\dots\dots\dots \quad (5.1)$$

Where $\overline{h}$ and $\overline{H}$are the means of the modeled and measured heads respectively. A value approaching unity is expected for a good calibration. A very poor calibration would have a value approaching zero. A more advanced definition of correlation with lag might show whether a model is responding too fast or too slowly.

Third, matching hydraulic heads at 95% of the wells to within 10m of the observed hydraulic heads. The hydraulic relief is about 796m. The model was assumed calibrated when the fit between observed and calibrated heads was within this criteria and calibration was evaluated based on the final spatial distribution of the difference between the observed and computed heads (Table 5.1).

The overall average difference between simulated and measured heads was expressed, as given in Anderson and Woessner (1992) using three statistical methods.

The mean error (ME) is the mean difference between measured heads and simulated heads. The mean head difference between calculated and observed heads can be expressed as:

$$ME=1/n \sum (h_m-h_s) \qquad (5.2)$$

Where h_m is measured head, h_s is calculated head and n is number of head measurements.

The ME of the calibration process for all observation measurements considered was about 7m.

The regression coefficient ($R^{2)}$ is the square of the Pearson product–moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model (equation 5.1)

The **r** of the calibration process for all observation measurements considered was about 0.98. The value of R^2 is closer to 1, showing there is higher agreement between the simulated and the measured heads

The mean absolute error (MAE) is the mean of the absolute value of differences in measured and observed heads. MAE between calculated and observed heads can be obtained from:

$$MAE=1/n \sum \left| (h_m-h_s)_i \right| \qquad (5.3)$$

The MAE calculated for hydraulic heads is about 22m

The root mean squared error (RMS) is the average of the squared differences in measured and simulated heads. Average RMS head difference can be calculated using the equation:

$$RMS= \{1/n \ \sum (h_m-h_s)_i^2\}^{0.5} \qquad (5.4)$$

The fitted RMS head for observation points is about 26m. This fit is considered well as there is high hydraulic relief in the area.

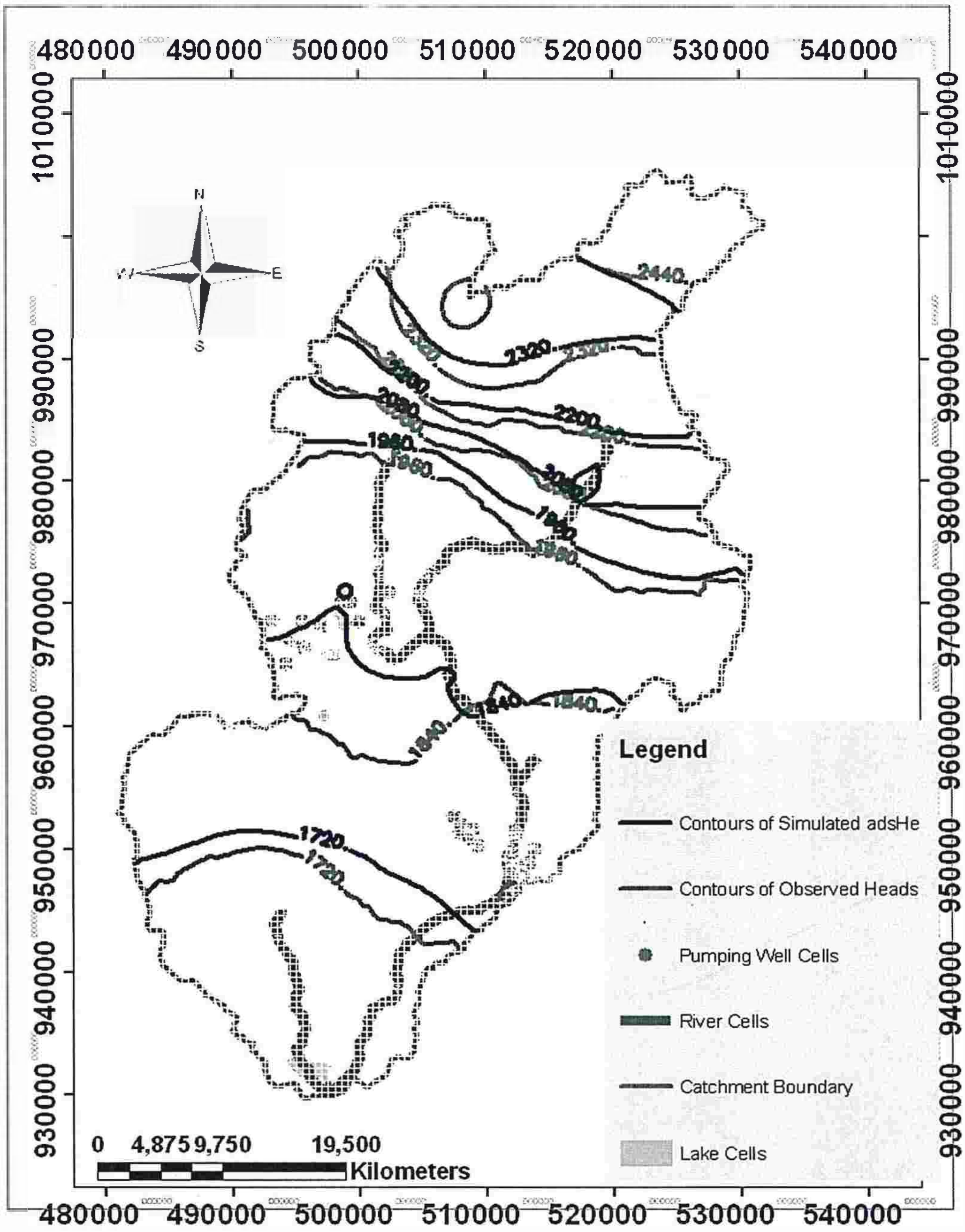
From the results of the above three statistical error analysis methods, the followings were observed.

-Mean error simply indicates skewness of the overall head calibration result to observed or calculated heads. Here, it showed that in the overall calibration of head levels, observed heads were greater than calibrated heads by about 7m.

-MAE and RMS show whether the calibration criteria set prior to calibration has been met or not. In this calibration process, the model was considered calibrated as these errors were less than the criteria set. As errors were normally distributed, the RMS was considered as the best measure of the overall calibration error.

-The ratio of RMS to the total head loss over the system was 26/796 or 0.033 which indicates that the error in the heads represented a very small fraction of the overall model response.

Figure 5.1 Comparison of Simulated and Obsrved Heads



Groundwater flow indicated by contours of simulated water levels is more or less similar to groundwater flow pattern indicated by contours of measured water levels. In some places, large differences between measured and simulated water levels might have resulted from poor estimates of model parameters during calibration or fluxes to or from rivers as some of the observation points were located near river banks. The similarities between simulated water levels and measured water levels indicated that most recharge and discharge is properly represented and adequately simulated. Moreover, it showed that the simulated distribution of hydraulic characteristic adequately represented the groundwater system. The calculated potentiometric surface is shown in figure 5.3 and it shows that head increases from south to north. It was represented by eight head intervals and the zonation was arbitrary. Any decision maker or practitioner can read topographic map or use altimeter of this area and can know the depth at with he can strike the water table.

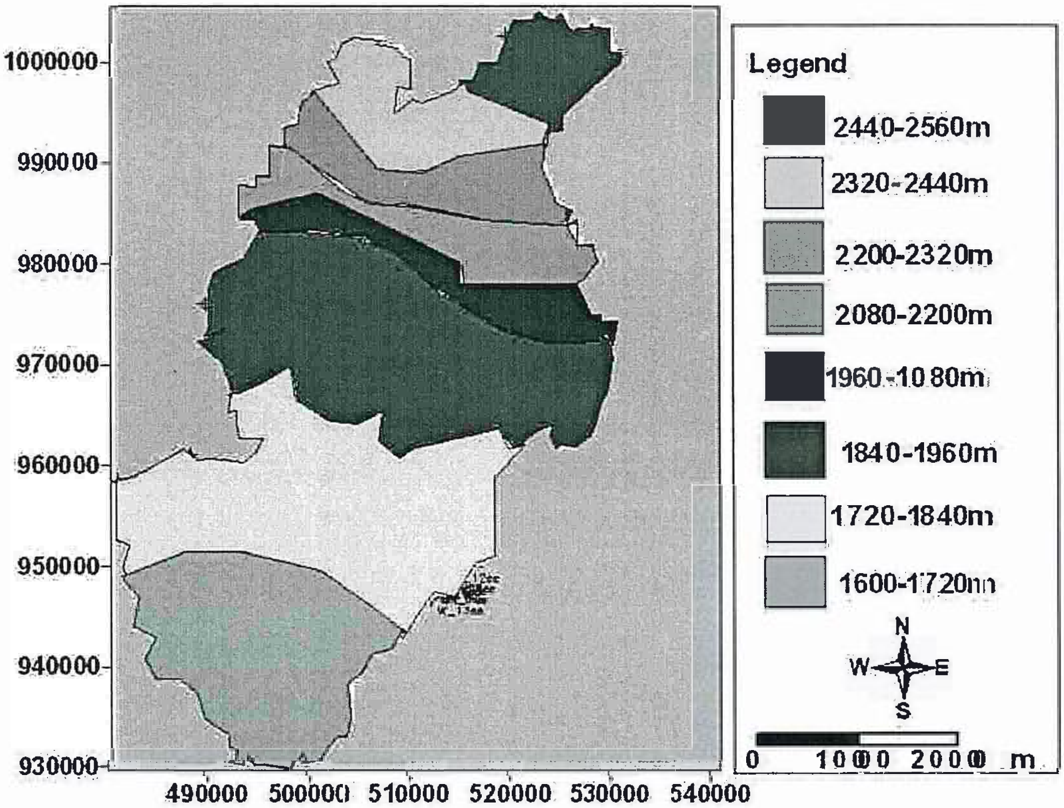


Figure 5.2 Simulated Potentiometeric Surfaces

In addition to contours, scatter plot of simulated heads against observed heads was used to show calibration fit. Observation points that lie on the straight line showed exact fit between head points, observation points are above the straight line show higher calculated heads and those points below the straight line show higher observed heads. Overall, it shows that the head differences are normally distributed and, high and low simulated values are evenly distributed through most parts of the area.

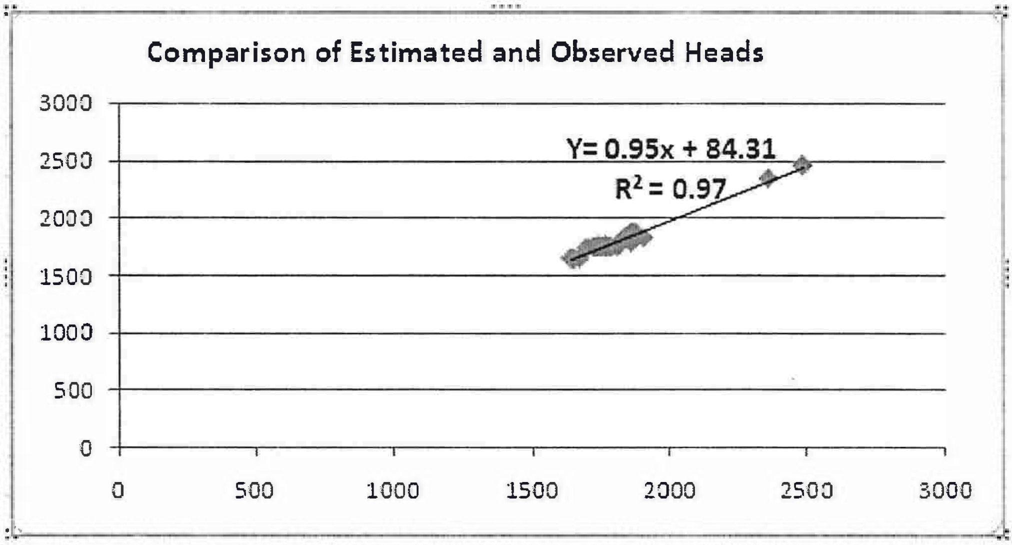


Figure 5.3 Scatter Plot of Head Distribution

Scattergrams are plots produced with measured heads on the horizontal axis, and modeled heads on the vertical axis, with one point plotted for each pair of data at selected monitoring sites. All the points should occur with a minimum degree of scatter about the line of perfect fit (a 45° line through the origin representing an unattainable perfect calibration). It is also important that the plotted points in any area of the scattergram are not grouped consistently above or below the 45° line in any segment of the plot, as this indicates a consistent over- or under-prediction, and a likely fundamental flaw in the calibration. Despite the apparent excellent fit, Figure 5.4 indicates a potential problem in this regard, as the modeled head generally slightly underestimates the measured head.

Name	X	Y	calhead	obsd head	obs-alc	(obs-alc)^2	|obs- alc |
BH_1	507714	955875	1785.838	1817.4	31.56	996.16	31.56
W_2	508079	952013	1766.001	1812.1	46.10	2125.12	46.10
W_3	512282	951356	1773.68	1765.9	-7.78	60.53	7.78
BH_2	507722	955887	1785.914	1818	32.09	1029.51	32.09
BH_3	503886	958637	1799.969	1860	60.03	3603.72	60.03
BH_4	509385	950325	1760.973	1766.92	5.95	35.37	5.95
BH_5	508995	951614	1766.273	1773.74	7.47	55.76	7.47
W_7	509020	950736	1761.892	1767.1	5.21	27.12	5.21
W_8	508684	951058	1762.551	1778.09	15.54	241.46	15.54
W_9	507950	951364	1762.058	1790.45	28.39	806.11	28.39
W_12	513773	949998	1772.175	1747.48	-24.69	609.84	24.69
BH_7	512602	947821	1763.155	1720.9	-42.25	1785.49	42.25
W_13	512159	946729	1757.175	1697.48	-59.69	3563.49	59.69
BH_8	512356	947895	1762.276	1725.3	-36.98	1367.22	36.98
W_14	512355	951516	1774.424	1767.75	-6.67	44.54	6.67
W-15	512011	949196	1765.048	1734.23	-30.82	949.75	30.82
W-16	513423	948940	1768.477	1739.8	-28.68	822.37	28.68
W-18	511976	948671	1763.176	1734.66	-28.52	813.16	28.52
W_19	512408	948682	1764.709	1738.86	-25.85	668.17	25.85
BH-10	509969	952000	1770.655	1783.9	13.25	175.43	13.25
W-21	511927	948292	1761.726	1752.7	-9.03	81.47	9.03
BH_12	499148	965330	1836.456	1866.75	30.29	917.73	30.29
W-23	493179	968613	1845.704	1837.63	-8.07	65.19	8.07
BH_14	495447	968060	1840.637	1864.7	24.06	579.03	24.06

W-24	494320	965101	1834.268	1870.56	36.29	1317.11	36.29
BH_15	493185	946241	1663.139	1672.08	8.94	79.94	8.94
BH-16	498233	939885	1662.156	1641	-21.16	447.58	21.16
BH-17	489485	943724	1660.372	1649.25	-11.12	123.70	11.12
BH_19	494054	968452	1844.104	1857.89	13.79	190.05	13.79
W-26	497100	968198	1837.859	1859.6	21.74	472.67	21.74
W-27	494829	967088	1838.552	1852.9	14.35	205.87	14.35
W-28	495561	968574	1842.192	1856.1	13.91	193.43	13.91
W_29	494598	967157	1839.124	1860.22	21.10	445.04	21.10
W-30	499320	970175	1845.737	1871.1	25.36	643.28	25.36
W-31	495765	966397	1834.602	1859.4	24.80	614.94	24.80
W_32	498633	970028	1841.352	1854.9	13.55	183.55	13.55
W-33	481178	958488	1885.113	1861.22	-23.89	570.88	23.89
BH_24	502364	970907	1836.497	1872.6	36.10	1303.43	36.10
BH_25	485970	485970	1848.243	1843.7	-4.54	20.64	4.54
BH_30	496646	967481	1832.848	1859.5	26.65	710.33	26.65
BH_32	492803	969204	1845.023	1849.32	4.30	18.46	4.30
BH_33	488305	960746	1884.639	1872.4	-12.24	149.79	12.24
BH_34	500204	963672	1885.123	1877.13	-7.99	63.89	7.99
BH_35	493545	968537	1882.7	1871.36	-11.34	128.60	11.34
BH_36	500424	974376	1890.323	1871.9	-18.42	339.41	18.42
BH_38	500494	974376	1840.529	1906.55	66.02	4358.77	66.02
BH_40	500766	973335	1840.664	1863.32	22.66	513.29	22.66
BH_46	501422	973727	1834.796	1868.5	33.70	1135.96	33.70
BH_47	492987	967055	1659.383	1653	-6.38	40.74	6.38
BH_49	495447	968068	1835.24	1860.5	25.26	638.07	25.26
BH_50	489950	976019	1838.052	1854.7	16.65	277.16	16.65

BH_51	499500	964500	1830.574	1847.44	16.87	284.46	16.87
BH_55	496234	939700	1834.925	1856.93	22.01	484.22	22.01
BH_57	496159	966870	1837.773	1869.2	31.43	987.66	31.43
BH-61	496147	967674	1791.427	1817	25.57	653.98	25.57
BH_64	496479	965700	2469.817	2488	18.18	330.62	18.18
BH-66	488391	961066	1891.797	1863.4	-28.40	806.39	28.40
OBS90	499228	964796	1791.427	1817	25.57	653.98	25.57
OBS95	499131	965767	2469.817	2487.7	17.88	319.80	17.88
OBS96	510393	991274	2357.071	2363	5.93	35.15	5.93
					7.23	**26.19**	**22.38**
					ME	**RME**	**MAE**

Table 5.1 Calculation and Observed Heads in Observation Wells

Using the calibrated model the budget of the whole model domain was calculated with a percent discrepancy of 0.12. It includes the following:

```
=================================================================
 WATER BUDGET OF THE WHOLE MODEL DOMAIN:
=================================================================
    FLOW TERM          IN              OUT                   IN-OUT
   CONSTANT HEAD    4.7425122E+03   2.1524365E+06    -2.1476940E+06
   WELLS            6.5664001E+02   1.7383678E+04    -1.6727037E+04
   RECHARGE         5.7027262E+04   0.0000000E+00     5.7027262E+04
    RIVER LEAKAGE   2.8192910E+06   7.0834363E+05     2.1109475E+06
-------------------------------------------------------------
         SUM          2.8817175E+06   2.8781638E+06    3.5537500E+03
 DISCREPANCY[%]     0.12
```

Table 5.2 Water Budget of the Whole Model Domain

Using the calibrated model, water budget of the whole model domain was calculated with a percent discrepancy of 0.12. It includes the following inflow components to the groundwater flow system: (1) Recharge from Constant Head Boundary, with a value of 1.73MCM per year (4.74x$10^3$$m^3$/day). (2) Groundwater recharge from precipitation, which is 20.82MCM per year (5.7X$10^4$$m^3$/day) and (3) groundwater inflow from the River Leakage with value equal to 1029.1MCM per year (2.82X$10^6$$m^3$/day) and the total inflow is 1051.83MCM per year(2.88X$10^6$$m^3$/day).

The simulated groundwater outflow from the system include (1) Discharge to the constant head boundary, which is 785.64 MCM per year (2.15X$10^6$$m^3$/day), (2) groundwater outflow through River Leakage with value equal to 258.55 MCM per year(7.08X$10^5$$m^3$/day) and (3) Groundwater outflow by well pumpage with a value equal to 6.35MCM per year(1.74x 10^4 m^3/day).

Generally, these values are somewhat different are somewhat different from the estimates made in the water balance of the conceptual model, which could be due to the larger aquifer thickness considered in the model and those parameter which area are not considered in the model. Table 5.2 shows the inflow and outflow components of the water balance and steady state hydrologic budget of the study area calculated by the model.

5.2. SENSITIVITY ANALYSIS

After calibration, the `next step is to introduce calibration parameters (hydraulic conductivity, pumping wells and Recharge) into the calibrated model to examine its response.

Groundwater models are sensitive to different model input parameters differently and the parameters for which the model is most sensitive, small changes in those parameters will result in large differences in simulated heads or fluxes. When the model is insensitive to an input parameter, the value of that parameter is more difficult to determine from the model calibration because large changes to the parameter do not cause large changes in hydraulic head.

During simulation when the effect of one parameter was being tested, the other parameters were set 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 was carried out, in this study, to understand uncertainty in the calibrated model caused by uncertainties in the estimates of aquifer parameters and stresses. The response of the calibrated numerical model to changes in model parameters like hydraulic conductivity and recharge was examined.

Sensitivity analysis test was done for variation in Hydraulic conductivity, recharge and well pumpage to note the effect on water level and stream leakage. The model was found to be most sensitive to the parameters, recharge and hydraulic conductivity.

The calibrated values of recharge and hydraulic conductivity were varied by 25%, 50% & 75% increases and decreases at different times to test the sensitivity of the model to the parameters. The results of Sensitivity analysis for the study were evaluated by calculating the Sum of Square Deviation between measured and calculated heads in the model area for the mentioned increase or decrease, in percent from the calibrated value, of the parameter. Calibrated model at the center of the plot (figure 5.4) represents the final model and the corresponding sum of square deviation, which is 720. A total of twelve model runs have been made by changing the hydraulic conductivity & recharge by the specified percents and the respective root mean squared head changes in percent from the calibrated value are shown in table 5.3 a.

The results of sensitivity analysis show that small errors in the values of the aquifer properties to which the model is most sensitive which in this case recharge and hydraulic conductivity can have significant effect on model simulation. However, other properties such as pumpage and river bed conductance can be varied in magnitude with little effect on the result.

Table 5.3a Results of Sensitivity Analysis Test on Water Levels

No	Change in sensitivity parameter from the calibrated value, in Percent	Respective root mean square head change from the calibrated value, in Percent
1	Recharge increased by 25,50 & 75	39, 48 & 57
2	Recharge decreased by 25, 50 & 75	29, 30 & 51
3	Hydraulic conductivity increased by 25, 50 & 75	27,28 & 31
4	Hydraulic conductivity decreased by 25, 50& 75	30, 45& 106

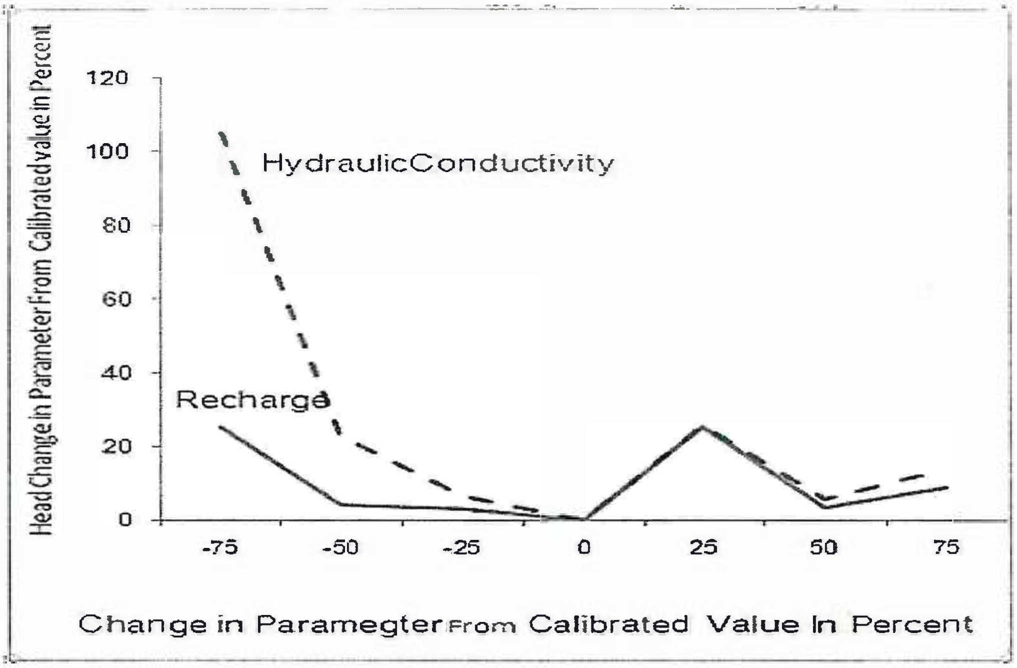


Figure 5.4 Plots of Results of Sensitivity analysis Test on Heads

In addition, sensitivity test was carried out to observe the effects of changes in recharge and hydraulic conductivity on river leakage. The calibrated recharge and hydraulic conductivity values were increased and decreased by 25%, 50% & 75% at different times and a total of twelve model runs have been made to observe general trend of changes in stream leakages. Accordingly, other factors being the same, equal percentage change in recharge and hydraulic conductivity values has resulted in more change in stream leakage in case of recharge than hydraulic conductivity. This shows that the model is more sensitive to recharge than hydraulic conductivity.

Table 5.3b Results of Sensitivity Analysis Test on stream Leakage

No.	Change in Sensitivity Parameter from calibrated value in percent	Respective changes in River Leakage from Calibrated value, in percent
1	Increase in Recharge by 25,50 & 75	1.11, 0.71 %-1.44

2	Decrease in Recharge by 25,50 & 75	0, 0 & 1.11
3	Increase in Hydraulic conductivity by 25,50 & 75	3.39, 5.57 & 9.03
4	Decrease in Hydraulic conductivity by 25,50 & 75	-4.23,-10.37 &-19.13

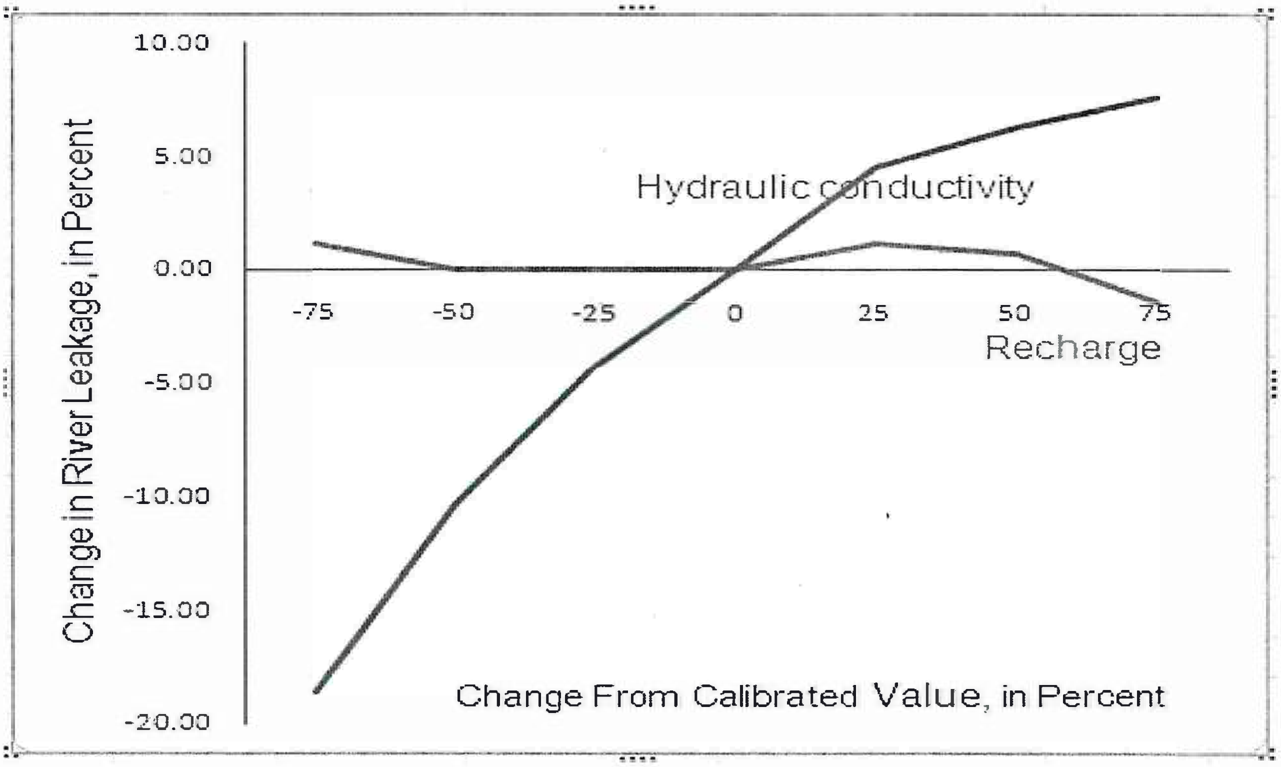


Figure 5.5 Plots of stream Leakage Sensitivity

In general, the Mojo River catchment groundwater flow numerical model constructed in this study is most sensitive to changes in recharge and hydraulic conductivity values. So, emphasis has been given during the calibration process in calibrating these parameters because they influence the model result greatly.

5.3 Scenario Analysis

The main purpose of groundwater flow modeling would most usually be to carry out resource management predictions for specified future periods, which often range into tens to hundreds of years.

Predictions are undertaken by running the model with the adopted (calibrated) parameters, and imposing hydrological stresses to represent the expected future climatic conditions, and the expected future groundwater management scenarios. The management scenarios usually comprise abstraction at a range of specified rates to achieve stated goals. The stated goals may involve determining irrigation or water supply allocations achieving dewatering objectives, or assessing alternative salinity management measures. The model is often also used to predict the groundwater-related environmental sustainability or impacts of the management scenarios, and to develop appropriate resource management plans, and to quantify water budget components.

In this model, the first scenario deals with simulated water levels due to decrease in recharge by 25,50 and 75 percent respectively which could be the case if the mild to extreme drought condition imposed on the aquifer system while water extraction is maintained at current rates.

An increase in Hydraulic conductivity caused an increased in stream leakage and vice-versa. An increase in recharge up to 50 percent increases stream leakage. But an increase beyond 50 percent is resulted in decreasing of stream leakage and vice versa

The second Scenario is an increment of pumpage to represent the possible future changes in water use in the basin, or to investigate the effects of water management practices that could mitigate potential adverse effects of increased water. As it can be seen from sensitivity results given in figure 5.6, changes in pumpage affected river leakage and water level.

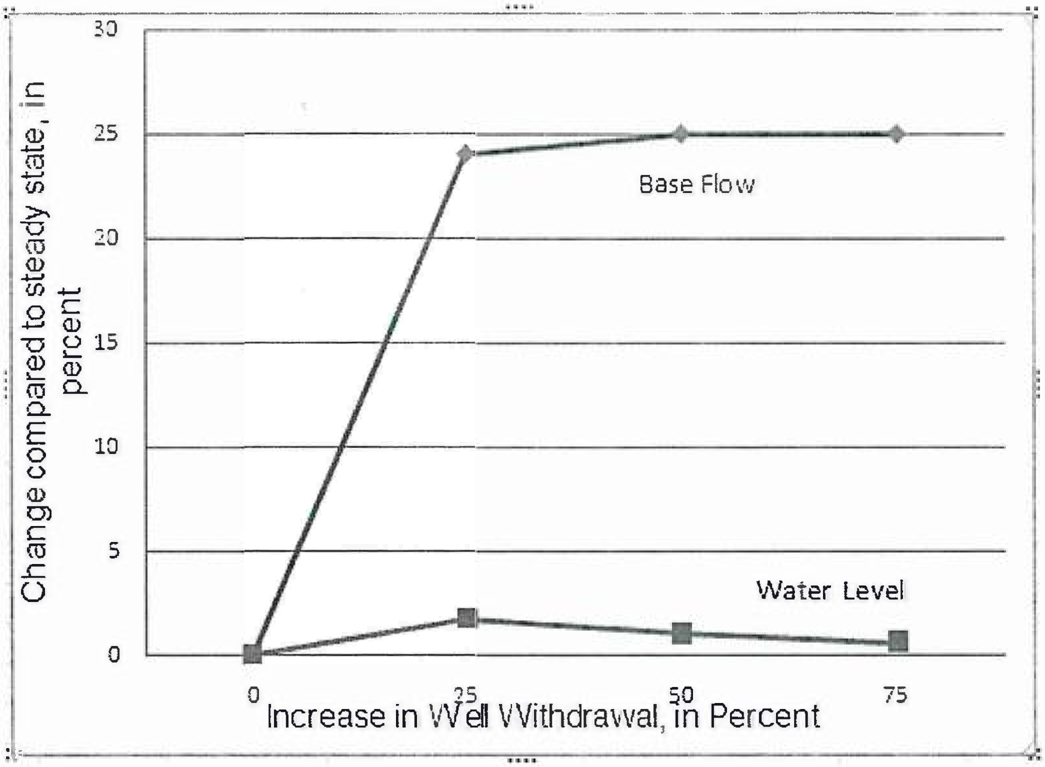


Figure 5.6 Trend of System Response to Increased Withdrawal Rates

The above figure shows the system respond in such a way that the water level and base flow decrease upon the increment of water withdrawal beyond 25 percent.

Generally, as withdrawal 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 is manifested by reduced inflow to streams and springs, reduced groundwater outflow or reduction in other discharge mechanisms. In addition, it also can induce recharge from surface water bodies such as streams or lakes causing water quality deterioration

The third scenario is the removal of lakes in the Mojo River Catchment. This is in consideration of the disappearance of the lakes, which could be due to some climatological or land use changes. The absence of these constant head from the model causes an increase of water level. All the wells are affected by this change. Simulation without the lakes results in increased groundwater outflow to the stream.

The other scenario, assuming 1% decrease in recharge amount per year, a 50% decrease was assumed to examine the response of the system after 50 years. Accordingly, the simulation result showed an average head decline of about 6.8m with highest fall of 36m and minimum of 5.7m. This scenario simulation resulted in a decrease of river leakage by 37% relative to the steady state simulated value

It is very common for models to be required to predict absolute values that represent the status of the groundwater-environmental system (e.g. quantify the sustainable groundwater resource allocation), rather than relative results (e.g. identify which bore field layout option impacts the least on a nearby river). Whereas a model could be used to assess scenarios in relative terms with little uncertainty, there is considerable uncertainty associated with absolute predictions. The accuracy and reliability of the prediction of specific or absolute values needs to be understood before robust management decisions can be made.

Prediction uncertainty arises mainly from the uncertain confidence in the (calibrated) model as a predictive tool, and uncertainties in predicting the magnitude and timing of future climatic and management stresses.

Addressing these uncertainties requires improved confidence in the model, and a sensitivity analysis of the effects of variable stresses. Uncertainties in predicting the magnitude and timing of stresses can be addressed by undertaking a sensitivity/uncertainty analysis of the prediction scenarios. The sensitivity analysis is used to rank the input data in terms of influences on model predictions, and uncertainty analysis can help identify the potential range of prediction outcomes, such that decision-making can be undertaken to suit the risk-evasiveness of the resource manager.

A range of prediction scenarios are usually required to be carried out, to try to predict the range of system responses to variations in climatic and management conditions (e.g. various durations of wet or average or dry conditions, and various ranges of (extreme) abstraction scenarios).

This process of running and analyzing predictions actually is one of improving the understanding of the system, and is one of the main areas where a modeling study can add value to an overall investigation.

One great benefit of developing a model as a predictive tool is the ability to answer "What if?" questions and to trial alternative management plans, although many modeling studies end with the completion of a few prediction scenarios that may have been poorly scoped at the study outset. Much greater value can be obtained from modeling studies by undertaking a staged program of prediction scenarios.

The first stage could comprise the simulation of a base case, against which other predictions may be compared. The base case would likely comprise a prediction of a "do nothing" or status quo type scenario for a period for which all other predictive runs will be carried out. This would commonly involve running the historical sequence of hydrological conditions, starting from initial conditions that reflect the current status of the aquifer. The project team should discuss and agree the composition of the base case run.

The second stage could involve running a few predictions to answer selected questions originally posed at the commissioning stage of the project (i.e. the reasons for developing the model in the first place. These prediction scenarios should be compared to the base case, and should themselves be subject to sensitivity/uncertainty analysis. The findings should then be adequately documented, and reviewed, prior to discussing and agreeing on other programs of prediction scenarios (and sensitivity/uncertainty analysis) to address other questions or issues that arise as the understanding of the system improves. These additional scenarios would likely also include some extreme ranges of management and climatic conditions, with the aim of identifying the envelope of predicted system responses.

5.4 MODEL LIMITATION

Limitations and uncertainties exist in any modeling study in regard to our hydrogeological understanding, the conceptual model design, and model calibration and prediction simulations, as well as recharge and evapotranspiration estimation and simulation. There are also limitations associated with the capabilities of the existing groundwater modeling software packages to adequately represent the complexities of any given hydrogeological system, and particularly in regard to surface-groundwater interaction. These limitations are best addressed by careful scoping of proposed modeling approaches at the outset. In some cases, the limitations may be so severe that there may be little value in putting the effort into a modeling study until more data and hydrogeological understanding is obtained, or until new technical methods are developed. As a model is a device that represents an approximation of a field situation, it is true that there are a number of limitations associated with it. Numerical ground water flow models are only approximations of complex natural systems and have uncertainty. Therefore, it is essential that for any ground water model to be interpreted and used properly these limitations be understood.

In the numerical groundwater flow simulation of Mojo River Catchment some of the associated limitations are:

- ✓ As common to all flow models, the inherent technical limitations such as accuracy of computations (hardware and software problems).
- ✓ Simulations of the groundwater system were based on various assumptions regarding the real natural system being modeled. In this study, some of these assumptions were that the aquifer was considered to be a single layer system, 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. Another deficiency is lack of understanding of a detailed geology in most parts of the area. Complex geology controls ground water flows.
- ✓ Hydrologic and hydrogeologic parameters used in the model were just an approximation of their actual field distribution, which can never be determined with 100% accuracy. Uncertainties stem largely from the fact that certain spatially variable properties such as hydraulic conductivity and recharge were represented as uniform values in discrete model cells over a large area. The fact that the fit

between simulated and observed hydraulic heads during calibration was not perfect is due to errors and uncertainties introduced into the model because of these factors.

- ✓ Theoretical differential equations describing ground water flow were replaced with systems of algebraic equations that are less accurate. The whole catchment was discretized in to a number of cells of equal size (500m by 500m). This level of discretization used to create the model limits the resolution of the numerical model. The level of discretization used was too coarse to incorporate the effects at local scale, like the effects of geological structures. In addition, 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.
- ✓ Trial and error calibration procedures, as followed in this study, don't produce unique solutions and are expected to introduce uncertainties in model results. In addition, the model was calibrated to water levels collected in different parts of the catchment at different times that may cause discrepancy between calculated heads and observed heads. Hence, the results of simulations considered under different scenarios reflect the error or uncertainty in the model and the outputs are used as general guides to help understand how the system will respond to new stresses and should not be considered as exact predictions.
- ✓ Irrespective of all these limitations, the model discretization and the simulation was adequate for studying the effects of groundwater withdrawal and to study the response of the hydrologic system to different scenarios. Thus, in the numerical groundwater flow simulation of the Mojo River catchment, in this study, as all the limitations and uncertainties involved are clearly stated, it is possible to assume the model to be reliable and good, and that it cannot be misused and the model outputs should be interpreted and applied by considering all these associated limitations

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Processing MODFLOW version5.0 (PM5) is used to in this study to simulate the groundwater flow of Mojo River catchment aquifer system under steady state condition to evaluate the effect of various stresses on the system. The obtained recharge is very small as compared to runoff because the basin is steep and not well conserved using soil and water conservation measures.

Estimated hydraulic conductivity used for numerical model range from 0.02m/day to 200m/day which were adjusted during model calibration. These values are adopted from previous estimations of literature values and their accuracy depends largely on the correct identification of the rock type.

The area was discretized into 152 cells arranged in rows and 120 cells arranged in columns, each cell representing 500m by 500m. A two dimensional profile model under steady state condition was developed to study the response of the system to different scenarios. Most model parameters and model stresses were varied spatially in the active model areas.

IN this study, a homogeneous, an isotropic, single aquifer layer (with thickness range of about 120-260m) that was assumed to have a hydraulic connection with surface water bodies was considered.

Water level data was collected from 136 wells and the hydraulic relief between the maximum (2800m in head water areas in the northern part) and minimum 1500m in low lying areas to the south. Ground water contours and flow directions were determined based on these observed heads. The general trend of the contours is east-west and the flow direction was determined to be from north to south, with some local variations. The flow line showed that there is a concentrated flow from north to south of the study area indicating that the southern part of the stated watershed is a discharge area.

The calibration criteria for heads were first generally fitting simulated heads to calculated heads and second fitting 95% simulated heads to calculated heads within a maximum difference of about 10m.

The simulated inflows and outflows in the steady state model were within reasonable limits of the observed inflows and outflows.

The water budget of the whole model domain was calculated with a percent discrepancy of 0.12. It includes the following inflow components to the groundwater flow system: (1) Recharge from Constant Head Boundary, with a value of 1.73MCM per year ($4.74 x 10^3 m^3$/day). (2) Groundwater recharge from precipitation, which is 20.82MCM per year ($5.7 X 10^4 m^3$/day) and (3) groundwater inflow from the River Leakage with value equal to 1029.1MCM per year ($2.82 X 10^6 m^3$/day) and the total inflow is 1051.83MCM per year($2.88 X 10^6 m^3$/day).

The simulated groundwater outflow from the system include (1) Discharge to the constant head boundary, which is 785.64 MCM per year ($2.15 X 10^6 m^3$/day), (2) groundwater outflow through River Leakage with value equal to 258.55 MCM per year($7.08 X 10^5 m^3$/day) and (3) Groundwater outflow by well pumpage with a value equal to 6.35MCM peryear($1.74 x 10^4$ m^3/day).

Model sensitivity analysis was carried out by considering three parameters, namely recharge, hydraulic conductivity and well pumpage. In addition, the effect of varying recharge and hydraulic conductivity on stream leakage was tested. It showed that stream leakage is directly related to changes in the parameters, but appreciable changes from the calibrated value resulted in case of change in recharge compared to hydraulic conductivity. This shows that stream leakage is more sensitive to recharge than hydraulic conductivity. 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 uncertainty of 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.

Given the associated limitations, as the model was intended to study the response of the hydrologic system, different scenarios of stresses were considered to examine it. The increased withdrawal simulation effect was also noted on stream leakage, subsurface outflow and groundwater heads. The effect on streams depends on the withdrawal rate and proximity of the pumped well to stream banks.

The results of these simulations show the response of the system and the accuracy of the results depends on future land use/ land 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.

6.2 RECOMMENDATIONS

Groundwater modeling is powerful tools to improve our understanding of groundwater flow systems. This work is the first attempt to model Mojo River Catchment groundwater flow. The model can be improved with additional hydrologic, geologic, hydrogeologic works, data collection and interpretation and the use of additional MODFLOW packages.

In order to increase the reliability of the groundwater flow model we recommend the following:

- ✓ There should be monitoring Wells
- ✓ Additional MODFLOW packages such as river routing shall be incorporated
- ✓ Detailed recharge estimation has to be carried out using different methodologies to conduct a detailed flow model simulation because recharge is the most influential model input parameter in the area as seen in sensitivity test.
- ✓ To represent the system in a more realistic condition, it is important to define the complex multi layer aquifer system and the respective hydraulic parameters for each aquifer; so that three dimensional groundwater flow models can be conducted properly.
- ✓ Possible methods that result in increase in groundwater recharge from precipitation and that reduce runoff should be employed. These include afforestation, soil conservation and collection of storm flow during intensive precipitation and recharging it to aquifers so that decrease in water levels could be minimized.
- ✓ Sufficient groundwater level monitoring wells should be placed in the whole catchment in order to understand the general fluctuations in ground water levels.

This helps to carry out transient ground water flow modeling, so that system response can be predicted with greater confidence.

- ✓ Due to uncontrolled increase in ground water withdrawal, groundwater level will decline that may result in reverse flow between surface water and ground water systems. As surface water sources in the area are highly polluted, this may lead to ground water system pollution over long time period. Therefore, frequent water quality monitoring wells should be drilled near polluted surface water sources in the catchment to evaluate influx of pollutants to aquifers.

7. REFERENCES

Adane Bekele(1999). Surface Water and Ground Water Pollution Problems in the Upper Awash River Basin, M.Sc thesis, University of Turku Finland.

Alem Tiruneh, (2006). Hydrogeology of Mojo River Catchment (Ethiopian Rift Valley).

MSc Thesis, Addis Ababa University, Addis Ababa

Anderson, M.P. and Woessner, W.W.(1992). Applied Ground Water Modeling. Simulation of Flow and Advective Transport, Academic Press. Florida.

Aregawi Gebrekidan (2007). Modeling Groundwater Flow and Its Sustainable UtilizationsHantebetWatershed,Msc.Thesis,Arbamich niversity,Arbaminch.

Ayinalem Ali (1999). Water Quality and Groundwater/River water Interaction in the Akaki River Basin (Sekelo). M.Sc Thesis, Addis Ababa University, Addis Ababa.

Berhanu Melaku (1982). Hydrogeology of Upper Awash Basin Upstream of Koka Dam. Ministry of Mines and Energy, Ethiopian Institute of Geological Survey (EIGS), Note No. 171, Addis Ababa.

Brooks, L.E., and Mason, J.L. (2005). Hydrology and Simulation of Groundwater Flow in Cedar Valley, Iron County, Utah: U.S. Geological Survey Scientific Investigations Report 2005-5170, 127p.

Brown, D.S., AND Raines, T.H.(2002). Simulation of Flow and Effects of Best Management Practices in the Upper Seco Creek Basin, South- Central Texas, 1991-98: U.S. Geological Survey Water Resources Investigations Report 02-4249, 28p.

Carlson, C.S., and Lyford, F.P. (2005). Simulated Ground-water flow for a Ppond-dominated Aquifer System near Great Sandy Bottom Pond, Pembroke,Massachusetts:U.S. Geological Survey Scientific Investigations Report 2004-5269, 43 p.

Chapman, M.J., Bolich, R.E., and Huffman, B.A. (2005), Hydrogeologic setting, ground-water flow, and ground-water quality at the Lake Wheeler Road research station, 2001–03, North Carolina Piedmont and Mountains Resource Evaluation Program: U.S. Geological Survey Scientific Investigations Report 2005–5166, 85 p.

Davis S. N. and DeWiest R.J.M. (1996). Hydrogeology, John Wiley and sons Inc. New York, pp463.

Dereje Nigussa (2003). GIS Based Groundwater potential and Aquifer Vulnerability Assessment in Akaki River Catchment, Central Ethiopia. M.Sc. Thesis, Addis Ababa University, Addis Ababa.

Desmone, L.A., Walter, D.A., Eggleston, J.R., and Nimirosky, M.T. (2002). Simulations of Groundwater Flow and Evaluation of Water Management Alternatives in the Upper Charles River Basin, Eastern Massachusettes: U.S. Geological Survey Water Resources Investigation Report 02-4234, 103p.

Fetter C.W. (1994). Applied Hydrogeology, 3rd ed., Prentice-Hall Inc., Englewood, New Jersey

F. Mazzarini, Tsegaye Abebe, F. Innocenti, P. Manetti, M.T. Pareschi (1999). Geology of the Debre Zeit area (Ethiopia) (with a geological map at scale 1:100,000). Journal of Acta Vulcanologica-Vol.11 (1) –1999.

Freeze, R. and Cherry, A. (1979). Groundwater. A Simon and Schuster Company, Eaglewood, New Jersey

Gannett, M.W., and Lite, K.E., Jr. (2004). Simulation of regional ground-water flow in the upper Deschutes Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 03–4195,84p

Gasparon M., Innocenti F., Manetti P., Peccerillo A. & Tsegaye Abebe (1993). Genesis of the Pliocene to Recent bimodal mafic-felsic volcanism in the Debre Zeit area, Central Ethiopia: volcanological and geochemical constraints. J. African Earth Sci. 17, pp145-165.

Hailesellasie Girmay and Getaneh Assefa (1989). The Addis Ababa-Nazareth Volcanics. A Miocene-Pleistocene Volcanic Succession in the Ethiopian Rift. SINET: an Ethiopian Journal of Science, vol 12(1), Addis Ababa

Hailesellasie Girmay (1985). Shallow Sensitivity Investigation in the Filwuha Fault. M.Sc. Thesis, Addis Ababa University.

Hoffmann, J.P., and Leake, S.A.(2005). Simulated water-level responses, ground-water fluxes, and storage changes for recharge scenarios along Rillito Creek, Tucson, Arizona: U.S. Geological Survey Scientific Investigations Report 2004–5286, 29 p.

Hunt, R.J., Saad, D.A., and Chapel,D.M.(2003). Numerical Simulation of Groundwater Flow in La Crosse County, Wiscinsin, and into Nearby Pools of the Mississippi River, Reston, Virginia: U.S. Geological Survey Water Resources Investigations Report 03-4154, 44p.

Huston, S.S., Strom, E.W., Burt, D.E., and Mallory M.J.(2000). Simulation of Projected Water Demand and Groundwater Levels in the Coffee Sand and Eutaw- Mcshan Aquifers in Union County, Mississippi, 2010 through 2050: U.S. Geological Survey Water Resources Investigations Report 00-4268, 43p.

Izuka, S.K. and Oki, D.S.(2002). Numerical Simulations of Groundwater Withdrawals in the Southern Lihue Basin, Kauai, Hawaii: U.S Geological Survey Water Resources Investigations Report 01-4200, 61p.

Jones, P.M.(2005). Simulated effects of water-level changes in the Mississippi River and Pokegama Reservoir on ground-water levels, Grand Rapids area, Minnesota: U.S. Geological Survey Scientific Investigations Report 2005–5139,13p

Kazmin Vet. al. (1980b). Report on the Geological Map of the Ethiopian Rift Valley. EIGS, Addis Ababa.

Kebede Tsehayu and Tadesse Hailemariam (1990). Engineering Geological Mapping of Addis Ababa, EIGS, Addis Ababa

Lamessa Mekonta (2001). Hydrogeological Controls in Sandstones of Ambo Area. M.Sc. Thesis, Addis Ababa University, Addis Ababa.

Long, A. J., Putnam, L.D., and Carter, J. M. (2003). Simulated Groundwater Flow in the Ogalalla and Arikaree Aquifers, Rosebund Indian Reservation Area, South Dakota: U.S. Geological urvey Water resources Investigation Report 03-4043, 76p.

Luleseged Ayalew (1990). Engineering Geological Characteristics of the Clay Soils of Bole Area, Their Distribution and Practical Importance. M.Sc Thesis, Addis Ababa University, Addsi Ababa

Mengesha Tefera, Tadiwos Cherinet and Workneh Haro (1996). Explanation of the Geological map of Ethiopia, Ministry of Mines and Energy, EIGS, Bull. No 3, Addis Ababa.

Murray, L.C., Jr., and Halford, K.J.(1999). Simulated Effects of Projected Groundwater Withdrawals in the Floridan Aquifers System, Greater Orlando

Metropolitan area, East- Central Florida: U.S. Geological Survey Water resources Investigations Report 99-4058, 30p.

Pinder, G. F. (2002). Groundwater Modeling Using Geographical Information System, University of Vermont, pp121-129.

Pope D.A., and Watt, M.K. (2004). Simulation of Groundwater Flow in the Potomac-Raritan-Magothy Aquifer System, Pennsauken Township and Vicinity, New Jersey: U.S. Geological Survey Scientific Investigation Report 2004-5025, 69p.

Reilly, T.E.(2001). System and Boundary Conceptualization in Groundwater Flow Simulation: Techniques of Water Resources Investigation of the U.S. Geological Survey, 38p.

Ruhl, J.F., and Cowdery, T.K.(2004). Regional ground-water-flow models of surficial sand and gravel aquifers along the Mississsippi River between Brainerd and St. Cloud, central Minnesota: U.S. Geological Survey Scientific Investigations Report 2004-5087, 21 p

Sisay Libasse(2006). Integrated remot sensing & GIS application for hydrogeological investigation. Unpublished M.Sc. Thesis Addis Ababa University, Ethiopia.

Smith, B. S.(2005). Simulated Changes in Water Levels Caused by Potential Changes in Pumping from Shallow Aquifers of Virginia Beach, Virginia: U.S. Geological Survey Scientific Investigations Report, 2005-5067,31p.

Solomon Tale(2000). The Extent of Surface and Groundwater Pollution in Addis Ababa. M.Sc. Thesis, Addis Ababa University, Addis Ababa.

Tamiru Alemayehu(1993). Preliminary Analysis of the Availability of Groundwater in Ethiopia, SINET: Ethiop. J. Sci., 16(2): 43-59, Addis Ababa University.