ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES

NUMERICAL GROUNDWATER FLOW MODELING OF THE AKAKI RIVER CATCHMENT

A thesis submitted to the School of Graduate Studies
Addis Ababa University

In partial fulfillment of the requirements for the degree of
Masters of Science in Hydrogeology

By

Ebasa Oljira

June 2006
Addis Ababa

ACKNOWLEDGEMENT

I wish to express my deepest appreciation and gratitude to my advisor Dr. Tenalem Ayenew for proposing the research problem, sharing me his time for valuable discussions, giving me his personal research materials and guiding me during the research work.

I gratefully acknowledge Oromia Water Resource Bureau for giving me sponsorship and other assistances during the study.

I would like to extend my thanks to Japan International Cooperation Agency (JICA) for allowing me to participate on the Second Training course on Groundwater Modeling for African Countries, where I got sufficient groundwater modeling knowledge.

All the staff members of the Earth Science Department of Addis Ababa University are highly appreciated for their direct or indirect contribution to this work. Institutions and offices from which data have been obtained are duly acknowledged. Among them are: Addis Ababa Water and Sewerage Authority (AAWSA), National Meteorological Services Agency, Ministry of Water Resources and Ethiopian Institute of Geological Surveys (EIGS). In addition, all relatives, friends and colleagues are duly acknowledged.

Finally, I would like to thank my mother, sisters and brother; especially my sister Dr. Birhane Oljira (Hadha Borri), for her invaluable encouragements and supports starting from my childhood until present. Above all, I thank my Lord and Savior Jesus Christ who has been the source of my strength through out my life.

Table of Contents

Page

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

CHAPTER SIX

CHAPTER SEVEN

List of Tables

List of Figures

List of Annexes

ABSTRACT

Akaki River Catchment is a sub catchment of Awash drainage basin with an approximate surface area of around 1462km^2, boundary length of 216km and it lies at the eastern edge of the Western Ethiopian plateau that descends to the Main Ethiopian Rift. The capital city, Addis Ababa and other smaller towns are found in this catchment. The catchment is totally covered with volcanic rocks of various ages that correspond to different stratigraphic units. The rocks were subjected to rift tectonics that is manifested by a number of fault systems having a general trend of the rift system (NE – SW).

As numerical groundwater flow models represent the simplification of complex natural systems, different parameters were assembled into conceptual model to represent the complex natural system in a simplified form. The conceptual model was input into the numeric model to examine system response.

Numerical groundwater simulation was carried out using MODFLOW, 1996 (McDonald and Harabaugh, 1988). Two dimensional profile model was developed considering the system to be under steady state condition and assuming flow system view point. Three scenarios of increased withdrawals and one scenario of decreased recharge were simulated to study system response. Model calibration was carried out by trial and error calibration method using groundwater contours constructed from heads collected in 122 observation points. The calibration showed that about 81% of simulated heads were within the calibration target and the overall root mean square error for simulated hydraulic heads is about 10.42m. The poor fit at some points was due to numerous limitations associated with the model.

Model sensitivity analysis was conducted by taking recharge and hydraulic conductivity as the model is most sensitive to them. A change in recharge by 20%, 40%, 60%, -20%, -40%, and -55% resulted in RMS head changes from the calibrated value by 17%, 58%,106%, 26%, 86% and 147%, respectively. Equal changes in hydraulic conductivity (in the order mentioned for recharge) resulted in RMS head changes from calibrated value by

12%, 33%, 55%, 19%, 90% and 193%, respectively. In addition, the effect of varying these two parameters on stream leakage was tested. Accordingly, changes in steady state estimated recharge by 15%, 30%, 45%, -15%, -30%, and -45% resulted in change in stream leakage from calibrated value by 12%, 24%, 36%, -20%, -24% and -28%, respectively. The same changes in hydraulic conductivity (in the order mentioned for recharge) resulted in stream leakage changes from calibrated value by 1.9%, 3.7%, 5.5%, -2.1%, -4.2% and -6.9%.

The results of the numerical simulations showed that increased well withdrawals by 15%, 25% and 45% resulted in RMS (Root Mean Square) head changes of 0.7m, 1.3m, and 2m, respectively. The same change in well withdrawal resulted in 1.4%, 2.4% and 3.7% respective changes in river leakages compared to the steady state simulated value. Similarly, these increased withdrawals resulted in reduction of the calibrated subsurface outflow by 3.4%, 6.4%, 9.1%, respectively.

On one hand 20% decrease in steady state simulated recharge resulted in reductions of groundwater level by 5.6m, stream leakages by 15.8% and subsurface outflows by 5%.

CHAPTER ONE

INTRODUCTION

1.1 Background

Due to the fact that the occurrence of groundwater is generally invisible and the velocity of groundwater flow is much small, studies of groundwater under both natural and artificial conditions have employed modeling techniques.

These days groundwater modeling has received great attention worldwide not only for groundwater resource assessment / management, but also for selecting sites for hazardous waste disposals and to study contaminant transport behavior in groundwater. In all aspects accurate hydrogeologic information is the core to the reliability of the modeling output.

During the past few decades, groundwater flow models have become one of the most important components in hydrogeological assessments. Numerical simulation models using computer programs for analyzing flow in groundwater systems have played an increasingly important role in the evaluation of alternative approaches to groundwater development and management.

Because of changes in climatic conditions and active construction activities, recharge to groundwater has been decreasing, and because of increase in population size water demand has been increasing at an alarming rate. This generalization is true for the Akaki River Catchment as the capital city, Addis Ababa, that increased in size to about 540km^2 and whose area was expanded in more than two folds between the years 1984 and 1994, is found at the heart of the catchment. 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. The most successful work was done in the Akaki well field and it was estimated that the groundwater from this specific site might meet more than 30 percent of water supply in Addis Ababa.

In the Akaki River Catchment groundwater is exploited by different industries and institutions, in addition to wells that are operated by AAWSA (Addis Ababa Water and Sewerage Authority) and used for public services. In long terms, extended and uncontrolled withdrawal may result in water level declines, which causes imbalances among hydrologic stresses. So, this groundwater flow modeling 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.

In addition, this thesis work gives an insight about the response of the Akaki River Catchment regional groundwater flow system to different possibly occurring scenarios like decreased recharge and change in ground water- surface water interactions. So, this model may be used as a tool to water resource managers to assess the regional effects of change in stresses to the steady state system. Moreover, it improves the understanding of the groundwater system and the regional effects of various groundwater use alternatives on the water resource of the catchment.

Any professional interested to work on related issues in the area can use this model as a reference to develop a detailed groundwater flow numerical model (transient and 3D model) and to study the behavior of contaminant transport in aquifers, as this area is highly susceptible to pollution from different industrial and domestic sources.

1.2 Objectives

The general objective of this study is numerical simulation of the regional groundwater flow system of the Akaki 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. Different scenarios of increased withdrawals and decreased recharge were simulated using Processing MODFLOW, 1996 (Harbaugh and McDonald, 1988) to study system response, the result of which can be used as a tool to understand the future risk of groundwater overexploitation.

Specifically, this study is intended to:
-Identify the study area boundary and conceptualize the boundary conditions.

-Construct hydrologic database of the area for model input parameters

-Carry out model sensitivity analysis test from which the most sensitive model input parameters can be known so that they might be treated with caution for further calibration in future studies.

-Conceptualize the general groundwater flow system using geochemical and isotopes data. This is used to support flow direction determined from water level data.

-Build a conceptual model of the hydrogeologic system of the Akaki River Catchment

1.3 Methodology

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

-Groundwater flow modeling software, MODFLOW 1996 (McDonald and Harbaugh, 1988 as developed by USGS) was used to simulate numerical groundwater flow system in the area under study. The general methodology followed during data assembly and the simulation process in this work is given in figure 1.6
-Construction of a conceptual model to simplify field problem and organize field data so as to analyze the system so readily. Before entered in to numerical model, all available data were assembled into conceptual model in a simplified form as the complete reconstruction of the field situation is impossible.
-Review of inventory of wells and springs in the catchment
-Water level collection

-Water chemistry data collection and interpretation to conceptualize groundwater flow

-Comparison of simulated water level with that obtained in the field during model calibration.

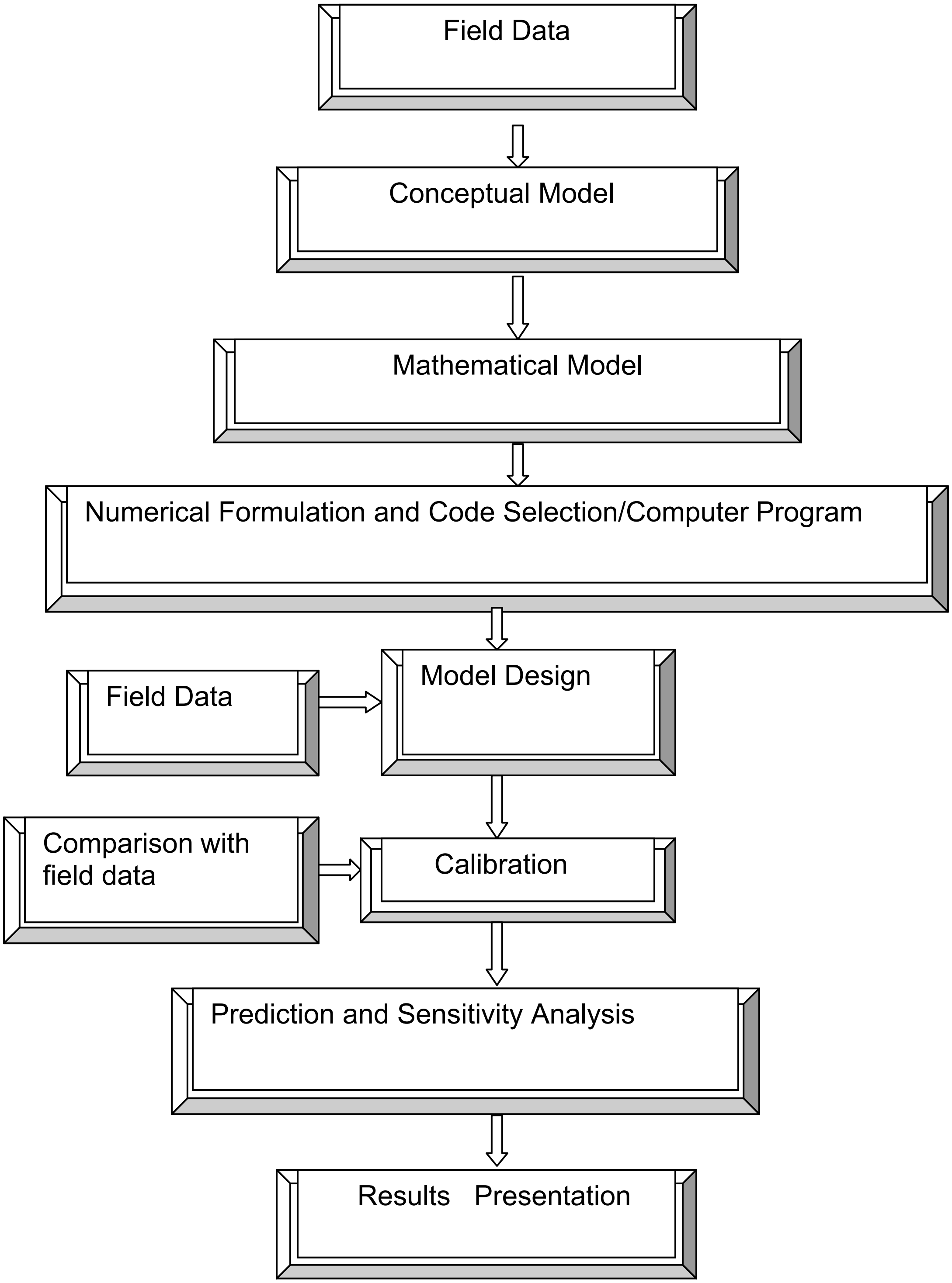


Figure1.1 The general methodology followed (Anderson and Woessner, 1992).

1.4. Scope of the Study

This groundwater flow modeling work was carried out in the Akaki River Catchment in which the capital city is found and includes areas bounded by topographic divides upstream of Aba Samuel Lake. Apart from area scope, the problem domain is limited to profile two dimensional groundwater flow modeling of the area under steady state condition considering one layer aquifer system. The model was calibrated using water levels measured in 122 wells.

In addition, this work presented groundwater chemistry and isotope hydrology of the area in a very concise way as applied for flow conceptualization.

1.5 Previous Works

In the past several geological, hydrogeological, pollution study and other related works have been performed for different purposes in the Akaki River Catchment, the main hydrogeological works were to plan and design water supply facilities for the city of Addis Ababa and surrounding towns in the catchment as the ever increasing water demand far exceeded water supply. Most of the previous works deal with specific issue, but comprehensive works were done by AAWSA. In addition, numerous works have been done by different scholars. Some of the relevant works done on the Hydrogeology were:

Berhanu Melaku (1982) investigated the general hydrogeology of the Upper Awash Valley, which includes the Akaki River Catchment.

The works done by Vernier et al. (1985) on preliminary hydrogeological investigation identified four aquifer types in Addis Ababa.

AAWSA and Seureca (1991) conducted a comprehensive study on groundwater around Addis Ababa between 1989 and 1991 and proposed potential groundwater sites for the city of Addis Ababa. Inventory of 257 wells and Piezometric level of the groundwater covering most parts of Akaki River catchment was produced. The investigation included test drilling that was done mainly in the east, southwest and northwest of Addis Ababa and recorded Water level evolution in most of the test wells for the period between November 1989 and October 1990. The study enabled classification of the test areas as follows:

- Area A – west of Addis Ababa between Welete Suk and Alem Gena and end east of the main Addis-Jimma road.
- Area B – east of Akaki between Koye and Tulu Dimtu
- Area C – west of Akaki and northwest of Aba Samuel Lake
- Low yield areas – these include the test wells drilled at Yeka Bole, Yeka Dale, Lege Dadi, Keranyo and Gefersa. According to the study Sululta was proposed as the fifth ground water investigation area. A number of wells were drilled for the purpose of water production and 4 monitoring wells were drilled between the well field and the Akaki River. Their purpose is to monitor the well field and to detect possible influx of contaminated water from the vicinity of the Akaki River.

Ayinalem Ali (1999) conducted water quality assessment and groundwater surface water interaction in Sekelo River in Great Akaki sub-basin. Adane Bekele (1999) studied pollution of surface and groundwater in the Upper Awash Valley.

Solomon Tale (2000) assessed the extent of groundwater- surface water interaction in the central part of the city.

According to AAWSA et al. (2000), AAWSA and AESL (Associated Engineering Services Limited), (1984) summarized well inventories made prior to 1984 (made in 1955, 1970 and1983) of the then existing wells, in and near the city and extended the description of drilled wells up to a total of 175.

AAWSA et al. (2000), in their attempt to undertake groundwater flow modeling of the Akaki well field, have assessed the general geological and hydrogeological features of the catchment. The numerical model was intended to assess the safe yield of the Akaki well field only. Accordingly, AAWSA et al. (2000) recommended that before implementing simulation results of abstraction it is advisable to start pumping at lower rate, about 30,000 m^3/d for about 6 months, in order to study the reaction of the aquifer and to re-examine and calibrate the model to the actual observed values.

Berhanu Gizaw (2002) carried out detailed assessments on the Hydrochemical and Environmental Investigation of the Addis Ababa region.

Dereje Nugussa (2003) conducted GIS based groundwater potential and aquifer vulnerability assessments in the Akaki River Catchment using DRASTIC approach. Accordingly, the study resulted in aquifer vulnerability map of the catchment.

Hydrogeological map of Addis Ababa, Akaki and Dukem areas was made for JICA (Japan International Cooperation Agency) by AG Consult (2004). Accordingly, the aquifer of the catchment was broadly classified in to three groups from north to south.

Tamiru et al (2005) studied the hydrogeology, water quality and the degree of groundwater vulnerability to pollution in Addis Ababa, Ethiopia.

CHAPTER TWO

AN OVERVIEW OF THE STUDY AREA

2.1 Location

The Akaki River catchment is located in the Western Ethiopian highlands of the Shewan plateau, and partly in the western margin of the Ethiopian Rift Valley floor. The capital city, Addis Ababa and other small towns such as Akaki, Sendafa, Burayu and smaller peasant association villages are found in this catchment.

The Intoto Mountain forms the northern drainage boundary of the Akaki River Catchment and other volcanic mountains bound it from the eastern, western and southwestern boundaries; these are Mt. Yerer, Mt. Wechecha and Mt. Furi, respectively.

The study area, the Akaki River catchment, has an approximate surface area of around 1462 km^2 and boundary length of 216 km, and approximately bounded between the geographic coordinates 8^0 45'20'' to 9^0 13'17'' N latitude and 38^0 34' 3''to 39^0 4'10'' E longitude. All maps in this work are given in UTM coordinates (zone 37).

As Addis Ababa is found in the northern central heart of the catchment, the study area is accessed in every direction by highways from the capital, that is, by the major roads stretching to Jimma, Wollega, Harar/Sidamo, Wallo and Gojjem. In fact, other minor roads are found in the catchment and these are used for traverses between villages and sites. The location map of the study area is shown in Fig 2.1.

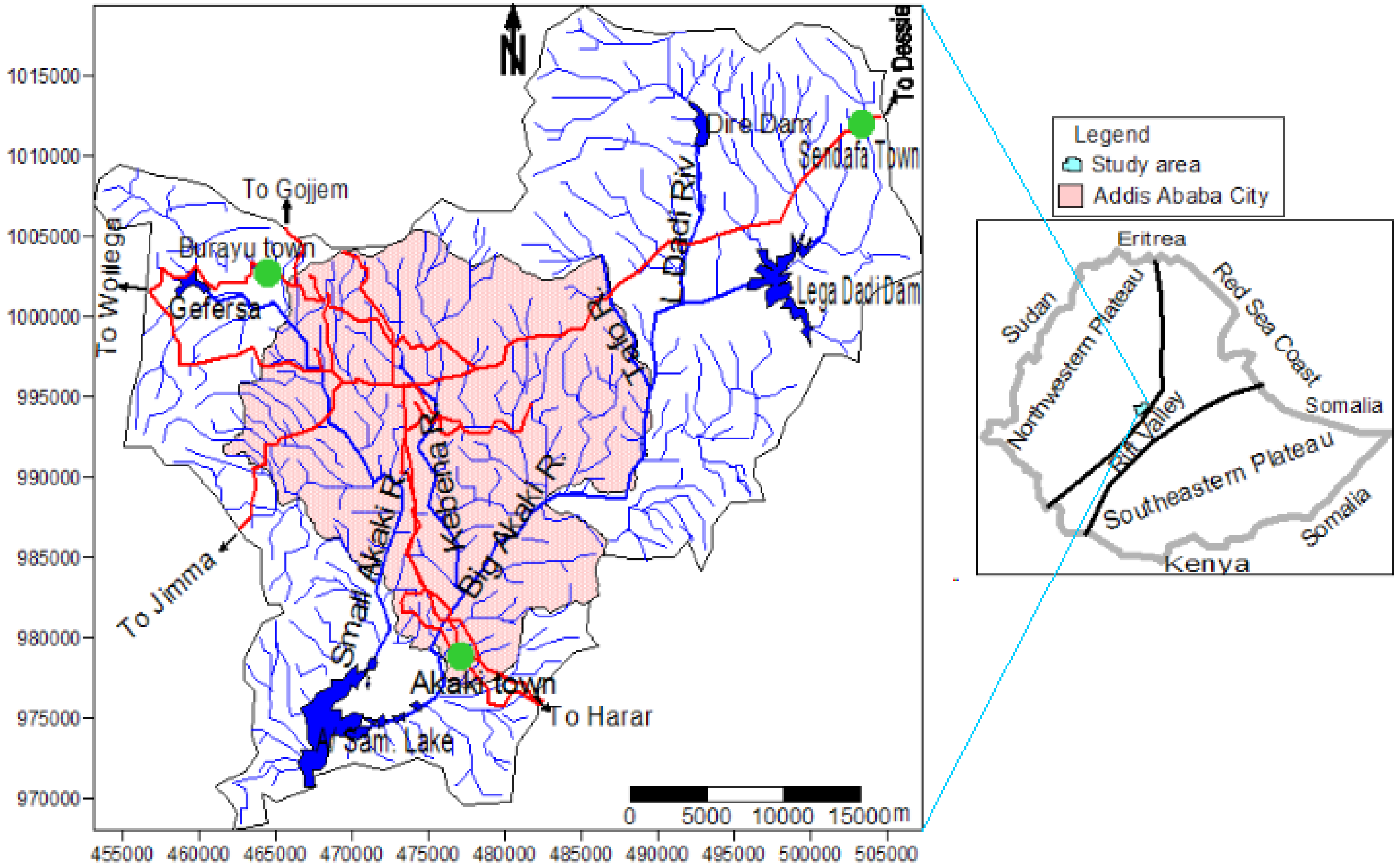


Figure 2.1 Location Map of Akaki River Catchment

2.2 Climate

Based on Rainfall, the climate of the area can be categorized in to two broad seasons: the dry season (winter) which covers the period from October to May and the wet season extends from June to September, with slight rainfall during autumn and spring. This seasonal variation of rainfall distribution with in the study area is due to the annual migration of the inter-tropical convergence zone, a low-pressure zone marking the convergence of dry tropical easterlies and moist equatorial westerlies across the catchment.

The highest and lowest mean maximum temperature over the record periods is 25^0c in dry season (March) and 20^0c in wet season (August), while the variation of mean monthly temperature values fall in the range of 7^0c (December) to 12^0c (March) throughout the year. From these values one can observe that daily variation in temperature in the area is more pronounced than the annual variation and the calculated mean annual temperature was around 16.32^0c (Solomon Tale, 2000). In general, one can classify the climate in this area as warm temperate climate.

2.3 Physiography

The Akaki River catchment is an extensive drainage system located at the eastern edge of the Western Ethiopian plateau that slowly descends to the Main Ethiopian Rift and has an elevation drop of about 1km in a space of about 30km towards the south (Figure 2.3). As it can be seen in this figure the topography close to the ridge in the north is sharp and tends to flatten towards south.

The present rugged landform of the area is due to volcano – tectonic activity that formed the plateau and rift followed by later erosion and river dissection. Akaki River catchment has an elevation range of 2040 to 3,300m above sea level (Topographic Map of Scale 1:50,000, EMA, 1973). Ridges/volcanic centers and mountain ranges bound the catchment.

The landform of the catchment is complex and changes within small distances; the central part resembles a wide caldera and is characterized by decreasing elevation in the direction of river flow. The southeastern tip of this catchment is relatively flat with recent quaternary deposits and NE –SW aligned scoria cone hills standing above the ground surface. The northeastern part of the catchment is also relatively flat. The northern part of the catchment has rugged topography & steep slopes, which in turn are characterized by rapids, and a high runoff coefficient compared to the southern part of the catchment.

Vernier et.al (1985) tried to characterize the Intoto mountain Range as a remnant edge of an old volcanic caldera, which has been collapsed southward by means of a wide system of step faults. This also shows that the landscape is the result of complex geological structures, which has been modified by erosional processes.

Peak elevation is found at: Intoto Mountain Range (peak elevation Mt. Intoto 3200m above sea level, Mt. Bereh 3,228m above sea level), Wechecha range (3,391m a.s.l), Mt. Furi (2839m a.s.l.) and Mt. Yerer (3100m a.s.l.) and the minimum elevation is found to the south of catchment (around Abba Samuel Lake (2060m a.s.l.)).

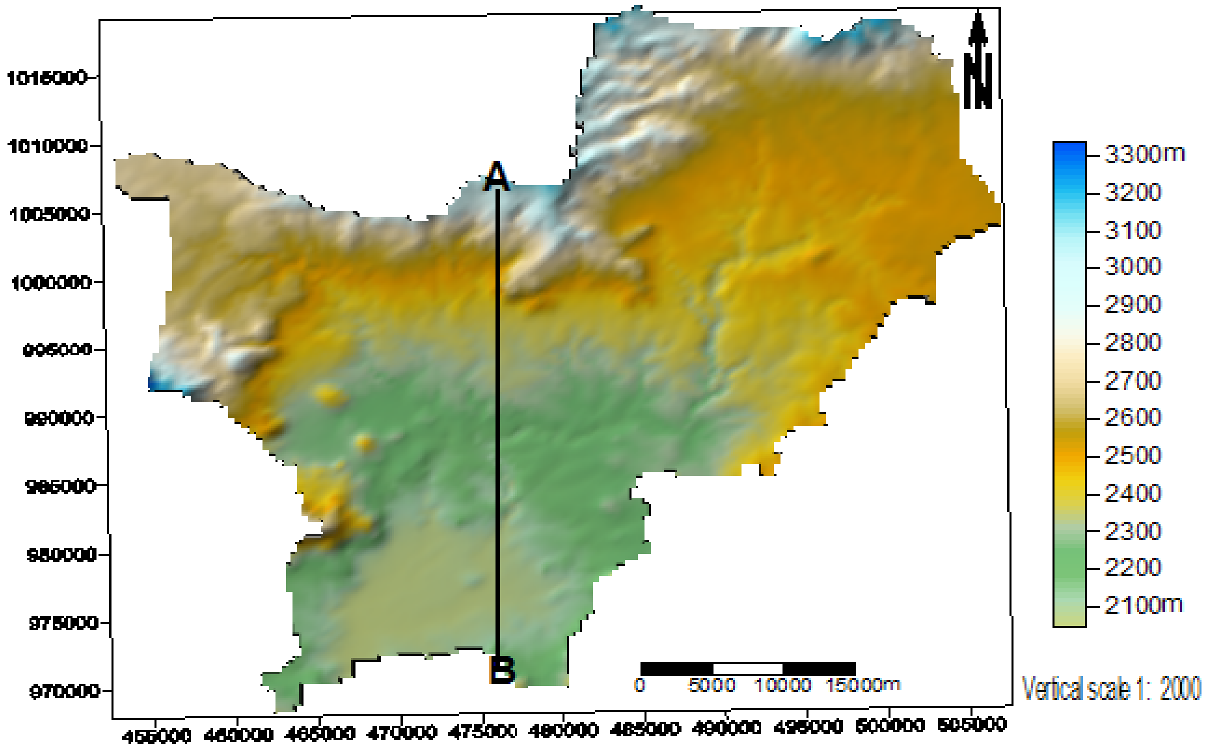


Figure 2.2 Elevation surface map of Akaki River Catchment

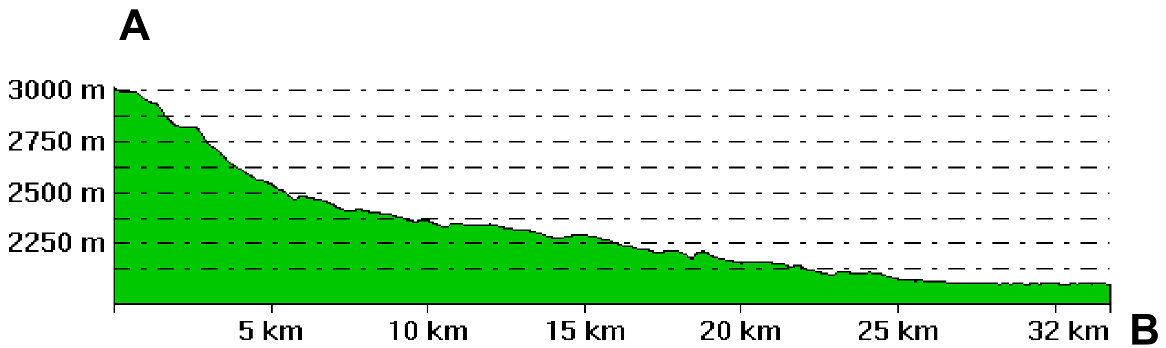


Figure 2.3 Profile showing elevation drop along line A-B

2.4 Land use / Land cover

Although very much diverse, the general land use/cover pattern of the catchment was broadly classified into four groups: forest, urban area, agricultural or open areas and water bodies, according to BCEOM- Seureca (2000).

In the northern part of the catchment on Intoto Mountains, the land is covered by forest, dominantly eucalyptus trees and the top of the mountain range is relatively flat that facilitates infiltration of precipitation into the ground. As the slope gets sharper towards the city a relatively higher runoff coefficient is expected.

Residential areas are found either as towns /city and villages or as sparse settlements of household. The Addis Ababa city is characterized by paved surfaces /built up areas, that cause very small infiltration of precipitation in to the ground and most of the rainfall is converted into surface runoff that drains into networks of rivers.
The other residential towns /villages in the catchment include, Sendafa, Akaki, Burayu and other moderately populated rural settlement villages. Some garden areas and woodland covers also characterize urban areas.

Although elevation peaks (hills, ridges), that are not convenient for farming, are widely distributed in the catchment, agricultural or open areas cover a large part of the catchment in the east, south and southwest directions. Such areas are less subjected to human influence in terms of change in soil permeability, and rainwater is assumed to infiltrate in this zone at a natural rate (BCEOM – Seureca, 2000).

There are about five man-made reservoirs /dams in the Akaki River catchment. These are: Gefersa I, II and III, Lega Dadi, Dire and Abba Samuel Lake. The first four serve for drinking water supply except Gefersa III which serves as a sediment trap while the last one was constructed for electric power generation (Yewendson Mengistu and Dereje Nugussa, 2002).

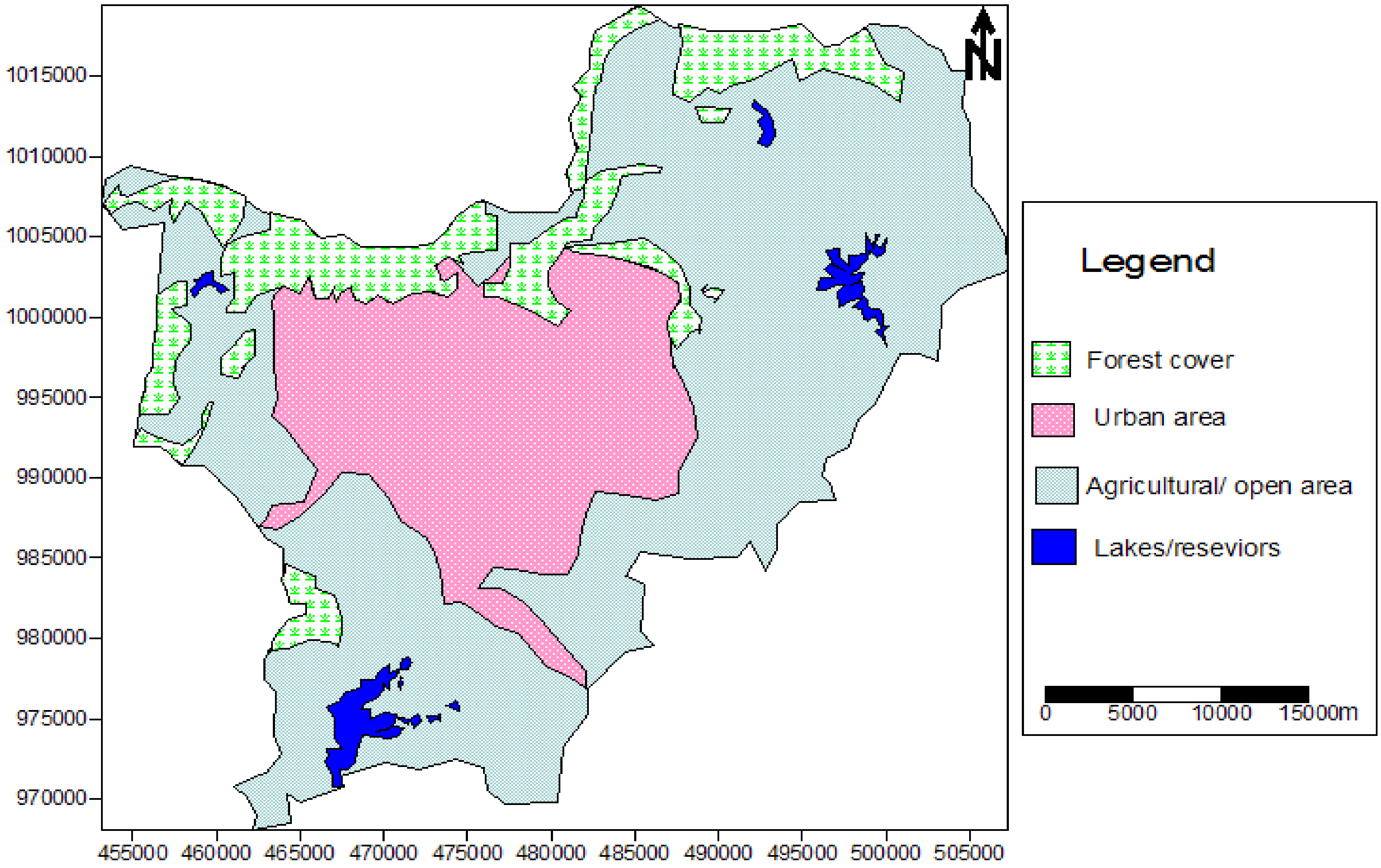


Figure 2.4 Land Use/Cover Map of the Akaki River Catchment

Accordingly, based on the distribution and areal coverage of each land use type in the catchment, the proportion of each was calculated as follows: forest covers about 15.45% of the total, agricultural/ open area 69.02%, urban areas 14.55% and water body/ wet lands cover about 1.5% of the catchment. Figure 2.4 shows a simplified land use /cover map of the catchment produced based on previous land use map information, topographic map of the region, and some field counterchecks.

2.5 Drainage

The Akaki River catchment comprises of numerous small rivers. The dominant ones are the Big Akaki, which drains the eastern part of the catchment area, and the Little Akaki that drains the western part of the catchment; and their respective tributaries. The two rivers form one of the biggest tributaries of the Awash River called Akaki River that enters Abba Samuel Lake, leaves the lake and passes through a gorge up to 100m deep which extends for about 8km before it joins the Awash River. Almost all the streams in the catchment originate from the northern part of the catchment. Refer figure 2.1

The Big Akaki suffers a total drop of about 600m in a river length of 95km from its origin to its confluence with the Awash River near Dodota, 1800m above sea level (AAWSA et al., 2000).

The Intoto Mountain range in the northern forms the surface water divide between the Blue Nile and Awash River basins. The drainage of an area is affected by numerous factors among which, rainfall, slope, vegetation, rock type and tectonic activity, infiltration capacity, soil types and thicknesses, are some. In the northern part of the catchment the drainage forms steep narrow gorges (facilitates runoff) which can be attributed to high rainfall, dense vegetation cover and high topographic elevation (>2800m). Where there are volcanic ridges /domes, drainage radiates in all directions forming radial or parallel drainage system. It is clear that areas with higher permeability have lower drainage density that in turn may decrease the surface runoff. These can be observed from the topographic map of the area in that areas with high elevation and that are not covered with vegetation have higher drainage density compared to flat lying areas and areas that are covered with vegetation (increases permeability). Generally, the drainage in the catchment is oriented nearly from north to south following the regional slope.

2.6 Summary of Hydrometeorology of the Area

In the study area there are five meteorological stations. They are located at Addis Ababa Observatory, Addis Ababa Bole, Akaki mission, Intoto and Sendafa areas. Meteorological data were collected from National Meteorological Agency and a simple arithmetic mean method was applied in order to evaluate the areal distribution and pattern of different meteorological parameters for the study area. The available meteorological parameters employed in this study were rainfall, pan evaporation, relative humidity (R.H), wind speed and relative sunshine hours. The average monthly values of these parameters and the duration of averaging are given in table below.

Table 2.1 Summary of mean monthly values of meteorological data for the study area

		Months												
Parameter	Station(periods)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Rainfall, mm	Intoto(1989-2004)	15.6	38.3	61	87.2	43.2	102.2	265.3	317.1	138.4	27.2	9.9	9.8	1115.2
	Sendafa(1991-2004)	20.8	18.5	47.7	52.4	43.7	118.6	328.8	308	106.1	49.1	3.6	3.8	1101.1
	Akaki (1975-2004)	14.1	29.8	76.7	86.1	68.5	115.2	255.4	258.5	118.8	25.1	3.6	3.2	1055
	AA Bole(1980-2004)	11.8	33.6	68	93	71.1	122.5	235.9	240.3	133.5	30.9	3.2	4.9	1048.8
	AA Obs(1980-2005)	14.2	39.1	68.9	91.5	83.7	136.2	262.4	272.9	168.7	34.9	5.8	9.2	1187.4
Mean		**15**	**32**	**64.4**	**82**	**62**	**119**	**270**	**279**	**133**	**33**	**5**	**6**	1100.5
Temp.^{0}c	Entoto (1989-2004)	19.1	19.7	19.9	19.4	20.1	17	15.9	15.9	15.8	16.8	18.6	17.5	215.9
	AA Obs (1980-2005)	23.9	24.9	25	24.5	25.1	23.4	21	20.9	21.7	22.7	23.1	23.2	279.6
	AA Bole(1980-2004)	23.8	23.8	26.3	24.8	25.3	23.5	21.2	21.1	21.8	22.9	23.2	23.2	280.8
	Akaki (1997-2004)	26.3	27.3	27.4	27.3	28	26.3	24.3	23.8	25.3	25.8	25.9	25.9	313.6
Mean		**23.3**	**24**	**24.7**	**24**	**24.6**	**15.9**	**20.6**	**20.4**	**21.2**	**22.1**	**22.7**	**22.5**	265.8
Pan Evap. mm	AA Bole(1987-2004)	186.1	190	190.8	177.4	202	106.2	62.3	60.6	99.5	287	189	171	1921.9
	AA Obs (1992-2004)	131.7	141	145	117.6	138.3	84.2	52.7	50.2	73	121	137	127	1319.4

Mean		**158.9**	**166**	**167.9**	**147.5**	**170.2**	**95.2**	**57.5**	**55.4**	**86.3**	**204**	**163**	**149**	**1620.7**
Sunshine Hr	AA Obs (1964-1993)	8.6	8.1	7.2	6.5	6.8	5.1	3	3.5	5	8.1	9	9.1	80
Mean		**8.6**	**8.1**	**7.2**	**6.5**	**6.8**	**5.1**	**3**	**3.5**	**5**	**8.1**	**9**	**9.1**	**80**
Wind speed km/hr	AA Obs (1982-2004)	0.7	0.7	0.8	0.8	0.7	0.5	0.4	0.3	0.5	0.8	0.8	0.7	7.7
Mean		**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.5**	**0.4**	**0.3**	**0.5**	**0.8**	**0.8**	**0.7**	**7.7**
R. H in%	AA Obs (1979-2004)	41.7	40.6	43.3	46.9	42.7	53.8	65.8	67.1	56.5	40.4	35.1	33.6	567.7
	AA Bole(1964-2004)	55.9	55.1	56.2	63.4	59.9	73.9	86.2	86.3	81.9	61.3	53.8	55.9	**790**
Mean		**48.8**	**47.9**	**49.8**	**55.1**	**51.3**	**63.9**	**76**	**76.7**	**69.2**	**50.9**	**44.5**	**44.8**	**678.8**

Table 2.1 …….continued

Precipitation was recorded in the catchment since 1900 at Addis Ababa Observatory except between 1941 and 1945. Long term minimum arithmetic mean monthly rainfall amount in the catchment was obtained in November (5mm) and the maximum value was for the month of August (279mm) for durations specified in the above table. Generally, the annual rainfall values decline with decrease in elevation and the effect of altitude on rainfall distribution is more clearly visible in the magnitude of rainfall recorded during the main rainy season than the annual values. The plot below shows the long term annual rainfall pattern of the area. The red line shows the decreasing linear trend of rainfall pattern in the area.

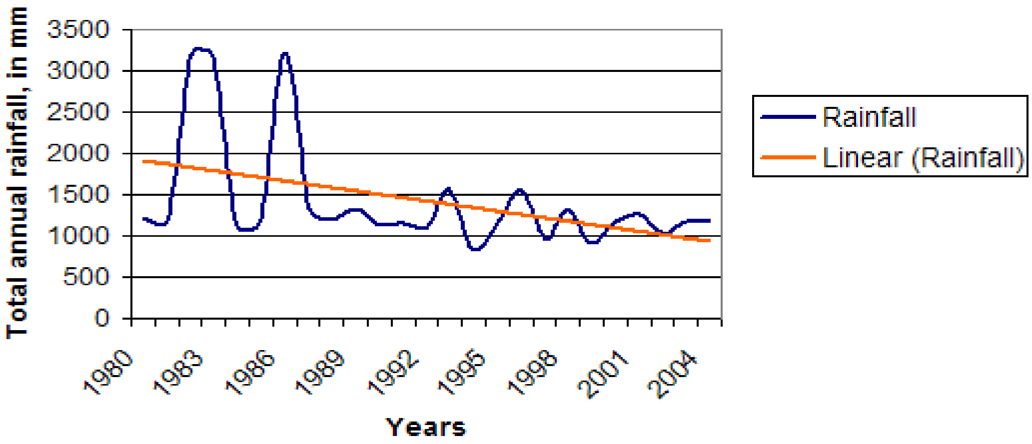


Figure 2.5 Total annual rainfall pattern at Addis Ababa Observatory (1981-2004)

Quantitative seasonal category (into dry and wet) based on rainfall distribution can be carried out using rainfall coefficient (R.C), which is the ratio of mean monthly rainfall(P_m) to one- twelfth of the annual mean of total rainfall(P_a), Daniel Gemechu(1977).

$$R.C = 12\, P_m/P_a$$

Table 2.2 Monthly Rainfall Coefficient of Akaki River Catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P_m(mm)	15	32	64.4	82	62	119	270	279	133	33	5	6	1101
R.C	0.1636	0.349	0.7022	0.894	0.6761	1.2976	2.944	3.042	1.45	0.3598	0.05452	0.06542	

-Months with R.C value less than 0.6 can be categorized as dry months (February, January, December, November and October).

-Months with R.C greater than or equal to 0.6 are classified as rainy months (March, April, May, June, July, August and September). Further, this can be grouped as:

-Small rain (R.C= 0.6 - 0.9): March, April and May

-Big rain (R.C ≥1):

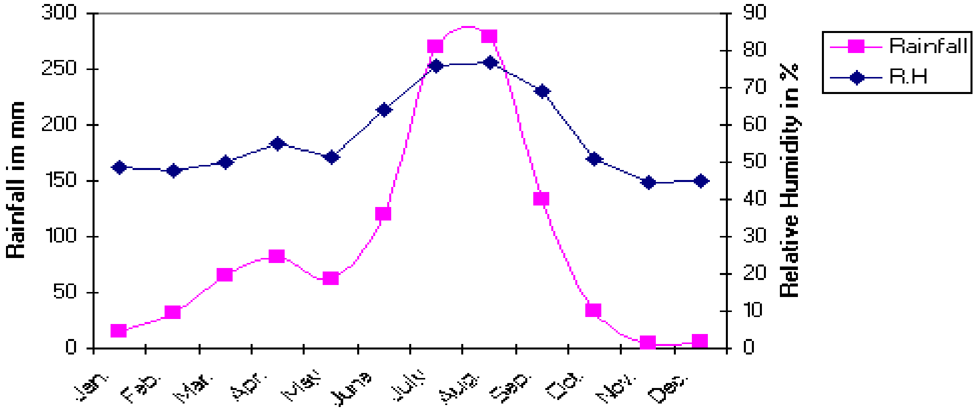
.Moderate Concentrations (R.C= 1.0 - 1.9): June and September

.High Concentrations (R.C= 2.0 - 2.9): July

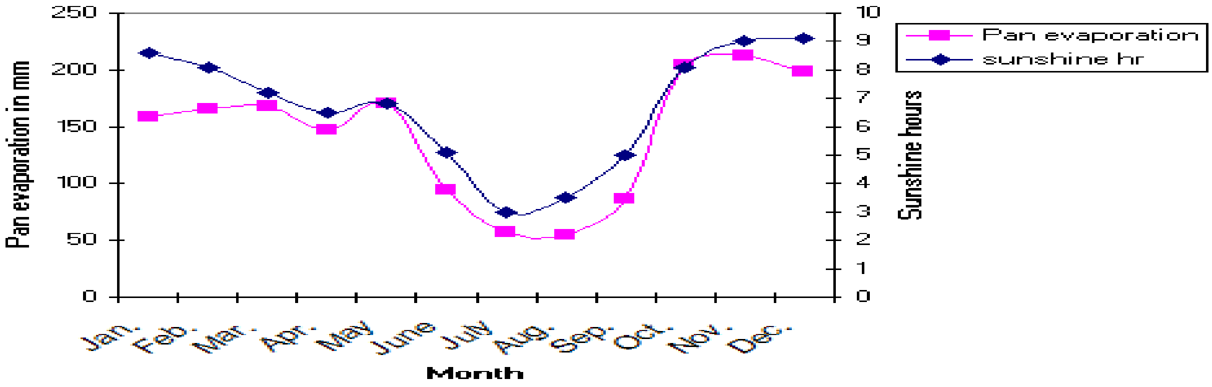
.Very High Concentrations (≥3.0): August

Overall, two precipitation categories can be made for the study area.

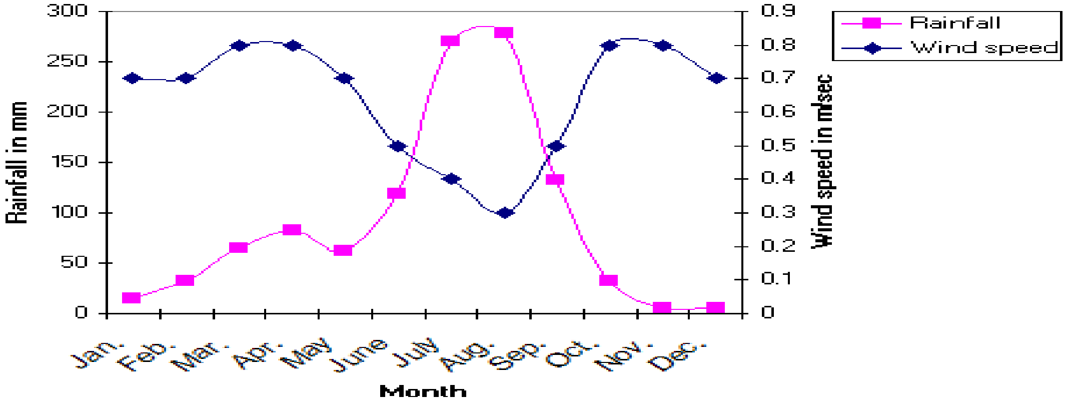
The variation and the values of other hydrometeorological parameters like temperature, relative humidity, and sun shine hours, pan evaporation and wind speed were given in the table 2.1 and the plots of the different parameters versus months are shown below.



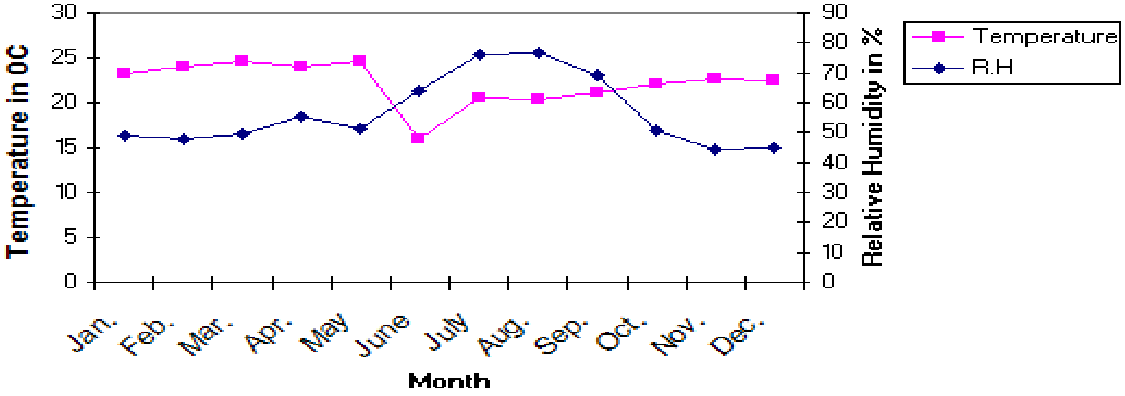
a) Rainfall and relative humidity plotted versus months



b) Sunshine hour and pan evaporation versus months



c) Rainfall and wind speed versus months



d) Temperature and relative humidity versus months

Figure 2.6 Plots of different meteorological parameters versus time (months).

Stream flow data for Big and Small Akaki Rivers were collected from Ministry of Water Resources. Using calculated mean monthly flow data, hydrograph of Big Akaki River was constructed based flow measured between 1981-2003 (data in annex 1). Maximum stream flow belongs to periods of intensive rainfall. The following table shows total annual flow of the streams.

Table 2.3 Summary of total annual flow (Q) of Big and Small Akaki Rivers.

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003			-
Big Akaki(Q)	298	171	250.9	227.2	289	288.8	114	214	299	340	376	108	203
	81.7	97.5	237.2	70.1	190	186.6	108	142	61.2	148	-	-	-
Small Akaki(Q)	-	-	-	-	-	-	-	-	-	-	-	293	864
	345	474	1675	387.2	2518	98.1	25.2	35.3	18.5	18.9			

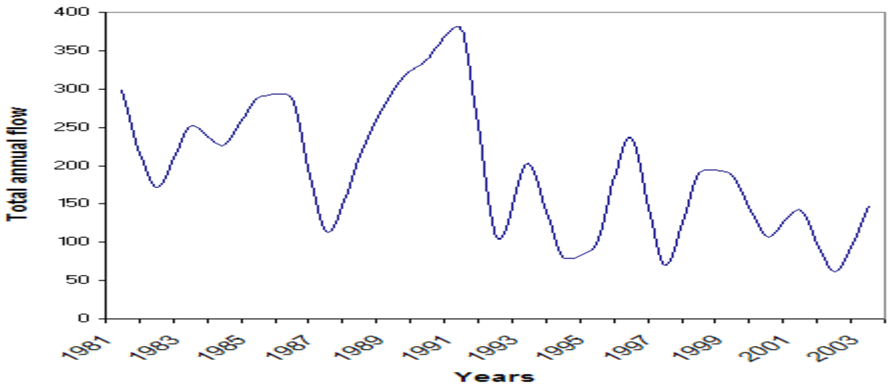


Figure 2.7a Long term annual flow of Big Akaki River

From the above table and figure, it is clearly seen that total annual variation in discharge of Big Akaki River showed a general decreasing trend over years considered. The monthly runoff amount of both streams has been given in annex 2.

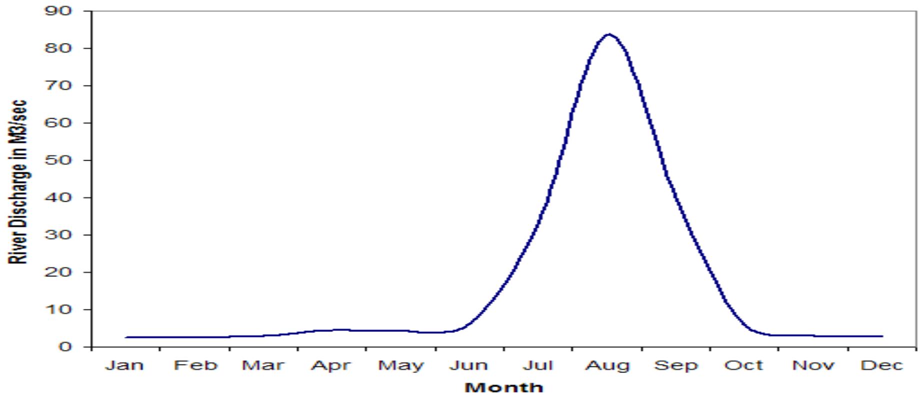


Figure 2.7b Hydrograph of Big Akaki River

The long term monthly minimum stream flow (in figure above) was considered to be equal to base flow. This was based on the idea of Wundt (1978) who mentioned that the long term monthly minimum stream flow is the best approximation of base flow, especially, for humid climate. Based on this, base flow to both streams was approximated to be 287712m^3/day or 3.33m^3/s (annex1),

CHAPTER THREE

GEOLOGICAL SETTINGS

3.1 Regional Geology

The oldest rock in the country, which forms the basement, is of Precambrian age. Overlying this basement rock is the Mesozoic sedimentary succession and/or Cenozoic Volcanics except where the basement rocks are overlain by Paleozoic sedimentary rocks, quaternary deposits or simply exposed to the surface. The largest part of the county (about 32%) is covered by volcanic rocks of different ages and types. One can categorize these volcanic rocks based on various criteria such as age (tertiary and Quaternary volcanics), and taking rift formation as a reference (pre- rift & post- rift volcanics). The volcanic rocks of the country can also be described as the Trap series volcanics and Aden Series volcanics, which is the same as to say post rift volcanics. The trap series represent the oldest volcanic rocks in the country compared to Aden series volcanics. The major uplifting followed by cracking of Horn of Africa gave rise to the formation of Trap series. It is comprised mainly of flood basalt with some trachytes and rhyolites, especially on its upper part. The trap series forms the northwest and southeast plateau, reaching its maximum development in central Ethiopia attaining a thickness of up to 3km, (Mengesha et. al 1996).

Trap series is hardly distinguished from the Aden Volcanic series based on the petrographic analysis, Mohr (1971). Hence though not conclusive, morphological distribution may be employed to distinguish them. The trap series predates the rift faulting and usually occupies great height of the Ethiopian and Somalian Plateau, where as the Aden Volcanic series are associated with well – preserved volcanic cones or lava flows, Mohr (1971).

Due to the fact that the Akaki River catchment lies between the plateau and the rift floor (Zennettin and Justin – Visentine, 1974) the geological history of the area is an integral part of the evolution /development of the Ethiopian plateau and the Rift system. According to Mohr (1964), the present morphology, and geological setting of this part of Ethiopia are the results of two major post-Paleozoic tectonic events, which were followed by important phases of volcanic activity. The first tectonic event (the epierogenic uplift), which occurred in late Mesozoic – Early Tertiary period, produced the Afro- Arabian Dome. As an immediate consequence of up arched landmass under tension, gave rise to the extrusions of voluminous basaltic magma through fissures (Mohr, 1983). The extrusion of the Trap Series fissure basalt of Ethiopia during Eocene - Oligocene was the major and widespread volcanic episode of the whole Cenozoic. According to Kazmin (1975), contemporaneous eruption formed shield volcanoes mainly consisting of basaltic lava and developed on both the southeastern & the western plateau in Miocene. The second tectonic event resulted in development of rift and associated volcanic phenomena during Tertiary-Quaternary period were superimposed on the long uplifted Afro-Arabian swell, whose axis runs about N-S.

The Main Ethiopian Rift (MER) was the result of extensional tectonics that trends in NNE-SSW. It started to develop in the Miocene. According to Zennettin et al., (1980), rift related volcanic rocks were outpoured when fissural volcanism in the adjacent plateau had died out.

Initial sagging of the MER started about 14 to 15 Ma and was followed by major episodes of rifting at 10, 5, 4 and 1.8 to 1.6 Ma. Each stage of rifting and down faulting was accompanied by a bimodal (silicic-mafic) volcanism in the rift and formation of basaltic and trachytic shield volcanoes on the rift shoulders & margins, (Kazmin et al., 1980). There were wide spread basaltic cinder cones erruption as well as restricted local flows of olivine basalt and olivine trachy- basalt in Akaki-Debrezeit areas, contemporaneously with the emplacement of per alkaline rhyolites, trachyte lavas and ignimbrites (Mohr, 1964).

Quaternary volcanism was not confined to rift; it also took place on plateaus, Mohr (1971). These quaternary alkaline basalts and trachytes were erupted along the pre- existing structures on the north-west and south-east plateaus. Their well preserved structures and unmodified geomorphologic features such as cinder cones and small collapse craters, in heavy rainfall and perennial stream region indicate their recent age, Mengesha et al (1996).
Even though the major geological structures in the country mostly parallel the rift system, some faults run transversally to it on Northwest Ethiopian Plateau. An example is the East -

West oriented lineament that extends from Kassam River in the east through Addis Ababa to Ambo in the west. This lineament, called Ambo Fault Belt, starts from the western escarpment of the rift, and goes further to Wollega, Mengesha, et al (1996). According to Mohr (1971), horst formation in Karakore area by uplifting of the long strip of escarpment took place at more or less similar time with the faulting of east - west oriented Ambo Fault Belt that cuts across the escarpment and uplifted its northern block, which was nearly during the Late Miocene time.

The regional geologic map, in which the Akaki River Catchment is located is presented in figure 3.1, adopted from the works of Adane Bekele (1999). The geology of the Upper Awash River Basin ranges in age from Upper Miocene to Holocene and consist of consolidated volcanics (Plateau and Rift volcanics), lacustrine and alluvial deposits. The summary of the geology of the regionally referred area is presented as follows:

3.1.1 Rift and Plateau Volcanics

. Alaji Basalt

Alaji Basalts crop out mainly in the Addis Ababa area. This unit is dominated by flood basalts which show variations in texture from aphanitic to highly porphyritic. Within this unit there is intercalation of welded tuff. A succession of up to 800m predominantly aphanitic flood basalt rests unconformablly on the eroded surface of the Mesozoic sediments represented by limestone of the Upper Jurassic Gabredare Formation and sandstone of the Cretaceous Amba Aradadm Formation.

. Termaber Formation

Termaber basalt is found in the plateau extending from Addis Ababa to Guder valley.
It is composed of basalts whose texture varies from aphanitic to completely porphyritic.

. Anchar Basalt and Arba Gurracha Silicics

In the Anchar area, the units are represented by about 400m of basalt with several intercalations of ignimbrites, the one at the base being 12.4Ma.

. Arba Gugu Basalt

This unit is a succession of lava flows piled up to 300m thick, composed of porphyritic pyroxene and/ or plagioclase basalt, erupted Arba Gugu shield volcano.

. Nazareth Group and Associated Unit

The Nazareth Group consist of a thick succession of ignimbrites, unwelded tuffs, ash flows, rhyolites, aphanitic basalt and trachytes; occupying the larger part of the rift floor and also outcropping in the escarpment and on the adjacent plateau margins.

. Bishoftu Basalt

The Bishoftu Basalt unit outcrops in the Akaki-Debrezeit area. It starts 15km South of Addis Ababa and reaches a thickness of about 10m at Akaki.

. Recent to Sub-recent Basalt, and Rhyolitic and Trachytic lava

The recent basalt outcrop South of Debrezeit and is composed of scoriaceous and vesicular basalt, scoriaceous and porphyritic trachy-andesite, phonolite and trachytic tuffs.

3.1.2 Volcano- Sedimentary Deposits

These are lacustrine and alluvial deposits. The lacustrine sediments are compact and fairly welded tuffs, ashes, silts, clays and diatomaceous sediments. Alluvial deposits are unconsolidated materials made of sand, silt and clay beds with brown, red and black color.

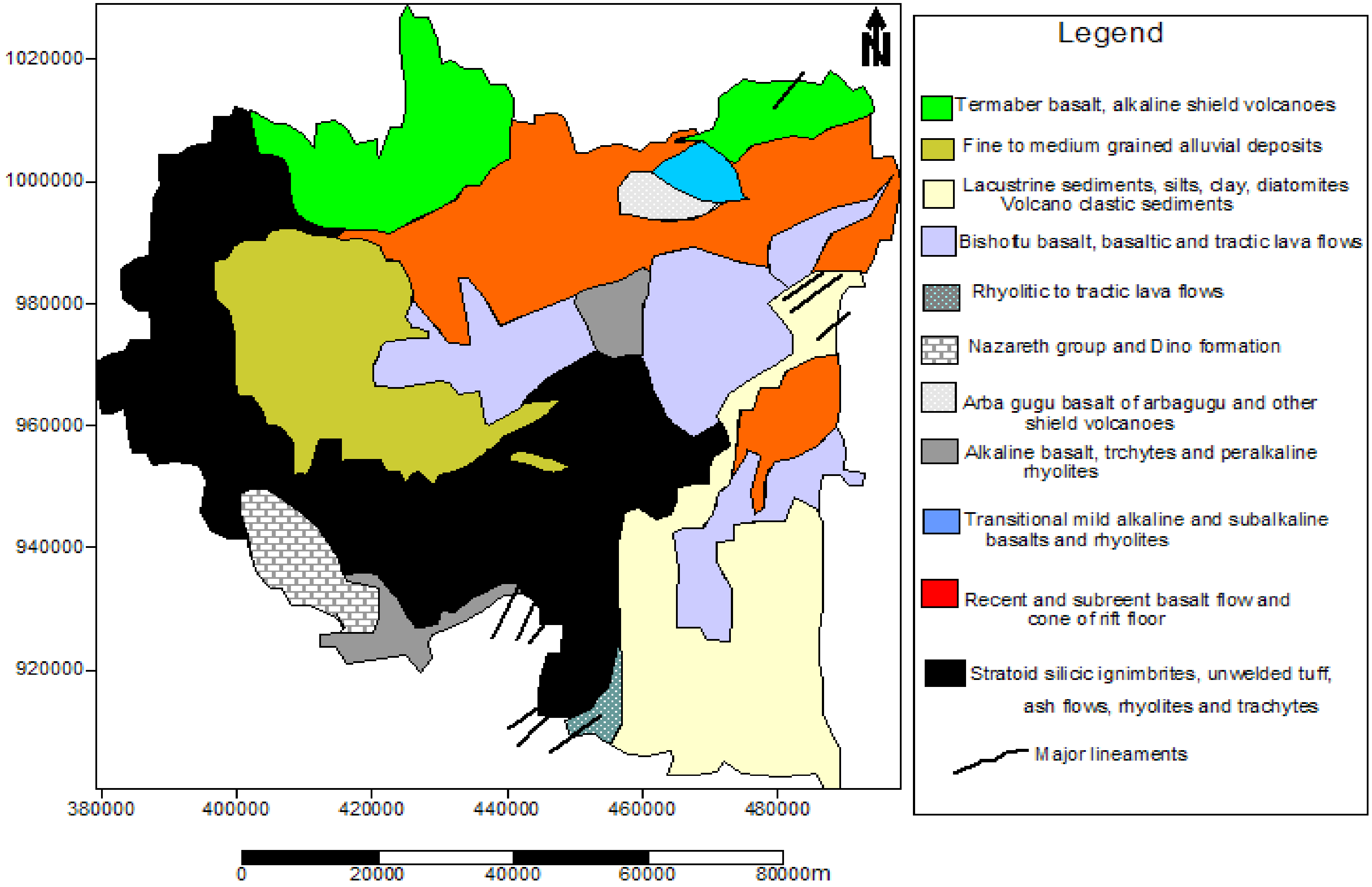


Figure 3.1 Regional Geological Map (Upper Awash River Basin)

3.2 Local Geology

The Akaki River Catchment comprises of wide range of volcanic rocks of different ages (Morton et al, 1979; Vernier and Cherinet, 1985; Tsehayu and H/Mariam, 1990; AAWSA & Seureca, 1991). In addition, different workers and scholars have contributed to the geology of this area, some are: Mohr (1964, 1966, and 1967), Kazmin (1975), Morton (1975), Zennettin et al. (1974, 1980), Hailesellassie Girmay and Getaneh Asefa (1989).

Due to the location of the study area with respect to the Main Ethiopian Rift, the rocks were subjected to rift tectonics that is manifested by a number of fault systems having a general trend of the rift system (Northeast – Southwest), but there are some faults and lineaments oriented East –West, Northwest - Southeast.

Morton et al (1997), using radiometric dating, tried to outline the rift ward younging of surfacial volcanic units along a 100km wide swath southeastwards from Blue Nile area on plateau through Addis Ababa – Debrezeit area on the rift margin to the rift floor axis at Wolenchiti.

The geology of the catchment compiled by BCEOM – seureca (2000) that shows the stratigraphy of the area between Sululta and Nazareth that was defined based on existing works has been adopted in this work. Hence, the lithostratigraphic units of the catchment can be outlined from the oldest (bottom) to the youngest (top) as follows:

3.2.1 Alaji Series (Lower Miocene)

This unit covers the Intoto Mountain and extends to the north beyond the study area. It comprises of basalts associated with rhyolites, trachytes, ignimbrites, tuffs and agglomerates. Earlier works further subdivided this series into Alaji Rhyolites and Intoto Silicics.

According to Zennettin et al. (1974) the Alaji Rhyolites and basalts were outpoured from the end of Oligocene until Middle Miocene. Hailesellassie Girmay and Getaneh Assefa (1989) showed that these units extend from Intoto to the North across the Sululta Plain. Morton et al. (1979) dated a sample from North of Addis Ababa and assigned an apparent age of 22.8 Ma that corresponds to Miocene time.

The Intoto Silicics make up a thick pile of flows, which accumulated along east - west running fault from Kassam River to Ambo and down thrown to southwards, and it becomes thinner away from this east – west running fault in both directions (Zennettin and Justin – Visentin, 1974). According to Hailesellassie Girmay and Getaneh Assefa (1989), the Intoto silicics are composed of rhyolites and trachytes with minor amount of welded tuff and obsidian. The rhyolitic lava flows out crop on the top and the foothills of the Intoto Ridge and is overlain by feldspar porphyritic trachyte & underlain by a sequence of tuffs and ignimbrites (Solomon Tale, 2000). Morton (1974) and Morton et al. (1979) dated the Intoto silicics as 21.5 Ma and 22 Ma, respectively.

3.2.2 Addis Ababa Basalts

They overlie Intoto Silicics and outcrops mainly occur in the Intoto Mountain, central Addis Ababa, along Akaki River course (south) in the vicinity of Lega – Dadi dam to the north of Lake Gefersa and southern part of the city. Their composition can be porphyritic olivine basalt, porphyritic feldspar basalt & aphanitic basalts. Individual flows are usually easily observed & paleosols & scoriaceous horizons are found at the bottom of flows in many places (Kebede Tsehayu and Taddese Hailemariam, 1990).

According to Solomon Tale (2000), olivine porphyritic basalt outcrop in the central part of the town (Merkato,Teklehaymanot and Sidist Kilo) and the distribution of plagioclase porphyritic basalt is little northwards around Sidist Kilo, General Wingate School and French Embassy. According to Morton (1974) and Vernier (1985), the thickness of the olivine porphyritic basalt varies from 1m or less in the foothills of Intoto, Lideta Air Field and Filwuha to greater than 130 meters at Ketchene Stream.

The basalt flows are inter-bedded with welded glassy and fiamme ignimbrite outcrops in the areas of Filwuha, Ginfle and Lideta Air Field. At many outcrops it is overlain by aphanitic basalt flow and underlain by olivine porphyritic basalt flow (Anteneh Girma, 1994); Morton et al. (1979) dated Addis Ababa Alkali Olivine Basalts to have an age of 6.9 Ma at Arat Kilo, 7.3 Ma at few kilometers from St. George Church and 5 Ma near Kebena Bridge.

The geological map of the study area presented in figure 3.2 was adopted from the works on hydrogeological map of Addis Ababa, Akaki and Dukem Areas by AG consult (2004).

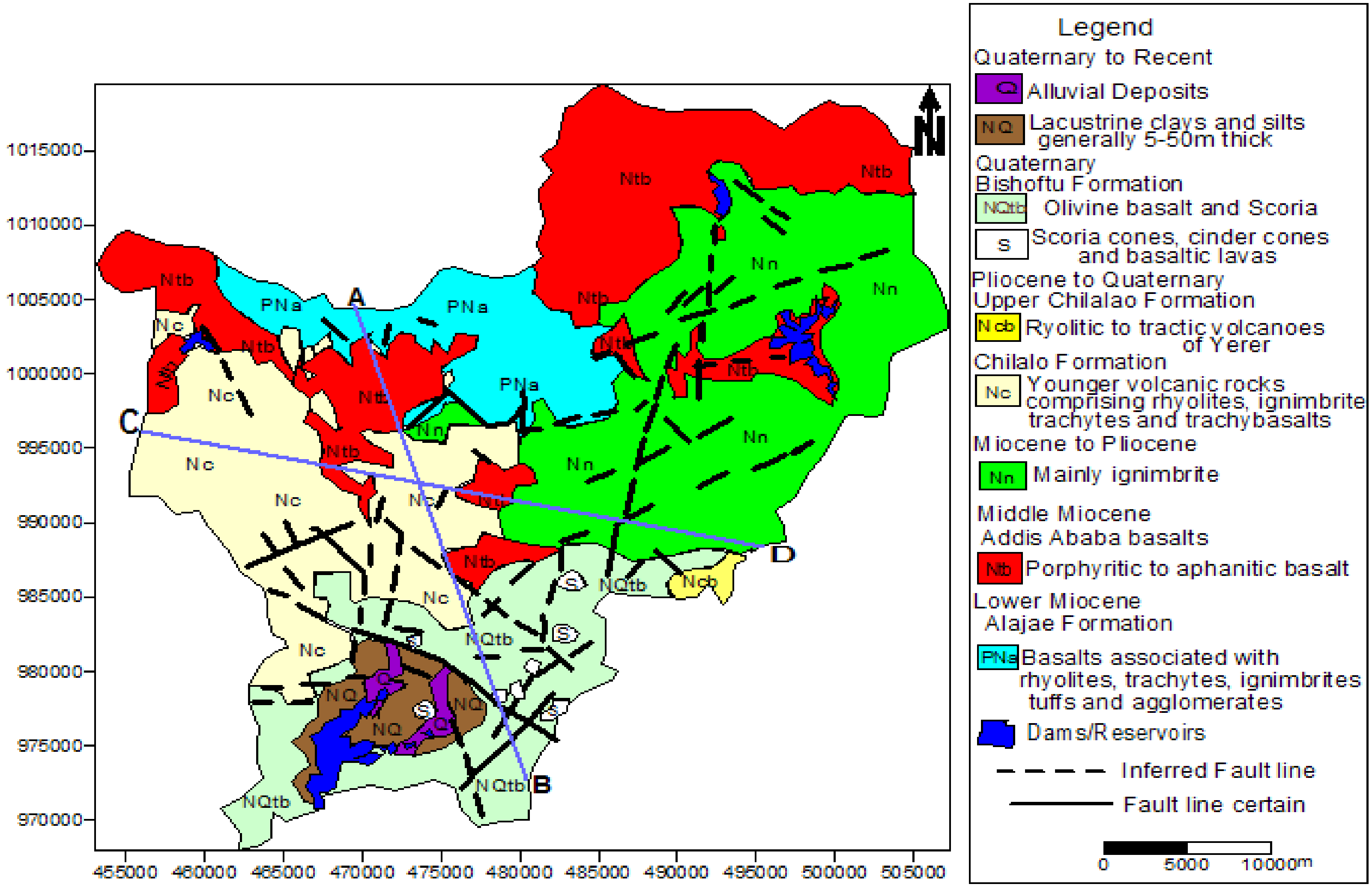


Figure 3.2 Geological Map of Akaki River Catchment

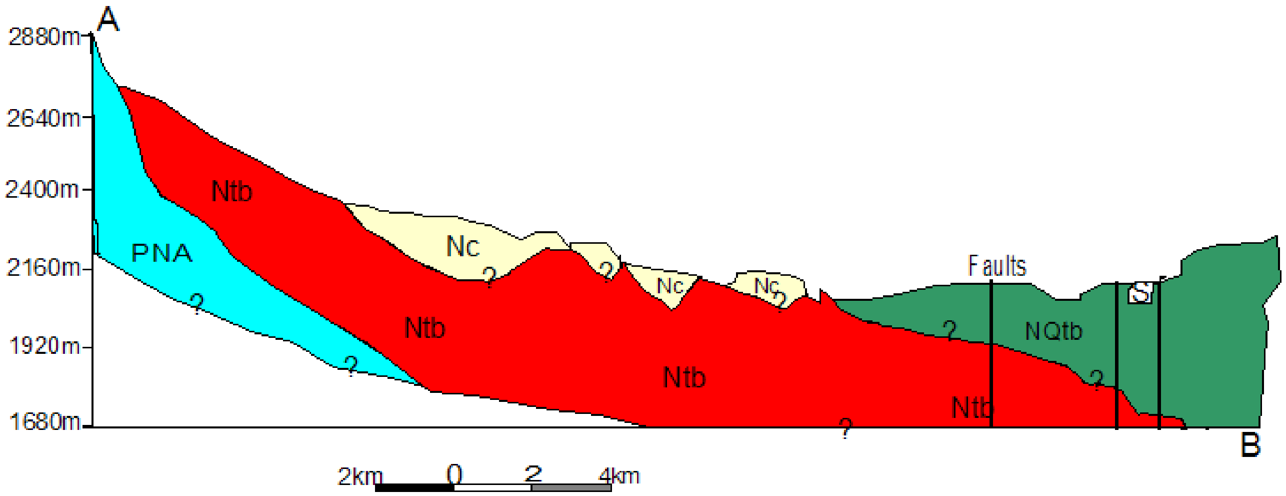


Figure 3.3a Geologic cross section along A-B of figure 3.2

? to show contact inference

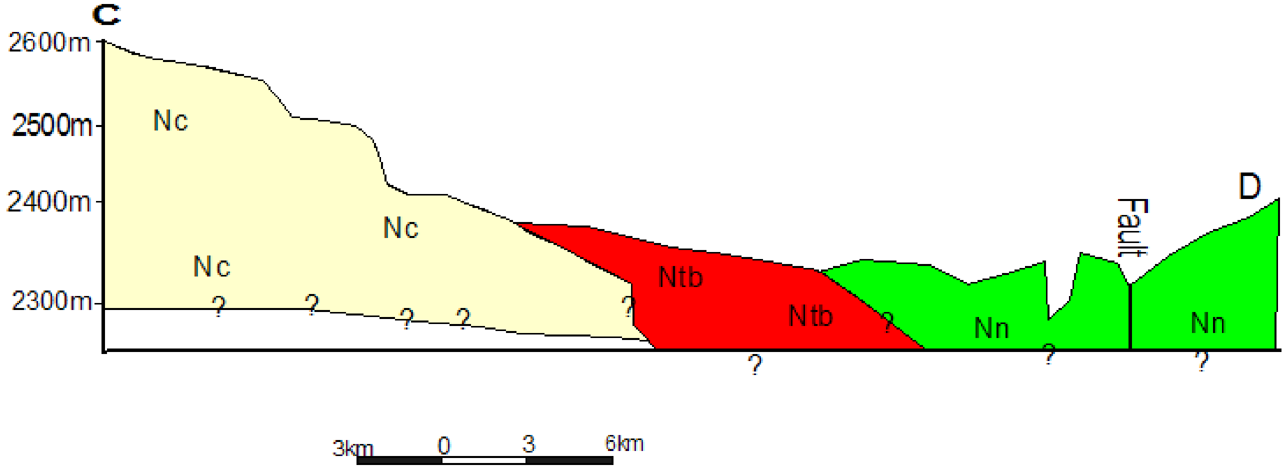


Figure 3.3b Geologic cross section along line C-D of figure 3.2

3.2.3 Younger Volcanics

These groups of volcanic rocks can broadly be classified in to Nazareth Group and Bofa Basalts. According to Hailesellassie Girmay and Getaneh Assefa (1989), the Nazareth Group rocks outcrop dominantly to the South of the Filwuha Fault and extend towards

Nazareth. Bofa Basalts are found south ward from Akaki River, southeastern part of Addis Ababa

3.2.3.1 Nazareth Group

Aphanitic basalt, welded tuffs, ignimbrites, trachytes and rhyolites make up this group of younger volcanics. Aphanitic basalt flows cover the southern portion of Addis Ababa, south of Asmara Road, especially the areas of Bole and Lideta. The flows show vertical and curved columnar jointing together with sub -horizontal sheet jointing (Anteneh Girma, 1994). Morton (1975) estimated the age of Mt. Yerer Volcano to be 3.5 Ma, which is similar to that of the aphanitic basalt in this area.

According to BCEOM – seureca (2000), trachy – basalt outcrops are found around Repi area and General Wingate School and associated with undifferentiated volcanics. It is underlain by the plagioclase and olivine porphyritic basalt, and overlain by the younger ignimbrite from which it is separated by tuffs and agglomerates (Hailesellassie Girmay, 1985).

According to Morton et al (1979), the most probable source of the lower welded tuff which is outcropped as a small discontinuous body in Western Addis Ababa (5.1 Ma) and Sululta (5.4 Ma) overlap with the period of activity of Wechecha Trachyte Volcanoes (4.6 Ma). An ignimbrite sheet (upper welded tuff) outcrop occurs in the northeast of Addis Ababa at the base of Intoto Mountain and Lega Dadi areas. This formation is gray colored, vertically and horizontally jointed (Hailesellassie Girmay and Getaneh Assefa, 1989). It is underlain by aphanitic basalt and overlain by young olivine basalts (Hailesellassie Girmay, 1985).

According to Anteneh Girma (1994), this group is underlain by tuff deposits and overlain by olivine porphyritic basalt flow to southeast of Addis Ababa. From a sample taken from Addis Ababa (near Asmara Road), Morton et al (1979) estimated the age of the rock to be 3.2 Ma, which overlaps with the period of activity of Mt. Yerer Trachytic Volcanoes.

Trachytic flow covers extensive areas in the west and southwest part of the catchment, from Mt. Furi Hana Mariam, Tulu Iyoo to Repi and Wechecha Range. The trachyte flow is underlain by tuff and overlain by alternating flows of plagioclase basalt and rhyolite at Repi (Anteneh Girma, 1994).

Rhyolite flows belonging to this group outcrop at the top and southern flanks of Mt. Yerer. The exposed thickness of the lava sequence is about 500m (Anteneh Girma, 1994). Morton (1975) determined the age of Mt. Yerer Rhyolite to be 3.3 Ma, and may be correlated to the Balchi Rhyolite of Zennettin et al. (1974).

3.2.3.2 Bofa Basalts

This unit comprises of olivine porphyritic basalt, scoria, vesicular & scoriaceous basalt, and trachy- basalt lava flows. They extend in to the south from Akaki River and the unit is as thick as 10 meters (Anteneh Girma, 1994). They appear to have upper thick basalt of 20 - 40m over the Akaki well field but thinner to absent in other places. They have well preserved shape of cones and marls.

According to AE- HBT AGRA JV (1998), this unit is overlain in places by scoria, tuff, sand and gravel. The underlying beds are series of relatively thin basalt flows alternating and complexly inter fingered with scoria and scoriaceous / vesicular basalt. Morton et al (1979) estimated the age of the basalt flow unit to be 2.8 Ma in Addis Ababa.

3.2.4 Lacustrine Deposits, Alluvial & Residual soils

These are quaternary to recent deposits. Lacustrine soils occur around Bole, Lideta, Mekanisa, between Abba Samuel Lake and Small Akaki River. The thickness of this deposit varies between 5m to 50m.

Alluvial deposits are found in some places along Small and Big Akaki Rivers, especially south and southwest of the capital city. Thick alluvial deposit occurs in the area between Akaki town and Abba Samuel Lake. Some deposits occur along the Kebena River, north west of Bole area. Soils, which are developed in-situ by the decomposition of rocks are located in the central, southeast, northeast, Gullele and Kolfe areas.

3.3 Geological Structures

It is in accordance with the location of the catchment at the shoulder of the Main Ethiopian Rift that the project area has been subjected to the rift tectonics, which is manifested by number of major and minor fault systems. As it can be seen from the map of the geological structures of area compiled by BCEOM – Seureca (2000), the general trend of most of these faults follow the rift system (NE – SW) orientation but there are some faults with orientation of east- west and northwest-southeast. The major lineament oriented along east-west that extends from Kassam River in the east through Addis Ababa to Ambo in the west, cuts across the western rift escarpment and uplifted its northern block (Zennettin et al., 1978) which was during the Late Miocene time. This lineament starts from the western escarpment of the rift and goes even further to Wollega (Mengesha, et al, 1996). Intoto silicics confined along this fault from the Intoto Ridge, which forms surface water divide between two vast basins in the country, namely Blue Nile (Abay) and Awash Rivers. The ridge forms the northern boundary of the study area and the fault has a down throw to the south in the catchment.

Another major lineament oriented in Northwest direction & situated to the Northeast of the Akaki well field extends between Akaki and Dukem (following the main Debrezeit highway) is one of the lineaments that do not follow the rift trend.

The other important lineament in the area is the Filwuha Fault. According to Kundo (1958), Morton (1974) and Hailesellassie Girmay (1985), the fault has a trend of NE – SW, which is in accordance with the rift trend structures. Even though Morton (1974) identified the fault as having a down throw to northwest, this was later disproved by Hailesellassie Girmay (1985) to be south, based on detailed mapping by resistivity survey of the fault. Moreover, he found the fault as having shallow depth, covered by thin soil layer of about 1 to 4m, not vertical and estimated its throw to be 40m (the approximate thickness of the welded glassy ignimbrite). The age of the fault may be bounded by the ages of the welded glassy ignimbrite and that of plagioclase aphanitic basalt which are 5Ma and 6.4Ma, respectively. Mohr (1964) measured the trend of the fault to be N 55^0 E and he assumed it to continue up to Debre Birhan .

The measured dominant preferred orientation of joints occurring in different rock units in north central part of the catchment is NNE – SSW, which is sub-parallel with the general trend of rifting (Kebede Tsehayu and Tadesse Hailemariam, 1990).

The density of faults increases to the southeast of the rift valley. Therefore, some of the basaltic lava and cinder cones situated to the Southeast & Northeast of the Akaki well field probably have erupted through these fractures as they are concentrated along the major NE –SW trending fault systems of Akaki and Dukem areas.

CHAPTER FOUR

Hydrogeochemistry and Isotope Hydrology for Flow Conceptualization

4.1 General

Hydrogeochemistry and Isotope hydrology have a vital role in hydrogeological applications and investigations as they can solve many problems independently or in combinations with other disciplines of sciences. They may help to characterize hydrochemical processes in ground water systems, to infer water origin or to determine flow directions.

From hydrogeochemistry one may be able to understand the degree of interaction between water and rocks, the origin of ground and surface waters, conceptualization of groundwater flow system, the degree of contamination of water and its specific use.

Stable isotope techniques are powerful tools in their own but are often used in combination with chemical data for reliable results. They show the degree of enrichment of water sample with respect to the rare or abundant isotope for a given element and this may help in conceptualizing flow and serve as a natural tracer for the origin of groundwater and to understand recharge processes.

In this study, hydrogeochemistry and isotope hydrology were employed to conceptualize groundwater flow in the Akaki River Catchment that may help in understanding the groundwater system dynamics.

Hydrogeochemical data and isotope data were collected from previously analyzed samples (AAWSA) in the catchment and the distribution is good enough to apply for the intended purpose. Almost the samples covered most parts of the catchment from north (Intoto) to the south (tip of the catchment at Aba Samuel Lake). In the following sections, the general hydrogeochemistry and isotope hydrology of Akaki river catchment is discussed in relation to groundwater flow conceptualization.

4.2 An overview of chemical characteristics groundwater of the area

In this work hydrogeochemical data was collected from 29 wells that cover most parts of the catchment (table 4.1) and the result was interpreted to help conceptualize groundwater flow in the aquifer system under consideration. For the purpose of this study some physical parameters, major cations, major anions, TDS and alkalinity etc were considered. Sample location points are shown in figure 4.3.

Naturally water contains few dominant cations and anions. The dominant cations are Na, K, Ca and Mg; the anions being HCO_3, Cl, SO_4. In unpolluted water the meq/l concentration of cations has to be equal to that of anions and any deviation signifies anthropogenic source contribution to the ions.

In Akaki River catchment there are both thermal and cold groundwater sources. For the purpose of this study, only cold groundwater chemistry was considered as the source of thermal groundwater is different, are from very deep source and the wells are found localized near Filwuha fault. According to Gizaw Berhanu (2002), thermal waters in the area are different from the rest by their high Na, HCO_3 and TDS. Thermal waters have high HCO_3 concentration of about 1500 –2500mg/l, have SO_4^{-2} concentration of about 50 – 500 mg/l, TDS reach a maximum of 1300mg/l in some wells and their specific conductance is about 1300 to 4000 μS /cm at 25^0c and generally were classified as Na-HCO_3 type water.

There is an enormous groundwater chemistry data available in the catchment, but for this study recent data of representative wells and springs was used. Accordingly, most water samples have relatively higher Na, Ca and Mg. In most, Ca and Na are dominant cations. Na concentration varies from 6.8mg/l (Eyasu spring) to 69mg/l (B-15). A Source of sodium can be natural processes like weathering of plagioclase feldspar (albite) or from human effects like effluents from domestic or industrial sources. The high Na value in some wells in this study area is mostly due to anthropogenic sources, as the wells are found in the most populated zone of the catchment.

No.	Well name	X	Y	TH(mg/l)	TA(mg/l)	EC	T,ºc	PH	Na	K	Ca	Mg	Cl	HCO3	SO4	Fe-tot	NO3	TDS
				(CaCO3)	(CaCO3)	µs/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	G/Ber Spring	470750	1003800	24	38	97	16.5	6.2	12	1.4	9.6	4.5	1	37	2	0.06	5.09	82
2	Girm. Well	466000	1003559	120	97	115	16.5	6.3	7.5	2.1	14	2.9	1.1	79	0.97	0.5	0.5	105
3	Sansuzi BH	465900	1002875	48	88	189	19	7.1	30	6.3	12	2.9	2.5	100	1.7	0.28	3.01	150
4	Tafo/Ropack	487800	1002200	64	206	502	16.7	8	30	4	3.2	19	2.9	123	6.5	0.024	0.9	169.5
5	Eyasu spring	466648	1001993	−	−	116	18.3	6.2	6.8	2.6	10.18	2.5	2.25	69	2.24	−	3.49	93.8
6	Ferensay BH	475000	1001300	62	114	275	−	7.8	50	3.1	12.8	7.3	1.5	139.1	11	<0.003	1.2	183
7	Gedera well	486196	1001300	115	79	530	19.1	7.4	65	2	29	9.5	4.7	325	3.6	<0.03	1.2	395
8	French Embassy	474300	1001005	−	−	310	−	7.9	26.6	5.5	27.8	6.9	11.4	149	6.2	−	2.1	248
9	KaraAlo well	484680	998578	229	206	250	21	6.8	13	2.2	28.5	6.5	2.1	150	3.1	0.5	0.3	203
10	Kara BH	484190	998500	120	130	265	22	7.2	55	2.2	33.6	6.3	1.1	125	2.9	1.09	1.33	247
11	B/College well	470227	996307	−	−	405	25	8.1	25	2.1	35	12.5	23.6	168	7.3	<0.005	40.5	362
12	T/ Mare. BH	471428	994760	296	190	714	22	7.2	41.9	2.9	65.6	29.8	65	231.8	13	<0.03	54.93	344
13	B/Med. BH	476691	994535	223	109	280	20	6.9	14.4	4.1	31.1	6.7	2.6	179	1.7	<0.01	3	290
14	T/ Dirigit BH	466050	993650	148	140	307	−	8.1	13.5	3.5	36	12	5	155	1.82	0.004	3.23	220
15	Repi/Roll BH	463850	993100	120	122	237	21	7.7	60	4.5	27.2	6.8	0.8	129.3	0.6	<0.003	3.81	232
16	Makanisa BH	470450	990125	140	180	365	22	7.5	45	7.3	41.6	8.8	3	200	0	<0.003	16.8	310
17	Lafto BH	471400	988250	240	230	527	19.5	7.43	22	4.9	69.6	16.8	3	219	0.2	0.025	11.075	330
18	Kality BH	475000	985800	258	220	566	−	7.45	40	6.3	65.6	13.4	2.5	230	27	0.03	5.5	395
19	Kality FF BH1	475050	984350	136	250	450		8	56	12.5	60	5.8	7.1	268.4	43	1.5	7.6	343
20	Fanta Spring	479600	981100	148	172	346	20.5	8.5	64	4	46.4	7.81	1.5	290	0.1	0.22	5.7	410
21	B-15	473200	979800	−	−	−	−	7.5	69	5.3	54.5	22.4	14.2	295	24.7	−	18.9	432
22	EP - 8	478998	977937	221	250	567	20	7.93	65	4	44	27	7	305	1	0.14	19	457
23	EP - 4	479942	977322	230	254	470	23	7.4	53.1	4.3	44	29.3	1.5	309.9	7	<0.003	15.51	435
24	BH-20	477945	976985	169	220	398	23	7.1	47.5	4.6	43.3	24	14.2	244	0.5	0.03	5	363
25	BH - 06	479696	976936	228	240	484	22	7.2	55.2	5.9	49.6	22.9	2	270	6	<0.003	17.8	438
26	Piez - 3	465402	976807	298	322	690	−	7.3	36.3	14.2	62	24.5	5	276	0.8	2.28	31.45	445
27	BH - 07	479405	976735	244	238	456	20	8.3	26	5	69.6	15.4	8	290.4	2.2	0.012	21	429
28	BH-17	478199	976361	220	254	504	−	8.2	48	4.4	68	23	7.7	266	9	−	12.3	417
29	BH - 22	477651	975923	220	236	548	20	7.8	60.03	3.9	50	23.2	12	287.9	0.9	−	15.95	450

Table 4.1 Physicochemical parameters of samples

Data Source: AAWSA (2003 and 2004)

Calcium value is also higher in most wells and the value ranges from 3.2mg/l (Tafo/Ropack well) to 69 mg/l (BH-7). The most probable source of Ca in samples in the area is weathering of rock forming minerals of volcanic rocks like plagioclase feldspar. In general, it was observed that the amount of Ca increases towards South. K concentrations for most waters are about 1.5 – 14 mg/l.

Specific conductance, which is a measure of the ability of a water to conduct an electric current, and total dissolved solids (TDS) are very much interrelated and they indicate the state of water salinity . Based on TDS amount, water is classified as fresh (0-10^3ppm), brackish (10^3-10^4ppm), salty (10^4 -10^5ppm) and brine (10^5ppm), Davis (1966). Referencing total dissolved solids, almost all the water samples are dilute with TDS < 500mg/l. The TDS value is small for wells in the northern part of the catchment (82mg/l for Gojjem ber spring) and the amount increases to wells towards south as the time of contact of groundwater with rocks increases and the interaction with different earth materials increases so that ions might be released into the water. Specific conductance is directly proportional to total dissolved solids. Total dissolved solids (mg/l) may be obtained by multiplying the conductance value by a factor between 0.55 and 0.75. In actual cases this factor must be determined for each water body, but remains approximately constant provided the ionic proportions of the water body remain the same. This factor is close to 0.67 for water in which sodium and chloride dominate, and higher for water containing high concentration of sulphate (Chapman, 1996). This can be used to countercheck the TDS value obtained by sample analysis. Most samples (like Gojjem ber spring, Sansuzi well, Eyasu spring) that have very low conductivity of < 250µS/cm are close the mountains area and they signify recharge zones, and the EC amount increases to the south that may attain values greater than 650 µS/cm as in some wells near discharge areas. The PH of samples ranges from 6.2 to 8.5, the lowest being that of dilute springs close to elevated recharge area (Intoto). The same trend holds true for water temperature variations, which is from 16.5^{o}c (in most northern samples) to 23^{o}c in samples to south. Total alkalinity as CaCO3 for most wells located to the northern part of the study area is commonly less than 200mg/l and the value increases to south, which indicates that these samples are at higher saturation state with respect to calcite than samples to the north.

Chloride shows little variation in wells considered, in most it is less than 10mg/l and higher values signify polluted wells (like T/ maremia well, Building college well) .Chloride can enter groundwater system from atmosphere through rain water or from weathering of igneous rock minerals like feldspathoid and sodolite or can be due to anthropogenic effects. Similarly, for polluted wells the nitrate amount is higher (for T/maremia well it is about 50.93mg/l and for Building College well it is about 40.5mg/l) compared to most wells with values less than 20mg/l. The source of such high nitrate is attributed to anthropogenic effect, mostly effluent from domestic sources like latrines or septic tanks. In general, nitrate concentrations greater than 10mg/l indicate human influences. Bicarbonate is the most dominant anion in almost all the samples and it contributes more than 50% of total dissolved solids amount.

Sulphate can join groundwater system from weathering of sulphate containing minerals, rain or decay of micro organisms. Its concentration in most samples considered is lower than an average value of 6.2mg/l with exceptional higher values in few boreholes that can be attributed to human influences.

Total Fe was considered as minor constituents in almost all the samples. Weathering of iron bearing rocks releases Fe^{3+}, which is less mobile in natural waters, but as it is reduced (based on PH) to more mobile form, Fe^{2+} the concentration in water increases. In this case, the total iron concentration is very low because the relatively higher PH of water doesn’t allow reduction to a more soluble form. Reduction is enhanced at PH lower than 5.

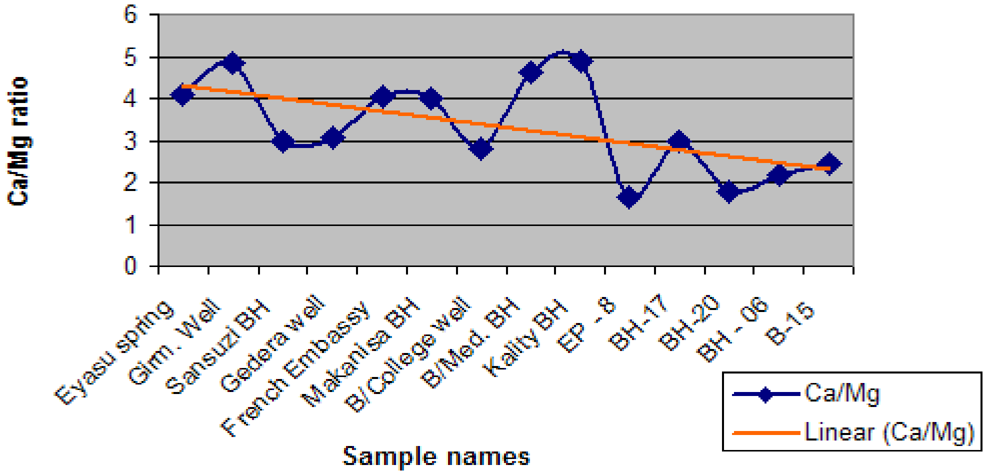
4.3 Water Chemistry and Groundwater Flow Direction

The main objective of considering groundwater chemistry in this study was to support the groundwater flow direction determined from water level data (section 5.8) using groundwater chemistry. Concentrations of ions in water that determine the water types depend on the mineral composition of the porous media and the rate/time of interaction of water with the media. In places where inert tracer concentrations vary spatially along groundwater flow path; the path followed by the tracer through the aquifer system delineates flow direction. One of such tracers used most often is chloride because of its very conservative and inert nature. In this study, chloride concentration shows small variation in unpolluted wells, with little increase to south, which can be due to additional chloride input along flow direction.

In addition, different ions ratios of representative water samples were employed to infer groundwater flow directions. The major indicators used were Ca/Mg ratio, Na/∑cations ratio, HCO_3 /∑anions, Ca+Mg / Na+K and Na/HCO_3 ratios.

Table 4.2 Ions ratios in representative samples used for flow direction inference

Well name	Ca/Mg	Na/ HCO3	Na / ∑cations	Ca+Mg/ Na+K	HCO3 /∑anions
Eyasu spring	4.07	0.1	0.31	1.35	0.89
Girm. Well	4.83	0.09	0.28	1.76	0.97
Sansuzi BH	3	0.3	0.59	0.41	0.93
Gedera well	3.05	0.2	0.62	0.57	0.97
French Embassy	4.03	0.18	0.39	1.08	0.88
Mekanisa BH	4	0.23	0.44	0.96	0.91
B/College well	2.8	0.15	0.34	1.75	0.7
B/Med. BH	4.64	0.08	0.26	2.04	0.96
Kality BH	4.88	0.17	0.32	1.71	0.87
EP - 8	1.63	0.21	0.46	1.03	0.92
BH-17	2.96	0.17	0.33	1.28	0.9
BH-20	1.8	0.19	0.4	1.29	0.93
BH - 06	2.17	0.2	0.41	1.19	0.91
B-15	2.43	0.23	0.46	1.03	0.84



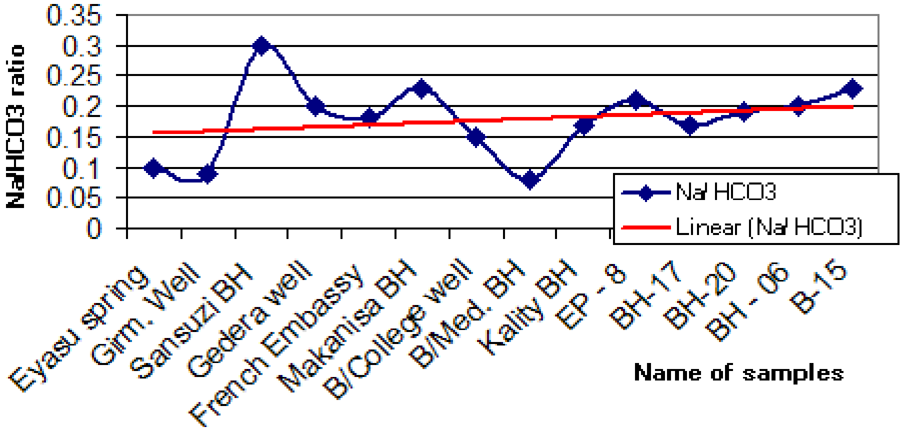


Figure 4.1 Ratio of Ca/Mg (upper) and Na/HCO_3 (lower) plotted against samples. The samples arrangement from left to right shows samples from north to south, respectively.

The above plots and table show that groundwater samples from northern part of the catchment have different chemical compositions compared to samples in the central and southern parts. Based on this, the general groundwater flow direction was inferred.

Groundwater samples from northern part (most left samples on the above plots) of the catchment have higher Ca / Mg ratio, lower Na / HCO_3 ratio, and higher Ca + Mg / Na + K ratio and lower Na / ∑cations ratio. In addition, as given in table 4.1, these samples have lower TDS / EC, PH and temperature values. On the other hand, samples from southern part of the catchment have lower Ca / Mg ratio, higher Na / HCO_3 ratio, lower Ca+Mg / Na+K ratio, higher Na / ∑cations ratio and higher TDS/EC, PH and temperature values. An increase in chemical parameters or ions ratios to the south indicated increased groundwater-rock interaction along flow path and longer residence time of water in aquifers. And a decrease of Ca / Mg and Ca+Mg / Na+K ratios to the south is due to removal of calcium with bicarbonates along flow paths. These variations in ions ratios and parameters following a general trend were used to define recharge areas and infer flow directions. Accordingly, the northern part of the catchment was defined as a recharge zone and groundwater flows from this area to the south, based on which the general groundwater flow pattern in the catchment was inferred to be from north to south. This trend is in a close agreement with the general groundwater flow direction defined from water level data. In addition, plots of TDS vs altitude and TDS vs well depth were used as indicators to infer the general groundwater flow direction. The samples were systematically arranged from left (South) to right (north).

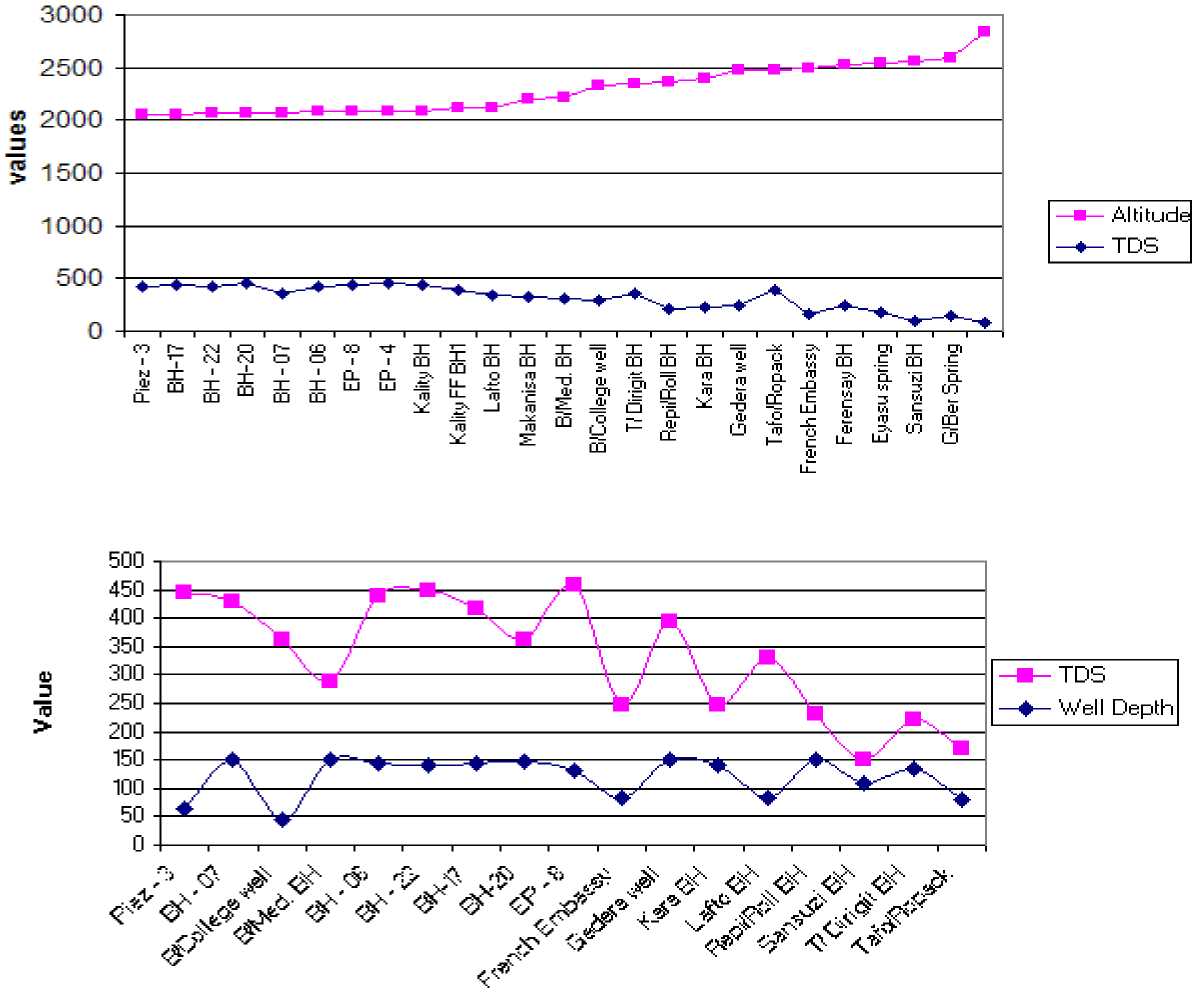


Figure 4.2 Plots of TDS vs altitude and TDS vs well depth against samples

N.B TDS is expressed in mg/l, and altitude and well depths are expressed in meters.

TDS vs altitude plot indicated an inverse relationship. Samples from northern part of the catchment are located at higher altitude and have lower TDS, and those at lower elevations have higher TDS values. As groundwater table is a subdued replica of surface topography, samples to the north were expected to have shallow water table compared to the south ones. As groundwater flows from an area of shallow water table to an area of deeper water table, this was used to infer that groundwater flows from north to south in the catchment following the surface morphology.

The plot of TDS vs well depth showed that as well depth increased, the TDS value also increased in the catchment. This is very rough conclusion because most shallow wells were highly polluted and have higher TDS values. In general, well depth increases from north to south in the catchment so does the TDS. This relation may be used in combination with other data to infer flow direction.

4.3 Isotope Hydrology

Environmental isotopes are naturally occurring isotopes of an element found in abundance in an environment. Stable isotopes can be used to know whether groundwater recharge is taking place at present time, in addition to their routine use in water resource assessment programmers. They may also show whether a water is modern or the climatic condition under which recharge took place. The use of isotopes in groundwater studies over chemistry is that in isotopes the water molecule itself is considered rather that the solutes in the water, which are from external sources. Sample points location is shown in figure 4.3.

Table 4.3 Isotope samples

No.	Well Name	**X**	**Y**	δ18 O(‰)	δ D(‰)	Tri .act (TU)	sigma	C-14(mod)	C-13(permil)
27	Akaki S A well	480252	976967	-0.74	-5.2	7.35	0.38	−	−
25	Akaki, EP4	479942	977322	-1.39	-2.6	0.81	0.2	78.1	-9.1
22	Akaki, EP5	478707	979650	-1.75	-0.8	−	−	85.3	-7.6
23	Akaki, EP6	479623	977680	-1.404	-3.1	0.85	0.17	89.2	7.68
24	Akaki, EP7	479459	977350	-1.99	-5.3	−	−	−	−
1	Akako Spring 2	478600	1006350	-3.3	-8.01	1.49	0.67	−	−
2	Asco G. spring	467212	1004259	-2.8	-6	0.9	0.18	67.5	-4.98
35	BH13	478695	976491	-0.71	-2.28	1.3	0.19	−	−
32	BH20	477945	976985	-5.04	-27.2	0	0.16	56.7	-7.53
34	BH-5B	476575	975607	-1.32	-1.17	0.2	0.16	−	−
16	Bole Med. Well	476691	994535	-2.41	-5.3	−	−	−	−
14	Building coll. Well	470227	996307	-3.13	-10.8	−	−	−	−
37	Cement factory-1	473450	991875	−	−	−	−	7.1	-9.34
7	Eyasu Spring	466648	1001993	-2.34	-6.2	0.39	0.17	−	−
21	Fanta Spring	478849	981223	-1.69	-1	2	0.5	−	−

8	Ferensay well	475185	1001446	-3.77	-14.5	–	–	7.1	-9.34
4	G/ber Spring	470578	1003754	-3.05	-6.7	0.85	0.17	99.7	-19.05
9	Gedera well	486219	1001227	-2.99	-7.7	1.3	0.5	–	–
5	Girm Well	466022	1003592	-2.89	-8.7	4.9	0.50	–	–
40	JICA	474500	987500	–	–	–	–	80.6	-7.82
12	Kara Alo well	484750	998607	-3.24	-12.9	–	–	6.5	-4.6
18	Kara roll well	464923	992809	-3.1	-10.3	–	–	–	–
11	Kotebe GW	484183	999230	-3.6	-15.5	0.3	0.16	–	–
3	Kuskuam	473998	1004000	-3.57	-10.28	1.1	0.14	80.5	-9.2
19	Lafto H/m well	471985	987830	-1.93	-3.8	0.28	0.16	–	–
29	Megenagna spring	478350	996700	-3.2	-4.36	5.7	0.34	6.5	-4.6
28	Merino well	479283	974400	-1.32	-0.5	0.4	0.5	–	–
36	P-1	478200	976850	-1.47	-1.6	0.33	0.8	90.2	-7.6
33	P-2	469050	970300	-2.27	-7.21	2.47	0.8	–	–
38	Kality airforce-1	476400	984800	–	–	–	–	88.3	-7.76
10	Paulos well	470123	1000121	-2.44	-5.2	–	–	–	–
6	Sansuzi Well	465794	1002766	-3.92	-15.6	0.2	0.8	–	–
20	Kality well	475532	984775	-1.59	-1.9	2.32	0.21	80.8	-7.82
13	Shola Diary well	479562	997182	-2.81	-7.4	–	–	–	–
30	SP-18	478850	1009500	-3.2	-4.08	3.92	0.28	–	–
31	SP-19	477320	983180	-3.2	-2.34	0	0.15	–	–
15	T/maremia well	471428	994760	-2.65	-7.1	0	0.8	10.4	-8.5
17	Tesfa D. well	466425	992809	-2.79	-7.4	0	0.5	–	–
39	zambian embassy	474600	995550	–	–	–	–	6.5	-4.6

Data Source: AAWSA(2003)

‘ -- ‘ data not available

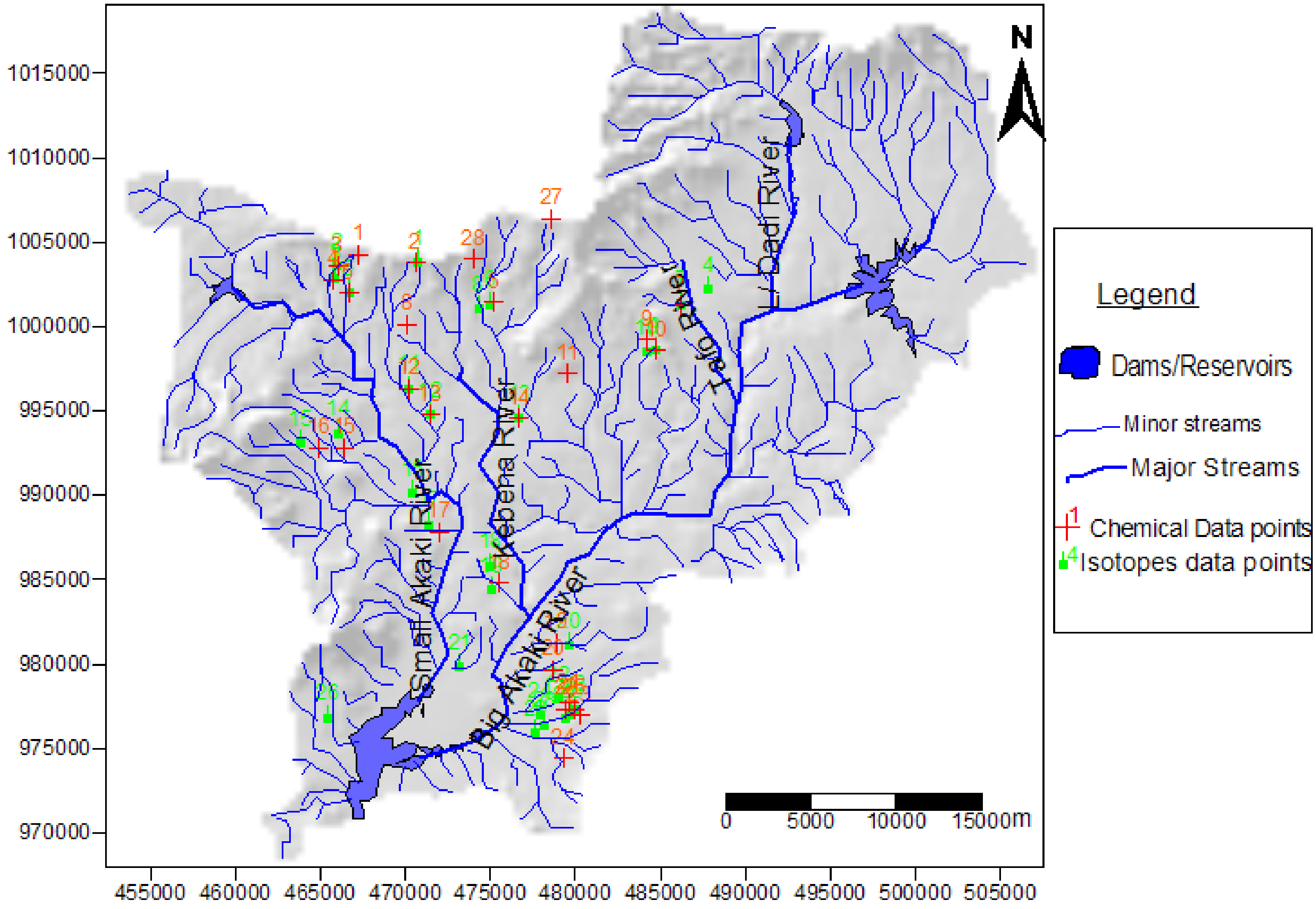


Figure 4.3 Locations of Water Samples Points

As applied in this study for flow conceptualization, oxygen and hydrogen isotopes data have been obtained from previously analyzed samples of 36 wells and springs(source: AAWSA). The data shows Oxygen ($^{18}O/^{16}O$) and Hydrogen ($^{2}H/^{1}H$) isotope ratios in groundwater samples considered as calculated with reference to VSMOW (Vienna Standard Mean Ocean Water).

To trace groundwater origin and flow direction using isotopes ($\delta^{18}O$ and $\delta^{2}H$), it is important to compare the amount in groundwater with that of precipitation. The local meteoric water line equation of Addis Ababa as calculated by Ayinalem Ali (1999) is $\delta^{2}H=7.5\delta^{18}O +12.4$, which is not dissimilar to that defined by Dansgaard (1964) for the northern continental hemisphere meteoric water line given by $\delta^{2}H=(8.1\pm1)\ \delta^{18}O + (11\pm1)$.

The amount of $\delta^{2}H$ and $\delta^{18}O$ in precipitation depends on various factors like altitude, temperature, latitude, continentality effect, rainfall amount and seasonal effects. According to Clark et. al., (1997), for every 100m rise in altitude there is depletion in ^{18}O isotopic amount of about -0.15 to -0.5‰ in precipitation; with respective depletion of about -1 to -4‰ ^{2}H in precipitation. The stable isotope values for precipitation in the area range from -35.9‰ in August to 52.3‰ $\delta^{2}H$ in March and the corresponding $\delta^{18}O$ value -6.6‰ to 5.83‰ (Ayinalem Ali, 1999).

The stable isotope value for water samples considered in this study ranges from -3.92‰ (in Sansuzi well) to -0.71‰ $\delta^{18}O$ (in BH13 well), and the value for $\delta^{2}H$ range is -15.6‰ (in Sansuzi well) to -0.16‰ (in Merino well). Comparison of the isotopic values in precipitation and groundwater samples considered shows that the groundwater is depleted compared to average precipitation composition. This may lead to infer that effective groundwater recharge in this area takes place from intensive (August/July) precipitation, or else the precipitation record might have been influenced by evaporation. Rainy season in this area starts in June, after a long dry period, that undergoes evaporation, enriching the falling precipitation (positive values of $\delta^{2}H$ and $\delta^{18}O$). In July and August, as temperature is lower and rainfall intensity is higher, precipitation in these months has negative isotopic values. Overall, the June precipitation is largely evaporated and a small amount will enter the upper part of the soil. Following this, comes the intensive July/August precipitation that infiltrates, replenishes the soil capacity and the excess water percolates into aquifers.

In general, it is possible to observe that the isotopic signature in precipitation is relatively enriched compared to groundwater samples in the catchment and this indicates that the isotopic composition of precipitation has been influenced and groundwater recharge is taking place during intensive precipitation. The highest precipitation occurs to the northern part of the catchment.

4.3 Summary

The chemical composition of water is controlled by many factors that include constituents of precipitation, mineralogy of watershed and aquifers, climate and topography, etc. The combined effects of these factors create diverse water types that change temporally and spatially.

From chemical and isotopic data that has been examined to observe relations and spatial patterns of water, it was possible to determine direction of groundwater flow. With the exception of some polluted wells, changes in chemical compositions of groundwater samples in the catchment from north to south traces flow directions. For natural waters, groundwater flows from recharge areas; generally characterized by low TDS/EC, higher Ca/Mg ratio, lower Na/HCO_3 ratio and higher Ca+Mg/Na+K ratios; to discharge areas characterized by high TDS/EC, high Na/HCO_3 and lower Ca/Mg ratios.

This generalization was observed in this catchment as these ions ratios change from northern side to the southern part following a general trend described above. The changes are in line with the fact that the concentrations of ions increase or decrease due to interaction of water with rocks (longer residence time) or precipitation of ions along flow direction. From this, groundwater flow direction can be inferred to be from North to South in the catchment using the ratios used.

As a small fraction of precipitation reaches the water table, the isotopic signal in most cases can be modified significantly. Though there is some inconsistency in isotopic composition of precipitation and groundwater observed in the area, it was observed that the source of groundwater is precipitation that takes place during intensive rainfall. Average isotopic composition of precipitation in the area is relatively enriched because it represents the average value in precipitation that falls in all rainy month; some months have enriched and others have depleted isotopic signatures. But groundwater recharge takes place from intensive precipitation that has a depleted isotopic signature. Isotopic values of samples considered from northern part of the catchment (located at higher altitude) were found to have depleted signatures compared to samples to the south (located at lower altitude). This shows that the degree of fractionation increases to south because of evaporation as temperature is elevated. Thus, as water flows from north to south along flow direction it becomes enriched in heavy isotopes of oxygen and hydrogen.

In general, groundwater flow directions determined from water level heads collected in the field (Section 4.8) are generally in accordance with primary flow directions indicated by geochemical and isotopes data. Overall the general flow direction determined was from north to south. In both cases deeper boreholes and thermal groundwater sources were not considered.

CHAPTER FIVE

Conceptual Model Development

5.1 General

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

Important steps in constructing a conceptual model include:

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

To define hydrostratigraphic units it is good to rely on hydrogeologic information. Site specific information on stratigraphy and hydraulic conductivity data is required to synthesize hydrogeologic information that is used to identify different hydrostratigraphic units. But due to lack of such detailed information in the case of Akaki River Catchment groundwater numerical modeling, a single aquifer system of an unconfined type was considered.

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, subsurface outflow and geochemical information were employed for the purpose of this study. Water level measurements were used to estimate flow direction and to infer connections between aquifers and surface waters. Hydrogeochemical data were employed to support flow directions determined from water level data.

Therefore, all the data required for the modeling work were assembled into the conceptual model to represent the field situation in a simplified form as the complete reconstruction of the system behavior is impossible. The different data and / or parameters that were input in to the conceptual model include, the geology /hydrogeology of the area as used to define hydrostratigrapic unit, groundwater flow divides and system boundaries, top and bottom elevations of the aquifer layer, hydraulic conductivity of the aquifer, direct recharge from precipitation, leakage of groundwater to surface water, groundwater pumping, natural groundwater discharge (in the form of springs) and subsurface outflow.

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.

5.2 Hydrogeology of Akaki River Catchment

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

Hydrogeologically, the study area is a complex catchment. Different aquifers have different hydrogeological characteristics, that is, lithologically different rocks with similar hydro geological behavior can be grouped into one class or lithologically similar rocks of different hydrogeological characteristics can be considered different in relation to their water yielding capacity. Previous works show that the Akaki 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 (Tamiru et al, 2005). The aquifers in the catchment were classified in to three broad categories based on their productivity (Hydrogeological map of Addis Ababa, Akaki and Dukem areas, 2004).

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. The transmissivities of these aquifers vary between mean minimum value of 616 m^2/day and mean maximum of about 37000 m^2/day. Scoria deposits, among the major aquifers are the most important unit from hydrological point of view. The interconnection of the voids has resulted in high permeability for these deposits. In the Akaki area the highly productive wells were drilled in these deposits.

Minor aquifers are those fractured and inter granular aquifers of old volcanic rocks covering the city of Addis Ababa & the bases of Intoto Mountain and Lega Dadi plains. Wells drilled in these aquifers often yielded between 2 l/sec and 5 l/sec. The transmissivity of these aquifers varies between mean minimum value of $3m^2$/day and mean maximum of about $1700m^2$/day.

Poor aquifers are fine - grained alluvial deposits intercalated with ash materials and well compacted lacustrine deposits, but this generalization is exceptional to alluvial deposits of sand and gravel types that cover smaller area in the catchment as wells drilled in them have good yields. The mountain ranges of Intoto, Wechecha and Furi are non aquifers because are generally not considered as groundwater containing materials in exploitable quantities.

Existing works show that confined, semi-confined, unconfined and perched aquifers are found in the catchment, but most of the aquifers are hydraulically interconnected which is justified by continuous piezometric surface that follows approximately the topographic surface. The groundwater level in the catchment ranges from artesian /flowing/ to more than 100m below ground level, for example, in some parts of city center, east Kality, Hana Mariam etc, the aquifers are confined with piezometric surface at or near(less than 1m) the ground surface.

Akaki River catchment is the catchment in which large number of wells were drilled by different institutions / individuals for various purposes at different times. Despite of this fact, most of the wells do not have a well data that is to its standard and those that have a well data are concentrated to some zone of the catchment (like Akaki well field). This data scarcity has resulted in problem in mapping one of the model input parameter, hydraulic conductivity. In addition, there is no access to take groundwater level measurements as the wells do not have observation pipes in most cases.

As the aquifer was considered as a homogeneous, isotropic and single layer, its properties were not expected to vary vertically with in the considered thickness, but there is a lateral variation from north to south or east to west. The thickness of the aquifer considered is roughly approximated to be 150-250m by using screen lengths and this value might be modified during model calibration.

5.3 Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of a fluid to move through interconnected void spaces in sediments or rocks. It is a function of both the fluid and the medium. The higher the hydraulic conductivity of a rock/sediment, the higher the water yielding capacity of the rock is. The hydraulic conductivity of fractured rocks depends largely on the density of the fractures and width of their apertures. The Akaki 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. Most pumping test and other well data found in the area were not to the standard field hydrogeological test of a carefully monitored pumping test with observation wells and in most of the cases recovery data measurement have been stopped after a short period before full recovery of the well (Ayinalem Ali, 1999). Numerous attempts have been made in the past to estimate the transmissivity/ hydraulic conductivity of the whole or part of the catchment by different authorities/individuals, some of which are: BCEOM – Seureca (2000) calculated the estimates of transmissivities at selected sites in the catchment and the result was in the range of 4 – 105,408m^2/day. According to Ayinalem Ali (1999), the hydraulic conductivity of the Akaki well field aquifers lies in the range of 7.4 to 674.8m/day. Because the point hydraulic conductivity obtained from well data does not cover the whole catchment and in other areas there is no standard well data, it posed difficulty in mapping the hydraulic conductivity of the area. Therefore, an attempt has been made to estimate the hydraulic conductivity, in this study, based on the geology of the area and the degree of fracturing/ weathering of the rocks, according to the values given on standard book, Freeze & Cherry (1979) and referencing previous work of Dereje Nugussa (2003). As it can clearly be seen in figure shown below, the catchment was subdivided in to different zones of different hydraulic conductivity values. One can observe a general increasing trend of hydraulic conductivity of the aquifer from the north (Intoto area) to the Akaki area (especially up to the Akaki well field). The value is low in the mountain areas, especially where acidic volcanic rocks are exposed and also less fractured & less weathered basalts are found. The northern tip of Intoto Mountain, where porphyritic to aphanitic basalts outcrop, the hydraulic conductivity is relatively higher. In the central part of the catchment (Addis Ababa city) the hydraulic conductivity is higher compared to the mountains area. The values in the city and surrounding areas to the west and east are within the range of 0.3m/day to 7.034667m/day. Highest values of hydraulic conductivity in the catchment were attributed to the Akaki well field area, which was found to have a value of about 103.68 to 216m/day. The aquifer in this area is made up of scoria and vesicular basalts that have higher productivity. The extent of aquifers in the well field is very limited as it is surrounded on all sides by rocks of low hydraulic conductivities. The approximated hydraulic conductivity values are adjusted during the model calibration step.

Table 5.1 Summary of transmissivity values (AAWSA, 2000)

Model areas	Transmissivity (m2/sec)		Transmissivity (m2/day)	
	min	*max*	*min*	*max*
North	3.01E-06	1.26E-02	0.26	1092
West	1.15 E-04	1.1 E-03	9.9	95
East	4.6 E-02	9.2E-05	4	8
Central A.A.	3.01E-06	0.067	0.26	5760
Akaki & Kality	3.19E-05	7.06E-02	2.76	6099
Akaki well field	2.12 E-02	1.22	1834	105,408
South (Dukem)	1.2 E-04	9.5 E-03	10	820

The storage coefficient at the well field ranges between 2% and 0.6% with mean value of about 1%. Elsewhere it ranges between 0.01% and 1% (AAWSA, 2000).

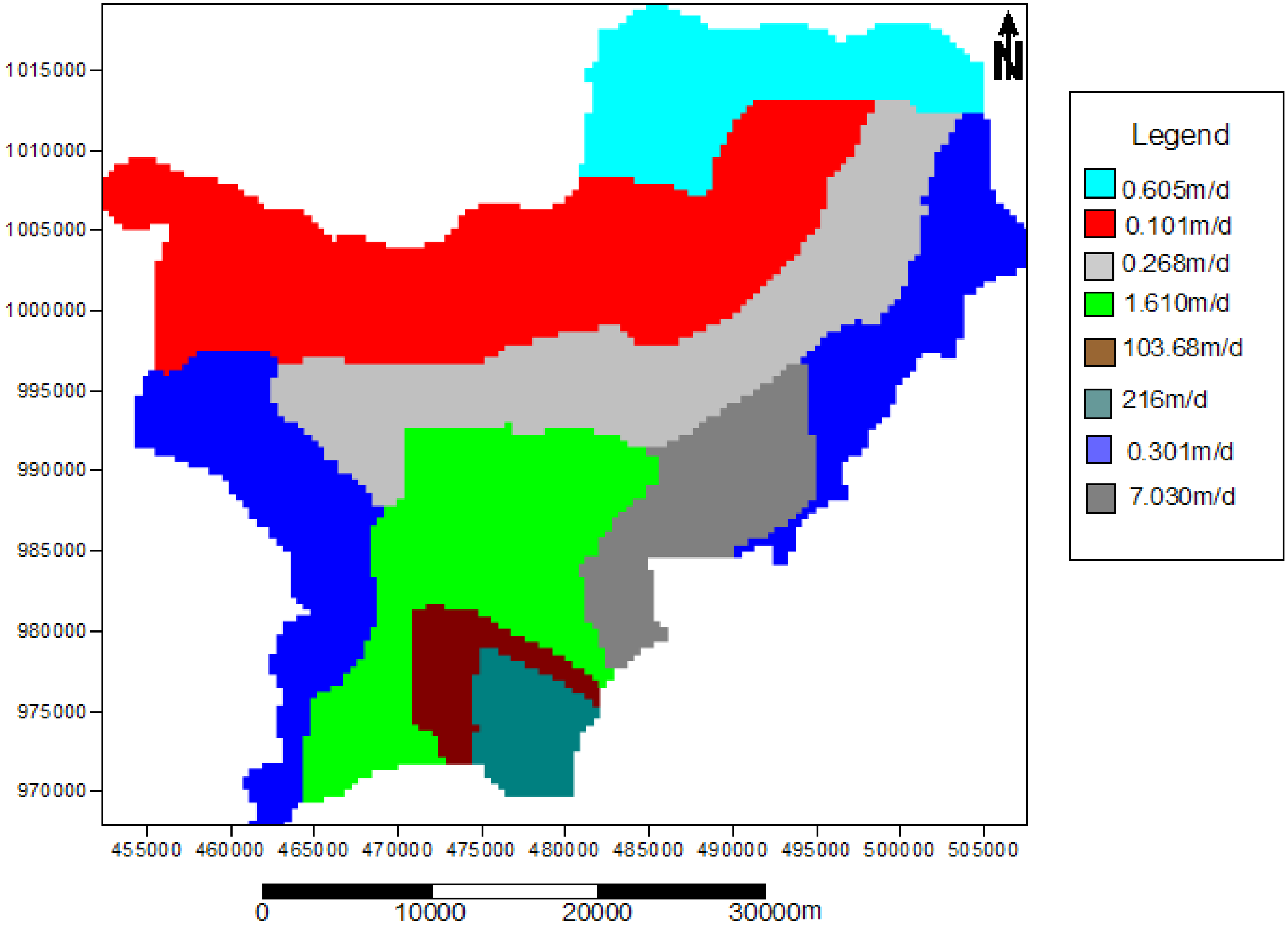


Figure 5.1 Hydraulic Conductivity zonation of the study area

5.4 System Boundary Conceptualization

The initial step in any groundwater flow modeling is the definition of the boundary of the study area. To have a good conceptualization of a hydrologic system, it is essential to identify and assign system boundaries appropriately.

System boundaries are classified in to two: physical boundaries and hydraulic boundaries (Anderson and Woessner, 1992). Physical boundaries of groundwater flow systems are formed by the physical presence of an impermeable body of rock or a large body of surface water. Hydraulic boundaries are result of hydrologic conditions, are invisible and they may include groundwater divides and streamlines.

In groundwater flow modeling, boundary conditions influence the extent of the flow domain to be analyzed or simulated. The extent of the flow domain is initially determined by the extent of the area of concern and it is preferable if it is bounded by physically observable features. Moreover, it should be noted that correct conceptualization of boundary is important to select an appropriate mathematical representation in the model so that the effect of the boundary on flow can be correctly understood.

In the Akaki River Catchment, the system boundary was carefully assigned based on field visits made and existing works. The geographic boundaries of the Akaki River Catchment groundwater flow model approximately corresponds closely with natural hydrologic boundaries across which groundwater flow was assumed to be negligible. This is true for the northern, eastern, northeastern, western and northwestern boundaries of the system. In the northern and northeastern boundaries of the catchment the model coincides with the Intoto Mountain ranges, in the southwestern it coincides with the Wechecha range and Furi Mountain, in the northeastern with Bereh Mountain and in the eastern side the study area is bounded with Yerer Mountain. On these sides, major topographic divides were assumed to coincide with groundwater divides. It should be remembered that groundwater divide is not really a boundary in nature, but as 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. In the case of Akaki 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.

The southern tip of the study area was represented as head dependent boundary because there is groundwater outflow that is partly outcropped as springs in Aba Samuel gorge. Flux is approximated to occur in this side of the catchment based on the head in the aquifer and the external source head. In this study the head in the external source is lower than the head in the aquifer, so groundwater is expected to be discharged from the aquifer system. The quantitative value and how it was simulated is given in chapter 6.

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, except on the south and southeastern part, that can be simulated reasonably well and that will minimize the effect of any artificial approximations. Simulation of boundary conditions is given in chapter six.

5.5 Groundwater Inflows and Outflows

5.5.1 Groundwater Recharge

In nature different types of recharges occur together, which lead to different recharge estimation techniques and this makes the quantification process difficult. In this study, direct recharge from precipitation was considered and it occurs in this area as there is a surplus of rainfall over evapotranspiration. The groundwater level of an area is directly influenced by the amount of water that enters the aquifer system, that is, areas with higher recharge amount have shallow groundwater level and in general, groundwater flows from recharge areas to discharge areas.

The spatial distribution of recharge is affected by a number of natural and anthropogenic factors, some of which are climatic factors, geology, and vegetation cover, topography and land use/cover etc. Based on all these factors, the global net recharge estimated for the whole country ranges from 50-150mm (Tesfaye Cherinet, 1988). Different scholars and institutions have made an attempt to estimate the recharge amount in the Akaki River catchment and in general the values estimated lie with in this global range.

In this study, recharge to groundwater was spatially grouped into various zones with different recharge values, according to the works of Dereje Nugussa (2003) and Tenalem Ayenew (an ongoing research). It is true that areal recharge may change significantly from one cell to another, but as little information is available on estimated recharge rates a constant value has been assumed over large portions of the study area. Groundwater recharge to aquifers in the catchment is derived from precipitation, mostly during intensive precipitation from June to September.

The recharge zonation map shown below in figure 5.2 was adopted from the works of Dereje Nugussa (2003) and an ongoing research of Tenalem Ayenew.

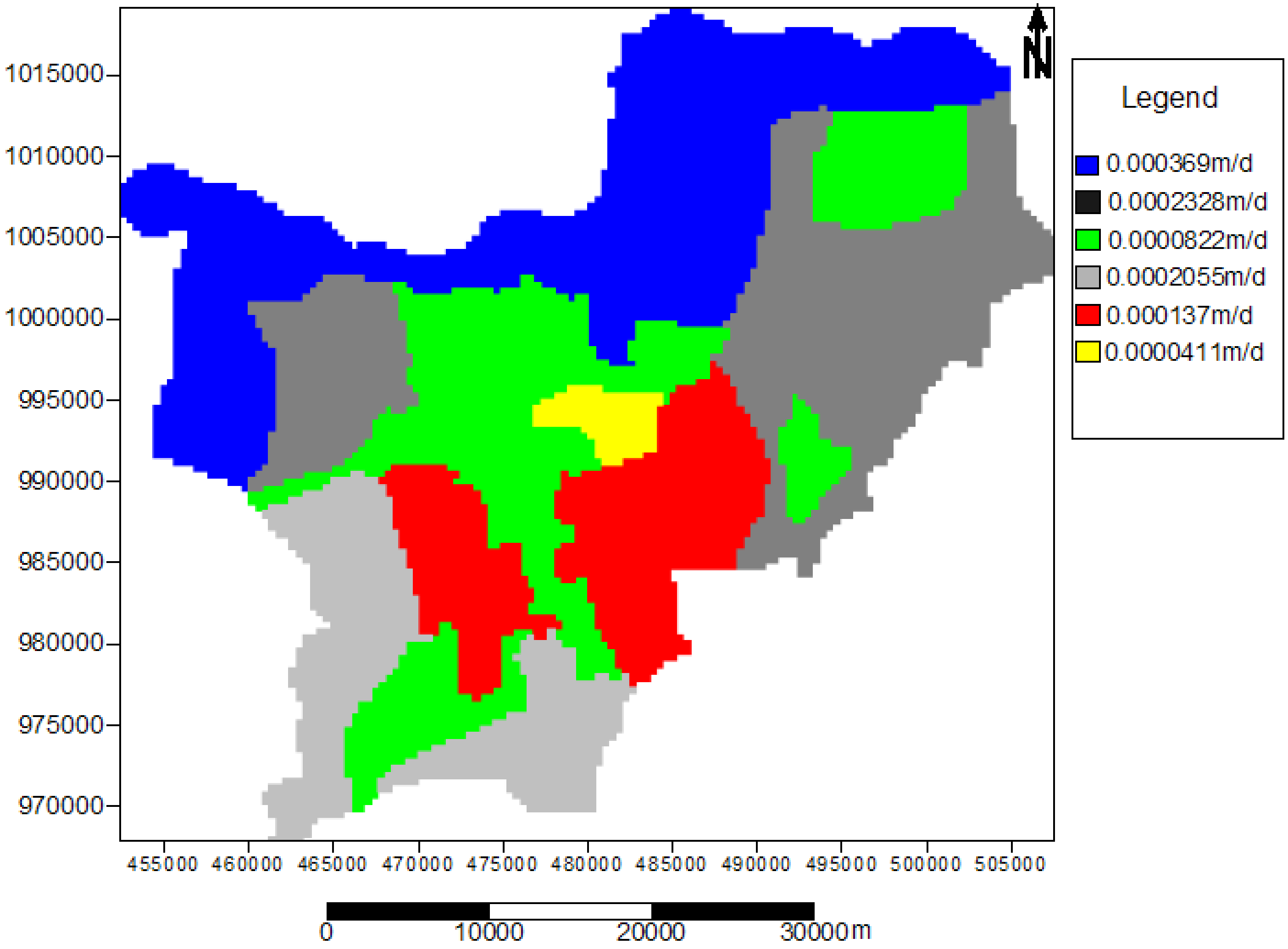


Figure 5.2 Recharge zonation map of the study area

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 and Northwestern Intoto, Wechecha Range and Bereh Mountain Ranges are assumed to have maximum recharge values relative to other zones. These areas are covered with thin soils or only with fractured and weathered acidic volcanic rocks that are covered with forest & shrubs. A recharge amount of 0.000369m/day has been assigned to this elevated zone.

- The next high recharge receiving zones are areas covered with relatively thin clay at second higher elevation and with land use/cover of agriculture or open field. The value is approximated to be 0.0002328m/day.

- In zones at the southern and southwestern 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 0.0002055m/day.

- The fourth zone that is approximated to receive a relatively higher recharge, next to the third zone, is the peripheral parts of the city especially the southern and western. In this zone the degree of urbanization is relatively lower compared to the center of the city and open garden/agricultural fields are common, making the recharge potential better than at the city center. For this zone the recharge is roughly approximated to be 0.000137m/day.

- The zones that are expected to get lower recharge in the catchment are the highly urbanized (central) part of the city, as urbanization results in sealing of the ground by asphalt and interception of rainfall by building roofs, thus enhancing runoff and evaporation. All other factors being the same (like topography, geology) urbanized areas get lower recharge compared to suburbanized areas. Similarly, the areas covered with thick clays of black cotton type (around Yerer and lacustrine clays around Lake Aba Samuel have approximately similar recharge amounts to the urbanized central zone of the city. Actually, under such clay soil coverage there is some initial recharge the beginning of rainfall but this amount of recharge is very low to join deeper aquifers. For areas included under this zone the recharge amount is approximately calculated to be 0.00008219m/day.

- The highly urbanized Bole area is underlain by thick clay soil of black cotton type. These combined effects are expected to lower the recharge amount in that particular area. Even though the factor by which these effects reduce the recharge amount was not known, one can boldly assume the recharge amount to be reduced by half compared to the urbanized areas. So, this zone is assigned a recharge amount of 0.0000411m/day.

5.5.2 Groundwater Discharges

At present groundwater is removed from aquifers in the Akaki River Catchment by withdrawal through wells for human consumption or industrial activities, subsurface outflow, spring discharge and base flow to rivers. The evapotranspiration loss from aquifers was considered to be negligible. The following sub sections discuss each discharge type.

5.5.2.1 Well Withdrawal

As Akaki River catchment encompasses the capital city, where large population live and different institutions/factories are found in the area, there is enormous number of wells drilled for various uses. The wells were drilled either for the purpose of supplying water to community, households or institutions/industries. Therefore, the rate of abstraction varies from well to well, being highest in wells that supply water to community and lowest in wells owned at household levels.

Almost all wells that supply water to the community are owned and operated by AAWSA. The abstraction rate of these wells was obtained from AAWSA and most of them are found in the Akaki well field and some are found in different corners of the city. These wells are 24 in number and the abstraction rate from these wells is listed in table 5.2.

Most of the wells that are owned at household levels have a lower withdrawal rates and were not considered in the simulation.

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. In all cases deeper boreholes and thermal wells were omitted as their source was expected to be different from shallow unconfined aquifers considered in this study.

Table 5.2 Groundwater abstraction rate of some public wells (Data: AAWSA)

No	Well Name	Location		Abstraction (m^3/day)
		X	Y	
1	BH 08	479061	976370	3616
2	BH 09	479240	977104	7808
3	BH 12	478808	976867	5216
4	BH 14	478580	976051	1280
5	BH 16	478347	976752	6912
6	BH 17	478199	976361	6496
7	BH 18	478154	975966	192
8	BH 22	477651	975923	480
9	Sansuzi	465900	1002875	36
10	Asko	465507	1002285	216
11	Ayer Tena	466050	993650	162
12	Kotobe Kara	484190	998500	345.6
13	Lafto Hana Mariam	471400	988250	583.2
14	Repi/ Roll	463850	993100	288
15	Shegole	468100	1001625	102.6
16	Mekannisa	470450	990125	1440
17	Kality Well	475000	985800	576
18	Bole Lemi	482850	989900	432
19	Kuskuam	472900	1003550	115.2
20	Ferensay Legasion	475000	1001300	316.2
21	Keranio	469817	989866	115.2
22	EP 04	479942	977322	1200
23	EP 06	479526	977468	900
24	EP 07	479021	977596	900

5.5.2.2 Subsurface Outflow

As it has been clearly outlined under system boundary conceptualization, the southern tip of the catchment is the only boundary along which groundwater is expected to flow out of the aquifers in the area. Some of this outflow is manifested as springs in Aba Samuel gorge, which was approximated to have a discharge of about 30l/sec (AAWSA, 2000). In fact, along this side more out flow is expected and was approximated in the numerical model.

5.5.2.3 Springs Discharge

Springs are outcropped at a point where groundwater table intersects the ground surface. In such cases the elevation of the spring eye represents groundwater level. In the Akaki River catchment, there are springs outcropped in different parts of the area. The discharges of most of these springs are lower and were not directly considered in the model. But one of these springs, Fanta that is used as a supplement to boreholes for Akaki town water supply, has a discharge rate of around 25 l/sec (AAWSA, 2000) and was incorporated in numerical simulation. The other smaller springs simply flow and join nearby stream channel and it is believed that they were indirectly incorporated in to the model through river package.

5.5.2.4 Base Flow

One can use water level surfaces in rivers/streams to predict the mode of interaction of groundwater and surface water as the one with higher hydraulic head feeds the other with lower head provided that there is a material with higher conductance between the river bed and the aquifer. Previous works show that groundwater and surface water in the study area have interaction and the aquifer system feeds perennial rivers in most stream reaches in the catchment (AAWSA, 2000). In this study, base flow to rivers was approximated to be equal to the long term average dry period flow for Big Akaki River at Akaki Bridge (from years 1981-2003) and for Small Akaki River (from years 1997-2003). Based on this, base flow approximated to both rivers was about 155520m^3/day.

5.6 Summary of Groundwater Balance

A steady state water balance describes interactions of aquifer- surface water systems and it provides a conceptual framework for groundwater flow models. 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 Akaki River Catchment aquifer system, as described in this work, includes 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 and sub surface outflows.

Table 5.3 Estimated Average Groundwater Balance of the Study Area.

No	Water Balance Component	Inflow (m3/day)	Outflow (m3/day)
1	Precipitation Recharge	326843.5	
2	Well Withdrawal		68261
3	Base flow		287712
4	Springs		2160
5	Subsurface Outflows		2592
	Total	**326843.5**	**360725**

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 difference between inflow and outflow in this study may be due to under estimation of recharge or it can be attributed to exaggerated estimation of any component of the outflows.

5.7 Groundwater Level Contours and Flow Patterns

Groundwater contours represent points that stand at the same water level elevations. In this study groundwater contours were constructed using heads measured in 122 wells and the general trend of the contours is east-west. Water levels of deep wells were not considered in contouring and flow direction determination because their source was not expected to be the same shallow unconfined aquifer considered in the study.

As a rule of thumb, groundwater flows from a position of higher hydraulic head to one of lower hydraulic head. In a map view, the hydraulic head of groundwater is represented by contours of the potentiometric surface. The groundwater flow direction is perpendicular to contours and the amount of change in hydraulic head divided by a specified distance along the direction of groundwater flow is the hydraulic gradient. As it can be observed in figure 5.3, the general groundwater flow direction in the Akaki River Catchment is dominantly from north to south, with some northeast-southwest flows, which is the same direction as that of the surface water. But some local variations opposite to the general trend were observed.

In general, one can observe in this catchment the fact that groundwater flows from recharge areas to discharge areas following morphology. The hydraulic head difference between the maximum and the minimum water levels in wells used as head observation points is about 581metres. This shows a high hydraulic relief and the existence high hydraulic gradient between the points.

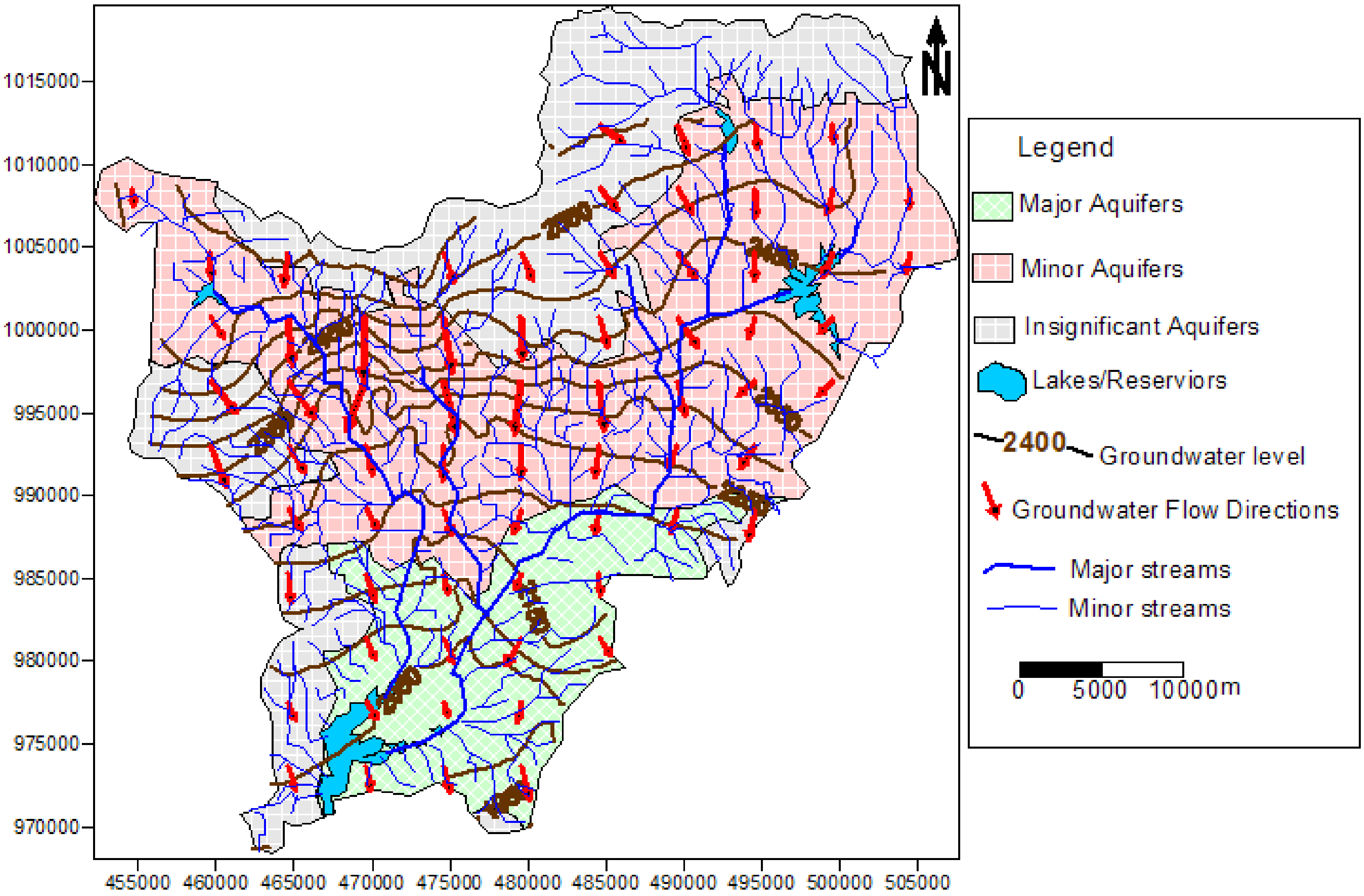


Figure 5.3 Groundwater Flow Patterns and Aquifer Productivity

CHAPTER SIX

NUMERICAL GROUNDWATER FLOW MODELING

6.1 General Concept and Modeling Approach

Numerical groundwater flow modeling helps to have a good understanding of the current or to predict the long term tendencies of a hydrogeological system and it allows an analysis of the movement of water through hydrogeologic 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 out put 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 standard hydrogeological data has been encountered in most parts of the catchment to have good estimates of these parameters but collection and assemblage of relevant hydrogeological data in the conceptual model has been made.

In recent years, numerical groundwater modeling has become a major part of projects dealing with groundwater exploitation, protection, remediation and it is the most useful tool to study the response of a hydrogeologic system to any 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 groundwater 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 groundwater flow models, the Akaki 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 was 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.

6.2. Governing Equation and Model Code

The movement of groundwater through porous media is described and solved, for a one layer unconfined aquifer system under a steady state flow (as used in this study), on the basis of the following partial differential equation, which is based on Darcy's law and the law of mass conservation (McDonald & Harbaugh, 1988). This equation assumes flow system view point that allows both vertical and horizontal components of flow throughout the system and there by allows treatment of flow in two dimensional profile (Anderson and Woessner, 1992).

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = \pm R \qquad \textbf{Equation (6.1)}$$

Where K_x and K_y are components of hydraulic conductivity in the x and y directions; h is hydraulic head and R is a general sink/source term that is defined to be intrinsically positive to represent recharge and negative for withdrawals of groundwater.

This equation describes the distribution of hydraulic head and flow throughout a continuous region. It is continuous in space and time, and generally cannot be solved analytically for practical applications involving complex system (Anderson and Woessner, 1992). Practically, the continuous system described in the above equation is replaced by a set of spatially and temporally discrete points using numerical methods, which form a set of simultaneous algebraic equations that describe the distribution of hydraulic head at each point and flow through the system in response to this head distribution. These simultaneous equations are set up in a matrix form and then solved.

A computer code or program solves a set of algebraic equations generated by approximating the partial differential equations that form the mathematical model. In this study, groundwater flow simulation was done by using the computer code, MODFLOW (McDonald and Harbaugh, 1988). MODFLOW is a versatile, modular, three dimensional, finite difference, groundwater flow modeling program used to construct numerical flow models of a specific area in all aquifer types under both transient and steady state conditions. As applied in this study, the program uses a block centered, finite difference method to simulate groundwater flow through porous media in a horizontal grid. From the many techniques available to solve set of simultaneous equations, in this study the Preconditioned Conjugate Gradient2 (PCG2) of MODFLOW with a convergence criteria of 0.0001m was employed.

A MODFLOW consists primarily of a set of input files that contain information on the physical properties of the modeled system such as the geometry, boundary conditions, internal properties (like distribution of hydraulic conductivity and storage coefficients) and sources/sinks such as groundwater recharge, streams and pumping wells (Anderson and Woessner, 1992). Once these files are created, the model program is run to solve a set of equations that describe the distribution of head at discrete points within the system and flow in response to that head distribution. This numerical method requires that the modeled domain be divided into discrete volumes, known as cells and the properties of material in each cell is assumed to be homogeneous.

6.3. Grid Design / Spatial Discretization

In a numerical model, the continuous problem domain is replaced by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells). The nodal grid forms the framework of the numerical model (Anderson and Woessner, 1992). A critical step in grid design is the selection of the size of the nodal spacing as the horizontal dimension depends on the expected curvature in the potentiometric surface and the change in head in the vertical direction influences the vertical nodal spacing. Other factors that influence the size of nodal spacing are the availability of data, variability of aquifer properties and the size of the area to be modeled.

The extent of the Akaki River Catchment in the north-south and east-west is 51,200m and 55,200m, respectively. The modeled catchment has an area of about 1462 km^2. The ground water flow system in this study was represented with an array of cells arranged in 128 rows and 138 columns in a single layer. The lateral dimension of the cells is 400m by 400m on each side. A regular grid has been adopted for the entire catchment and each cell has homogeneous property. The groundwater flow equation discussed above is formulated at the center of each model cell. Flow area and gradient used to determine flow through the cell are determined at the center of each cell and represent the average area and gradient through the cell. Because finite difference model grid must be rectangular, certain cells represent areas outside the modeled area (may have any shape). Such cells are considered inactive (Figure 6.1) and were identified by assigning a value of “0” to entries of I-BOUND array in boundary condition & groundwater flow equation is not solved for such cells. Cells that represent lakes/reservoirs with constant head were identified by assigning “-1” to entries of I-BOUND array in boundary condition and such cells show an inexhaustible supply of water. A single aquifer of one layer system was considered for the purpose of groundwater flow modeling in this study.

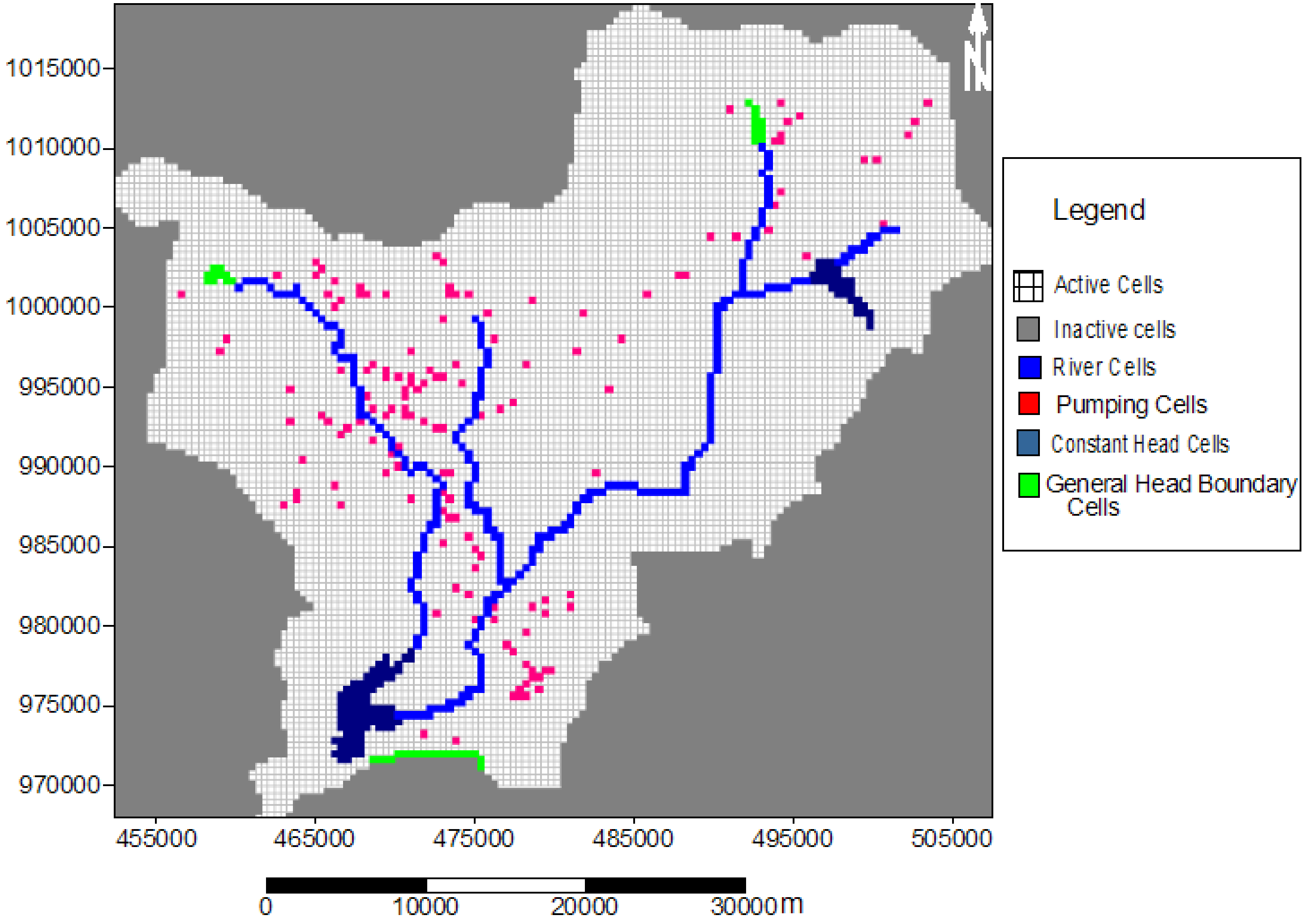


Figure 6.1 Model Grid Design

6.3.1 Top of layer

It is the top elevation of the aquifer layer under consideration. In this study, the aquifer was considered to be single layer and unconfined. Generally, the top layer elevation was considered to be the elevation of ground surface and in this case nodal values of ground surface elevation were interpolated from USGS (United States Geological Survey) digital elevation data. The interpolation was done at a resolution of 400m by 400m and then loaded into MODFLOW top elevation array. At points like lakes/reservoirs where elevation value misses in the USGS digital elevation data, the elevation of the points were patched based on the values of nearby points.

6.3.2 Bottom of layer

It is the bottom elevation of aquifer layer being modeled. In this study, the aquifer thickness lies within the range of 150-250m 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 of cells during simulations. Hence bottom elevation was obtained by subtracting a range of 150-250m from elevation top in most parts of the catchment. In fact, the thicknesses of the aquifer are 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. The relative thickness variation in most parts of the aquifer can be clearly observed in figure shown below.

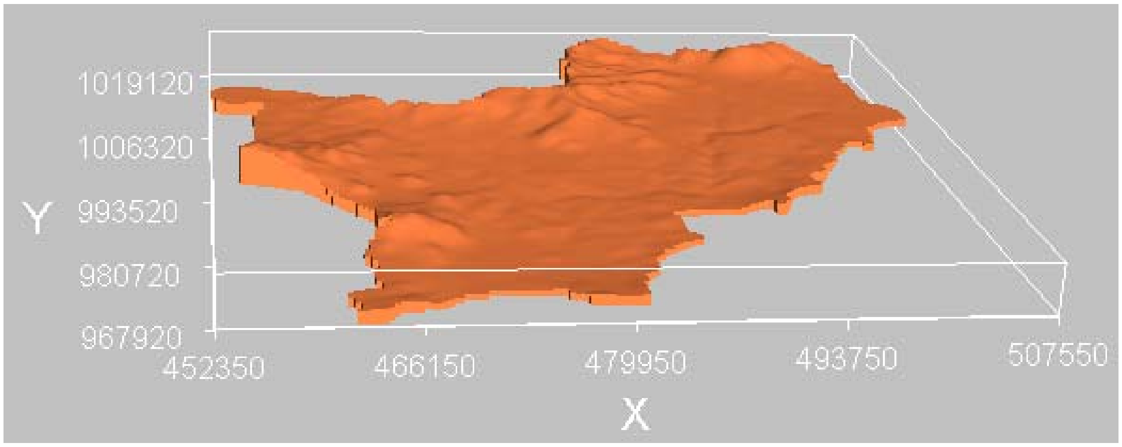


Figure 6.2 Relative thickness variation of the aquifer

6.4 Model Input Parameters

6.4.1 Initial & Prescribed Hydraulic Head

It is the initial stage at which groundwater level stood in an aquifer system. Processing MODFLOW pro needs this initial head to start simulation. For this simulation, it was obtained by subtracting a constant (that approximates static water levels) over a large area from the layer top elevation. Based on this, the catchment was sub divided broadly into two: the northern part of the catchment where water that recharges to aquifer comes to the ground as local flow systems (smaller springs), the initial hydraulic head was approximated to be equal to or less than the topographic elevation in few meters. In the central and southern part of the catchment the initial hydraulic head was approximated to be 50m below the ground elevation. The real value of water level elevation was given as initial heads in cells represented by constant heads.

6.4.2 Boundary Conditions

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain (Anderson and Woessner, 1992). The boundaries chosen for the model describe mathematically how the simulated groundwater system interacts with the surrounding hydrologic system. Computer simulations of groundwater flow systems numerically evaluate the mathematical equations governing the flow of fluids through porous media. This equation is a second order partial differential equation with head as the dependent variable. To determine a unique solution of such a mathematical problem, it is necessary to specify boundary conditions around the flow domain for head or its derivative.

One requirement for the solution of a mathematical equation that describes groundwater flow is that boundary conditions must be prescribed over the boundary of the study area domain. It is important to note that in solving groundwater flow problem, boundary conditions are not simply mathematical constraints. They generally represent the sources and sinks of water within the system. In addition, their correct selection, that is, the location of the boundaries and their numerical representation in the model, is critical to the development of an accurate model that can simulate system response correctly under any proposed scenario.

A thorough understanding of boundary conditions and the different ways to simulate them is required to select the best mathematical representation in a groundwater flow model because many physical features that are hydrologic boundaries can be mathematically represented in more than one way. In mathematical analyses of groundwater flow system, three common mathematical boundary conditions are specified (Anderson and Woessner, 1992). These are: Specified head, Specified flow, Head dependent flows.

In groundwater flow simulation of Akaki River catchment all the three boundary conditions were applied. Nodes that represented specified head boundary in the model were simulated with a head that is unchanging. Such heads represented an inexhaustible supply of water, that is, the groundwater system may pull water from the boundary or may discharge water in to the boundary with out changing head at the specified head node. In the Akaki River catchment, there are four man made reservoirs/dams (Aba Samuel Lake, Lega Dadi Dam, Dire Reservoir and Gefersa Dam). These were represented as specified head nodes in the model except Dire and Gefersa reservoirs that are located at upstream of the catchment. In this numerical groundwater flow simulation such nodes were identified by assigning the value '-1' to entries of I-BOUND array in MODFLOW. This boundary condition is very strong and was selected assuming that the lakes/reservoirs (Aba Samuel and Lega Dadi) stages are not affected/less affected by stresses imposed on them during the simulation. The water surface elevations of Aba Samuel Lake (2025m) and that of Lega Dadi (2425m) were given as initial heads to cells representing such constant head nodes.

The flux across head dependent boundary depends on the difference between user supplied head on one side of the boundary and model output head on the other side. In case of Akaki River Catchment, this boundary was assigned to the southern tip of the catchment. This flux was simulated by using the General Head Boundary Package of MODFLOW. This package simulates fluxes based on heads on both sides of the boundary. Here the calculated aquifer head along the general head boundary cells (average head 2020m) is higher than head in the external source estimated by the altitude of Aba Samuel gorge springs (1988-1998m a.s.l), which indicated that there is flow across this boundary to the external from the study area. This was clearly seen in the field as it is not far south of the Aba Samuel Lake where the Akaki well field aquifer partly pinches out against gorge and some of the southward flowing groundwater is out cropped as springs in the gorge.

The flux across this boundary was calculated using the conductance of the interface (C_b), head in the aquifer (h) and head in the external source (h_{source}). The flux Q_b is given as:

$$\mathbf{Q_b = C_b (h_{source} - h)} \qquad \textbf{Equation (6.2)}$$

Only C_b and h_{source} were estimated and MODFLOW calculated the fluxes based on the head in the aquifer using these estimates. The C_b value calculated for these boundary cells ranges from 35-85m^2/day. The general head boundary condition assumes continuous linear discharge or leakage. In this case it represented continuous removal of groundwater from the aquifers in the catchment to the adjacent aquifer system or as springs.

In addition, the reservoirs located at upstream of the catchment (Dire and Gefersa) were simulated as general head boundaries and the input parameters were estimated in similar ways as in the above. The interface conductance was calculated using the relation, C_b =KLW/M (the same as defined for rivers). K was assumed to be 1/10 to 1/100 of the hydraulic conductivity value of surrounding rock unit, interface thickness (M) was assumed to be 0.05 to 0.1m and LW was considered to have represented the area of the respective reservoirs. So, this calculated C_b was shared among each cell that represented respective reservoirs.

The upper boundary of the system was simulated as specified flux as recharge was applied to the water table. The lower boundary was assumed to be a no flow boundary. As the remaining boundaries of the catchment were not defined as unique boundary conditions, MODFLOW automatically assumes such boundaries as inactive. The value '0' was assigned to cells at the external of such boundaries to make them inactive and no flow occurs across such boundaries (figure 6.1). Head values are not calculated for cells represented as inactive cells.

6.4.3 Model Stresses and Fluxes

The fluxes into or out of the aquifer in the Akaki River Catchment as applied into the model and simulated by MODFLOW 1996 (McDonald and Harbaugh, 1988) are summarized under the following sub-sections. Various MODFLOW packages were used to simulate model stresses, but it should be noted that the packages selected were not the only options to simulate these parameters. The considered stresses include recharge to the aquifers, discharge to rivers, well withdrawal and spring discharge, and sub surface outflows.

6.4.3.1 Groundwater Recharge

It is clear that recharge to the aquifers in the catchment is directly from precipitation during intensive rainy seasons. As it was pointed out under recharge section, the catchment was subdivided in to different zones of recharge (Figure 5.2) based on the rock types, land use/land cover and in fact based on recharge amount of the catchment.
The recharge was simulated as specified flux by using the Recharge package of MODFLOW with the option recharge ‘‘Applied to the top grid layer’’ and is not expected to change with water level changes. Recharge was the only expected inflow component to the aquifers. Actually, the recharge value was modified during the calibration process.

6.4.3.2 Well Withdrawals and Springs Discharge

There are a large number of wells in the Akaki river catchment. In this study, those active wells (that are currently in use) with high withdrawal rate were considered and simulated using the Well Package of MODFLOW (McDonald and Harbaugh, 1988). Wells that are owned by AAWSA and other Public wells have a known withdrawal rates, and pumping rate of other wells was initially estimated based on minimum pumping hours and later adjusted during calibration. A pumping well was assigned to a cell according to field coordinates (UTM) .Due to the coarser grid size used in this study two or more wells were assigned in to a single cell and the sum of pumping rate of each well was considered in such cases. The well package simulates wells as a specified flux. To simulate removal of water from aquifers through well withdrawal, a negative value of the rate of daily abstraction (given in m^3/d) was assigned to the entry of recharge rate in well package of MODFLOW.

There are a number of variable discharge springs in the interior of the study area. Most of these springs have low discharges and/ or 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. Only Fanta spring was considered in the simulation (discharge rate of about 25l/sec).

6.4.3.3 Base Flow of 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 are 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:

$$\mathbf{Q_{Riv} = C_{Riv} (H_{Riv} - h), \text{ when } h > R_{Bot}} \qquad \textbf{Equation (6.3)}$$

$$\mathbf{Q_{Riv} = C_{Riv} (H_{Riv} - R_{Bot}), \text{ when } h < R_{Bot}} \qquad \textbf{Equation (6.4)}$$

Where Q_{Riv}: 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 beds 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:

$$C_{Riv}=KLW/M \qquad \textbf{Equation (6.5)}$$

The river bed sediment hydraulic conductivity was assumed to be 1/10 to 1/100 of the nearby formation hydraulic conductivity, and the stream bed thickness was approximated to 0.05 to 0.5m. The length and width of river segment was highly variable from cell to cell and was approximated for each cell. Based on these values, the average hydraulic conductance of river bed sediments was approximated to be around 200m^2/d (the highest 395m^2/d and the lowest below 50m^2/d). The values were re-approximated for each cell and entered into the River Package of MODFLOW for simulation. Model cells were designated as river cells along major perennial rivers and their tributaries.

6.4.3.4 Subsurface Outflow

As it has been discussed under boundary condition section, subsurface outflow occurs along the southern tip of the catchment. This outflow was simulated using the general head boundary Package of MODFLOW. It uses interface hydraulic conductance, head in the aquifer and head in the external source to calculate flow through the boundary. In the Akaki River Catchment the heads at or outside the boundary is lower than the head in the aquifer, which results in loss of water from the groundwater system. Heads at or beyond the boundary were approximated by the water level altitude of Aba Samuel gorge springs and head in aquifer was calculated during simulations. Interface hydraulic conductance was approximated using the same procedure as river bed hydraulic conductance and adjusted during model calibration. So, based on this, the program calculated the amount of water loss using the input variables according the relation:

$$Q_b = C_b (h_b - h) \qquad \textbf{Equation (6.6)}$$

Where, Q_b= flow through the boundary C_b= interface conductance
h = head in the aquifer h_b= head at or beyond the boundary

Interface hydraulic conductance was estimated to be about 35 to 85m^2/day. Average head in the aquifer was around 2020m which is higher than head in the external source estimated by the water level elevations of Aba Samuel gorge springs (1988-1998m a.s.l). This head difference resulted in groundwater outflow from the aquifer system approximated by the discharge of Aba Samuel gorge springs (about 25 l/sec). The model simulated subsurface outflow amount is higher than the field approximated value because additional flows that have not outcropped as springs were expected to occur along this side.

6.5 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 calibration 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 hydrogeological 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.

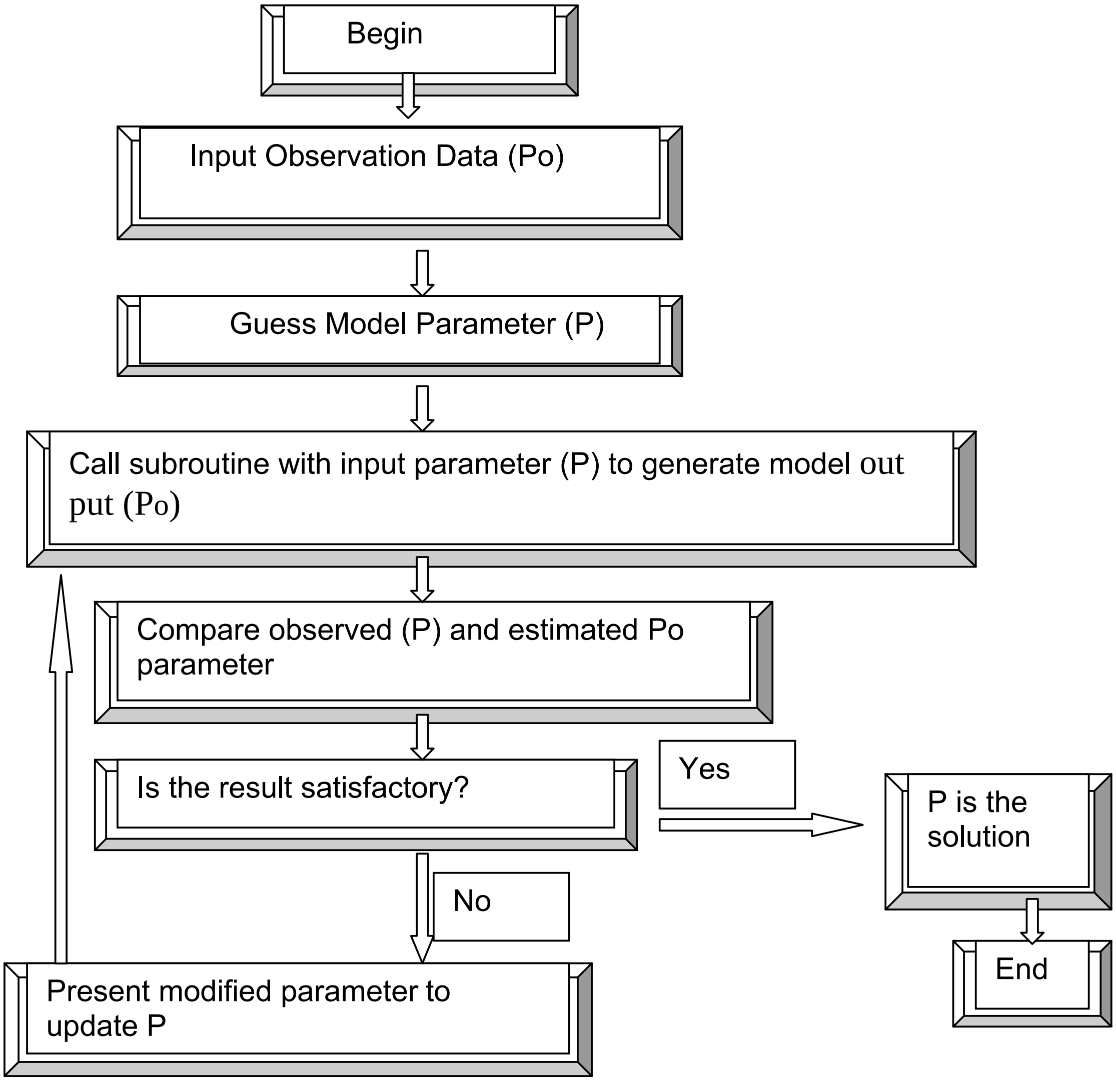


Figure 6.3 Trial and Error Calibration Procedure Ne- Zheng Sun, 1994)

6.5.1 Data used for Calibration

The Akaki River catchment groundwater model was calibrated to steady state condition of average heads collected at different times in different parts of the catchment. Head observations for calibration of Akaki River Catchment groundwater flow model consisted of water level measurements data from 122 wells (figure 6.4).

Observation points were not evenly distributed throughout the model domain but clustered geographically in Addis Ababa city and Akaki well field areas, but 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, in others (that have observation pipes) head measurement was conducted for the purpose of this calibration work and still in others(like Monitoring Wells of AAWSA) average head of daily long term water levels was used. This seems to cause some discrepancy but it can be accepted hydrologically because time series water level fluctuations in wells in the catchment can be assumed to be negligible. This was learnt from those wells in the catchment for which long term water level data was available.

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.

For those wells which have long term daily head data measurements, the head data were scrutinized carefully and anomalous values that can be due to measurement or location errors & pumping effects were removed from the calibration data set. In addition, for those wells whose water level measurement was carried out for the purpose of this calibration, care has been taken in measuring heads in that measurement was taken before large amount of water was pumped from the wells or it was waited until water level was recovered to its approximate initial condition.

Groundwater head contours were constructed from these water levels/heads and matching field contours with calculated contours was made during model calibration. During the longer calibration process, initial estimates of model input parameters; especially recharge, hydraulic conductivity, streambed and general head boundary interface conductances were adjusted within reasonable limits to have a better fit. Initially adopted recharge values and zones were modified with in plausible ranges based on land use, rocks types and precipitation amounts. Accordingly, recharge to the elevated northern and western areas covered with forest was increased from 0.000369 m/d to

0.000411m/d and recharge to the city was modified a little because no much recharge was expected to occur other than the initial estimates as the land use condition enhances more runoff than infiltration. Less populated garden zones and farm lands at the outskirt of the city were assigned a relatively higher recharge amounts within the range of 0.000111- 0.000242m/d based on rock types and land uses. These recharge values yielded groundwater heads that closely matched observed heads in most parts of the catchment.

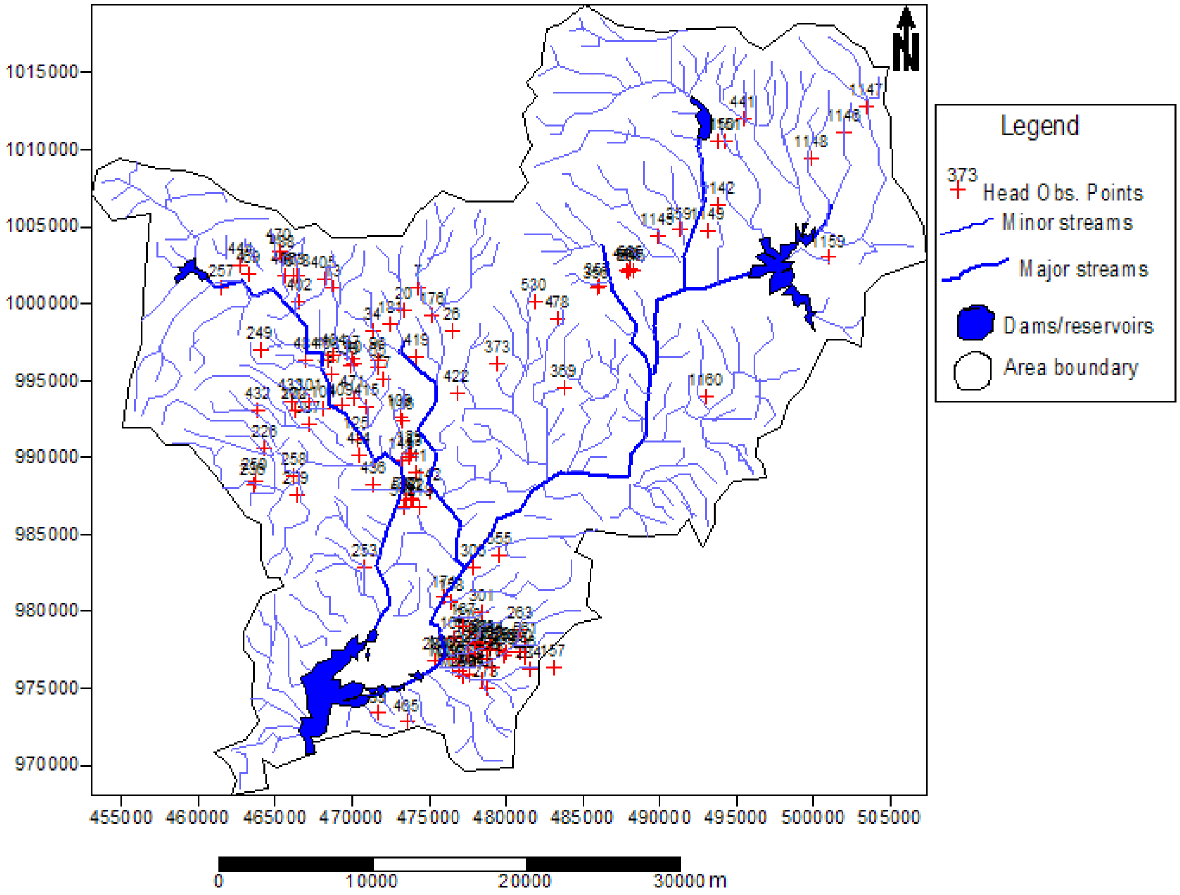


Figure 6.4 Location of Observation points used for Head Calibration

Horizontal hydraulic conductivity was adjusted manually to get better fit between observed and calculated heads. Initial zones were modified to obtain better fit of heads by adding separate zones, widening or narrowing of initial hydraulic conductivity zones

and changing the initial hydraulic conductivity values within zones. The final calibrated hydraulic conductivity values ranged from 0.2657m/d to 198m/d. The lowest value is to the north central part of the study area and the value increases to south attaining a maximum of about 198m/d in the Akaki well field areas.

In addition, stream bed conductances were adjusted to make the match between calculated and observed heads or flows better. Stream bed conductances were lowered in river cells to the southern and western part of the study area to an average value of 120m^2/d. The value for northeastern part of the catchment was larger, greater than 200m^2/d in most cells. These approximated values yielded reasonable fits.

6.5.2 Calibration Results

The effectiveness of the calibration process was evaluated by comparing measured heads with simulated heads for each observation wells used and for stream flows. Two calibration criteria were set for this calibration. Initially visual matching of simulated groundwater contours to those of observed contours was set. As can be seen in figure 6.5, the observed and simulated potentiometric surfaces are generally similar in shape 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 a long period.

Secondly, matching simulated hydraulic heads at 80% of the points to within 15m of the observed hydraulic heads. This criterion can be considered sufficient because 15m is about 2.6% of the difference between the maximum and minimum hydraulic heads of the estimated water levels in the study area, which is about 581m. The model was assumed calibrated when the fit between observed and calibrated heads was with in this criteria and calibration was evaluated based on the final spatial distribution of the difference between the observed and computed heads (Table 6.1).

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

The Mean Error (ME) is the mean difference between measured heads and simulated heads. It is expressed as:

$$\mathbf{ME=1/n \sum (h_m-h_s)} \qquad \textbf{Equation (5.7)}$$

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

The ME of the calibration for all observation measurements considered was about 0.95m.

The Mean Absolute Error (MAE) is the mean of the absolute value of differences in measured and observed heads. MAE can be obtained from:

$$\mathbf{MAE=1/n \sum \left| (h_m-h_s)_i \right|} \qquad \textbf{Equation (5.8)}$$

The MAE calculated for hydraulic heads is about 8.48m

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:

$$\mathbf{RMS= \{1/n \sum (h_m-h_s)_i^2\}^{0.5}} \qquad \textbf{Equation (5.9)}$$

The fitted RMS head for observation points is about 10.42m. This fit was considered good 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 0.95m.

-MAE and RMS show whether the calibration criteria set prior to or during 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 (figure 6.6), 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 10.42/581 or 0.018, which indicates that the error in the heads represented a very small fraction of the overall model response.

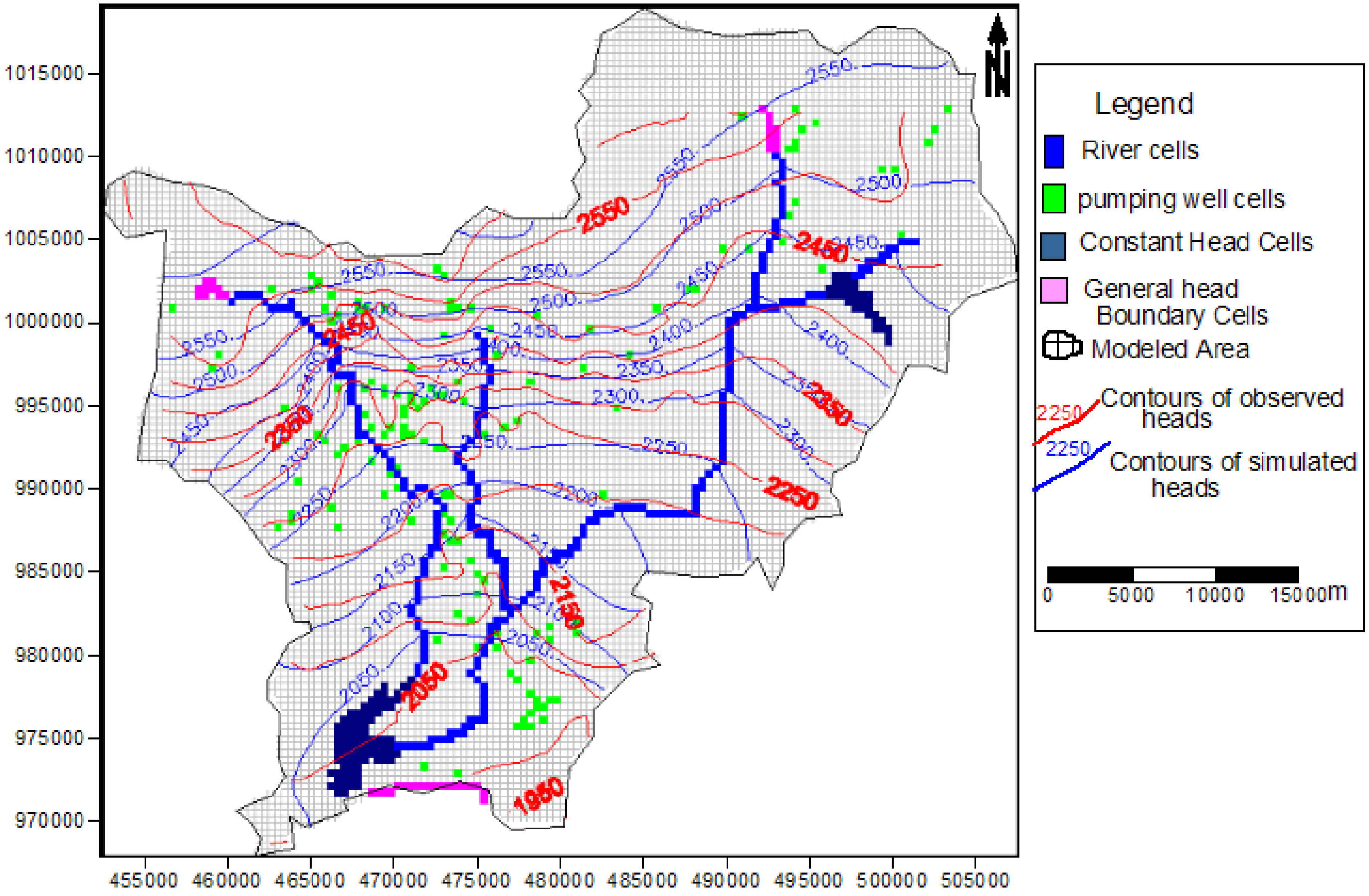


Figure 6.5 Comparisons of Simulated and Observed Heads

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 (figure 6.5). In northern central parts of the catchment, large differences between measured and simulated water levels might have resulted from poor estimates of model parameters during calibration or due to fluxes to /from rivers as some of these 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 as shown in figure 6.8 was represented by seven head intervals zones. It indicates that head increases from south to north.

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 show exact fit between head points, observation points that are above the straight line show higher calculated heads and those points below the straight line show higher observed heads compared to simulated 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. Location of observation points is shown in figure 6.4.

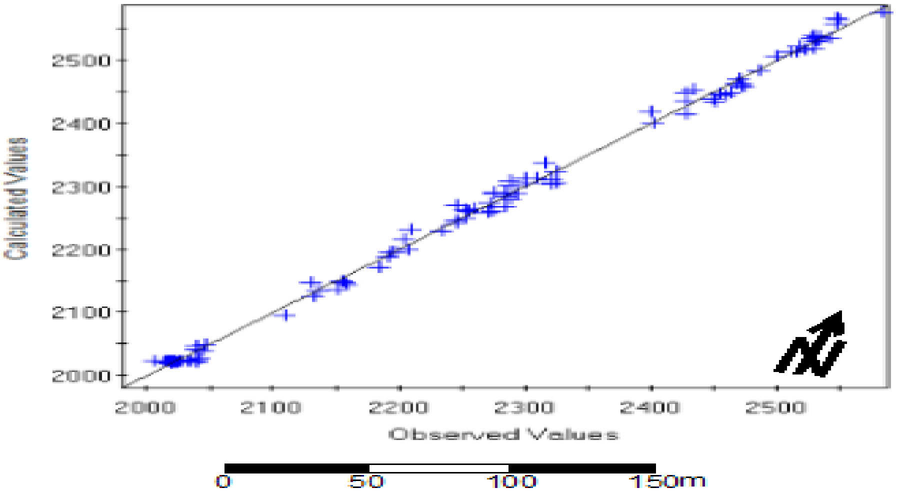


Figure 6.6 Scatter Plot of Head Distribution

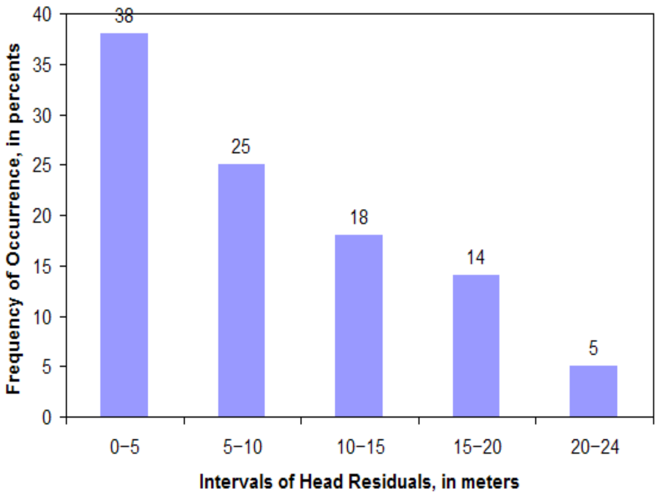


Figure 6.7 Histogram showing error distributions

Moreover, as depicted in histogram above, one can clearly observe the distribution of the absolute value of the difference between observed and simulated hydraulic heads and the frequency of occurrence. Absolute head residuals above 15m can be attributed to uncertainties in estimated stresses and hydraulic parameters, and most of these wells are in elevated parts of the catchment except few wells to the center of the area or some wells near streams. As a whole, the steady state groundwater flow model adequately simulated water levels observed at different times in different parts of the catchment. Simulated water levels were within 15m of observed water levels for about 81% of the head observation points and the value was higher for about 23 points, which represented 19% of the total.

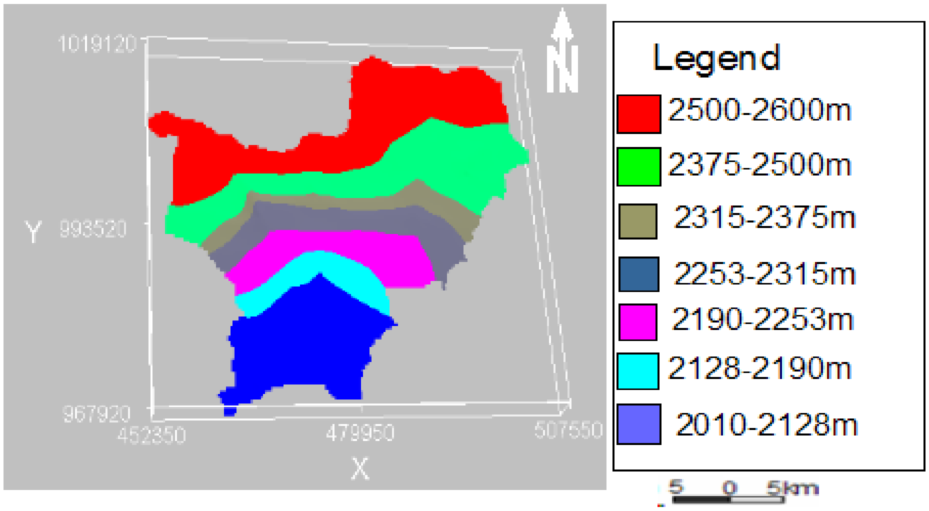


Figure 6.8 Simulated Potentiometric Surface

Table 6.1 Calculated and Observed Heads in Observation Wells

Obs Name	X	Y	calc. head	Obs. head	obs-calc	(obs-calc)²	│obs- calc│
465	473576	972821	2021.91	2007	-14.9	222.3	14.9
MW04	477185	975729	2021.82	2014	-7.8	61.1	7.8
MW01	476454	976951	2022.019	2015	-7	49.3	7
MW02	476523	976374	2021.96	2015	-6.9	48.4	6.9
MW03	476972	976152	2021.87	2015	-6.8	47.2	6.9
304	478998	977937	2022.13	2016	-6.1	37.5	6.1
TW01	478019	977900	2022.06	2016	-6.1	36.7	6.1
169	476600	978200	2022.25	2018	-4.3	18.1	4.3
288	478019	977985	2022.09	2018	-4.1	16.8	4.1
289	479820	977156	2021.72	2018	-3.7	13.8	3.7
291	477651	975923	2021.69	2018	-3.7	13.6	3.7
302	478463	977506	2021.97	2018	-3.9	15.8	3.9
99	471705	973386	2019.34	2019	-0.3	0.11	0.3
167	477233	979000	2022.52	2019	-3.5	12.4	3.5
273	478713	974977	2021.83	2019	-2.8	7.9	2.8
278	479061	976370	2021.62	2019	-2.6	6.8	2.6
284	481507	976221	2021.62	2019	-2.6	6.9	2.6
296	481205	976968	2022.02	2019	-3.1	9.1	3
297	476523	976374	2021.96	2019	-2.9	8.7	2.9
271	478399	975589	2021.71	2019.5	-2.2	4.9	2.2
157	483093	976323	2022.23	2020	-2.2	4.9	2.2
292	479942	977322	2021.89	2020	-1.9	3.6	1.9
227	477477	977216	2021.99	2022	0	0	0
299	477185	975729	2021.82	2022	0.2	0.03	0.1
282	476454	976951	2021.42	2023	1.6	2.5	1.6
283	475402	976807	2021.56	2024	2.4	5.9	2.4
303	444000	977700	2021.92	2025	3.1	9.5	3.1
300	480895	977403	2022.08	2026	3.9	15.3	3.9
456	478808	976867	2022.07	2028	5.9	35.1	5.9
216	477609	978690	2022.39	2032	9.6	92.4	9.6
308	477945	976985	2022.39	2034	11.6	134.9	11.6
272	466250	993050	2024.22	2035	10.8	116.1	10.8
538	479526	977468	2022.42	2035	12.6	158.3	12.6
158	476400	980600	2041.15	2039	-2.2	4.6	2.2
215	478463	977722	2021.96	2040	18	325.4	18
230	479021	977596	2021.82	2040	18.2	330.4	18.2
263	480900	978800	2046.59	2040	-6.6	43.5	6.6
561	481224	977845	2027.41	2041	13.6	184.7	13.6
301	478450	979950	2038.71	2044	5.3	27.9	5.3
171	476000	980900	2048.87	2047	-1.9	3.5	1.9
253	470800	982900	2094.88	2110	15.1	228.6	15.1
306	477900	982875	2095.72	2110	14.3	203.9	14.3
548	473326	986813	2146.45	2131	-15.4	238.6	15.4

555	479576	983656	2124.22	2133	8.8	77.1	8.8
218	474429	986828	2134.16	2136.5	2.3	5.5	2.3
142	475000	987800	2135.76	2152	16.2	263.7	16.2
542	473466	987247	2149.99	2156	6	36.2	6
381	473760	987300	2146.75	2157	10.3	105.2	10.3
382	473925	987175	2143.02	2159.5	16.5	271.8	16.5
141	474100	989000	2170.68	2185	14.3	204.9	14.3
436	471400	988250	2189.15	2192.5	3.4	11.2	3.4
143	473225	989850	2195.5	2193	-2.5	6.3	2.5
133	473750	990050	2196.06	2198	1.9	3.8	1.9
434	470450	990125	2215.77	2205	-10.8	115.9	10.8
129	473800	990250	2199.67	2207	7.3	53.6	7.3
125	470300	991200	2231.84	2210	-21.8	477.1	21.8
259	466400	987600	2228.96	2234.5	5.5	30.7	5.5
258	466200	988800	2241.41	2246	4.6	21	4.6
387	467150	992150	2269.32	2246	-23.3	543.8	23.3
116	473200	992400	2245.9	2247	1.1	1.2	1.1
236	463600	988200	2262.09	2252.5	-9.6	92	9.6
109	473100	992600	2249.75	2254	4.3	18.1	4.3
104	468100	993200	2260.58	2255	-5.6	31.1	5.6
250	463700	988500	2264.13	2261	-3.1	9.8	3.1
415	470950	993300	2258.03	2271	12.9	168.2	12.9
101	467200	993600	2274.48	2272	-2.5	6.2	2.5
409	469280	993350	2260.94	2275	14.1	197.7	14.1
226	464300	990600	2288.15	2275.5	-12.6	159.9	12.6
77	472000	995100	2291.3	2276	-15.3	234.2	15.3
100	466250	993050	2289.65	2285	-4.6	21.6	4.6
422	476800	994200	2285.09	2285	-0.06	0	0.06
471	470100	993850	2267.43	2285	17.6	308.7	17.6
484	467000	996300	2309.29	2288	-21.3	453.1	21.3
369	483750	994550	2280.16	2289	8.8	78.1	8.8
433	466050	993650	2301.18	2289	-12.2	148.3	12.2
397	468650	995450	2288.53	2294	5.5	29.9	5.5
408	468425	996350	2304.61	2300	-4.6	21.3	4.6
96	471700	996300	2312.68	2301	-11.7	136.4	11.7
404	468800	996600	2313.09	2309	-4.1	16.7	4.1
432	463850	993100	2336.16	2316	-20.2	406.5	20.2
37	470000	996400	2311.6	2321	9.4	88.3	9.4
39	469900	996000	2302.85	2321	18.1	329.3	18.1
40	470100	996100	2305.34	2322	16.7	277.5	16.7
419	474175	996550	2323.76	2325	1.2	1.5	1.2
65	471700	995900	2304.99	2326	21	441.1	21
373	479450	996115	2323.5	2326	2.5	6.3	2.5
176	475200	999200	2419.07	2401	-18.1	326.6	18.1
26	476500	998250	2401.07	2403	1.9	3.7	1.9
478	483350	999064	2435.38	2428	-7.4	54.5	7.4
34	471300	998200	2414.69	2428.5	13.8	190.8	13.8
249	464000	997000	2449.3	2429	-20.3	412.1	20.3
359	491300	1004800	2453.55	2434.5	-19.1	362.9	19.1
1149	493164	1004738	2438.83	2450	11.2	124.7	11.2

181	472500	998700	2433.36	2451	17.6	311	17.6
564	487953	1002003	2446.5	2454	7.5	56.2	7.5
545	488253	1002102	2445.3	2460	14.7	215.9	14.7
535	488086	1002300	2448.68	2463	14.3	205.2	14.3
440	487800	1002200	2449.1	2463.2	14.1	198.9	14.1
20	473400	999600	2463.06	2469	5.9	35.3	5.9
1145	489895	1004401	2463.38	2469.5	6.1	37.4	6.1
530	481878	1000148	2471.19	2470	-1.2	1.4	1.2
357	486000	1001115	2459.97	2472	12	144.8	12
1142	493781	1006397	2462.85	2472	9.19	83.6	9.1
356	485925	1000975	2458.234	2474	15.8	248.6	15.8
402	466550	1000150	2484.22	2487	2.8	7.8	2.8
7	474300	1001005	2506.31	2501	-5.3	28.2	5.3
13	468800	1001007	2514.52	2511	-3.5	12.4	3.5
1148	499841	1009483	2513.58	2516.5	2.9	8.5	2.9
1146	501942	1011164	2523.55	2518	-5.5	30.7	5.5
1151	494194	1010610	2518.16	2523	4.8	23.4	4.8
1147	503458	1012821	2535.22	2529	-6.2	38.6	6.2
1150	493750	1010560	2518.31	2529.5	11.2	125.3	11.2
447	465600	1001855	2540.49	2531	-9.5	90.1	9.5
405	468200	1001600	2529.81	2532	2.2	4.8	2.2
441	495433	1012074	2532.37	2533	0.6	0.4	0.6
363	466175	1001800	2537.85	2534	-3.8	14.8	3.8
378	466440	1001760	2536.29	2542	5.7	32.7	5.7
469	463266	1001971	2558.62	2547	-11.6	135	11.6
257	461500	1001023	2567.81	2548	-19.8	392.3	19.8
488	465410	1002944	2565.03	2548.8	-16.2	263.3	16.2
444	462743	1002521	2576.95	2585	8.1	64.9	8.1
470	465243	1003393	2572.6	2588.8	16.2	262.4	16.2
					0.95	**10.42**	**8.48**
					ME	**RMS**	**MAE**

In addition, the overall magnitude of base flow to streams was also reasonably simulated in the area. As can be seen in table 6.2 shown below, about 57% of the total simulated outflow from the system was primarily leakage to rivers. The mean absolute river leakage residual between the calculated and the observed value was about 16%. This difference is due to uncertainties in estimation of river bed hydraulic conductance or coarser grid size used because model cells represented river cells at a point where a river segment crossed a cell. Also the approach of representing stream stage by a fixed value standing for average conditions may have resulted in inaccuracies in flow rates.

From conceptual and simulated groundwater budgets shown in table 6.2, one can clearly observe that the steady state model simulated more inflows and outflows compared to the estimated one. The only source of groundwater inflow considered in the conceptual budget was areal recharge from precipitation and was approximated to be about 315,466 m^3/day. The fact that the estimated groundwater inflow and outflow budgets are not equal can be attributed to low estimates in recharge amounts or exaggerated estimates in one of the outflow components. The overall simulated budget is excess compared to the observed one, which could be due to contribution from dams and reservoirs represented as constant or general head boundary conditions.

Table 6.2 Comparison of Estimated and Simulated Water Balances

		Observed (m3/day)		Calculated (m3/day)	
No.	Budget Component	Inflow	Outflow	Inflow	Outflow
1	Recharge	326843.5	–	315466.3	–
2	Specified Constant Flux in Constant head	–	–	12916	75701
3	River Leakage	–	287712	17636	212268
4	Head dependent flux in GHB	–	–	20656	10448
5	Wells	–	68261	–	68261
6	Springs (Fanta spring)	–	2650	–	–
7	Subsurface Outflow (A/ Samuel gorge Sp.)	–	2592	–	–
	TOTAL	**326843.5**	**361215**	**366674.3**	**366678**

Given the uncertainties in the estimation of recharges and discharges, the overall observed water balance can be taken as a sufficient approximation of the actual groundwater flow system. As a whole, the steady state numerical model has reasonably represented the behavior of groundwater system under consideration.

6.6 Model Sensitivity Analysis

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

The calibrated values of recharge and hydraulic conductivity were varied by 20%, 40% & 55% increases and decreases at different times to test the sensitivity of the model to the parameters. A total of twelve model runs have been made by changing the hydraulic conductivity & recharge by the specified percents and the respective root mean squared head changes in percent from the calibrated value are shown in table 6.3a.

In all simulations, it was observed that the model was less sensitive to parameter changes in the southern part of the catchment compared to north, that is, absolute water level changes were minimal to the southern part in all sensitivity simulations. Head changes in Akaki well field water level observation wells in most runs were less than 5meters but on parts of the catchment where elevation is higher water level changes observed were higher, this is clearly seen in wells located in the northern and central part of the city, Legatafo-Sendafa areas and Burayu area. To clarify this statement let us consider water level changes from calibrated value in few wells, located in different parts of the catchment, to similar changes in parameters from calibrated values. One of the wells located in the most northern part of the catchment is a well near Dire dam. The absolute water level changes from the calibrated value in this well when recharge was decreased by 50%, increased by 25% and increased by 75% was 10m, 5m and 15m, respectively. Similarly an increase in hydraulic conductivity by 25% and a decrease in it by 75% resulted in water level change from the calibrated value by 4m and 46m, respectively in the same well. On the contrary, for AAWSA(Addis Ababa Water and Sewerage Authority) MW01 (found near Akaki well field area) for the same parameter changes (in the order mentioned for Dire well) head changes from the calibrated value were 1m, 3m, 1m, 0.5m and 4m, respectively. This general trend holds true for wells in the area. The following table and plot show the result of sensitivity of the model to changes in recharge and hydraulic conductivity.

Table 6.3a Results of Sensitivity Analysis Test on Water Levels

No	Change in sensitivity parameter from the calibrated value, in %	Respective absolute RMS head change from the calibrated value, in %
1	Recharge increased by 20,40 & 60	17, 58 & 106
2	Recharge decreased by 20, 40 & 55	26, 86 & 147
3	Hydraulic conductivity increased by 20, 40 & 60	12, 33 & 55
4	Hydraulic conductivity decreased by 20, 40& 55	19, 90 & 193

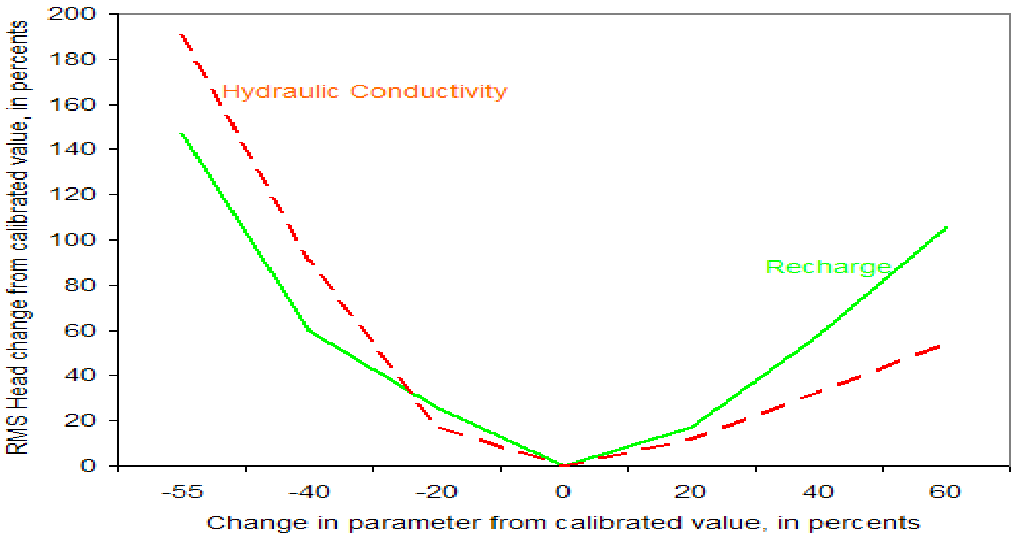


Figure 6.9a Plot of the Results of Sensitivity Analysis Test on Heads

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 15%, 30% & 45% at different times and a total of twelve model runs have been made to observe the 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 greater changes in stream leakage in case of recharge than hydraulic conductivity. This shows that the model is more sensitive to recharge than hydraulic conductivity.

As it can be seen from sensitivity results given in table 6.3b and figure 6.3b, changes in both parameters affected river leakage in a similar fashion, but with different magnitudes. An increase in either parameter resulted in an increased stream leakage and vice-versa.

Table 6.3b Results of Sensitivity Analysis Test on Stream Leakage

No.	Change in Sensitivity Parameter from calibrated value in percent	Respective changes in Stream Leakage from Calibrated value, in percent
1	Increase in Recharge by 15,30 & 45	11.9, 23.9 & 35.8
2	Decrease in Recharge by 15,30 & 45	-11.9, -23.6 & -27.5
3	Increase in Hydraulic conductivity by 15,30 & 45	1.9, 3.7 & 5.5
4	Decrease in Hydraulic conductivity by 15,30 & 45	-2.1, -4.2 & -6.9

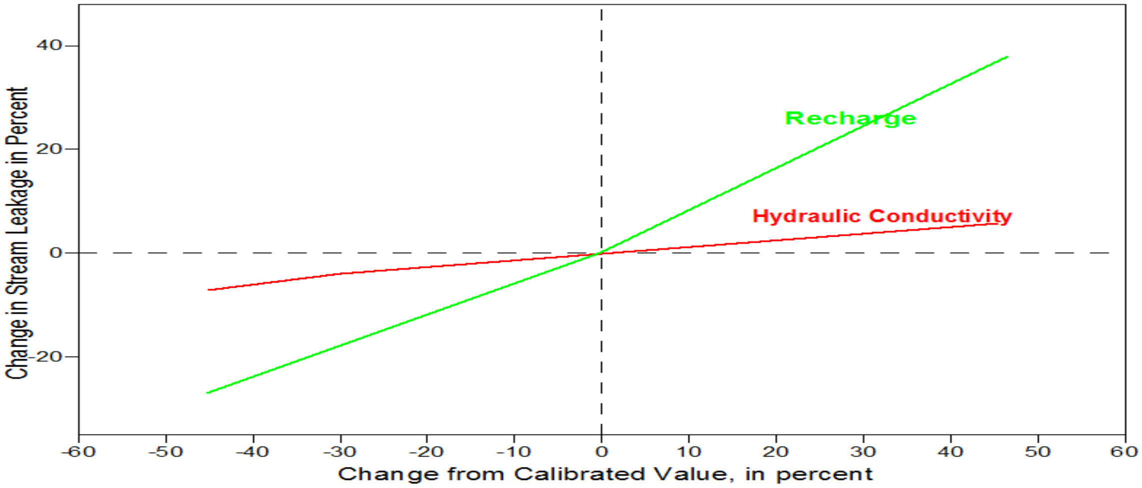


Figure 6.9b Plot of Stream Leakage Sensitivity Result

In general, the Akaki 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 estimating these parameters because they influence the model result greatly.

6.7 Scenario Analysis

Having a calibrated model that was tested for sensitivity as capable of simulating water level elevations or fluxes and given its associated limitations, it is possible to use the model to simulate the resulting changes in water levels and fluxes due to new proposed scenarios and project the likely effects.

As it has been clearly stated under section 1.3, numerical groundwater flow model simulated in this study was intended to test the response of the hydrologic system to different scenarios. So, Alternative scenarios were developed to test the response of the hydrologic system to changes in water uses or hydrologic stresses under steady state condition. System response was evaluated by using fluxes and heads of the calibrated model as a baseline and compared with resulting changes in stream leakage, changes in water table elevation and changes in groundwater outflow in the new scenario simulation.

Changes in water levels and fluxes caused by increased groundwater withdrawal in the whole catchment, and the effect of local increase in groundwater withdrawal of Akaki Well field on Aba Samuel gorge springs and local river reaches were simulated using the model. The effect of changes in water levels and fluxes caused by decreased recharge due to less than normal precipitation that may result from weather modifications was also simulated. In addition, the response of the system in the absence of interaction of lakes/reservoirs with groundwater has also been tested using the numerical model.

It should be noted that the results of the scenarios depend on future land use, population growth, weather conditions, hydrologic stresses etc, and may not be used as a predictive tool to generate absolute amounts in the future, but used primarily to test the response of the system. In general, the results of the scenarios or their accuracy depend on the validity of the assumptions behind the scenarios. Moreover, errors introduced due to limitations associated with the numerical model also affect the results of the scenarios and should be taken into considerations during interpretation and application of results.

In all scenarios, other model parameters were kept to the steady state values except the stress for which the projection was carried out and the resulting changes in water levels and fluxes were interpreted as the response of the system to the changes introduced on it. In the following sections, a result of each scenario is discussed.

6.7.1 Effects of Increased Groundwater Withdrawals

As Addis Ababa city is expanding and industries/factories are flourishing in different parts of the Akaki River Catchment, it is reasonable to assume that the water demand will increase too. To meet this increasing demand, it is must that the existing boreholes should be pumped at greater rates or new boreholes with higher capacity should be drilled in the future. This truth can be seen from large number of wells drilled since recently in the catchment. By virtue of this, it is logical to think that groundwater withdrawal will increase in the catchment and it is necessary to project its future effects on groundwater table and fluxes of the area so that an appropriate water management practices that could mitigate the likely adverse effects of increased withdrawal may be proposed. So, using the flow model, two scenarios of increased groundwater withdrawals were tested. In the first scenario, three increased withdrawal rates were simulated by considering all active wells in the catchment and the increased withdrawal amounts were distributed among existing wells in proportion to the current contribution of each source to the daily withdrawal rate. The current withdrawal rate estimated under steady state simulation was 68,261m^3/d and about 60% of this pumping is from public wells in the catchment. Withdrawal rate from public wells can be considered exact because it was obtained from the daily / monthly / annual records of the respective institutions. Withdrawal rate from other operational wells was estimated based on minimum pumping hours and was adjusted during model calibration. Therefore, the current estimated groundwater withdrawal rate from the catchment can be considered as the minimum reasonable amount.

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. This can be manifested by reduced stream leakages, spring discharges, subsurface groundwater outflows or reduction in other discharge mechanisms. In addition, it also can induce recharge from surface water bodies such as streams or lakes.

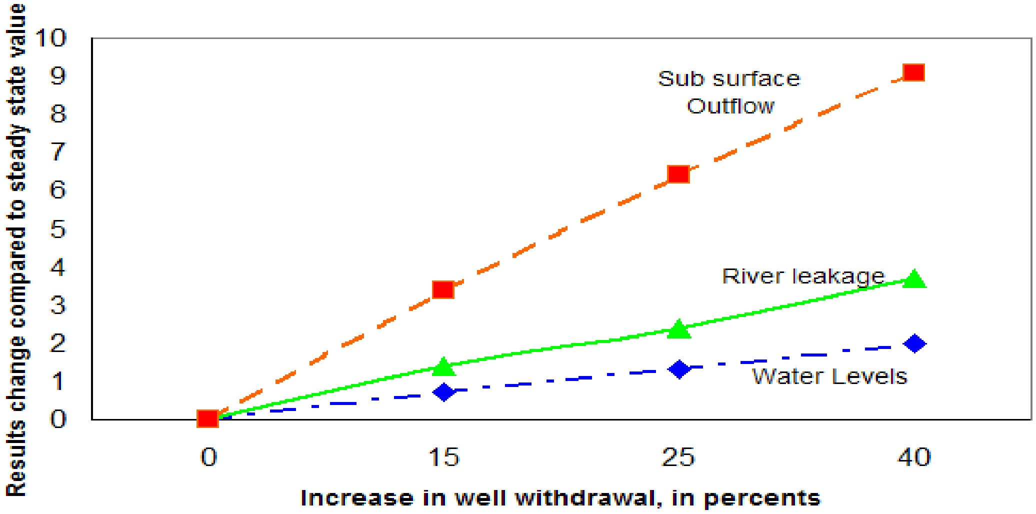
The steady state withdrawal rate was increased by 15%, 25% and 40% to study the response of the system in this scenario. These increases are equivalent to withdrawing additional 10239m^3/d or 118l/s, 17065m^3/d or 197l/s and 27304 m^3/d or 316 l/sec over the whole catchment, respectively and the increased withdrawals were distributed among the existing wells (not assigned as new wells). Model simulated results of stream base flow, water table elevations and subsurface outflow in the scenarios were compared with model calculated steady state results, and the differences showed the response of the system to the assumed scenarios.

Accordingly, increasing the steady state withdrawal rate by 15% resulted in reductions of stream leakage by about 1.4%, subsurface outflow by 3.4% and average groundwater level by 70cm compared to the steady state value. Increasing the steady state well discharge by 25% resulted in reductions of stream leakage by 2.4%, subsurface outflow by 6.4% and average water level by 1.3m (with a maximum of 3m and a minimum value of 0.2m). Similarly, increasing the steady state withdrawal by 40% resulted in reduction of calculated stream leakage by 7894m^3/d, which is 3.7% of the calculated steady state value. This reduction is due to falling of groundwater table, which used to feed the streams, below stream bottom elevations at some stream reaches. The average groundwater level decline in this scenario was about 2m with a minimum of 0.14m and a maximum of 5m. In addition, the effect of increasing well withdrawal has influenced the steady state estimated sub surface outflow. The steady state estimated value was about 6,679m^3/d (includes discharge of Aba Samuel gorge springs and additional sub surface outflows) and this scenario simulation decreased the out flow by 9.1%. This result is summarized in table 6.4.

Thus, additional groundwater pumping would most likely result in a decline of groundwater levels and a reduction in natural discharges based on the intensity of pumping (shown in figure 6.4). These observed changes simply represented regional effects of the proposed groundwater withdrawals. In fact, water levels in individual pumped wells are likely lowered depending on local aquifer properties, well construction and well location relative to surface water bodies. Water level changes in individual wells can be exaggerated or diminished relative to the regional representative value. From the above three simulation results, one can observe that the development of new groundwater sources would not pose appreciable impact in case of 15% increase in withdrawal as the head decline in this case is insignificant relative to the steady state withdrawal rate and the natural discharges were not altered highly.

Table 6.4 System response to increased groundwater withdrawal

No.	Increase in groundwater withdrawal from steady state value, in %	Decline in head, in m	Reductions in river leakage, in %	Reduction in sub surface outflow, in %
1	15	0.7	1.4	3.4
2	25	1.3	2.4	6.4
3	40	2	3.7	9.1



N.B Water level change is expressed in meters, and changes in river leakages and subsurface outflows are expressed in percents.

Figure 6.10 Trend of System Response to Increased Groundwater Withdrawal Rates

In the second scenario, increased groundwater withdrawal in the Akaki Well field was simulated to see the effect on groundwater level changes, to understand changes induced on sub surface out flow along the southern limit of the catchment and to evaluate the effect on nearby stream reaches. In this case, the current withdrawal in the well field from active wells (given in table 5.1 as BHs and EPs) was increased to about 108,000m^3/day for scenario test, which is around 3 fold increase. Here, the additional withdrawal was assigned as new hypothetical pumping wells in the well field area. The simulation result indicated that stream leakage decreased by 0.9% relative to the whole steady state value, but showed 12% decrease for Big Akaki River segments near the well field area. The water table declined by 5-8m in head observations in and near the well fields, the highest being in the well field. This head decrease, in turn resulted in decreased subsurface outflow (Aba Samuel gorge springs and additionally simulated outflows) along the southern boundary by 18.4% of the steady state simulated value. From these simulation results it is possible to infer that long term withdrawal at this rate may lead to drying of the Aba Samuel gorge springs and may reverse groundwater flow direction between streams and aquifers due to lowered groundwater level by large amounts compared to steady state amounts.

Generally, if future water demand conditions force groundwater to be withdrawn at rates simulated in these scenarios, other parameters not changed, there will be hydrologic imbalance between groundwater inflow and outflow conditions that may cause sustainable decline in groundwater level. This in turn results not only in source depletion but also may cause pollutants to enter the groundwater system from polluted surface water sources.

To mitigate such large decline in groundwater level, it is necessary to develop alternative water supply options like surface water treatments or to locate productive wells in near by aquifers that may not have hydraulic connections with aquifers in the area under consideration.

6.7.2 Effects of Altered Recharge

This scenario simulates a case of decreased recharge to aquifers that may result from lower than normal precipitation (weather modification) and/or city expansion. It is real that changes in climatic conditions from time to time are affecting precipitation amount in the country adversely and are reducing recharge to groundwater as the main source of recharge is precipitation. From the plot of total annual precipitation at Addis Ababa Observatory for the years 1980 to 2004 (shown in figure 2.2) it was clearly observed that there is a general declining trend in rainfall pattern, and also base flow (that can approximate recharge roughly) for Big and Small Akaki Rivers (from years 1992 to 2003) showed a general decline of about 0.5 to 1%(rough estimation) per year. In addition, as the city is expanding and different construction activities are currently active in the area, this may hinder water to reach surface/soil because of roof interception and sealing of ground with impervious surfaces, leading to higher runoff. Although difficult to quantify exactly, other factors assumed unchanged, the future decrease in recharge amount will be inevitable and rough estimates made above can be used to study system response. So, it was found important in view of the modeler to test the response of the hydrologic system to such a scenario such that alternative remedial measures may be proposed, based on the simulation output, to keep groundwater level in a steady state condition.

Based on the maximum decline of dry period base flow (1%) per year given above, that may approximate maximum recharge decline roughly, a 20 years period was assumed to study system response. Therefore, in this scenario the simulated response of the system to decreased recharge was compared with the steady state simulated water level, stream leakage and subsurface outflow; and the differences showed changes induced due to the decreased recharge. The steady state simulated recharge was decreased by 20% and the simulation results showed an average head decrease of 5.6m over the whole area; with highest fall of 16m in wells to north and a minimum of about 0.75m in wells to south. In addition, the stream leakage showed a substantial decrease compared to the simulated steady state value and the change was about 15.8%. The sub surface out flow showed a decrease of about 5% and this value was smaller than expected as head decline along the southern part of the area was relatively lower because of reduced leakage of groundwater to surface water.

So, solutions should be forwarded to tackle such environmental unfriendly problem. One means of reducing such an effect is by enhancing artificial recharge from residential roof top runoff during intensive precipitation. Run off can be collected from residential areas (especially Addis Ababa area) through artificial channels constructed for this purpose that can direct runoff to areas of recharge or it can be retained in reservoirs for later time recharges. This will reduce storm water flows and result in an increase in groundwater recharge so that water level declines can be reduced. In addition, under such conditions, withdrawal will not cause depletion of base flow, and reductions in sub surface outflows will substantially be reduced. This will keep water level and fluxes to be restored more or less to balanced conditions.

6.7.3 Effects of Dried Lakes/ Reservoirs

The source water stored in lakes/reservoirs like Aba Samuel, Dire, Gefersa and Legadadi is either runoff during precipitation or leakage from groundwater system. In this numerical model simulation, two of them were represented as constant heads and two as general head boundary conditions as they were expected to have an interaction with groundwater system based on their respective heads (discussed in previous sections). These lakes/ reservoirs are all artificial surface water bodies constructed for different purposes and have got a direct or an indirect influence on groundwater of the area. Hence, this scenario is intended to test the response of the system in the absence of interaction of groundwater system with these surface water bodies.

The simulation results showed an average rise in groundwater level by 5m compared to the steady state simulated water level, with maximum value of 12m in wells near Aba Samuel Lake. Wells close to Dire and Gefersa dams showed head decline of around 4m .Wells near Legadadi dam and that are at distance from the reservoirs showed little or no head changes. Leakage to streams increased by 11.1% compared to the steady state simulated amount, which might be due to elevated groundwater level relative to the stream bottom elevations. For the same reason, the subsurface outflow along the southern tip of the catchment was increased three folds. In general, as the simulation results showed, there is a groundwater leakage from aquifer systems to these lakes/ reservoirs under the existing water level. Therefore, in the absence of interaction of groundwater with these surface water bodies, a general groundwater level rise was observed. In fact, there are some exceptions to this general conclusion as those low pumping wells whose cone of depression doesn't expand longer were not influenced by this effect. Thus, in addition to runoff that enters into the reservoirs/lakes during intensive precipitation, the groundwater leakage to the lakes plays an important role for the existence of the lakes.

6.8 Model Limitations

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 groundwater flow models are only approximations of complex natural systems and have uncertainty. Therefore, it is essential that for any groundwater model to be interpreted and used properly these limitations be understood.

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

- Simulation of the groundwater system was based on various assumptions regarding the real natural system being modeled. In this study, some of these assumptions were that the system was represented as single layer, the aquifer is unconfined and simulation was made assuming that the system is under steady state condition, which can never be known in the absence of long term water level data. Another deficiency is lack of understanding of a detailed geology in most parts of the area. Complex geology controls groundwater 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.
- The whole study area was discretized in to a number of cells of equal size (400m by 400m) and input into the numerical model for simulation. The level of discretization used was too coarse to incorporate the effects at local scale, like the effects of structures (faults like Filwuha faults and other minor faults and lineaments). 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.

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 Akaki River Catchment, in this study, as all the limitations and uncertainties involved were clearly stated, it is possible to assume the model to be reliable and good, and that it cannot be misused .Therefore, the model outputs should be interpreted and applied by considering all these associated limitations. 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.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Groundwater takes the lion's share in water supply of the area as parts of the city and different institutions or industries rely on groundwater sources for their water demands. Therefore, the potential of this precious resource should be properly assessed and managed using different hydrogeological investigation methods like flow models.

Akaki River catchment is found in the western Ethiopian highlands of the Shewan Plateau, and partly in the Rift valley floor western margins. The modeled area is part of Akaki River catchment that is found at upstream of Aba Samuel Lake and with an area of 1460km^2.

In this study, a homogeneous, an isotropic and a single layer aquifer was considered. Water level data was collected from 122 wells and the hydraulic relief between the maximum (2588m in head water areas in the northern part) and minimum (2007m in low lying areas to the south) measured water levels in wells used for observation was about 581m. Groundwater contours and flow directions were determined based on these observed heads. The general trend of groundwater flow direction was determined to be from north to south, with some local variations. The flow trend conceptualized using hydrogeochemistry was nearly similar to that determined from water level data. Accordingly, cold water samples from northern part of the catchment were found to have lower Na / ∑of cations, Ca+Mg / Na+K, TDS or EC, PH and higher Ca / Mg ratios. This values change following a trend to south and this trend was used to infer flow direction.

Groundwater recharge is from precipitation and the amount is higher for the northern part relative to southern or central zones of the catchment. Outflows from the groundwater system include well withdrawal, subsurface outflow, base flow to rivers and springs discharge. The inflow and outflow values agreed with in reasonable limits given the limitations in estimating the different flow components.

Numerical groundwater flow model was used to study the response of the Akaki River catchment groundwater system to different scenarios. As numerical groundwater flow models represent the simplification of complex natural systems, different parameters were input into the conceptual model to represent the system in a simplified form.

The model was calibrated using contours constructed from heads measured in 122 observation points. Recharge, hydraulic conductivity and stream bed conductances were varied within reasonable limits during model calibration. Model calibration was considered sufficient when observed heads and simulated heads were within the calibration criteria set during calibration, which includes visual comparison of simulated heads to calculated heads and fitting 80% simulated heads to calculated heads within a maximum difference of about 15m. Large differences between calibrated and observed heads at some places were due to lower degree of accuracy of model input parameters, overall limitations of the model design like coarser grid size, or due to error in observed heads, etc. The simulated inflows and outflows in the steady state model were within reasonable limits of the observed inflows and outflows. The difference, especially lower observed inflow, was due to under estimation of recharge or exaggerated estimates in one component of outflows.

Model simulated heads were found to be sensitive to recharge and hydraulic conductivity, but the degree varied from northern to southern part of the catchment. The northern part is more sensitive to changes in these parameters than the southern part. In addition, varying recharge and hydraulic conductivity on stream leakage showed that changes in simulated leakages are directly related to changes in these parameters. In general, if a model is more sensitive to one parameter than the others, the degree of uncertainty of that parameter will have a greater effect on the model results than the other parameters. So, in case of future detailed groundwater modeling, case has to be taken in calibrating these parameters to which the model was most sensitive.

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

Accordingly, an increase in well withdrawal by 15%, 25% and 40% over the whole catchment resulted in an average decline of the steady state water level by 70cm, 1.3m and 2m, respectively and caused the steady state stream leakage to be reduced by about 1.4%, 2.4% and 3.7%, and subsurface outflow by 3.4%, 6.4% and 9.1%, respectively. Similarly, increased groundwater withdrawal in the Akaki well field by three folds compared to the steady state value resulted in reduction of the steady state calculated river leakage by 12% for river segments near the well field. This withdrawal resulted in head decline of about 5-8m in wells in and near the well field areas; the highest being in wells located in the well field. This localized increase in well withdrawal resulted in reduction of subsurface outflow by 18.4% relative to the steady state simulated value.

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 was manifested by reduced stream leakages, springs discharges, groundwater outflow or reduction in other discharge mechanisms. In addition, it also can induce recharge from polluted surface water bodies such as streams or lakes causing water quality deterioration.

In the second scenario, a 20% decrease in recharge was considered to examine the response of the system. The simulation resulted in an average head decline of about 5.6m, with highest fall of 16m in wells to the north and minimum of 0.75m in wells to south. This scenario simulation has resulted in a decrease of river leakage by 15.6% and subsurface outflow by 5% compared to the steady state simulated amount.

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

7.2 Recommendations

Based on the overall numerical simulation process of the Akaki River Catchment and the results of the model, the following recommendations were forwarded:

- The concerned bodies should be worried about the increasing demands on water supply and develop a means that would minimize the flow of water that is not suitable for domestic use at present and design sufficient hydrologic database from which future public supply sources can be proposed.

- The groundwater yielding potential of aquifers in the whole catchment should be known and a maximum withdrawal limit over the whole catchment should be set.

- Detailed recharge estimation has to be carried out by combining methodologies like chloride mass balance with convectional methods so as 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 divide the aquifer system into different layers and estimate their respective hydraulic parameters. This is useful to carry out a three dimensional groundwater flow model simulations properly and efficiently in the area.

- Sufficient groundwater level monitoring wells should be placed in the whole catchment in order to understand the general fluctuations in groundwater levels. This helps to carry out transient groundwater flow modeling, so that system response can be predicted with greater confidence.

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

- As the groundwater impact in the area reaches Dukem plain, the southeastern boundary of the catchment should be properly represented using an appropriate boundary condition.

- 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.

- Alternative water supply sources like large scale surface water treatments or groundwater from different aquifer systems in nearby areas should be developed to alleviate sustainable groundwater level decline in the area.

REFERENCES

AAWSA, BCEOM, SEURECA and TROPICS (2000). Addis Ababa water supply project - stage III A groundwater - Phase II, modeling of Akaki well field, V1, Draft main report. Addis Ababa Water and Sewerage Authority, Addis Ababa, Ethiopia.

AAWSA and SEURECA (1991). Addis Ababa water supply project stage III, detail report, and Groundwater resource, V4. Addis Ababa Water and Sewerage Authority, Addis Ababa, Ethiopia.

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

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

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 Gizaw (2002). Hydrochemical and Environmental Investigation of Addis Ababa Region, Ethiopia, Ph.D Thesis, Faculty of Earth and Environmental Science, Luidwing –Maximillians-University of Munich, Germany.

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 groundwater flow for a pond-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, groundwater 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.

Daniel Gamachu (1977). Aspects of climate and water budget in Ethiopia, Addis Ababa University press, Addis Ababa, 71p.

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

Dereje Nugussa (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.

Ely, D.M. and Kahle, S.C. (2004). Conceptual model and numerical simulation of the groundwater-flow system in the unconsolidated deposits of the Colville River Watershed, Stevens County, Washington: U.S. Geological Survey Scientific Investigations Report 2004-5237, 72p.

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

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 groundwater flow in the upper Deschutes Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 03–4195,84p

Hailesellassie 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, groundwater 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 groundwater levels, Grand Rapids area, Minnesota: U.S. Geological Survey Scientific Investigations Report 2005–5139, 13p

Kazmin V et. 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 survey 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, Addis 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, AA.

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 groundwater-flow models of surfacial 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.

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: Ethiopia J. Sci., 16(2): 43-59, Addis Ababa University.

Tamiru Alemayehu, Dagnachew Legesse and Tenalem Ayenew (2005). Hydrogeology, Water Quality and the Degree of Groundwater Vulnerability to Pollution in Addis Ababa, Ethiopia.

Tenalem Ayenew (1998). The Hydrogeological System of the Lake District Basin, Central Main Ethiopian Rift. PhD Thesis. ITC Publication No.64. Enschede, The Netherlands.

Tesfaye Cherinet (1988) Hydrogeological Map of Ethiopia, Scale 1:2,000,000. Ministry of Mines and Energy, EIGS, Addis Ababa.

Tesfaye Cherinet (1993). Hydrogeology of Ethiopia and Water Resources Development. EIGS, Addis Ababa.

UNESCO (2004). Groundwater Studies. An International Guide for Hydrogeological Investigations. IHP-VI, Series on Groundwater No.3, pp395-399.

Walter, D. A. and Masterson, J.P. (2003). Simulation of Advective Flow under Steady State and Transient Recharge Conditions, Camp Edwards, Massachusettes Military Reservation, Cape Cod, Massachusettes: U.S. Geological Survey Water-Resources Investigations Report 03-4053, 59p.

Yewondosen Mengistu and Dereje Nugussa (2002). Large Dams in Ethiopia. Library Paper, Department of Geology and Geophysics, Addis Ababa University.

ANNEXES

Annex1 Long term monthly flow of Big Akaki River

Year	Months												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total
1981	2.5	2.5	7.1	6.4	2	2.1	43.6	108.30	109.6	7	3.6	3.5	298.2
1982	4.7	3.7	3	4.5	5.2	3.3	30.3	69.10	37.9	4.5	2.7	2.4	171.3
1983	2	2	1.3	1.4	5.4	5.4	22.5	145.60	56.8	4.9	2.1	1.5	250.9
1984	1.7	2	1.3	1.4	3.2	14.3	86.3	69.30	40.7	3.2	2.2	1.6	227.2
1985	2.2	2.1	2	2.5	7.5	4.6	40.2	159.70	52.2	8.7	3	4.1	288.8
1986	3.2	3.2	5.7	8.3	4.2	9.2	28.7	70.60	41.1	11.7	4.9	1.8	192.6
1987	2	2.2	7	11	10.4	8.3	23.2	33.60	8.9	2.6	2	2.8	114
1988	3.4	3.6	2.9	5.2	3.1	4.4	25.3	80.70	63.9	12.3	5.9	3	213.7
1989	2.6	3	2.7	7.1	4.4	6.3	48	150.20	60.6	6.3	3.8	4.3	299.3
1990	3.9	8.6	9	16.9	5.1	6.8	39.8	173.30	55.7	11.9	4.3	4.2	339.5
1991	3.83	4.17	5.14	4.16	3.08	9.50	56.80	148.20	112.30	11.50	8.40	9.00	376.1
1992	2.6	3	1.8	2	2.2	2.4	13.7	40.6	31.7	3.9	2	2.1	108
1993	1.7	2.3	1.5	5.3	3.9	8.4	35.6	77.2	57.6	6	1.7	1.4	202.6
1994	1.2	0.91	1.4	1.5	1.7	2.6	14.7	29.7	21.2	2.8	2.1	1.9	81.7
1995	1.8	2.8	2.4	4.4	2.9	3.2	12.6	47.4	14.7	2.2	1.5	1.6	97.5
1996	1.6	1.1	2.2	2.4	3.6	17.6	56.1	108.5	31.4	5.6	3.7	3.4	237.2
1997	3.42	2.30	2.61	2.30	1.90	3.10	15.00	29.50	6.10	1.80	1.20	0.88	70.1
1998	1.2	1.1	1.1	1.2	4.6	3.3	31	90.9	40.3	9.7	2.7	2.4	189.5
1999	1.90	1.70	1.92	2.30	4.80	5.70	27.80	99.60	16.20	9.20	8.90	6.60	186.6
2000	2.70	1.80	2.33	4.40	6.20	4.70	15.00	50.20	12.80	4.10	2.40	1.80	108.4
2001	1.70	1.90	3.10	3.20	3.60	7.50	44.70	56.20	13.80	2.40	1.90	1.80	141.8
2002	1.90	1.70	2.09	2.80	2.40	8.80	9.40	19.30	8.30	1.60	1.40	1.50	61.2
2003	1.30	1.50	1.40	2.70	4.40	3.80	31.40	69.70	26.60	5.50	–	–	148.3
total	55.1	59.2	71	103	95.8	145.3	751.7	1927.4	920.4	139	72.4	63.6	4404.7
average	2.4	2.6	3.1	4.5	4.2	6.3	32.7	83.8	40	6.1	3.1	2.8	191.6

Annex 2 Monthly runoff of Big Akaki River

	Months											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	5.88	4.617	5.805	4.97	5.271	10.243	73.727	318.984	46.766	27.851	25.767	20.268
2000	8.282	4.946	6.837	13	12.69	12.236	38.144	160.483	-	12.191	7.072	-
2001	5.111	4.379	9.129	6.43	10.39	18.837	137.05	171.528	40.621	7.198	5.468	5.393
2002	5.889	4.579	6.414	7.47	5.475	10.334	44.33	59.527	24.575	4.829	3.986	4.657
2003	3.917	4.272	4.052	7.32	4.343	8.441	73.02	232.724	80.672	16.141	-	-

Annex3 Long term monthly flow of Small Akaki River

Year	Months												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total
1992	0.16	0.14	0.14	0.38	1.47	1.99	14.69	95.87	165.89	10.3	1.24	1.03	293.3
1993	1.06	1.22	0.77	4.24	1.3	3.75	70.81	465.48	290.4	22.8	1.54	0.55	863.9
1994	0.14	0.16	0.56	0.3	1.9	5.31	18.48	132.03	158.77	19.4	4.48	3.12	344.6
1995	2.87	2.96	2.41	5.51	2.58	4.2	48.51	288.85	98.97	10.2	3.85	3.47	474.4
1996	0.99	0.13	0.51	0.57	3.08	14.49	120.8	1230.1	286.57	9.65	4.52	3.57	1674.9
1997	3.53	2.09	2.05	2.73	2.58	4.88	72.99	230.68	43.4	9.72	9.79	2.76	387.2
1998	2.62	3.92	7.86	8.57	12.5	17.55	289	1249.9	860.15	54.9	6.07	4.66	2517.6

1999	0.1	0.083	0.075	0.06	0.07	0.38	4.22	68.24	22.25	2.33	0.196	0.12	98.1
2000	0.11	0.094	0.097	0.13	0.18	0.513	3	12.69	6.701	1.14	0.37	0.19	25.2
2001	0.17	0.113	0.66	0.206	0.69	2.3	6.36	16.4	6.74	1.14	0.37	0.17	35.3
2002	0.19	0.111	0.15	0.124	0.07	0.3	3.79	8.67	4.54	0.28	0.134	0.19	18.5
2003	0.13	0.098	0.101	0.53	0.1	0.3	3.79	8.67	4.54	0.28	0.134	0.19	18.9
total	12.1	11.1	15.37	23.35	26.5	55.9	656.3	3807.5	1948.9	142	32.69	20	6751.8
average	**1.01**	**0.93**	**1.28**	**1.95**	**2.21**	**4.7**	**54.69**	**317.29**	**162.41**	**11.8**	**2.72**	**1.67**	**562.7**

Annex 4 Monthly runoff of Small Akaki River

	Months											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	2.05	1.54	1.542	1.191	1.433	7.515	86.205	1395.1	440.31	47.641	3.869	2.392
2000	2.182	1.8	1.974	2.55	3.621	10.159	61.39	259.6	132.6	23.2	7.269	3.81
2001	3.42	2.08	13.444	4.07	14.08	46.32	130.1	335.3	133.3	-	-	3.462
2002	3.802	2.04	2.983	2.45	1.513	5.063	77.45	177.3	89.82	5.803	2.647	3.877
2003	2.745	1.81	2.074	10.5	2.119	-	-	-	-	-	-	-

Annex 5 Monthly rainfall at different stations

station: INTOTO

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1989	4	75.8	105.4	181.2	5.8	98.2	409.5	323.4	293.9	11.7	0	14.5	1523.4
1990	0	156.6	42.5	117.9	17.6	100.5	325.1	499.7	180.8	x	1.5	0	1442
1991	12.8	64.9	156.2	37.5	37	171.2	258.5	395.2	146.7	1.4	0	44.2	1325
1992	52.4	31.5	14.6	42.7	84.6	131.6	247.8	387	188.6	42.4	0.7	8.1	1232
1993	15.3	44.6	5.7	147.5	49	123.3	266.1	407.6	183.2	28.7	0	0	1271
1994	0	0	62.2	56	91	154	336.3	306.9	142.5	0.3	24.4	0	1173
1995	0	96.3	29.7	186.1	84	98	297	222.1	133.7	5	0.2	22.7	1174
1996	31.1	12.2	121.6	78.3	95.2	242.7	387.2	493.9	x	1.2	0.6	0	1464
1997	21.2	0	18.6	77.3	27.4	76.3	256.3	240.8	89.3	88.3	90	0.2	985
1998	25.3	25.3	45.2	47	149.5	149.2	369	376.3	134.4	44.5	0	0	1365
1999	15.8	6.3	34.9	25.4	37	127.7	283.1	280.4	105	54.7	0.2	0	970
2000	0	0	5.2	108	91.4	110.7	252.8	359.1	132.8	17.2	33.5	1.7	1112
2001	20.6	5.5	142.1	29.8	141.7	164.3	285.6	321.4	92.5	52.4	0	1.8	1257
2002	16.8	50.4	88.8	67.4	49.2	138.7	293.1	262.9	97.1	10.7	0	28	1103
2003	5.2	11.9	57.1	117.3	14.5	188	370.7	248.9	136.1	0	6.8	25.6	1182.00
2004	28.8	31.3	46.7	124.6	13.8	166	271.9	334.7	124.8	49.7	1.1	x	1193
total	249.00	612.6	976.5	1395.5	988.7	2240.4	4910	5460.3	2181.4	408.2	159	146.8	
average	15.6	38.3	61	87.2	43.2	102.2	265.3	317.1	138.4	27.2	9.9	9.8	1115.2

Station:
SENDAFA

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1991	15.9	20.5	118.1	0.5	x	x	x	218.9	134.5	9.4	0	5.6	523
1992	10.7	46.5	1	29.1	32.5	69.6	257.5	357.9	151.4	55.5	0	0	1011
1993	4.3	105.2	0	x	x	x	457.2	353	158.4	13.7	0	0	1091
1994	0	0	0	64.1	11	130.7	337.9	184.1	122	0	6.4	0	856
1995	0	11.4	106.2	116.7	42.9	22.5	230.8	338.8	x	0	0	0	869
1996	69.4	5.6	99.3	x	x	187.2	341.3	338.6	121.4	0	0	0	1162
1997	44.5	0	29.4	60	44.8	149.7	303.8	251.1	84.7	72	34.6	0	1074.6
1998	28.9	23.3	5.8	27	38.2	68.8	359.1	289.7	152	98.9	0	0	1091.7
1999	0	1.2	56.3	11.8	25.4	144.7	441.6	365.2	74.8	79.6	0	0	1200.6
2000	0	0	0	44	87.9	166	352.2	373.4	113.9	5	10	0	1152.4
2001	0	35.3	154.1	9.2	135.2	149.5	335.5	276.8	27.4	9.8	0	0	1132.8
2002	21.2	3.4	67.2	20.6	60.9	144.4	246.8	289.1	85.4	0	0	27.4	966.4
2003	75.5	0	29.7	126.9	1.7	120.6	304.4	373.4	122.4	0	0	19.7	1174.3
2004	21.2	7.1	2.2	118.9	0	69.8	307	303	30.6	0	0	0	859
total	291.6	259.5	669.3	628.8	480.5	1423.8	4275	4313	1378.9	343.9	51	52.7	14167.1
average	20.8	18.5	47.7	52.4	43.7	118.6	328.8	308	106.1	49.1	3.6	3.8	1101.1

Station: AKAKI MISSION

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total
1975	0	0	3.8	107.2	58.5	175.2	347.2	308.3	281.6	19.9	0	0	1301
1976	0	17	19.5	92	93.8	195.3	282.4	325.3	83.6	7	46.6	0.5	1163
1977	80.5	29.9	80.8	67.4	108.2	158	289.7	329.4	108.4	225.7	5	0	1483
1978	2.4	84.4	607	50.4	39.7	153.8	150.6	328.2	194.6	45.5	0	0	1656
1979	106.4	28.2	107.6	57.6	122	75.9	243.2	241.4	96.5	13	0	4	1095
1980	28.5	36.8	54.7	55.8	56.8	111.8	381.5	364.4	64.4	13.1	0	0	1167
1981	0	13.3	179.8	143.9	1.3	46.2	402.6	186.5	219	5	0	0	1197
1982	12.1	35.4	39.5	94.6	75.2	63.5	199.6	275.1	124.2	25.8	11	8.1	964
1983	1.8	33.3	15	147.3	175	83	278	275	138.7	9.2	0	0	1156
1984	0	0	40.4	5.1	130	215.3	277.9	227.1	57.2	0	0	1.9	954
1985	3.6	0	32.4	71.8	96.6	96.5	294	324.1	164.3	1.6	0	0	1084
1986	0	95.4	66.9	148.7	68.2	143.4	189.4	216.5	86.1	9.4	0	0	1024
1987	0	65.6	181.9	80.7	187.7	69.3	202	246.9	81.7	4.4	0	0	1120
1988	0	44.5	0	96	23.8	124.6	255.9	278.1	254.2	35.4	0	0	1112
1989	2.1	63.8	53.8	226.3	7.1	58.6	264.2	301	170.9	37.9	0	0	1185
1990	7.7	120.6	48.4	129.4	37.8	78.9	280.7	222.9	117.3	5.8	1.2	0	1050
1991	0	37.6	62.4	11.6	45.6	90.4	263.7	308.5	113.4	4.4	0	56.5	994
1992	34.7	24.2	30.5	15.5	25.6	100.4	218.4	276	86.7	43.3	0.2	0	855
1993	1.2	53.9	5.6	118.4	62.5	116.5	218	251.5	118.3	20.5	0	0	966
1994	0	0	62.7	72.2	20.2	125	251	168.9	106.8	x	11	0	817
1995	0	25.4	63.7	102.1	20.9	95.7	269.2	242.3	79.5	0	0	4.8	903
1996	15.3	0.3	79.7	38.8	90.5	240.1	292.5	234.1	119	1.9	0	0	1112
1997	27.6	0	29.5	102.7	25.2	57	203.6	203.4	82.5	114.9	10.3	0	856
1998	32.7	30.2	19.6	69.3	159.9	116.9	207.8	280	118.5	36	0	0	1070
1999	1.3	1.8	91.8	12.1	44.7	92.8	282.6	300.7	61.7	65	0	0	954
2000	0	0	29.1	93	64.9	100.1	188.9	210	124.1		23.4	3.8	837
2001	0	20.7	121.2	23.6	118	142.6	257.5	145	64.9	2.2	0	0	895
2002	31.1	10.5	87.1	82.4	76.6	108	167.3	187	52.4	0.6	0	17.7	820
2003	19.6	24.3	23.9	114	2.9	125.4	325.1	307.4	112.4	0	1.9	0	1056.9
2004	13.6	15.8	62.4	154.2	15.4	95.2	177.7	189.1	80.9	4.8	x	x	809
total	422.2	895.9	2301	2584.1	2054.6	3455.4	7662	7754.1	3563.8	752.3	105.6	96.8	31647.7
average	14.1	29.8	76.7	86.1	68.5	115.2	255.4	258.5	118.8	25.1	3.6	3.2	1055

Station: Addis Ababa Bole

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1980	23..6	26.8	64.3	74.3	44.4	129.1	268.1	214.8	118.6	0	0	0	940
1981	0	42.6	217.5	79	18.4	56.9	273.9	256.1	162.5	24.7	0	2.7	1134
1982	26.6	96.4	90.2	48.1	73.5	63.6	220.3	221.6	142.8	19	40.7	4.9	1047
1983	12.4	41.2	28.9	113.7	186.9	56.1	217.9	213.7	202.2	35.9	0	1.5	1110
1984	0	0.4	11.6	11.6	135	334.2	313.7	180.4	98.8	0	0	7	1092
1985	35.1	0	49.1	130.3	92.8	110.9	209.8	260.8	168.6	29.8	0	0.4	1087
1986	0	37.6	56.2	216.6	37.7	175.2	167.9	222.3	107.4	31.6	0	2.5	1055
1987	0	49.1	180.1	85.7	154.6	71.9	155.9	98.1	57	16.6	0	0.4	869.4
1988	4.7	33.4	6.7	157.9	34.7	93.2	181.4	265.3	187.3	27.3	0	0	91
1989	3.4	33.7	58.4	143.3	0	88.1	218.1	318.6	150	36.8	0	7.9	1058
1990	3.2	161.1	60.4	144.5	25.2	48.3	204.2	413.4	143	46.1	2.1	0	1251
1991	0.2	29.6	134.1	15	7.7	107.5	279.4	287.9	123.1	4.4	2.1	0	991
1992	14.5	28	35	58.6	55	82.2	254.8	223.3	157	64.4	2.2	0.4	975

1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0	0	1207.8
1994	0	0	52.9	70	31.7	112.9	242.2	199.3	100.9	0.5	11	0	2815.4
1995	0	81.3	73.3	140.3	95.9	78.2	165.1	256.9	97	0	0	28.6	1016.6
1996	20.5	5.8	126.2	95.4	128.1	289.7	346.3	312.7	211.4	0.2	0.4	0	1537
1997	29.1	0	22.1	66.8	44.8	128	257	160.7	94.7	58.6	15.3	0	877.1
1998	66.6	40	43.8	99.8	197.7	153.4	270.7	236.8	173.4	139.4	0	0	1431
1999	4.4	0	35	17.8	30.5	104.6	294	270.5	62.8	127.1	0	0	946.7
2000	0	0	17.6	109.7	95.2	102.1	192.9	221.9	157.5	19.6	7.5	0	924
2001	0	10.3	165.3	14.8	106.7	163	274.4	179.1	107.3	10.6	0	0	1031.5
2002	30.6	25.9	79.4	36.6	49.6	109	213.9	233.6	72.6	0.5	0	32.8	884.5
2003	4.8	34.1	48.9	121.9	33	128	226.4	238.4	130.2	4.6	0	33.3	1003.6
2004	26.1	11.7	32.4	104.2	7	120.6	240.6	230.1	122.1	50	0	0	944
total	293.9	841.1	1701	2324.2	1777.6	3063	5898	6008	3338	772	81.3	122.4	
averge	11.756	33.644	68.04	92.968	71.104	122.52	235.9	240.32	133.52	30.88	3.252	4.896	

Station A.A (OBS)

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Rainfall
1980	23.2	36.6	45.3	88.5	54.2	126.2	385.1	297.4	111.9	51.5	0	0	1219
1981	0	75.5	176	82.9	3.9	50.1	266.5	320.9	182.1	13.3	0	5.2	1176.4
1982	48.7	80.9	57.8	103.7	115.9	31.9	259.3	257.9	133.8	64.4	43.2	12.8	3192
1983	18.3	21.7	48.7	117	237	109.3	199.3	244.7	160.9	26.3	0	8.8	3175
1984	0	8	8.8	8.4	127.8	220.8	296.1	295.6	142.4	0	4.4	16.3	1129
1985	14.2	0	17.5	96.3	83.7	112.2	270.4	327.7	205.9	58	3.3	1.2	1190
1986	0	35.7	88	197.6	125.4	179.5	180.1	264.2	127.8	36.1	0	0	3220
1987	0.5	63.4	248.9	82.4	241.3	92.9	196.5	254.4	115.2	21.3	0.8	0.3	1318
1988	9.7	53.4	5.3	144.6	16.6	106.2	277.9	299.3	229.7	59.9	0	0	1203
1989	0.8	75.9	75.7	154.4	0.5	120.9	357.7	325.3	187.7	14.8	0	7.1	1321
1990	0.8	155.9	59.2	106.4	20	88.8	218.7	268.6	184	16.2	6	0	1125
1991	0	74.5	106.6	34.7	55.3	191.1	248.9	262.6	126.4	3.4	0	50	1153
1992	20.2	33.7	20.2	41	52	109.1	248.5	294.7	209.4	69.7	0	2.9	1101
1993	10.8	67.2	16.1	157.9	97.2	208.3	274	426.5	243.3	62.1	0	4.5	1568
1994	0	0	82.4	82.3	63.3	123.4	309.1	223.0.	142	0.5	14.7	0	817.7
1995	0	69	41.5	174.4	68.2	102.9	190.2	314.9	136.1	0	0	48.4	1145.6
1996	28.1	5.2	106.8	128.2	122	258.5	266.4	338.7	294.2	0.2	0.2	0	1548.5
1997	39.2	0	24.5	51.3	38.5	104	272.6	194.3	113.8	62.4	50.3	1.5	952
1998	55.2	20.5	49	48.5	154.2	124.4	285.4	260	213.6	116.9	0	0	1327
1999	2.9	0.3	28.8	16.3	23.8	119.6	268.6	305.3	88.4	55.4	0	0	909
2000	0	0	2.4	49.9	110	144.5	244.8	306.2	250.6	46.4	21.1	0	1176
2001	0	12.2	210.8	25	168	213.5	248	246.4	131.7	14.6	0	0	1270
2002	14.7	21	90.1	56.5	63.1	172.5	255.2	215.9	108.8	0.2	0	16.5	1014
2003	10	34.1	62.6	99.3	20.2	151.8	291.8	233.3	214.1	0.8	1.5	54.9	1174
2004	24.8	20.3	49.5	139.9	30.1	141.9	248.5	268.6	164	76.9	0	0	1164
2005	45.9	51.6											
total	368	1016.6	1723	2287.2	2092.2	3404.3	6560	6823.4	4217.8	871.3	145.5	230.4	
average	14.15	39.1	68.9	91.49	83.69	136.17	262.4	272.94	168.71	34.85	5.82	9.2	1187.4

REFERENCES

- AAWSA and AE, 1993a: Review of feasibility study and preliminary design report, water supply project stage III, Final report, V.1, Main report, 1-1 to 13-8. Addis Ababa water and Sewerage Authority, Addis Ababa, Ethiopia.
- AAWSA and AE, 1993b: Review of feasibility study and preliminary design report, water supply project stage III, V. 2, Appendices, A1– to G 1 –11. Addis Ababa Water and Sewerage Authority, Addis Ababa, Ethiopia.
- AAWSA and AE, 1993c: Review of feasibility study and preliminary design report, water supply project stage III, executive summary, final report, 1-1 to13-8. Addis Ababa water and Sewerage Authority, Addis Ababa, Ethiopia
- AAWSA, BCEOM, SEURECA and TROPICS, 2000: Addis Ababa water supply project - stage III A groundwater - Phase II, modelling of Akaki well field, V1, Draft main report. Addis Ababa Water and Sewerage Authority, Addis Ababa, Ethiopia.
- AAWSA and SEURECA (1991) Addis Ababa water supply project stage III, detail report, and Groundwater resource,V4. Addis Ababa Water and Sewerage Authority, Addis Ababa, Ethiopia.
- AAWSA, TAHAL and SHAWEL (1992) Akaki water supply project feasibility study, V1, main report. Addis Ababa Water and Sewerage Authority.
- Adane Bekele, 1999: Surface Water and Ground Water Pollution Problems in the Upper Awash River Basin, M.Sc thesis, University of Turku Finland.
- Anderson, M.P. and Woessner, W.W., 1992: Applied Ground Water Modeling. Simulation of Flow and Advective Transport, Academic Press. Florida.
- 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 Gizaw,2002: Hydrochemical and Environmental Investigation of Addis Ababa Region, Ethiopia, Ph.D Thesis, Faculty of Earth and Environmental Science, Luidwing –Maximillians-University of Munich, Germany.
- 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 Mnagement 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 pond-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.
- Ely, D.M., and Kahle, S.C., 2004, Conceptual model and numerical simulation of the ground-water-flow system in the unconsolidated deposits of the Colville River Watershed, Stevens County, Washington: U.S. Geological SurveyScientific Investigations Report 2004-5237, 72p.
- Fetter C.W., 1994: Applied Hydrogeology, 3rd ed., Prentice-Hall Inc., Englewood, New Jersey
- 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 Reprort 03–4195,84p
- 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 V et. al., 1980b: Report on the Geological Map of the Ethiopian Rift Valley. EIGS, Addis Ababa.
- Kazmin V., Explanation of the Geological Map of Ethiopia, EIGS, bul. No.1
- Kebede Tsehayu and Tadesse Hailemariam, 1990: Engineering Geological Mapping of Addis Ababa, EIGS, Addis Ababa

- Lamessa Mekonta, 2001: Htdrogeological 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:Techiniques 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
- 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.
- Tenalem Ayenew, 1998: The Hydrogeological System of the Lake District Basin, Central Main Ethiopian Rift. Ph.D Thesis. ITC Publication No.64. Enschede, The Netherlands.
- Tenbus, F.J., and Fleck, W. B., 2001: Simulation of Groundwater Flow and Transported of Chlorinated Hydrocarbons at Graces Quarters, Aberdeen Proving Hround, Maryland: U.S. Geological Survey Water Resources Investigations Report 2001-4106, 51p.
- Tesfaye Cherinet, 1988: Hydrogeological Map of Ethiopia, Scale 1:2,000,000. Ministry of Mines and Energy, EIGS, Addis Ababa.
- Tesfaye Cherinet, 1993: Hydrogeology of Ethiopia and Water Resources Development. EIGS, Addis Ababa.
- UNESCO, 2004: Groundwater Studies. An International Guide for Hydrogeological Investigations. IHP-VI, Series on Groundwater No.3, pp395-399.
- Walter, D. A., and Masterson, J.P., 2003: Simulation of Advective Flow Under Steady State and Transient Recharge Conditions, Camp Edwards, Massachusettes Military Reservation, Cape Cod, Massachusettes: U.S. Geological Survey Water-Resources Investigations Report 03-4053, 59p.
- Yewondosen Mengistu and Dereje Nigussa, 2002: Large Dams in Ethiopia. Library Paper, Department of Geology and Geophysics, Addis Ababa University.