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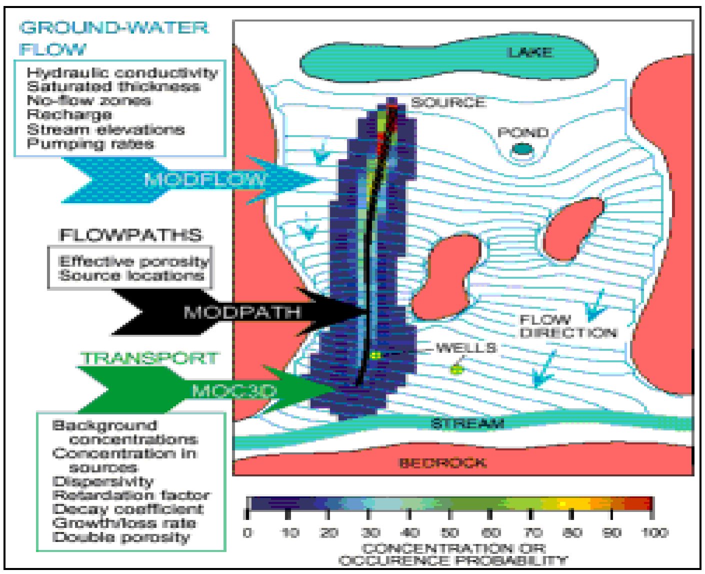
Analysis of Subsurface Contaminant Transport in Akaki Well Field and surrounding areas, Central Ethiopia



A Thesis Submitted to the School of Graduate Studies of Addis Ababa University

in Partial Fulfillment of the Requirements for the Degree of Master of Science in Geo-Environmental Systems Analysis

BY

LETA GUDISSA SHAQA

ADDIS ABABA

July 2007

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUTE STUDIES

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Analysis of Subsurface Contaminant Transport in Akaki Well Field and surrounding areas, Central Ethiopia

By

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Table of Contents

Page

Acknowledgement

First of all, I would like to thank the 'Almighty God', who made it possible for me to begin and finish this work successfully.

It is my privilege to acknowledge the deep-hearted gratitude to my advisors Dr. Asfawossen Asrat, Assoc. Prof., Isotope Geochemistry and Igneous Petrology and Dr. Worash Getaneh, Assoc. Prof., Economic Geology, Department of Earth Sciences, Addis Ababa University, for the discussion and comments throughout the pursuit of this project. Their guidance and constant encouragement made me strong enough to complete the present research work successfully.

The support of Dr. Balemwal Atnafu, Head of the Earth Sciences Department, Addis Ababa University was critical to this undertaking and I wish to thank him for his support, encouragement and cooperation without which it was impossible to carry out the research study. I wish to acknowledge, with thanks the support of the Addis Ababa Water and Sewerage Authority (AAWSA), especially Ato Solomon Waltenigus Senior Hydrogeologist; Ethiopian Institute of Water Technology and Japan International Co-operation Agency (JICA), particularly Ato Shumet Kebede; Water Works Design and Supervision Enterprise, particularly Ato Engida Zemedkun, where I received all kinds of co-operation and data/information needed to conduct my research project and AG-Consult Consulting Hydrogeologists and Engineers Ato Shiferaw Lulu, Senior Hydrogeologist and Deputy Manager for his extraordinary help in sharing his experience, and for his assistance.

Finally, I am indebted to all my colleagues and friends particularly Dejene Legesse who have helped me a lot on technical aspects of the MOD FLOW tool and Mihreteab S/Birhan, Obse Melkamu, and Michael Negussie for proof reading and feedback on my manuscript.

Acronyms

AAWSA:	Addis Ababa Water and Sewerage Authority
AESL:	Associated Engineers Service Limited
COMPLANT:	Chain National Complete Plant Import and Export Corporation
WWDE:	Water Well Drilling Enterprise
BCS:	Black Cotton Soils
JICA:	Japan International Co operation Agency
DEM:	Digital Elevation Model
EPA:	Environmental Protection Authority
CSA:	Central Statistical Authority
UNDP:	United Nations Development Program
ECA:	Economic Commission for Africa
AU:	African Union
SEC:	Specific Electrical Conductivity
GPS:	Global Positioning Systems
CBE:	Charge Balance Error
NE, NW, SE, SW:	North-East, North-West, South-East, South-West
E-W, N-S:	East-West, North-South
UTM:	Universal Transverse Mercator
EMA:	Ethiopian Metrological Agency
EHA:	Ethiopian Highway Authority
GWL:	Groundwater Level
EPM:	Equivalent Porous Media
SWL:	Static water Level
TDS:	Total Dissolved Solids
WHO:	World Health Organization
TNTC:	Too Numerous To Count
CBW:	Clay Bound Water
PCZ:	Persistent Contaminant Zone

List of Figures

Page

List of Tables

List of Appendices

ABSTRACT

The acute need for water in big cities like Addis Ababa calls for an integrated water resources development approach that considers the entailing environmental factors. This task becomes even more pressing as industrialization and development advances. In view of this, the current study aims to identify potential movement of pollutants in a well-field, and specifically to identify the pathways of pollutants and their spatial movement in the aquifer.

The study area, the Akaki well field and surrounding areas including the towns of Kality and Akaki, is located in the Awash drainage basin, southeast of the Addis Ababa city centre. The well field provides more than 30 % of the drinking water supply of Addis Ababa.

A groundwater flow model was constructed to analyze contaminant transport in a fractured system. The model was then calibrated with both under steady state and transient state flow conditions, in order to prove that the model represents the actual conditions. Modeling tools have been eventually used to calculate path lines and travel times of contamination. This approach involved the introduction of particles at contaminant sources upstream of wells and at the well field it self, then identifying the path lines, and determining the spatial distribution of the contaminants through steady state flow field at initial step and finally through transient state flow field.

The individual measured data for nearly 120 wells were interpolated using kriging method and each cell in the model was assigned its value. The well data base is obtained from AAWSA. The physical parameters are well organized; however, the Hydrochemical data are too old and does not indicate real sign of pollution.

The results revealed that the flow lines intersect with the Akaki River in numerous places. Furthermore, the flow lines converge towards Akaki well field from all directions, implying that any contaminated water from the upper part of the aquifer will be pulled into the wells, indicating a high risk of vulnerability of the well field to pollution.

The following recommendations are helpful in curbing the risks posed. Manufacturing activities having pollution potential must be limited in special areas sufficiently far from water supply wells; the chemical quality of groundwater must be monitored and Environmental policy must be implemented with particular emphasis for the protection zones around the well field.

This study generated a model and recommendations that allows decision makers to establish a framework for regulating contaminants that are likely to pose risks to drinking water in the well-field.

1. Introduction

Water is the most important substance for human existence. It is an essential nutrient. Hence, the need for the management of water resources is crucial. This task becomes even more pressing as industrialization and development advances. It is easily fragile resource threatened by pollution. For instance a USA report revealed that cancer mortality due to exposure of groundwater to hazardous chemicals is increasing (Yesehak Worku et al., 1998).

There may be several aquifers layered on top of another that have different water quality. Moreover, the quality of ground and surface waters are linked. Therefore, monitoring, mapping and testing groundwater movement and contaminant flow is important because:

- Most water uses depend heavily on ground water;
- Prediction of contaminant transport needs to be thoroughly understood;
- Contaminant transport analysis and protection of a certain specific area is vital for the success of water resources management, health care of the communities and generally for sustainable development of our society;
- Understanding governing factors such as geology and geomorphology for contaminant transport take major parts in finding solutions for most pollution problems;
- The ability to reliably predict the rate and direction of groundwater flow and contaminant transport in the aquifer systems would be of great value in planning and implementing the remediation of contaminated aquifers.

1.1 Background

The rapid expansion of Addis Ababa city necessitates exploration of groundwater in various localities, by various means. The Akaki well field provides 30 % of the water supply of Addis Ababa. However, it has been indicated that it requires a delicate aquifer management to avoid over-abstraction from the well field (Tamiru Alemayehu et al., 2005). Over abstraction not only shortens the life of the well field but also draws polluted waters from the surrounding highlands. The present study intends to understand the travel time of contaminants from potential sites of pollution in the area to some wells in the well field, as well as the recharge and discharge mechanisms and delineate the path lines of the contamination.

Groundwater flows vertically and horizontally through the aquifers at rates that are influenced by gravity and the geologic formations of the area. As surface and groundwater are intimately linked to each other within the hydrologic cycle, there might be leakage from the highly polluted Akaki river that drains most parts of the city of Addis Ababa.

The quality of well water in this area depends on the location and depth of the wells, as well as the pumping rate of water abstraction. In the area, where large-scale industries have been expanding over the years, pollution due to disposal of untreated industrial waste seems to be imminent. Moreover, manufacturing, quarrying and agricultural activities that increase the influxes of solutes to water are prevalent in the area and locally increasing concentrations from harmless to toxic levels.

The geological as well as structural make up of the area, which is part of the rift system, determines the nature of the aquifers such as the rock matrix, fracture orientations and frequency, and effective aperture width, which in turn determine contaminant flow directions and intensities. The area is densely fractured by lineaments, fissures, fractures and joints trending along the NE-SW, E-W, N-S, and NW-SE directions, which on average follow the regional direction of the East African rift system. Permeability and transmissivity of the rock matrix in the well field are also high, facilitating the accidental and/or deliberate introduction of all kinds of contaminants into the groundwater system and their transport within the aquifer.

1.2 Previous Works

In Addis Ababa and its surrounding areas, both surface and groundwater resources have been investigated in terms of potential, flow models, and vulnerability by a relatively good number of investigators [e.g. Alemayehu , 1983; AAWSA and AESI, 1984; Vernier, et al., 1985; Tesfaye, 1988,1993; AAWSA and SEURECA, 1991; AAWSA et al., 1992; AAWSA et al., 1993 a, b; Anteneh, 1994; WWDE, 1996; AAWSA and COMPLANT, 1997; Eccleston, 1997; AAWSA, 1999; Aynalem, 1999; AAWSA et al., 2000; Gebrekidan, 2000; Alemayehu, 2001; Berhanu, 2002]. EPA (1997) has surveyed pollutant load on three rivers of the city. Abegaz (1999) summarized the state of industrial pollution in Ethiopia in which one of the industrial areas being investigated is the Akaki area. These studies, although they vary in scope and degree of geological and geochemical information, they have stressed that the quality of surface water is often affected by uncontrolled waste disposal of domestic and municipal wastes and industrial effluents. They further indicated that these would have potential impact on the quality of groundwater of the region.

1.3 Statement of the problem

The increasing need for drinking water calls for careful consideration and integration in the development process of all environmental factors.

There is no detailed national investigation which clearly puts and determines precisely how and how far contaminants migrate in subsurface environments of the proposed area, although the continual disposal of unknown amount of sewage, garbage, and even toxic pollutants into Akaki River and its tributaries is clearly observed. Such contaminants may eventually enter into the aquifer system through porous, permeable media that are cut by numerous structures or clay materials that lose their filtration capacity. This may pose not only a problem in utilizing the resource as drinking water but also incurs a huge later investment to clean it, or even impossible to pump the polluted aquifer if once it has been affected by such pollutants.

Since contaminants that reach the groundwater generally move very slowly, continued leakage in one spot will lead to a gradual accumulation. In most natural settings, contaminant accumulations in the environment are not very serious because the natural concentrations of these contaminants are low in waters and soils (Berhanu Gizaw, 2002). The problem aggravates when human activities locally upset the natural cycle. Cities and other residential communities contribute mostly sewage, with traces of household chemicals mixed in. Most industries and factories pour out their effluent through out fall pipes into the environment increasing the variety of pollutants in water resources. Therefore, industries discharge concentrated doses of contaminants into water. Contaminants dissolved in water eventually diffuse into the subsurface rock matrix. This diffusion can act to spread out the contaminant plume in space and time, or to retard it. In situations where transient water flow is involved, water is stored in and released from the rock matrix and this can also draw contaminants to wells. Therefore, modeling the transport of contaminants in a well-field which is clearly under threat by industrial wastes is not only a timely venture but also a strong instrument in alleviating relevant problems of drinking water in a city where the population is increasing at an alarming rate.

Environmentally incompatible industries like skin and hide, chemical, metal and textile factories etc are unfavorably located along the Akaki road. The NO_3^- detected covers a wide range (0.04-241 mg/l); the Mn^{2+} level reached up to 1.5 mg/l; Cd^{2+} in EP-6 well were 19.74 μg/l; and Cr^{3+} was 182 μg/l in Tiliku Akaki river sampled at Akaki bridge (Berhanu Gizaw, 2002). All of them exceed their respective WHO guideline limit (50 mg/l, 0.1 mg/l, and 3μg/l respectively). These amounts are more likely to be originated from industrial activities.

1.4 Objectives

1.4.1 General objective

The general objective of this study is to investigate the mechanism of contaminant transport in the Akaki well field. The work will model the flow paths and distance of transport in the aquifer of contaminants introduced at contaminant sources upstream of the wells. The model will be used to predict the extent of pollution in the well field, which will be eventually used to recommend preventive measures and ways of effective utilization of the groundwater resource.

1.4.2 Specific objectives

In order to use a numerical model on contaminant transport in the well field, the following specific objectives are identified:

- Generate heads by numerical groundwater flow model and calculate velocity distribution;
- Locate critical sources of pollutants by reverse particle tracking;

- Trace out contaminant flow paths leaking from the source into groundwater, and estimate their flow direction and discharge points;
- Delineate capture zones and well head protection areas; and
- Predict the contaminant distribution in time and space.

1.5 Methodology

To describe water flow and transport in fractured systems; the fractured system is represented by a set of matrix blocks of well defined geometry. Then, the MODFLOW package represented by matrix blocks, and an advection contaminant transport model known as PM Path is adopted as methodology (Harbaugh AW, Banta ER, Hill MC and McDonald MG, 2000).

The model simulates three-dimensional solute transport in flowing groundwater using particle tracking to represent advective transport. This involves the introduction of particles at contaminant sources upstream of wells and see the path lines and how far the contamination moves through steady state flow field at initial step and finally through transient state flow field.

The study has been conducted using primary data from several field investigations and secondary data selected from previous works. The modeling was conducted following the procedure below:

- constructing the groundwater model and performing flow simulations;
- calibration of the model both under steady state and transient state flow conditions, in order to prove that the model represents the actual conditions;
- calculating the path lines and travel times of contamination using the modeling tools;

A detailed flow chart is constructed to show the modeling process (fig.1.1).

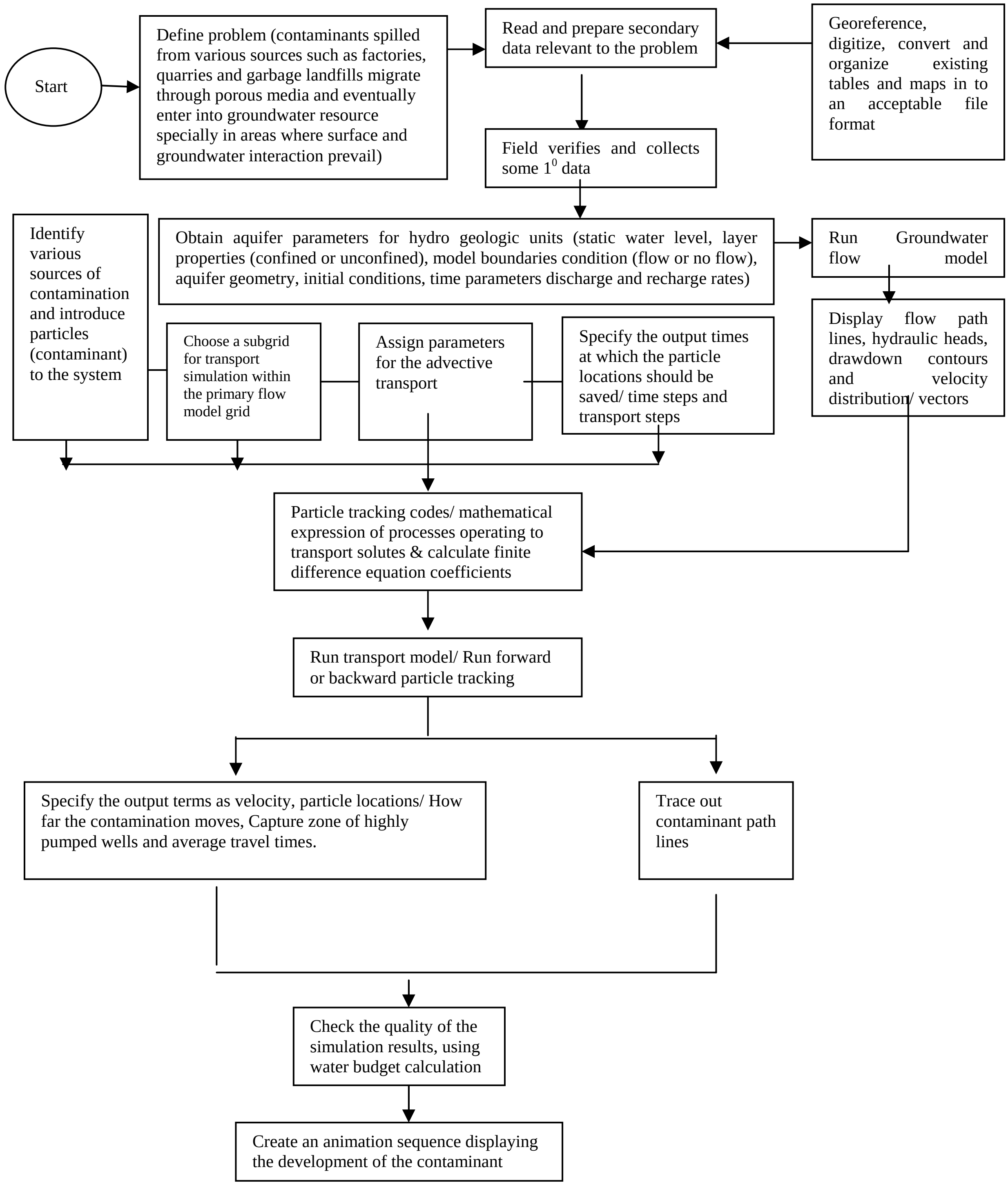

Fig.1.1 The Detailed flow chart for the research work

The development of a model and simulations of the groundwater conditions in the study area basically require the understanding of the geology, hydrogeology, geomorphology and hydroclimatology of the area. This basically required gathering and organizing of primary and secondary data using appropriate soft wares and making analysis to gain reasonable results. Therefore, in pursuit of the overall objectives, this study followed scientifically approved procedures.

Desk work: It focused on literature review and assessment of previous works; preparation of topographic and geological base maps and aerial photos interpretation; data verification (charge balance for selected water analysis, and plotting the result of water analysis on stiff and/or piper diagrams, and geochemical interpretations; collection of field equipment and scientific instruments such as SEC, pH meters, GPS, etc.; organizing data and data input to software; analysis of organized data; and presentation of results using appropriate softwares.

Field work: The principal work included site observation and verification of previous geological map including structural features of the area and its hydrogeological setting.

Post-field work: This work encompassed revision of geological and hydrogeological maps; evaluation of geochemical data, borehole geologic logs and geophysical results from previous studies; data processing using appropriate soft wares mentioned below and preparation and writing of draft and final thesis work.

The following softwares have been used in one or the other stages of the modeling process:

- Global Mapper 7, Golden Surfer 8, and 3D Master for data preparation and in put into the model and presentation; and

- The latest version of Processing Mod flow for data analysis and simulation,

Conceptualization of the groundwater-flow regime is based on data that contain lithologic information obtained from field observations and well logs, hydraulic heads measured in wells, and hydraulic properties determined from pumping test.

1.6 Application of results

The results of this work can be significant contributions to wider investigations on water resources in the city and other parts of the country carried out by relevant Federal, Regional or local agencies, public interest groups or development NGOs. The information required to understand the effects of contaminants released into the environment is centered on understanding the destiny and pathways of contaminant flows.

It also helps to

- understand the fluid-rock interactions in emanating pollutants within the groundwater system;
- get prepared ahead in regulating contaminants that are likely to pose risks to drinking water;
- establish effective prevention strategies to control and prevent further expansion of groundwater contamination;
- establish a framework to alert the policy makers to take the necessary measures;
- create awareness among the public in how man-made activities have caused and will have caused pollution to the environment; and
- prepare a working model in solving similar problems elsewhere in the country.

2. Environmental Setting of the Study Area

2.1 Location and Aerial Extent of the Study Area

The project area lies within the Akaki river catchment (fig. 2.1). It is situated some 23 km south-east of Addis Ababa, in Akaki-Kality sub city and crossed by a railway and the Addis Ababa-Debrezeit road. The study area, which lies between UTM values of 473000-485000 Easting and 970000-986000 Northing, covers an area of about 192 square kilometers. The area of the well field is 16 sq. km, in the lower part of Akaki river catchment. The well field is found in the area between 476000-480500 E and 974700-978000 N (Ayenalm Ali, 1999).

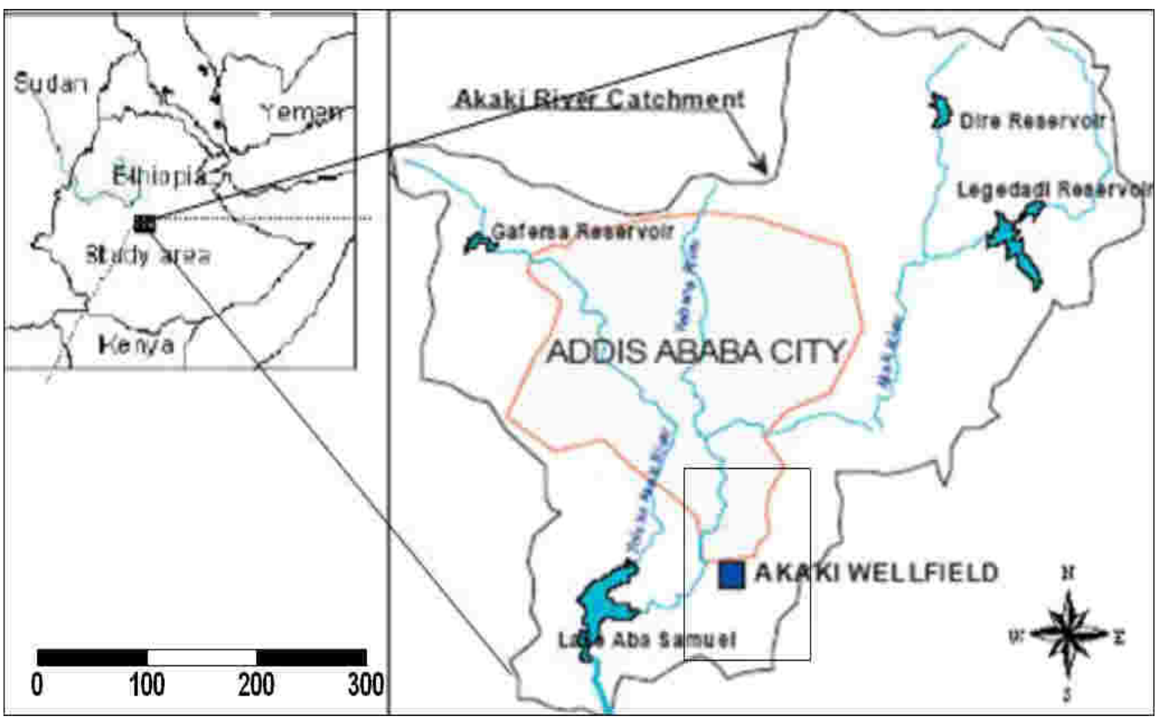

Fig. 2.1. Regional location map of the Akaki catchment with major reservoirs, lakes, rivers and Addis Ababa city in which the Akaki well field is located (modified after Shiferaw Lulu et al., 2005).

The specific study area is delineated from topographic map of SE Addis Ababa (1:50,000), sheet 0838B2, edition 1995 and presented in fig. 2.2.

The map provides information on the size, shape and distribution of features on the land surface, the location of lakes, swamps, springs, boreholes and streams, as well as important cultural information such as the location of buildings, rail roads, and highways.

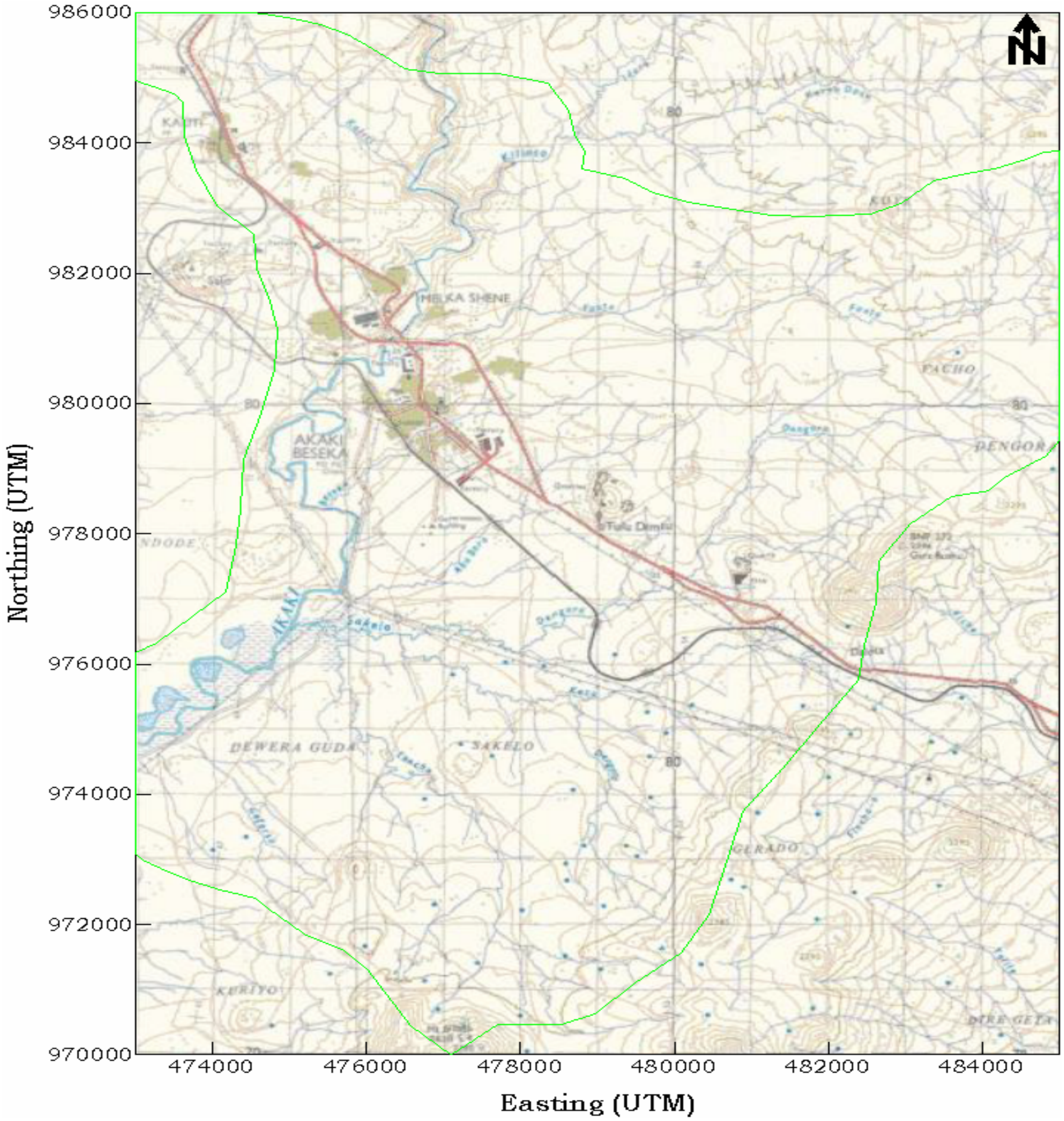

Fig. 2.2. The specific study area is delineated by green line. The map shows well locations, drainages, drainage divides and site topography.

2.2 Geomorphology and Drainage

2.2.1 Physiography

The area is part of the Central Lava Highlands and Massifs, and Awash plain within the Western Highland Plateaus (EMA, 1981). It features diverse topography ranging from isolated volcanic hills in the central east and south to flat plains with elevation of about 2100m in the central west and southwestern portion of the map area. The area is surrounded by trachytic volcanic mountains. The Akaki Beseka Town lies at an elevation of about 2160, where the Salo quarry and Akaki textile factory are located to its North.

The highest elevation in the area is about 2475 meters (Mt.Guji) to the south and the lowest elevation is 2020 meters to the southwest (Aba Samuael lake). The southeastern drainage divide, which separates the Akaki and Dukem Rivers drainage systems, passes very close to the Akaki well field. Volcanic activity resulted in the building up of higher mountain areas such as Mt.Bilbilo-2380m, Mt.Guji-2475m, Gerado ridge-2245m, Gara Bushu-2346m (fig 2.2). The morphology of the study area is a direct reflection of the different volcano-stratigraphic processes, tectonic activities and the action of erosion between successive lava flows. However, generally gentle morphology and flat lands characterize most part of the study area (central and western). The Akaki River forms most of the western boundary. The northern boundary has also relatively flat topography with only minor hills dotted sparsely.

2.2.2 Digital Elevation Model (DEM)

The digital elevation model of the area shows that there is a sharp topographic variation close to the ridge in the south, east and northeast parts, while the area is relatively flat towards the center (fig. 2.3). The

Elevation difference between the peak of the highest ridge and the lowest point in the Akaki River is 520m. Figure 2.4 shows a satellite DEM image (top) and a profile section (bottom) indicating high and low areas along the line of interest.

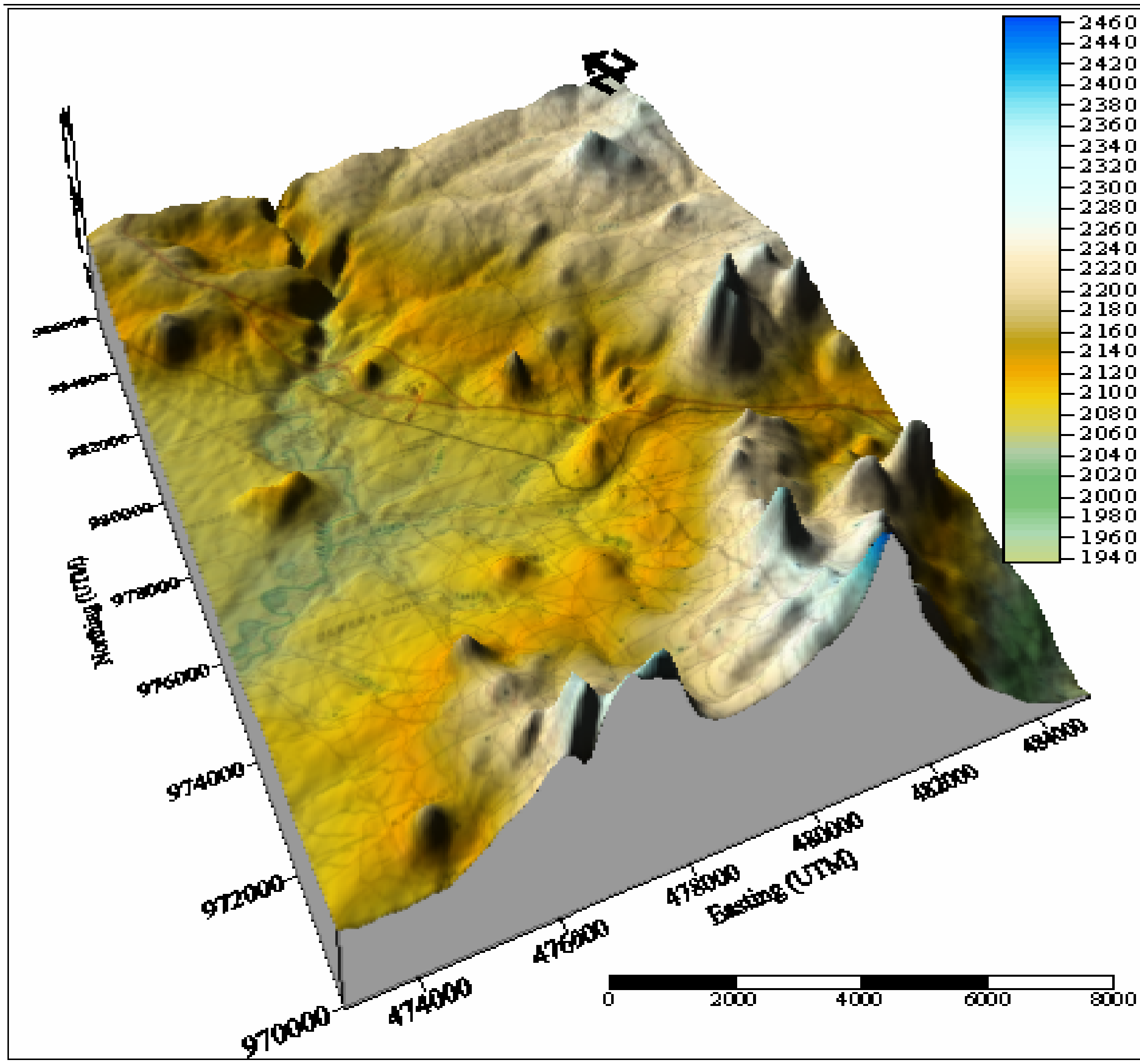

Fig. 2.3 3D Digital Elevation Model of the study area constructed from a topographic map using the Golden software surfer 8.

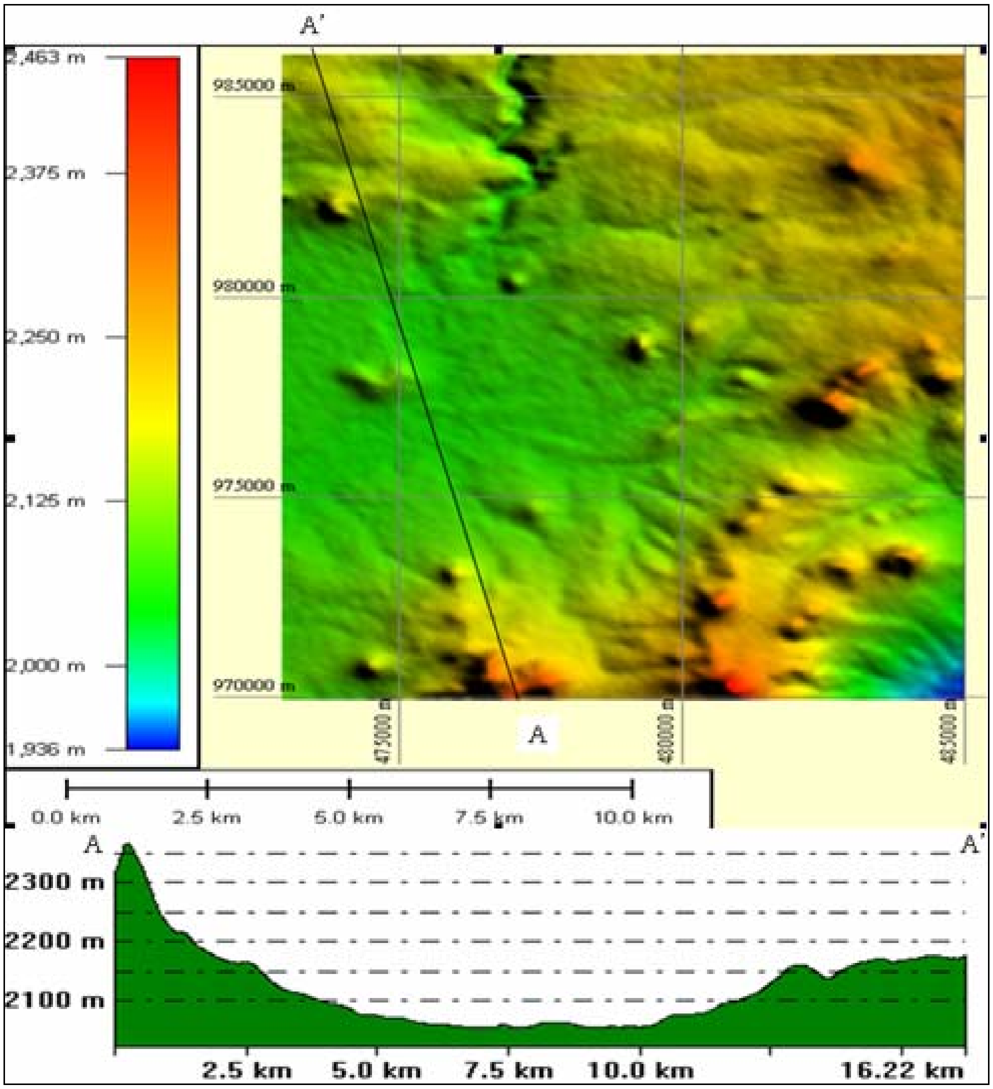

Fig. 2.4 Top view of satellite DEM image of the study area showing relief of the area and a profile along the AA' line.

2.2.3 Drainage

The Akaki well field is situated in the lower part of the Akaki River catchment within the drainage basin of Dengora and Keta which join to form Sekelo, which in turn flows into the Tiliku Akaki River. The drainage in the area in general flows southwesterly to Aba Samuael Lake. Most of the streams in the area are intermittent except the Akaki River. Denderitic drainage patterns are apparent in the region.

2.3 Climate

The Climate of Addis Ababa is Woina Dega (Appendix 1a, b, and c) (Daniel Gemechu, 1974 cited in Yirga Tadesse, 2004). The Rainfall of the area is nearly bimodal (two peaks): the Belg rains (February to May) and Kiremt (main) rains (June to September). The highest rainfall peak is in August. The study area receives rainfall from Atlantic Equatorial Westerly during the main rainy season and from Gulf of Aden and Indian Ocean during March and April months. There is low to negligible amount of rainfall in the other months. Addis Ababa is located in the region where the rainy months are closely distributed.

2.4 Geology of the study area

2.4.1 Regional geology

The aquifers to the north of Akaki well field mainly covering the Addis Ababa city are weathered and fractured volcanic rocks with minor sediments deposited among different series of lava flows. The major lithologic units in the area are listed and described below.

Alluvial and Residual Soils: These soils occur around Aba Samuel lake, Akaki town, small Akaki river and along Akaki rivers. They are quaternary to recent deposits. The thickness of this deposit varies between 5 and 50m.

Akaki, Dukem and Debrezeit Basaltic lava, Spatter and Cinder cones: these are the main volcanic sequences in the Akaki well field. They extend in the area between Akaki and Dukem. They are composed of olivine basalts, scoria, vesicular basalt and scoriaceous basalt. They are volcanic sequences of quaternary time. The well field area consists of relatively thick basalt (20-40m thick but thinner to absent in places, AE-HBT AGRA JV, 1998 cited in Berhanu Gizaw, 2002), 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 and vesicular basalt.

Wechecha Furi and Yerer Volcanic Complexes: these complexes which unconformably overlie the Addis Ababa basalt in the western and southeastern parts of Addis Ababa are composed of trachy-basalts, trachyte, ignimbrite and tuff. They are complexes of Upper Pliocene.

Addis Ababa Basalt (Basalts of Central and Southern Addis Ababa): these are basalts, with porphyritic olivine, porphyritic feldspar, and aphanitic basalt varieties commonly observed as individual flows. They are basalts of Upper Miocene to Pliocene. Palesols and scoriaceous horizons are common in many places at the bottom of flows (Tsehayu and H/Mariam, 1990 cited in Berhanu Gizaw, 2002).

2.4.2 Lithologic Units in the Study Area

Volcanic rocks dominate the study area with subordinate alluvial sediments. The volcanic rocks are the lower basaltic flows and younger basaltic scoria and lava (Aynelam Ali, 1999). The lower basalt flows constitute the oldest outcropping rock unit and the alluvial sediments along the Akaki River and Sekelo stream form the youngest unit. The lower basalt flows are exposed in the western part of the study area. The logs show intercalations of massive basalt, scoriaceous basalt and pyroclastic rocks such as scoria and tuff (Aynelam Ali, 1999).

The eastern part of the study area exposes younger basaltic rocks dominated by scoria cones and associated flows. Scattered cones of basaltic scoria are also exposed in the west, south, southeast and northern sections of the study area. The scoria cones are aligned along northeast-southwest direction, parallel to the trend of rift faults. These rocks are in places covered by recent alluvial sediments.

The lithology at the well field is extremely variable. Mixture of alluvial and lacustrine materials such as sand, clay, gravel, volcanic ash and tuffs are variably found at certain depths. In general, the thickest scoria deposits are located in the EP wells series of the Akaki town water supply situated at the north-eastern part of the well field.

2.4.3 Stratigraphy

The lithologic units in the study area from the oldest to the youngest are: trachy basalt, Ignimbrites, tuff and volcanic ash, Akaki basalt, scoria and scoriaceous basalt, and recent alluvial deposits.

Ignimbrite (Miocene to Pliocene)

Ignimbrite covers the northern part of the study area. It is composed of sanadine minerals. Coarse grained and consists of numerous clasts. They are characterized by columnar jointing.

Trachy Basalt (Pliocene to Quaternary)

The trachy basalt exposed in only few localities along road cut near Akaki mission, along Akaki river gorge near Akaki textile factory, Kality areas, between Tulu Dimtu and EHA quarry, and along Dengora stream (Aynelam Ali, 1999). It is composed of laboradorite, andesine, clinopyroxene, olivine, and augite as phenocryst (Ayenalm Ali, 1999). It is highly fractured and porous. Calcite exists as secondary mineral in veins and may act as a substitute of plagioclase (Haile Selase Girmay and Getaneh Assefa, 1989 cited in Aynelam Ali, 1999).

Akaki Basaltic Lava (Quaternary)

The Akaki basalt flow covers most areas of the Akaki town and surrounding area. It is highly vesicular, olivine (±pyroxene) aphyric basalt. The vesicles are filled with secondary minerals (calcite). The thickness of this unit varies between 10 and 100m. Jointing is common.

Scoria and Scoriaceous Basalt (Quaternary)

Scattered cones of scoria are exposed in many sections of the study area. They are aligned along northeast-southwest direction. They are composed of feldspar and mafic minerals like olivine and pyroxene. It has inclined bedding dipping in NW direction and the thickness of the beds reaches up to 1 meters (Ayenalm Ali, 1999). The scoria deposits are loose basic pyroclastic materials.

Alluvial Deposits (Quaternary to recent)

The detrital materials derived from elevated areas of Entoto, wechecha, furi and yerer are transported and deposited along the Akaki River courses (fig. 2.5) (Tamiru Alemayehu et al., 2005). It covers a small area in the northwest along Akaki River and wider area to the south west. It is a loose material consisting of clay, silt, sand and gravel in different proportions.

2.4.4 Structures and Weak Zones

Addis Ababa is situated at the western margin of the Main Ethiopian Rift. The rocks are subjected to rift tectonics, as manifested in a number of fault systems having a general trend of the rift system (NE-SW). There are also some faults and lineaments oriented E-W, N-S, and NW-SE. Some of the basaltic lava and cinder cones concentrated along southeast to northeast of the well field likely erupted following the NE-SW trending fault systems. A relatively dense fault network and lineaments is observed in the well field (fig. 2.6). Field investigations by AAWSA et al., (1993 cited in Berhanu Gizaw, 2002) suggested that micro-structures such as fissures, fractures, conduits and joints are abundant at the outcrops on the mountain side and deep cut river sides in the vicinity of Addis Ababa which play a key role in facilitating groundwater recharge and contaminant transport. Parts of the Akaki river bed are following the main fault line. This also has its own implication in contaminant percolation at the river bed and migration down the aquifer.

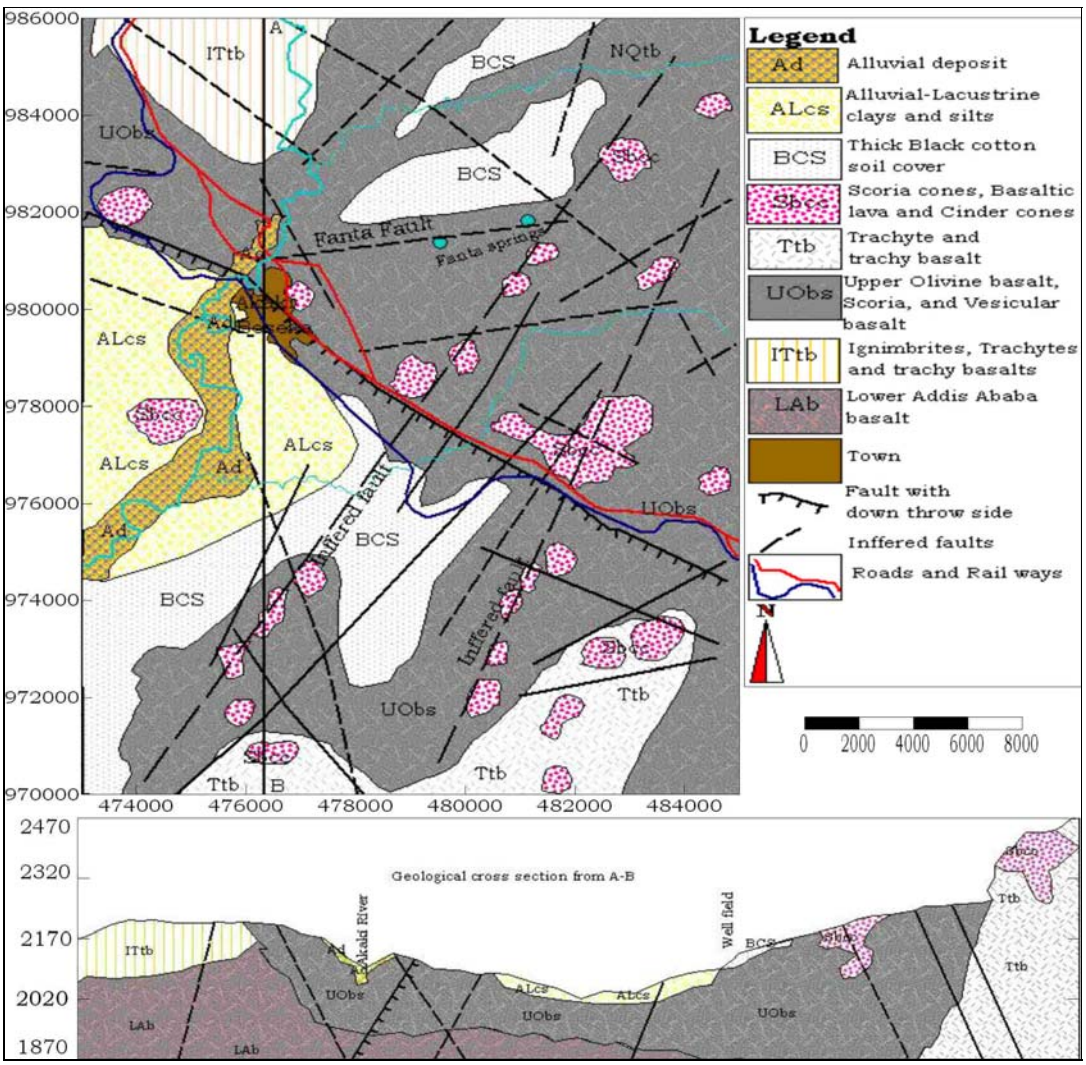

Fig. 2.5 Geological map of the study area (modified after AG consult, 2004). Vertical exaggeration is 5x horizontal scale.

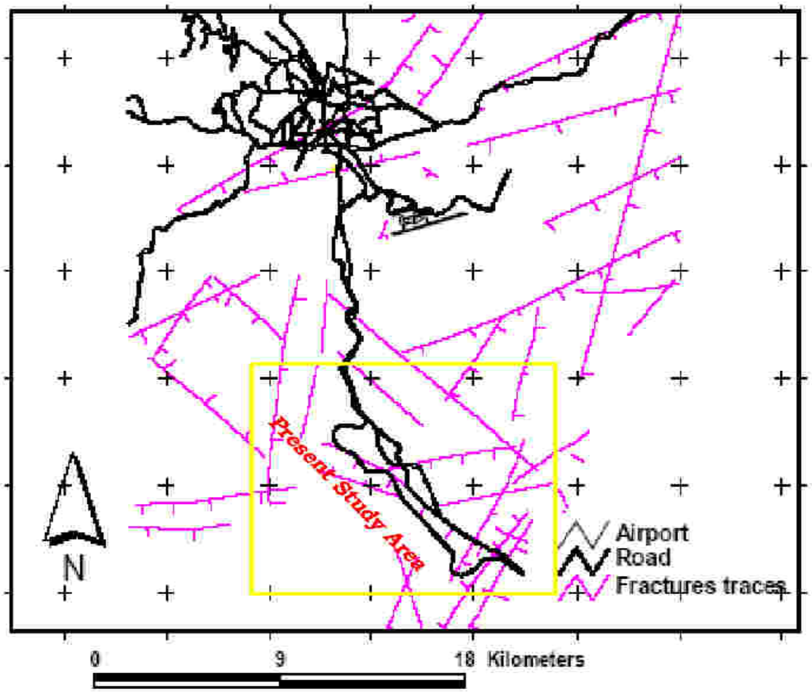

Fig 2.6 Fracture map indicating relatively dense fracture traces in the current study area (modified after Tamiru Alemayehu et al., 2005).

2.4.5 Subsurface Geology from Geological and Geophysical Logs

Lithological logs were used to classify aquifer media, type of vadose zone and depth of soil profiles. An attempt has been made to evaluate the geological log, and resistivity log of the boreholes in the area (Appendix 3). Since resistivity logging is only possible below the static water level, the evaluation of the upper parts of the borehole depends solely on the geologic log.

Variation in resistivity is primarily caused by differences in the character of the subsurface rock and presence of water. Dry formations have poor electrical conductance and show very high resistivity. Increasing water saturation of the pores or cavities in the formation reduces its resistivity; the reduction in resistivity is partially controlled by the porosity. This occurs because water (in its natural condition) is an electrical conductor, and its presence in the interconnected cavities reduces the overall resistivity of the formation. There are, however, general differences in the resistivity of various saturated formations. Silt, clay and shale have very low resistivity, sand and gravel with fresh water have moderate to high resistivity.

In addition to aquifer material, water quality also affects resistivity. Formations filled with highly mineralized water show relatively low resistivity. Water in the fissures containing ions (e.g. Na^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, So_4^{2-}) reduces the resistivity of the rock. In contrast, those saturated with fresh water have relatively higher resistivity (Fletcher & Driscoll cited in Ayenlam Ali, 1999).

The geologic logs of the study area indicate that the major formation of the aquifer is basaltic in composition, while the water quality analysis revealed that the water is generally fresh. Therefore, the shape of the resistivity log curves depends mainly on the degree of fracturing and presence or absence of water. Correlation was found to be difficult due to the lenticular nature of the units, rapid lateral changes within units, and variable dips (due to different centers of volcanic activity depositing materials in different places in various periods). Since rocks of various ages are distributed in the study area aquifer characterization becomes a difficult and complex task.

2.5 Soil media

Black cotton soils cover an area of about 20% of the Akaki catchment (Fig. 2.7). All the soil types in the area have a relatively higher hydraulic conductivity (Berhanu Gizaw, 2002).

Table 2.1 Soil types of the study area based on grain size distribution of triplicate soil samples collected from various soil horizons and representative soil types in the area (modified from Berihanu Gizaw, 2002).

No	Sample	%							
		Cl	**Si**	**Sa**	**Gr**	**Total**	**Cl+Si**	**Cl+ Si+Sa**	**Cl+Si +Sa+Gr**
1	Akaki BCS 1	1.0	8.4	90.6	0.0	100.0	9.4	100.0	100.0
	Akaki BCS 2	1.0	6.9	92.1	0.0	100.0	7.9	100.0	100.0
	Akaki BCS 3	0.9	8.9	90.1	0.0	100.0	9.8	100.0	100.0
	Aver.	**1.0**	**8.1**	**90.9**	**0.0**	**100.0**	**9.1**	**100.0**	**100.0**
2	TuluD1	0.0	0.0	21.7	78.3	100.0	0.0	21.7	100.0
	TuluD2	0.0	0.0	26.7	73.3	100.0	0.0	26.7	100.0
	TuluD3	0.0	0.0	22.7	77.3	100.0	0.0	22.7	100.0
	Aver.	**0.0**	**0.0**	**23.7**	**76.3**	**100.0**	**0.0**	**23.7**	**100.0**

Note: BCS-Black Cotton Soils, TuluD- Tulu Dimtu, Cl+Si-Clay+Silt, Cl+Si+Sa-Clay+Silt+Sand, Cl+Si+Sa+Gr- Clay+Silt+Sand+Gravel, f-fine, m-medium, c-coarse, S-Sand (main), s-sand, s'-sand (rare), U-silt (main), u-silt, u'-silt (rare), G-gravel. The soil was classified based on grain sizes: Clay (<0.002mm); Silt (0.002-0.06mm); Sand (0.06-2mm) and Gravel (2-60mm). The scoria, residual soils and black cotton soils of these types generally expected to have total porosity ranges of 25-50%.

Residual soils are commonly seen in most parts of the area with varying thickness (0.5 to 16m). On the other hand, due to intensive erosional activities, there is poor soil development (shallow soil profile or only patchy occurrences) on most parts of the slopes. Black cotton soil is the dominant type of soils in the area, where erosion superseded by deposition. The variation in the characteristics of soils resulted in variations of infiltration and water holding capacity. Generally, the older basic and acidic rocks are weathered to form thick soil profiles. In places where young basalts and welded tuffs occur, the thickness of the soil cover is reduced (Tamiru Alemayehu et al. 2005). Alluvial deposits are poorly sorted sand to gravel sized sediments, with high porosity, inter-granular permeability, and water infiltration capacity.

The soil consists mostly of mineral grains of varying sizes as well as varying amounts of organic matter. The clay fraction of the soil consists of mineral particles less than 2 µm in diameter. Clay minerals have an unbalanced negative electrical charge at the surface.

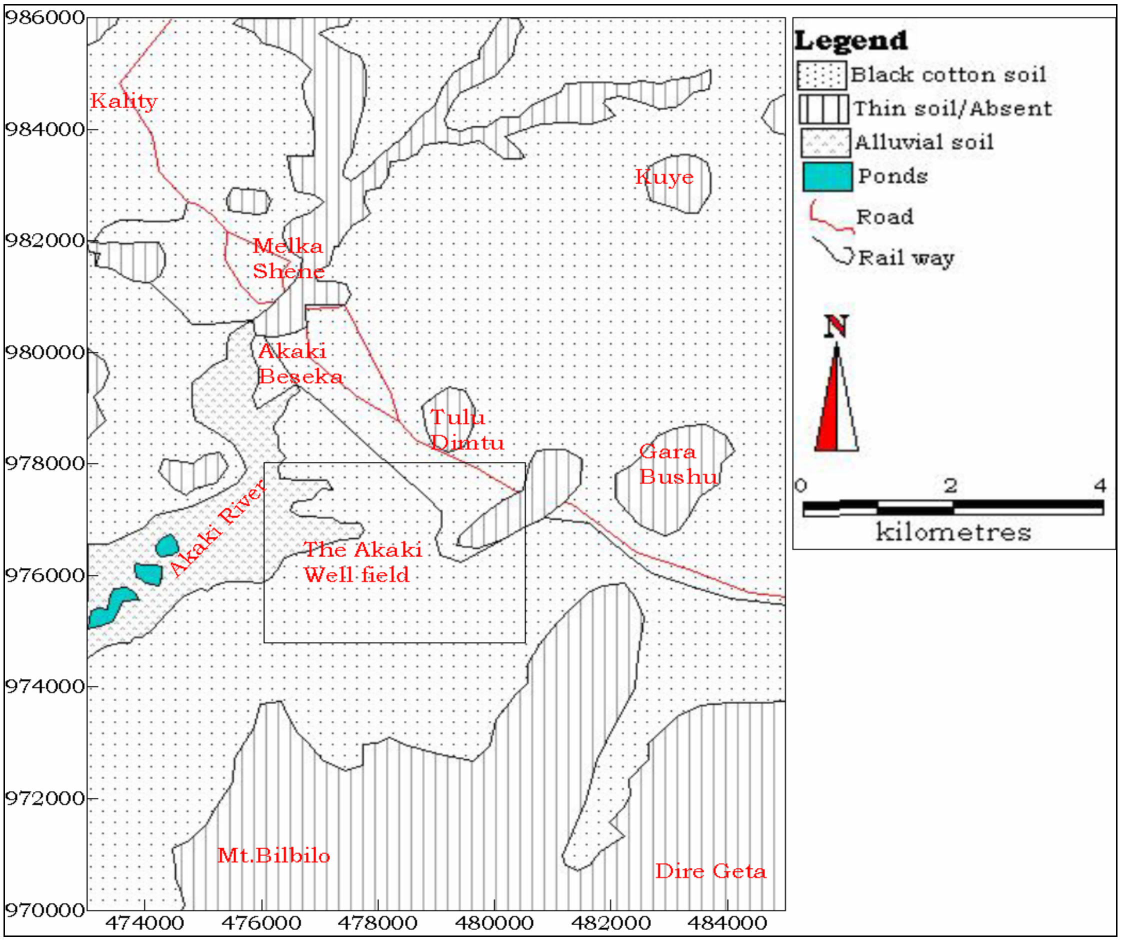

Fig.2.7 Generalized soil map of the area (Modified after Tamiru Alemayehu et al., 2005).

2.6 Land use/Land cover

The general land use pattern of the catchment, though very diverse, was broadly classified into Urban, agricultural and open areas with rock exposures (grazing site) (fig. 2.8). Akaki town and Kality areas represent the urban quarter of the catchment, which is characterized by paved surfaces. In this part of the catchment, most of the rainwater is converted into surface runoff and drained into network of streams and rivers with little water infiltrating into the ground. There are also settlements in Tulu Dimtu, in Dalota, in the area between Dalota and Garado, around sekelo, and Gara Bushu.

The Agricultural area (non-irrigated) covers a large part of the catchment in the east, south and southwest. In this area, cereal crops like wheat, teff and barely are cultivated. Vegetable farms on small plots of land along the terraces of the valleys (big Akaki) are also common. Moreover, in the northern part of the study area such as Kality and Akaki Beseka, urban settlement and Industries are common especially along the main road to Debrezeit.

The study area comprises the main industrial zone of the country with various types of industries. Quarries for construction materials, like the EHA quarry, are common near Tulu Dimtu. Prospecting for new quarry sites or expansion of existing ones is also going on.

Some shrubs and trees are also present in some parts of the study area.

2.7 Hydrological and Hydrogeological Settings

2.7.1 Hydrology

Run off

Akaki River Catchment is mainly drained by two rivers: the Big Akaki, draining the eastern part, and Little Akaki, draining the western part of the catchment. Both the rivers emerge from the Entoto range and flow to the south-east. The Big Akaki and Little Akaki join at Aba-Samuel Lake, a man made reservoir downstream of Akaki well field.

Since 1981, the Big Akaki River commanding a catchment area of 885 km^2 is gauged at the Addis-Debrezeit Road Bridge. The station is equipped with an automatic hydrometric recorder and seven staff gauges to measure manually. The discharge records reveal that 82% of the annual run-off is generated in July, August and September only, emphasizing that the groundwater contribution to the river is minimum compared to the run-off generated in the wet season (Yirga Tadesse, 2004).

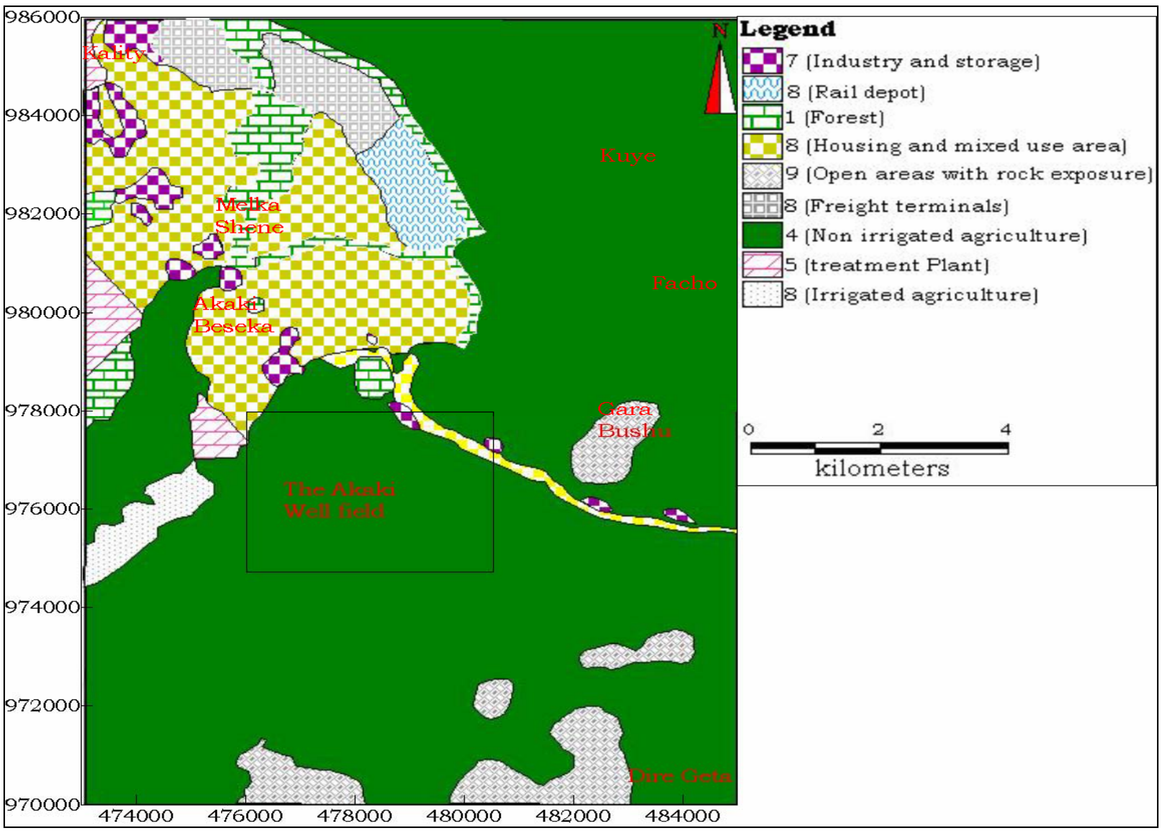

Fig.2.8 Simplified Land use/Land cover map of the study area showing levels of potential danger to groundwater pollution (modified after Tamiru Alemayehu et al., 2003).

2.7.2 Hydrogeology

The complex vertical and lateral distribution of the volcanic rocks, their wide compositional, structural and textural variability, and their different level of weathering and variable topographic position diversified the hydrogeological behavior of these rocks in the area. The aquifer system is non homogeneous both vertically and horizontally. According to Ayenalm Ali (1999), the study area can be divided into:

1 an extensive aquifer with fracture permeability, which is the main aquifer covering large parts of the western area;
2 scoria cones with fracture and/or intergranular permeability which is a good recharge area for the extensive lower basalt flows; and
3 a localized aquifer with intergranular permeability which is the alluvium exposed along the Akaki river and Sekelo stream.

2.7.2.1 The Aquifer Media

Alluvial sediments: these are poorly sorted sand to gravel sized sediments, with high porosity, inter-granular permeability, and water infiltration capacity. These patches of sediments along the river are localized aquifers useful for extracting water from shallow depths, although they are vulnerable to contamination from the Akaki River.

Weathered and fractured volcanic rocks and pyroclastic deposits: scoriaceous basalts in the Akaki well field show both high porosity and secondary fracture permeability attributed to the tectonic activity. The weathered basalt (partly changed to clay) has high total porosity but very low effective porosity implying low hydraulic conductivity. The secondary permeability is low as where the fractures are filed by clay particles, limiting water movement. However, the clay layers are pronounced in few boreholes (e.g. bh 02, bh 03b, bh 17), and are not laterally extensive (Aynelam Ali, 1999). This may lead to perched aquifer situations where the clays are overlain by more permeable rocks.

Although the thickness of the scoria in the well field is highly variable, all the drilled wells have high yields suggesting that the interbedded scoria and basalt at the well field are equally important as an aquifer. Therefore, the aquifer can be assumed to be made up of mainly weathered and fractured volcanic rocks and pyroclastic deposits such as scoria, fractured scoriaceous and vesicular basalts, ignimbrites, tuffs and ashes (AAWSA et al., 2000).

2.7.2.2 Water Level

Depth to water level in each well was obtained by subtracting the water level elevation from the ground surface elevation. Depending on the hydrogeological setting, the depth to water does not necessarily coincide with the Static Water Level (SWL). Therefore, to evaluate such conditions the depth to water is determined by the type of aquifer (confined or unconfined) and information extracted from well data. Where confined aquifers were identified (Kality area), the corresponding SWL of that well was excluded from mapping depth to water.

The groundwater level around Fanta and Kality are shallow in the range of 1 m to 34 m below ground surface. Areas with red color shade in Fig. 2.9 show shallow depths usually ranging from 1 to 10 m below ground level. The cross symbols indicated in the same area show the locations of flowing wells considered in mapping depth to static water level of the area.

Comparisons of ground elevations and static water elevation at respective wells of the area are shown in fig 2.10. The potentiometeric surface indicates that the groundwater is in connection with the surface water of Big & Little Akaki Rivers north of Akaki Bridge.

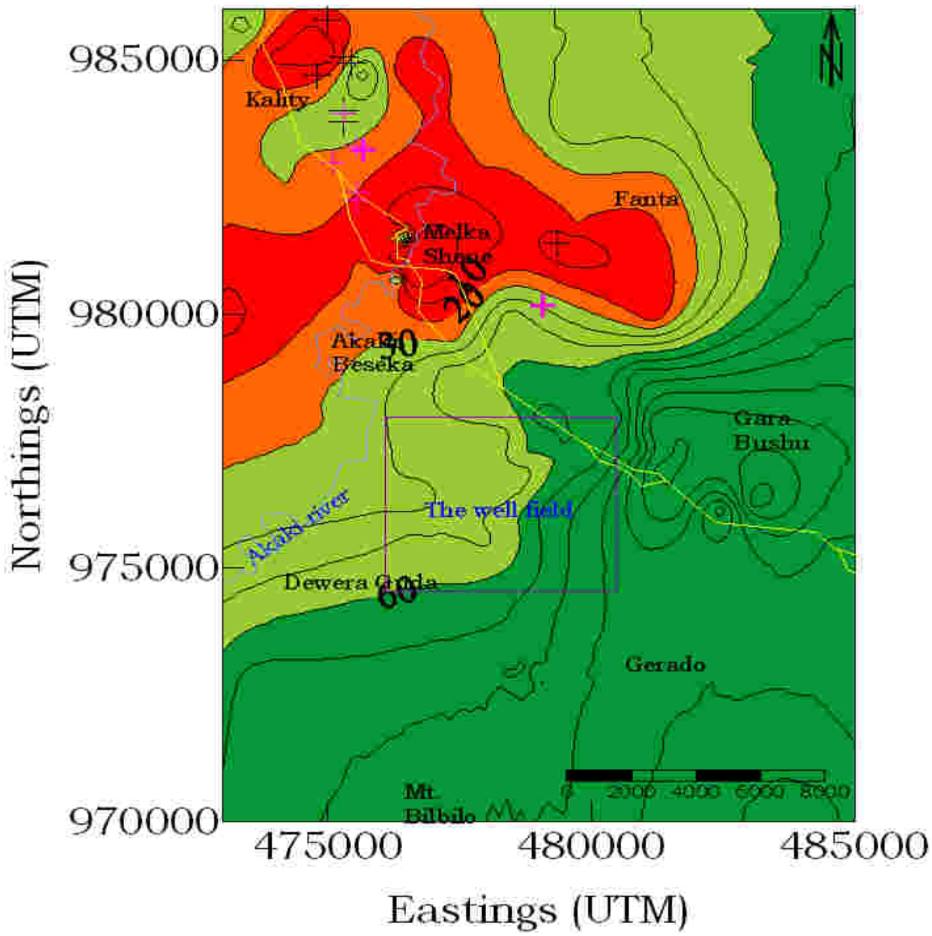

Fig. 2.9. Plot of depth to groundwater level in the study area.

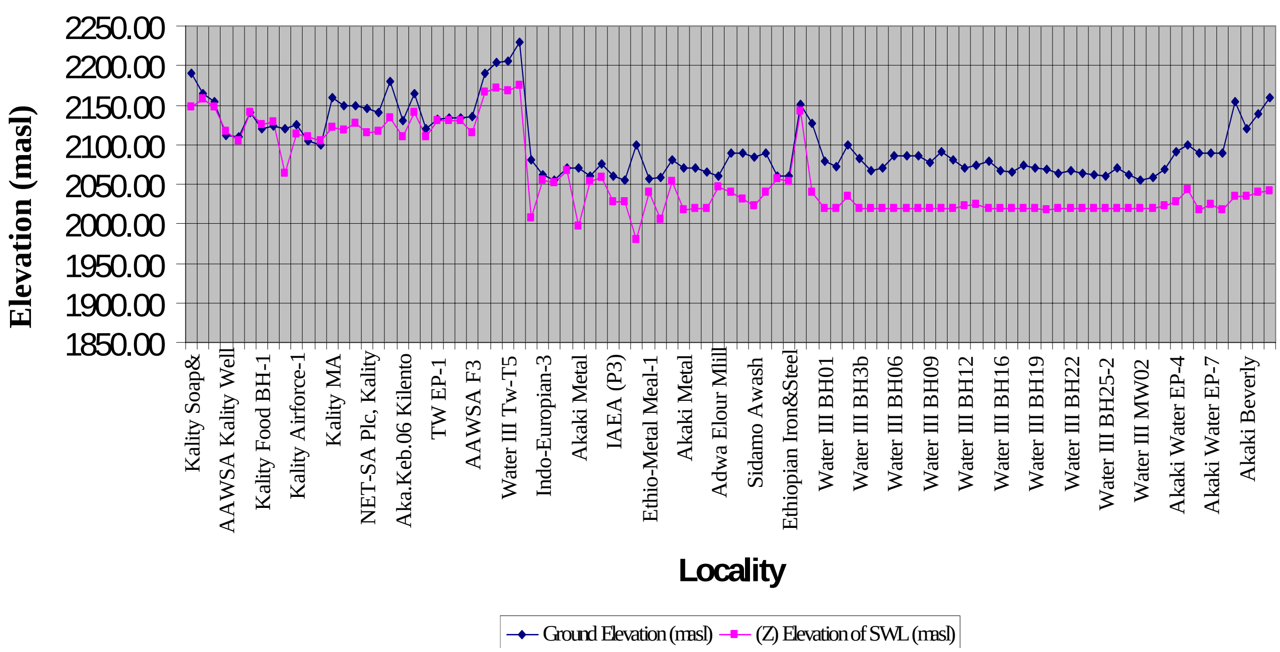

Fig. 2.10. Comparison of ground surface elevation and elevation of SWL at respective wells location of the area that have spatial variations.

2.7.2.3 Regional and Local Groundwater Flow Directions

The elevations of water level in boreholes are used to determine the general direction of groundwater flow in the study area. In general, the groundwater movement is sub-parallel to the surface water flow direction and more or less controlled by the topography of the area. The piezometric surface constructed from groundwater point inventory made during previous studies showed that the general groundwater flow direction in Addis Ababa is from north to south in the upper & central part and towards south & south-east in the lower parts of the catchment. AGRA (1998) assumed local groundwater flow direction in the well field is from NE towards the SW where natural springs exist in the Aba Samuel Gorge.

Analysis of water table data has shown that on relatively regional scale the groundwater flows from the water divide to the discharge area on the river valleys. Convex contour lines at the northeastern and northwestern corners of the area (fig. 2.11) indicate regions of groundwater recharge, while concave contour lines at centre and along Akaki River are associated with groundwater discharge areas. The regional groundwater flow direction is therefore, from the north to the well field and Akaki River. However, because of limitations of the water level data, particularly in the southern part of the study area, it is not possible to depict the local groundwater flow directions in this area accurately.

The flow lines, sketched perpendicular to the contour lines, show the direction of groundwater flow. Shallow local patterns of groundwater flow near surface water are emphasized in this study, as shallow aquifers are more susceptible to contamination from anthropogenic sources.

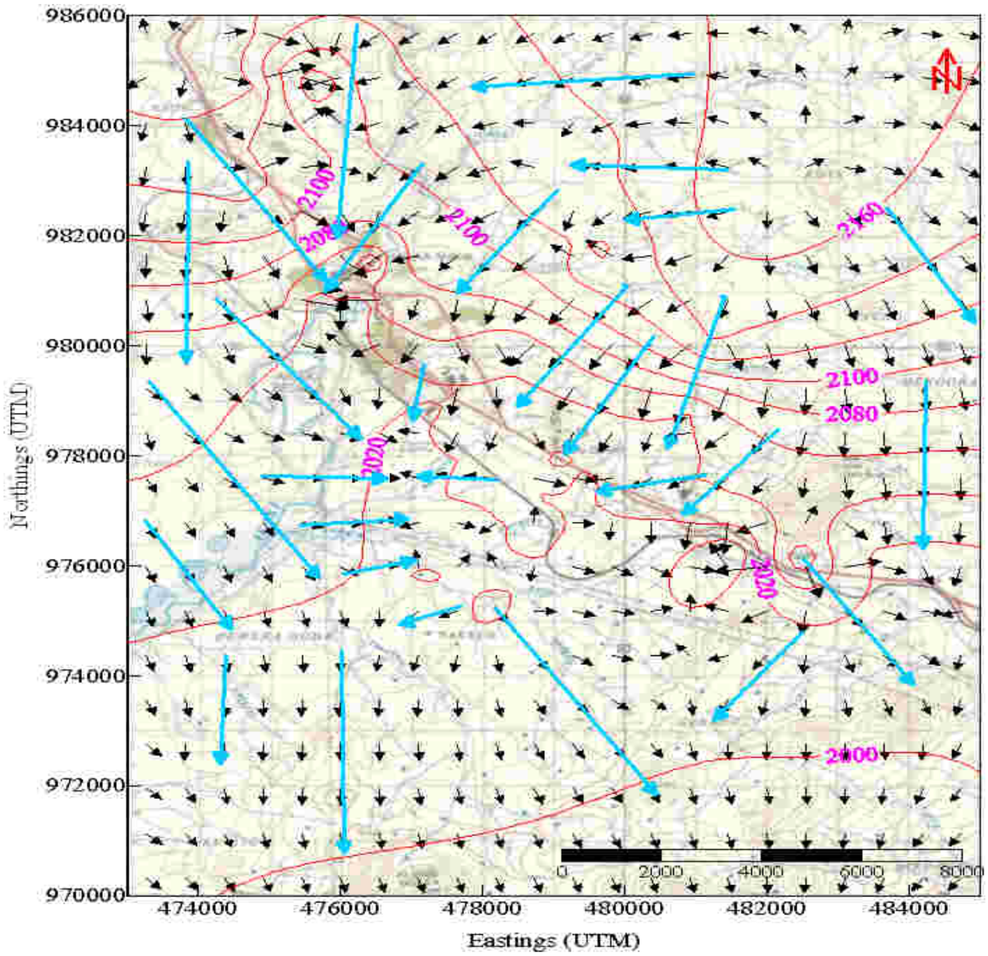

Fig. 2.11. Map of regional and local groundwater flow direction, in the study area.

2.7.2.4 Groundwater Recharge and Discharge Conditions

In developing a conceptual model of a flow system, it is important to consider the topographic setting. Topographically higher areas are typically zones of intake or recharge, while topographically lower areas are areas of exfilitration or discharge. In most areas, the volcanic aquifers show semi-confined to unconfined nature while in few areas (like Kality), confined aquifers are penetrated. The recharge to the groundwater which takes place within the Akaki catchment to the north of Akaki Bridge is considered contributing to the base flow. Water enters a confined aquifer in an area where the confining beds rise and the aquifer is exposed to surface (recharge areas), and also enter by leakage through fractures and pores of the confining beds.

In the study area, water enters into aquifers from natural recharge areas such as at a number of scoria cones where bed rocks are exposed and where clay and black cotton soil coverage is thin. Eventually it infiltrates towards discharge areas, where it flows out as springs, seepage zones or it may be tapped by a number of wells in the well field or drainage systems. The young patches of basaltic scoria such as Indode, Mt. Bilbilo, Mt.Guji, Gerado, Gara Bushu, Dengora Chefe, EHA Quarry and Tulu Dimtu are the main local recharge areas.

3. Groundwater Flow Model

3.1 Introduction

Modeling in hydrogeological investigation helps to understand the current and predict the long-term tendencies of an aquifer system. In line with this, AAWSA et al. (2000) did the most recent modeling in the Akaki well field in order to assess its potential. The overall aim of this model was to determine reasonable and rational groundwater resources exploitation mechanisms. The model simulates various future scenarios of exploitation in order to determine the change in the piezometric level. Based on this, the model proposes a suitable pumping /abstraction rate for the well field as indicated in Table 3.1.

Table. 3.1. Total abstraction rates considered and the simulated drawdown for various time gaps in the well field (AAWSA et al., 2000).

Pumping rate (m^3/day)	**5 years (m)**	**10 years (m)**	**20 years (m)**
30,000	6.8	11.3	18.1
40,000	9.0	14.8	23.7
50,000	11.3	18.7	29.9
60,000	13.5	22.2	35.6
72,000	16.2	26.8	42.9
82,000	18.2	30.3	48.5
92,000	20.7	34.2	54.8
102,000	22.9	37.7	60.4

The objective of the current model, on the other hand is to characterize flow in a given aquifer in order to determine the distribution of hydraulic head over different time and space, flow velocity, and flow direction. The results of the model will then be used in contaminant transport analysis.

3.2 Development of Conceptual Model

Models are conceptual descriptions or approximations that describe physical systems using mathematical equations—they are not exact descriptions of physical systems or processes. The applicability or relevance of a model depends on how closely the mathematical equations approximate the physical system being modeled. It also depends on a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations. It is because of the difficulty to determine certain parameters and many uncertainties in the values of data required by the model, that a model must be viewed as an approximation and not an exact duplication of field conditions.

The conceptual model will be used to identify the appropriate hydro-stratigraphic layers to use with homogeneous or heterogeneous feature, which can be incorporated in the numerical model.

3.3 General Assumptions

Several general simplified assumptions are used in the simulation of ground water flow, and the development and calibration of the model. These include:

- Fractures and weathered zones through which water flows are considered as porous medium to which Darcy's Law (Getachew Asmare, 2005) can be applied.
- Net recharge from precipitation is not spatially uniform because there is heterogeneity in the spatial distribution of hydraulic conductivity, geology, total precipitation, and slope;
- Aquifer heterogeneity, vertical anisotropy, and the presence of fracture and faults impact the spatial distribution of hydraulic conductivity. Consequently, a zonation approach is adopted where similar hydraulic conductivity values are assigned to specific regions on the basis of above factors.
- Vertical flow is assumed to be negligible since one aquifer system/single layer is considered.

- Different boundary conditions are assumed in the model: head dependent boundary is used on the wet land of Akaki and Akaki river it self and flux boundary is assumed at north, NE, and NW. Because hydraulic head is constant through out the entire time and there is groundwater inflow from north to the area.

3.4 Governing Flow Equations

The three-dimensional finite-difference groundwater flow model of McDonald and Harbaugh (1998) was used for the computer simulations. The mathematical model simulates flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system. This model is based on the following governing equations for anisotropic, heterogeneous aquifer.

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)\text{-W=0.....Steady state flow condition}$$

(Eq. 1)

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)\text{-W=Ss}\frac{\partial h}{\partial t}\text{ ...Transient flow condition}$$

(Eq. 2)

Where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axis, which are assumed to be parallel to the major, axes of hydraulic conductivity (LT^{-1});

h is the potentiometeric head (L);

w is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1});

Ss is the specific storage of the porous material (L^{-1});

t is time (T).

In general, Ss, Kxx, Kyy, and Kzz are functions of space (Ss=Ss (x, y, z), Kxx=Kxx (x, y, z), etc) and w is a function of space and time (w=w (x, y, z, t).

The set of algebraic equations that result when approximating a groundwater flow model using the method of finite differences is normally solved using a combination of matrix and iterative solution techniques (Anderson and Woessner, 1992).

3.5 Modeling Approach

The Processing Mod flow (PM) software (Version 7.0.17), developed by the United States Geological Survey and Chiang & Kinzelbach (1999-2002) has been used for the construction of the flow model of the study area. A three-dimensional model grid was used to represent a two-dimensional aerial flow through a single layer. This numerical groundwater modeling software which is an enhanced version of Processing Mod Flow is developed by Web Tech 360 Inc. in 2002-2003 based on the original work of Chiang & Kinzelbach (1991-1998).

In order to use a finite difference approximation, a grid is superimposed over the topographic map of the study area, and aquifer hydraulic parameters necessary to solve the flow equation are averaged over the area of cell or grid block and assigned at a node at the center of the block. Finite-differences compute the average head value for a cell at the node. In the block-centered formulation, the nodes for which water levels are simulated are located at the center of the grid cells. These cells are the smallest volumetric units over which the hydraulic properties are assumed constant.

PMWIN has professional graphic user interface, the supported codes and other useful modeling tools. The Main Features of PMWIN Pro are:

a) Data Input Facilities:

- Support models with up to 1,000 stress periods, 200 layers and 250,000 cells in each model layer.
- Graphical grid design tools.
- Specify model parameters using cell-by-cell, zones, and poly line tools.
- Interactive model display in both plan view and cross-sectional view.
- Rotate and align the model grid over the site base map.
- Overlay maps in AutoCAD (.dxf), SURFER BLN, or bitmap image (.bmp) formats.
- Imports existing MODFLOW files.
- Import / export model parameters from/ to SURFER and ASCII files.
- Interpolation of discrete data to model grid by means of Inverse Distance Telescopic method.
- Mesh Refinement for creating a local scale refined model from a large-scale model.
- Both steady state and transient models can be created.
- Customizable display colors of model features, such as rivers, well, and drains.
- Weighting, kriging, or triangulation.

b) Simulation:

- Support MODFLOW-88/96/2000, MT3D, MT3DMS, MT3D99, RT3D, MOC3D, PMPATH, UCODE, and pest-asp.
- Support the Stream flow-Routing package, Horizontal-Flow Barrier package, Reservoir package, and Time-Variant Specified Head package.

c) Model Calibration:

- Parameter estimation (often referred to as automatic calibration) using MODFLOW-2000, PEST-ASP or UCODE.
- Detailed summaries of model calibration results (scatter plots and time series plots) and statistics (estimated parameter values and sensitivity values).

PMWIN pro requires the use of consistent units throughout the modeling process. For instance, if one use length (L) units of meters and time (T) units of seconds, hydraulic conductivity will be expressed in units of (m/s), and pumping rates will be in units of (m^3/s).

3.6 Model Design

3.6.1 Spatial Discretization of Model Grid

In MODFLOW, an aquifer system is replaced by a discretized domain consisting of an array of nodes at which hydraulic heads are calculated and associated in finite difference blocks (cells).

The model area encompasses the limits of the local flow system of the Sekelo and Keta streams and extended up to Mt. Bilbilo and Guji to the south. The model spans an area of 192 km^2. The model grid consists of 24 columns and 32 rows. It consists of 768 cells with a regular grid spacing of 500 m x 500 m. The geographic boundaries of the model grid were determined by using a topographic map scanned and saved in Jpg file format. The image map was projected in metric coordinates (UTM) and Adindan datum, and then imported into MODFLOW. A finite-difference grid superimposed over a 192 km^2 area was designed and constructed based on the simplification of a conceptual model representing the physical properties of the groundwater system. Fig. 3.1 represents this three dimensional conceptual geospatial model frame work showing the number of columns, rows and layers used in the current model.

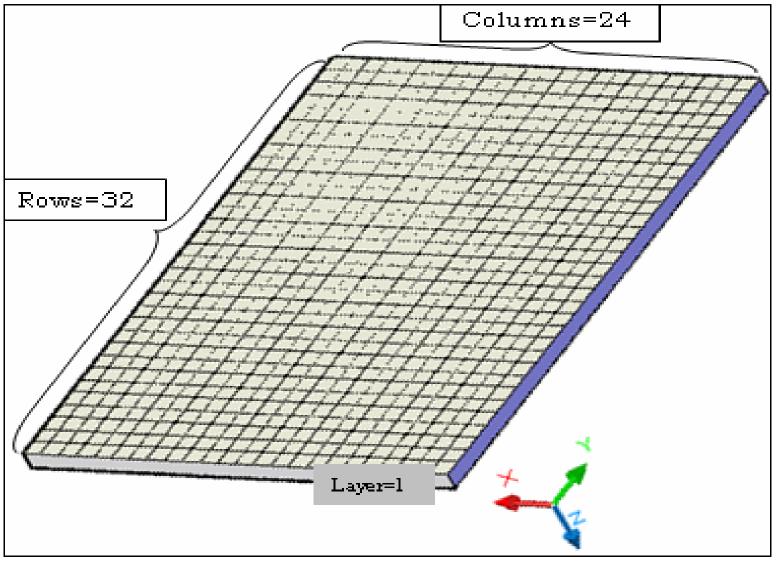

Fig. 3.1. 3D conceptual geospatial model frame work.

3.6.2 Model Boundary Conditions

Boundary conditions are mathematical statements that specify the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the domain. Both physical and hydraulic boundary types were used to define the area domain. Boundaries are defined in both the vertical (Y axis) and horizontal (X axis) planes**.** The base of the volcanic aquifer is the basement volcanic rock where groundwater flow is negligible. Because no flow is assumed to the bottom of the volcanic aquifer, it is a specified-flux (no-flow) boundary. Since flow can not take place parallel to the actual groundwater contour lines, no flow boundary has been assumed in some parts of the eastern and western boundaries of the study area (Fig.3.2). The basic boundary condition array (I Bound array) contains a code for each model cell (positive 1-for active cell, negative 1-for constant head cell and 0-for inactive cell or where no flow takes place within the cell).

To help visualize the model site, a DXF file or a raster graphics image of the area is used to overlay as a site map with the locations of the boundaries and the pumping wells indicated. Because there are no significant massive rocks that inhibit flow across them, most of the cells in the study area are treated as flux boundaries. There are also few cells with constant head along Akaki River in wetlands or marshes near Aba Samuel Lake. These are cells in which hydraulic head is kept fixed at a given value all over the entire simulation time. By default and convention the area outside the model domain is deemed to be a "no flow" and as such it is not necessary to set this area to inactive.

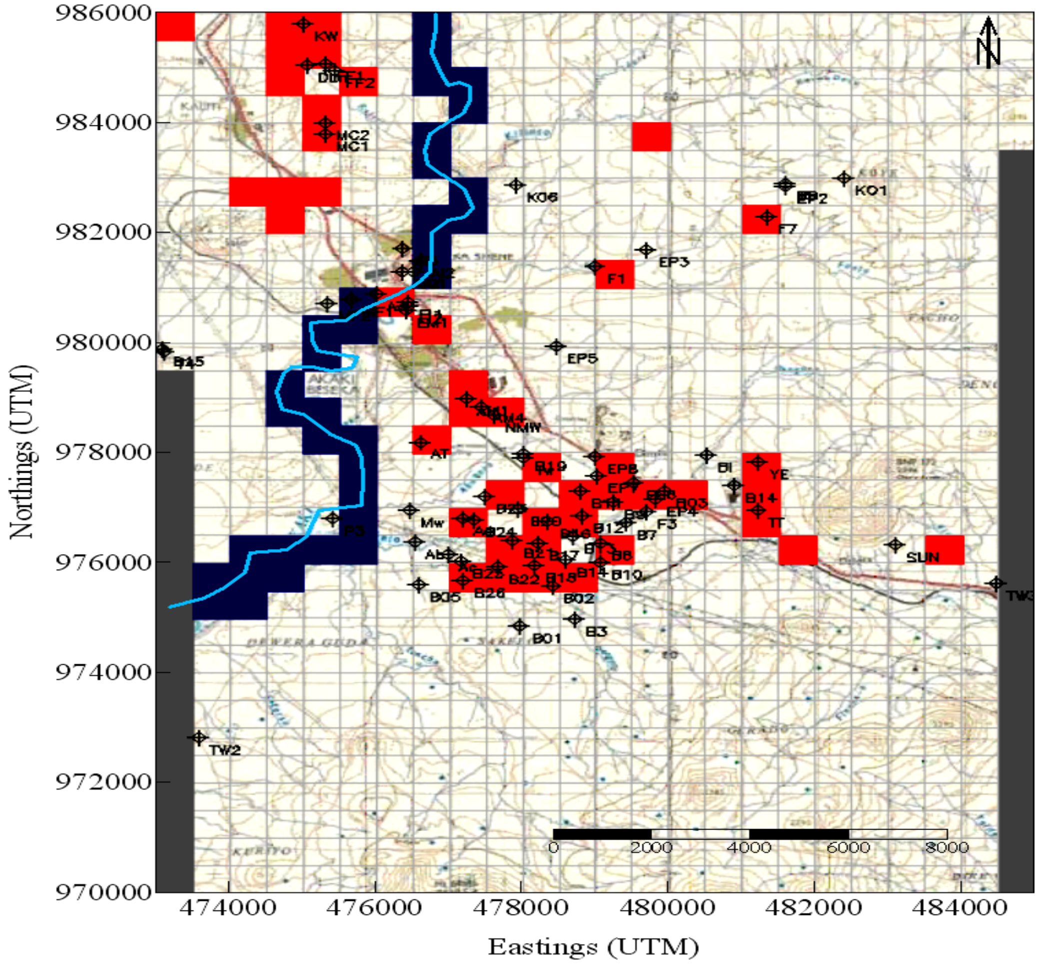

Fig 3.2. A map of the model boundary conditions and distribution of mesh and existing boreholes. Red=active boreholes; dark blue= constant head; black circles= non active wells; turquoise=river.

3.7 Specification of the Geometry of the System

The aquifer in the lower basalt is assumed to be semi-confined. The alluvial sediment is a local unconfined aquifer with intergranular porosity. In order to identify the groundwater flow it is necessary to identify hydro-stratigraphic units (number of aquifer, aquitards, aquicluide, etc.) that have common physical and chemical characteristics. The concept of hydro-stratigraphic classification is the same as the concept of stratigraphic facies classification (gravel, silt, sand, etc).

The aquifer layers within the model area are hydraulically connected, and as observed from the geological logs of the boreholes and cross-sections the lithological units are highly irregular in shape. They do not extend more than one kilometre to justify a multi-layer representation of the reservoir.

Although the geometry of the aquifer systems in the catchment area is highly variable, and discontinuous; the hydrogeological conditions of the system are similar. Therefore, the model layer in this area was treated as a single layer for the following reasons:

(i) Since the area is a volcanic terrain, most of the units are not continuous laterally. The aquifer in the area, particularly the scoria and scoriaceous basaltic lava flows are not single continuous unit rather they are discontinuous patches representing local flows. Therefore, it is difficult to identify well-defined distinct units.

(ii) The water level of the aquifers deeper than 170 m rises and maintains the regional water level elevation around Akaki Well field. This indicates that the water in the aquifers deeper than 170 m is hydraulically connected with the water of the shallow aquifer. Therefore, almost all of the aquifer parameters are not defined for individual layers. They are obtained as a cumulative effect or total effect of all layers. Therefore, at this stage it is difficult to treat them separately as individual layers.

The aquifer structure had been determined by preparing DEM, which was used to construct the top elevation of the aquifer and loaded to MODFLOW matrix. The bottom elevation of the aquifer (1990 m a. s. l.) had been prepared by taking into account the elevation difference between the highest initial head elevation (2253 masl) and that of elevation of the bottom of well with maximum depth in the area. Therefore, one-model layer was used to represent the study region extending vertically from 2253 m a. s. l. to 1990 m a. s. l.

Since the upper surface of the aquifer is determined by the water level elevation, the aquifer thickness is variable as a result of fluctuation in the water table. Since the aquifer's top elevation cannot be uniform throughout the model, it is not possible to set a single value of model top elevations to the entire grid. Therefore, the initial hydraulic heads explained below are used as top of the model layer.

3.8 Physical Parameters of the System

The model should generally have values specified initially for all necessary parameters. The spatial input parameters are initial hydraulic head, horizontal anisotropy, horizontal and vertical hydraulic conductivities, transmisivity, recharge, discharge, storage coefficient, specific storage or specific yield and effective porosity. The temporal input parameters are time unit, number of stress periods, time steps and transport steps. Therefore, values were assigned to each active grid cell, based on its location within the study area.

3.8.1 Initial Hydraulic Heads

Initial hydraulic heads distribution in the study area was obtained form the well database in the area. The hydraulic heads distribution was imported to MODFLOW at the beginning of the model run. This initial data were interpolated using kriging method (Harbaugh AW, Banta ER, Hill MC and McDonald MG, 2000) and each cell in the model was assigned its head value.

The ground elevations at each model cells are extracted from DEM (hgt) of the area, and then an average depth to static groundwater level (40 meter) from the well database in the study area is subtracted from each DEMs obtained. The results of this calculation are used as initial prescribed hydraulic heads in each cell for the initial specification of head values. But some of them are later altered through calibration process particularly at borehole locations. Finally, these results are loaded to MODFLOW matrix and used in the modeling process.

3.8.2 Horizontal Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn controls the rate at which groundwater will flow under a given hydraulic gradient. Hydraulic conductivity is important because it controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of contaminants. The hydraulic conductivity data were assigned by classifying certain zones based on the geology, hydrogeologic and geomorphologic conditions (fig.3.3).

To specify the horizontal hydraulic conductivity, initially the hydraulic conductivity map was produced from hydraulic conductivity values of boreholes distributed in the area. Then, the map is overlaid on the model grid, and the obtained respective average values are assigned to each model cells. Higher hydraulic conductivity values are obtained in the well field (8.35E-03 m/s), southern (6.35E-05 m/s) and south eastern (2.94E-04 m/s) sections of the area. Smaller values are obtained north, northeast, and west of the well field.

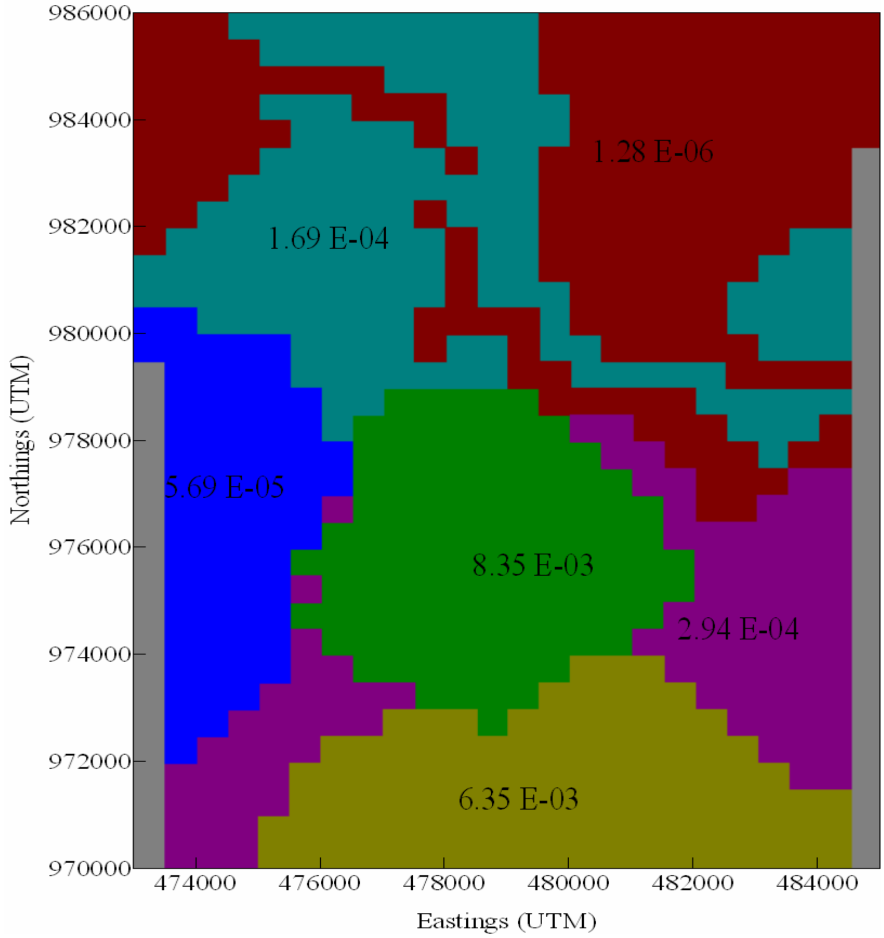

Fig .3.3 Map showing the distribution of hydraulic conductivity used in the model (units: m/s).

3.8.3 Horizontal Anisotropy

Horizontal anisotropy is the ratio of the horizontal hydraulic conductivity along columns to horizontal hydraulic conductivity along rows (fig.3.1) i.e., the ratio of (Kh) along columns to (Kh) along rows. They are assumed to be equal to 1 representing that both hydraulic conductivities along Eastings and Northings at particular location or cell are the same.

3.8.4 Vertical Hydraulic Conductivity or Leakance

PMWIN Pro calculates vertical leakance by using the following rules. Vertical leakance between the layers i and i+1 is given as the value of the i^{th} layer. Therefore, since MODFLOW assumes that the bottom layer is underlain by impermeable material; the leakance data are not required for the bottom layer of multiple layer models or for a single layer model like the one currently dealt with.

3.8.5 Transmissivity

The transmisivity (T-value) calculated from pumping tests in the well field reveal that it ranges between 1834 m^2/day to 105, 408 m^2/day. To the north of Akaki well field and Kality area, T-values range from 2.8-6,099m^2/day (Yirga Tadesse, 2004).

The transmisivity values are converted to hydraulic conductivity by dividing T-values with aquifer thickness. The calculated hydraulic conductivity values vary between 7.4 to 674.8 m/day. These values lie in the range of permeable basalt (Aynelam Ali, 1999). Low transmisivity value is obtained from the EP wells located at the north-eastern part of the well filed. Generally the aquifer shows a gradual increase in transmisivity towards the well field. Therefore, the well field has relatively high transmissivity value but it is surrounded by rocks of low values showing that the highly productive aquifer at the well field has very limited extent (fig.3.4).

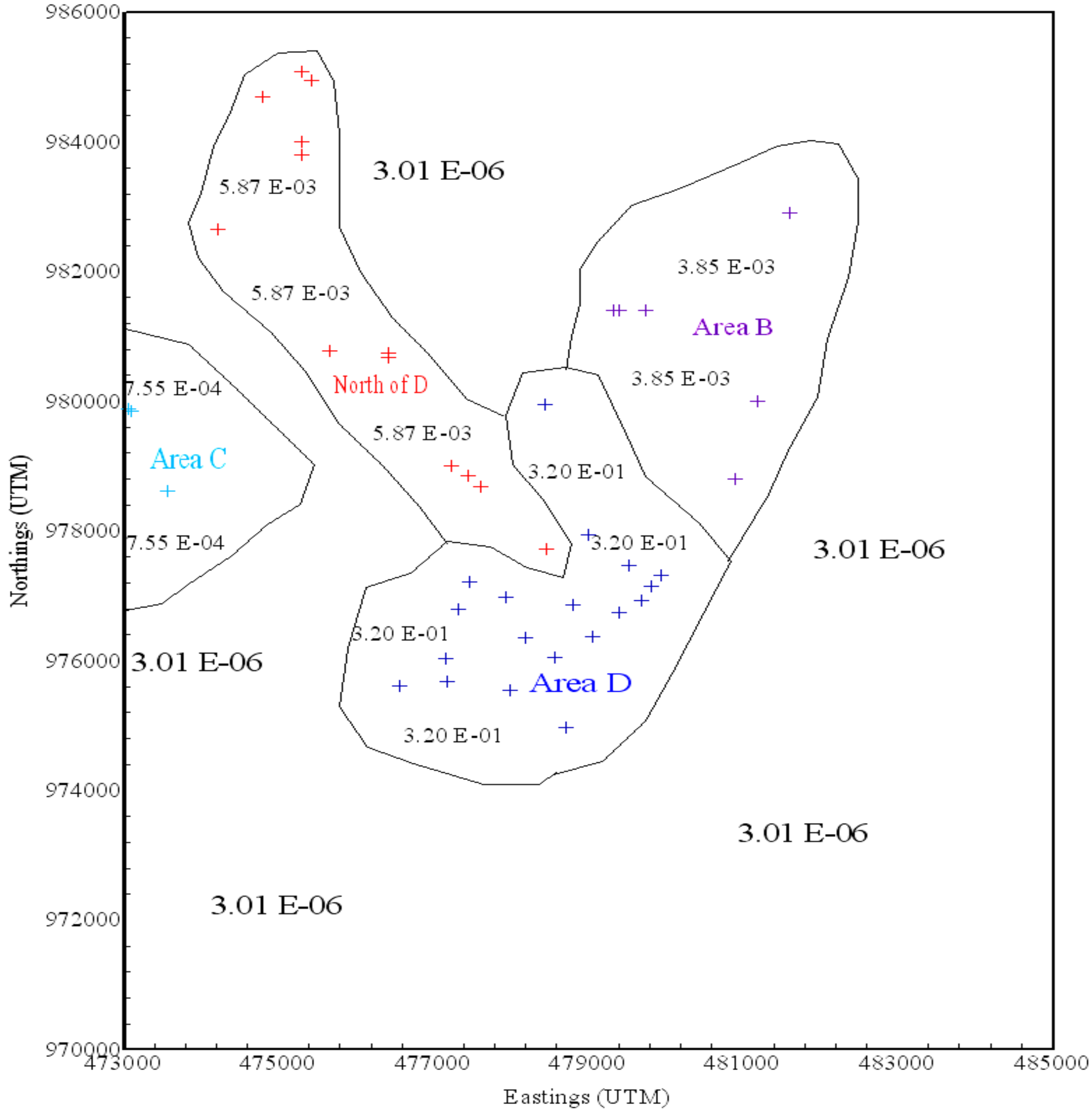

Fig. 3.4. Map of transmissivity distribution in the study area showing high values in the well field (Area D) and low values in the surrounding areas (units:m2/s, Symbols show location of individual measured transmissivity used to calculate the indicated average values).

3.8.6 Groundwater Recharge

Natural recharge to the saturated zone in a groundwater reservoir come form vertical percolation of precipitation and from the losses of the streams flowing after important rains in the upper part of the catchment.

Direct recharge refers to precipitation that contributes to soil moisture content and crosses the water table and becomes part of the groundwater flow system. The recharge input assigned was assumed to be spatially variable and mainly two zones were used in the model. The recharge of 74 mm/year occurs in the model area of Addis Ababa, Akaki, and Dukem towns (AAWSA, BCEOM, SEURECA and Tropics, 2002).

However, in the current model, with a distribution more adapted to the hydrogeological conditions (permeability), two recharge zones have been considered. The above stated recharge (74 mm/year) is assumed to take place in all areas except where black cotton soil is widely present (the well field and north of the well field) and where in the previous model assumed to have a zero recharges. However the Akaki black cotton soils have higher proportion of medium sand having good hydraulic conductivity (Berihanu Gizaw, 2002). Therefore, recharge of 11.1 mm/year in black cotton soil cover areas is used rather than the Zero value in the previous model. To accurately determine this mean recharge value of infiltration a hydrologic model was built and calibrated.

The net recharge is the difference between total precipitation and the cumulative loss by direct runoff and effective evapotranspiration. A positive value is used to represent recharge into the aquifer system.

Recharge is assumed to take place in all areas. Most recharge to the groundwater occurs only during the wet season. Since the rainfall distribution in Addis Ababa is bimodal (Belg and Kiremt seasons), the annual total recharge of 74 mm/year is fairly distributed for these seasons with the other months having negligible recharge (Table 3.2).

The amount of water recharging the project area in terms of volume is equal to infiltration depth times the size of the area. Therefore, the total volume of water recharging the study area is equal to 30199 m3/day (Table 3.3).

Table 3.2. Summary of the recharge distribution over different seasons of the year.

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual RE (mm/year)
% Distribution of the RE	10	25	35	15	0	0	0	0	5	5	5	0	100
Monthly Recharge (mm/month)	7.4	18.5	25.9	11.1	0	0	0	0	3.7	3.7	3.7	0	74
No. of days	30	31	31	30	31	30	31	31	28	31	30	31	
RE (mm/day)	0.247	0.597	0.835	0.37	0	0	0	0	0.119	0.119	0.123	0	

Table 3.3. The total volume of water recharging the study area.

	Infiltration depth (a) (m/day)	**Size of the Area (b) (m2)**	**(a x b) (m3/day)**
Soil covered area	0.0000303	50,000,000	1515
Remaining area	0.000202	142,000,000	28684
Total		192,000,000	30199

3.8.7 Groundwater Output/ Discharge

The discharge particularly pumping wells directly reflects human activities. The discharge data used in the groundwater model are obtained from the well database. The discharge system of the aquifer is composed of springs, rivers and pumping wells. Pumping well or currently active discharge wells in the study area and their respective pumping rates are specified. A negative value is used to indicate a pumping well, indicating that water is being extracted from the system.

Table 3.4. A generalized summary of wells in the area.

No	Borehole	Well used for	Remark
1	Ep 4 to 8	Akaki town water supply	
2	Bh 01 to 26	Addis Ababa water supply	There is no Bh 15, Bh 03a and 05a were abounded and replaced by 03b and 05b
3	Mw 01 to 04	Monitoring wells	
4	Others	Private owned and community wells	

The existing pumping wells in the model are simulated by prescribing an output flow equal to the discharge of the well in the corresponding cell. The total output taken into account from the active wells is 0.376958 m^3/s or 32569.1712 m^3/day. Actual daily discharge (m^3/day) is calculated with an average 6 hrs production per day, and then multiplied by well yield (m^3/hr). Non operational wells, test wells, and monitoring wells and stand by wells are excluded and only currently active operational wells are included in estimation of the above discharge.

3.8.8 Storage Coefficient, Specific Storage and Specific Yield

These parameters are required in simulating transient flow condition. The storage coefficient around the well field is 8% where elsewhere values are smaller with 0.3 % in Fanta spring area, 2.5 % to the west of Akaki town and 4% in the remaining areas. This is because pumping is relatively high in the well field. The percentages represent the volume of water released from storage per unit surface area per unit decline in hydraulic head. This is possible for young scoriaceous deposits, which are highly porous with effective porosity even higher than for sand and gravel aquifers. For a confined layer, storage coefficient can be calculated using user-defined specific storage and the elevations of the top and bottom of each layer. Specific storage is equal to storage coefficient divided by thickness of the aquifer. For an unconfined layer, the storage values are equal to specific yield. Storativity (S-value) calculated from pumping tests in the well field ranges between 0.0065 (0.6%) to 0.016 (2%).

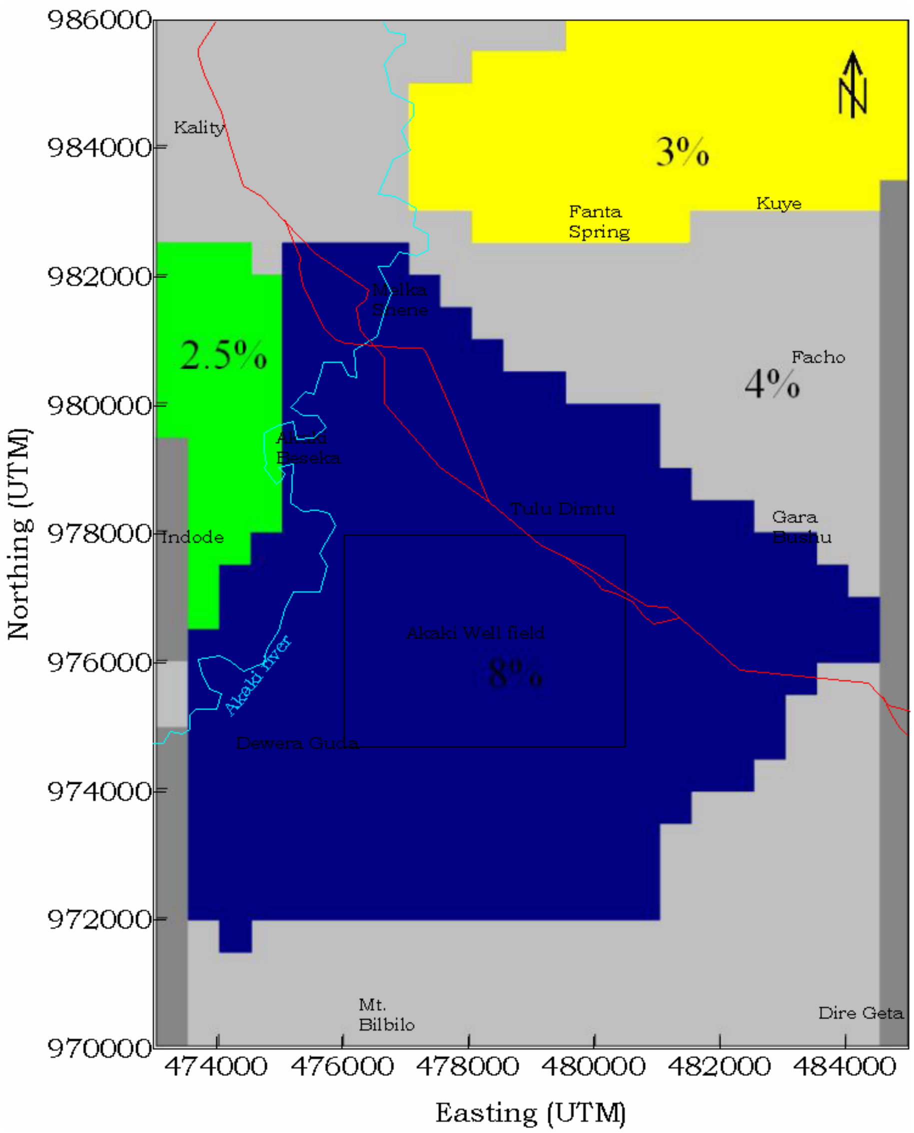

Fig. 3.5. A map of distribution of storage coefficient in the study area.

3.8.9 Effective Porosity

Effective porosity is the sum of the interconnected pore space, i.e., excluding isolated pores. Total porosity, on the other hand, is the volume of the reservoir rock which is fluid (water) filled, expressed as a percentage or a fraction of the gross (bulk) rock volume. Although a flow simulation model does not require effective porosity parameter, it is necessary for the computation of travel times and contaminant transport processes. However, determination of effective porosity requires core analysis (humidity-dried or oven-dried) or log analysis (density log or neutron log) which is beyond the scope of this work.

For the vast majority of rocks in the study area, effective porosity equates to total porosity, because most of them are composed of non-clay minerals coarser than silt. Though the total porosity of basalt is generally low, fractured and weathered basalt of Akaki area is assumed to have high effective porosity. The scoriaceous deposits are assumed to have higher effective porosity values.

The black cotton soil and scoria of the area constitute higher proportion of medium sand and medium gravel respectively. According to Tenalem Ayenew and Tamiru Alemayehu (2001), a representative value of the effective porosity for medium sand is 28% and medium gravel is 24%. The mean value of the total porosity which is a measure of the existing voids, expressed as the ratio (in percentage) of the volume of the voids, V_v, to the total volume, V_T for medium gravel is 32 %, and for medium sand is 39 %. Therefore, effective porosity of 35 % is used in the model

3.8.10 The Temporal Parameters

The temporal parameters are summarized in fig. 3.6. The time unit used is seconds, and a stress period, time step and transport step of one year are specified at steady state flow conditions.

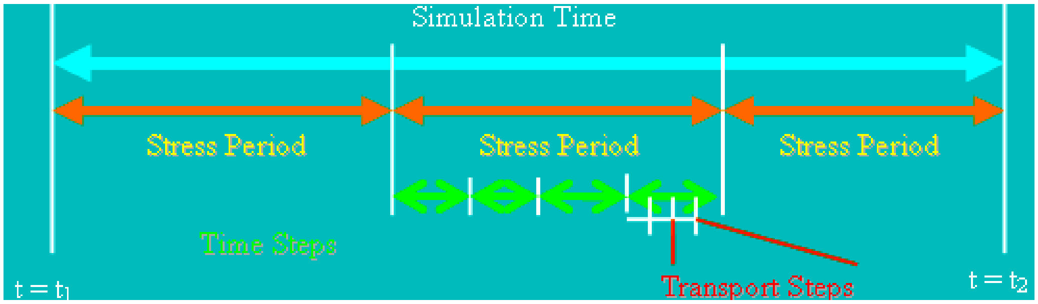

Fig.3.6. Schematic diagram showing classification of time parameters.

3.9 Model Calibration

Calibration of the model:

- is a process of updating selected model parameters based on the results of previous simulations to derive a close match between the observed steady-state water levels and calculated hydraulic heads;.
- consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model that is calibrated to a set of conditions, which are not representative of actual field conditions; and
- typically involves calibrating to steady state and transient conditions.

A graphical comparison between actually measured and model computed heads is shown in fig. 3.7 and 3.8.

The most effective calibration technique for the adjustment of the hydraulic conductivity field in the model was to initially delineate fewer conductivity zones and then gradually increase the number of zones based on the geology and permeability of the hydrogeologic unit in the area. Hydraulic conductivity was continually adjusted during calibration according to the geology and permeability in each hydraulic conductivity zone.

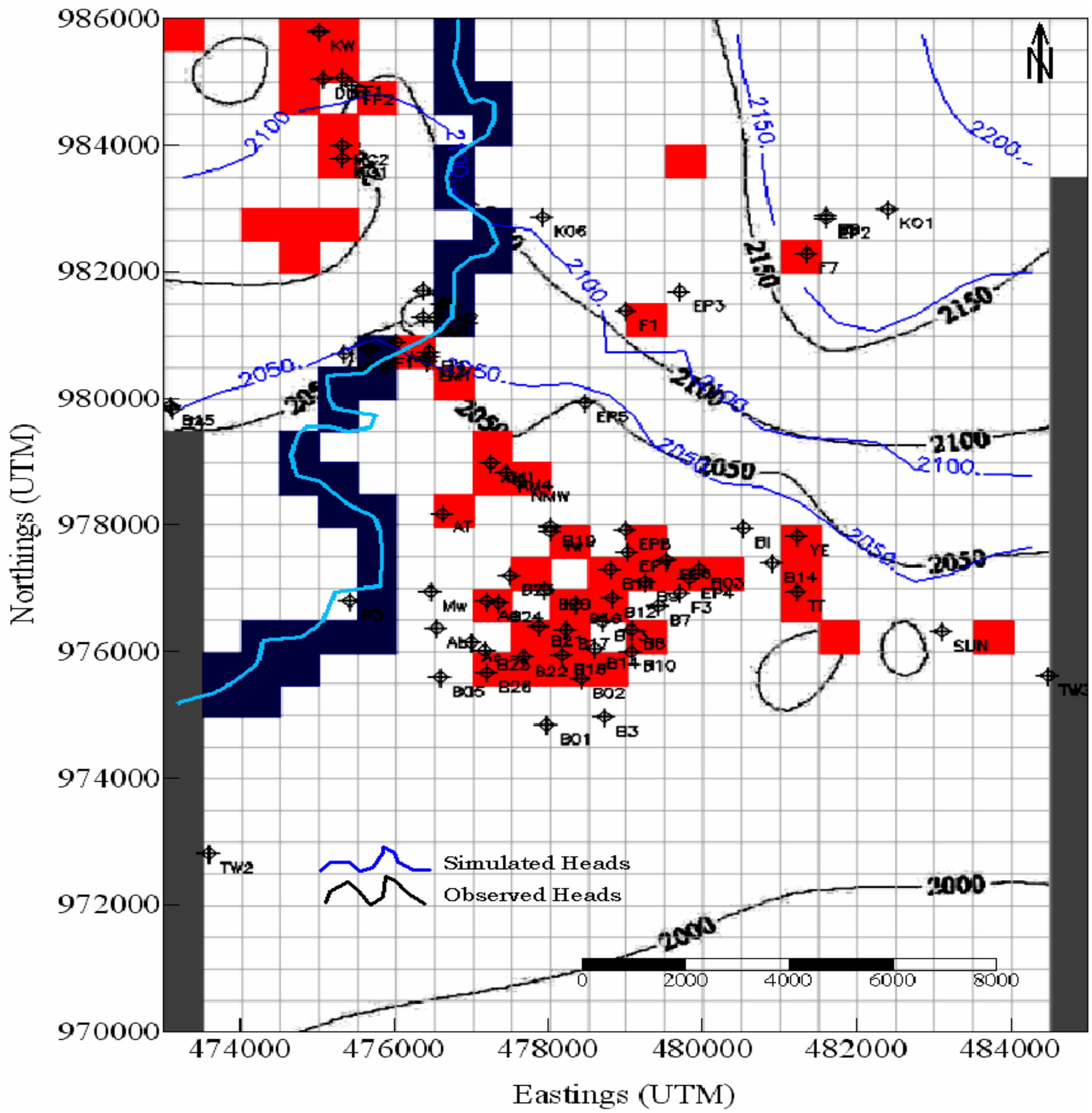

Fig.3.7. Map of actual observed heads with simulated heads used to calibrate the model in steady state flow conditions.

3.9.1 Calibration Criteria

The calibration criteria involved comparison between the measured and simulated heads. The model was considered calibrated when the following criteria were met:

1) Simulated flow directions agreed with those represented in the water table map constructed from the static water level measurements;
2) The calculated heads reasonably matched the measured or inferred heads; with correlation coefficient of 0.9699.
3) Visual inspection of the areal distribution of the residuals or differences between heads interpolated from the water level map and simulated heads indicated no consistent pattern of positive and negative high or low values.

3.9.2 Steady State Flow Calibration

This process aims at checking the overall coherence of the selected assumptions of the modeling and at identifying the suitable hydraulic conductivity value. After numerous trials, satisfactory simulation result of the flow, the piezometric levels and hydraulic conductivity has been obtained. The observed and calculated head values are well correlated with a correlation coefficient of 0.9699 fig.3.8.

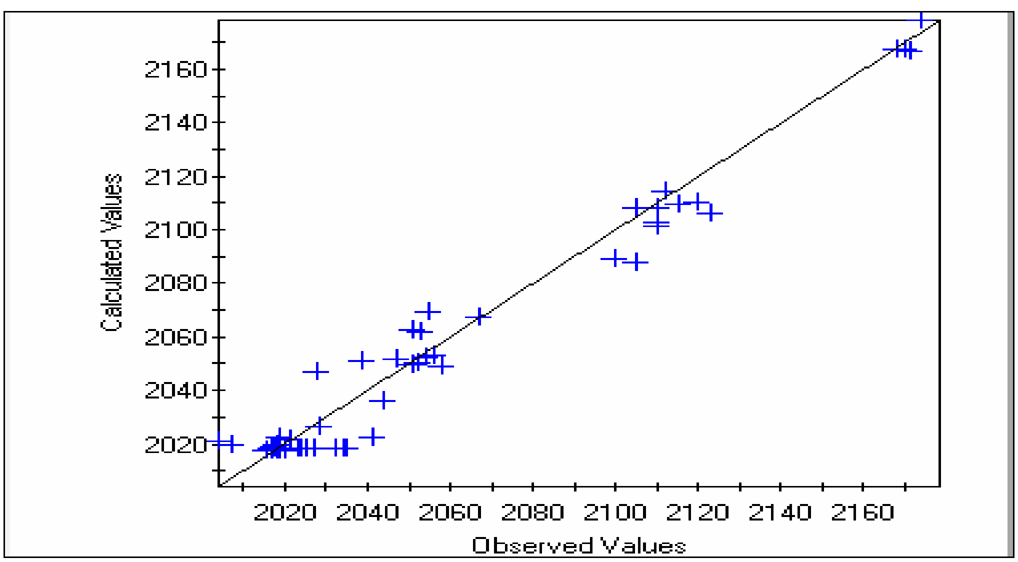

Fig.3.8. A scatter diagram of calculated and observed heads in the study area. (The correlation coefficient is equal to 0.9699).

3.9.3 Transient State Flow Calibration

The transient state calibration mainly takes into account the calibration of the storage coefficient by integrating changes in the water level and abstraction rate with time. The available groundwater level changes with time as a result of the pumping in the well field between August 2002 and August 2004 are used. The calibration started with the storage coefficient values of the old model of AAWSA (2002), but these values are slightly modified in few areas; so that the observed and simulated heads under transient state conditions match.

After many trials, a satisfactory reproduction of the observed piezometric levels was obtained. At the end of this phase of calibration (fig 3.9) it is concluded that the modelling work has simulated the actual hydrogeological condition of the area and constituted a coherent unit making possible to simulate the behaviour of the aquifer system as well as the contaminant transport. The calibrated model can reasonably simulate the actual groundwater flow, and it can be used for future groundwater flow, and solute transport simulations.

In addition to the calibration processes explained above, to check the accuracy of the simulation results, MODFLOW calculates volumetric water budget for the entire model at the end of each time step. The water budget provides an indication of the overall acceptability of the numerical solution. The percent discrepancy of in- and out-flows for the model is calculated and acceptably small (0.11%) table 3.5. This means the model equations have been correctly solved.

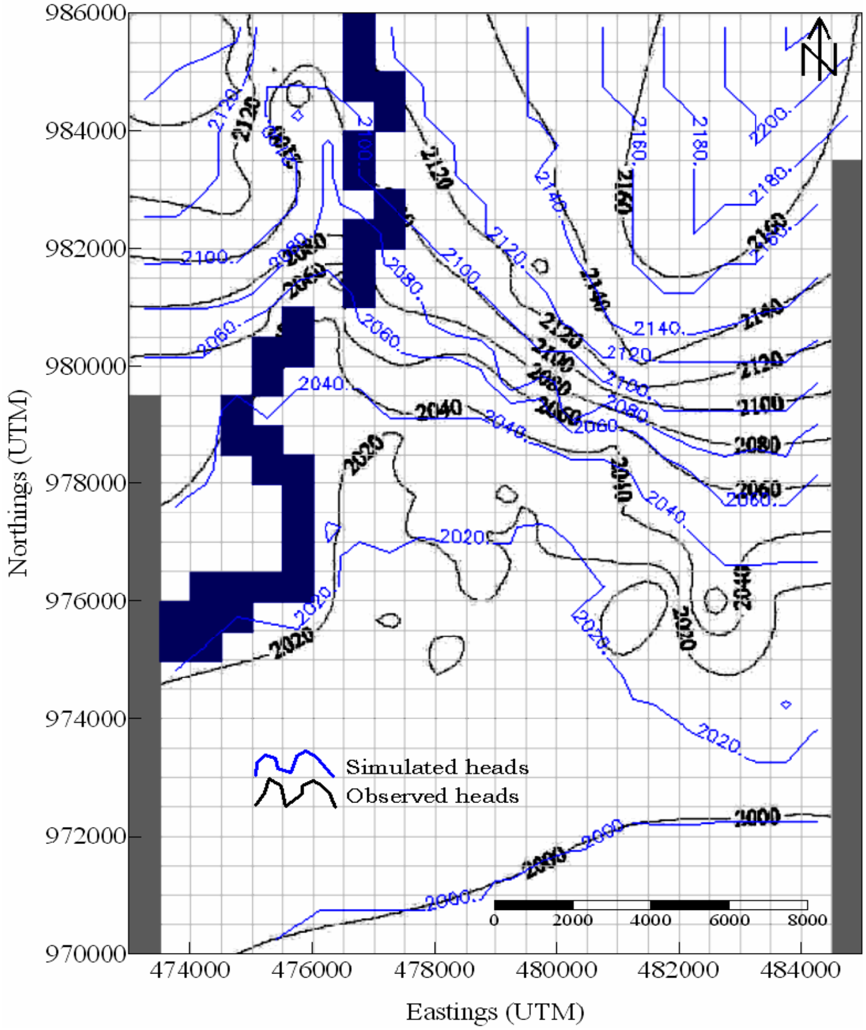

Fig 3.9. Comparison of the actual head contours with that of simulated heads in transient state condition.

Table 3.5. Water budget of the whole model domain during time step-1 of stress period-1. Unit of the flow terms: M^3/S.

FLOW TERM	IN	OUT	IN-OUT
STORAGE	8.2467209E+01	8.1595268E+01	8.7194061E-01
CONSTANT HEAD	1.1303267E+00	1.1670703E+00	-3.6743522E-02
WELLS	0.0000000E+00	1.0639998E+00	-1.0639998E+00
RECHARGE	3.1726831E-01	0.0000000E+00	3.1726831E-01
SUM	**8.3914803E+01**	**8.3826340E+01**	**8.8462830E-02**
DISCREPANCY [%]	0.11		

3.10 Sensitivity Analysis

The overall performance of a groundwater model may be better analyzed through a sensitivity analysis of its aquifer parameters. The sensitivity analysis allows the groundwater investigator to better understand the system's response to changing parameters. Sensitivity analyses were used to refine initial estimates of input parameters during model calibration, and to determine which input parameters had the largest effect on simulated head values after model calibration.

If the model is sensitive to an input parameter, additional data on that variable can help improve calibration. Increments and decrements of 10 percent were applied to horizontal hydraulic conductivity, transmissivity and rainfall recharge. Sensitivity refers to sticking to the reference mode (to the actual flow pattern) even when key parameters are changed. Therefore the model was found to stick to the actual flow pattern with change in transmissivity and recharge except change in hydraulic conductivity.

4. An Advective Solute Transport

4.1 Hypothesis and Assumption of the Solute Transport (PMPATH)

Water carrying contaminants (fig. 4.1) may enter into the underlying porous aquifer from quarries, highly polluted Akaki River (Berhanu Gizaw, 2002) that drain the urban centre, and most creeks of Sekelo sub-basin into which most factories and industries directly release their effluent. Effluents are released both under natural conditions where groundwater and surface water interact (loosing streams) in recharge areas up gradient and exit at discharge areas down gradient (wet lands, water supply wells, lake and ponds), and under artificial conditions where flow paths fall within the capture zone of wells under maximum pumping conditions.

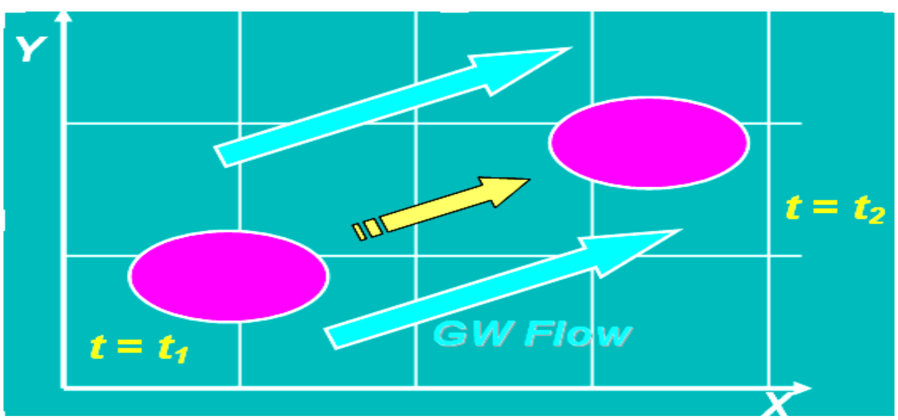

Fig.4.1. Conceptualization of the process by which solutes transport by moving groundwater (convective transport).

It is assumed by PMPATH that fluid properties are homogeneous and that concentration changes don't significantly affect the fluid density or viscosity and hence the fluid velocity. Therefore, solute transport equation is applied in an incompressible fluid flowing through porous medium implies that all changes in fluid storage are represented by changes in porosity in the three dimensional transport equations.

4.2 Factors Governing Contaminant Transport

Water pollutants do not always enter the groundwater system directly, instead they tend to be removed or reduced in concentration with time and distance traveled (Tamiru Alemayehu et al., 2005). Understanding the factors that govern contaminant transport particularly in this area is, therefore, crucial. Rate of pollution attenuation depends on the geology, local hydrogeological situations, geochemical processes and the type of pollutants. Moreover, mechanisms of pollution attenuation include filtration, sorption, chemical processes, microbiological decomposition and dilution. These factors affect contaminant migration in one or another, and are explained below.

4.2.1 Implication of Geology on Transport

The geology of the area including rate and extent of physical and chemical weathering of rocks, and the density and orientations of the structures affect the rate of infiltration of polluted water. The moving water leaches not only the free cations removed from the mineral structures but also transport species that enter water as a consequence of chemical weathering. Thus, the weathered rocks of the area, associated structures and their orientation would have facilitating effect in contaminant migration.

4.2.2 Hydrogeological Favorability/ Suitability for Transport

4.2.2.1 Porosity and Permeability of the Aquifer Media

The groundwater circulation and the dispersion of pollutants depend on the hydrogeological characteristics of the material such as porosity, permeability, and hydraulic conductivity. To identify the pathway and final destination of pollutants, it is necessary to describe the earth materials with a particular reference to their infiltration capacity (Tamiru

Alemayehu et al., 2005). Groundwater movement, and contaminant movement and accumulation in unconsolidated pyroclastic aquifers are determined by fragment size, sorting and the degree of cementation of particles.

The infiltration capacity of water in the black cotton soils of the area is high at the beginning of the rainy season through the cracks formed in the previous dry season, and reduces when the amount of precipitation increase. As a consequence, contaminants that enter cracks of the black cotton soil during the dry seasons will later move down with infiltrating water during the rainy season. On the other hand, when clay is not a dominant constituent of the soil, there is relatively a constant infiltration of water in the rainy season through the highly porous and permeable rocks of the area (Tamiru Alemayehu et al., 2005).

4.2.2.2 Surface and Groundwaters Interaction

Traditional water resources management treats surface and groundwater as separate entities. However, it is apparent that the movement of water between surface and groundwater provides a major pathway for chemical transfer between terrestrial and aquatic systems. Nearly all surface water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with groundwater in various ways. In many situations, surface water bodies gain water and solutes from groundwater systems while in others surface water is a source of groundwater recharge and causes change in groundwater quality (Fig.4.2). Pollution of surface water can cause degradation of groundwater quality and conversely pollution of groundwater can degrade surface water. Thus, effective water management requires a clear understanding of the linkage between surface and groundwater at any point and time in a given hydrogeologic setting.

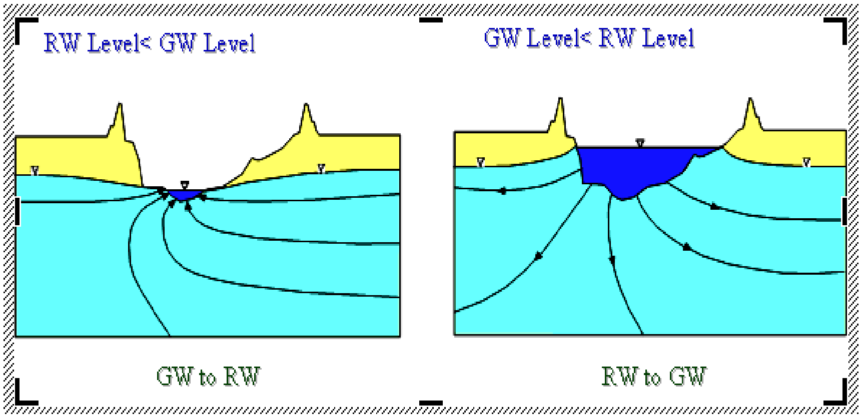

Fig.4.2. Rivers and groundwater connection; a gaining stream (left) and a losing stream (right).

The Akaki river may temporarily become a losing stream. When the hydraulic gradient in the aquifer adjacent to the river is reversed due to draw down of water table during the dry seasons of the year, water flows from the river into the groundwater. This might also be promoted through increasing pumping rates in wells (Aynelam Ali, 1999).

Surface water pollution has already recorded in many parts of Addis Ababa (Alemayehu T., 2001). Groundwater pollution is also becoming a major threat particularly where the groundwater table and the surface water coincide, like around Kality (Berhanu Gizaw, 2002). AAWSA et al. (2000) have pointed out that the aquifer near Kality feeds both the Little Akaki and Big Akaki rivers and their tributaries, from their headwaters up to a point near Akaki bridge, as the groundwater level is higher than the river bed level, along their courses, although they recommended further investigation. Down stream of this point and up to Aba Samuel hydropower plant, the groundwater level becomes lower than the river bed. They believed that there is no hydraulic connection between the aquifer and the surface water bodies in this part.

However, some other previous investigations (Aynelam Ali, 1999) and the current study show that there is possibility of leakage through the deep cutting fractures even down the Akaki bridge. However, the extent of interaction of the river and the groundwater system shows seasonal variation.

The pH, EC, TDS, and total coliform concentration in the groundwater reflect the influence imposed by polluted surface water, implying the strong seepage of surface water into the groundwater system .Such mixing theory is corroborated by actual chemical, e.g., TDS versus Ionic concentration, and stable isotope data (Aynelam Ali, 1999). A linear correlation between conservative constituents further indicates mixing (Berhanu Gizaw, 2002).

The rate of seepage is often greatest in areas where wave action may restrict the deposition of finer sediments. Therefore, the locations where the polluted Akaki River interacts with the underlying groundwater vary from place to place.

4.2.2.3 Effect of Unsaturated and Impermeable Layer

Aquifer types (confined and unconfined), and thickness of unsaturated zone have an effect on movement of contaminations in the subsurface. Even though the unsaturated zone in the well field is thick (30-60 meters), tectonic activity (structures) in the area create favorable pathways for transport.

The thick non-saturated zone in the well field can act as a geochemical and bacteriological filter, because of its negligible permeability. The aquiclude (massive rocks or clays) prevents both downward and upward groundwater flow from the surface to an aquifer and from a deep aquifer to a shallow aquifer, respectively. It is, therefore, unlikely that the contaminated surface water flow into the aquifer in areas where these units are found. Though the leakage of contamination can be attenuated by the black cotton soil in some localities, the Akaki River could still have impact on the surrounding alluvial aquifer.

4.2.3 Geochemical Processes Affecting Transport

The relative abundance of ions in groundwater is determined by the geochemical reactions as among the groundwater and the various minerals in the aquifer media. Geochemical reactions such as hydrolysis and complaxation, precipitation/dissolution, oxidation/reduction, sorption and portioning, as well as advection and hydrodynamic dispersion processes all affect the movement of contaminants in the environment. However, the relatively large number of contaminants in the water doe not allow at this stage to identify the chemical behavior of each of them at this stage.

In this study, only an advection process is dealt with. Part of the water in the Akaki well field flows by advection and hydrodynamic dispersion from the aquifer situated under the city of Addis Ababa and Akaki town which are potential pollution source areas. Therefore, quality of groundwater located upstream of the well field can have an impact on the quality of water in the well filed.

4.2.4 Effect of the Slope on Transport

Slope variability of the land surface is an important factor in groundwater vulnerability assessment as it determines the amount of surface runoff produced, the precipitation rate and displacement velocity of the contaminant (Civita and De Maio, 2000 cited in Tamiru Alemayehu et al., 2005). Furthermore, the slope may be genetic factor of the soil type and thickness that indirectly facilitate the attenuation potential of the hydrogeological system.

Slope also determines the extent of runoff of the pollutant and the degree of settling sufficient for infiltration. Areas with steep slopes, having large amounts of runoff and smaller amounts of infiltration, are less vulnerable to groundwater contamination (Napolitano, 1995 cited in Tamiru Alemayehu et al., 2005). Generally, low to gentle slopes, i.e., surface zones where a pollutant may be less displaced under gravity action are highly vulnerable. The study area which is dominated by gentle slopes, except few steep slopes in the south and east, is highly vulnerable to groundwater contamination.

4.3 Human Activities having Pollution Potential in the Area

Factories that dispose untreated effluents and household sewage have been causing pertinent and wide spread surface water contamination in Addis Ababa. The Kaliti sewer treatment plant, located south of the city and northeast of the Akaki well field, receives waste from sewer lines and waste disposal trucks. Water used for washing and cleaning, heating and cooling processes, is disposed without treatment from industries contaminated with various chemicals. All possible sources of contamination including industries (steel, pulp, paper, pigments, caustic soda paint, pump, brewing, textile, food processing, and meat packing factories); dairy farms, open-air slaughtering, quarries, agricultural plots, grave yards, dense settlements, and open market areas are prevalent in the area. The main polluting industries are generally aligned along the Addis Ababa-Debre Zeit road.

The small agricultural plots are irrigated with either the river water which is contaminated with toxic substances dumped into it from the close by industries (particularly the Akaki Textile Factory) and/or through industrial liquid waste directly applied on the farmlands.

The sewage collected using vacuum trucks is discharged into drying beds constructed near the Kaliti waste stabilization pond. The chemical composition of the river water, therefore, likely represents the mix of natural as well as artificially induced ions.

4.4 Locations of Potential Contaminations

The following locations are selected as potential contaminant areas that may have an impact on the well field. These are

- Tulu Dimtu scoria which is highly fractured, porous and permeable rock sequence; it is located on a relatively elevated topography and the beds are partly tilted; the site has been used as a grave site; the well field is found at a lower elevation close to the foot of the hill;
- Gelan metal industry (located at 480653.000, 976985.000; elevation, 2130 m.a.s.l) is located on the way to Debrezeit road near Tulu Dimtu scoria, adjacent to Dengora stream to which it releases its liquid waste; the Dengora stream then crosses through the center of the well field downstream the factory;
- Kality treatment plant to which the highly polluted rivers that drain the Addis Ababa city, most sewerage lines, and few sanitation systems are directed; and
- Akaki Mesfin Zelelew dairy farm (located at 481507.396, 976220.970; elevation 2100 m.a.s.l) in order to know the potential leakage of pollutants from the farm (bacteria, animal wastes, etc).

4.5 Predictive Simulations of Contaminant Analysis

Solute transport simulation (Fig. 4.3) provides an ideal means to synthesize the controlling processes, evaluate their interactions, and test the effectiveness of remedial measures. The present study investigates the travel time of contaminants from their sources to the well field, the recharge, discharge and path lines of the contamination.

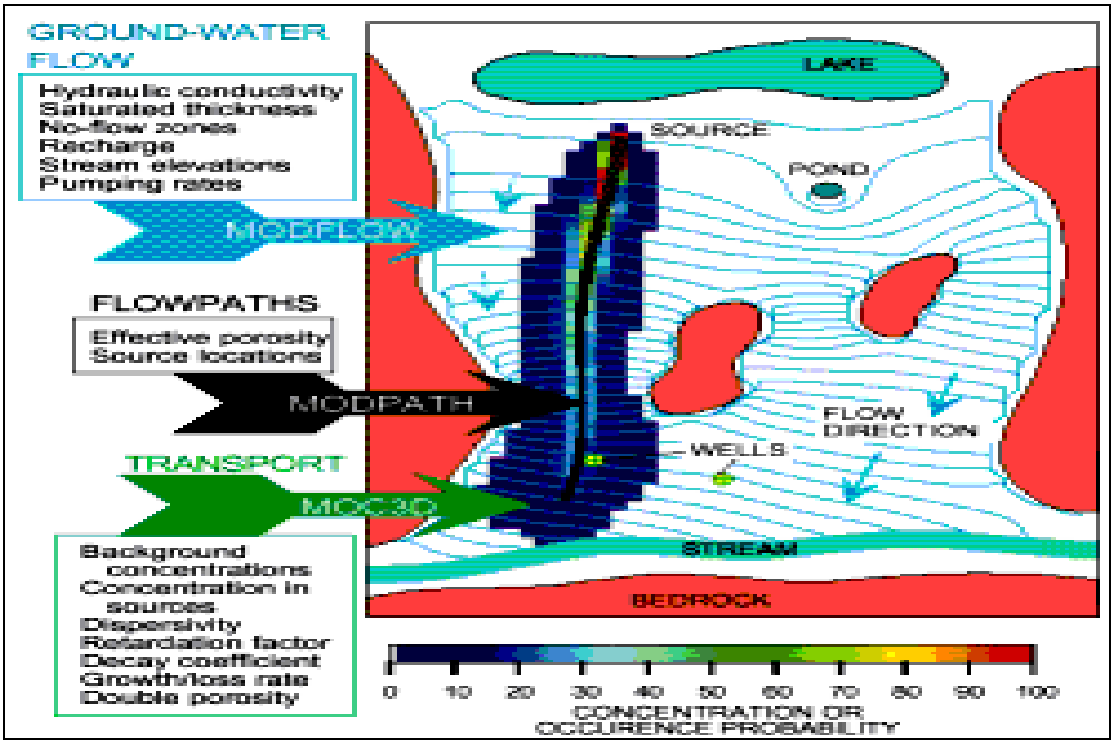

Fig. 4.3. A typical input and illustration of output for simulation of groundwater flow and solute transport using MODFLOW, MODPATH, and MOC3D softwares.

Particles are injected at selected locations and their travel times as well as their path lines are calculated by running particles forward. Contaminant locations which affect the well field are then distinguished from those which do not. Delineation of capture zones of the pumping wells has been conducted by using PMPATH which loads the current model automatically, where particles are placed around the pumping wells. The capture zones of different years are therefore examined by running particles backward.

Since contaminations are mostly considered to be from a surface source, they are placed only on a top cell face (face 5) fig. 4.4.

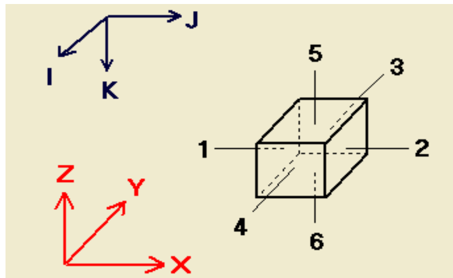

Fig.4.4. Various faces of an individual cell.

4.5.1 Pollutant Travel Time

The travel time for pollutants in the Akaki well field is calculated using the hydraulic conductivity values obtained from the existing well pumping results (Tamiru Alemayehu et al., 2005).

Lateral separation is considered to be the velocity times the time of travel (Lawrence et al. (2001) cited in Tamiru Alemayehu et al., 2005).

The distance separation concept can be used to calculate the travel time of pollutants vertically from the surface towards the water table.

For instance the SWL for BH 07 in the Akaki well field is 67.26 m. The travel time, T is equal to vertical distance separation divided by the hydraulic conductivity of this well (67.26 m/ (0.008 m/s)) = 8407.5sec or 2.30hours). In general the time required for bacteria to reach the groundwater level in the fractured scoriaceous basaltic aquifer ranges between $2^1/_2$ hours and 4 hours which could be effective during a single heavy rain (high recharge) period. In the Akaki well field bacteria can easily move to a depth of 50 meters (Tamiru Alemayehu et al., 2005). The calculated travel time could hold true in the case where the scoriaceous basalt outcrops on the surface. Otherwise, delay in bacterial movement is expected in the case of thick vadose zone made of black cotton soil.

The same concept was applied to calculate the horizontal travel time of contaminants in the aquifer taking into account the spatial variation in hydraulic conductivity and following the particle path lines.

Contaminants are introduced at sources upstream in cells (21,18), (15, 20), (5, 3) and (7, 3) and the distance of travel of contaminants through the steady state flow field is observed for 120 days, 180 days, 5 years, and 10 years travel times, respectively (figures 4.5 - 4.8).

Figure 4.5 shows that the simulated groundwater flow direction is to the well field almost from all directions and the velocity is relatively higher in areas where there is high gradient. In the other areas it has relatively slow velocity as can be seen from the length of velocity vectors to the extent they seem dots in most areas. Therefore, any contaminants released at these two velocity locations will have different travel times, with short travel time corresponding to the high velocity areas and long travel times corresponding to low velocity areas. Moreover, the cross-section shows (bottom of fig. 4.5) that the groundwater flows from Akaki River towards the well field.

The cross-section to the right of fig. 4.5 shows the recharge and discharge areas of contaminants. The contaminant at cell (5, 3) is initially injected above potentiometeric surface; meanwhile moves within the aquifer but later comes on the surface of groundwater. However, contaminant at cell (7, 3) is injected at the potentiometeric surface and remains below the water surface entirely. Therefore, remediation may not be easy for contaminants at cell (7, 3).

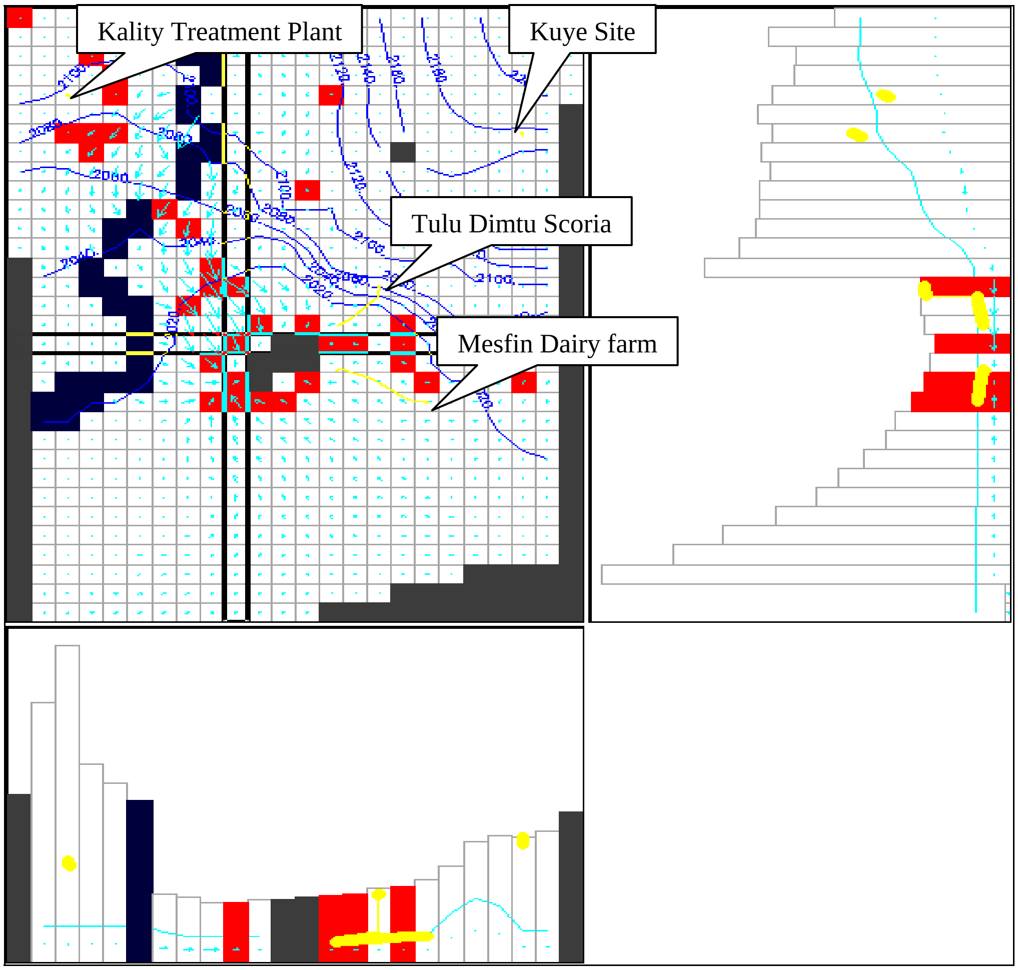

Fig .4.5. Contaminant path lines of 120 days travel time, from Tulu Dimtu scoria, cell (15, 20) and Mesfin Zelelew dairy farm, cell (21, 18). The lines get very close to one of the wells in the well field. (Note that in this figure and figures 4.6-4.8 (i) the velocity vectors show the direction and magnitude of groundwater and contaminant flow velocity. The length of arrows indicates relative magnitude of groundwater and contaminant velocity. The direction of arrows indicates local flow direction during the given stress period and time step; (ii) the yellow lines represent contaminant stream lines, the turquoise arrows represent velocity vectors and turquoise line in the cross-sections represents the groundwater surface (potentiometeric surface); and (iii) the cross-section shows the projection of row 18 and column 10 through the center of the well field).

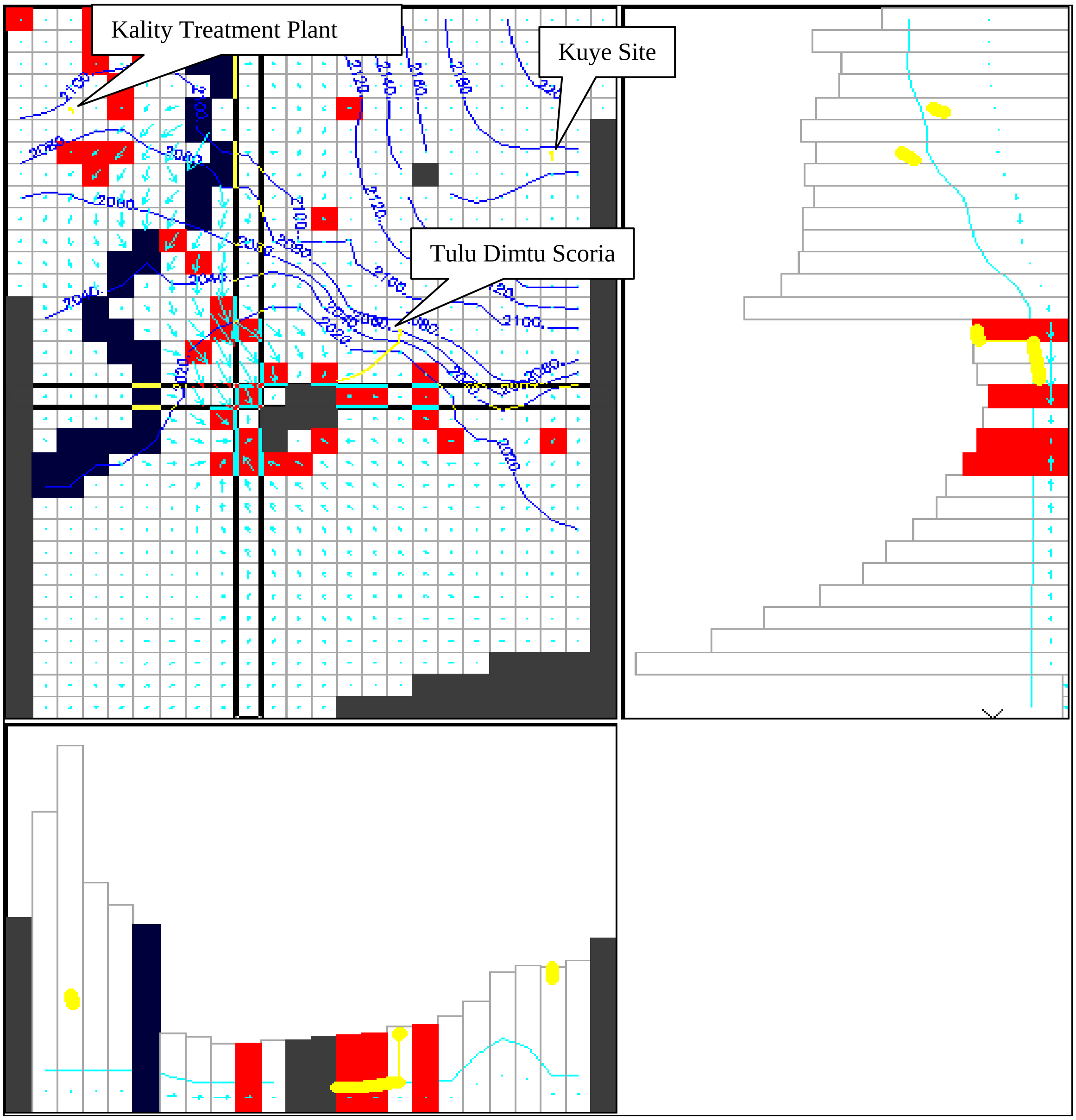

Fig.4.6. Contaminant path line after 180 days of travel time from Tulu Dimtu scoria, cell (15, 20). Now it has arrived one of the wells in the well field.

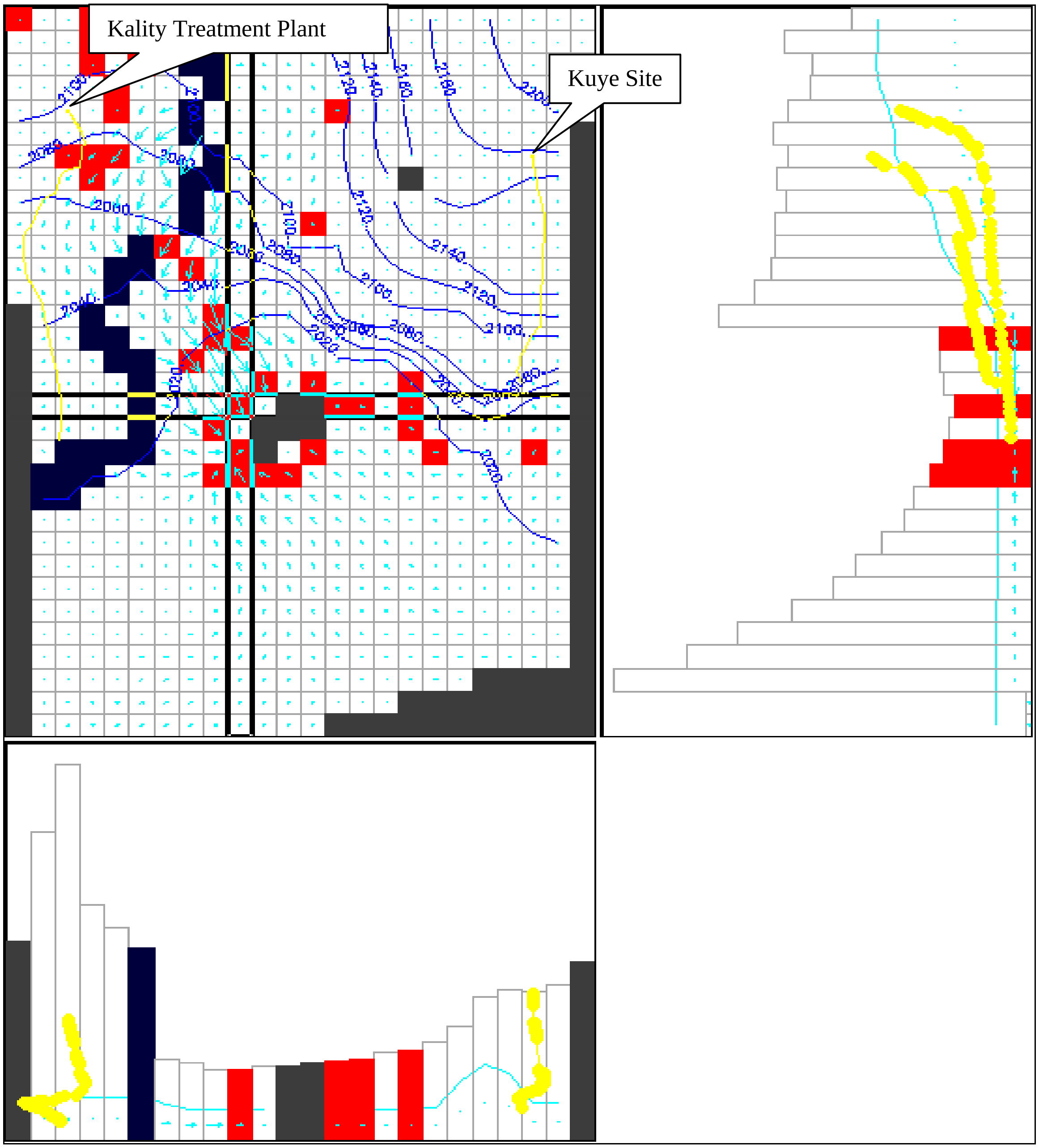

Fig.4.7. 5 years streamlines; Particles injected at the cell (5, 3), Kality area and cell (7, 3) and flow towards the wetland that serve as sink and to the well field, respectively.

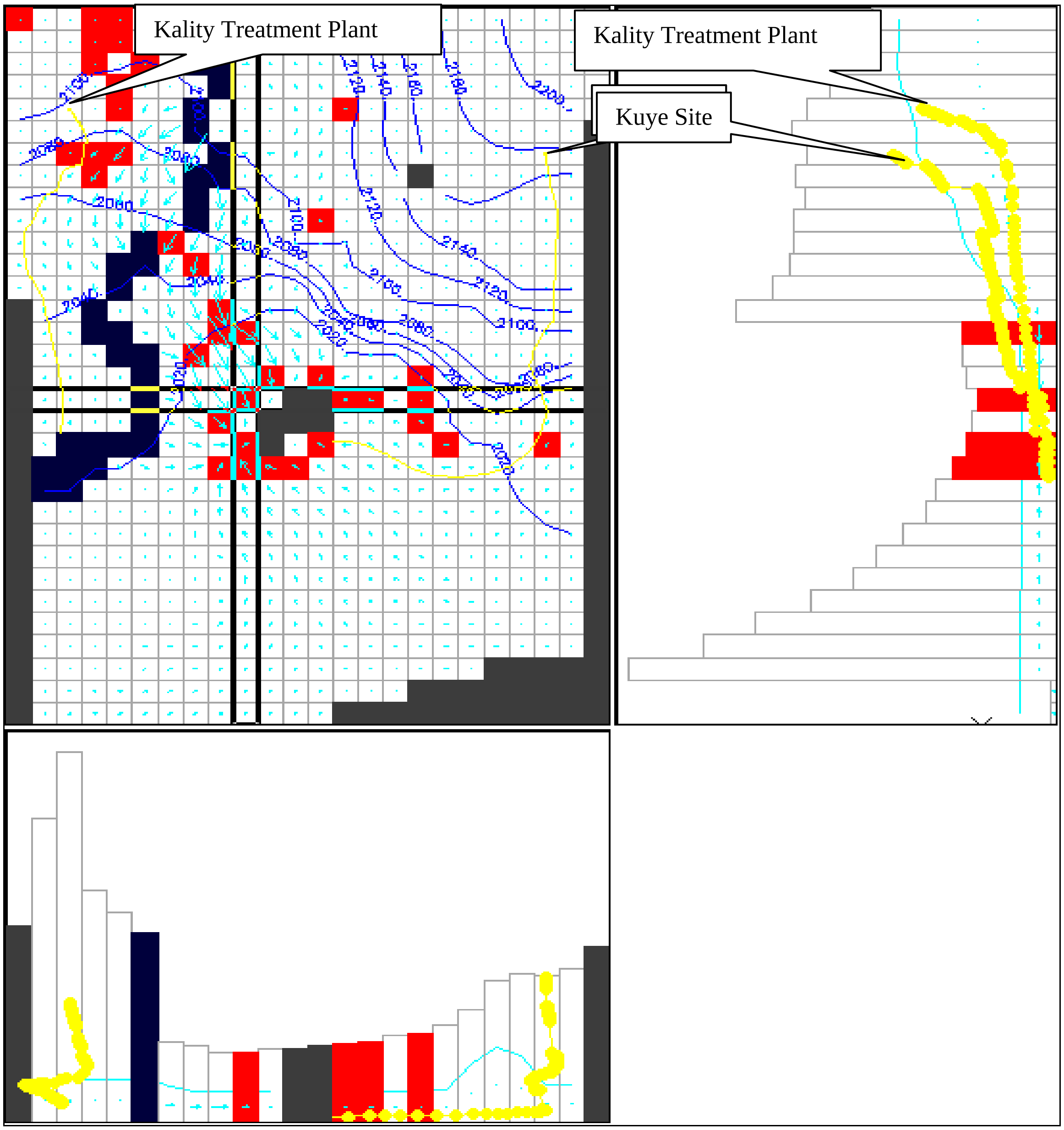

Fig.4.8. Contamination introduced at cell (7, 3) upstream has arrived the well field after 10 years of travel time. It is shown in fig. 4.7 above that contamination from the same site travels only certain distance between the well field and the injected location in 5 years travel time. The flow is not linear as contaminants from cell (5, 3), (15, 20), and (7, 3) record different travel distances over the same time period (fig.4.6). Flow is more rapid where the porosity is high and stabilizes towards the end of the simulation.

4.5.2 Capture Zone of the Well Field

Contamination at a well site can be due to introduction of pollutants either within or outside a casing. An improperly constructed well can therefore act as a contamination site of groundwater. The requirements which are most often violated and pose a threat to groundwater quality include lack of adequate grouting, lack of a proper seal at the top of the casing, and lack of a concrete slab around the well casing.

Due to the unique nature of the aquifer type in the area in that it has high transmissivity ranging between 1834 m^2/day to 105, 408 m^2/day and the prevalent tectonic features (aligned scoria cones, fractures and faults mainly due to the effect of Main Ethiopian Rift) in the Akaki well field, major contamination is expected to come from areas outside the casing. As a result, the capture zones indicated in figs. 4.9 and 4.10 are determined. The capture zone agrees with the results of protection zones delineated by Tamiru Alemayehu, et al. (2005) in their groundwater vulnerability assessment.

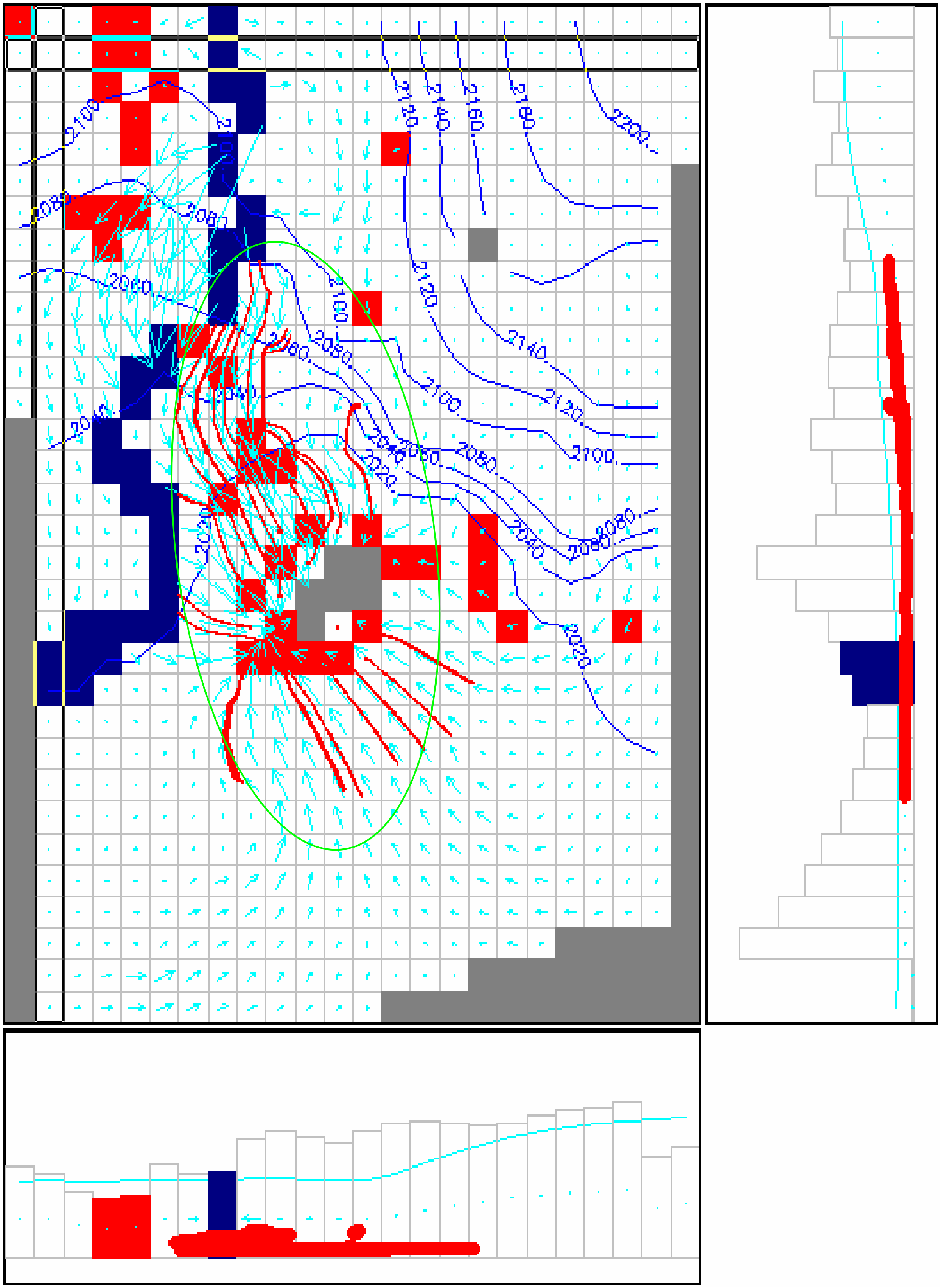

Fig.4.9. Steady state hydraulic head distribution in the model layer and capture zones of the pumping wells in the well field in 92 days.

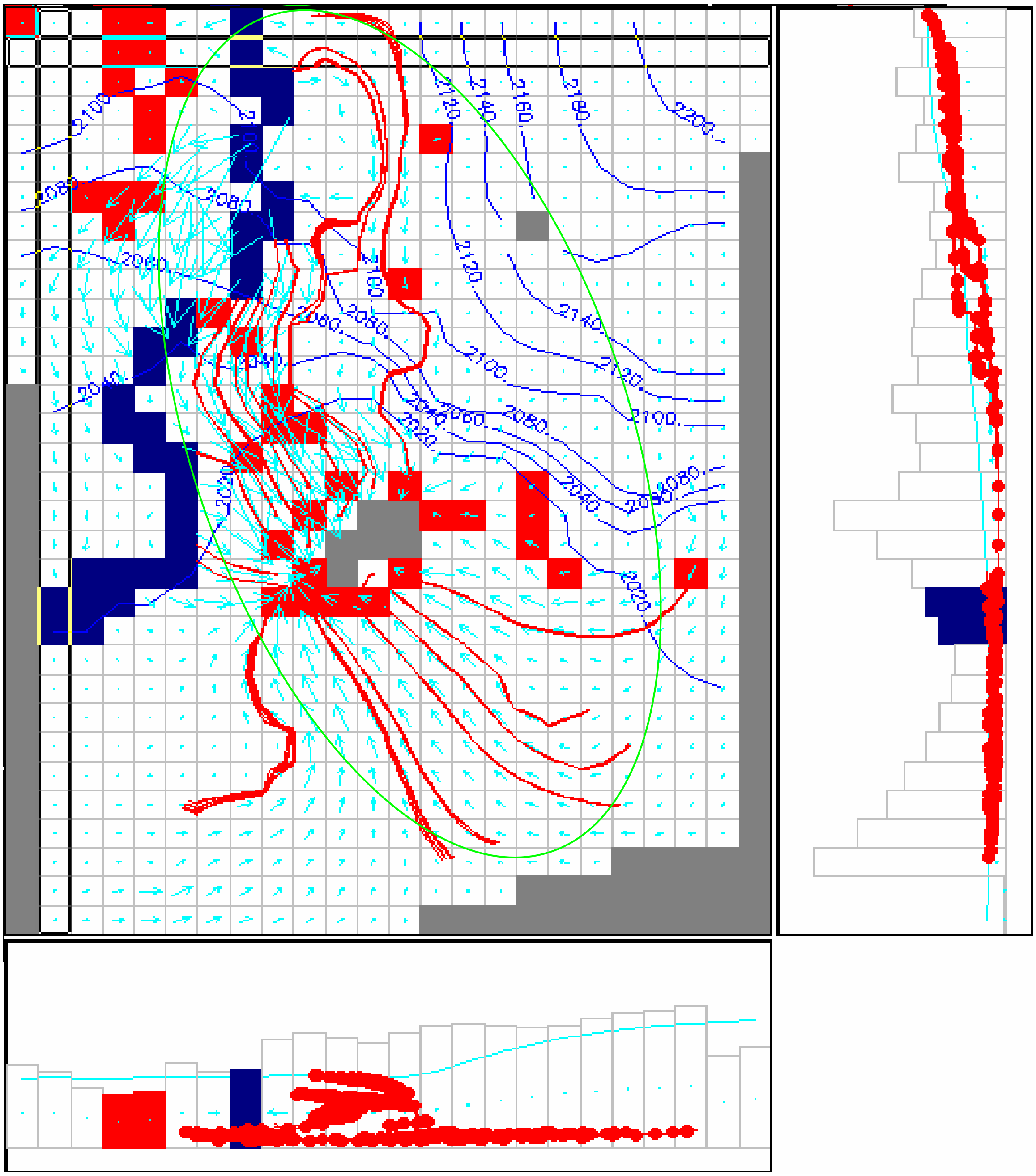

Fig.4.10. Steady state hydraulic head distribution in the model layer and capture zones of the pumping wells in the well field in 10 years. In this case contaminants from most of the study areas will be captured. In contrary to this, within 92 days, only areas close to the well field are captured.

5. Discussion

5.1 Impact of Draw down on Contaminant Migration

The draw down evolution in time of the Akaki well field at a constant pumping rate of 30,000 m^3/day (suitable pumping rate selected for abstraction of the well field; by allowing maximum of 20 meters draw down until 20 years time) is presented in table 5.1 and figure 5.1. Accordingly, pumping causes the highest draw down in the well field itself followed by the Dalota site, and moderately for Upstream Dukem, Fanta and Downstream Dukem.

According to AAWSA et al. (2000), the discharge of Fanta spring which is situated upstream of the well field will be reduced and will even be dry after 10 years for most of the pumping situations. Even with suitable pumping rate, the drawdown in the well field will reach 20m after 17 years. Within 20 years, pumping in the well field would cause 23m draw down in Akaki well field depending on the amount of pumping. Around Kality, in the same period, the wells would be affected with a drawdown of about 5m.

During pumping and subsequent draw down within a well, contaminants can be attracted to the highly pumped well, and eventually contaminating the whole well field and decreasing the life of most of the wells before the estimated 20 years life.

Table 5.1 Impact of pumping Akaki well field at a constant pumping rate of 30,000 m^3/day.

Site	**5 years**	**10 years**	**15 years**	**20 years**
Akaki well field	**9.5**	**14.8**	**18.6**	**21.6**
Dalota	5.0	9.1	12.3	15.0
Dukem Upstream	3.4	6.9	9.8	12.2
Dukem Downstream	0.4	1.3	2.4	3.3
Fanta area	0.8	1.7	2.5	3.3

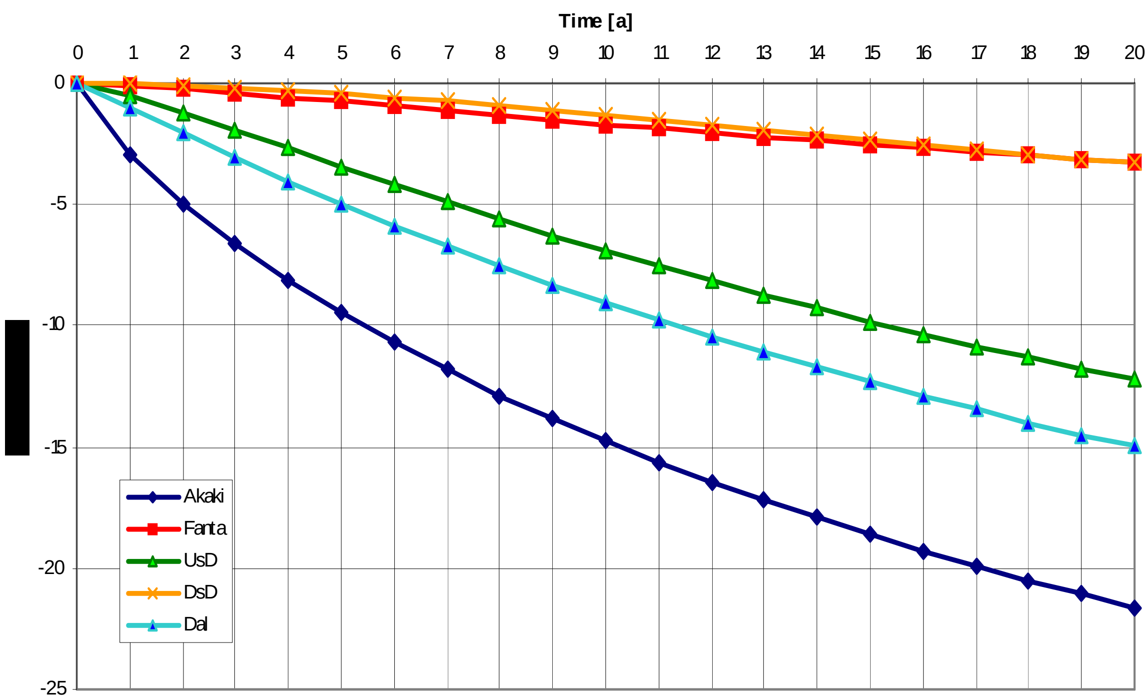

Fig. 5.1 Draw downs in Akaki wells and areas surrounding Akaki caused by pumping Akaki well field. The following legends represent UsD: Upstream Dukem, DsD: Downstream Dukem and Dal: Dalota)

Maps of equal values of draw down or the shape of the isovalues is elliptical, with its long axis oriented along the northeast direction (fig.5.2). This shape can be attributed to the fact that the main pumping wells (BH17, BH16, BH12, and BH09) are aligned along the northeast direction as well as the fact that the permeability of the reservoir is anisotropic and the highest value is in the northeast direction, likely due to the major tectonic line aligned in the same direction. Furthermore, the well field area which is with gentle gradient (with wide water table contour spacing, fig. 5.2) is characterized by higher hydraulic conductivity or permeability.

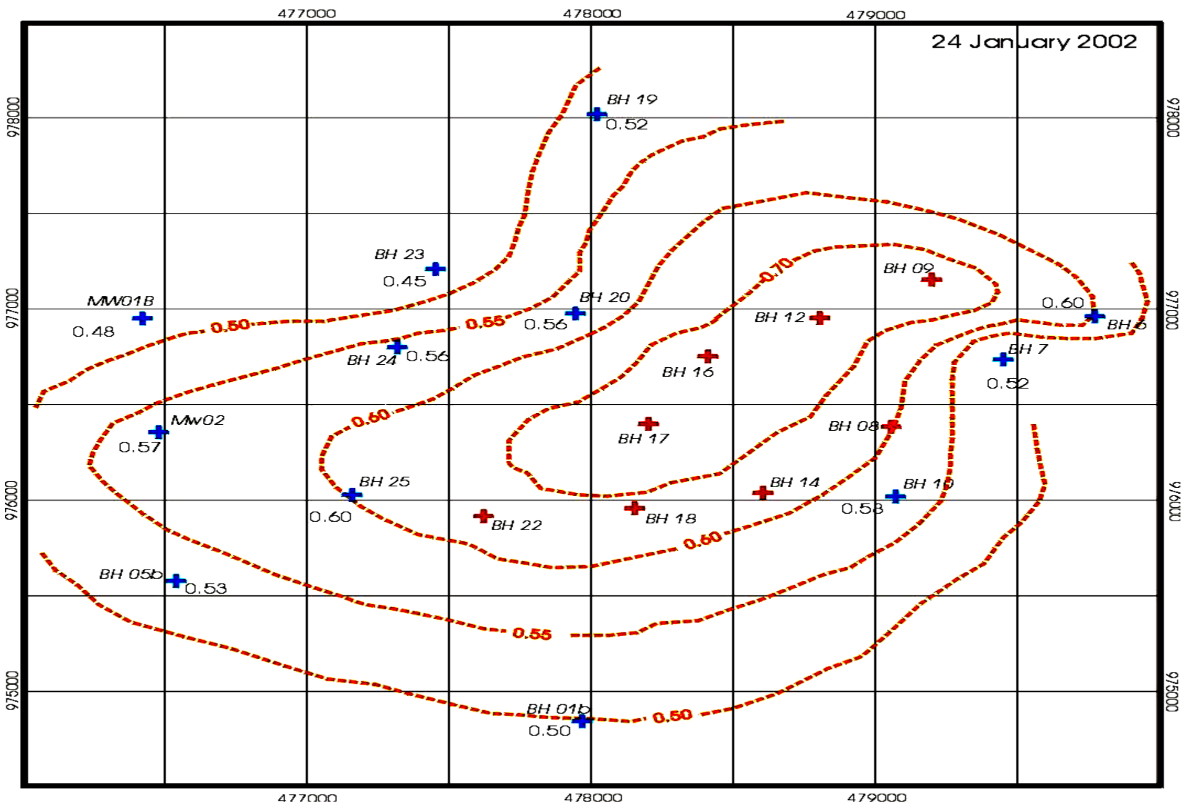

Fig.5.2. Map of equal drawdown around the well field (modified after Addis Ababa Water Supply Project Stage III A – Groundwater Phase II, 2002).

The rate of contaminant migration into the aquifer depends on many factors including the following:

- the permeability of matrix and transmissivity of rocks; the latter is high in the well field area, facilitating fluid movement;

- intercalation of basalt flows separated by baked soils which form weak zones at the contact; such soils were probably formed by weathering during the interval between the flows and are likely to be fissured and of high permeability; low values of apparent resistivity (50 to 100 Ωm) at the contact zones (Aynalem Ali, 1999) corroborates this;
- the columnar joints of the basalt;
- the orientation of some structures like the inclined bedding of most scoriaceous basalts dipping in the NW direction allowing easy percolation of fluids;
- intensive network of fractures facilitating fast groundwater circulation and contaminant migration; the joints are closely spaced in most areas (15-200cm in the basalt, 5-100cm in the trachy basalt and tracyte, and 2-100cm in the ignimbrite, Tamiru Alemayehu, 2005).

5.2 Impact of Soil Cover on Contaminant Migration

Soil is considered to be the first defense-line of the hydrogeological system (Civita and De Maio, 2000 cited in Tamiru Alamayehu et al., 2005). The characteristics of the soil influences the amount of recharge infiltrating into the ground, the amount of potential dispersion, and the purifying process of contaminants to move vertically into the vadose zone. The presence of fine-textured materials such as silts and clays can decrease relative soil permeability and block contaminant migration. The electrostatic attraction between the surface of clay particle, the soil water molecule, and the solute dissolved in the water may prevent contaminant transport into groundwater. Therefore, porosity and permeability of soil control the vertical as well as horizontal movements of contaminants by surface and subsurface water.

In the Akaki well field, particle size distribution analysis done on lacustrine (black cotton soils) and Tulu Dimitu scoria based on the standard methods (DIN 18123, German Norm), sieve analysis and sedimentation, indicates that the lacustrine soils have relatively lower (10^{-5} to 10^{-4}m/s) hydraulic conductivity values followed by the residual soil (10^{-4} to 10^{-3}m/s; Berhanu Gizaw, 2002). The Tulu Dimitu scoria, which is assumed to be similar to the main aquifer of the Akaki well field, has the highest hydraulic conductivity (10^{-3} to $5*10^{-2}$m/s). The results are consistent with the generally accepted ranges of hydraulic conductivities in unconsolidated sediments.

As indicated in Table 2.2, higher proportion of the grain size distribution of all samples show sand and gravel for Akaki black cotton soils and Tulu Dimitu scoria, respectively. Therefore, even the black cotton soils which appear to be impermeable to infiltrations and assumed impermeable in previous studies, have of course relatively low permeability in the region but they are permeable to fluids and hence may not be considered as “zero permeability zone”.

The scoria can be categorized as very highly permeable followed by residual soils (highly permeable). In addition, due to intensive erosional activities, there is poor soil development (shallow soil profile) or only patchy occurrences on most parts of the slope which proves the lack of defense line to the hydrogeological system.

Actually, the danger zones are areas of rock exposures and faulted zones. For hydrocarbon contamination, it is important to consider hydraulic conductivity of the scoriaceous basalt, which on average is 340m/day, and is very high if the rocks outcrop on the surface and if the spill occurs on fractures. In that case, if for example an oil spill occurs outside the delineated area (A and B, fig 5.3) there is a possibility of arrival of pollutant to the well field (Tamiru Alemayehu et al., 2005).

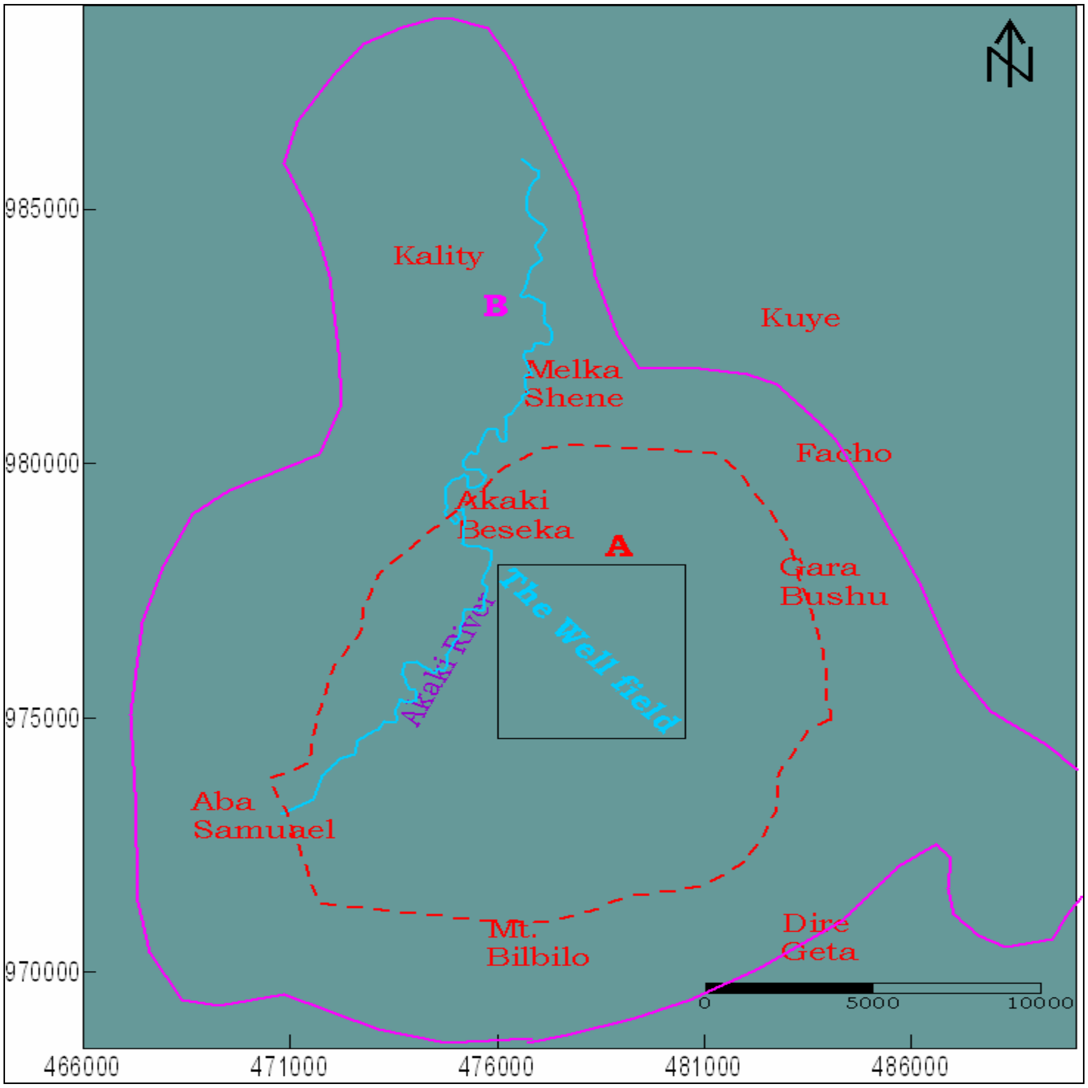

Fig.5.3 Protection zones delineated around the well field (Tamiru Alemayehu et al., 2005).

5.3 Impact of the Akaki River on Contamination of Shallow Wells

The river shows wide channel and slow flow velocity that allows enough time for the infiltration process near the Akaki Bridge on Big Akaki River to occur. The alluvial sediments of this area are characterized by high water infiltration capacity. The recharging water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. Hence there is higher danger of contamination in shallow wells from the Akaki River. Even though there is Clay layer observed in lithologic logs pronounced in few boreholes (e.g. bh 02, bh 03b, and bh 17).They are not laterally extensive (Aynelam Ali, 1999).

Depth to static water level (the depth of the water table) gives an idea of the minimum distance that a pollutant has to travel to reach the saturated zone. As the depth to water table increases there is a greater chance for attenuation to occur, as deeper water levels imply longer travel times. The groundwater in few areas (Kality and Fanta) is shallow and is susceptible to contamination. In the long run, the lowering of the water level due to pumping may change hydraulic conditions at the bottom of the river increasing the degree of infiltration of polluted water.

Generally, though urbanization and industrialization are the immediate sources of contamination, uncontrolled and improper abstraction of water along with suitable geological and hydrogeological setting of area facilitate contaminant migration. Even though the effect of contaminant migration is currently minimal, the model developed in this study clearly shows that contamination of the well field is imminent, unless strong protection policy as well as aquifer management strategy is implemented.

5.4 Monitoring of Wells for Control of Contaminants

Groundwater quality monitoring not only help to know the current existing situation but also helps in building models and simulate changes in concentration of contaminants. Groundwater monitoring in the area can be conducted using the water supply wells in the well field and other wells surrounding it (Table5.2). These wells are selected based on their representative spatial distribution and their proximity to the well field (fig.5.4). Taking also into account how long the contaminants take to arrive at the centre of the well field from their respective locations, half of the length of their travel times are assigned as the frequency of analysis. So we can have at least half to quarter of its full travel time to control the contaminant before it pollutes the whole well field.

Even though there are few activities of monitoring surface water quality (at inlet to Aba Samuael Lake, on Tinishu and Tiliku Akaki rivers, and at Akaki Bridge), the analysis should consider all major ions, nitrates, nitrites and some heavy metals, and their change should also be regulated for groundwater.

It is important to closely observe if pollution has taken place near or in the well field. If for example pollution is noticed in the highway area, the nearest wells (Ep-07 and BH-09) should not be stopped because they can be used to control the pollution. If pumping is stopped in the polluted wells the whole well field can be contaminated. Instead their discharge should be increased and the water should be disconnected from the system and discharged under a controlled mechanism out of the well field.

Table.5.2. Selected water quality monitoring wells and monitoring programs for the well field.

Well Name	**Location**	**Travel time (days)**	**Frequency of Analyses**
BH17	X:478199 Y:976361	<30	Two analysis per month
BH23	X:477477 Y:977216	40-60	One analysis per month
BH3b	X:478713 Y:974977	90-105	One analysis every two months
BH5b	X:476574 Y:975607	90-105	One analysis every two months
EP8	X:478998 Y:977937	40-60	One analysis per month
EP4	X:479942 Y:977322	40-60	One analysis per month
EP1	X:479340 Y:981400	360-400	Two analysis per Year

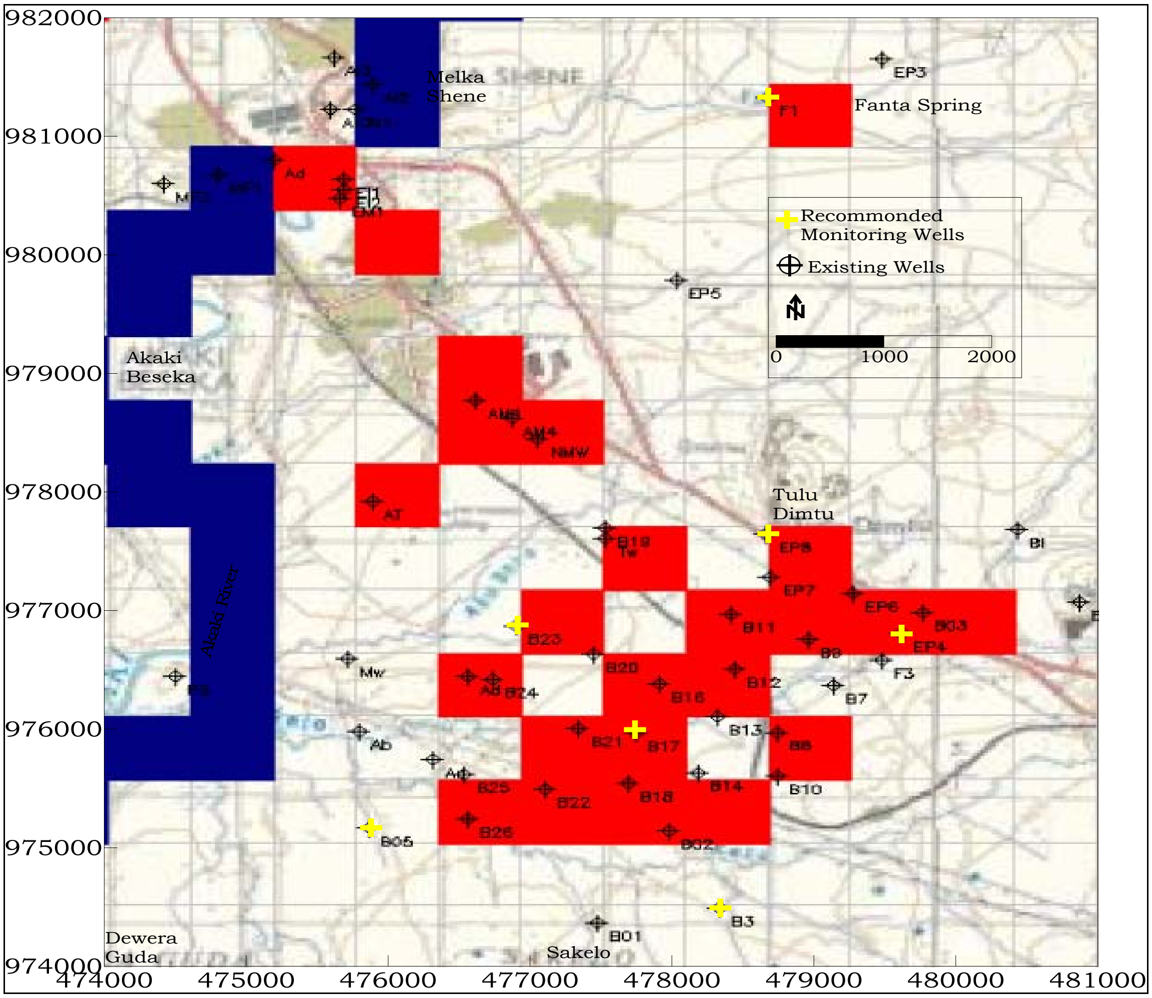

Fig.5.4 Spatial distribution of selected monitoring wells surrounding the well field.

6. Conclusions and Recommendations

6.1 Conclusions

The major conclusions of this study are:

1. The Akaki well field is highly vulnerable to contamination from surface waters and direct infiltration. Even though the groundwater level around the Akaki River is located at about 30 m below the river bed, there is a hydraulic link between the river and groundwater through rock fractures. The river has direct impact on the nearby wells that tap water from alluvial layer. The quality of the surface and groundwater up stream will determine the quality of water in the well field.
2. In the catchment, the groundwater flow lines converge towards Akaki well field from all directions, implying that contaminants are carried into the well field from all directions.
3. The intensive pumping of groundwater from the Akaki well field results in rapid decline of groundwater levels, leading to disturbance in the steady state flow system of the groundwater, eventually resulting in increased velocity of groundwater flow towards the depression zone. This process potentially facilitates the rapid flow of contaminated water from upstream sections of the aquifer to the well field.
4. Currently, the degree of contamination of the groundwater is negligible giving certain time to avert the problem. However, the model indicates that the groundwater path lines with contaminated water injected at contaminant sources upstream will reach in the well field in less than10 years time.
5. Flow is not linear through out the system, rather it is more rapid where porosity and transmissivity are high (well field and Akaki

town) and stabilizes in relatively low transmissivity areas (Fanta and Kuye).

6. Generally, though urbanization and industrialization are the immediate sources of contamination, the geological and hydrogeological make-up of the area facilitates contaminant migration.

6.2 Recommendations

In view of tackling the actual and potential contamination risks of the Akaki well field and the Akaki river catchment in general, more effort should be made to:

- coduct contaminant transport analysis taking into account chemical reactions, atteunation and multiple layer aqufier;
- create closed–loop water supply systems at industrial enterprises involving effluent reuse;
- design and improve sewerage and landfill systems in Addis Ababa city and Akaki town reducing the amount of pollution over time;
- implement strict environmental policy (e.g., type of fertilizers, industries, agricultural practices etc. to be allowed in the area) on the pumping sites with particular emphasis on the protection zones established around the well field;
- limit activities having pollution potential in special areas sufficiently far from water supply wells;
- introduce and implement legal control mechanisms (e.g., strict rules on treatment of effluents before disposal);
- set standards to discharges of potential bodies and penalties for non-observance of requirements; and
- closely monitor the chemical quality of groundwater in the well field and surrounding areas in addition to the surface waters.

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Appendices

Appendix 1 Meteorological data

a) Monthly Rainfall Data for the Years (1975-2005)												
	Monthly Rainfall				Lat	08°.52'		Altitude	2120m			
Region:	SHOA				Long.	38°.48'						
Station:	AKAKI MISSION											
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	0.0	0.0	3.8	107.2	58.5	175.2	347.2	308.3	281.6	19.9	0.0	0.0
1976	0.0	17.0	19.5	92.0	93.8	195.3	282.4	325.3	83.6	7.0	46.6	0.5
1977	80.5	29.9	80.8	67.4	108.2	158.0	289.7	329.4	108.4	225.7	5.0	0.0
1978	2.4	84.4	60.7	50.4	39.7	153.8	150.6	328.2	194.6	45.5	0.0	0.0
1979	106.4	28.2	107.6	57.6	122.0	75.9	243.2	241.4	96.5	13.0	0.0	4.0
1980	28.5	36.8	54.7	55.8	56.8	111.8	381.5	364.4	64.4	13.1	0.0	0.0
1981	0.0	13.3	179.8	143.9	1.3	46.2	402.6	186.5	219.0	5.0	0.0	0.0
1982	12.1	35.4	39.5	94.6	75.2	63.5	199.6	275.1	124.2	25.8	11.0	8.1
1983	1.8	33.3	15.0	147.3	175.0	83.0	278.0	275.0	138.7	9.2	0.0	0.0
1984	0.0	0.0	40.4	5.1	130.0	215.3	277.9	227.1	57.2	0.0	0.0	1.9
1985	3.6	0.0	32.4	71.8	96.6	96.5	294.0	324.1	164.3	1.6	0.0	0.0
1986	0.0	95.4	66.9	148.7	68.2	143.4	189.4	216.5	86.1	9.4	0.0	0.0
1987	0.0	65.6	181.9	80.7	187.7	69.3	202.0	246.9	81.7	4.4	0.0	0.0
1988	0.0	44.5	0.0	96.0	23.8	124.6	255.9	278.1	254.2	35.4	0.0	0.0
1989	2.1	63.8	53.8	226.3	7.1	58.6	264.2	301.0	170.9	37.9	0.0	0.0
1990	7.7	120.6	48.4	129.4	37.8	78.9	280.7	222.9	117.3	5.8	1.2	0.0
1991	0.0	37.6	62.4	11.6	45.6	90.4	263.7	308.5	113.4	4.4	0.0	56.5
1992	34.7	24.2	30.5	15.5	25.6	100.4	218.4	276.0	86.7	43.3	0.2	0.0
1993	1.2	53.9	5.6	118.4	62.5	116.5	218.0	251.5	118.3	20.5	0.0	0.0

1994	0.0	0.0	62.7	72.2	20.2	125.0	225.1	168.9	106.8	X	11.0	0.0
1995	0.0	25.4	63.7	102.1	20.9	95.7	269.2	242.3	79.5	0.0	0.0	4.8
1996	15.3	0.3	79.7	38.8	90.5	240.1	292.5	234.1	119.0	1.9	0.0	0.0
1997	27.6	0.0	29.5	102.7	25.2	57.0	203.6	203.4	82.5	114.9	10.3	0.0
1998	32.7	30.2	19.6	69.3	159.9	116.9	207.8	280.0	118.5	36.0	0.0	0.0
1999	1.3	1.8	91.8	12.1	44.7	92.8	282.6	300.7	61.7	65.0	0.0	0.0
2000	0.0	0.0	29.1	93.0	64.9	100.1	188.9	210.0	124.1	X	23.4	3.8
2001	0.0	20.7	121.2	23.6	118.0	142.6	257.5	145.0	64.9	2.2	0.0	0.0
2002	31.1	10.5	87.1	82.4	76.6	108.0	167.3	187.0	52.4	0.6	0.0	17.7
2003	19.6	24.3	23.9	114.0	2.9	125.4	325.1	307.4	112.4	0.0	1.9	0.0
2004	13.6	15.8	62.4	154.2	15.4	95.2	177.7	189.1	80.9	4.8	3.4	0
2005	31.4	7.3	33.9	119.0	140.7	139.9	234.8	231.0	149.7	9.1	15.2	0.0

b) Monthly Mean Min. Temp. In °c

						Alt.	2120mt					
Region	Shoa					Long.	38°.48'					
Station	Akaki					Lat.	8°.52'					
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1951	5.8	9.5	12.2	11.3	11.4	10.3	12.0	12.5	11.2	11.1	8.3	8.5
1952	6.1	9.7	11.5	12.6	11.6	11.1	12.2	12.5	11.4	8.9	6.5	7.0
1953	7.4	9.3	10.6	12.8	11.2	11.9	12.5	12.0	10.9	8.3	6.8	8.1
1954	4.5	9.1	10.7	10.4	10.9	10.7	11.6	11.6	10.9	8.0	5.9	5.9
1955	9.5	6.5	9.4	10.7	10.0	9.8	11.0	11.5	11.1	7.5	6.6	
1956			9.8	11.0	9.2	9.1	10.8	11.7	11.7	10.9	6.6	7.6
1957	8.8	12.8	15.0	14.7	14.4	13.6	15.8	15.1	9.5	2.8		
1996												12.1
1997	15.0	14.4	15.9	18.0	16.6	15.5	14.8	14.8	14.5	14.5	14.8	11.5
1998	14.0	14.4	16.0	16.2	15.8	14.9	14.9	14.6	14.5	14.3	11.3	9.4
1999	10.5	10.5	13.8	14.5	15.1	14.2	13.7	13.3	14.4	13.2	10.8	9.4
2000	9.2	10.0	12.9	15.0	15.0	13.0	13.9	14.1	14.1	X	11.4	10.3

2001	10.1	11.8	13.4	15.3	15.4	13.9	13.9	14.6	13.5	13.0	14.4	15.1
2002	X	16.3	14.2	12.6	15.7	15.0	14.5	14.1	13.8	13.8	12.6	13.7
2003	11.8	13.2	14.2	15.1	15.0	15.0	14.2	14.1	15.0	14.9	14.9	12.8
2004	14.6	14.2	14.6	15.9	16.2	15.6	14.7	14.6	14.9	14.6	14.2	14.4
2005	13.6	15.2	16.5	16.1	16.0	15.4	15.2	15.6	15.6	16.0	14.6	13.7

c) Monthly Mean Max. Temp. In °c

						Alt.	2120m					
Region	Shoa					Long.	38°.48'					
Station	Akaki					Lat.	8°.52'					
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1951	27.6	28.5	29.1	28.5	27.8	27.3	23.9	24.4	25.8	26.4	27.8	28.2
1952	29.4	30.4	30.5	26.5	29.5	27.0	24.2	23.3	25.8	27.4	28.8	28.8
1953	29.6	29.9	30.5	28.5	30.7	26.9	21.7	24.1	25.6	28.9	29.4	28.5
1954	29.2	30.4	30.4	30.6	30.4	25.9	22.4	22.5	23.8	27.5	29.4	29.5
1955	29.0	30.2	31.1	29.9	30.5	26.2	23.9	23.0	23.4	28.4	30.4	x
1956			32.2	28.7	29.0	26.2	22.5	23.6	25.4	26.5	28.5	30.2
1957	29.5	28.8	28.3	28.7	28.9	27.9	24.4	25.1	26.7	30.5		
1996												23.8
1997	25.8	26.3	28.1	26.3	28.6	27.2	24.2	24.3	25.8	24.9	24.9	25.7
1998	25.8	27.3	27.5	29.1	27.6	26.6	24.1	23.0	24.4	25.0	25.3	24.9
1999	25.9	27.2	26.5	27.3	28.0	26.4	23.4	23.6	25.1	24.6	25.0	25.2
2000	26.2	27.0	27.6	27.2	27.0	25.0	24.5	23.7	24.6	X	25.7	25.7
2001	26.3	27.2	26.1	27.6	26.9	25.6	24.6	24.7	25.8	26.9	26.4	26.4
2002	X	27.5	27.4	26.9	28.5	27.0	25.8	24.6	26.1	26.9	26.5	26.2
2003	26.6	28.3	27.9	27.3	28.9	27.1	23.7	23.6	24.9	26.6	26.6	25.7
2004	27.5	27.5	27.9	26.5	28.6	26.3	23.9	24.3	25.6	25.9	26.6	26.7
2005	27.1	29.0	28.2	27.8	26.8	26.3	23.7	24.6	24.5	26.2	26.3	26.1

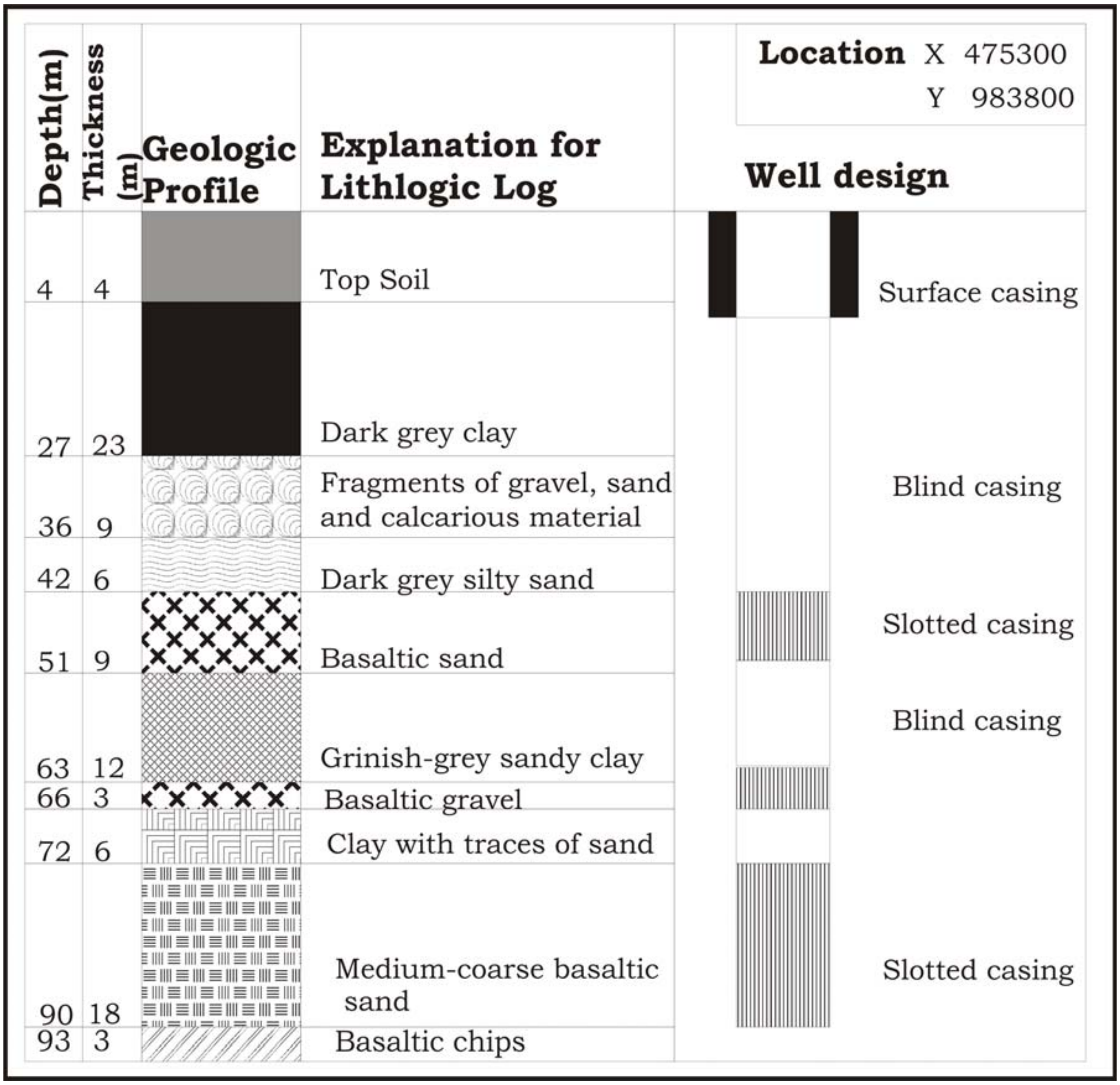
Appendix.2 Well data bases of physical parameters.

Location X	Y	Dep (m)	G.Alt. masl	SWL mbgl	SWL masl	Q l/s	DWL mbgl	D.D (m)	Aqui. Thi (m)	Tran. m^2/d	Clay thi.(m)
473069	979881	116	2057	5.8	2052		19.82	14.02	23.0	117.0	61.0
473108	979851	103	2058	7.07	2051		15.41	8.34	9.0		23.0
473433	985658	98	2191	44.18	2147	6	56.45	12.27		10.7	8.0
473566	978610	122	2070	23.5	2047		26.90	3.40	15.0	95.0	30.0
473576	972821	150	2081	74	2007	9	85.00	11.00		172.8	10.0
473900	985100	72	2165	8	2157	2	36.60	28.03			
474225	982650	178	2150	30.78	2119	3	142.3	111.5		2.8	
474556	983625	219	2160	38.75	2121						
474641	985622	68	2155	8.2	2147		44.50	36.30	25.0	7.4	
474788	982924	124	2150	23.54	2126		42.78	19.24		60.0	4.0
474800	984700	71	2140	0.5	2140	7	2.15	1.65		32.0	
474928	982697	104	2145	30.38	2115		38.47	8.09	30.0		6.0
474957	982383		2140	24	2116		44.00	20.00			
475000	985800	12	2112	0	2112	15	109.5	109.5			
475050	985050	24	2110	5.31	2105	3					
475300	983800	93	2105	flow	2105	6	20.90	20.90		50.0	
475300	983800	140		0		5	15.55	15.50		30.4	37.0
475300	984000	129	2100	flow	2100	6	51.90	51.90		22.3	
475300	985080		2120		2120	4				158.5	
475300	985325		2130			2					
475336	980717	179	2075	17.1	2058	3	127.0	109.9			
475400	982500	70	2137			1					
475402	976807	63	2060	31.4	2029						
475430	984955		2123		2123	13				382.0	
475650	984750		2120	57	2063	3					
475662	980784	52	2055	27.4	2028		37.70	10.30		23.0	
475800	981300	170	2100								
476000	980900	40	2060	13	2047	1					
476350	981300	65	2060	7.4	2053		13.20	5.80		50.0	
476369	981717	64	2062	7	2055	3	29.70	22.70			
476400	980600	120	2056	16.9	2039		53.90	37.00		4.0	
476400	980700	126	2058	53.4	2005		70.10	16.70			
476400	984800	90	2125	12	2113		46.22	34.22			40.0
476427	980749	44	2060	4	2056	3	13.40	9.40		75.3	
476430	980669	62	2060	6.5	2054	6	15.40	8.90		109.0	

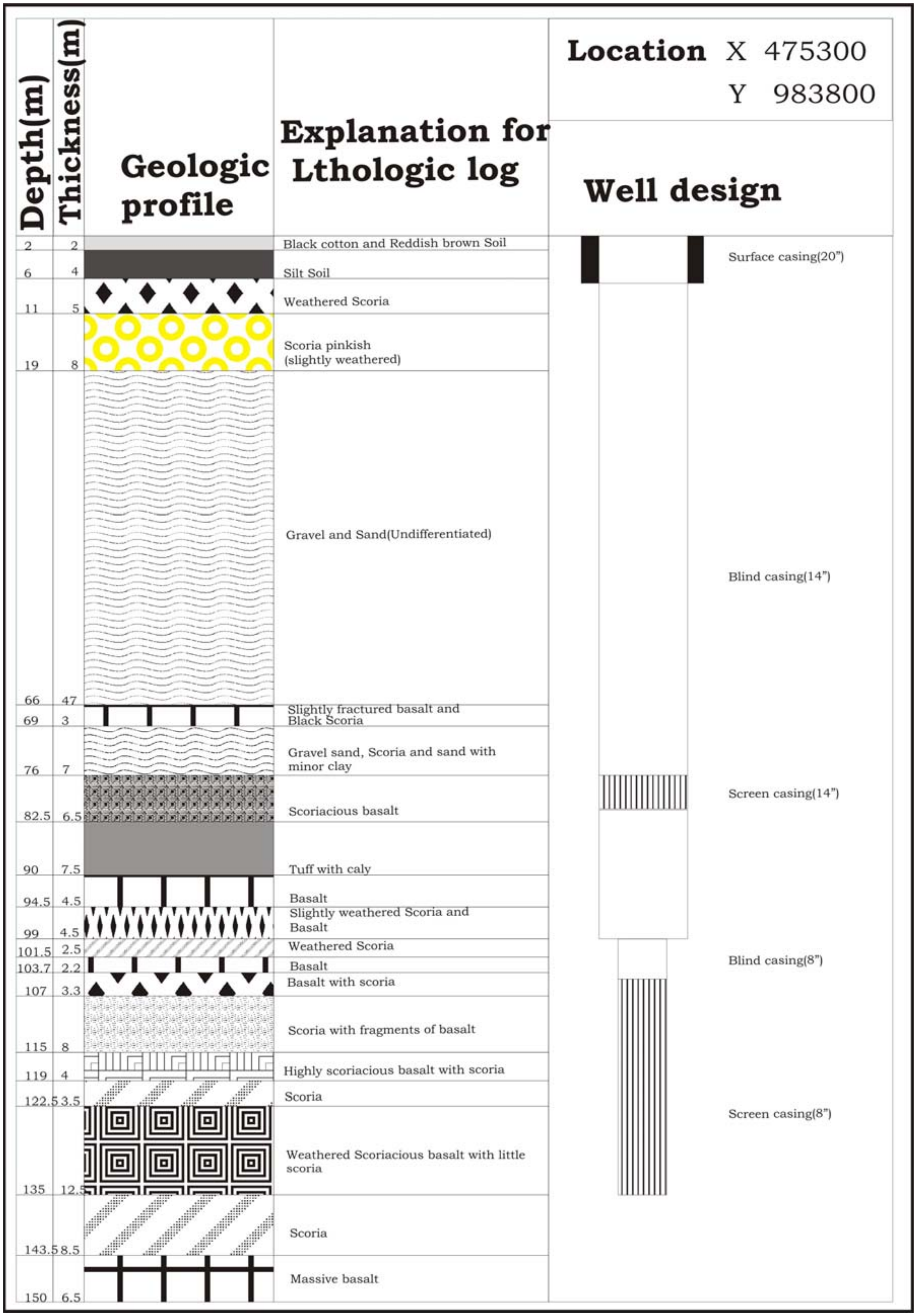
476454	976951	129	2062	42.2	2019						
476500	981300	53	2055	3.7	2051		14.30	10.60			
476500	981500	79	2070	73	1997	4					
476521	980711	120	2061			6					
476523	976374	60	2055	35.55	2019						
476574	975607	142	2070	51.4	2019		52.90	1.50		11923	25.0
476600	978200	79	2065	46.4	2019		48.80	2.40			
476600	981500	126	2070	3.5	2067		73.50	70.0			
476762	980541	97	2062			5					
476972	976152	120	2059	40.3	2019						
477162	976038	135	2061	42	2019		42.02	0.02	48.0	43372	5.0
477181	975680	116	2070	51	2019				33.0	98800	11.0
477185	975729	114	2069	46.5	2022						
477233	979000	82	2070	51	2019	3				45.3	
477330	976793	130	2062	42.9	2019		48.13	5.23	28.0	4631	14.0
477400	979500	96	2080	27.4	2053		72.10	44.70			
477446	978851	82	2070	52.4	2018	4				20.0	
477477	977216	145	2064	44	2020		45.25	1.25	51.0	10791	13.0
477500	979300		2080			2					
477609	978690	116	2090	57.7	2032	3	69.20	11.50		53.0	
477651	975923	142	2067	47.9	2019		49.97	2.07	47.0		11.0
477800	979500	99	2085			2					
477856	976402	151	2064	44.7	2019		44.96	0.26	40.0		12.0
477900	982875	52	2130	20	2110	0					
477945	976985	148	2068	49.9	2018		53.27	3.37	56.0	2272	17.0
477972	974859	133	2079	59	2020		63.98	4.98	27.0		8.0
477992	975552	132	2068	48	2020				26.0	9100	
478019	977900		2069								14.0
478019	977985	150	2070	51.5	2019		53.28	1.78	58.0		19.0
478154	975966	140	2074	54.1	2019		54.42	0.32	51.0		26.0
478199	976361	144	2065	45.9	2019		46.37	0.47	34.0	55738	12.0
478347	976752	148	2068	47.5	2020		53.46	5.96	52.0		16.0
478347	976752	200		47.58							
478399	975589	122	2073	53	2020		53.53	0.53	22.0		17.0
478425	981350	50	2110			2					
478450	979950		2100	55.82	2044	11	58.10	2.28	32.0	5288	
478463	977506	123	2090	50	2040	4					
478463	977722	150	2090	50	2040	4	56.50	6.50		6100	
478580	976051	130	2079	59.2	2019		59.52	0.32	43.0	25600	24.0

				50.2					76.0		17.0
		130							16.0		14.0
478808	976867	152	2071	47.5	2023		48.07	0.57	50.0	28100	7.0
478998	977937	130	2090	73.48	2017		79.52	6.04	44.0	2995	
479000	981400	120	2120	10	2110		16.00	6.00			
479021	977596	126	2090	64.82	2025	5	81.22	16.40			
479058	976020	130	2091	72.2	2019		72.20	0.00	43.0		3.0
479061	976370	144	2087	67.2	2019		67.25	0.05	45.0	49600	15.0
479246	977104	146	2078	58.7	2019		58.83	0.13	35.0		13.0
479340	981400	109	2131	0.73	2131		13.51	12.78	25.0	478.0	3.0
479400	981400	100	2133	2.7	2131		3.20	0.50	41.0	492.0	3.0
479400	981400	74	2134	2.8	2131		4.30	1.50	36.0	492.0	3.0
479405	976735	151	2086	67.2	2019		67.44	0.24	51.0	43700	8.0
479526	977468	129	2090	71.7	2018	5	87.28	15.58		1834	
479576	983656	132	2180	46.2	2134						
479696	976936	145	2087	67.8	2019		67.93	0.13	47.0	10541	6.0
479700	981700	116	2135	20	2115						
479740	981400	126	2134	3.38	2131		44.80	41.42	38.0	317.5	
479820	977156	92	2085	62.5	2023	5	62.60	0.10		7900	
479942	977322		2091	64.44	2027	13	71.34	6.90	54.0	2480	
480517	977974	170	2100	65	2035				72.0		
480895	977403	104	2120	84.8	2035		84.87	0.07	24.0		6.0
480900	978800	160	2126	86	2040		87.90	1.90	34.0	210.0	0.0
480965	977576	132	2139	98.87	2040		100.9	2.05			
481200	980000	150	2150	11	2139		29.20	18.20	63.0	33.0	7.0
481200	980000	173	2151	8.9	2142		34.20	25.30	5.7	33.0	5.0
481205	976968	184	2155	121	2034		122.0	1.00			
481224	977845	148	2160	119	2041		134.6	15.60	24.0	86.8	
481337	982304	135	2190	23.35	2167		32.35	9.00			
481507	976221	132	2100	120	1980	5	121.0	1.00			
481600	982850	136	2204	33.48	2171		39.00	5.52	50.0		5.0
481600	982900	120	2205	35.1	2170		36.70	1.60	27.0	820.0	18.0
481600	982900	120	2205	37.33	2168		48.40	11.07	36.0		6.0
482400	983000	83	2230	56.15	2174						
482480	976133	181	2150	73.28	2077	3	98.00	24.72	30.0		
483093	976323	207	2159	137.6	2021		159.6	22.00		0.4	
484475	975622	220	2104	100	2004	30					0.0
84933	975498		2114								

Appendix. 3 Representative logs of the Ministry of Defense Well at Kality Military Camp 1 (a) and BH 06 in the well field (b) showing the subsurface geology and thickness of the stratum.



(a)


Depth(m)
Thickness(m)
Geologic profile
Explanation for Lthologic log
Location X 475300
Y 983800
Well design
2 2 Black cotton and Reddish brown Soil
6 4 Silt Soil
11 5 Weathered Scoria
19 8 Scoria pinkish (slightly weathered)
Gravel and Sand(Undifferentiated)
66 47
69 3 Slightly fractured basalt and Black Scoria
76 7 Gravel sand, Scoria and sand with minor clay
82.5 6.5 Scoriacious basalt
90 7.5 Tuff with caly
94.5 4.5 Basalt
99 4.5 Slightly weathered Scoria and Basalt
101.5 2.5 Weathered Scoria
103.7 2.2 Basalt
107 3.3 Basalt with scoria
115 8 Scoria with fragments of basalt
119 4 Highly scoriacious basalt with scoria
122.5 3.5 Scoria
135 12.5 Weathered Scoriacious basalt with little scoria
143.5 8.5 Scoria
150 6.5 Massive basalt
Surface casing(20")
Blind casing(14")
Screen casing(14")
Blind casing(8")
Screen casing(8")

(b)

Declaration

I, the undersigned person, declare that this thesis is my original work, has not been presented for a degree in any other university and that all sources of materials used for the thesis have been duly acknowledged.

Name:	Leta Gudissa Shaqa
Signature:	----------------------
Date of submission:	August 2007