Steady-state groundwater flow and contaminant transport modelling of Akaki wellfield and its surrounding catchment (Addis Ababa, Ethiopia)

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by

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Abstract

The study focuses on groundwater modelling of the Akaki catchment and the Akaki wellfield in particular under steady state flow conditions. Besides that, advective contaminant transport modelling was implemented in Akaki wellfield to delineate capture zone. The aquifer system was modelled using PMWIN (Chiang and Kinzelbach, 1998) as pre and post processor for MODFLOW (McDonald and Harbaugh, 1988). The aquifer was simulated under confined/unconfined condition and is represented by a single layer of 100m constant thickness. The grid cells of the model were taken 400x400m for Akaki catchment with the area of 1500 km^2. A grid size of 400x200m was used to represent the wellfield which is approximated 197.3 km^2 in extent. Model input parameters were determined based on analysis of pumping test data.

The recharge condition in Akaki catchment is characterized by three sources of water: rain recharge, the river bed infiltration and the seepage from Aba Samuel and Legedadi lakes. In addition, the recharge conditions in Akaki wellfield include a fourth component which is inflow from the northern and north-western boundary. Outflow (discharge) conditions from the aquifer are characterized as base flow, springs, subsurface lateral flow and well abstractions. Boundary conditions were assigned to the model domain to simulate inflow and outflow terms of the model domain. The Chloride Mass Balance Method (CMB), semi-distributed water balance model and recursive digital filter methods were employed to estimate the recharge in the catchment. From the water balance as simulated by the catchment's model, the total average base flow estimated is 92 MCM/yr or 62 mm/yr. From the water balance model described in chapter 3, it is found that a base flow and recharge value of 130 MCM/yr or 87 mm/yr is found. Using the digital filter method, the base flow and recharge values are roughly 65 MCM/yr (63mm/yr) indicating good agreement between the models.

The trial and error method was used to calibrate the models using the observed and simulated hydraulic heads. The water budget of the area reached equilibrium conditions with recharge from precipitation 158 MCM/yr, well abstraction some 23 MCM/yr, 8 MCM/yr as out flow from the catchment at the catchment outlet, 130 MCM/yr seepage from aquifer to the surface water bodies and 11 MCM/yr from surface water bodies to the aquifer. Optimised parameters (hydraulic conductivity and recharge) are spatially distributed over the model area.

Furthermore, PMPATH, has been used at the wellfield eventually 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 wellfield itself, then identifying the path lines, and finally determining the spatial distribution of the contaminants through steady state flow field. The flow lines converge towards Akaki wellfield from all directions, implying that any contaminated water from the upper part of the aquifer will end in the wells, indicating a high risk of vulnerability of the wellfield to pollution. The following recommendations are helpful in curing 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 an environmental policy must be implemented with particular emphasis on the protection zones around the wellfield.

Key Words: Addis Ababa - Akaki - Modelling - Modflow - Volcanic aquifer - Groundwater - PMPATH

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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
EPA:	Environmental Protection Authority
EMA:	Ethiopian Metrological Agency
BCS:	Black Cotton Soils
DEM:	Digital Elevation Model
GPS:	Global Positioning Systems
CEC:	Cation Exchange Capacity
NE, NW, SE, SW:	North-East, North-West, South-East, South-West
E-W, N-S:	East-West, North-South
UTM:	Universal Transverse Mercator
EHA:	Ethiopian Highway Authority
GWL:	Groundwater Level
SWL:	Static Water Level
DWL:	Dynamic water Level
TDS:	Total Dissolved Solids
µS	Micro Siemens
mm	Milimeter
masl	Meter above mean sea level
Fig.	Figure
GIS	Geographic Information System
EC	Electrical conductivity
CMB	Chloride mass balance
AAO	Addis Ababa observatory
ITCZ	Inter-tropical convergence zone
K	Hydraulic conductivity
T	Transmissivity
MCM	million cubic meters
mg/l	Milligram per liter
mm	millimetre
ppm	parts per million
SC	Specific capacity
MER	Main Ethiopian Rift
GW	Groundwater

1. Introduction

1.1. General

Rapid population growth, urbanization and increased demand of water in domestic and industrial production have led to fresh water shortage in many parts of Ethiopia and to an increasing dependence on groundwater. With continuous increased withdrawals from groundwater reservoirs results in systematic or continuous lowering of water table. Hence, the need for better management of water resources is crucial. This task becomes even more pressing as urbanization, industrialization and development advances. Easily fragile resource like water can be affected by pollution. Groundwater modelling is an essential tool to evaluate the groundwater flow and quantifying its potential. It also helps understanding and predicting the behaviour of the groundwater system in response to future stresses due to abstraction or meteorological forcing. A mathematical model simulates groundwater flow indirectly by means of governing equations which represent the physical process that occur in the system together, with equations that describe the head or flow along the boundaries of the model (Anderson and Woessner 1992). The same points apply to groundwater flow and contaminant transport modelling. Tamiru (2001) indicated that there is surface water pollution as a consequence of industrial effluents, municipal and house hold waste disposal in the area of investigation. Besides that, Gizaw (2002) has also conducted hydrochemical and environmental investigation of the Addis Ababa region which can serve as information for this research.

In the region rocks are exposed to tectonic effects of the Ethiopian rift with plenty of faults, lineaments, fissures, fractures, conduits and joints trending NE-SW, E-W, N-S, and NW-SE. Moreover the density of the structures increases to the SE of Addis Ababa around the Akaki wellfield. Soil investigation done in the area also reveals a relatively higher hydraulic conductivity of most soil types. Most pollutants irrespective of source are transported overland and through the soil by rain water and ultimately find their way into the groundwater. The soil filters the water, absorbs and removes many contaminants, though the excess contaminants may pass through the zone of aeration and enter the groundwater in the zone of saturation.

The delineation of a protection zone in Akaki wellfield is the process that determines the geographical area that should be included in a protection zone program. This area of land is managed to minimize the potential of groundwater contamination by human activities that occur on the land surface or in the subsurface. Proper implementation of aquifer protection zoning will ensure water quality benefits in the long term. As a result, the unpolluted water sources will aid in good health of the people, animals and ecosystems. Therefore, delineating capture zones and wellhead protection areas; prediction of the contaminant distribution in time and space is necessary for managing ground water resources and designing optimal mitigation plan in areas like the Akaki wellfield, which is at risk due to unregulated solid and liquid waste disposals from its upper stream areas. For this purpose, an advective transport modelling known as PMPATH will be applied in the area under investigation. PMPATH will also be used to analyze flow paths and travel times in the groundwater.

1.2. Statement of the problem

The Akaki wellfield is the largest wellfield in Addis Ababa city and is serving as source of water supply for the city. The groundwater table of the wellfield is continuously declining due to abstraction of large amount of water mainly for water supply of the city. In order to better understand and to predict the flow system, groundwater flow modelling needs to be applied to regional groundwater system and the Akaki wellfield in particular.

The increased need for drinking water calls also for careful consideration and integration in the development process of all environmental factors. There is no detailed national investigation, which clearly puts and determines how contaminants (pollutants) 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 pollutants may eventually enter the aquifer system through porous, permeable media that are highly dissected by numerous structures. 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 the contaminants that reach the groundwater generally move very slowly, continued leakage at one site will lead to a gradual accumulation. In most natural settings, pollutant accumulations in the environment are not very serious because the natural concentrations of these contaminants are low in waters and soils (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 dispose their effluent through fall pipes into the environment increasing the variety of pollutants in water resources. Therefore, modelling the transport of contaminants in a wellfield, 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 are unfavourably located along Akaki road. The $NO3^-$ 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 (Gizaw, 2002). All of them exceed their respective WHO guideline limit of 50 mg/l, 0.1 mg/l, and 3µg/l respectively. The amounts are more likely to be originated from industrial activities.

1.3. Objectives

1.3.1 General objective

The general objective of this study is to investigate the groundwater flow system in the Akaki catchment as well as its wellfield by using numeric groundwater modelling. Besides that travel times and paths of pollutant migration in wellfield will be assessed.

1.3.2 Specific objectives

The primary objectives will be achieved through the following sub objectives:

- Analyze hydrochemical data using geostatistics and GIS to determine the recharge, and its spatial distribution.
- Develop conceptual models and based on that, to build a numeric model, which can be used to simulate the groundwater flow under steady state conditions.

- Generate hydraulic heads in the wellfield by numerical groundwater flow model and calculate velocity distributions;
- Determine travel time and travel paths of contaminants in the wellfield which can help in delineating the wellhead protection area (capture zone).

1.4. Research questions

By these objectives the following research questions are formulated:

- Can hydrochemical data be used to evaluate the recharge?
- Can a conceptual model be transformed in a numeric model that represents the simplified field situation of the aquifer system?
- Can a calibrated groundwater flow model improve our understanding of groundwater flow and contaminant flow pattern in the wellfield?
- How is the abstraction rate from the wellfield affecting the contaminant movement?

1.5. Research hypothesis

- The calibrated groundwater flow model of Akaki wellfield can simulate observed heads with less than 15% (0.15 m) of root mean squared error.
- An advective contaminant transport model known as PMPATH can simulate contaminant movement in the area with time which can be used for delineation of protection zone.

1.6. Previous works

Concerning geology of Addis Ababa region, different papers have been written. Hydrogeological study of Akaki catchment with special emphasis on the problems of groundwater recharge has been carried out by Demlie (2007). Previously detailed hydrogeological investigation has been also carried out by Anteneh (1994) in his masters thesis "Hydrogeology of Akaki Area". As cited in a thesis, many geoscientists like Mohr (1967), Morton et al. (1966), Kazmin (1978), Morton et al. (1979), Zanettin and Justin Visitin (1974), Mohr .P.A.(1983) have discussed the geology of Addis Ababa region in their studies. Girmay and Assefa (1989) discussed the volcanic strategraphy of rock units outcropping at the vicinity of Addis Ababa-Nazareth area. Regarding surface and ground water potential of Addis Ababa region, AAWSA and SEURECA (1989) have conducted valuable works. Assessments to assure the feasibility of surface and groundwater as a source of water supply in Akaki area have been carried out by AWSA (2000). The geology and hydrogeology of Akaki (Sekelo) sub basin with particular emphasis to its hydrochemistry and interaction between the surface and ground water has been investigated by Aynalem (1999) in his master thesis "Water Quality and Ground Water/Akaki River Interaction in the Sekelo Basin (Lower Akaki River Sub Basin)". Specific references to water well drilling, Construction, Pumping test data, water quality data, Geological and geophysical logs in Akaki wellfield are included in water well construction report by AAWSA as a client and WWDE (Water Well Drilling Enterprise) as a contractor in 1996. Similar activities have been carried out for 25 water wells drilled in the Akaki wellfield for the supply of Addis Ababa by AAWSA as a client and COMPLANT as contractor in 1997.

In Addis Ababa, and its surrounding areas, both surface and groundwater resources have been investigated in terms of potential, and vulnerability by a relatively good number of investigators such as Vernier (1993); AAWSA-SEURECA (1991); Anteneh (1994); Eccleston (1997); Aynalem (1999); AAWSA (2000); Gebrekidan (2000); Tamiru (2001); and Gizaw (2002). EPA (1997) has surveyed pollutant load on three rivers of the Addis Ababa city. These studies, although they vary in scope and degree of geological and geochemical information, 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. Demelie (2007) studied the recharge in the area and he stated that recharge takes place over the entire surface area, major recharge takes place within the Intoto sector of the catchment, serving as a so-called mountain block recharge. Moreover, hydrochemical and environmental isotope data indicated additional recharge sources from wastewater, leakage from mains and reservoirs. In addition to that, Tamiru et al. (2005) did aquifer vulnerability of the whole Akaki catchment and water quality assessment.

1.7. Methodology

The study is conducted using data issued from literature; secondary data collected from offices, water sampling and laboratory analyses. The methods to be followed in this research are based on the objectives formulated in section 1.3.

1.7.1. Pre fieldwork

Literature review and collection of satellite images such as ASTER and LANDSAT were the core methods that were employed in the office. The literature review was done based on both national and international literatures. Collection of many secondary data as much as possible, preparing satellite imageries, and becoming familiar with various appropriate Softwares like PMPATH, Aqua Chem. 4.0, Aquifer test, Golden Surfer Software 8, Arc View 3.3, Visual Modflow pro, Arc GIS 9.2 etc as well as scientific instruments such as, pH meters, GPS, EC meter and sample bottles were some of pre field works accomplished. In addition to this, literature review related to recharge estimation and principle of ground water and contaminant flow modelling was part of the pre fieldwork. The reports of the area were reviewed to get insight about the problem and to define the work direction of the research. Besides that field equipment for fieldwork such as GPS, pH meter, altimeter, compass, dipper and EC meter were prepared.

1.7.2. Field work

The following points summarize the field work:

- Collection of water samples from springs, boreholes, rainfall and surface water bodies for chemical analysis (major cations and anions). Samples were filtered by 0.45µm or less before actually sampled and prepared for preservation. they are taken in polyethylene bottles with tight cap and then stored in relatively cold areas to prevent reaction of constituents of water in the sample. In addition to this, water samples were acidified using HCl or HNO_3 for storage purpose depending on the purpose of sampling. The analysis result from the water samples was applied for identification of the regional and local flow systems, determination of water types and for assessment of groundwater quality in the area.
- Spot measurements of EC, pH, bicarbonate (alkalinity), Cl, and NO_3- were carried out.
- Meteorological data were collected from National Meteorological Service (Rainfall, temperature, wind speed, humidity, etc).
- Taking readings of boreholes location and elevation using GPS
- Collection of monitoring groundwater level data from Addis Ababa Water and Sewerage Authority and related organizations.

- Well completion and pumping test data are also crucial requirement for characterization of the aquifer and are collected from Water Works Enterprise, Addis Ababa water and sewerage authority (AAWSA) and other related organizations.
- Collecting of geophysical data conducted during the feasibility studies (available reports).
- Delineation and field verification of the study area and identification of physical boundaries
- Locating pollutant sources or sites.

1.7.3. Post field work (data processing and analysis)

During this stage, the data collected during the pre field and fieldwork was processed and analyzed.

- For the processing purpose, GIS and geostatistics were extensively used. For example, ILWIS was applied for kriging in order to interpolate point measurements.
- Well completion data analysis to determine the position of screen, aquifer thickness and number of layers in combination with well log cross- section.
- Determination of aquifer parameter maps
- The water samples collected during the fieldwork were analyzed and processed for the major cations and anions to understand the geochemical property and water type detection. The laboratory analysis result were processed and presented using AQUACHEM software. The determination of the chloride concenteration in rainwater and its concentration in ground water was part of this analysis as it will be used for recharge estimation by using chloride mass balance method.
- Constructing a steady state groundwater flow models and calibration of the models.
- Simulation of the migration of pollutants, analysis of the intrusion of contaminant plume, and prediction of the time and direction (flow path) of contaminant in fractured rock systems will be carried besides laboratory work.

1.7.4. Methods to apply PMPATH (Advective transport model)

PMPATH is powerful tool for wellfield management and decision making because of this, it were used for the following purposes:

- calculating the travel times of contamination from their sources to wellfield and path lines of the contamination
- Delineation of capture zones of pumping wells and wellfield protection areas

General assumptions used when using PMPATH includes:

- Fluid properties are homogenous,
- Concentration changes do not affect the fluid density and viscosity and hence fluid velocity
- Contaminant moves with the same speed as ground water
- Pollutant movements are dependent specifically to effective porosity.

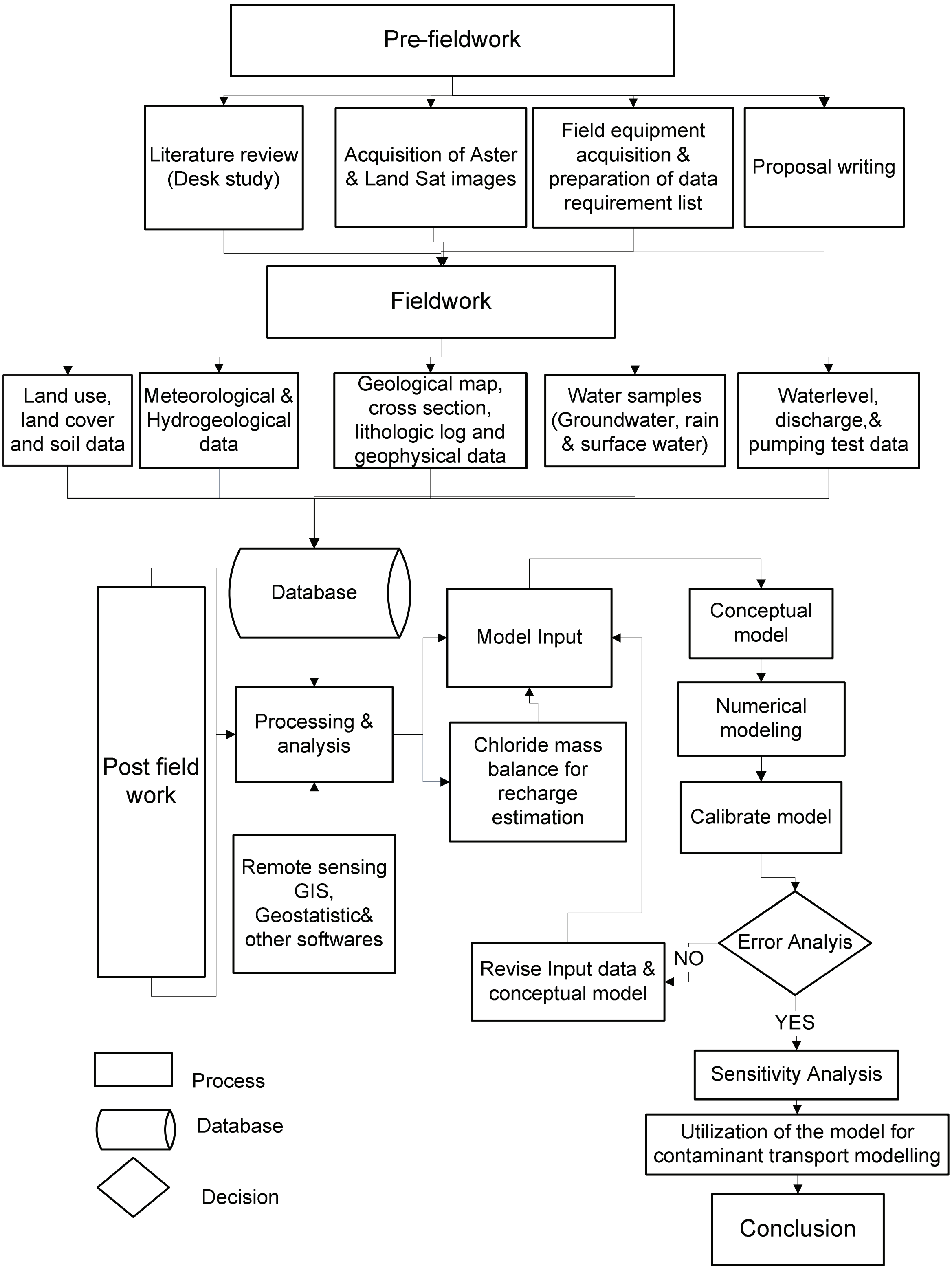


Figure 1. Research methodology for flow modeling

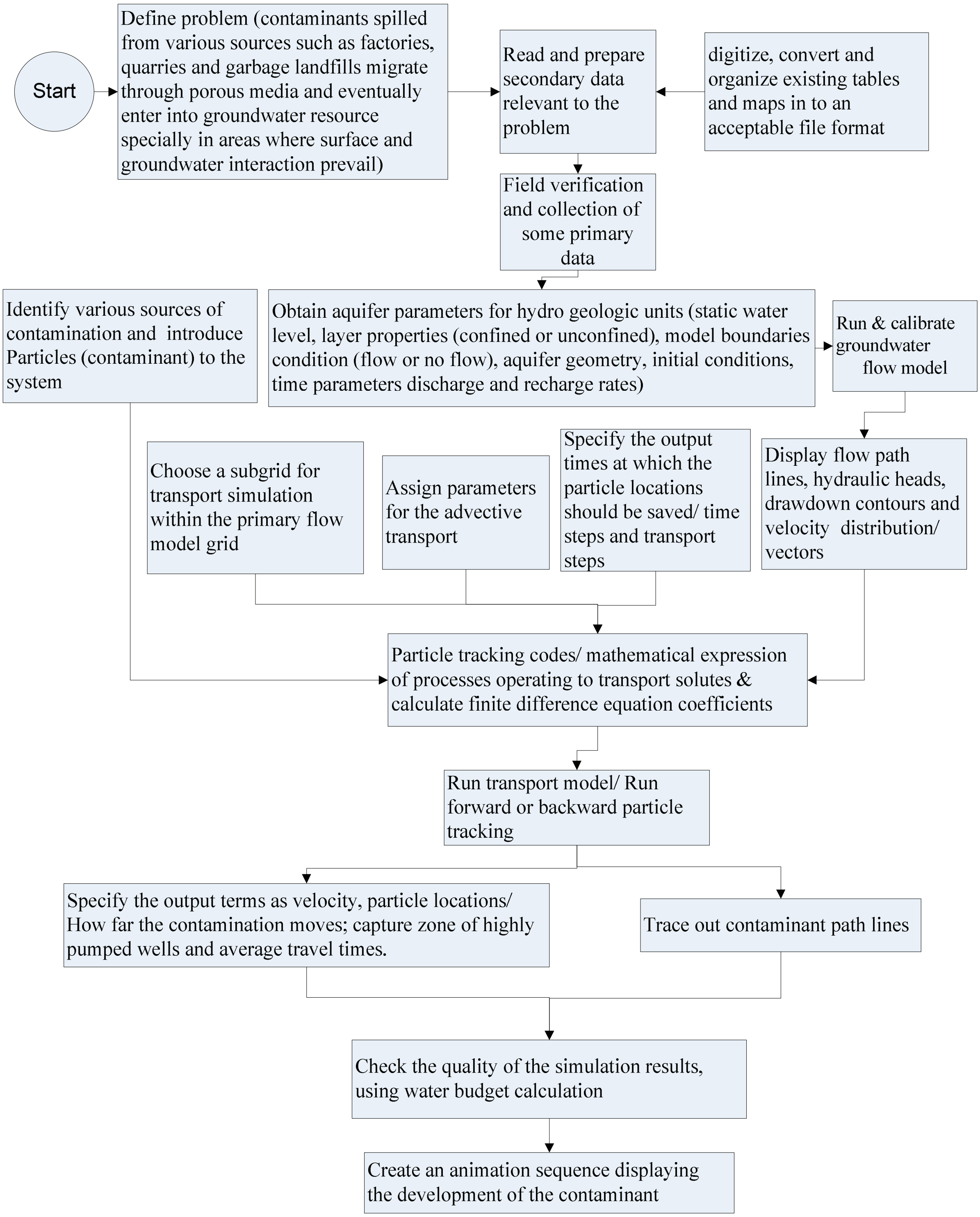


Figure 2. Research methodology for PMPATH

1.8. Thesis outline

The research is sub divided in to seven chapters and the contents are summarized briefly as:

Chapter1: discuses about introduction of the research that include the problem statement, the objective of the research and research questions which the research tries to answer on the basis of the available data. Methods Applied and previous works are also discussed in this introductory chapter.

Chapter 2: Gives an introduction of study area in terms of location, climate, topography, hydrology, geology, hydrogeology, hydrochemistry, well logs and subsurface conceptualization, aquifer types and water level monitoring in response to external stresses.

Chapter 3: Numerical groundwater modelling mainly designed to discuss the model setup, code selection, spatial discritization, and input parameter determination. This chapter also discusses the recharge in Akaki catchment.

Chapter4: Describes the Akaki catchment's steady state model execution, calibration and water balance assessment. This chapter also addresses model limitations and sensitivity analysis.

Chapter 5: Describes characteristics of the wellfield, development of its conceptual model, input parameters, model calibration and water balance calculations.

Chapter 6: Describes an advective solute transport modelling on the wellfield particularly giving focus on factors affecting contaminant transport, human activities having pollution potential, delineation of capture zone and wellhead protection areas of the wellfield. In addition, this chapter explains the distribution of contaminant in groundwater in terms of space and time.

Chapter 7: Discussion, Conclusion and recommendations
Discusses the result of the recharge estimated by different methods, subsurface conceptualization, aquifer types and travel paths and travel time of contaminants in the wellfield. In this final chapter, matters which can not be addressed are also recommended to be implemented for the future.

2. The study area

2.1. Location, digital elevation model and climate

The Akaki catchment is located in central Ethiopia along the western margin of the main Ethiopian rift valley. The catchment is situated at the north western Awash River basin between $8^0 46^{'}$–$9^0 14^{'}$ N and $38^0 34^{'}$–$39^0 04^{'}$E. It is bounded to the north by the Intoto ridge system, to the west by Mt. Menagesha and the Wechecha volcanic range, to the southwest by Mt Furi, to the south by Mt Bilbilo and Mt Guji, to the southeast by the Gara Bushu hills and to the east by the Mt Yerer volcanic centre. The Akaki catchment has an area of about 1500 km^2. Addis Ababa is located at the centre of the catchment (Figure 3). Surface water reservoirs located within the study area include Legedadi, Gefersa, Dire and Aba Samuel (See figure 5).

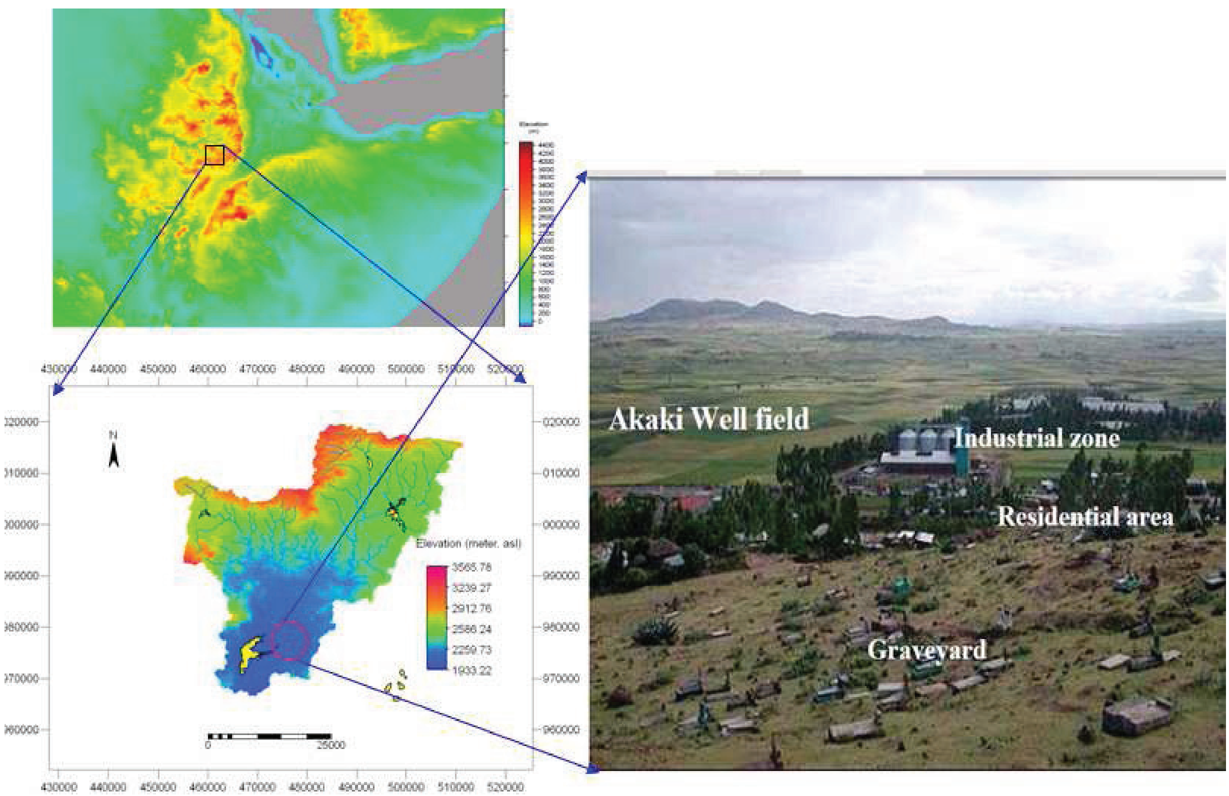


Figure 3. Location map of the study area

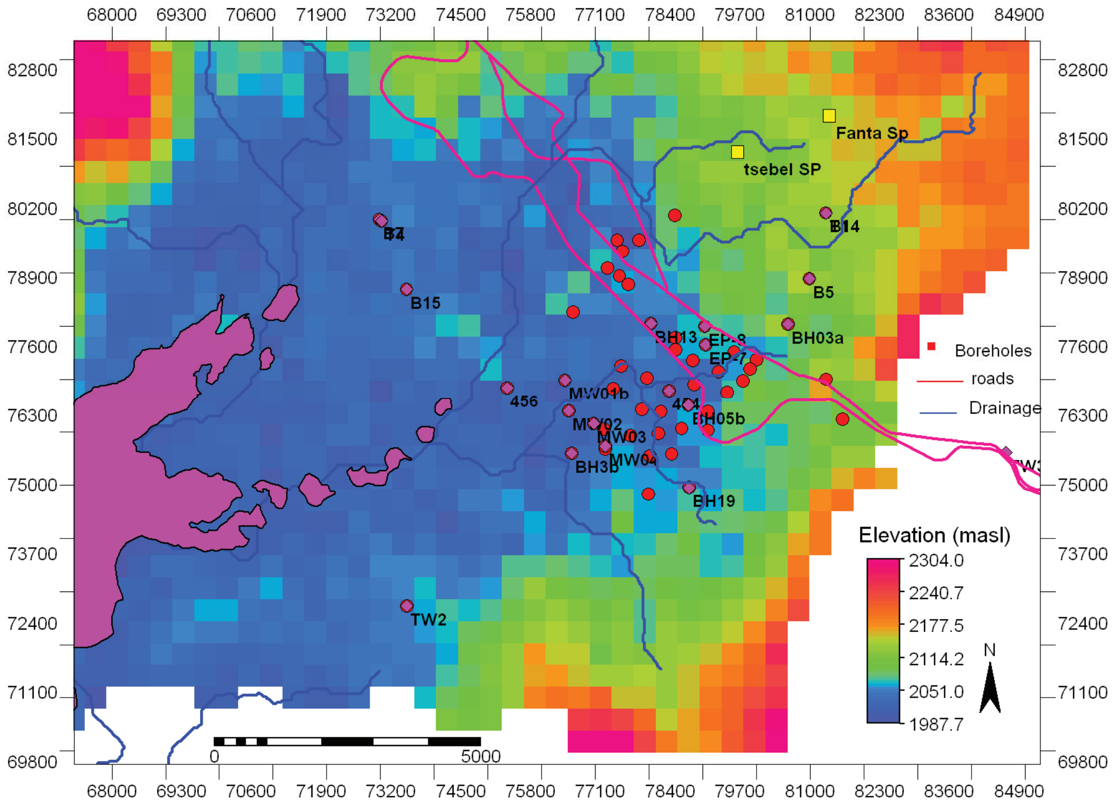


Figure 4. Detailed location map of the Akaki wellfield.

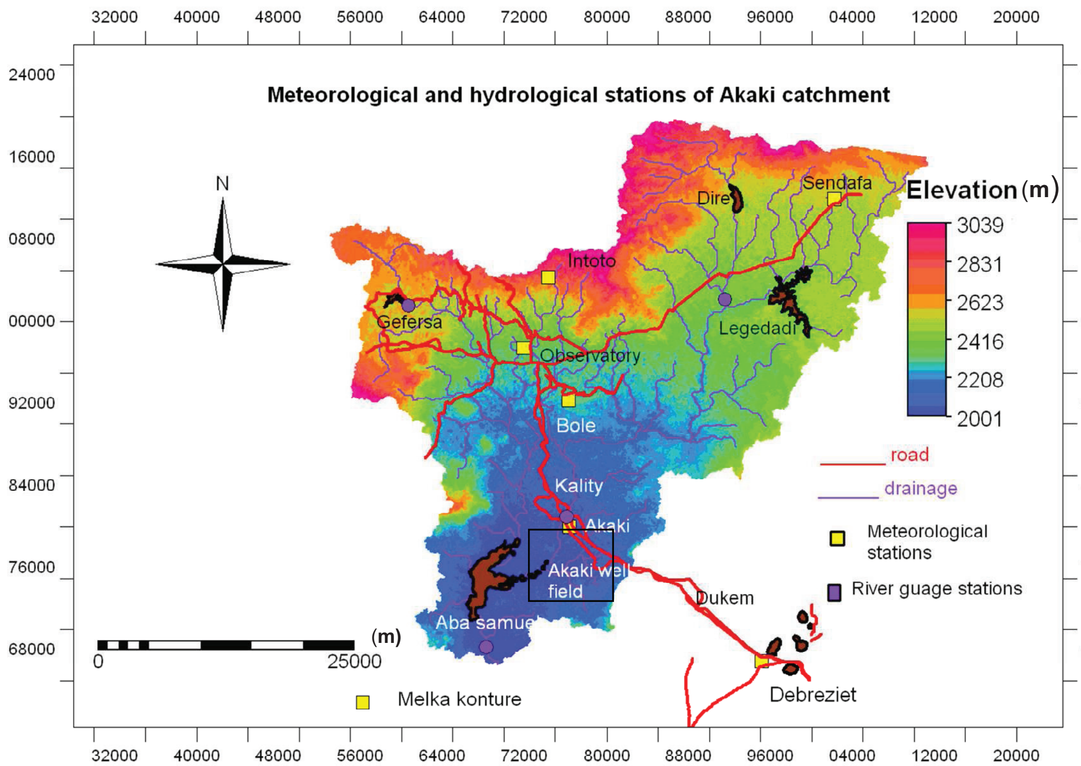


Figure 5. Location map of hydrological and meteorological stations in the Akaki catchment

2.1.1. Digital elevation model

A digital elevation model, DEM is extracted from Level 1A image of ASTER using ERDAS IMAGINE to a 15 meters resolution. Ground control points were prepared from the topographic maps of the study area to check the vertical accuracy of the DEM. The vertical accuracy of the DEM was adapted to the topographic map's vertical accuracy by extracting elevation value from topographic map at a number of check points. The procedure is described in detail in Appendix 5. Corrected Elevation from the ASTER DEM is applied to define the ground elevation of the boreholes, to define the aquifer top and bottom, to construct cross-sections, to determine rainfall distribution as well as recharge in the catchment, and to define elevation of the bottom of the riverbed for the use of river package. Furthermore the DEM plays a key role in defining of the model boundary in the conceptual model formulation.

2.1.2. Climate

Despite its proximity to the equator, the study area experiences a temperate Afro-Alpine climate. Daily average temperatures range from 9.9 to 24.6 ^{0}C (Fig.11) and annual mean rainfall is 1224 mm/yr, as measured at the catchment by hyposometric method (see Fig.8, rainfall map). The climate of the Akaki catchment is characterized by two distinct seasonal weather patterns. The main wet season, locally known as Kiremt, extends from June to September, contributing about 70% of the total annual rainfall (Figure 6). A minor rainy season, locally known as Belg, contributes moisture to the region from mid February to mid April (Daniel, 1977).

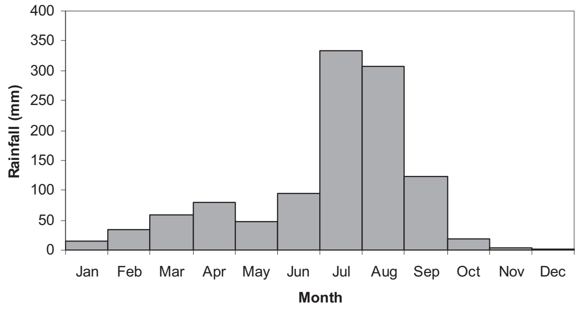
EMA (1988) defined five traditional climatic zones: "Kur" (Alpine), 3000m and above; "Dega" (temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical), 1500 to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m. The Climate of Addis Ababa is Woina Dega (Daniel (1977). 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.

2.1.3. Precipitation

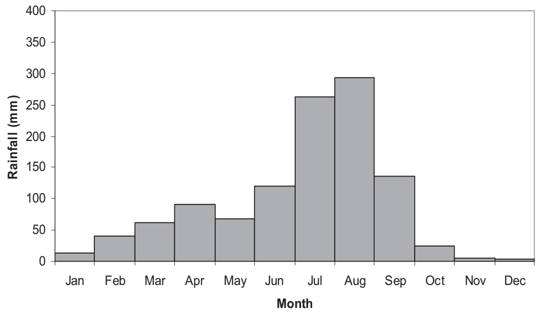
The variation in the seasonal distribution of rainfall in Ethiopia can be attributed by the reference to the position of the Inter-Tropical Convergence Zone (ITCZ), the relationship of between upper and lower air circulation, the effects of topography and the role of local convection currents and the amount of rainfall (Daniel, 1977).

According to Daniel (1977) classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region there are seven rainy months from March to September/and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August.

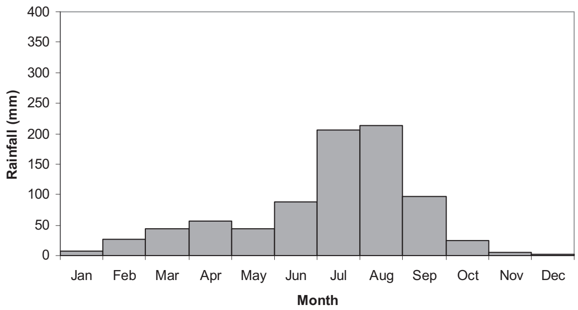
As stated above, prior to determine rainfall distribution in the catchment, the ASTER DEM was corrected from vertical scale errors by adapting to topographic map accuracy. After obtaining corrected digital elevation model for the whole catchment, the elevations of rainfall stations are extracted from digital elevation model surface and mean annual rainfall of each station is determined. Finally the elevations and mean annual rainfall of all stations are correlated to determine the spatial rainfall distribution of the catchment.



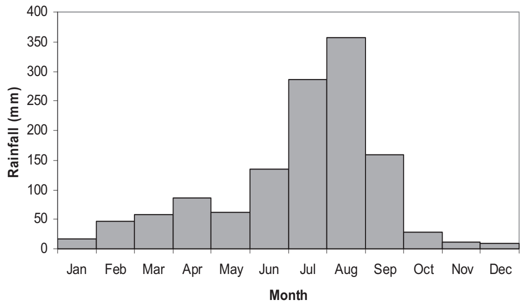
Rainfall distribution at Sendafa station (SEN)



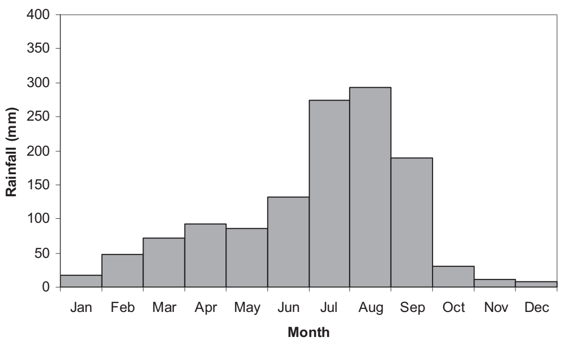
Rainfall distribution At Akaki station (AK)



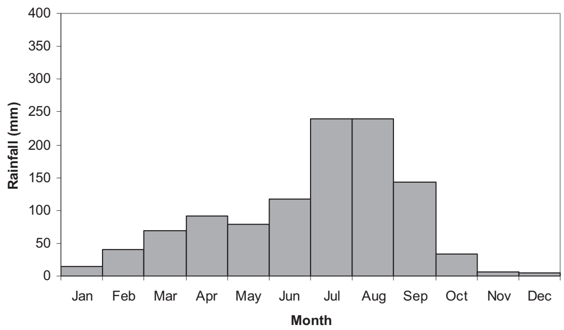
Mean monthly rainfall distribution At Debreziet station (DZ)



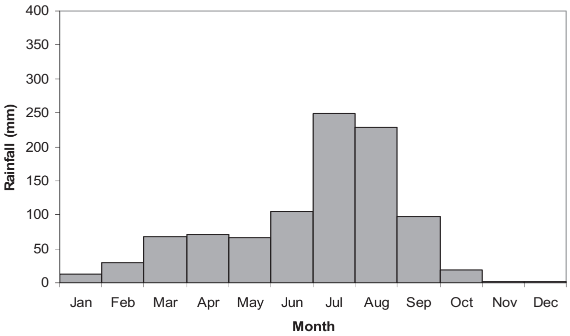
Mean monthly rainfall distribution At Entoto station (INT)



Mean monthly rainfall distribution At Addis Ababa university Geophysical observatory station (AAO)



Mean monthly rainfall distribution At Addis Ababa Bole station (AAB)



Mean monthly rainfall distribution At Melka Kuntur station (MK)

Figure.6. Mean monthly distribution of rainfall in Akaki catchment

Table 1. Digital elevation model versus mean annual rainfall of Akaki stations (1981 – 2003)

Name of stations	X	Y	DEM elevation	RF
Akaki	476486	979917	2040	1117.1
Sendafa	502257	1011809	2532	1286.6
Debreziet	495194	966825	1850	900
AA0	471986	997321	2457	1244.6
Melka Konture	456328	962787	1880	947.6
Bole	476413	992272	2307	1178.7
Intoto	474400	1004200	2772	1394.3

As shown in the Table 1 and Figure 7 below, the annual rainfall value is observed to increase with elevation. Therefore, the hypsometric method is used for rainfall estimation in the catchment. Therefore, the mean annual rainfall is 1224 mm/yr with maximum and minimum RF of 1705 and 970 mm/yr. Using hypsometric relationship between rainfall and elevation, the rainfall distribution map of Figure 8 is produced using ILWIS script.

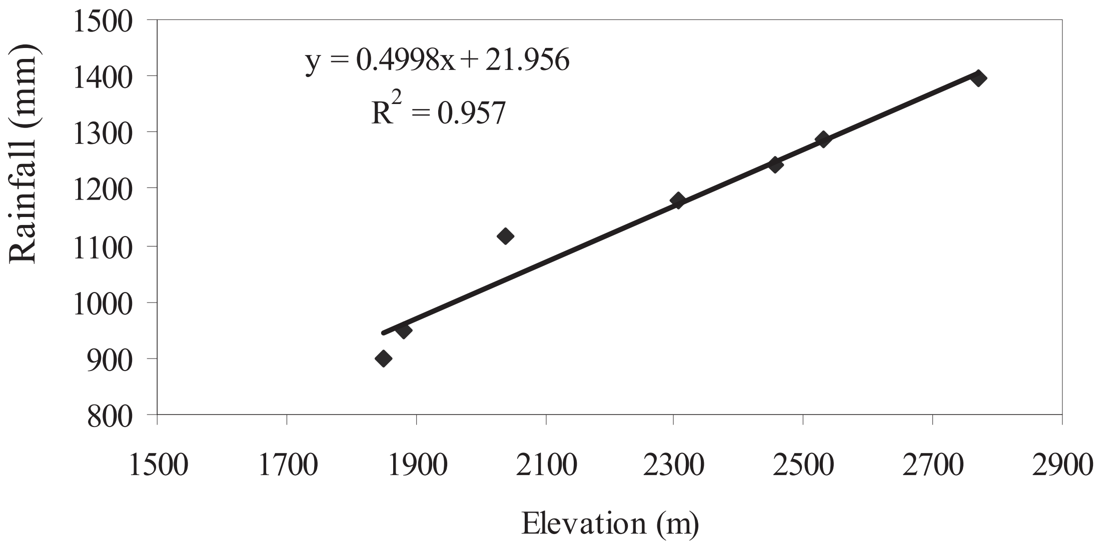


Figure 7. Variation of annual rainfall with elevation in Akaki river catchment

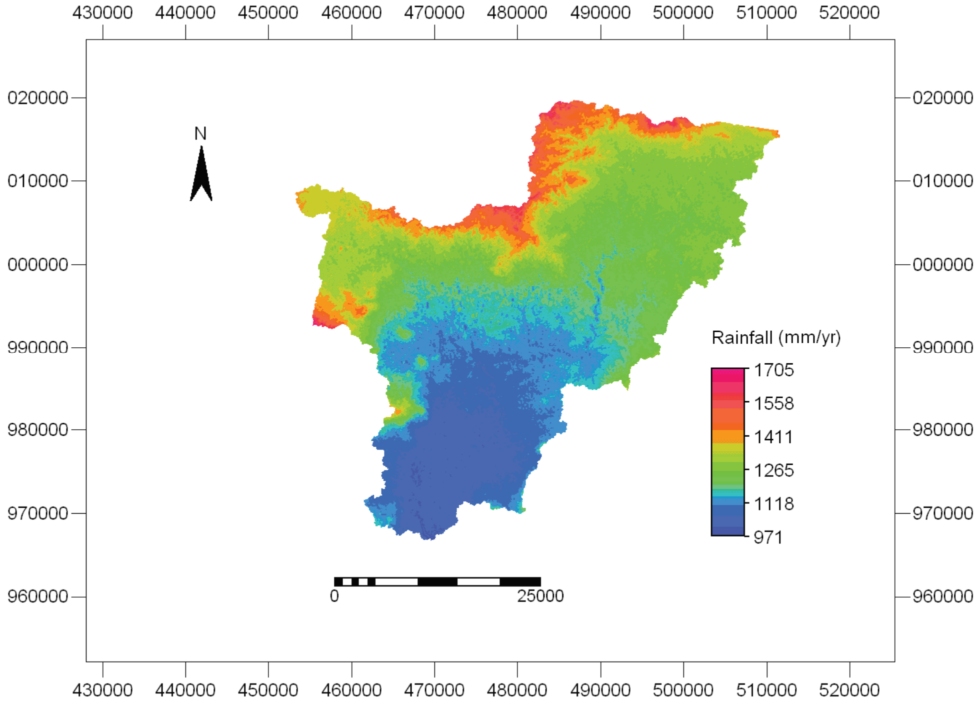


Figure 8. Spatial distribution of rainfall in the Akaki catchment

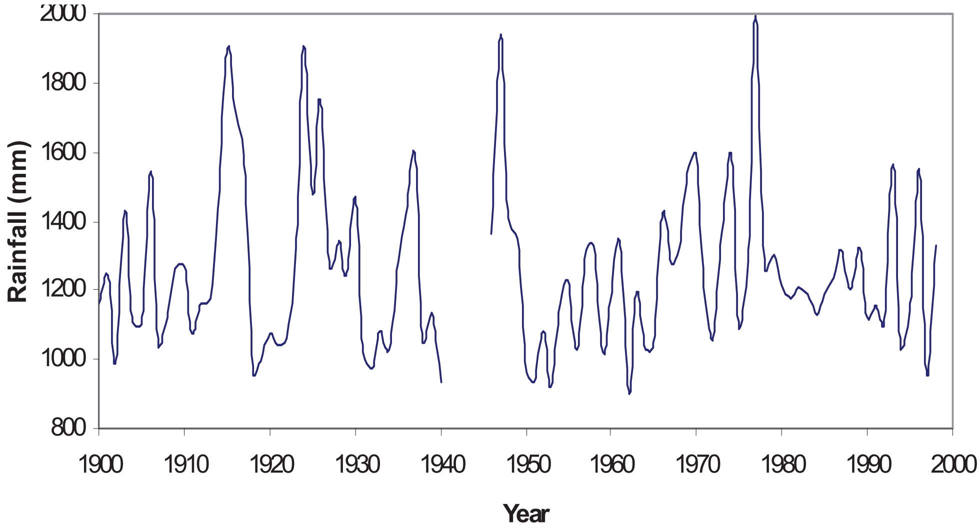


Figure 9. Temporal variation of annual rainfall about the mean – Addis Ababa Observatory

2.1.4. Temperature

Under normal conditions, air temperature decrease with increasing altitude at a mean rate of 0.7 °C for every 328 feet (Fetcher, 1998). This works also in Ethiopia where temperature decreases with increasing elevations. Daily average temperatures range from 9.9 to 24.6 °C. and mean monthly temperature ranges between 15°C and 18 °C.

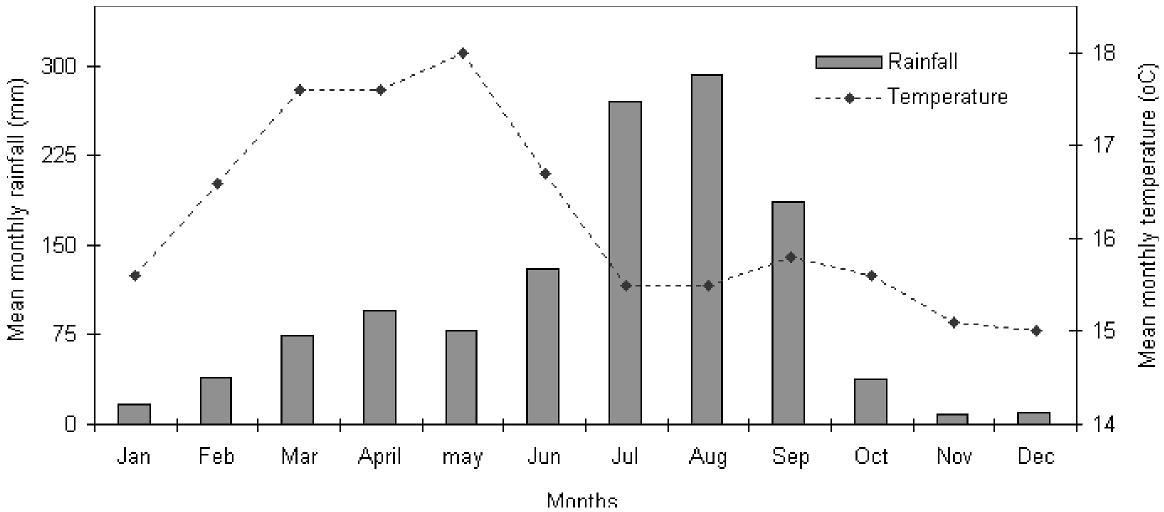


Figure 10. Relationship between temperature and rainfall in the catchment (1989 – 2005)

Table 2. Maximum and minimum monthly temperature in the catchment

Temp.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Ann. Ave.
Max.	23.3	24.1	24.6	23.9	24.6	22.9	20.3	20.1	21.1	22.4	22.6	22.8	22.7
Min.	8.2	9.5	10.9	11.5	11.7	10.8	10.8	10.8	10.5	9.2	7.9	7.5	9.9

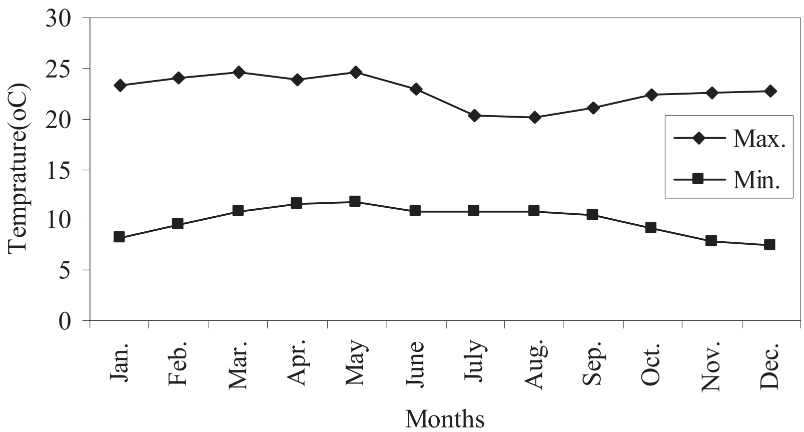


Figure 11. Temperature variations in Akaki catchment

2.2. Hydrology

The Akaki River, left bank tributary of the Awash River, has an extensive drainage system with a catchment area of 1500 km^2. It originates from the Intoto range, north of Addis Ababa, and drops about 600 m in a river length of 95 km from its origin to its confluence with the Awash River near Dodota. The Akaki river watershed includes two main river systems: the Akaki proper (big Akaki river), draining the eastern part of the catchment area, and the Little Akaki, draining the western portion. These two rivers meet in Abba Samuel reservoir, a man-made lake formed by damming of the Akaki River in the 1930's. South of the Abba Samuel dam, the Akaki river has cut a gorge up to 100 m deep, which extends for about 8 km. The Akaki river flows into the Awash river at a point approximately 18 km to south of the Abba Samuel reservoir. The Akaki wellfield is situated within the drainage basin of Sakelo River, which flows into Akaki River just before Abba Samuel reservoir.

The Akaki River is gauged since 1981 at the Addis Ababa - Debre Zeit Road Bridge, with a catchment area of 885 km^2. This station does not include the flow from the little Akaki River. This hydrometric station is equipped with an automatic water level recorder and 7 staff gauges (1- m long each). The mean annual discharge of Akaki river at this point is computed from the record for the period of 1981 to 2005, and is found to be 9517 l/s or 10.75 $l/s/km^2$ which is equivalent to mean annual yield of 339 mm. The monthly distribution of runoff volume at Akaki Bridge in an average year is shown in Figure 12.

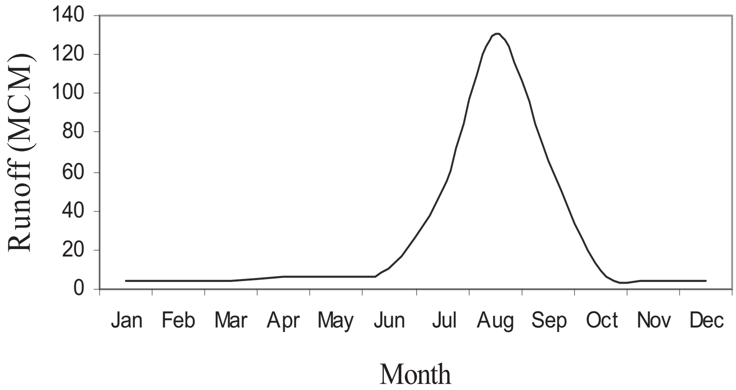


Figure 12. Monthly variation of runoff at Akaki bridge, 1981 – 2005, (AAWSA, 2000)

As (AAWSA, 2000) indicated that more than 82% of the annual runoff is generated in July, August and September only; emphasizing the fact that groundwater contribution to surface water is low as compared to direct runoff generated during the main rainy season. A trend of increase in low flow with time has been observed in the flow record. This may be attributed to the ever-increasing wastewater flow into Akaki River as Addis Ababa is expanding in terms of development and population. A significant portion of the low flow at this station is, in fact, sewage originated.

There are three man-made reservoirs in the Akaki catchment, commanding a sizable part of the catchment area. They facilitate transfer of water from one part of the catchment to the other in the form of water supply for domestic and industrial consumptions. One has to consider this human influence on the hydrological process while studying the water balance of the catchment. It is also worth mentioning that sizeable quantity of sewage, originating from Addis Ababa City, is discharged into both Akaki Proper and Little Akaki rivers. In particular, the sewage flow has modified the low flow regime of the river to a great extent, and it could pose a serious threat to the groundwater in the area in terms of pollution if the former recharges the latter.

2.3. Geological and hydrogeological setting

Owing to its location along the western margin of the main Ethiopian rift, the geological history of the Akaki catchment is an integral part of the evolution and development of the Ethiopian Plateau and the rift system. The catchment is covered by volcanic rocks overlain by fluvial and residual soils, in which black cotton soils are predominant, varying in thickness from a few centimetres to about 20 m (AAWSA, 2000). The main lithologies include basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites and tuff (Figure 13). These highly weathered, fractured lithologies favour the circulation and storage of subsurface water.

2.3.1. Geology

Several geological studies have been carried out in the region. The most important ones are Morton et al. (1979) and Girmay and Assefa (1979). From field investigations and previous geological studies a simplified hydrogeological map was established (Fig. 13). According to AAWSA-Seureca (1991) the following lithostratigraphic units can be identified in the catchment.

Alaji Formation:

It includes rhyolites, trachytes, tuff, agglomerate, and aphianitic basalt. This unit is dominant in the northern and central part. Earlier works further subdivided this series into Alaji rhyolites and Intoto Silicics (Zanettin and Justin- Visentin, 1974). It extends from Intoto to the northern adjacent Blue Nile (Abay) basin (Girmay, and Assefa, 1989). The Intoto trachyte overlies the Alaji basalts. The Intoto Silicics represents massive Oligocene fissure-basalt, rhyolites, and trachytes with minor welded tuff and obsidian (Morton et al., 1979).

Addis Ababa Basalts:

These basalts overlay the Intoto Silicics and cover the central and southern part of Addis Ababa. Usually individual flows are easily observed and paleosoils and scoraceous horizons are common in many places. Olivine porphyritic basalt outcrop in central Addis Ababa with a thickness varying from 1 m or less in the foothills of Intoto to more than 130 meters in central Addis Ababa (Vernier, 1985).

Younger Volcanics

This group includes the Nazareth Group and Bishoftu Formations.

The Nazareth Group rocks outcrop dominantly south of the Filwuha Fault. They are composed of aphianitic basalts, welded tuffs, ignimbrites, trachytes, and rhyolites. It is overlain by aphianitic basalt and underlain by porphyritic basalt. The exposed thickness of the lava sequence is about 500 m (Girma, 1994).

The Bishoftu Formation consists of olivine porphyritic basalt, scoria, vesicular and scoraceous basalt, and locally trachy-basalt lava flows. They are localized in the south and are 20 to 40 m thick in the Akaki wellfield. Locally it is overlain by scoria, tuff, sand, and gravel. This unit forms the major aquifer of the region.

Recent Deposits

These include alluvial, residual, and lacustrine deposits. The thickness varies between 5 m and 50 m near river banks in the south (AAWSA, 2000). It is often overlain by dark younger black cotton clayey soils. Alluvial deposits are found in some places along the Little- and Big-Akaki rivers, particularly south and southwest of Addis Ababa. Residual soils are located in the central, southeast, northeast, and western flatplains.

2.3.2. Hydrogeology

The groundwater circulation and the dispersion of pollutants depend on the hydrogeological characteristics of the material more specifically hydraulic properties such as porosity, permeability and . The origin, flow and chemical constituent of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrogeological units through which it moves. Moreover, the stresses due to tectonism and weathering govern the hydrogeochemical characteristics of earth materials. Volcanic rocks mainly basalts, rhyolites, trachytes, scoria, trachy-basalts, welded and unwelded tuffs are the dominant rock outcrops in the area. Besides, unconsolidated materials of different origin also occur in the study area. These rocks are the major groundwater supply for large parts of Addis Ababa.

The main structures, joints, fractures, and normal faults, are all related to the extensional rift tectonics in the area. A prime example is the Filwoha Fault, along which thermal activity is observed. The aquifer properties in the Akaki catchment are controlled by the litho-stratigraphy of the volcanic rocks and the structures that affect them. More specifically, the hydraulic complexity of these volcanic rocks is caused by their complex spatial distribution, their different reciprocal stratigraphic relationships, their significant compositional, structural and textural variability, and their different levels of tectonization and weathering (Vernier, 1993). These volcanic aquifers can be considered as a double porosity medium due to the fact that both the matrix and the fracture porosity contribute to the transmission and storage of subsurface water.

- Scoria, scoraceous basalt and intra-formational gravel and sand layers constitute highly productive aquifers with primary porosity and permeability.
- Highly weathered and fractured basalts, fractured tuff, ignimbrite and other pyroclastics constitute highly productive aquifers of secondary porosity and permeability.
- Basalt with some fractures, vesicles and sparsely spaced joints, ignimbrites and agglomerates form moderately productive aquifers in the area (Girma, 1994; AAWSA, 2000; Tamiru, 2001).

These units have been grouped into an uppermost shallow phreatic aquifer constituted by layers of alluvial sediments, weathered and fractured volcanics and a confined–semi-confined volcanic aquifer of widespread areal coverage (Girma, 1994). These multilayered, heterogeneous unconfined, semi-confined and confined aquifers feature multi-stock works. Furthermore, it was observed that highly transmissive areas do not correspond to high storativity areas, because of differential fracturing and weathering of the volcanic aquifers (AAWSA, 2000).

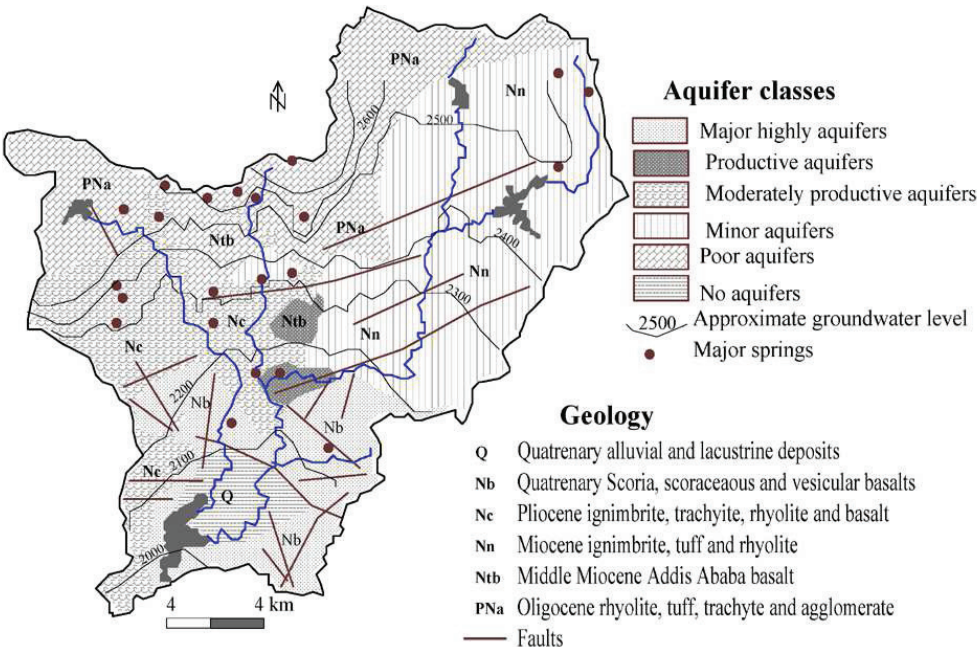


Figure 13. Simplified hydrogeological map (after AG consult, 2004)

Relatively better hydrogeological information is collected in the central and southern part of the catchment where most of the wells are concentrated. Major contributions to the hydrogeology of the area come from studies related to the water supply of the city of Addis Ababa (AAWSA-Seureca 1991; AAWSA 2000) and academic works (Girma, 1994; Aynalem, 1999; Gizaw, 2002; Demlie, 2007). These studies provided important information to develop the conceptual hydrogeological model of the catchment. Field hydrogeological investigation indicates variable aquifer hydraulic parameters. Most of the aquifers are unconfined with productivity increasing towards the south.

The borehole logs show variable lithology and degrees of fracturing. However, due to the high permeability the different hydrostratigraphic units are hydraulically connected. The pumping test data indicates that the system behaves as an unconfined aquifer. The existing data shows that the catchment is composed of both inter-granular and fracture permeability aquifers. The inter-granular porosity aquifers are alluvial sediments and pyroclastic and scoraceaous volcanic rocks forming the upper more permeable layer. The fractured aquifers are composed of basalts, ignimbrites, trachytes, and rhyolites with a relatively less permeable bottom second aquifer system. Basalts and ignimbrites are generally highly fractured and permeable and have been classified as good aquifers. The scoraceous and vesicular basalts have yields up to 1296 m^3/day. Faulted ignimbrites and basalts make good aquifers, while less fractured and less jointed basalts, including alkaline flood basalts of the Addis Ababa area, form moderate aquifers with yields of up to 432 m^3/day and 260 m^3/day, respectively. Poor aquifers are fine-grained alluvial deposits with volcanic ash and lacustrine deposits. In contrast to this general observation, the alluvial deposits of sand and gravel types have a very good yield forming the shallow aquifers. Based on the analysis of existing well data, as well as those gathered for this research, confined aquifers have been identified in the city of Addis Ababa. These are mainly hot waters along the Filwoha fault, which are considered to be isolated and which have no direct connection with the unconfined system.
Therefore, according to previous studies, the main aquifers in the Akaki catchment can be categorized into three groups:

1. Shallow aquifer: made of weathered volcanic rocks and alluvial sediments along the river valleys.
2. Deep aquifers: made of fractured volcanic rocks at which boreholes are drilled for drinking water supply purpose.
3. Thermal aquifer: that is located at depth greater than 300m.

2.4. Geomorphology and drainage system

Addis Ababa is located on the shoulder of the Western Main Ethiopian Rift Escarpment. The morphology is a direct reflection of the different volcanic stratigraphic successions, tectonic activities and the action of erosion between successive lava flows.
The city was founded at the southern flank of Entoto ridge (3565 m a.s.l.) and expanded in all directions. This ridge marks the northern boundary of the city following the east-west trending major fault (Ambo-Kassam). Other prominent volcanic features surrounding the city are Mt. Wochacha in the west (3385m a.s.l.), Mt. Furi (2839m a.s.l.) in the southwest and Mt. Yerer (3100 a.s.l.) in the southeast.
These typical volcanic features are mainly built up of acidic and intermediate lava flows. Thus, they are characterized by rugged landscapes and steeper slopes. The general inclination of the slope becomes lower towards the southern part of the project area particularily around the wellfield.
The center of the city lies on an undulating topography with some flat land areas. The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city. Moreover, it is not uncommon to see sharp changes in the inclination of the slope and some flat land areas in different parts of the city.

The Akaki River catchment, which includes the city of Addis Ababa and the wellfield area, is an extensive drainage system arising from the Entoto Mountain Range north of Addis Ababa. The south eastern drainage divide, which separates the Akaki and Dukem River drainage systems, passes very close to the Akaki wellfield. This divide includes peaks of Gara Bushu (2346 m), Mt. Guji (2475 m), and Mt. Bilbilo (2380 m).The Akaki wellfield is situated within the drainage basin of the streams Dengora and Keta which join to form the Sakelo, which in turn flows into the Akaki river. The surface catchment area is bounded eastwards and southwards by a topographic limit: volcanoes Mt. Furi, Mt. Yerer, Gara Bushu, Mt. Guji and Mt. Bilbilo. Geomorphology of the area is shown in figure 15, which is done by constructing shaded relief map based on SRTM DEM.

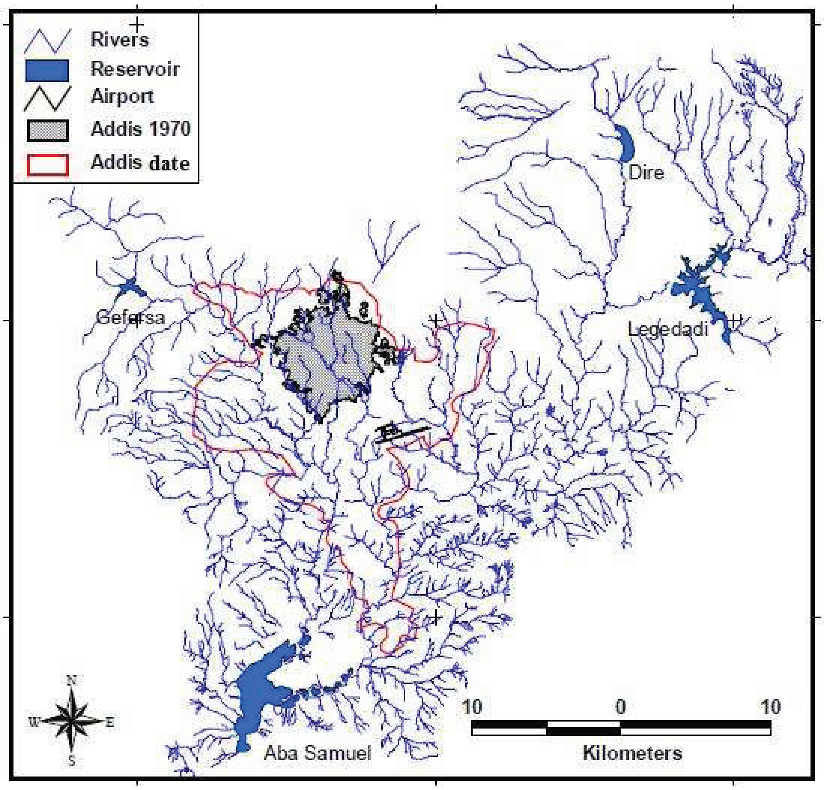


Figure 14. Drainage and urban development of Addis Ababa area

2.5. Hydrochemistry

Water chemistry data can be used to infer groundwater flow directions, to define intended use of water, identify sources and amount of recharge and to define local and regional flow systems (Anderson and Woessner, 1992). Water quality is the constituents of water as affected by natural processes and human activities and determines the intended use of water (Strickland et al., 1997). The major inorganic constituents of water originate when water in the form of precipitation dissolves atmospheric gases such as carbon dioxide and reacts with minerals on the surface of the earth (Freeze and Cherry, 1979). The quality of groundwater first depends on the composition of the recharge water, the interactions between the water and the soil, soil-gas and rocks with which it comes into contact in the unsaturated zone, and the residence time and reactions that take place within the aquifer (Freeze and Cherry, 1979).

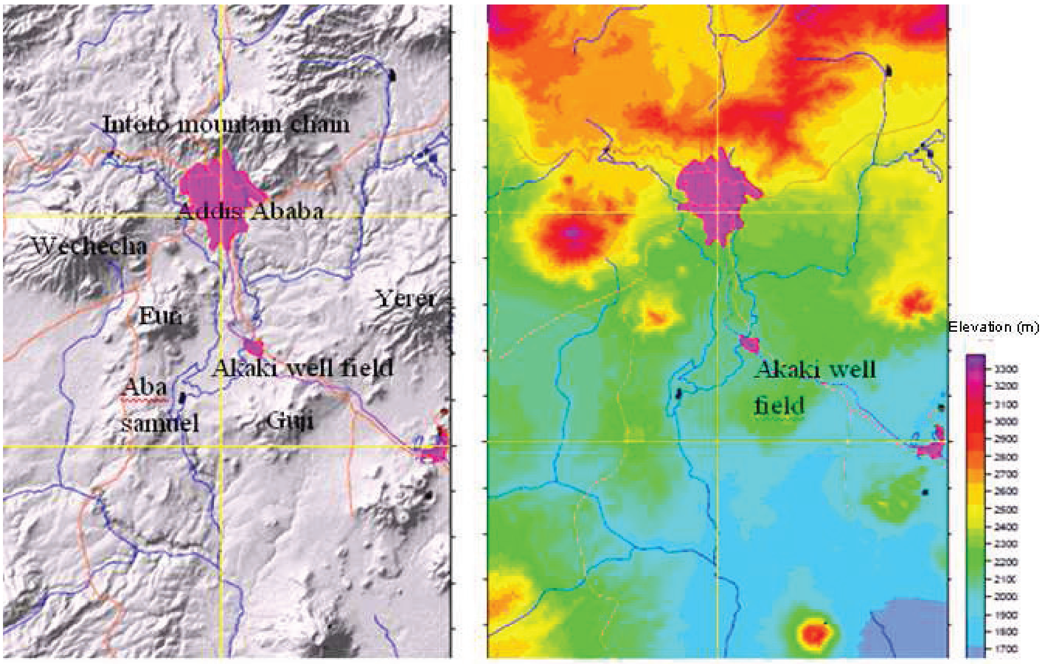


Figure 15. Geomorphology of the Akaki catchment

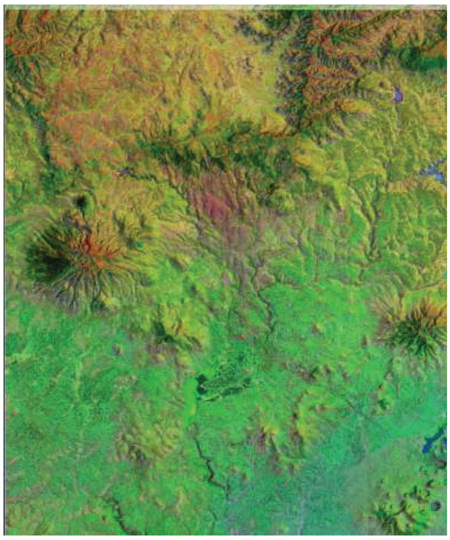


Figure 16. Landsat imagery with shaded relief map

2.5.1. Water quality parameters

The water quality parameters considered during assessment of water quality include nitrate, chloride, pH, acidity, alkalinity and electrical conductivity as well as major cations and anions. According to (WHO, 1993), the water quality parameters concentration range aims at safe guiding the health of human being as well as other water use like irrigation, industry and domestic use.

2.5.2. Field sampling procedure

Water samples were taken from both boreholes and river waters. Certain parameters such as temperature, pH, electrical conductivity, etc are difficult to preserve during the storage and are measured in situ in the field. Duplicate samples were taken from each point for major ions determination in the laboratory by adding acids in the field for preservation purpose. Sample containers, which do not interact with the constituents intended to be determined during storage, were chosen. It is common practice to use filtered (0.45 µm membrane filter) samples for metals in order to ensure that only dissolved species (which take part in most geochemical reactions and are used in chemical equilibrium equations) and not suspended constituents, which may be contributed from the wells are determined. So samples were filtered by this way and almost all suspended clays and other materials are removed.

2.5.3. Chemical analysis results

To check the quality of measurements done in the laboratory there are various methods used to indicate the correctness of the results (See figures 15, 16 and 17). Table 4 shows the quality check results according to Hounslow (1995).

2.5.4. Reliability check

The accuracy of the water analysis was checked with the anion-cation balance. Water is naturally balanced system. Ideally the sum of anions expressed, in meq/l must be exactly equal to the sum of cations, in meq/l, in any sample. The principle of the anion–cation balance is that the sum of cations and sum of anions are equal because the solution must be electrically neutral. Therefore, In a electrically neutral solution, the sum of the cations should be equal to the sum of anions in meq/l which is also equal to EC/100 (µs/cm) (Hounslow, 1995).

$$Electroneutrality(\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} * 100 \quad (1)$$

Based on the electroneutrality, analysis of water samples with a percent balance error <5% is regarded as acceptable (Fetter, 2001). But in very dilute or saline water, up to 10% error may be considered as acceptable due to the errors introduced in measuring major ions in dilute groundwater or in the multiple dilution require for analysis of concentrated groundwater (Fetter, 2001). The cations-anions balance results are found to be acceptable as the balance does not deviate from the 10% criterion (see table 4 below). The analysis results indicate that the dominant dissolved cations in the groundwater of the area are Na^{+}, Ca^{2+}, and Mg^{2+} with lower levels of K^{+}. And the major dissolved anions in the groundwater include: $HCO3^{-1}$. This gives mixed cation bicarbonate water in the area. Table 3 and 4 below shows that in general groundwater quality is fair.

Table 3. ITC laboratory chemical analysis result (2008)

Water points	Ca (mg/l)	Mg(mg/l)	K(mg/l)	Na (mg/l)	Cl (mg/l)	SO4 (mg/l)	HCO3 (mg/l)	NO3 (mg/l)	PO4 (mg/l)	EC (µs/cm)
EP-04	53.0	37.9	10.2	43.9	11.7	5.0	366.1	19.9	0.1	448
BH-05	77.1	35.4	8.7	35.4	4.9	5.5	402.7	24.4	0.2	530
BH-01	53.2	30.8	9.7	37.5	3.2	4.0	353.9	17.7	0.6	438
BH-10	55.2	35.3	8.4	29.6	5.0	4.0	366.1	18.6	0.7	458
F3	44.8	26.3	12.9	70.4	11.7	7.5	390.5	19.5	0.2	545
Iron & steel BH	92.3	39.7	10.6	47.7	9.2	10.5	518.7	19.5	0.3	646
Akaki metal products Factory BH	57.3	29.7	10.8	64.2	23.7	7.5	408.8	20.4	0.2	510
Spare Parts BH	73.2	30.6	7.4	44.1	6.6	7.5	396.6	18.0	0.3	470
Fanta Minch/ spring (Cs-1)	61.3	31.8	8.6	44.5	20.0	7.5	384.4	19.0	0.1	536
Dongora river	90.2	26.9	8.8	41.0	18.4	13.5	396.6	3.1	0.0	572
Fanta river	73.0	15.0	9.9	45.3	7.1	6.5	353.9	7.1	0.0	437
Fanta river near tsebel spring	54.3	11.6	8.5	34.3	4.7	5.5	305.1	6.2	0.0	442
Big Akaki, at theAkaki bridge	58.8	12.2	14.5	60.4	22.4	13.0	317.3	13.7	1.5	460
Kebena River at Bole Bridge	60.8	15.7	16.0	47.6	41.0	12.0	305.1	26.1	1.9	539
Rain water (RW-1)	5.6	0.6	5.3	4.2	0.7	0.0	36.6	0.0	0.0	104

Table 4. Ionic balance of the water samples

Water points	Ca^{+2} (meq/l)	Mg^{+2} (meq/l)	K^{+1} (meq/l)	Na^{+1} (meq/l)	Cl^{-1} (meq/l)	$SO4^{-2}$ (meq/l)	$HCO3^{-1}$ (meq/l)	$NO3^{-1}$ (meq/l)	$Po4^{-3}$ (meq/l)	EC/100 (us/cm)	Σanion	Σcation	balance
EP-04	2.6	3.1	0.3	1.9	0.3	0.1	6.0	0.3	0.0	6.5	6.8	7.9	-8.0
BH-05	3.8	2.9	0.2	1.5	0.1	0.1	6.6	0.4	0.0	7.7	7.3	8.5	-8.1
BH-01	2.7	2.5	0.2	1.6	0.1	0.1	5.8	0.3	0.0	6.4	6.3	7.1	-5.9
BH-10	2.8	2.9	0.2	1.3	0.1	0.1	6.0	0.3	0.0	6.6	6.5	7.2	-4.5
F3	2.2	2.2	0.3	3.1	0.3	0.2	6.4	0.3	0.0	7.9	7.2	7.8	-3.9
Iron & steel BH	4.6	3.3	0.3	2.1	0.3	0.2	8.5	0.3	0.0	9.4	9.3	10.2	-4.7
Akaki metal Factory BH	2.9	2.4	0.3	2.8	0.7	0.2	6.7	0.3	0.0	7.4	7.9	8.4	-3.1
Spare Parts BH	3.7	2.5	0.2	1.9	0.2	0.2	6.5	0.3	0.0	6.8	7.1	8.3	-7.3
Fanta Minch/ spring (Cs-1)	3.1	2.6	0.2	1.9	0.6	0.2	6.3	0.3	0.0	7.8	7.3	7.8	-3.3
Dongora river	4.5	2.2	0.2	1.8	0.5	0.3	6.5	0.1	0.0	8.3	7.4	8.7	-8.5
Fanta river	3.6	1.2	0.3	2.0	0.2	0.1	5.8	0.1	0.0	6.3	6.3	7.1	-6.4
Fanta river near tsebel spring	2.7	1.0	0.2	1.5	0.1	0.1	5.0	0.1	0.0	6.4	5.3	5.4	-0.2
Big Akaki at akaki bridge	2.9	1.0	0.4	2.6	0.6	0.3	5.2	0.2	0.0	6.7	6.4	6.9	-4.2
Kebena River at Bole Bridge	3.0	1.3	0.4	2.1	1.2	0.2	5.0	0.4	0.1	7.8	6.9	6.8	0.6
Rain water (RW-1)	0.3	0.0	0.1	0.2	0.0	0.0	0.6	0.0	0.0	1.5	0.6	0.6	-1.6

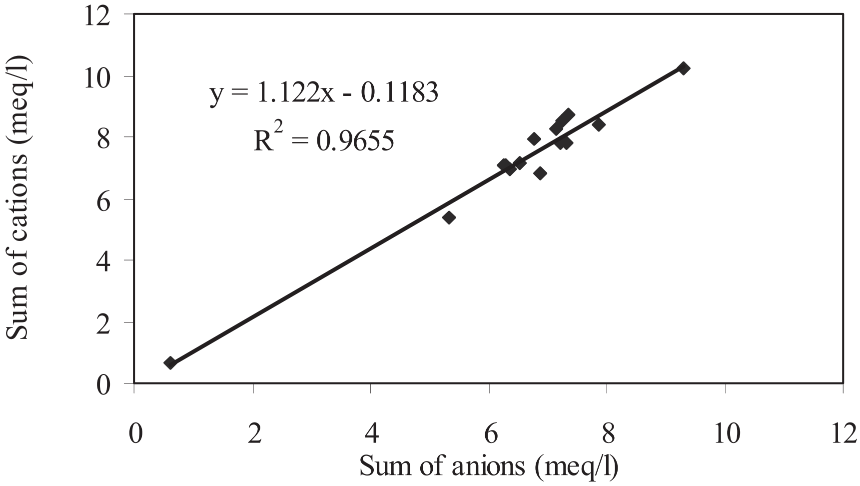


Figure 17. Graph of regression analysis of sum of anions against sum of cations

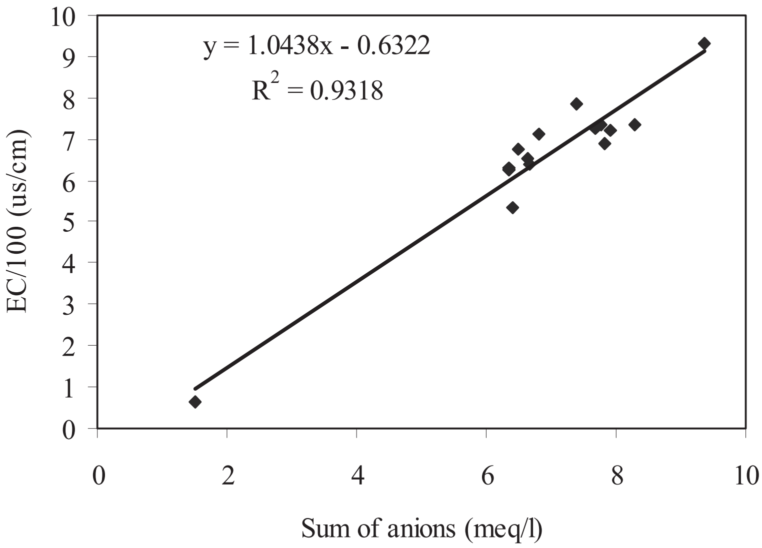


Figure 18. Graph of EC/100 (μs/cm) against sum of anions (meq/l)

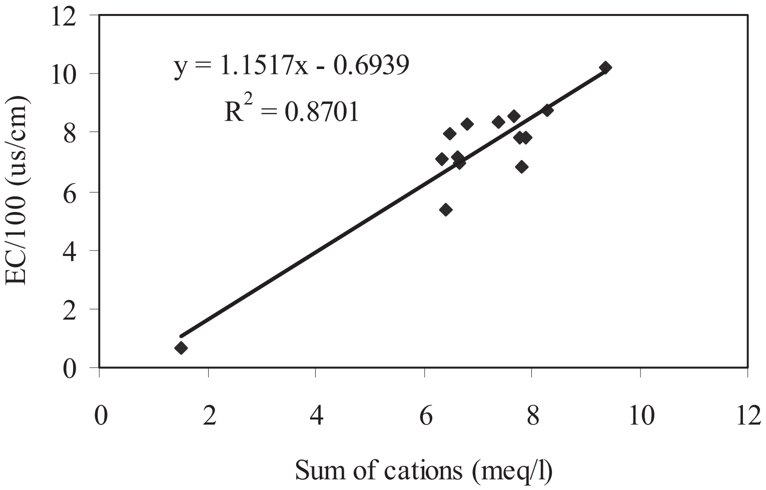


Figure 19. Graph of EC/100 (µs/cm) against sum of Cations (meq/l)

2.5.5. Presentation of results

Piper diagrams show the effect of various factors, including major ion composition of possible source waters, as well as the proportions of mixing between those water sources in the samples. The effect of geochemical interactions between water and aquifer materials also can be understood from Piper diagram. The analysis result of the major anions and cations are plotted in Piper diagrams and Stiff diagrams for determination of the water type. As discussed in Fetter (2001), Stiff diagrams are useful in making a rapid visual comparison between water from different sources. The water samples from the area are presented in the Piper. Selected representative samples were also plotted on Stiff diagrams (See Fig 20 and 21 for details).

2.5.6. Water type deduction

The chemical laboratory results for all sampled points were imported in AQUACHEM v.5.1 software. Aquachem is a software package developed specifically for graphical and numerical analysis and of water quality data. The Piper diagram for 2008 dataset is shown in Figure 19. Groundwater in the basin is highly mineralized with mixed cations with dominant cations being calcium, sodium and magnesium respectively and bicarbonate as anion. The water type deduced from the Piper plot is mixed cation bicarbonate water type, typical of shallow fresh groundwater.

Table 5. Water type of the present study in the catchment (2008)

Water point	X	Y	Water type
EP-04	479118.5	977807.4	Mg-Ca-Na-HCO3
BH-05	476680.7	975819.8	Ca-Mg-HCO3
BH-01	478061.4	975076.1	Ca-Mg-Na-HCO3
BH-10	479155.1	976241.9	Mg-Ca-HCO3
F3	479779.2	981769.5	Na-Ca-Mg-HCO3
Iron & steel BH	476743.0	980936.4	Ca-Mg-Na-HCO3
Akaki metal products factory BH	476760.5	980804.8	Ca-Na-Mg-HCO3
Spare Parts BH	478347.8	977935.0	Ca-Mg-Na-HCO3
Fanta minch/ spring (Cs-1)	481354.8	981983.2	Ca-Mg-Na-HCO3
Dongora river	480153.1	977540.5	Ca-Mg-Na-HCO3
Fanta river	480856.6	981603.1	Ca-Na-HCO3
Fanta river near tsebel spring	478892.9	981633.9	Ca-Na-HCO3
Big Akaki at theAkaki bridge	476505.7	981305.8	Mg-NO3-Cl
Kebena river at Bole bridge	475606.3	994069.1	Ca-Na-HCO3
Rain water (RW-1)	472708.4	996421.5	Ca-Na-K-HCO3

The Piper diagrams are widely used for interpretation and classification of water. The concentration in meq/l of major cations and anions from different water points analyzed in the area are plotted in the Piper diagram. From the diagram two types of water can be identified:

1) Mg-NO3-Cl water type
2) Mixed cation bicarbonate water type

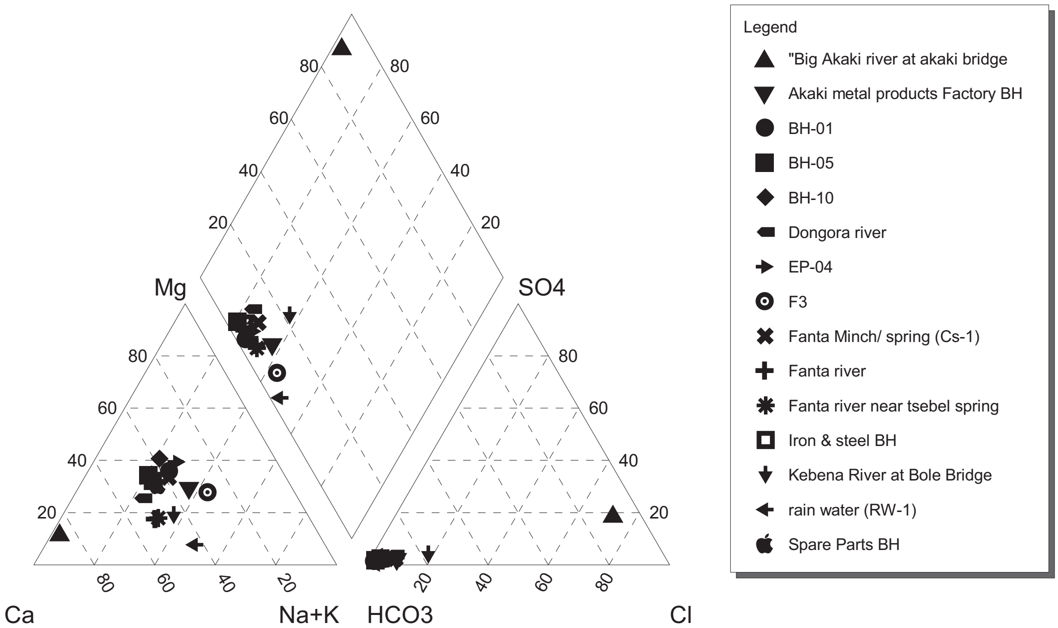


Figure 20. Piper Diagram showing the distribution of water types for water points

Akaki Bridge reveals a Mg-NO3-Cl and other rivers in the area are of Ca-Mg-Na-HCO3 and Ca-Na-HCO3 type. A shift of water chemistry towards SO4+ Cl and NO3 is mostly related to the infiltration of contaminants into the rivers or subsurface rather than natural dissolution processes. The two Stiff diagrams below in Fig. 21 indicate the two water types. All groundwater samples are more or less similar with the Dongora river stiff diagram.

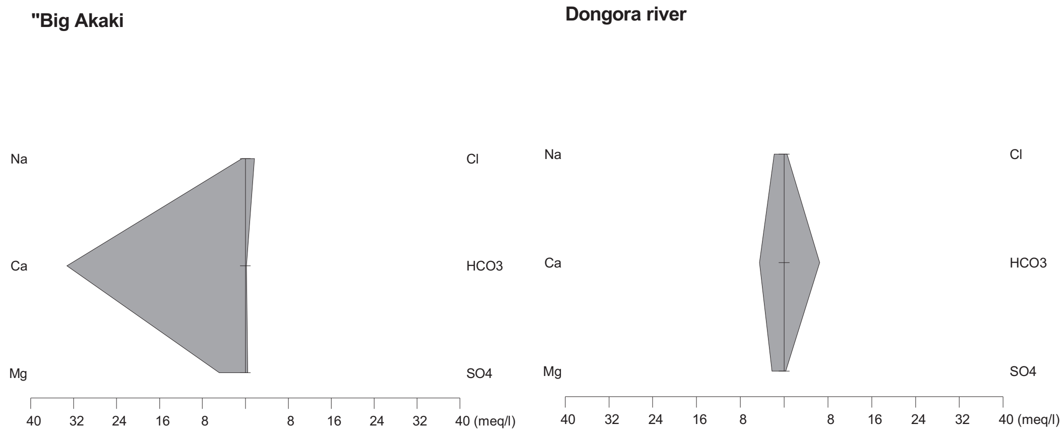


Figure 21. Stiff patterns of water samples from Akaki catchment

2.6. Subsurface conceptualization of the model domains

The area is made up of multi-aquifers having different hydrogeological characteristics. The existing data shows that the area is composed of both inter-granular and fracture porosity type aquifers. The fractured aquifers are composed of different volcanics such as weathered and fractured basalts, ignimbrites, trachytes, rhyolites, and welded tuffs. Basalt and ignimbrites found in the upper Awash basin are mostly tectonized and fractured; and therefore have good permeabilities (Berhane Melaku, 1982) as cited in AAWSA(2000). All types of aquifers are found in the area: i.e confined, semi-confined and leaky confined aquifers, including perched and leaky aquifers (AWSA-Seureca, 1991)

The depositions of alluvial materials between basaltic materials result in a large and very complex geological structure with highly variable lithology. As a result the water level surface in the wells is not everywhere smooth and continuous, and the discontinuities can be attributed to either topography or both vertical and horizontal change in lithology. Perched aquifer conditions are recognized by the position of the water strike and the recorded static water level. Static water level is below the water strike position in semi-confined conditions.

In the research area, the geological age of volcanic rocks varies from Young Volcanics (Pliocene) to Alaji Series (Lower Miocene) and the age of the rocks is becoming younger towards the rift system. Moreover, the elevation of the area decreases to the rift as well. These variations of age and elevation affect the weathering and fracturing of volcanic rocks to give variable recharge and aquifer characteristics. Moreover, the structures are also affected by the distribution of groundwater and its location in the area (e.g. Filwoha Fault). All the above factors affect the groundwater distribution and aquifer characteristics of the area. Therefore, defining aquifer geometry is a very difficult task that remains ahead.

Groundwater resource evaluation and requires knowledge of various physical properties and hydraulic parameters of aquifers and aquitards which includes hydraulic conductivity, storativity, specific yield, etc. In order to define these parameters, in addition to pumping tests of various types, sampling and water analysis in individual layers of water bearing formations is crucial. All the wells in the Akaki wellfield are concentrated within small areas without having sound scientific justification. In most cases, therefore, a hydrogeological description and interpretation is made by qualitative analysis of the surface information. Figure 22 shows the North-South well log correlation in the Akaki catchment after Dereje Nigusse, (2003). The figure shows the irregular layers of clay, porous rock, gravel, weathered regolith and hard rock. The highly variable static water levels are also shown. Figure 23 below shows a detailed map of the Akaki Wellfield area. Boreholes EP4 to EP8 are Akaki town water supply wells. The wells BH01 to BH26 are Addis Ababa water supply wells. In this well group there is no BH15. Borehole BH 03b and BH 05a were abandoned as they are found to be low yield and dry borehole respectively. Instead of these two boreholes; BH03a, BH05b have been drilled. Four observation wells, MW01 to MW04 are monitoring wells found at the vicinity of the Akaki River.

2.6.1. Well log correlations

According to Devis et al., (1966) as cited in Dereje Nigusse (2003), well log correlation helps in determining the stratigraphic sequence of lava beds, buried soils and other features which extract influence on the movement of groundwater. The lithologies of most geological formations tend to vary significantly both laterally and vertically. The lithology, stratigraphy and the geological structures that affect the rocks largely controls the nature and distribution of aquifers and aquitards in a geologic system. To investigate these factors, borehole log is mandatory. However it is very difficult to get well documented and consistent data for most of the boreholes that could provide full information about the subsurface lithostratigraphy and characteristics of aquifers. See East–west well log correlation of Akaki catchment in Appendix 4. A lithostratigraphic classification of the wellfield has been prepared using the information obtained from more than 20 boreholes. The depth of production wells ranges from 119 m to 170 m and test wells from 60 m to 300 m from normal ground level.

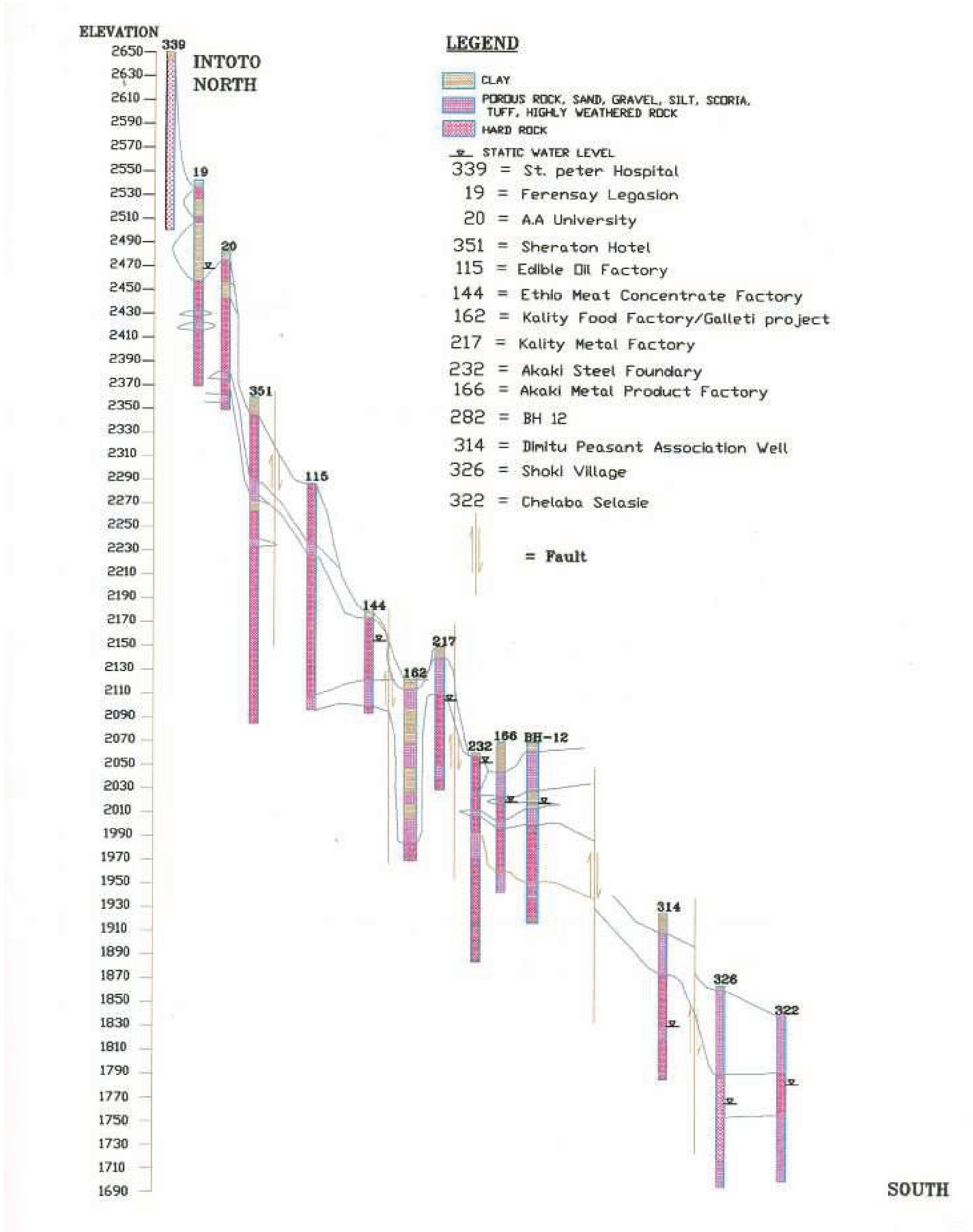


Figure 22. North-South cross-section of well logs in the Akaki catchment (Dereje Nigusse, 2003)

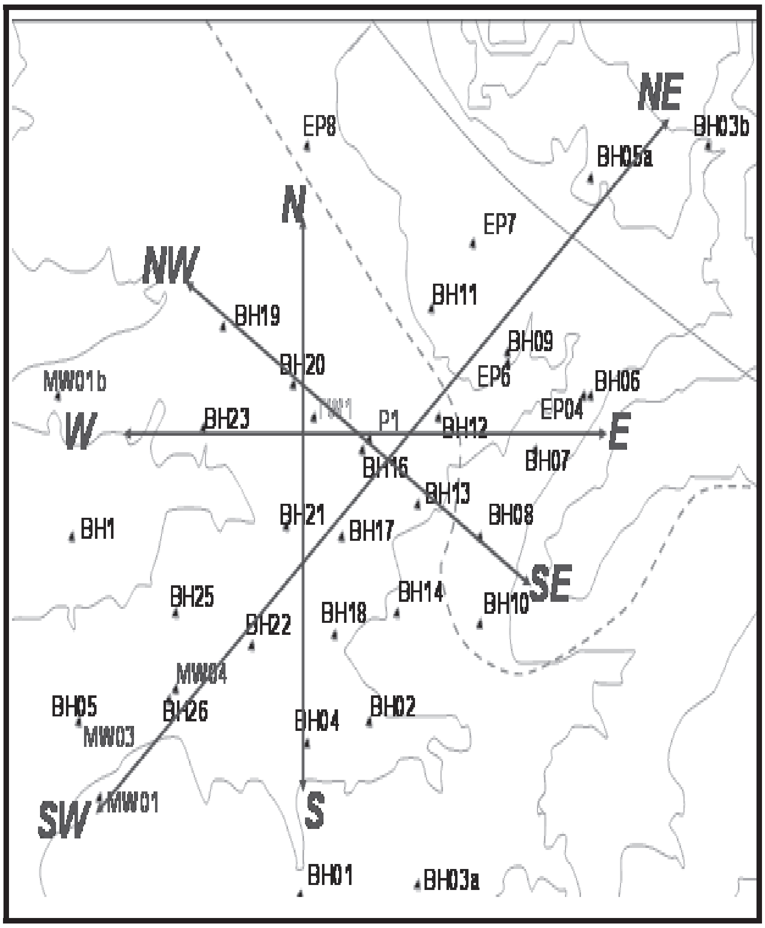


Figure 23. Location map of the Akaki wellfield showing productive and monitoring wells.

The map also shows the location of cross-sections along N-S, E-W, NE-SW, NW-SE in the Akaki wellfield (see also NW-SE and W-E cross-sections in Figures 23). N-S and NE – SW cross-sections are shown at Appendix 3.

The diameter of wells drilled for water supply of Akaki and Addis Ababa is 24 inch from the ground surface to a depth of 10 to 25 m, 17.5 inch in the middle part and 12.5 inch from around 80 to 100 m till the bottom of the borehole. The observation wells have diameters of 12.25 inch from the ground surface to a depth of 6 or 10 m whereas in the lower part the diameters vary from 9.6 to 8.5 inch.

The lithologic descriptions supported by resistivity and self potential log of boreholes along with the field hydrogeological information have been used as a basis for classifying the hydrostratigraphic units. More emphasis is given to the resistivity and self potential log than the strata description in the geologic log. Yet the resistivity and self potential logging are only possible below the depth of static water level (See Figure 24 as an example for BH23). Self potential logging is used for acquisition of information concerning the salinity of water in porous rock. As it can be proved from the geologic logs, the formation is basaltic rock with fracture permeability. In water filled drill holes in rock with fracture permeability usually no interpretable SP curve is attained (Repsold, 1989). In addition to this, results of water quality analysis show fresh water. Therefore, the shape of the resitivity log curves depends mainly on the degree of fracturing and the presence or absence of water. The water in the fissures contains ions such as Na^+, Ca^{2+}, Cl^-, SO_4^{2-} which reduce the resistivity of the rock. Because of the limiting factor to use the spontaneous potential (SP) log in this formation, resistivity log curves are mainly used in conjunction with the geologic log to determine the stratification of the aquifers, aquitards and aquicludes in the wellfield. In some boreholes SP curves show good correlation with resistivity curves.

In hydrogeological mapping and ground water modelling, aquifers, aquitards and aquicludes are defined using the concept of hydrostratigraphic units by suppressing small local lithological variations. Several geological formations may be combined into a single hydrostratigraphic unit depending on the scale of the problem domain and the hydrogeological character of the rocks. Furthermore, water bearing zones often depend on the degree of fracturing and to a lesser extent on lithology.

Based on the analysis of existing data as well as those gathered for this research, semi-confined (e.g. most boreholes) and perched (e.g. almost the upper part of boreholes BH12 and BH13) aquifers within the wellfield and confined aquifer close to Akaki bridge (located at x=476790, y=981229, z=2038m) have been identified. The wellfield is characterized by multi-layered aquifers where the confining layers are considered to be massive basalt and paleosols. The depositions of alluvial materials between volcanic materials result in large and complex hydrogeological conditions with variable and unpredictable lithostratigraphical correlation. The following figures of cross-sections show how the hydrostratigraphy of the wellfield looks like by constructing diagrams from boreholes along NW-SE and E - W sections of the wellfield (see Fig. 23 for the location of the cross-sections). For More hydrostratigraphic crossections and well logs of the wellfield, see Appendix 1 and 3.

Based on the chemical and lithological variations, the aquifers are divided in to two broad classes; the upper aquifer (<150m depth) and the deeper aquifers (up to 300m) (Demilie, 2007). The thickness of the aquifer is not known since the drilling was terminated within the water bearing layers of the wellfield. The types of aquifers are identified to be semi-confined and perched (Demilie, 2007).

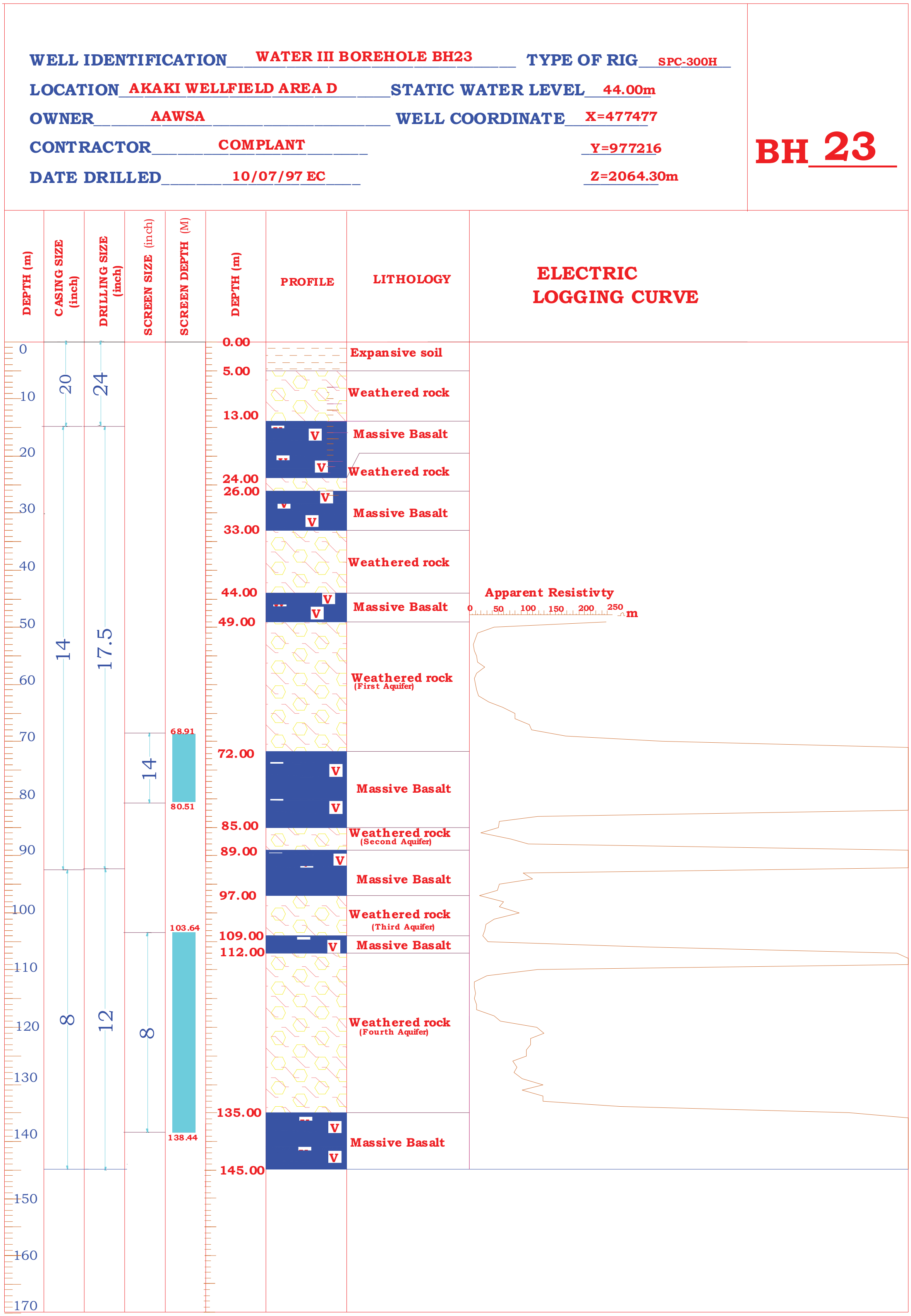


Figure 24. Geological and geophysical log of Borehole 23 (BH 23) in Akaki wellfield

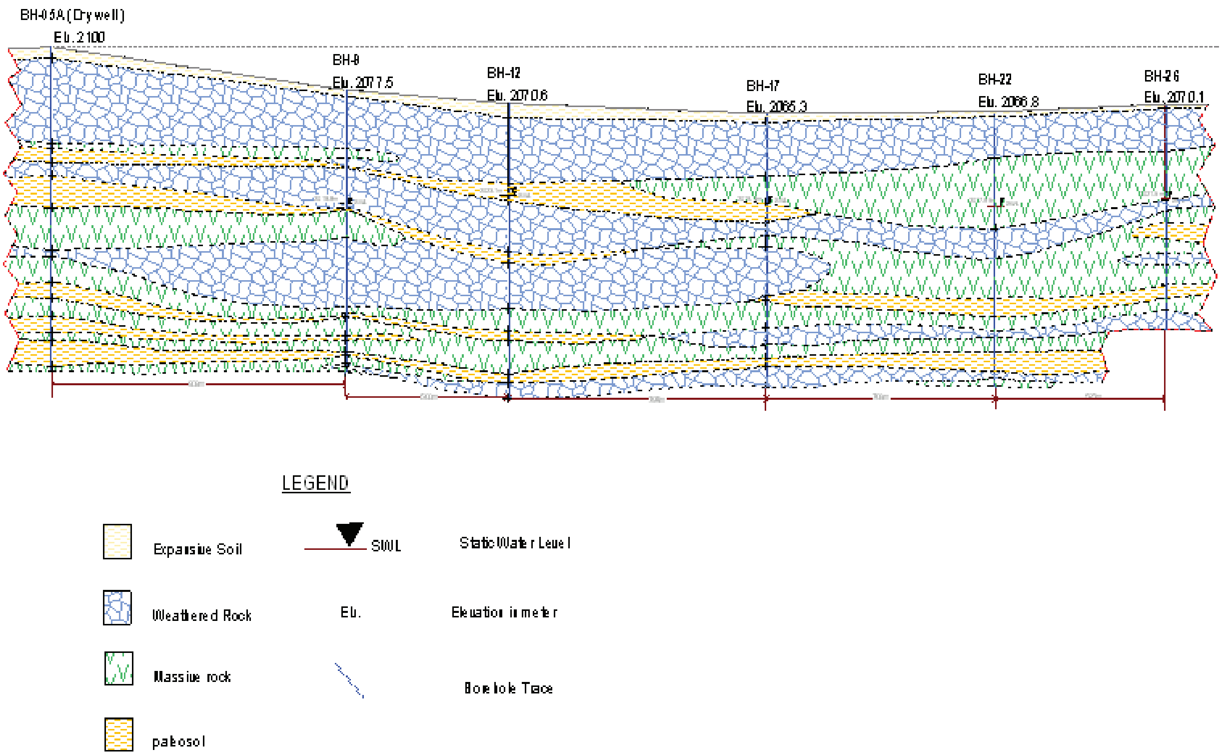


Figure 25. Lithological cross – section along NW – SE in the Akaki wellfield (see Fig. 23)

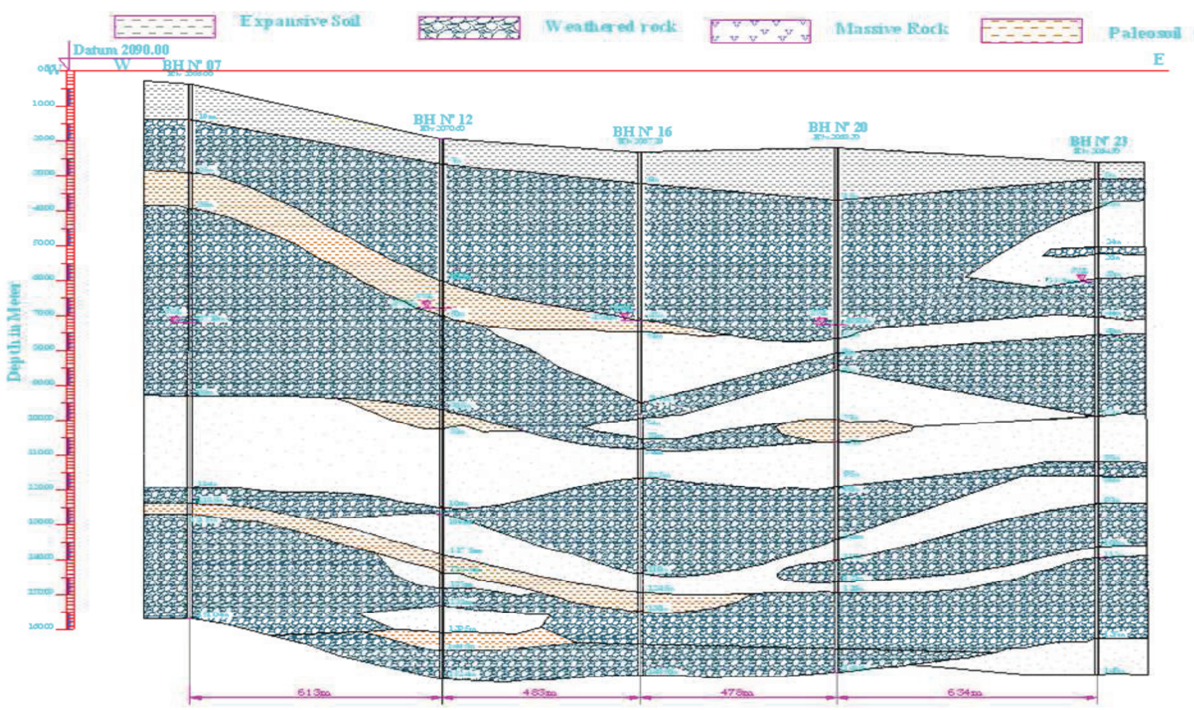


Figure 26. Lithological X- sections along E-W in the wellfield (2.2 km) (see Fig. 23)

2.6.2. Well test analysis

In the Akaki wellfield, standard well tests were not carried out during water well drilling. In some cases data recording have been stopped after a short period of time. In addition to this, partial penetration of wells and uncertain boundary conditions are the main limitations for the right interpretation of diagnostic plots. For example, Aynalem (1999) has identified various types of boundary conditions. These are impermeable boundary in EP4, permeable boundary in BH18, casing and well storage effect in BH12.

For illustration purpose, some semi-log and log-log plots of a few boreholes has been presented below (more pumping test curves are attached in Appendix 7). BH20 shows the leaky aquifer characteristics while BH17 shows behaviour of unconfined aquifers. EP4 deviates from the diagnostic curves, perhaps because of boundaries. The Akaki wellfield aquifer is mainly characterized as leaky-confined to semi-confined.

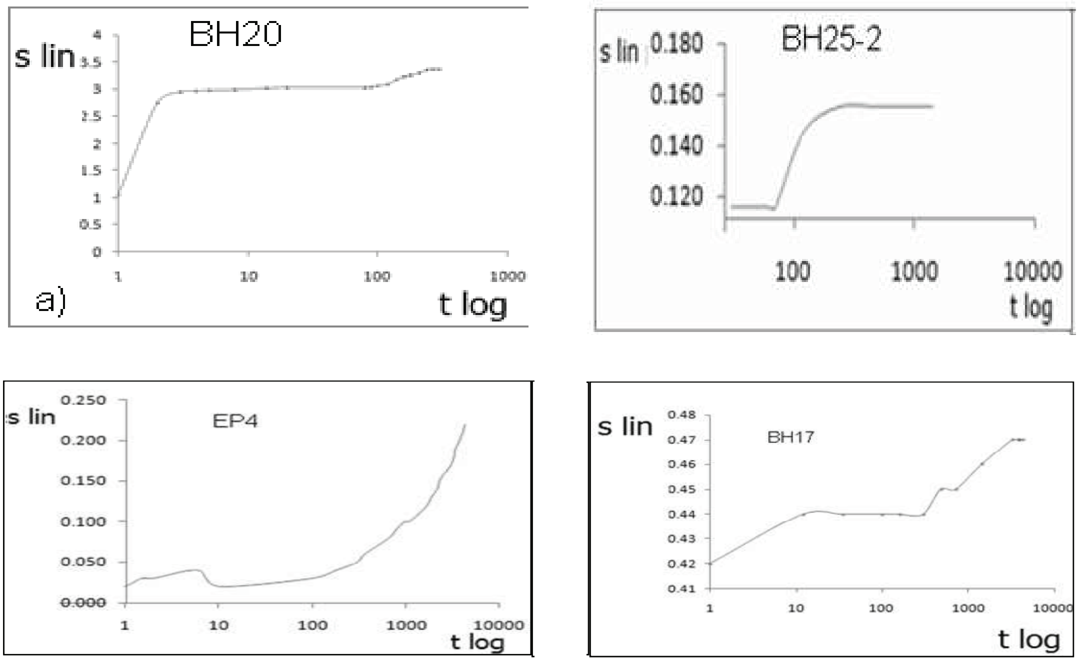


Figure 27. Semi-log plot of time-drawdown curve for selected wells

In the Akaki wellfield, boreholes to the north of Debrezeit road are reported by AAWSA (2000) to be dry and unproductive. This could be because of the deep groundwater level along the Debrezeit highway, since all the units above the static water level are composed of impermeable materials. More observations on the situation here are given by the drilling contractor called COMPLANT during 2001.

2.6.3. Water level and abstraction monitoring

The general trend of the water level evolution in the wellfield from May, 1999 to January, 2002 is presented below in Figure 29. The eleven wells designed for phase I, had been planned to begin pumping between February and June 2001; however, due to technical problems the wellfield was not functional until 30th November 2001. Between 13 and 26 November 2001 trial pumping effectively started on the 30th November 2001 and continued until 24th January 2002 when all the pumps failed and become defective due to technical faults. Because of technical problems only eight out of eleven wells were operational during the commissioning of the wellfield. These pumps have been removed from the wells for replacement and in the mean time four smaller pumps have been air lifted and started pumping from 18th March 2002. Therefore, the pumping at the wellfield can be roughly divided into four periods:

- Low abstraction (Jan 1999-Nov 2001) (5000 m^3/day)
- Run trials (13 to 26 November 2001)
- Test by AAWSA (30th November 2001 to 24th January 2002) (25000 m^3/day)
- Exploitation by AAWSA, which started from 18th March 2002 (>40000 m^3/day)

Table 6. Summary of Phase I abstraction at Akaki Wellfield. (Nov 2001-Apr 2002)

	Volume pumped (m3)	Average discharge rate (l/s)	Contribution out of the total pumped (%)
BH12	328943	26.0	16.3
BH09	491882	39.0	24.4
BH16	436396	35.0	21.6
BH17	410221	33.0	20.3
BH14	82434	6.5	4.0
BH08	227216	18.0	11.3
BH22	28287	2.2	1.4
BH18	12053	1.0	0.6
Total	2017435	160	100

Piezometers located around the wellfield were monitored to measure the piezometric impact (drawdown) of the wellfield in operation. The data collected are used to identify directly hydrodynamic parameters of the aquifer near the wellfield and above all to calibrate more accurately the model. More than 4000 water levels have been collected since June 1999 to end of April 2002 (including the monitoring data obtained from AAWSA between May 1999 and June 2001). Since the monitoring has started before the start of the pumping operation, the data shows clear picture of the groundwater level evolution. When the wellfield was pumped, around 20 piezometers were measured weekly and daily.

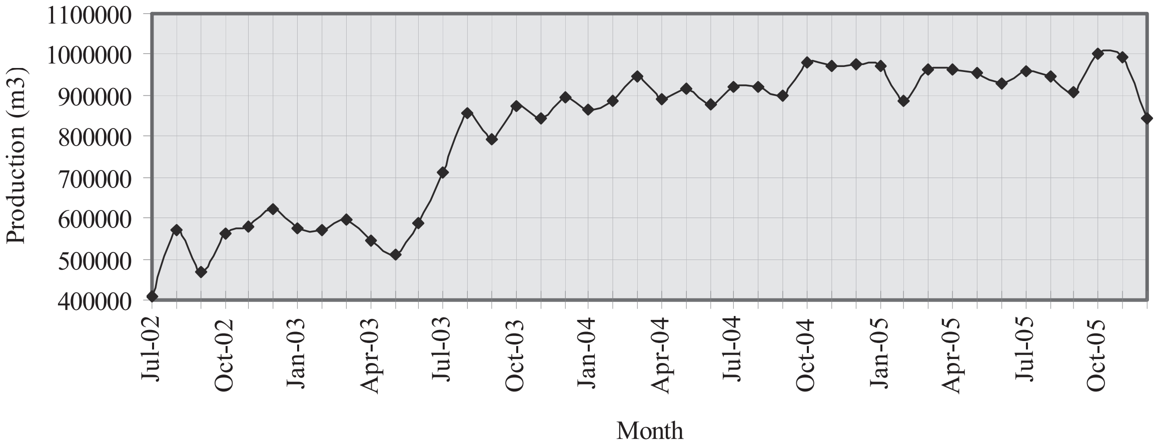


Figure 28. Akaki wellfield actual monthly production from July 2002 – October 2005

Table 7. Annual production figures of the Akaki Wellfield (2002-2005)

No	Year	Yearly Production (m^3)	Monthly average (m^3)	Daily average (m^3)
1	2002	3210296	267525	8917
2	2003	8368264	697355	23245
3	2004	11054472	921206	30707
4	2005	11323801	943650	31455
5	2006		0	0
6	2007		0	0

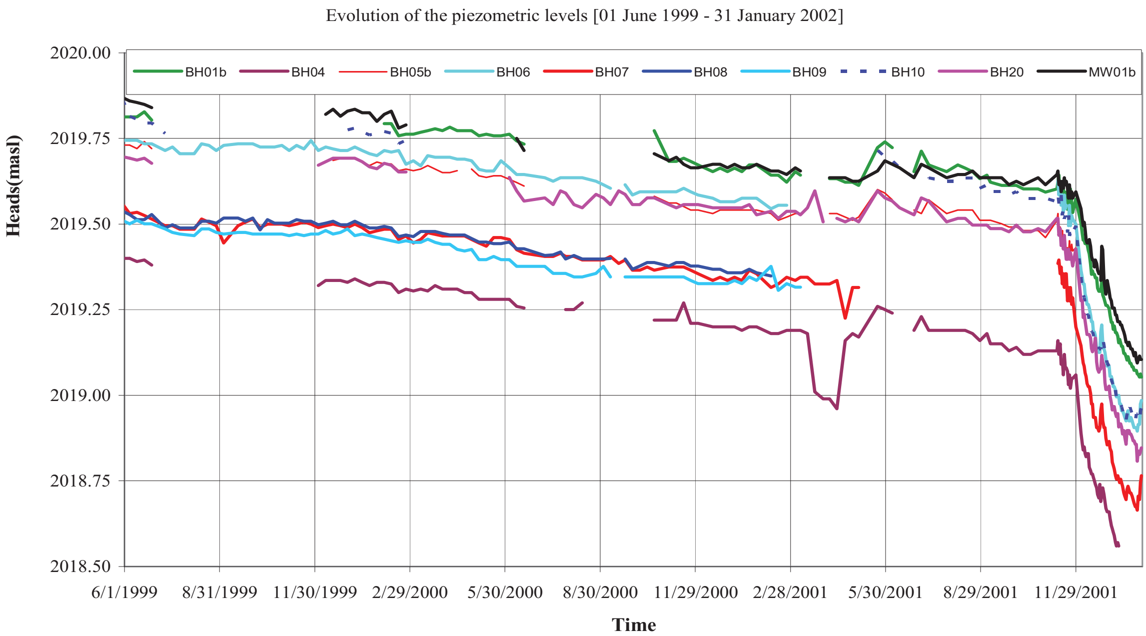


Figure 29. Evolution of groundwater levels from May 01, 1999 to January 24, 2002

The response of the water level in the wellfield during the rains and after the rainy season is not significant although some small peaks appear between July and September (Figure 29). The water level shows continuous decline with little peaks in the months between July and October. In general over the last 3 years the water level in the wellfield declined for an average of about 0.15m. The change in the groundwater level during the pumping period for 56 days (beginning of 2002) is shown in Figure 30. The groundwater level declined with higher slope until the 24th of January corresponding to the high rate of pumping (average of 260 l/s). After stoppage of pumping for 53 days the level tends to recover to its natural value, however the recovery rate was slow and it did not recover to its original level before beginning of pumping. The water level again started to decline after March 18th (beginning of the second pumping period) with a smaller slope as compared to the first pumping period because of the smaller abstraction rate about 193 l/s.

The situation became more steady after the well testing in the beginning of 2002. As can be seen from the water level data logger shown in Fig. 30, continuous decline of water level for one meter is identified between the periods of August, 2002 to Sept, 2004. From September, 2005 to November, 2005 The decrease in water level is in the order of 2 m/year or slightly less due to 950000 m^3/month.The continuous decline without much fluctuation seems to indicate that seasonal recharge effects are not important in the wellfield area or abstraction is much larger than recharge.

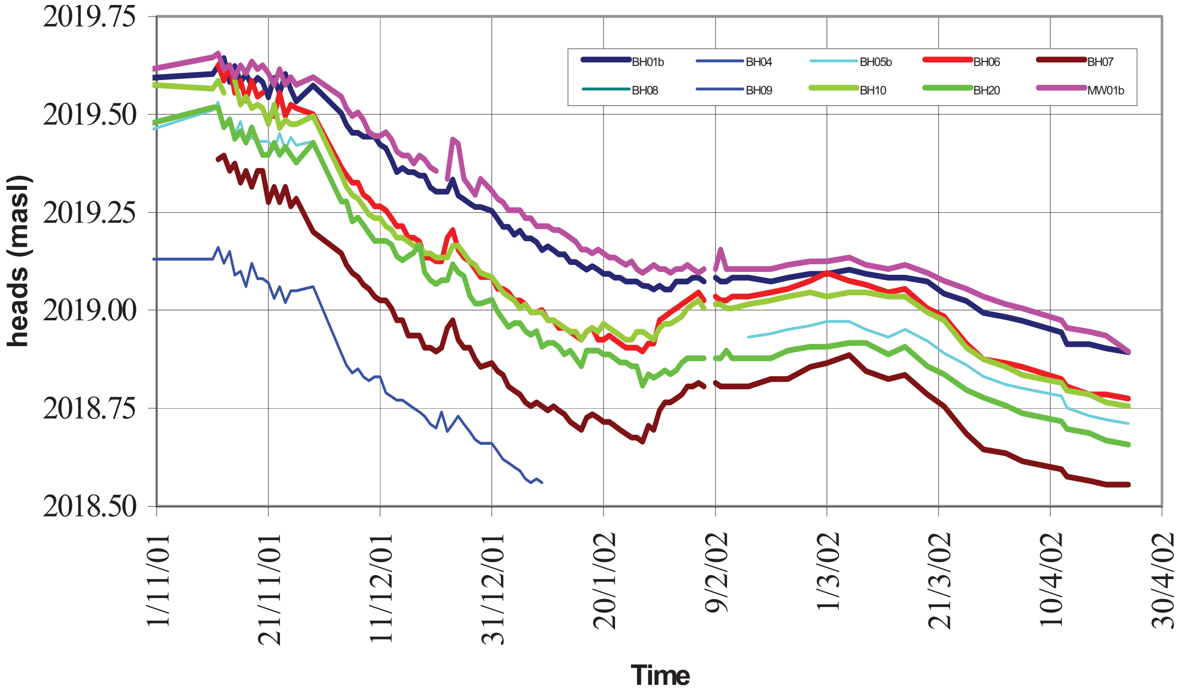


Figure 30. Evolution of the piezometric levels during the pumping (1/11/2001-30/ 04/2002)

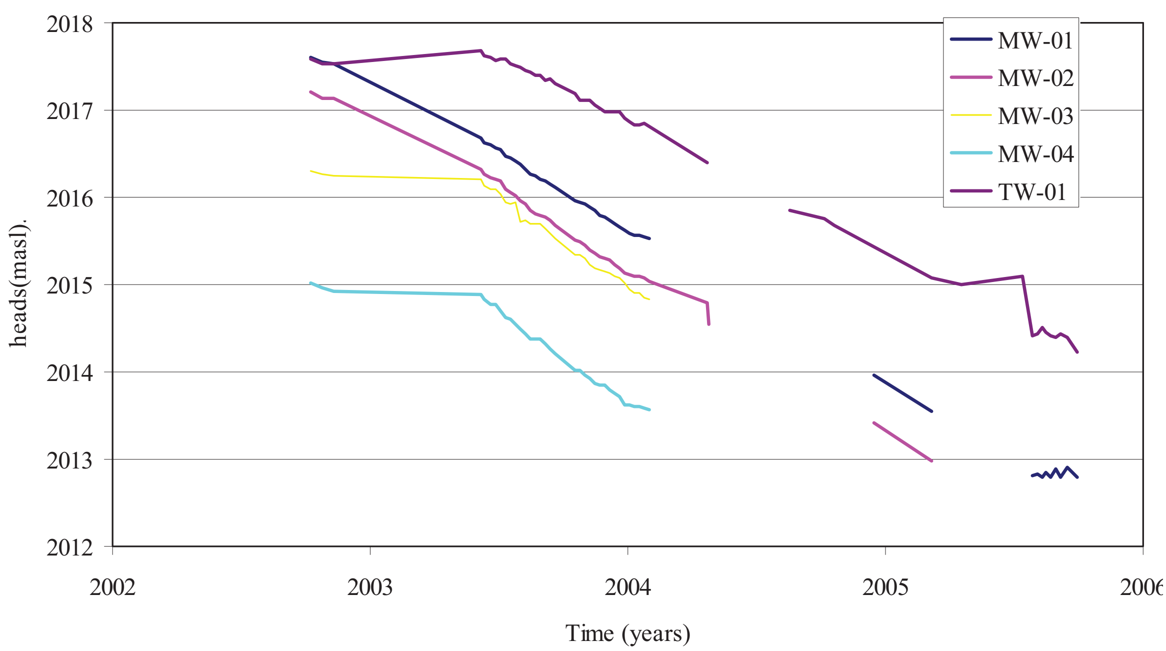
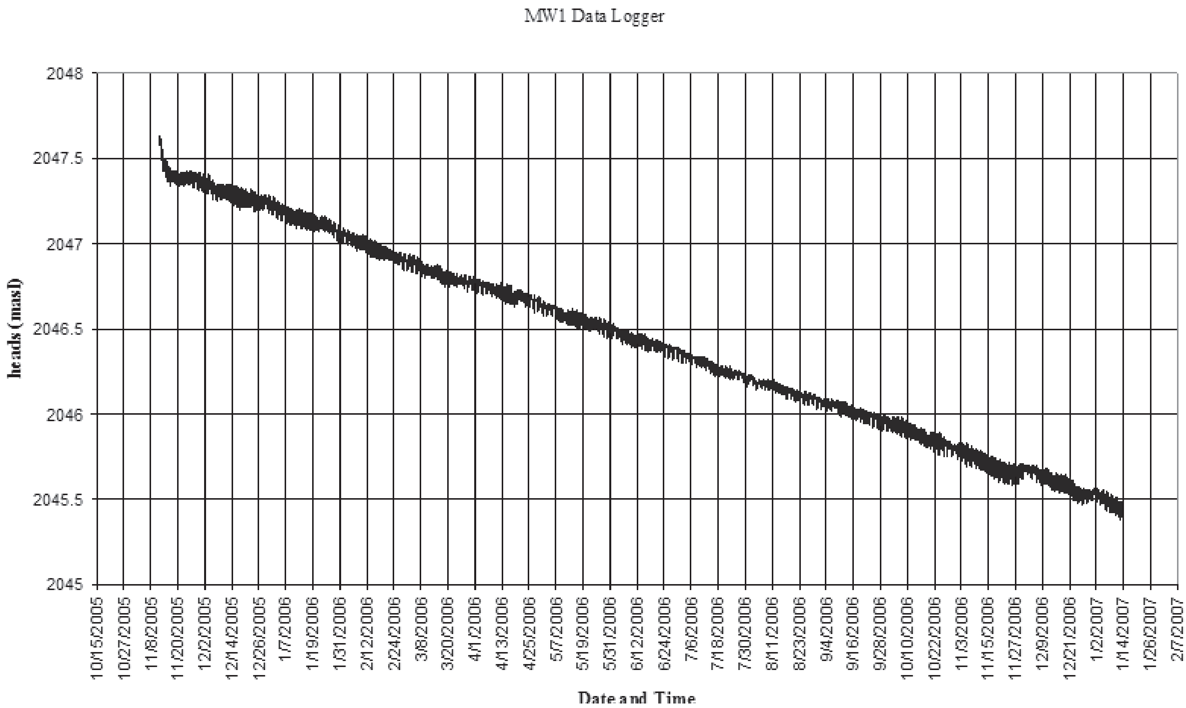


Figure 31. Akaki wellfield water level monitoring report, 2002 to 2006, (see fig.23).



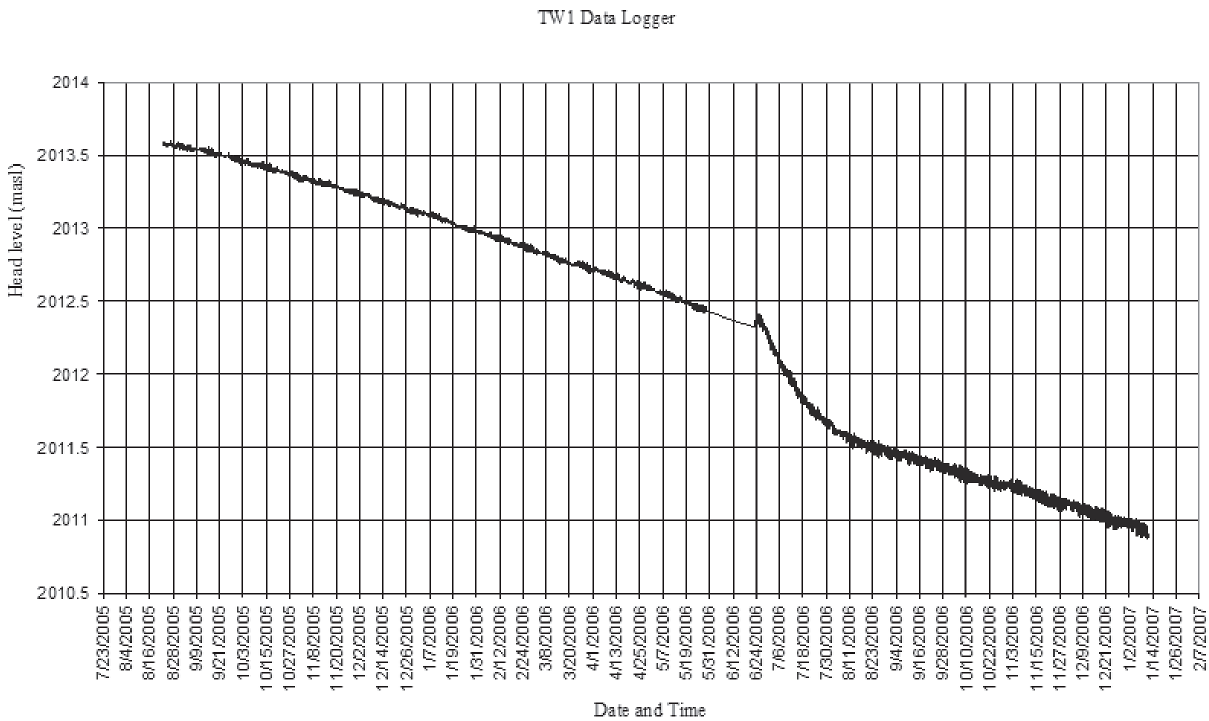


Figure 32. Hydrographs of MW1 (top) & TW1 (2005 - 2007 (bottom)

3. Groundwater flow modelling of Akaki catchment

3.1. Introduction

Groundwater modelling is used to make predictions about a groundwater system's response to a stress, to further increase our understanding on the hydrological system in the catchment and its wellfield. The groundwater model was used as a tool for understanding the system, its behaviour and for predicting its response to external stresses. The developed model serves as a tool to improve our understanding on the catchment's groundwater flow system. In this study, steady state models are developed for the aquifers in the Akaki catchment, and the Akaki wellfield in particular. The results of the wellfield model will then be used in contaminant transport analysis.

3.2. Development of conceptual model

Completion of model conceptualization process is necessary prior to determining the modelling approach to be used. After building the data base required for the model, the next step is developing a conceptual model. This is the most important part of the modelling process. The key data requirements in the process of conceptualization are selecting data on hydro-stratigraphic units, surface water bodies, recharge and discharge zones. The use of model conceptualization is to create a simplified model of the system to be simulated, by simplifying a system to an extent that a logical model approach with appropriate model algorithms can be defined (Rientjes, 2007). Conceptual model of the catchment in figure 33 describes how water enters an aquifer system, how it flows through the aquifer system and how it leaves the aquifer system.

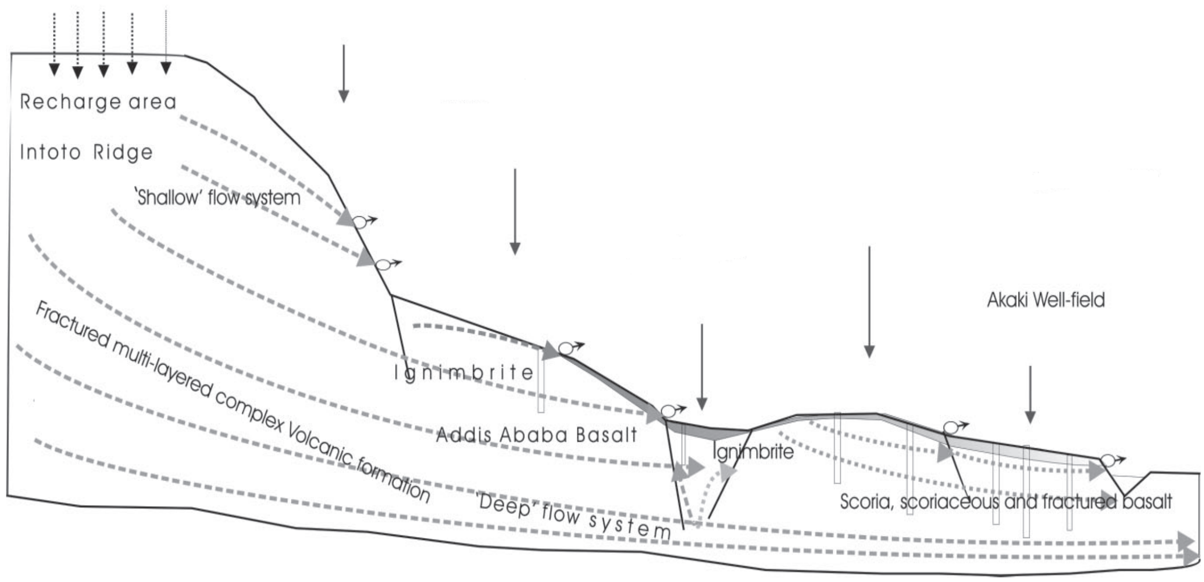


Figure 33. N–S conceptual model of GW flow in the Akaki catchment (Demlie, 2007)

Table 8. . Parameters considered in conceptualization of the system (Aquaterra consultant, 2000)

Feature	Description	Comment
Boundaries	Location and type of boundaries for the area to be modelled	Boundary types include specified flow, specified head, and head-dependent flow, etc
Geological framework	Geological units, and corresponding hydrostratigraphic units and model layers, and associated aquifer parameters. Bedrock configuration and aquifer or aquitard characteristics.	Hydrostratigraphic units comprise geological units with similar aquifer properties. Several geological formations may be combined into one hydrostratigraphic unit (or model layer), or a geological formation may be subdivided into aquifer and confining units (or several layers).
Hydrological framework & stresses	Recharge and discharge processes and dominant aquifer flow mechanisms	Definition of aquifer media type (porous medium, & fractured rock), and surface-groundwater interaction processes.
Human-induced factors	Anthropogenic influences on the system	Pumping, drainage, etc.

3.3. General Assumptions

Several general simplifying assumptions are introduced to simulate groundwater flow, and to develop and to calibrate 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 itself and flux boundary is assumed to the north, NE, and NW. Drain package is assigned to small reservoirs.

3.4. Governing Flow Equations

The three-dimensional finite-difference groundwater flow model of Harbaugh et al., (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. Steady state and transient flow equations are shown in (2) and (3) respectively.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(kz \frac{\partial h}{\partial z}\right)-W=0 \qquad (2)$$

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t} \qquad (3)$$

Where

H = Potentiometeric head (L);

W = Volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1});

Ss = Specific storage of the porous material (L^{-1});

T = Time (T).

k_x, k_y, and k_z 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});

In general, S_s, k_x, k_y, and k_z are functions of space (S_s=S_s (x, y, z), k_x=k_x (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. Modelling Approach

The Processing Modflow (PM) software (Version pm5), developed by the United States Geological Survey and Chiang and Kinzelbach (1998) 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 modelling software which is an enhanced version of Processing Modflow is developed by Web Tech 360 Inc. in 2002-2003 based on the original work of Chiang and Kinzelbach (1998).

In order to use a finite difference approximation, a grid is superimposed over the digital elevation model 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. The finite-difference method is used to compute the average head value in all model cells. 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 requires the use of consistent units throughout the modelling 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 (ms^{-1}), and pumping rates will be in units of (m^3s^{-1}).

3.6. Geographic Extension of the model

The model area encompasses the limits of the regional flow system of the Akaki river and to the south extended up to the Abba Samuel gorge. The northern, western and eastern catchment boundaries of the Akaki River are taken as no-flow boundary. General head boundaries are used at the outlet of the catchment below Abba Samuel lake at the gorge where springs are emerging to simulate the amount of water flowing out of the catchment.

3.7. Spatial discretization of Model Grid

The catchment boundary was delineated by the application of DEM hydro processing package in ILWIS software. The extraction operation constructs catchments: these are calculated for each stream found in the output map of the drainage network ordering operation (ITC, 2001).

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 (Lubczynski, 1997, Rientjes, 2007).

The model area encompasses the limits of the flow system of the Akaki river and extends up to Mt. Bilbilo and Guji to the south. The model spans an area of 1500 km². The model grid consists of 150 columns and 135 rows with 20250 active cells and regular grid spacing of 400 m x 400 m. The geographic boundaries of the model grid were determined by using ASTER DEM as background map. The image map was projected in metric coordinates (UTM) and Adindan datum, and then imported into MODFLOW. A finite-difference grid superimposed over a 1500 km^2 area was designed and constructed based on the simplification of a conceptual model representing the physical properties of the groundwater system.
Fig. 34 represents this three dimensional conceptual geospatial model frame work showing the number of columns, rows and layers used in the current model.

3.8. Model structure

The aquifers within the model area are very complex and cannot be separated and it is assumed that they are hydraulically connected. The geological logs of the boreholes and cross-sections in the model area and the wellfield show high irregularity of different lithological units. They do not have sufficient extent to justify a multilayer representation of the reservoir. Also due to the fact that the study is for long term pumping, it is assumed that multilayer effect will have very little consequence on the outcome of the model. Therefore, a single layer structure is adopted for the model. The horizontal variation can be accommodated by the variable hydraulic properties. Although there is vertical variability it is not considered in the model.

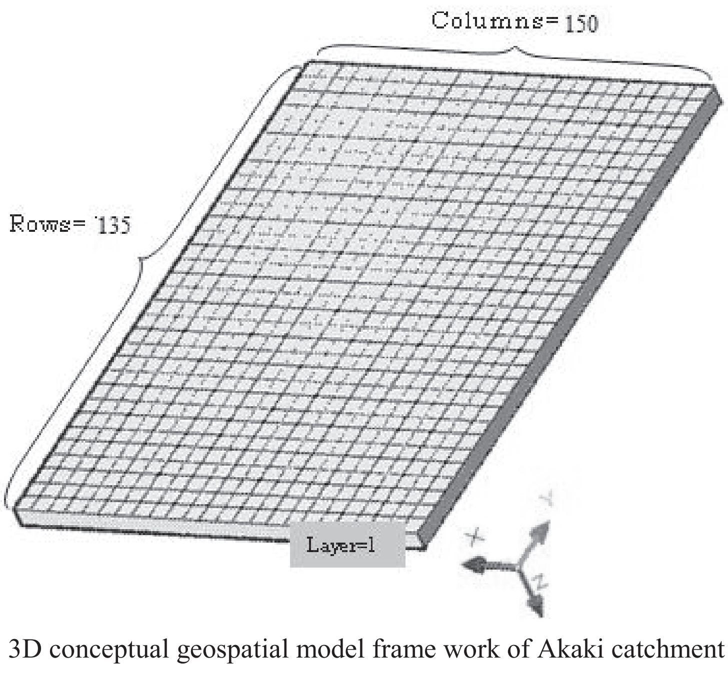


Figure 34. 3D conceptual geospatial model frame work of Akaki catchment

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 geometry of the aquifer systems in the catchment area is highly variable, and discontinuous. Nevertheless, the model was developed with a single layer for the following reasons:

- The aquifer in the area, particularly the scoria and scoraceous basaltic lava flows are not a single continuous unit. They consist of small discontinuous patches representing local flows. Therefore their effect disappears on a larger scale.
- The water level of the aquifers deeper than 170 m rises and maintains the regional water level elevation around Akaki Wellfield. 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 and at this stage it is not practical to treat them separately as individual layers.
- The available data show that the geological conditions are very complex and assumption of different model layers is impossible because of
    - The non uniform and highly variable and complex nature of volcanic aquifer related to lava flows
    - The fracturing of the rocks
    - The scarcity of adequate well test data from subsurface geological layers separately
- Vertical flow is assumed to be negligible since one aquifer system/single layer is considered.

3.9. Physical parameters of the system

The model should generally have values specified initially for all necessary parameters. The spatial input variables are initial hydraulic head, horizontal anisotropy, horizontal and vertical hydraulic conductivities, recharge, discharges, and effective porosity. Therefore, values were assigned to each active grid cell, based on its location within the study area.

3.9.1. Initial hydraulic heads

Initial conditions refer to the hydraulic head distribution in the system at the beginning of the simulation (Anderson and Woessner, 1992). For the present case, the static water level records of the wells are interpolated within the model to obtain the initial hydraulic heads for the entire model. Initial hydraulic heads distribution in the study area was obtained from the well database in the area.
The hydraulic heads distribution was interpolated first using ILWIS and imported to MODFLOW at the beginning of the model run and each cell in the model was assigned its head value. This initial data can also be interpolated using kriging method (Harbaugh et al., 2000) in MODFLOW.

The ground elevations at each model cell are extracted from corrected ASTER DEM of the area, and then depth-to-static-water level values from the well database 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. Similarly, other input maps are prepared by using ILWIS software and are loaded to MODFLOW in the form of matrix to be used in modelling process.

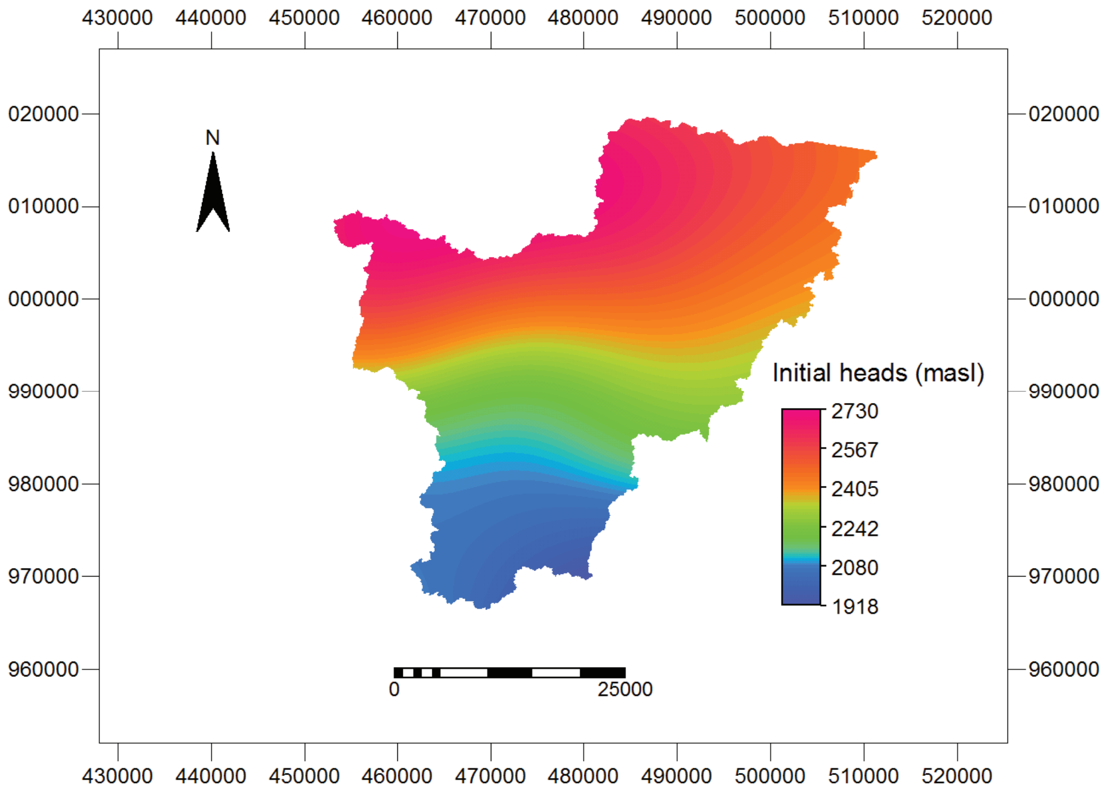


Figure 35. Initial hydraulic head values of the catchment

3.9.2. 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.

3.9.2.1. Horizontal Hydraulic Conductivity

One of the important hydraulic parameters required for a steady-state groundwater flow model is either transmissivity or hydraulic conductivity in a distributed fashion cell by cell across the model grid. Zonation for the input parameters was carried out based on geological information, point hydraulic conductivity and transmissivity data of the pumping tests. Initially, the hydraulic parameters estimated from pumping test results of previous studies were applied; later the parameters were adjusted during the calibration process.

To specify the horizontal hydraulic conductivity, initially the hydraulic conductivity map was produced from hydraulic conductivity values of boreholes distributed in the area. The hydraulic conductivity data were assigned by interpolating the pumping test data in ILWIS and classifying certain zones based on the geology, hydrogeologic and geomorphologic conditions (Fig.36).

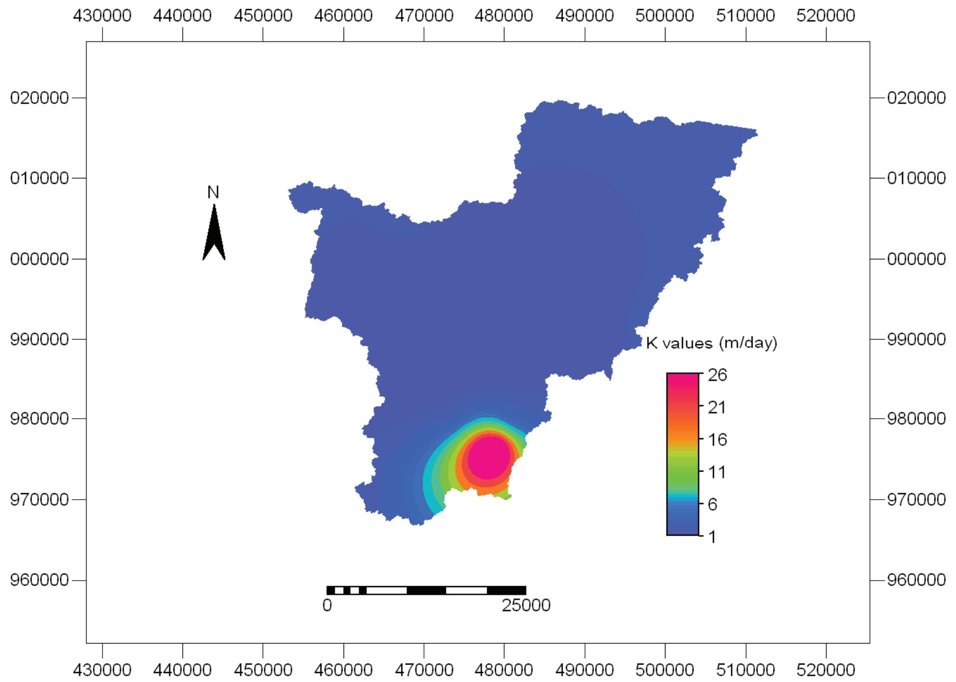


Figure 36. Hydraulic conductivity values of the catchment

Then, the map is overlaid on the model grid, and then obtained respective average values are assigned to each model cells. Higher hydraulic conductivity values are obtained in the wellfield (26 m/day), Smaller values are obtained north, northeast, and west of the wellfield with the minimum value reaching 1 m/day (see Fig.36).

3.9.2.2. 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 ith 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. Because of this, vertical hydraulic conductivity is not required for this single layer models.

3.9.3. Horizontal Anisotropy

Horizontal anisotropy is the ratio of the horizontal hydraulic conductivity along columns to horizontal hydraulic conductivity along rows i.e., the ratio of (K_h) along columns to (K_h) 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. As the result of this, no anisotropy was assumed in the models.

3.9.4. Aquifer geometry

The demarcation of the aquifer extent was made based on the available technical details of the boreholes. Top of aquifer elevation was assigned based on the static water level of the area. The bottom elevation of the aquifer was obtained by subtracting one hundred meters from the top of aquifer.

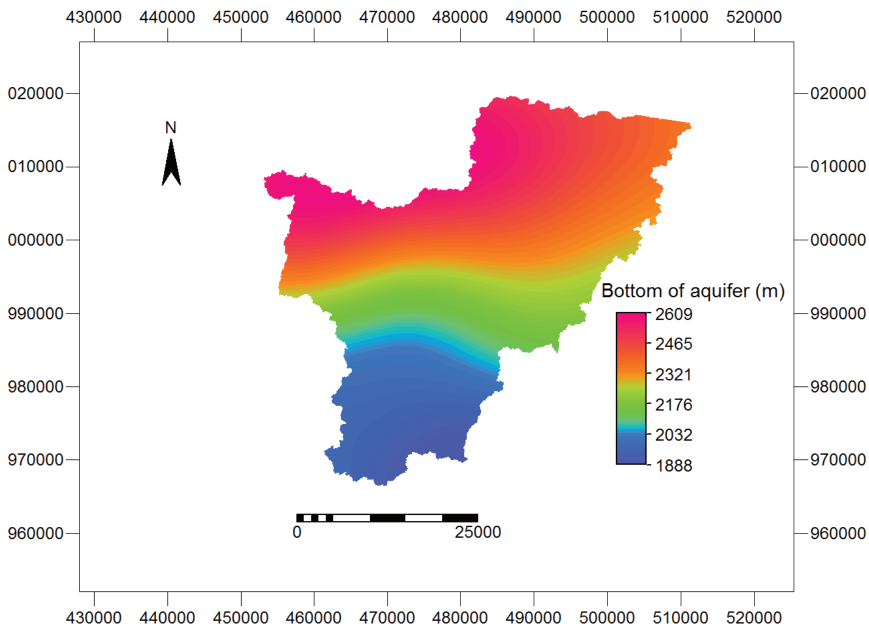


Figure 37. Bottom of the aquifer

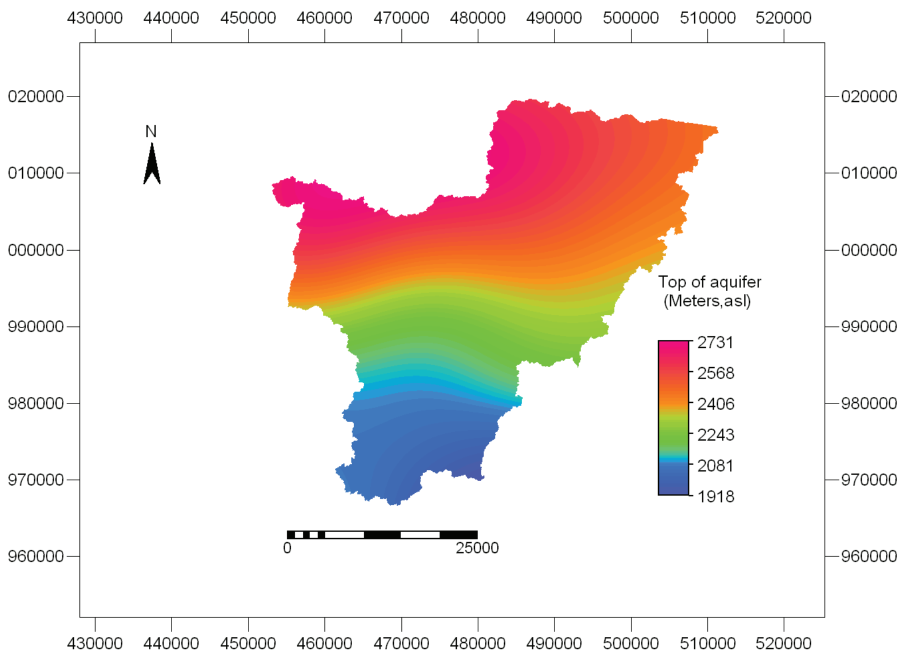


Figure 38. Top of the aquifer

3.9.5. Aquifer thickness

Aquifer thickness of the catchment is obtained by subtracting the top of aquifer from bottom of aquifer. Aquifer is found to have an average thickness of 100m.

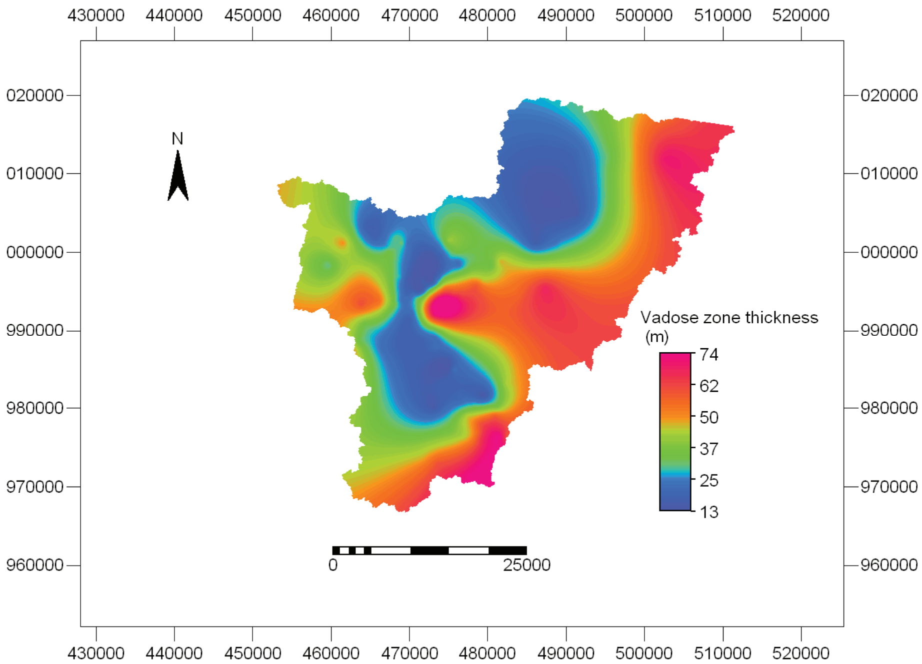


Figure 39. Vadose zone thickness map

3.9.6. Transmissivity

The transmissivity (T-value) calculated from pumping tests in the Akaki catchment and wellfield reveal that it ranges between 6 m^2/day to 105408 m^2/day. To the north of Akaki wellfield and Kality area, T-values range from 3 - 6m^2/day (Yirga Tadesse, 2004 as cited in Gizaw, 2002).

The transmissivity values are converted to hydraulic conductivity by dividing T-values with aquifer thickness. The calculated hydraulic conductivity values vary between 7 to 675 m/day in the wellfield. These values lie in the range of permeable basalt (Aynelam, 1999). Low transmissivity 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 transmissivity towards the wellfield. Therefore, the wellfield has relatively high value but it is surrounded by rocks of low values showing that the highly productive aquifer at the wellfield has very limited extent (Fig.39). Transmissivity values were calculated by Logan's approximation method. according to Logan, 1964, from specific capacity by the following relationship.

$$T = 1.22 * Sc \qquad (4)$$

Where T = Transmissivity (m^2/day) and SC = specific capacity (m^2/day)

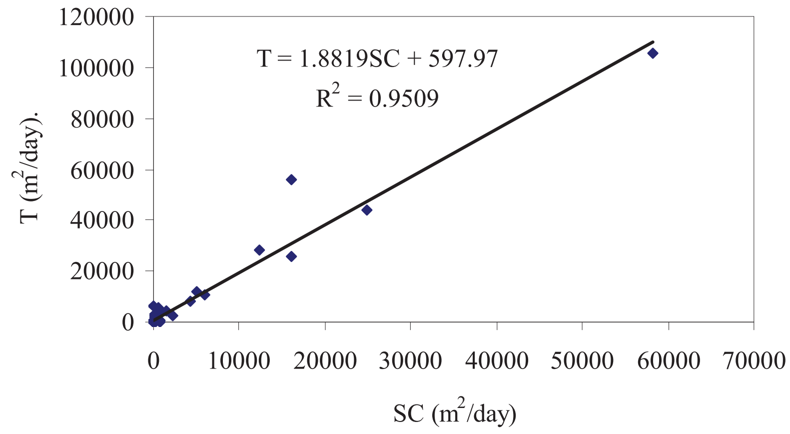


Figure 40. Comparison of Specific capacity and values in the catchment

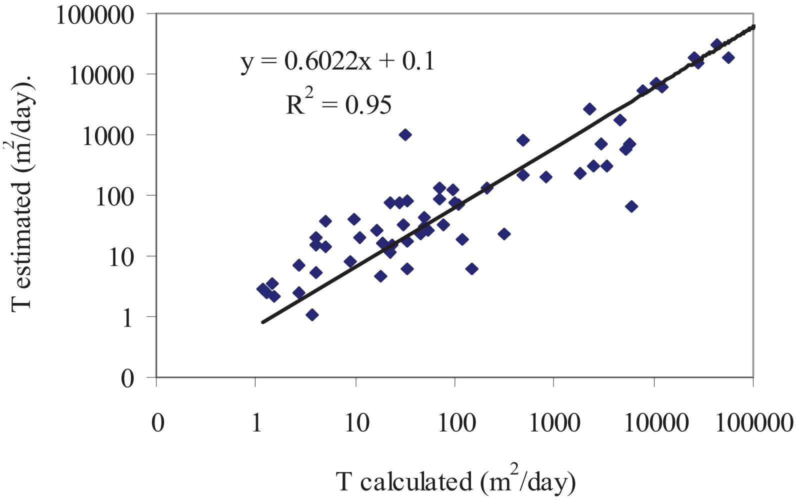


Figure 41. Comparison of pumping test and Logan estimated values in the catchment

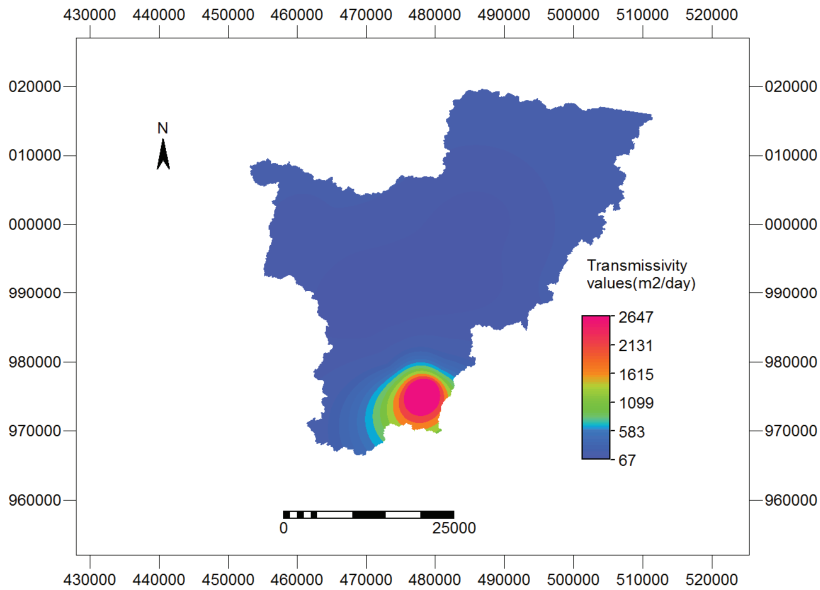


Figure 42. Transmissivity map of the area.

3.9.7. 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 steady state 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 equals to total porosity, because most of them are composed of non-clay minerals coarser than silt and at the same time they are highly affected by tectonics. Though the total porosity of basalt is generally low, fractured and weathered basalt of Akaki catchment area is assumed to have high effective porosity. The scoraceous deposits at Akaki wellfield 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 et al. (2005), 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 30 % is used in the model.

3.9.8. Boreholes and observation wells

Most of the boreholes in the catchment are concentrated on the southern and central part. The data base of the boreholes was collected from the concerned offices in Addis Ababa including AAWSA. There are no proper data base management of the boreholes and it is difficult to obtain a continuous time series groundwater level monitoring for almost all boreholes. In almost all wells, the pumping well serves as an observation well except for six monitoring wells in the wellfield. In the area, the well abstractions were implemented using the well package of MODFLOW.

3.9.9. Model Boundary Conditions

In modelling, we are interested in a specific part from the continuous real world system. Thus, the effect of real world in terms of hydrological influences at the model boundaries must be described. Correct selection of boundary conditions is a critical step in model design (Anderson and Woessner, 1992) , because the boundaries largely determine the flow pattern. In other words, mass exchanges across the boundaries are simulated and hence incorrect boundary conditions generate errors in the water balance of the system under study. In groundwater flow system, we can use physical boundaries including impermeable geologic formations and surface water bodies or hydraulic boundaries that include groundwater divides and flow lines. For the case of Akaki catchment and wellfield, the boundary conditions will be selected based on the actual ground field condition of the site.

For the present study specified flow (no flow) boundaries and head dependent flow boundaries (Cauchy boundary conditions), river and drain packages were applied. A general head boundary package was employed to simulate groundwater outflow through the southern outlet of the basin below Aba Samuel lake for the catchment modelling. General head boundaries are normally used along the edge of the model to allow groundwater to flow into or out of the model under a regional gradient. If the water elevation rises above the specified head, water flows out of the aquifer. The expression applied for the head dependent flow in the general head flow boundary is:

$$Q_b = C_b \times (h_b - h) \quad (5)$$

Qb	=	Simulated hydraulic head (L)
C_b	=	Hydraulic conductance of the boundary (L^2 T^{-1})
h_b	=	Hydraulic head at or beyond the boundary, imposed head,(L)
h	=	hydraulic head in the aquifer (L)

As discussed in the conceptual model formulation, Akaki river is in hydraulic contact with the groundwater. The flow of water between an aquifer and overlying river is commonly simulated using the river package. (See Appendix 10). The expression for which river package is based on is:

$$Q_{RIV} = C_{RIV} \times (H_{RIV} - h) \qquad h > R_{BOT} \quad (6)$$

$$Q_{RIV} = C_{RIV} \times (H_{RIV} - R_{BOT}) \qquad h \leq R_{BOT} \quad (7)$$

$$C_{RIV} = (K \times L \times W) / M \quad (8)$$

Where,

Q_{RIV}	=	Rate of leakage between the river and the aquifer (L^3 T^{-1}),
C_{RIV}	=	Hydraulic conductance of the river bed, (L^2T^{-1}),
H_{RIV}	=	Head in the river (L),
H	=	Hydraulic head in cell (L),
R_{BOT}	=	Elevation of the bottom of the riverbed (L),
K	=	Hydraulic conductivity of the riverbed material (LT^{-1}),
L	=	Length of the river within a cell (L), W is the width of the river (L) and
M	=	Thickness of the riverbed (L). (See Appendix 9 for river package of the catchment)

The recharge to the aquifer from the loosing reaches of the river is assumed to take place by the vertical areal recharge which is part of recharge mechanisms in the catchment.

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. The base of the volcanic aquifer is the basement volcanic rock where groundwater flow is negligible. At the bottom of the layer, the no-flow boundary was assigned assuming that the boundary coincides with the fresh volcanic rocks. On the left hand side of the model (western side), eastern, northern of the model area, no-flow boundary (Q = 0) was assigned. It was assumed that the boundary of the model coincides with the water divides as they are located along topographic high areas.

The river package is assigned to little and big Akaki rivers, which are the main rivers in the catchment. Drain Package is assigned to small reservoirs such as Dire and Gefersa since they are feed by springs. Constant head boundary is given to big reservoirs such as Abba Samuel and Legedadi lakes. These are cells in which hydraulic head is kept fixed at a given value all over the entire simulation time.

Field hydrogeological observations, hydrochemical and isotopic studies indicate that groundwater flows out of the southern tip of the basin (Gizaw, 2002; Demlie, 2007). This area is treated as a general head boundary. General-head Boundary was given to outflow zone below Aba Samuel lake which is out let of the catchment. The large reservoirs such as Aba Samuel and Legedadi are treated as constant head cells. A total of 150 pumping wells are considered with a pumping rate varying between 10 and 7808 m^3/day. There are no recharging wells. 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.

Table 9. Major types of model boundary conditions (Aquaterra consultant, 2000)

Boundary Type	**Technical Description**	**Common Applications**	**Effects of Boundary Condition on Solution**	Comment
Specified Head (the head value is specified and the model calculates the flow across the boundary to or from the model domain)	First Type Or Dirichlet Boundary	Rivers, coastlines, lakes, groundwater divides, known pumping water levels in bores, dewatering targets.	Easiest to solve, but constrains solution to greatest degree (can artificially constrain solution too greatly).	Commonly used because head data can be measured much easier than flow data. It allows an inexhaustible amount of water flow (calculated by the model) into or out of a model.
Specified Flow (the flow value is specified and the model calculates the head at the boundary)	Second Type or Neumann Boundary	Impermeable boundary, groundwater divide or streamline, infiltration source, evaporation sink, lateral inflow or outflow, other known sink or source fluxes (eg. adjacent aquifer or pumping bore)	Moderately difficult to solve, and involves moderate constraints on solution.	The "no flow" boundary is a special version of the specified flow boundary, used to define low permeability formations adjacent to or underlying aquifers, or for streamlines
Head-dependent Flow (model calculates the flow for the given head)	Third Type Or Cauchy (mixed) Boundary	Leaky rivers, drains, flow to or from adjacent aquifers, basement leakage, springs.	Most difficult to solve, and involves least constraints on solution. Can form a very complex and sensitive boundary condition.	Care is required in some cases, as the model calculated flow is subject to a conductance parameter, and this may violate some calibration assumptions.

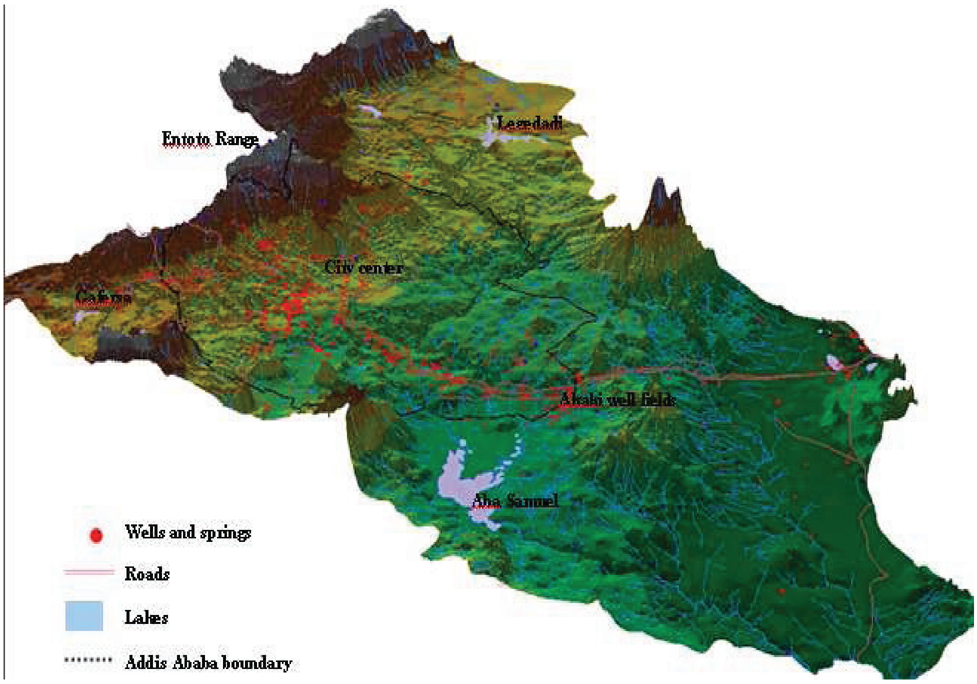


Figure 43. 3D view of the Akaki catchment

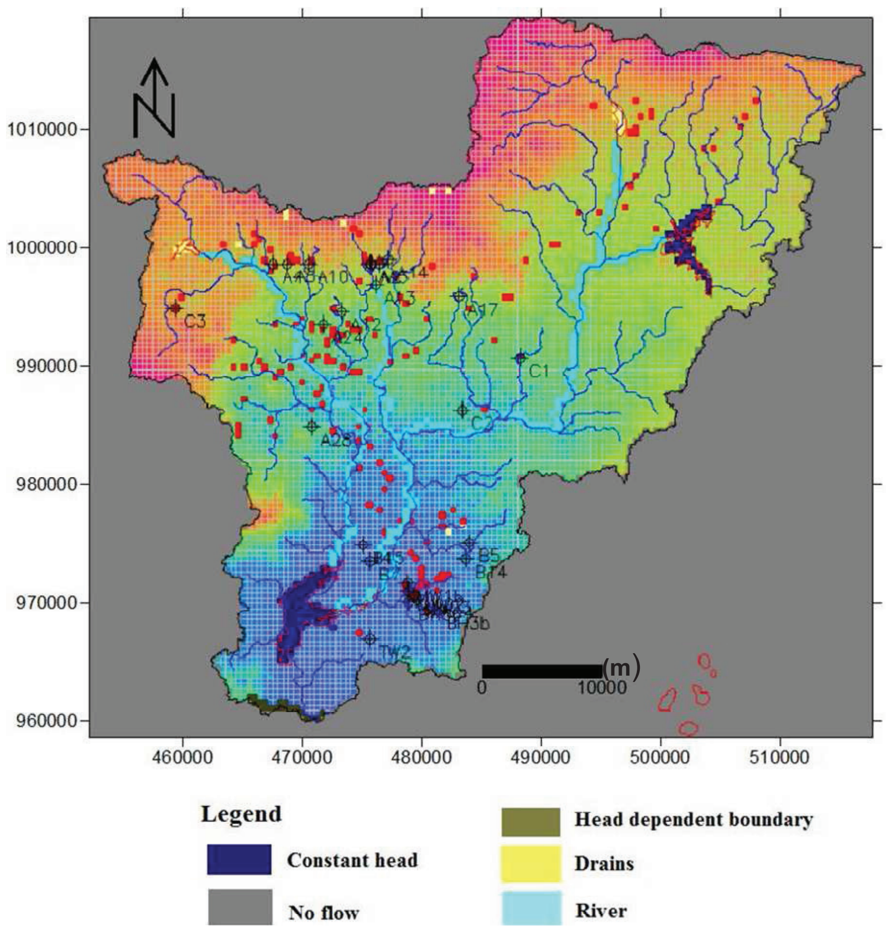


Figure 44. Boundary conditions of the model domain

3.9.10. Sinks and sources of the modelled area

Rainfall is the main source of water to the aquifer system of catchment. Recharge processes are explained in section 3.9.11. Average recharge flux determined by CMB was compared to the other methods. CMB results were compared with other model results and through application of recharge package in Modflow, its average value was assigned to the model. The annual recharge value was converted into daily values.

Evapotranspiration and well abstractions are major sinks of the model for this particular catchment.
Total well abstractions of 23 MCM/yr, which may include private, factory and water supply wells of AAWSA are applied to the model. The current abstractions may be closer to 50MCM/yr but there is no well managed database of current abstraction. Springs and small reservoirs (Dire and Gefersa) are simulated by giving drain package since they are feed by groundwater and used as starting point of rivers.
A head dependent boundary (outflow zone) was placed at Aba Samuel gorge spring sites south of wellfield. Moreover, base flow to the rivers (effect of river heads to surface water) was simulated by river package in the model (see groundwater water balance). Constant head was given to Aba Samuel and Legedadi reservoirs. Groundwater evapotranspiration was ignored since it is assumed that there will not be much groundwater loss from saturated zone in afro alpine climate at mountain top like Addis Ababa and deep rooted trees like eucalyptus trees that are capable of abstracting large amount of groundwater are cut on the past decades. Besides that there is also no data which is available on it in the area.

3.9.11. Recharge

Recharge is often the most important factor in evaluating regional aquifer systems in arid and semi arid environments and it is unfortunately the most difficult to quantify (Wood and Sanford, 1995). Natural recharge to the saturated zone in a groundwater reservoir comes from 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. Recharge is assumed to take place in all areas. A positive value is used to represent recharge into the aquifer system. 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 average recharge is fairly distributed for these seasons with the other months having negligible recharge. Several methods for estimating of groundwater recharge have been developed and can be divided into the physically based and chemical and isotopic methods (Simmers, 1988).

Previous recharge studies in the catchment

Various attempts had been made to estimate groundwater recharge in the akaki river basin (AAWSA-Seureca, 1991; Tahal 1992; AAWSA, 2000). As cited in Gizaw (2002), an earlier estmate (Tadese Belachew, 1975) assumed that the net replenishment in the Aakaki basin is 95 mm, i.e. 7.3% of mean annual rainfall of 1300mm. AAWSA(2000) estimated the mean annual recharge to be 105.4 mm using a semi distributed water balance equation at annual time scale which is equivalent of 9.6 % of mean annual rainfall in the catchment. Taking the area of the catchment (1464 km^2) direct natural recharge volume is $154x10^6$ m^3. Demlie (2007) was found that the chloride mass balance estimate of recharge in the catchment is 265 mm, which amounts to 24% of the weighted mean annual area precipitation of the catchment. He suggested that the CMB method, with limited data, has over estimated the mean annual groundwater recharge rate. Besides that Demlie (2007), did also groundwater recharge estimation using semi distributed catchment water balance. He obtained total weighted mean annual recharge of 105.4 mm/yr which accounts for 10% of the mean annual areal precipitation. AWSA (2000) found 51 mm/yr of recharge with a semi-distributed water balance model as will be discussed later.

3.9.11.1. Groundwater recharge estimation by chloride mass balance method (CMB)

Groundwater resource studies require the estimation of the quantity of water moving downwards from the soil zones as a potential recharge (Rushton et al., 2006). Yongxin and Beekman (2003) stated that the chloride mass balance method was applied for recharge estimation worldwide in recent time. According to Simmers et al. (1997), chloride is the most important environmental tracer and has been used to estimate rates of groundwater recharge under a wide range of climatic, geologic and soil conditions. The most widely used chemical technique to estimate groundwater recharge is the Allison and Hughes (1978) developed chloride mass balance technique based on earlier work by (Eriksson, 1969 and Gieske, 1992). This method is inexpensive, easy to use and gives reasonable results when reasonable data is available. However, the method has its own limitations. It can not be used when other sources of chloride other than only from meteoric water are present in the subsurface; such as from saline water or from dissolution of evaporates (Beekman et al., 1997). The chloride mass balance method is applicable to various environments (Gieske, 1992).

The method has several shortcomings, one of which is that the method cannot be used in environments affected by other sources of chloride other than total atmospheric fallout. Thus the following assumptions are made to apply the method.

- Chloride is conservative and will not undergo any chemical reaction with the geologic material.
- Precipitation is the only chloride source in groundwater

The basic equation used to calculate the annual groundwater recharge with the assumption negligible chloride dry deposition in an area is based on equation 9.

Chloride in rainwater and groundwater

The chloride concentration in the rainwater and groundwater of the study area that are collected from the catchment in Sept. 2008 are analysed in ITC, the Netherlands for the determination of recharge in combination with the chlorides of 2008 determined by Demelie (2008).

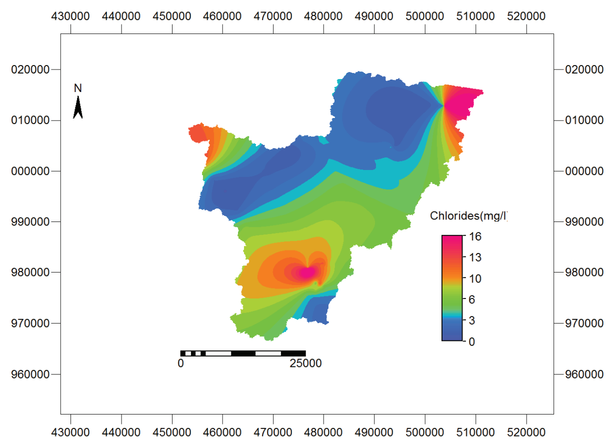


Figure 45. Chloride map of groundwater in the Akaki catchment

3.9.11.2. Basic assumptions of chloride mass balance

The chloride mass balance is used to estimate average areal recharge to a groundwater basin. The underlying assumptions for this method are:

- The only source of chloride is rainfall
- Chloride ion is not leached from the aquifer formation
- The chloride ion behaves conservatively under steady state conditions and there are no sources and sinks for chloride ion,
- Recharge to the aquifer is only by direct precipitation on the surface and subsequently recharge through unsaturated zone which assumes that rainfall is not carried out of the catchment by runoff,

Chloride meets these requirements since it is a conservative ion not taken up nor is it leached from vegetation or aquifer formations in the study area in significant amounts. It is assumed that the cities effluents, approximately 50 MCM/yr, are mainly drained by surface runoff. 10 % of the effluents is assumed to be recharged back to aquifer (Tamiru, 2001). Up to today except 1000 tones per year from the city resulting from urban return flow, no sources or sinks of chloride have been reported in the study area. According to Edmunds et al. (1994) nutrient cycling of plants may interfere with the movement of the solutes on the annual basis. However a steady state condition may be assumed in areas with stable landscape, so that there is a balance between solutes removed by plant uptake and the amount of solutes created by plant decomposition. This assumption only holds when there is no addition from fertilizers or permanent removal by crop harvesting or transfer by grazing animals (Obakeng, 2000). When there is a balance between the chloride flux at the surface and chloride flux below the evapotranspiration and mixing zone, and the above discussed assumptions are met, the following mass balance excluding dry deposition term was defined (Eriksson, 1969):

$$P \times Cl_p = R_T \times Cl_{gw} \tag{9}$$

Where
P = Precipitation (mm/yr)
Clp = Chloride content in rainfall (mg/l)
R_T = Total recharge rate (mm/yr)
Cl_{gw} = Chloride content in groundwater (mg/l)

Different flow components in the unsaturated zone contribute to the chloride concentration in the groundwater. Total chloride deposition comprises both wet and dry deposition. Wet deposition refers to a chloride content in rainfall while dry deposition is the chloride that falls with dust and aerosols during dry season. Dry deposition can be estimated by rinsing the rain gauge or totalizer with deionised water during dry periods (Gieske, 1992). Eriksson (1985) stated that the average groundwater chloride content is calculated as harmonic mean of chloride concenterations. The formula is given by equation 10.

$$Cl_{gw} = \frac{N}{\sum_{i=1}^{N} \frac{1}{Cl_{gw}}} \tag{10}$$

Where
Cl_{gw} = Groundwater chloride concentration of samples (mg l^{-1})

N = The total number of observations

Based on the collected groundwater samples, the mean, maximum and minimum chloride content in the groundwater of Akaki catchment is 6.9, 23.7 and 0.6 mg l^{-1} respectively.

Based on the method, the following results are obtained:

- Average chloride concentration in rain water (0.8 mg l^{-1})
- Harmonic mean of chloride content in groundwater (3 mg l^{-1})
- Average annual rainfall (1224 mm/yr)
- The estimated recharge based on CMB is 326 mm $year^{-1}$ which is 24 % of the average annual rainfall, which in turn is 1224 mm/yr, in the area.

Thus the estimated recharge may range between 272 to 410 mm/yr depending on the range of chloride concentrations in both rain and groundwater. This figure sets the upper limit to the recharge because effluents from the city are also infiltrating to groundwater elevating the chloride contents. Hence recharge is overestimated by this method for this particular catchment. Furthermore, part of the chlorides released from effluents is flushed out by surface runoff.

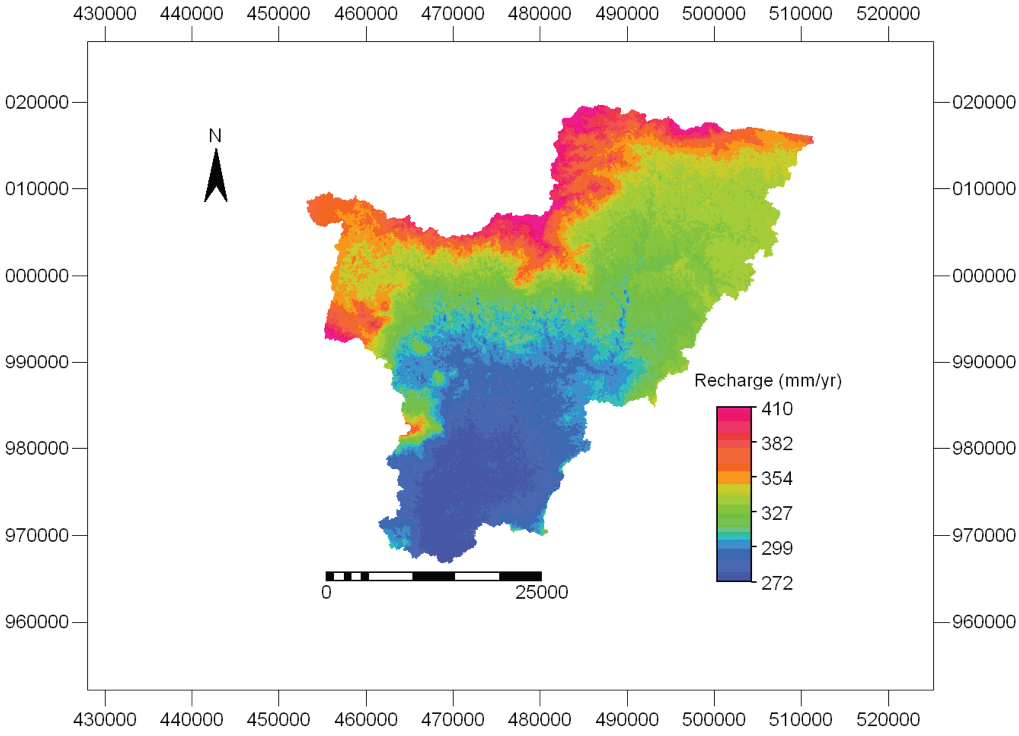


Figure 46. Spatial distribution of groundwater recharge

Despite the fact that the method is simple and inexpensive, there are a number of uncertainties associated with the method in estimating recharge. Given that input chloride concentrations can vary significantly from site to site within a region of investigation, it is not surprising that CMB estimations are site specific (Yongxin and Beekman, 2003). In most cases, the long-term average chloride in rainfall is not available. Measured atmospheric input of chloride, often only short term records of chloride is assumed to be representative for a long period. But an area of concern as rainfall and chloride deposition during the past may be different from today. As discussed by Yongxin and Beekman (2003), other areas of concern include the uncertainty in the measured chloride content of rainfall and rainfall amount. The largest uncertainty associated with recharge estimation that utilises the chloride mass balance approach is the determination of chloride concentration in the rainfall. Furthermore rainfall amount is generally difficult to measure, and is highly variable. The absence of long-term rainfall quality data in the present study is one of the main limiting factors affecting the accuracy of the method. Another uncertainty source for the chloride mass balance approach is the sampling density and analysis accuracy of the chloride concentration of the groundwater. As part of the fieldwork, samples from rainwater and groundwater were collected and analysed for their chloride content that are utilised in the chloride mass balance method of recharge estimation.

3.9.11.3. Baseflow separation: digital filter methods (recharge from baseflow)

Baseflow separation from hydrograph deals mainly with dividing the stream flow records into quick runoff and baseflow components. Several base flow separation methods have been developed. One of the methods is the recursive digital filter separation method. This method has been used in signal analysis and processing to separate high frequency signal from low frequency signal (Lyne and Hollick, 1979). The method involves in baseflow separation as high frequency waves which can be associated with direct runoff and low frequency waves with baseflow (Eckhardt, 2005). Thus, the following digital filter equations, obtained from Automated Baseflow Separation for Canadian Datasets (ABSCAN) software, have been used in baseflow separation from total river flow.
Eckhardt (2005) presented general formulation of a two-parameter filter in which the baseflow index, BFImax and the filter parameters α need to be determined.

$$Q_{b(i)} = \frac{(1-BFI_{\max})aQ_{b(i-1)} + (1-a)BFI_{\max}Q_i}{1-aBFI_{\max}} \quad (11)$$

Where α refers to the groundwater recession constant and BFImax sets the maximum value of the baseflow index BFI which is the long term ratio of baseflow to total streamflow. $Q_{b(i)}$ is the baseflow at time step *i*, $Q_{b(i-1)}$ is the baseflow at the previous time step *i-1*, Q_i is the stream flow at time step *i*, BFI_{max} is the maximum value of the baseflow index that can be measured. In fact it is a subjective parameter that needs to be determined based on the type of catchment. Eckhardt (2005) suggested values for his parameter BFImax based on the results obtained in his work in different catchments. He mentioned that BFImax values about 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with porous aquifers, and about 0.25 for perennial streams with hard rock aquifers, but he noted that this should be further studied in order to determine it especially using tracer experiments.

In this study, a baseflow index value BFImax of 0.25 was used as a predicted value in accordance with the Eckhardt's assignment for perennial streams with hard rock aquifers since the Akaki catchment is characterised mostly by fractured volcanic aquifers. Besides that recursive digital filter with filter parameter of 0.995 were used to separate daily stream flow data into direct runoff and base flow. Based on the Eckhardt filter method, the total annual river flow of 540 MCM (360 mm) and total annual baseflow of 95 MCM (63 mm) has been determined by current study. This means that according to this method, the total annual recharge of the Akaki catchment is about 95 MCM (63 mm). (See Figure 47 below)

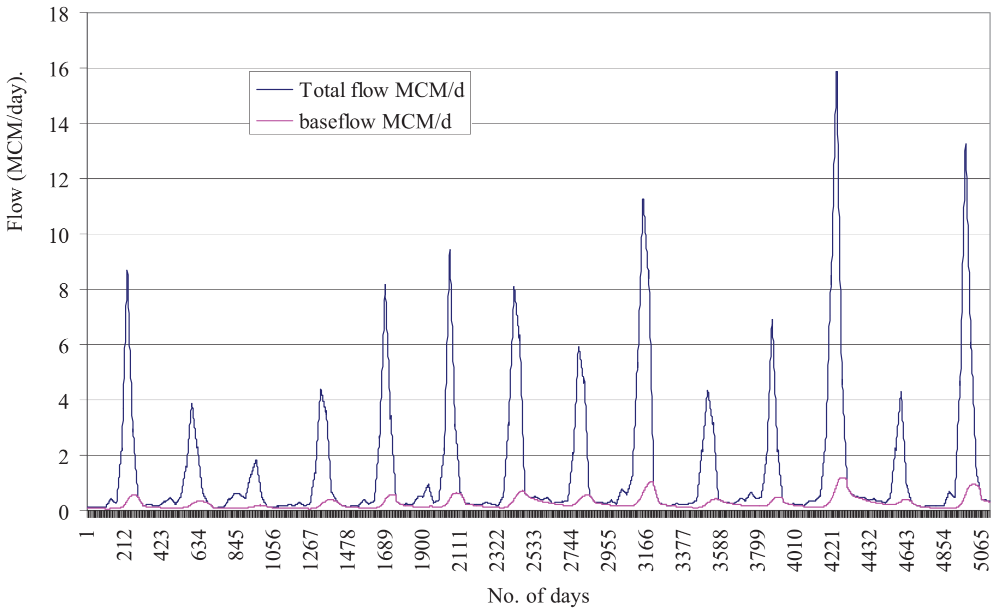


Figure 47. Baseflow simulation from total flow in Akaki catchment

3.9.11.4. Recharge estimation using semi-distributed water balance model

With the aim of estimating groundwater recharge at monthly time step, a semi-distributed water balance model was developed by AWSA (2000). The effect of urbanisation on the hydrological processes is taken care of by considering a portion of the ground surface to be impervious. Rain that falls on impervious surface is assumed to be completely converted into runoff after fulfilling the initial minor losses. Thus, the impervious portion of the catchment area doesn't contribute to both evapotranspiration and infiltration processes. The structure of the model for pervious portion of the catchment is shown schematically in figure 48. In the figure 48, BF stands for base flow, SRO for surface runoff, and RIF for interflow.

The model has three parameters:

SMAX = the maximum water holding capacity of the unsaturated soil
B = the portion of the free water in the soil zone that becomes recharge
CG = baseflow recession constant

The runoff coefficient is considered to be a function of the soil moisture state. Whatever portion of the rainfall that infiltrates into the soil, it will first satisfy the soil moisture deficit. The gravity water in the soil store, which is soil moisture in excess of the maximum amount of tension water, SMAX, will be partitioned into groundwater recharge and interflow (or subsurface flow) based on the value of the parameter B. That is,

```
IF(SM>SMAX) THEN
RECHARGE (RCH) = B * (SM-SMAX)
INTERFLOW (RIF) = SM-SMAX-RCH
ELSE
RCHARGE (RCH)=0
INTERFLOW(RIF)=0
ENDIF
```

It is assumed that the aquifer is always feeding the river in the upper part of the catchment in the form of baseflow, which is estimated, considering the groundwater store to act as a single linear reservoir, as:

BF=BF0*CG + RCH*(1-CG)

Where, BF0= base flow in the previous month

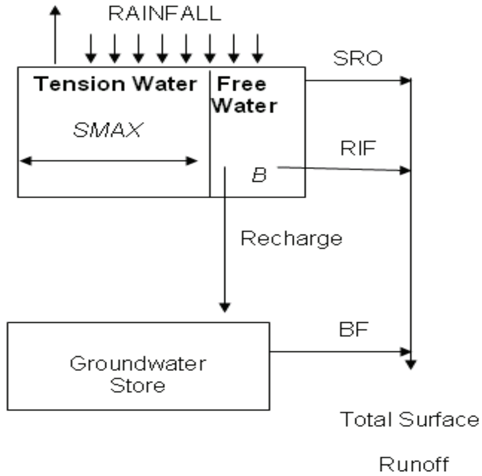


Figure 48. Schematic diagram of the water balance model

The Akaki catchment area up to Aba Samuel hydropower plant is subdivided into nine sub-catchments in order to account for spatial variation of input variables such as rainfall and catchment characteristics (or model parameters). The potential evapotranspiration measured at Addis Ababa Observatory is assumed to apply for the entire catchment, as there is no other Meteorological Station in the region where evapotranspiration is measured. Furthermore, the parameter values are assumed not to vary from one sub-catchment to another for this particular version of the model.

The model is then applied for each sub-catchment and the runoff generated over each sub-catchment is accumulated to yield the simulated flow volume at Aba Samuel. The monthly flow volumes observed at Akaki Bridge have been transposed to the catchment's outlet at Aba Samuel by area ratio method, and these derived values are taken as observed values for the purpose of model calibration and verification. The model is calibrated against eleven years (1985 – 1995) monthly runoff data by minimizing the sum of the square of differences between observed and simulated values, and then verified by using data from an independent period of three years (1996 – 1998). Table 4 gives the optimized values of parameters and the statistical measure of model efficiency in the calibration and verification periods.

Knowledge in groundwater recharge of the catchment is one of the critical parameters required in water balance calculations, which in turn provide valuable information in long-term resource utilization.

Based on the observation of the large spatial and temporal variability in climatic condition as well as soil and land use hetrogeniety, AAWSA (2000) developed a semi distributed monthly water balance model rather than the common empirical methods in a recharge estimation. The recharge estimation has been one of the key factors in assessing the potential of the catchment. Therefore, the assumptions made, the method of calibration and verification, and the results obtained of the study are summarized below.

Assumptions made

- Recharge area: all areas except where low permeable lacustrine clay (Aba Samuel lake, the wellfield, Dukem plain and bole areas) and thick clay soils (Sendafa and Alemgena areas) are widely present. (See Appendix 12)

- Runoff: rain that falls on the impervious surface was assumed to be completely converted into runoff after fulfilling initial minor losses (no infiltration process).
- It was assumed that the aquifer was always feeding the river in the upper part of catchment in the form of base flow, which was estimated, considering the groundwater store to act as a single linear reservoir.
- The potential evapotranspiration measured at Addis Ababa Observatory was assumed to apply for the entire catchment, as there was no other meteorological station in the region where evapotranspiration was measured.
- Further more, the parameter values were assumed not to vary from one sub catchment to other for this particular case.

Modelling

- The Akaki sub-catchment area up to Aba Samuel hydropower plant (see Appendix 12 for map) was subdivided in to nine sub-catchments in order to account for the spatial variation of input variables such as rain and catchment characteristics (model parameters). The model also accounts for transfer of water from one part of the catchment to another and interaction of different land uses with the hydrological processes.
- The model was then applied for each sub-catchment and runoff generated over each sub-catchment was accumulated to yield the simulated flow volume at Aba Samuel.
- The model took aerial average monthly rainfall and potential evapotranspiration for each subcatchment and gives out monthly runoff at the outlet of the catchment and groundwater recharge.

Calibration

- Automatic calibration of SMAX, CG and B is done by means of the simplex method (Press et al, 1986)
- The monthly flow volumes observed at Akaki bridge have been transposed to the catchment outlet by area ratio method, and these derived values were taken as observed values for the purpose of model calibration and verification.
- The model was calibrated against eleven years (1985 – 1995) of monthly runoff data by least square calculations between observed and simulated values, and then verified by using data from an independent period of three years (1996 – 1998)

The efficiency of the model in terms of simulating the observed runoff values was evaluated by the Nash-Sutcliffe coefficient criteria. Efficiencies of 88 and 79 are obtained for the calibration and verification periods respectively.

Results and accomplishments

- Once the monthly recharge series for each sub catchment was generated, the mean annual recharge value for each sub-catchment was computed by summing the whole series and then averaging it over the number of sub-catchments using weighted averages.
- The over all mean annual recharge (infiltration) rate in the Akaki river catchment has been estimated to about 87 mm/year. This figure is higher than 51 mm/yr originally found by AAWSA (2000). But this seemed to be caused by small errors in the FORTRAN code provided by AAWSA (2000).

Nash-Sutcliffe coefficient

Nash-Sutcliffe coefficient measures the efficiency of the model by relating the goodness-of-fit of the model to the variance of the measured data, Nash-Sutcliffe efficiencies can range from -∞ to An efficiency of 1 corresponds to a perfect match of modelled discharge to the observed data. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (-∞<E<0) occurs when the observed mean is a better predictor than the model. Besides, due to frequent use of this Nash-Sutcliffe coefficient, it is known that when values between 0.6 and 0.8 are generated, the model performs reasonably. Values between 0.8 and 0.9 tells that the model performs very good and values between 0.9 and 1 indicates that the model performs extremely well (Deckers 2006).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim(i)} - Q_{obs(i)}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs(i)} - \overline{Q_{obs(i)}}\right)^2} \qquad (12)$$

Where: R^2 : Nash-Sutcliffe coefficient, $Q_{Sim(i)}$: simulated flow, $Q_{obs(i)}$: observed flow and $\overline{Q_{obs(i)}}$: average of observed flow. The value of coefficients for both calibration and verification phases are shown in the Table 10.

Table 10. Summary of results of the monthly water balance model

Optimized parameter values			Model efficiency (R^2) %	
SMAX (mm)	B (-)	CG (-)	Calibration	Verification
292.297	0.99	0.418	87.72	79.14

Figure 49. Compares graphically the observed and simulated monthly flow volumes at Aba Samuel for the entire length of record. As can be seen from this figure the two series match reasonably well particularly in the calibration period.

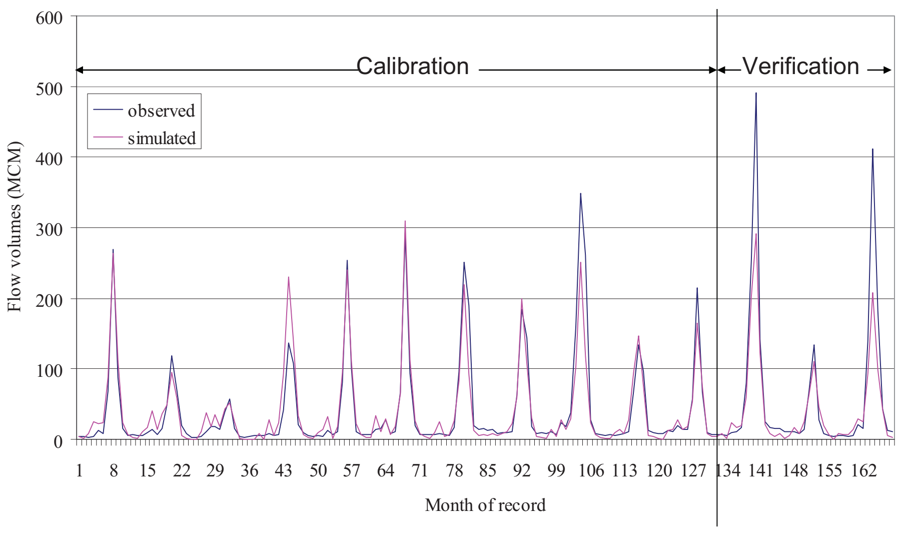


Figure 49. Monthly Flow Volumes at Aba Samuel

Once the monthly recharge series is generated, the mean annual recharge value for each sub-catchment is computed by summing the whole series and then averaging it over the number of years of record. It should be noted that the mean monthly and annual recharge values reported in Table 11 were obtained after accounting for the portion of areas of Black Cotton Soil in each subcatchment, which are considered to have no contribution in recharging the aquifer. The figure 50 yields a mean annual recharge value of 87 mm/year for the entire catchment (See Appendix 14 for map).

Table 11. Average monthly and annual recharge (mm) for each subcatchment.

Subcatchment	Jan	Feb	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct	Nov.	Dec	Annual	Area
sub1	0	0	0	0	0	0	37.5	61.4	0	0	0	0	98.9	167.3
sub2	0	0	0	0	0	0	46.4	60.9	0	0	0	0	107.3	223.5
sub3	0	0	0	0	0	0	16.2	52.7	1.1	0	0	0	70.1	115.2
sub4	0	0	0	0	0	2	31.2	85.0	4	0	0	0	122.3	242.1
sub5	0	0	0	0	0	1.7	19.2	71.8	2.5	0	0	0	95.2	252.7
sub6	0	0	0	0	0	0	7.6	52.6	0	0	0	0	60.2	250.6
sub7	0	0	0	0	0	0	18.0	55.9	4.2	0	0	0	78.1	36.0
sub8	0	0	0	0	0	0	8.7	56.9	4.9	0	0	0	70.4	63.2
sub9	0	0	0	0	0	0	3.7	33.2	0.5	0	0	0	37.4	146.0

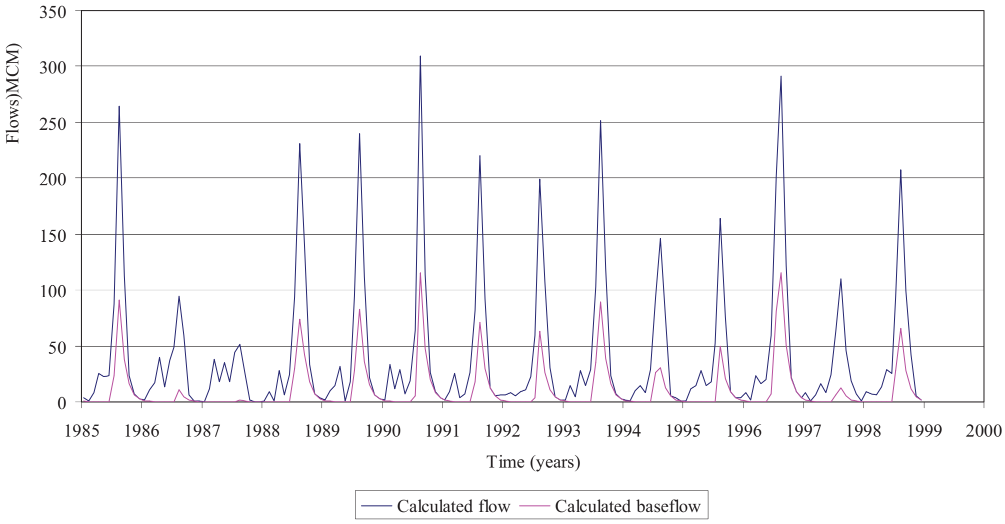


Figure 50. Calculated total flow and base flow at Aba Samuel

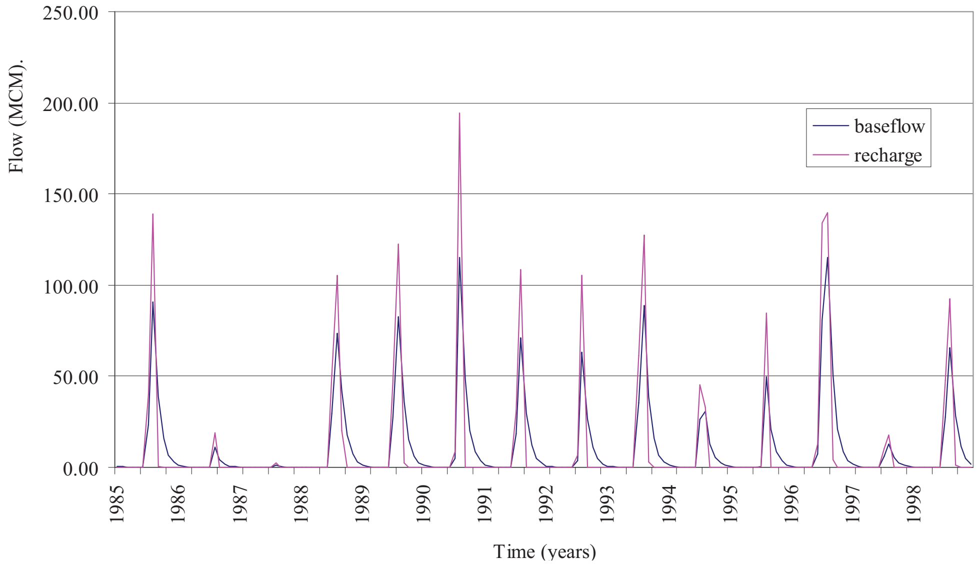


Figure 51. Relation between base flow and recharge with time

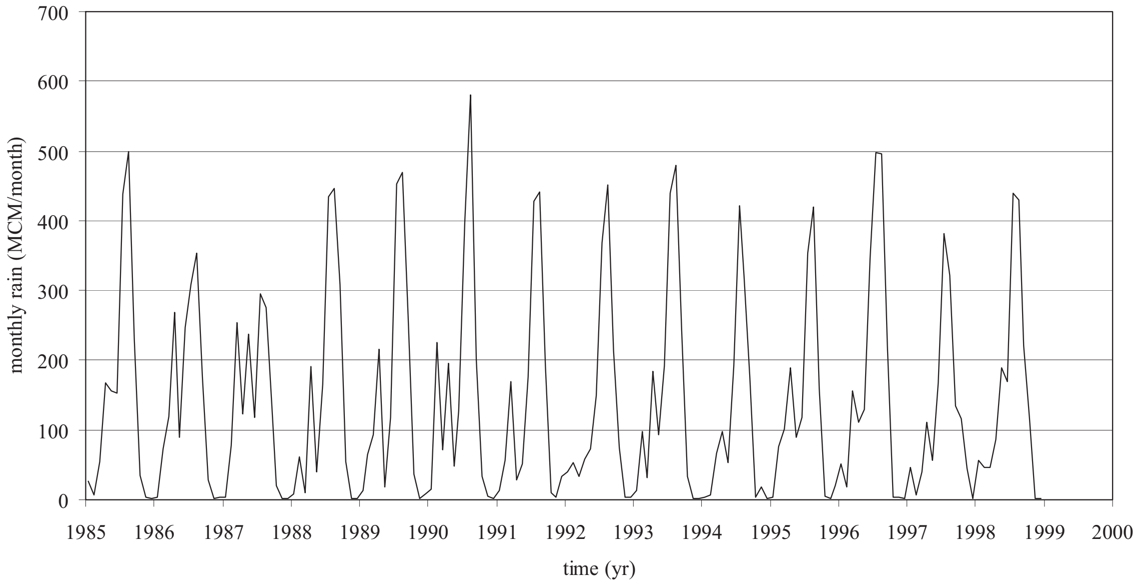


Figure 52. Monthly rainfall (1985 – 1999)

The following are the results of the semi distributed water balance model of the Akaki catchment:

- The average calculated flow at Aba Samuel is 492 MCM/yr (328.5 mm/yr)
- Recharge or base flow in the area is calculated as 130 MCM/yr (87mm/yr)

Note: AWSA (2000) has done this model and found recharge of 51 mm/year._The approach taken by (AAWSA, 2000) seem to be reasonable, however as discussed later in the following section the exclusion of significant part of the catchment as totally impermeable proves to be unrealistic. Besides that errors in the water balance are corrected. Hence, the mean recharge rate of the catchment is believed to be greater than 51mm, in which case even the estimate of Tehal (1991), which is 63 mm may be a conservative one.

Urbanization results in land surface impermeabilization and reduces the direct infilteration of excess rainfall, and hence accelerates direct runoff. This surface impermeabilization includes construction of roofs and paved areas such as major highways, minor roads, parking lots, industrial areas, air port, etc. since this fraction of impervious surface, due to urbanization, within the urban catchment reduces groundwater replenishment, it is deducted from the total urban catchment contributing to recharge. For the city of Addis ababa, in which informal settlements are progressively consolidated in to urban center, about 25 % of the city is assumed to be impervious surface which does not directly contribute to the direct natural recharge. Similarly, Lerner et al. (1990) suggests 75% of natural recharge for urban areas with rainfall greater than 1000 mm/yr which is the case to the study area.

Conclusions on the recharge of the catchment

Recharge to hydrogeologic units occur through natural processes and antropogenic activities, including:

- Direct recharge from precipitation through out the catchment, and surface and subsurface runoff occurring primarily in the Furi, Wechecha and Intoto mountains and hills located along the western, Northwestern, northern and northeastern boundaries of the Akaki catchment.
- Indirect recharge because of the leakage from sewers and water mains in the Addis Ababa city sector of the catchment

- Indirect recharge as the result of leakage from reservoirs and streams, traced especially in groundwater within the southern part of the catchment.

Three surface water reservoirs (Dire, Gefersa, and Legedadi) give 80% of water supply to the city of addis Ababa which in total of 175000 m^3/day. Total well abstraction from the catchment including Akaki wellfield is 23 MCM/yr (may be larger now). Hydrogeological investigation carried out in Akaki area by AAWSA-THAL(1992) as cited in Tamiru (2001) showed that from the total water supplied to AA, about 70% returns as sewerage to the rivers and 60% of the returned flow has an outlet through big Akaki river and the remaining 40% joins little Akaki river. In the study area there is a significant contribution from sewerage that passes through drainage system into nearby streams. Ward et. al (1990) as cited in Tamiru (2001) noticed that the discharge of effluents in to the stream channels and abstraction of water from the stream channel may represent a very large percentage part of the natural flow and must therefore, be taken in to account in the integrated water balance analysis. "Approximate indicative" conceptual chloride mass balance in the catchment" is written as below)

- So chloride mass balance equation in the catchment will be modified in to the following equation

$$C_p p = C_{ET} + C_u U + C_{gw} A + C_U DR + C_R R + C_{gw} B \quad (13)$$

Where:

C_p = Chloride in precipitation (mg/l)
P = Precipitation (mm/yr)
C_{ET} = Chloride content on evapotranspired water (mg/l)
ET = Evapotranspiration
C_u = Chloride of Urban water supply (dams)
U = Urban water supply
C_{gw} = Harmonic mean of groundwater chloride (mg/l)
DR = Direcr runoff
B = Baseflow
R = Return flow (70 % of the urban water supply, U).

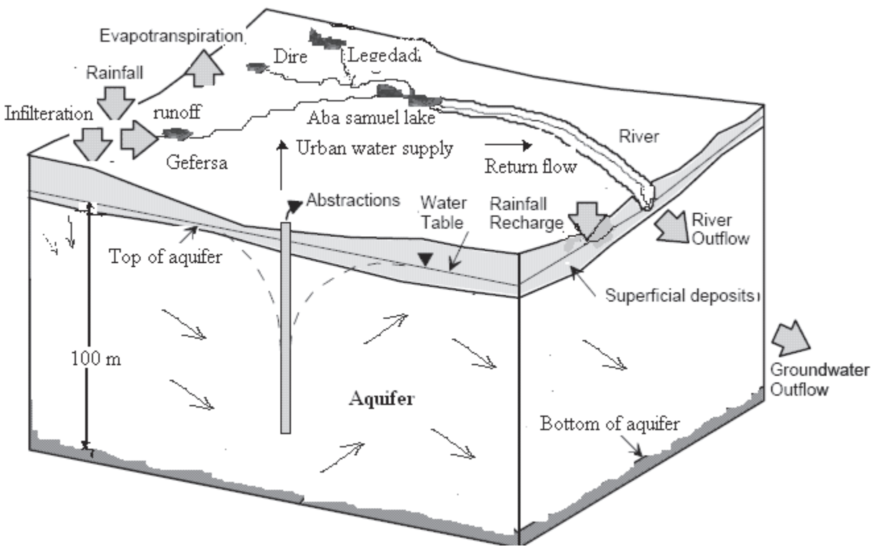


Figure 53. Groundwater surface interactions in the study area.

4. Calibration and execution of Akaki catchment model

The calibration process involved adjusting of the inputs of the model such as parameters, boundary conditions and sinks or stresses etc. in order to make a good match between the simulated and observed state variables. The model to be a good representative of the real world, the difference between the simulated and observed state variables should be as small as possible. This procedure requires the calibration target which is referred to as goodness of fit criterion (Rientjes, 2007). The calibration target is commonly defined as calibration value with its associated error (Rientjes, 2007). The error in the calibration is determined by various aspects like accuracy of measurements, complexity of the system being modelled and the applied model resolution. With these challenges, setting the calibration criterion is a tedious task. Besides the real situation of the field, the calibration was done manually by trial and error method until the minimum difference between the simulated and observed groundwater heads was obtained. The changed parameters are hydraulic conductivity and recharge flux. The scatter plot of measured heads against simulated heads was produced, and shows good results.

4.1. Calibration of the model

Calibration of the model requires that field conditions at a site to be properly characterized. Lack of proper characterization may result in a model that is calibrated to a set of conditions, which are not representative of actual field conditions (Anderson and Woessner, 1992).

4.2. Calibration target and uncertainty

Before starting calibration process in modelling, the selection of calibration target is required. Hydraulic heads obtained from groundwater level measurement in the Akaki catchment were used as calibration values. The calibration target was to match simulated hydraulic heads by the model with observed head values. Hydraulic heads (DWL) for calibration purpose were obtained from groundwater level measurement of year 2004. Besides that, static water level records, measured during the drilling time of wells in the catchment as there were no data collected in water level after completion of drilling activities, were used to check the accuracy of the model with out imposing well abstraction to it. See chapter 3.

It should be clear that most of the measured hydraulic heads data are associated with errors due to the following reasons as is usually the case in Ethiopia.

- The static water level measurements were taken just after well completion.
- There are no monitoring wells which are well distributed in the catchment.

The monitoring wells are only found in the wellfield and the water level observations are carried out on the pumping wells only in other part of the catchment. Because of this reason, the observed head values may not represent the actual water levels.

Table 12. Model Calibration Performance Measures (Aquaterra consultant, 2000)

Item	Performance Measure	Criterion
1	**Water balance** Difference between total inflow and total outflow, including changes in storage, divided by total inflow or outflow, expressed as a percentage.	Less than 1% for each stress period and cumulatively for the entire simulation.
2	**Iteration residual error** The calculated error term is the maximum change in heads (for any node) between successive iterations of the model.	Iteration convergence criterion should be one to two orders of magnitude smaller than the level of accuracy desired in the model head results. Commonly set in the order of millimetres or centimetres.
3	**Qualitative measures** Patterns of groundwater flow (based on modeled contour plans of aquifer heads). Patterns of aquifer response to variations in hydrological stresses (hydrographs). Distributions of model aquifer properties adopted to achieve calibration.	Subjective assessment of the goodness of fit between modelled and measured groundwater level contour plans and hydrographs of bore water levels and surface flows. Justification for adopted model aquifer properties in relation to measured ranges of values and associated non-uniqueness issues.
4	**Quantitative measures** Statistical measures of the differences between modelled and measured head data. Mathematical and graphical comparisons between measured and simulated aquifer heads, and system flow components.	Criteria should be selected from the list of residual head statistics. Consistency between modelled head values (in contour plans and scatter plots) and spot measurements from monitoring bores. Comparison of simulated and measured components of the water budget, notably surface water flows, groundwater abstractions & evapotranspiration estimates.

4.2.1. Steady State Flow Calibration

This process aims at checking the overall coherence of the selected assumptions of the modelling and at identifying suitable hydraulic conductivity and recharge values. After numerous trials, satisfactory simulation result of the flow, the piezometric levels and hydraulic conductivity has been obtained. The calibration process was done using trial and error method by varying mainly aquifer hydraulic conductivity values and comparing calculated heads to those measured in wells.

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.

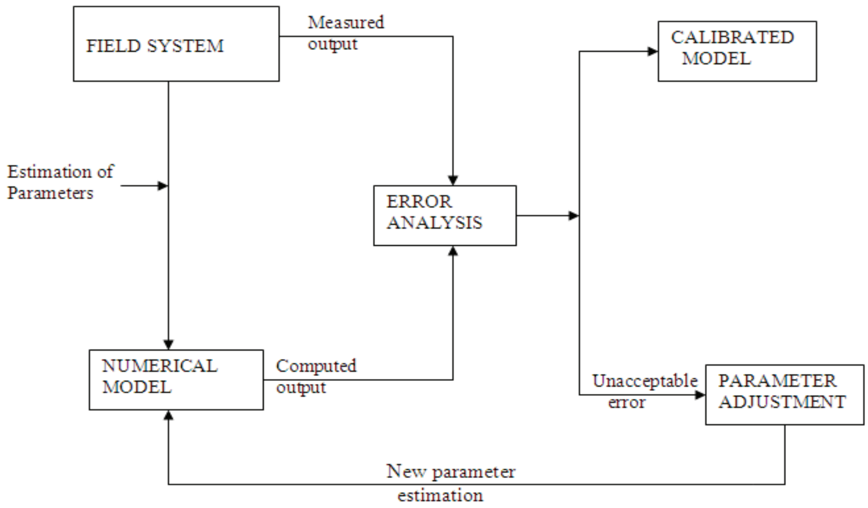


Figure 54. Trial and error calibration procedures (Adapted from Anderson and Woessner, 1992)

4.2.2. Calibration results

The best fit results (Fig 55 & 56) were achieved when the model domain was divided into regions with different hydraulic conductivity zones. Subdivisions into zones were done based on geology and hydrogeology of the model domain. As the result of this, subdivision in to zones should be regarded as indicative only and then fine tune the hydraulic conductivity values until the model results match with field situations.

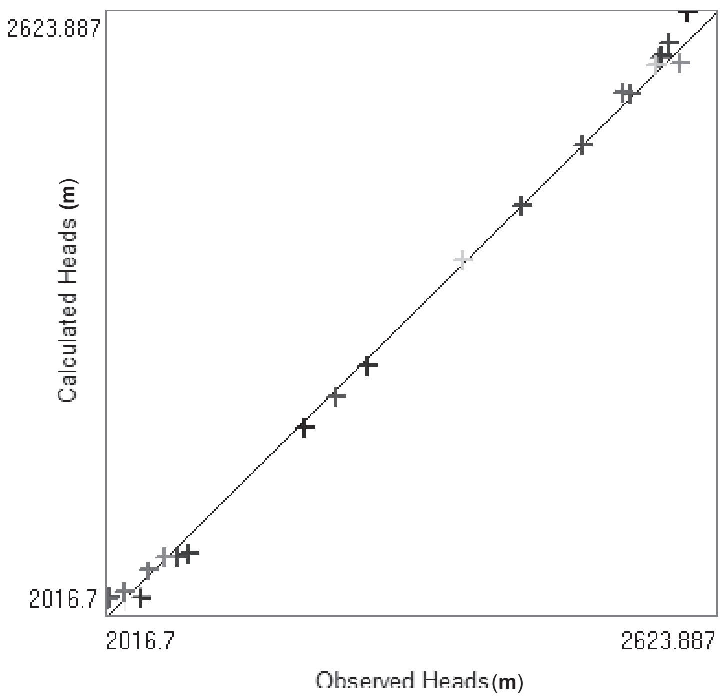


Figure 55. Scatter diagram of calculated and observed heads in the study area

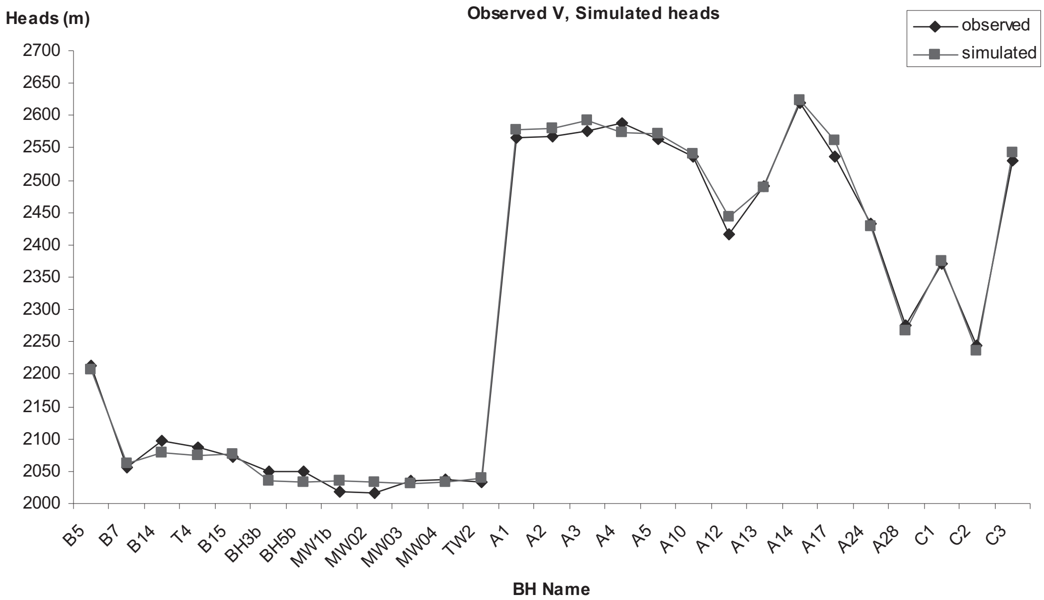


Figure 56. Comparison between actually measured and model computed heads

For calibration purpose, SWL of the boreholes are not used since the catchment's model is done with significant amount of groundwater withdrawal. Because of this reason, dynamic water levels of bore holes listed in the table 13 below are used for model calibration. For calibration the DWL values of only 27 boreholes in the catchment were used. Then, normalized static water levels of 364 wells were used in the model with out well abstractions (external stresses) to see the accuracy of the model. See figure 57.

Table 13. Steady state flow Simulated vs. observed hydraulic heads (m.a.s.l)

X	Y	Observed heads (m)	Simulated heads (m)	(obs-simu)	ABS (obs-sim)	(Obs-sim)^2
481200	980000	2212.5	2206.352	6.148	6.148	37.797904
473566	978610	2056.5	2061.756	-5.256	5.256	27.625536
480900	978800	2097.4	2079.431	17.969	17.969	322.884961
473108	979851	2086.5	2075.587	10.913	10.913	119.093569
473069	979881	2072.93	2076.004	-3.074	3.074	9.449476
478713	974977	2049	2035.296	13.704	13.704	187.799616
476574	975607	2049.8	2034.148	15.652	15.652	244.985104
476454	976951	2018.9	2035.307	-16.407	16.407	269.189649
476523	976374	2016.7	2032.8	-16.1	16.1	259.21
476972	976152	2035.3	2030.833	4.467	4.467	19.954089
477185	975729	2036.8	2032.269	4.531	4.531	20.529961
473576	972821	2032.7	2039.876	-7.176	7.176	51.494976
473600	1001013	2566	2578.391	-12.391	12.391	153.536881
473700	1001012	2568	2580.722	-12.722	12.722	161.849284
474300	1001005	2576	2592.161	-16.161	16.161	261.177921
466200	1001008	2587.9	2573.239	14.661	14.661	214.944921
467200	1001017	2563	2570.711	-7.711	7.711	59.459521
468900	1001007	2537	2540.775	-3.775	3.775	14.250625
474000	999400	2490	2489.564	0.436	0.436	0.190096
475000	1001300	2620	2623.887	-3.887	3.887	15.108769
470000	996400	2432	2429.542	2.458	2.458	6.041764
469150	988720	2275	2267.528	7.472	7.472	55.830784
485115.1	993909	2370	2374.065	-4.065	4.065	16.524225
480667.4	989984	2243.36	2237.027	6.333	6.333	40.106889
458690.7	997661	2530.61	2543.086	-12.476	12.476	155.650576

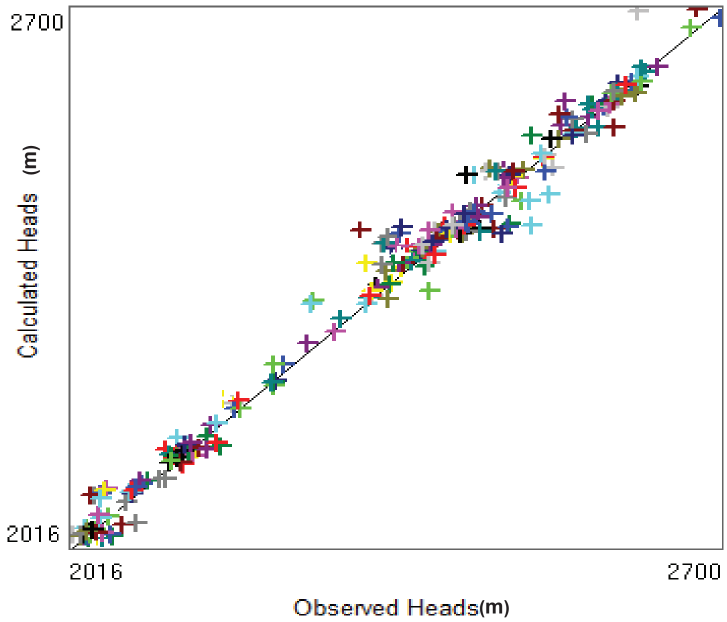


Figure 57. Scatter diagram of calculated & observed heads (m), when 364 bore holes are used.

4.3. Evaluation of calibration

The results of the calibration should be evaluated both qualitatively and quantitatively (Anderson & Woessner, 1992). The calibrated results were evaluated based on the calibration target and assessment of the mass balance of the system (table 12). Flow direction was determined based on the simulated head distribution and comparison is made with the flow direction determined in the conceptual model and by previous studies conducted by Tamiru (2001). A scatter plot of measured against simulated heads is another way of showing the calibrated fit (Fig.51, 52, 53). The scatter plots are visually examined to see whether points in a plot deviated from the straight line. Furthermore the calibrated model outputs were evaluated by applying the three common ways of error quantifying methods (Mean error, Mean absolute error and Root Mean Squared error).

$$RMSE = \left[\frac{1}{n} \Sigma_{i=1}^{n} (h_c - h_o)_i^2 \right]^{0.5} \qquad (11)$$

The mean error is the mean differences between observed heads and calculated heads

$$ME = \frac{1}{n} \sum_{i=1}^{n} (h_c - h_o)_i \qquad (12)$$

The mean absolute error (MAE) is the mean of the absolute value of the differences in observed heads and calculated heads

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |(h_c - h_o)_i| \qquad (13)$$

Where, n is the number of observations, h_c the calculated head (L) and h_o is the observed head (L)

The calibration of the model will be evaluated by using all these objective functions giving emphasis to the RMSE since it is best evaluation method as compared to the other two methods.

Table 14. Errors of the calibrated model

Evaluation function	Error (m)		
	ME	MAE	RMSE
Value	-0.39918	5.37964	8.05441

4.4. Groundwater balance

One of the most basic ways to quantitatively evaluate the movement of groundwater through an aquifer system is through the water budget. The fundamental equation for a water budget is that the sum of inputs minus the sum of outputs equals the change in storage of the groundwater system:

$$\Delta S = Q_{in} - Q_{out} + R - E_g - Q_{abs} \qquad (14)$$

Where ΔS = change in groundwater storage

For a groundwater system of the Akaki catchment, inputs to the aquifer include direct recharge from precipitation, indirect recharge from surface water runoff, groundwater inflow from outside the system boundary (only true for the wellfield), or recharge from anthropogenic sources (Lundmark et al., 2007). Groundwater outputs of the area include discharge as springs, discharge to surface water bodies, loss to the atmosphere by evapotranspiration (E_g), groundwater outflow to outside the system boundary, and pumping for domestic, agricultural and industrial uses. It is summarized for steady state as:

$$R + Q_{in} = Q_{out} + E_g + Q_{abs} \qquad (15)$$

R = Groundwater recharge from rainfall
Q_{in} = Lateral groundwater inflow (zero since no flow boundary from northern, western & eastern sides)
Q_{out} = Groundwater outflow from outlet of the catchment, base flow and springs
Eg = Groundwater evapotranspiration (negligible) because of afro alpine climate.
Q_{abs} = Flow from external groundwater sources and sinks (e.g. well abstractions)

Groundwater evapotranspiration reduces effective recharge or discards recharge completely causing a lowering of the groundwater table in extreme cases (Lubczynski, 1997). Evapotranspiration comprises of the surface evaporation, evapotranspiration from the unsaturated zone, and evapotranspiration from saturated groundwater zone. It must however be emphasized that no method has been developed yet to determine groundwater evapotranspiration correctly. Most deep rooting trees, capable of taking groundwater from depth, have been cut over the last decades. Besides that there is no data regarding groundwater evapotranspiration and difficult to quantify with limited time. Because of these reasons, it is assumed as negligible. The water balance is established based on the modelling water budget tool in Modflow.

Table 15. Water balance in Steady state flow obtained through Akaki catchment model calibration

area= 1500 km^2

Flow term	m^3/day IN	m^3/day OUT	m^3/day IN-OUT	MCM/yr IN-OUT	mm IN-OUT
Constant head	16791	104099	-87308	-32	-21
Wells	0	62763	-62763	-23	-15
Drains	0	11747	-11747	-4	-3
Recharge	432672	0	432672	158	105
ET	0	0	0	0	0
River leakage	2992	252912	-249920	-91	-61
Head dependent boundaries	0	20933	-20933	-8	-5
SUM	452455	452454	1	0	0

From this water balance, the total average base flow obtained from the model is 92 MCM/yr
or 62 mm/yr. From water balance model described in chapter 3, it is found base flow and recharge value of 130 MCM/yr or 87 mm/yr. using digital filter method, the base flow and recharge values are roughly 95 MCM/yr (63mm/yr) indicating good agreement between the models.

The evaluation of the calibrated model result shows that:

- Most of the simulated heads were within the pre-established calibration target.
- Water balance discrepancy was zero.
- The overall results of the groundwater model are comparable with the measured well data and in agreement with conceptual model.

The measure of errors evaluated by ME, MAE and RMSE are in the acceptable range according to the pre-determined error criteria.

Though the overall result of the model was comparable with the measured well data, few observations which are not uniformly distributed over the model domain are utilised in the calibration process. Ideally calibration values should be measured at a large number of points uniformly distributed over the model domains. Thus it is not possible to conclude that the calibration is accurate by only quantifying the errors using ME, MAE and RMSE with out considering the distribution of the residuals.

4.5. Groundwater outputs (in water balance)

The aquifers have three major outputs:

4.5.1. Springs

- **Springs in Aba Samuel Gorge**, which is due to sideways intersection of the piezometric surface with the gorge. About 10 springs are reported in the gorge. The yield of the seven springs is estimated by (AAWSA, 2000) and a collective discharge between about 30 l/s (2592 m^3/day) and 60 l/s (5184 m^3/day) considered to be reasonable.
- **Fanta Spring**, which is being used for water supply of Akaki town. The spring, which is capped, for the water supply has a recorded yield (from Akaki Water Supply Water Meter) of 13 l/s (1123.2 m^3/day) to 22 l/s (1901 m3/day) with average of about 18 l/s (1555.2 m^3/day). However, its yield is over 22 l/s (1901 m^3/day) including the non-capped parts (see water balance of Akaki wellfield model).

- **Other springs,** there are a number of other small springs over the study area whose discharges are not measured frequently. For these springs a total of 30 l/s (2592 m^3/day) is assumed excluding the hot springs of central Addis Ababa.

4.5.2. Base flow to the rivers

Essentially part of the flow of big Akaki River comes from groundwater discharge. In dry season this contribution gives the major part of the observed rate. According to 2008 model, the base flow to the rivers from groundwater is 252912 m^3/day, which is 92 MCM/yr.

4.5.3. Abstraction of the wells

As described above the total groundwater abstraction with boreholes is estimated to be about 136986 m3/day) which is approximately 23 MCM/yr (15mm/yr). For a volcanic aquifer such production rates are high. Production over 20 % of the estimated recharge in a hard rock aquifer may not be advisable for a sustainable use, because the estimated recharge might not be available as it can get access to be conveyed to deeper zones or other areas following fracture.

4.6. Model validation

In model validation, the normal procedure is to define a set of measurements or observations of system variables, where part is used for model calibration and the remaining part is used for model validation. Model validation was not possible here because the data set was too short.

4.7. Uncertainty of the model calibration and model limitations

Uncertainty in hydrologic modelling may be due to model conceptualization, input parameters and/or inherited in natural processes. Simply, model uncertainty arises from incomplete understanding of the system being modeled or inability to accurately reproduce hydrological processes with mathematical and statistical techniques (Das & Lewis, 2007). The study area is complex in terms of geological setting and hydrometeorological processes which give rise to significant heterogeneities and anisotropy.

The built model of the present research is associated with a number of uncertainties. First of all the hydrogeological heterogeneity caused difficulties in the conceptual simplification of the field condition. Despite the complex and heterogeneous nature of the aquifer system, assumptions and simplifications were made during the conceptualization of the system. Definitely uncertainties will be introduced as a result. Various forms of heterogeneity in the porous media properties can be very different from the fluid flow behaviour in the individual zones (Das & Lewis, 2007). There are generally few locations where observations are available, and the geological structure of the aquifer is only partially known. The main constraints in the process were data gaps and the poor quality of the available data. Important data such as screen length and aquifer thickness are not well documented.

Another area of uncertainty is resulting from defining the boundary conditions of the model domain. The boundary conditions were defined based on the surface physical features such as geology, rivers, dams and surface water divides. Finally, the area is conceptualized as a single layer which can probably simplify the system much.

5. Akaki wellfield flow modelling

5.1. Introduction

The Akaki wellfield is situated in the lower part of the Akaki River catchment within the drainage basin of Dongora and Keta which join to form Sekelo, which in turn flows into the big 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. Dendritic drainage patterns are apparent in the area. Although the lithology is mainly volcanic in origin, with different successive lava flows, the scoraceous lavas have a very high storage and transmissivity. For this reason, a wellfield was developed here with a large number of wells, clustered closely together. (See figures 4 and 5)

5.2. Hydrogeology of the wellfield

5.2.1. Geology

Lithologic units in the wellfield

Volcanic rocks dominate the study area with subordinate alluvial sediments. The volcanic rocks are the lower basaltic flows and younger basaltic scoria and lava (Aynalam, 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. These lower basalt flows are exposed in the western part of the study area. The logs show intercalations of massive basalt, scoraceous basalt and pyroclastic rocks such as scoria and tuff (Aynelam, 1999). The eastern part of the study area exposes younger basaltic rocks dominated by scoria cones and associated flows. 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 wellfield 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 wel field (See Fig. 58).

Structures and weak zones

As stated previously, 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 wellfield likely erupted following the NE-SW trending fault systems. A relatively dense fault network and lineaments is observed in the wellfield (Fig. 58 and 59). Field investigations by AAWSA et al.,(2000) cited in 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.

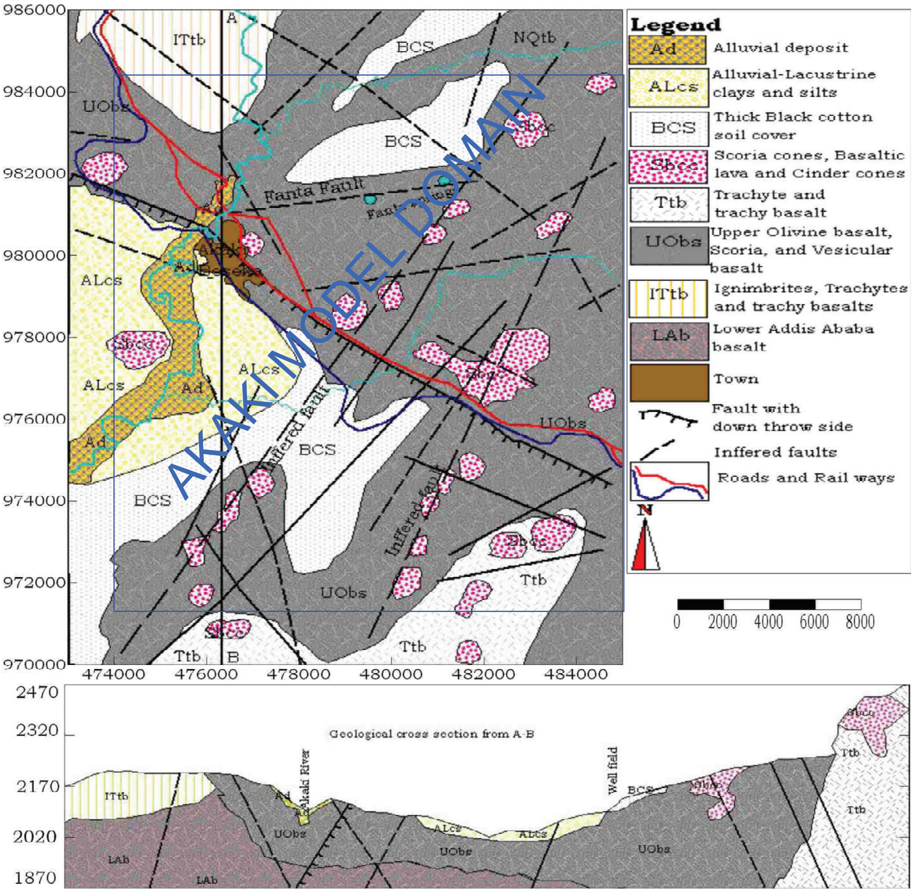


Figure 58. Geological map of the study area (modified after AG consult, 2004).

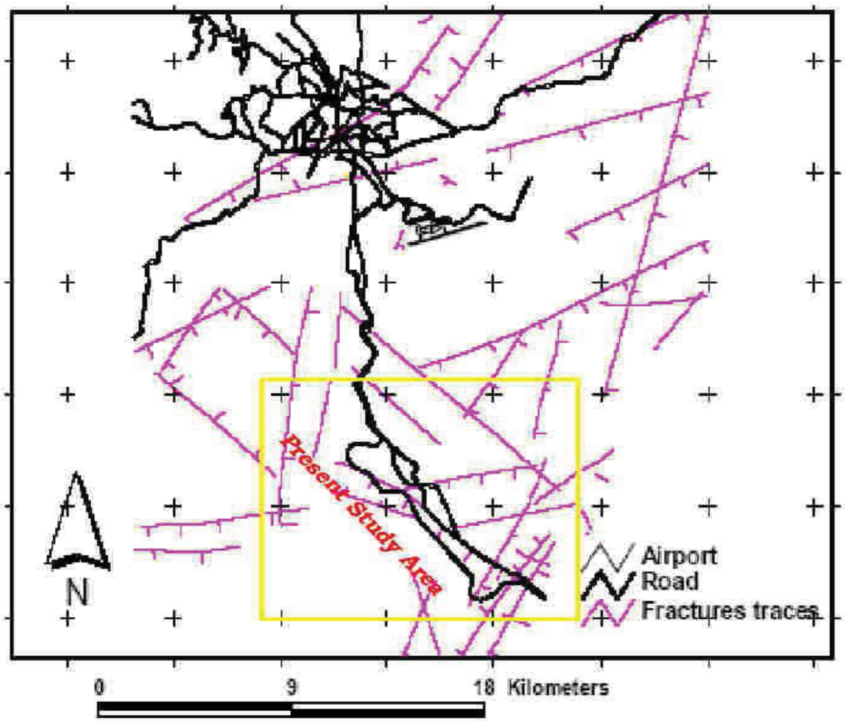


Figure 59. Dense fracture traces in the wellfield area (modified after Tamiru et al., 2005).

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 1 and 2). 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. 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.

5.2.2. 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. AAWSA (1998) as cited in AAWSA (2000) assumed local groundwater flow direction in the wellfield 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. 69) 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 wellfield 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 (See Figure 69) 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.

5.2.3. 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 discharge. In most areas, the volcanic aquifers show locally confined, mostly semi-confined to unconfined nature. 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 there is water entering to the study area from the upper boundary as influx to it. Groundwater also flows towards discharge areas, where it flows out as springs, seepage zones or it may be tapped by a number of wells in the wellfield 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.

5.2.4. 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. Comparisons of ground elevations and static water elevation at respective wells of the area are shown in Fig. 60. The potentiometric surface indicates that the groundwater is in connection with the surface water of Big & Little Akaki Rivers north of Akaki Bridge.

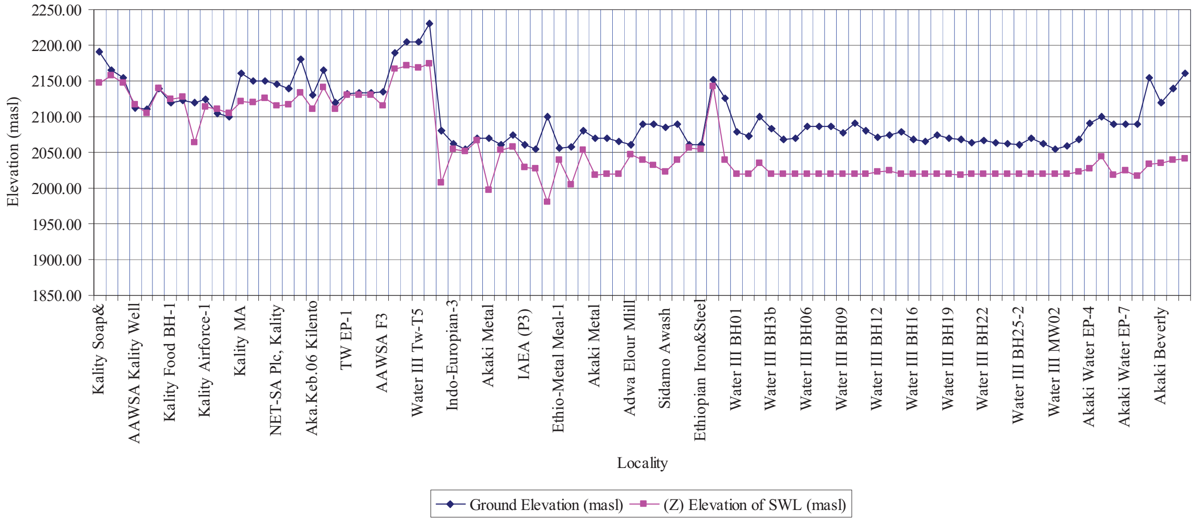


Figure 60. Comparison of ground surface elevation and normalized SWL in the wellfield.

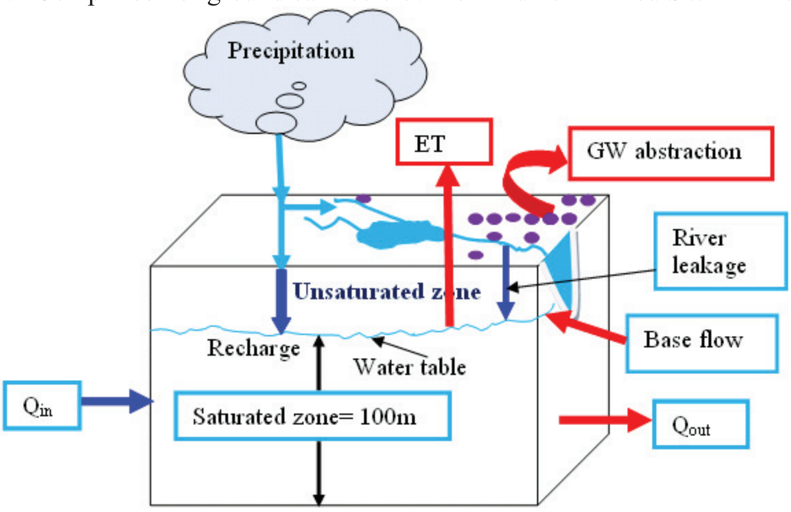


Figure 61. Conceptual model of Akaki wellfield.

5.3. Groundwater model of Akaki wellfield

A conceptual model is a simplified representation of the essential features of the physical hydrogeological system, and its hydrological behaviour, to an adequate degree of detail.

5.3.1. 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 197.3 km². The model grid consists of 44 columns and 74 rows. It consists of 3256 cells with a regular grid spacing of 400 m x 200 m. The geographic boundaries of the model grid were determined by using a DTM. A finite-difference grid superimposed over a 197.3 Km^2 area was designed and constructed based on the simplification of a conceptual model representing the physical properties of the groundwater system.

5.3.2. Input parameters of the wellfield model domain

The spatial input parameters are initial hydraulic head, horizontal hydraulic conductivity, recharge, top of aquifer, bottom of aquifer, and effective porosity. Therefore, values were assigned to each active grid cell, based on its location within the study area. Top of aquifer elevation was assigned based on the static water level of the area and bottom elevation of the aquifer was obtained by subtracting one hundred meters from the top of the aquifer

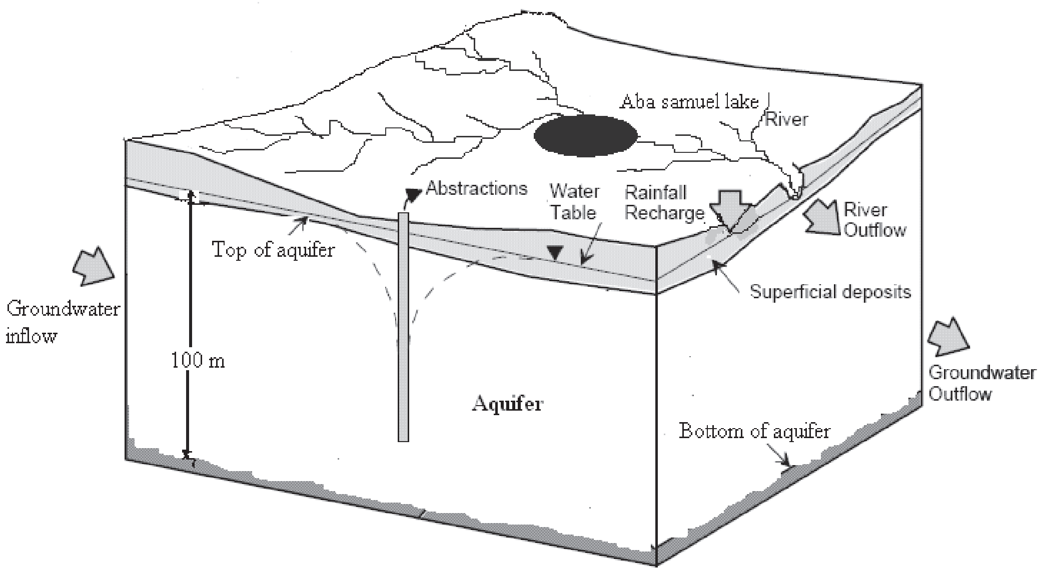


Figure 62. Block diagram shows conceptual model of Akaki wellfield

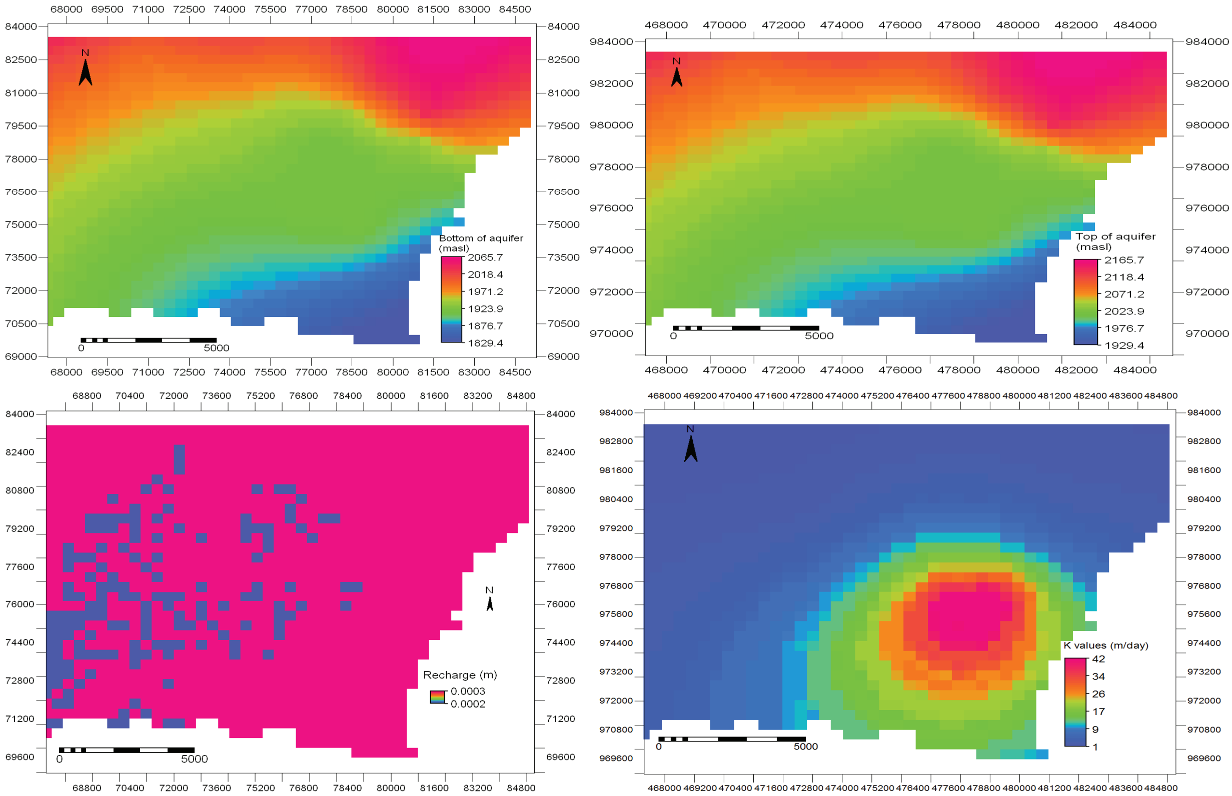


Figure 63. Input parameters of wellfield model

5.3.3. Model boundary conditions

Constant head is fixed to Abba Samuel Lake since its level does not much fluctuate with time. The base of the volcanic aquifer is the basement volcanic rock where groundwater flow is negligible. Since no flow is assumed to the bottom of the volcanic aquifer, it is taken as a specified-flux (no-flow) boundary. No flow boundary has been assumed in eastern boundaries of the study area (Fig 65). Head dependent boundaries are assigned to the northern, North western and southern part to simulate incoming and outgoing fluxes in the model domain. By default and convention the area outside the model domain is set to inactive.

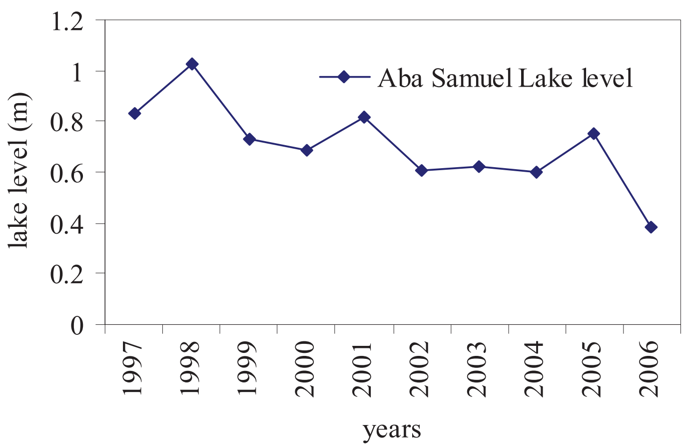


Figure 64. Aba Samuel lake level (MOWR, 20007)

5.3.4. Surface-groundwater interaction

Surface-groundwater interaction can form a critical component of the water budget, as well as an essential feature of the conceptual model, and often forms the most complex and uncertain parts of a model. From a groundwater perspective, it is commonly assumed that direct simulation of the unsaturated flow system is not critical, and that leakage from surface water to groundwater occurs instantaneously. To simulate groundwater–surface water interaction in the model domain river package, type of head dependent boundary, is used. It is used to assess the gains to the river (base flow) and the loss of water from the river towards aquifer (river leakage). In addition, constant head boundary at Aba Samuel lake is used to simulate the groundwater and surface water interaction process.

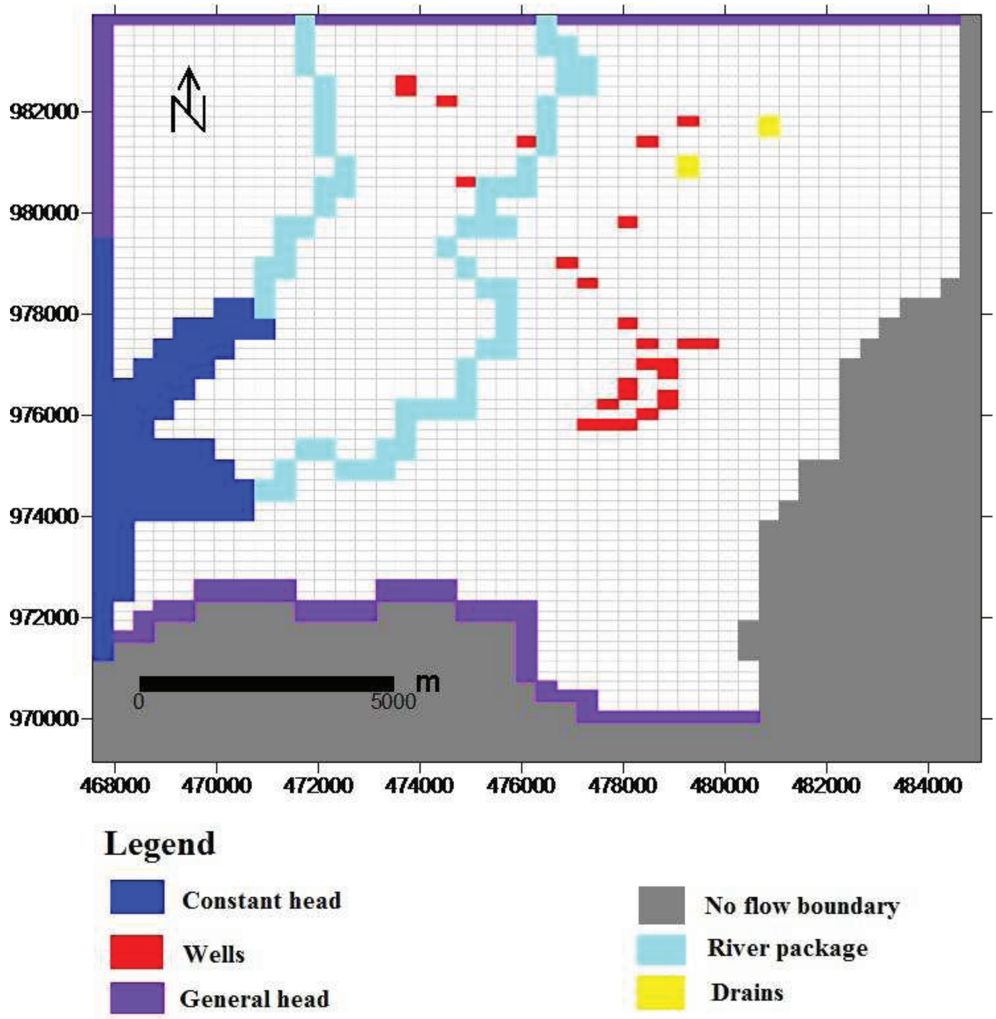


Figure 65. Boundary conditions of the wellfield model

The unregulated well abstractions are some of the external stresses facing the Akaki wellfield. The total well abstractions imposed to the model domain are long term average abstractions until to date. At the wellfield, it is taken as long term average abstraction but at the northern, north western and north eastern sides of the model domain, the abstraction records of 2004 are imposed. In this way, the total abstraction given to model is 58604 m^3/day.

Table 16. Well abstractions applied to the model.

Layer	Row	Col	Stress rate (m3/day)	Well no.
1	7	16	-88	1
1	8	16	-88	2
1	9	18	-220	3
1	9	34	-150	4
1	11	30	-150	5
1	13	22	-137	6
1	13	28	-150	7
1	14	34	-547	8
1	15	13	-94	9
1	16	13	-94	10
1	17	19	-123	11
1	17	22	-125	12
1	17	30	-1901	13
1	18	22	-125	14
1	21	27	-2400	15
1	25	24	-137	16
1	27	25	-300	17
1	31	27	-136	18
1	33	28	-1340	19
1	33	30	-2500	20
1	33	31	-500	21
1	35	28	-5216	22
1	35	29	-7808	23
1	36	29	-5874	24
1	37	27	-6912	25
1	38	27	-4384	26
1	38	29	-1116	27
1	39	26	-6496	28
1	39	29	-3616	29
1	40	28	-1472	30
1	41	25	-860	31
1	41	26	-328	32
1	41	27	-2280	33
1	53	11	-549	34
1	55	16	-390	35

5.4. Model calibration

General

A graphical comparison between actually measured and model computed heads with and without pumping scenario is shown in Figs 66, 67 and 68. After numerous trials, satisfactory simulation result of the flow, the piezometric levels and hydraulic conductivity has been obtained

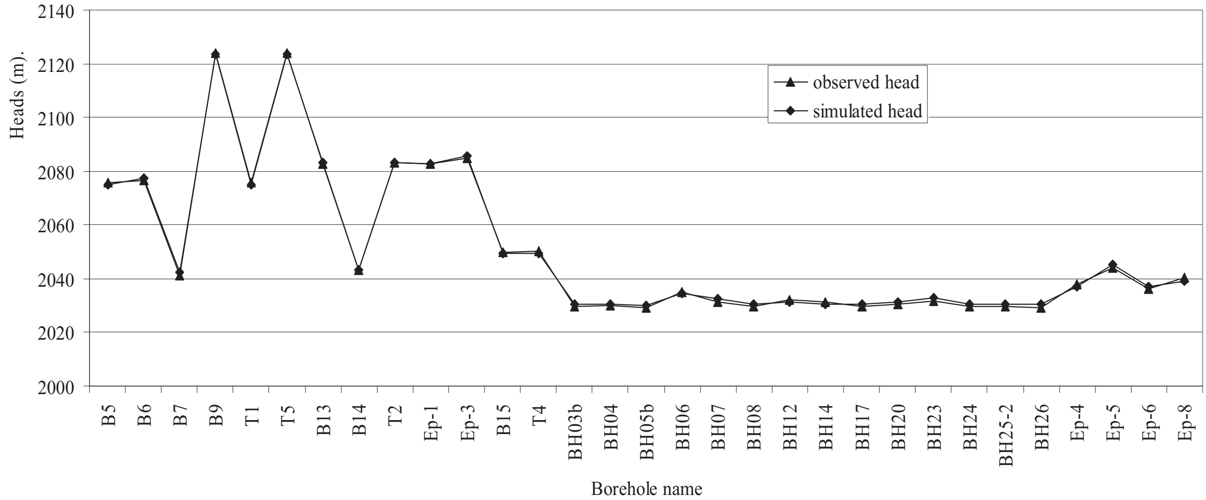


Figure 66. Wellfield steady state model calibration using static water levels with no abstractions

Total of 31. boreholes are used for model calibration and they are shown in the scatter diagram below.

Table 17. Errors of the calibrated model (unit: meter)

Evaluation functions	ME	MAE	RMS
Values	-0.154	0.713	0.768

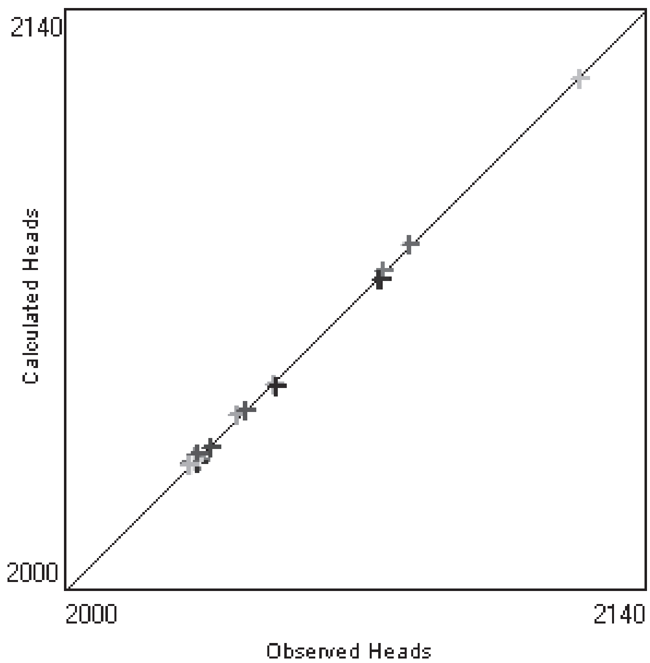
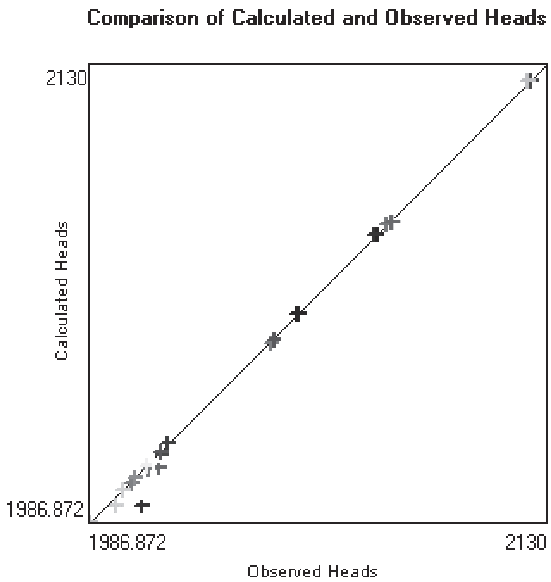


Figure 67. Calculated and. observed heads (m) of the wellfield without well abstraction

Table 18. Boreholes used for model calibration under non-pumping scenario.

BH_name	observed head(masl)	simulated head (masl)	0bs-simu	ABS(0bs-simu)	(0bs-simu)^2
B5	2075.8380	2074.9620	0.8760	0.8760	0.7674
B6	2076.7700	2077.3340	-0.5640	0.5640	0.3181
B7	2041.3250	2042.2090	-0.8840	0.8840	0.7815
B9	2124.0000	2123.4450	0.5550	0.5550	0.3080
T1	2075.8000	2074.9620	0.8380	0.8380	0.7022
T5	2124.0000	2123.4450	0.5550	0.5550	0.3080
B13	2082.7000	2083.2800	-0.5800	0.5800	0.3364
B14	2043.4000	2043.3790	0.0210	0.0210	0.0004
T2	2083.1630	2083.2800	-0.1170	0.1170	0.0137
Ep-1	2082.6000	2082.8390	-0.2390	0.2390	0.0571
Ep-3	2085.0000	2085.7720	-0.7720	0.7720	0.5960
B15	2050.0000	2049.5070	0.4930	0.4930	0.2430
T4	2050.2700	2049.3760	0.8940	0.8940	0.7992
BH03b	2029.4890	2030.4460	-0.9570	0.9570	0.9158
BH04	2030.2000	2030.4030	-0.2030	0.2030	0.0412
BH05b	2029.4000	2030.1910	-0.7910	0.7910	0.6257
BH06	2035.0000	2034.4960	0.5040	0.5040	0.2540
BH07	2031.4000	2032.3280	-0.9280	0.9280	0.8612
BH08	2029.8000	2030.6350	-0.8350	0.8350	0.6972
BH12	2032.2000	2031.4060	0.7940	0.7940	0.6304
BH14	2031.4500	2030.5480	0.9020	0.9020	0.8136
BH17	2029.8000	2030.5410	-0.7410	0.7410	0.5491
BH20	2030.5000	2031.2490	-0.7490	0.7490	0.5610
BH23	2031.9000	2032.8290	-0.9290	0.9290	0.8630
BH24	2029.7000	2030.5030	-0.8030	0.8030	0.6448
BH25-2	2029.7000	2030.3620	-0.6620	0.6620	0.4382
BH26	2029.4000	2030.3000	-0.9000	0.9000	0.8100
Ep-4	2038.0000	2037.1700	0.8300	0.8300	0.6889
Ep-5	2044.2000	2045.2540	-1.0540	1.0540	1.1109
Ep-6	2036.3500	2037.0840	-0.7340	0.7340	0.5388
Ep-8	2040.4260	2039.0140	1.4120	1.4120	1.9937

The acceptability of a calibration can be assessed by judging whether each of the performance measures listed in Table 19 conforms to specified criteria. The RMSE of 1.1 meter is still much below the target but figure 68 shows that under the circumstances the fit is quite good.



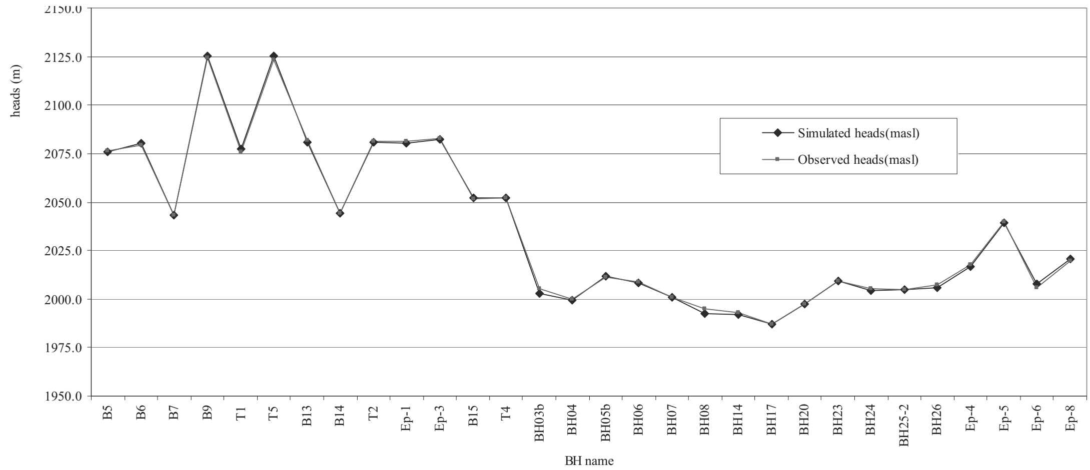


Figure 68. Observed & simulated heads of Akaki wellfield, calibrating with pumping senario.

Dynamic Normalized hydraulic head (DWL) valued collected during 2004 are used for Akaki wellfield calibration with external stresses, well abstractions.

Table 19. Evaluation of calibration with pumping scenario

Evaluation of calibration			
Eror measured (m)	ME	MAE	RMSE
value	0.189	0.84	1.1

Table 20. Observed and simulated heads of Akaki wellfield with pumping scenario

BH Name	x	y	Simulated heads(masl)	Observed heads(masl)	obs-sim (m)
B5	481200	980000	2075.82	2076.20	0.38
B6	470800	982900	2080.22	2079.30	-0.92
B7	473566	978610	2043.29	2043.33	0.04
B9	481600	982900	2125.35	2124.30	-1.05
T1	481200	980000	2077.22	2075.80	-1.42
T5	481600	982900	2125.35	2123.30	-2.05
B13	478400	981400	2081.01	2082.00	0.99
B14	480900	978800	2044.28	2044.40	0.12
T2	479400	981400	2081.01	2081.20	0.19
Ep-1	479340	981400	2080.50	2081.60	1.10
Ep-3	479740	981400	2082.17	2083.00	0.83
B15	473069	979881	2052.16	2051.80	-0.36
T4	473108	979851	2052.06	2052.30	0.24
BH03b	478713	974977	2002.74	2005.41	2.67
BH04	477992	975552	1999.47	2000.00	0.53
BH05b	476574	975607	2011.95	2011.40	-0.55
BH06	479696	976936	2008.20	2008.77	0.58
BH07	479405	976735	2000.93	2000.90	-0.03
BH08	479061	976370	1992.37	1995.12	2.75
BH14	478580	976051	1992.02	1993.00	0.98
BH17	478199	976361	1986.87	1986.90	0.03
BH20	477945	976985	1997.29	1997.29	0.00
BH23	477477	977216	2009.26	2009.05	-0.20
BH24	477330	976793	2004.27	2005.47	1.20
BH25-2	477162	976038	2004.83	2004.78	-0.05
BH26	477181	975680	2005.85	2007.12	1.28
Ep-4	479942	977322	2016.48	2017.60	1.12
Ep-5	478450	979950	2039.61	2040.00	0.39
Ep-6	479526	977468	2007.58	2005.75	-1.83
Ep-8	478998	977937	2020.76	2019.43	-1.33

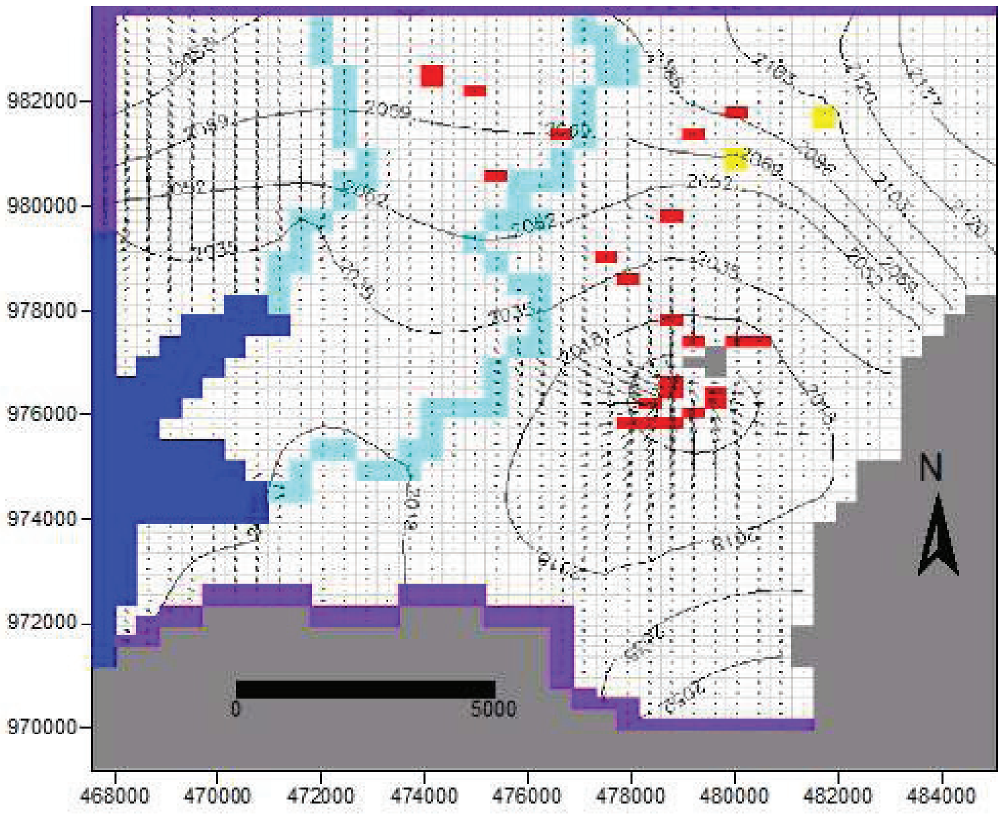


Figure 69. Flow nets in the wellfield after calibrating the model with dynamic water level of 2004

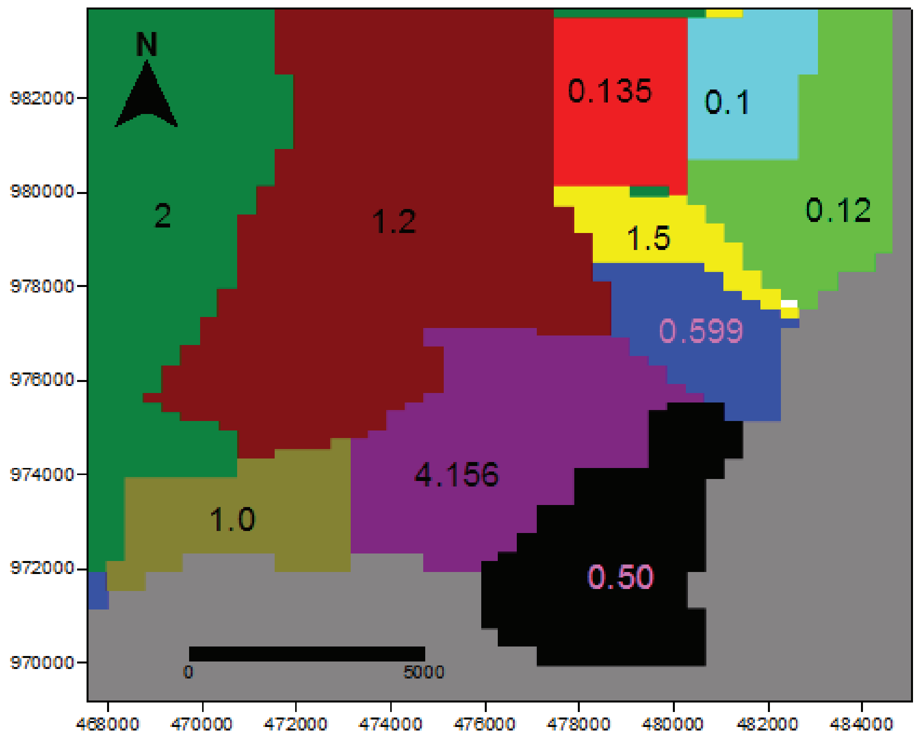


Figure 70. Hydraulic conductivity values (m/day) used for wellfield calibration

5.5. Water budget of wellfield

For a groundwater system of Akaki wellfield, inputs include direct recharge from precipitation, indirect recharge from surface water (Akaki river, Aba Samuel lake) (Q_{riv}), groundwater inflow from upper part of the system boundary (Q_{in}). Groundwater outputs may include discharge as springs, discharge to surface water bodies as baseflow to rivers, loss to the atmosphere by groundwater evapotranspiration (ET), groundwater outflow to outside the system boundary (Q_{out}), and well Abstruction for domestic, agricultural and industrial uses. It is steady state flow which can be summarized as:

$$R + Q_{in} + Q_{riv} = Q_{out} + E_g + Q_{baseflow} + Q_{well} + Q_{spring} \quad (18)$$

R	=	Groundwater recharge from rainfall
Q_{in}	=	Lateral groundwater inflow from northern, western sides of the wellfield domain.
Q_{out}	=	Groundwater outflow from out let of the wellfield, simulated by general head boundary
E_g	=	Groundwater evapotranspiration is negligible because of afro alpine climate.
Q_{well}	=	Ground water abstraction through wells
Q_{spring}	=	Groundwater out flow to the surface via spring, which is simulated by drain package
$Q_{baseflow}$	=	Base flow to the Akaki river which is simulated by river package.

Table 21. Groundwater balance with out well abstraction in the wellfield

area= 197km^2

Flow term	m^3/day IN	m^3/day OUT	m^3/day IN-OUT	MCM/yr IN-OUT	mm/yr IN-OUT
Constant head	15208	15730	-521	-0.2	-1
Wells	0	0	0	0.0	0
Drains	0	2249	-2249	-0.8	-4
Recharge	42660	0	42660	15.6	79
ET	0	0	0	0.0	0
River leakage	1996	44753	-42756	-15.6	-79
Head dependent boundaries	21951	19084	2867	1.0	5
SUM	81816	81816	0	0.0	0.0

Table 22. Wellfield water balance with well abstraction, calibration by DWL(2004).

area= 197km^2

Flow term	m^3/day IN	m^3/day OUT	m^3/day IN-OUT	MCM/yr IN-OUT	mm/yr IN-OUT
Constant head	15691	15425	266	0.1	0
Wells	0	36170	-36170	-13.2	-67
Drains	0	1066	-1066	-0.4	-2
Recharge	42660	0	42660	15.6	79
ET	0	0	0	0.0	0
River leakage	9742	26496	-16754	-6.1	-31
Head dependent boundaries	24396	13265	11132	4.1	21
SUM	92489	92489	0	0.0	0.1

5.6. 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 25 percent were applied to horizontal hydraulic conductivity, and rainfall recharge. The resulting hydraulic heads were then compared with the observed hydraulic heads and mean average error; absolute average error and root mean squared error were calculated for each parameter. Then the calculated average errors in the hydraulic heads were plotted against the multiplying factors as shown in figures 71 and 72. It was found that slight changes in either the aquifer hydraulic conductivity or slight changes in recharge rate affect dramatically the distribution of hydraulic head throughout the area. The sensitivity plots show that the recharge generates non-linear sensitive response while sensitivity towards hydraulic conductivity generates linear response. The model is equally sensitive to both increase and decrease of hydraulic conductivity on the other hand; the calibrated model is more sensitive to recharge fluxes increment than to recharge rate reduction.

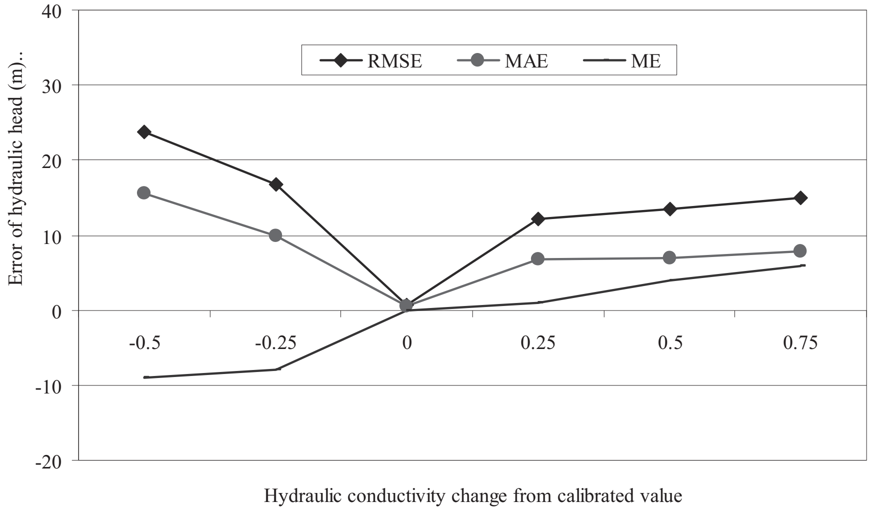


Figure 71. Sensitivity plot of the calibrated model with respect to hydraulic conductivity

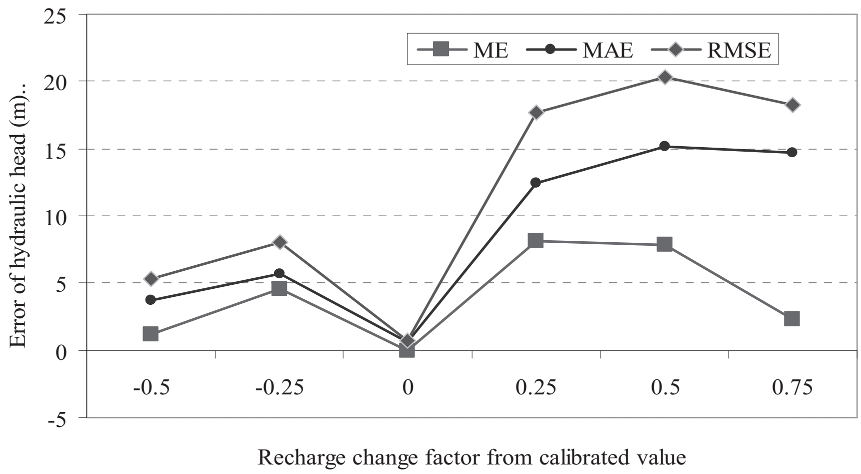


Figure 72. Sensitivity plot of the calibrated model with respect to recharge

6. An advective solute transport modelling of Akaki wellfield, PMPATH

6.1. General

PMPATH is an advective transport model running independently from PMWIN Pro (Chiang and Kinzelbach, 1998). PMPATH retrieves the groundwater models and simulation result from PMWIN Pro and MODFLOW. A semi-analytical particle-tracking scheme is used to calculate the groundwater paths and travel times. Moreover, PMPATH provides various on-screen graphical options including head contours, drawdown contours and velocity vectors for any selected model layer and time step. Both forward and backward particle tracking are allowed for steady state and transient flow simulations. In this respect, PMPATH can be used to simulate advective transport in groundwater to delineate contaminant capture zones, and wellhead protection areas. PMPATH creates several output files including hydraulic heads distribution, velocity field, and travel times of particles.

6.2. Hypothesis and assumption of the solute transport (PMPATH)

Water carrying contaminants (Fig. 73) may enter into the underlying porous aquifer from Tilu dimtu quarries, highly polluted Akaki river (Gizaw, 2002) that drain the urban centre, and most streams 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 and exit at discharge areas (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.

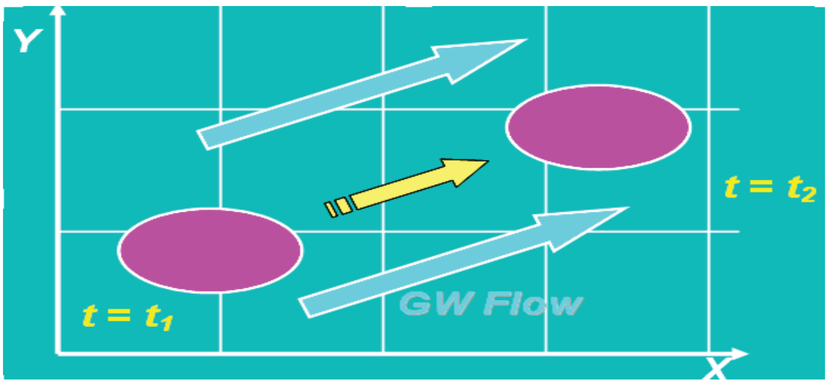


Figure 73. Conceptualization of the process by which solutes transport by moving groundwater

It is assumed by PMPATH that fluid properties are homogeneous and that concentration changes do not significantly affect the fluid density or viscosity and hence the fluid velocity. As the result of this, it is assumed that pollutant moves at the same velocity as water. Given the initial position of a particle anywhere in a cell, the coordinates of any other point along its path line within the cell, and the time of travel between them, can be computed directly. For steady-state systems, the exit point for a particle entering a cell at any arbitrary location can be computed in a single step. By following the particle as it moves from cell to cell, it can be used to trace the path of a particle through any multidimensional flow field generated from a block-centered finite-difference flow model.

6.3. Factors governing contaminant transport

Water pollutants tend to be removed or reduced in concentration with time and distance traveled (Tamiru et al., 2005). Understanding the factors that govern contaminant transport particularly in this area is, therefore, crucial. The 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.

6.3.1. Implication of geology for 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 have a facilitating effect in contaminant migration.

6.3.2. Hydrogeological suitability for transport

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, et al., 2005). Groundwater and contaminant movement as well as 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 increases. 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, et al., 2005).

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 74). 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.

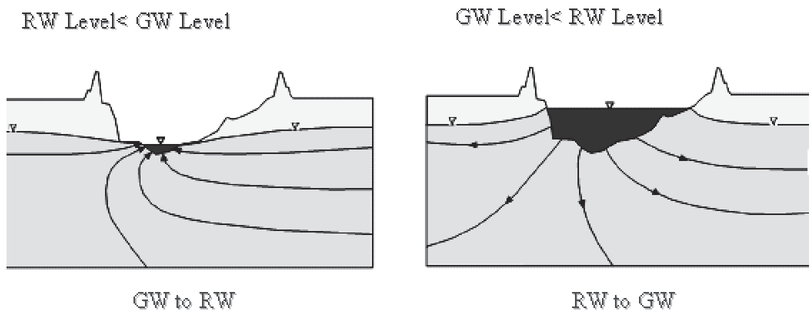


Figure 74. Rivers and groundwater connection; a gaining stream (left) and a losing stream (right).

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, 1999). Surface water pollution has already recorded in many parts of Addis Ababa (Tamiru, 2001). Groundwater pollution is also becoming a major threat particularly where the groundwater table and the surface water coincide, like around Kality (Gizaw, 2002). AAWSA et al. (2000) as cited in Tamiru (2001) 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. Downstream of this point and up to Aba Samuel hydropower plant, the groundwater level becomes lower than the river bed. It is believed that there is no hydraulic connection between the aquifer and the surface water bodies in this part.

However, previous investigations (Aynelam, 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 may show 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, 1999). A linear correlation between conservative constituents further indicates mixing (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.

Aquifer types (confined leaky and unconfined), and thickness of unsaturated zone have an effect on movement of contaminations in the subsurface. Even though the unsaturated zone in the wellfield is thick (30-60 meters), tectonic activity (structures) in the area create favorable pathways for transport.
The thick unsaturated zone in the wellfield can act as a geochemical and bacteriological filter, because of its low permeability (mostly black cotton soil). 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 flows 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.

6.3.3. 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, 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 does not allow at this stage to identify the chemical behaviour of each of them. Part of the water in the Akaki wellfield 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, the quality of groundwater located upstream of the wellfield can have an impact on the quality of water in the wellfield. In this study, only an advection process is dealt with.

6.3.4. Effect of the slope on transport

Slope variability of the land surface is an important factor in groundwater vulnerability and pollution 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, 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, 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.

6.4. 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 wellfield, 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.

6.5. Locations of potential contaminations

The following locations are selected as potential contaminant areas that may have an impact on the wellfield. 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 wellfield is found at a lower elevation close to the foot of the hill;
- Gelan metal industry (located at 480653, 976985; 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 Dongora stream then crosses through the center of the wellfield 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, 976220; elevation 2100 m.a.s.l) to know the potential leakage of pollutants from the farm (bacteria, animal wastes, etc).

6.6. Predictive simulations of contaminant analysis

Solute transport simulation 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 wellfield, the recharge, discharge and path lines of the contamination.

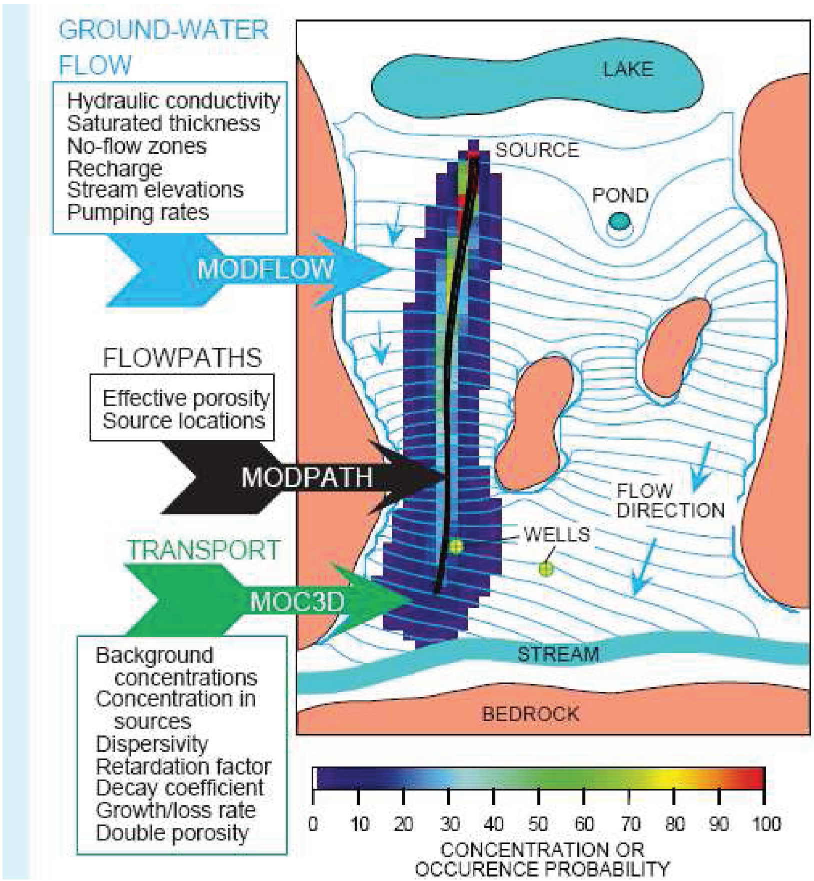


Figure 75. Simulation of GW flow & solute transport (Chiang & Kinzelbach (1998)

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 wellfield 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). See fig. 76.

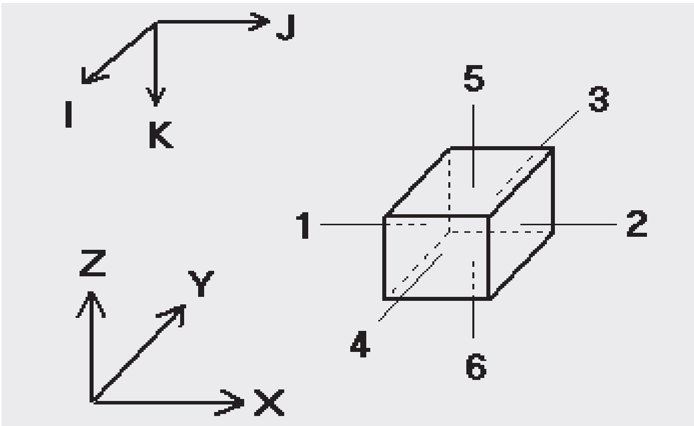


Figure 76. Various faces of an individual cell.

6.7. Pollutant travel time and direction of tracking computation

PMPATH provides the option of tracking particles forward in the direction of groundwater flow, or backward toward points of recharge. For backward tracking, particles terminate at points of recharge, rather than points of discharge. The backward tracking option often provides an efficient means of delineating the source of recharge to localized points of discharge, such as wellfields or drains.

Contaminants are introduced at sources upstream in cells (40,18), (35,39), (33, 35) and (31, 26) and the distance of travel of contaminants through the steady state flow field is observed for 100, 150, 800, 300 and 30 years travel times, respectively (Figures 78 - 82). Figure 77 shows that the simulated groundwater flow direction is to the wellfield almost from all directions and the velocity is relatively higher in areas where there is a 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.

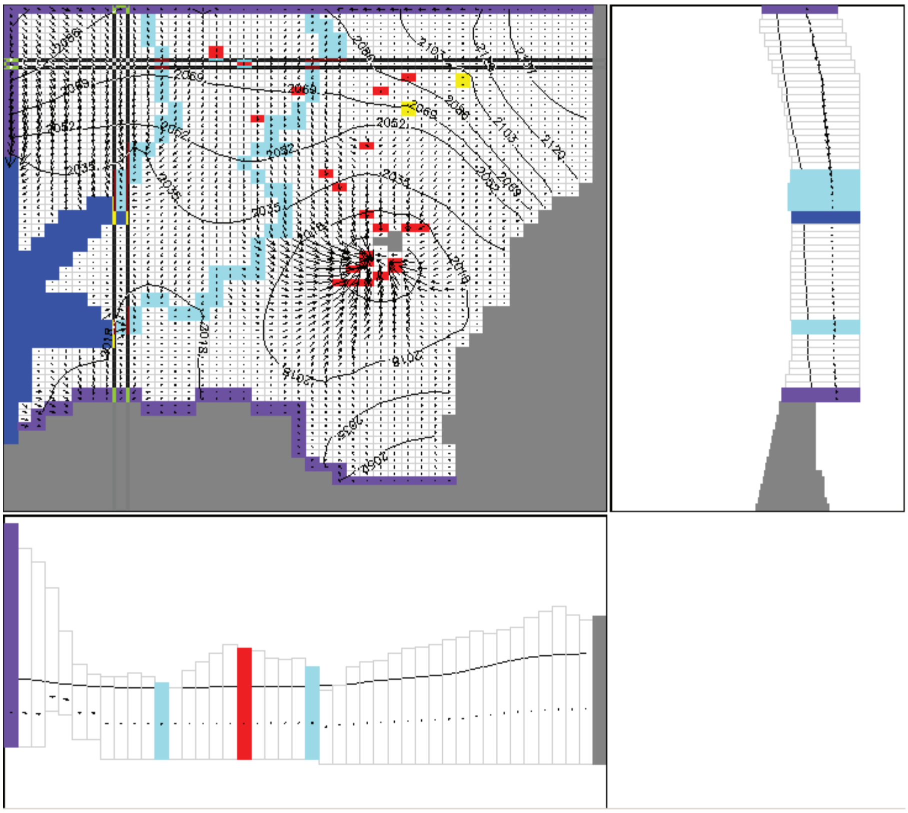


Figure 77. Flow nets showing column and row projections

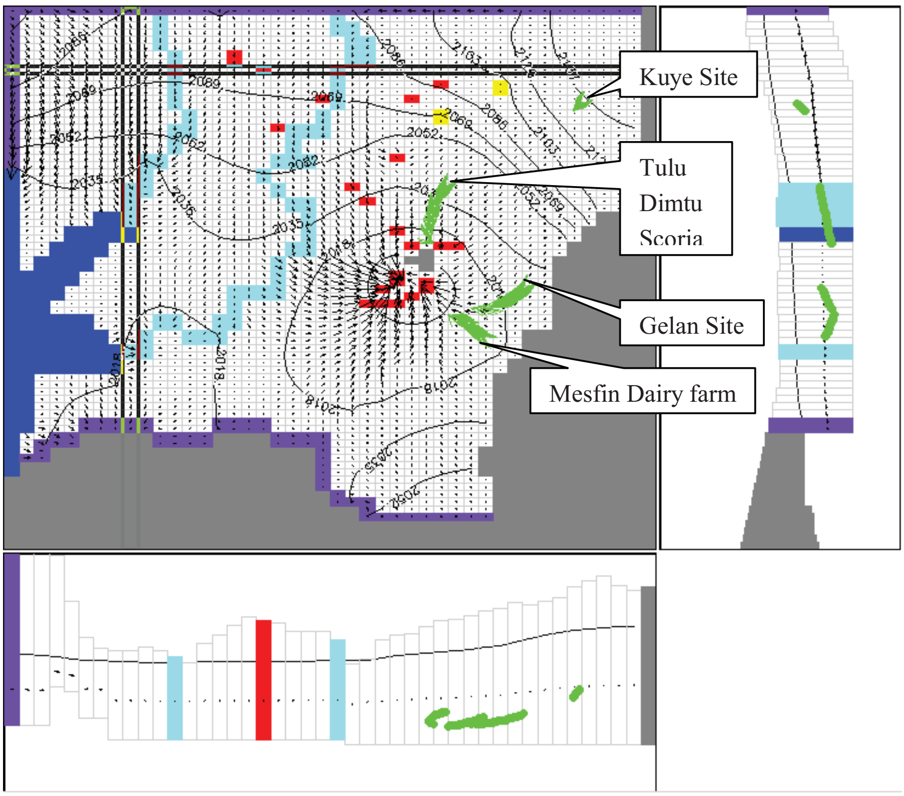


Figure 78. Contaminant path lines of 100 years travel time, from pollutant sites

Figure 78 clarifies the path that contaminant follows at time duration of 100 years from pollutant sites such as Tulu Dimtu scoria grave yard, cell (31, 26), Mesfin Zelelew dairy farm, Gelan metal factory, cell (35, 39) and kuye site, cell (40,18). The contaminant path lines from Tilu Dimtu scoria get very close to one of the wells in the wellfield. (Note that in figure 78 and Figures 79-81 (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 green lines represent contaminant flow (stream) lines moving with the same velocity as groundwater, the dark arrows represent velocity vectors and black line in the cross-sections represents the groundwater surface (potentiometric surface); and (iii) the cross-section shows the projection of row and column through the center of the wellfield.

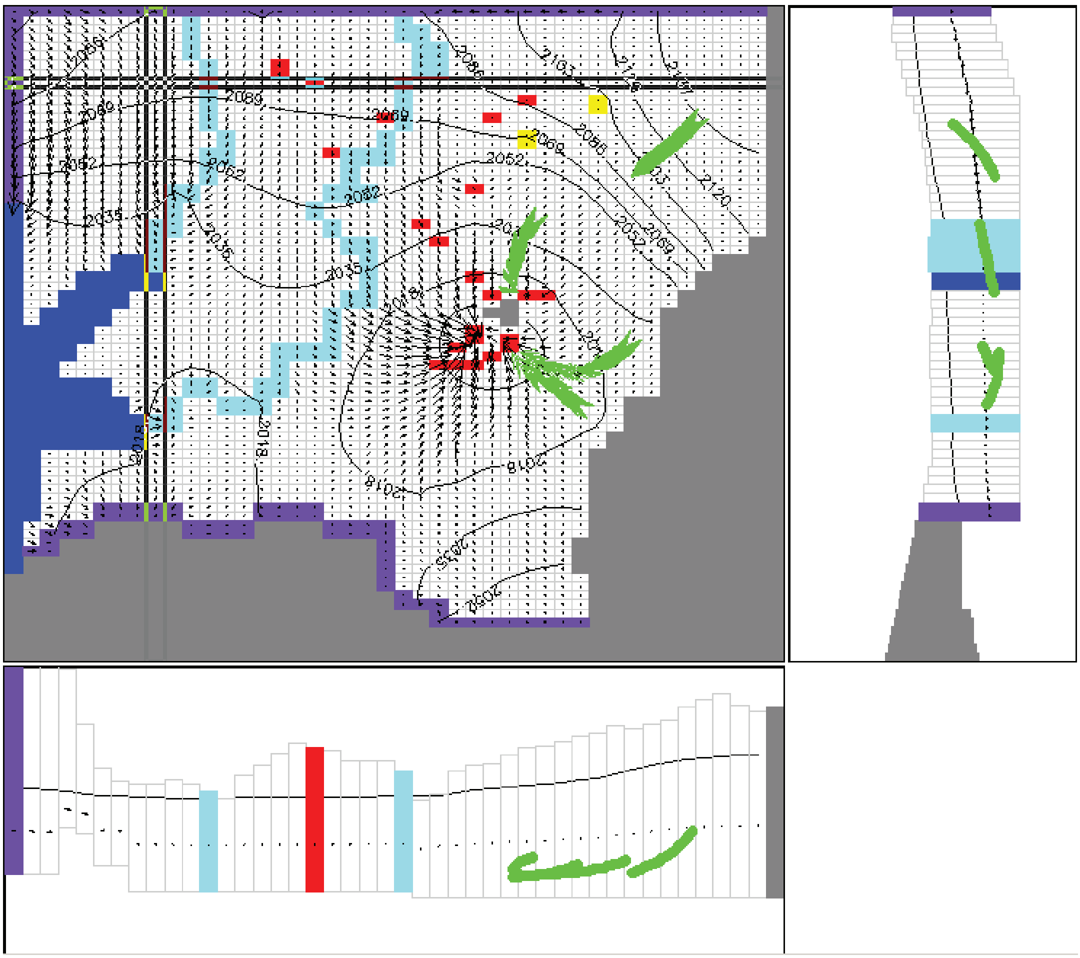


Figure 79. Contaminant migration from pollutant sites with in 150 years.

Pollutants start to enter approximately at about 150 years to the wellfield from both Mesfin dairy farm and Gelan metal industry. But contaminant from Tilu Dimtu scoria has entered into one of the wells in the wellfield at 100 years time span.

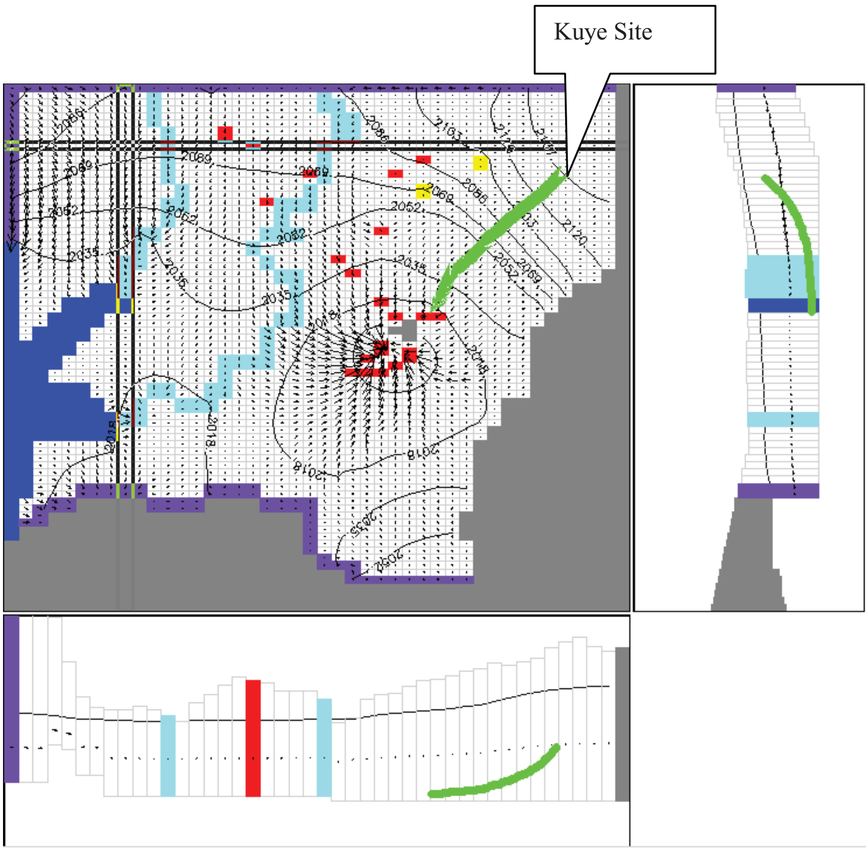


Figure 80. Contaminant entering to wellfield from kuye site at about 800 years.

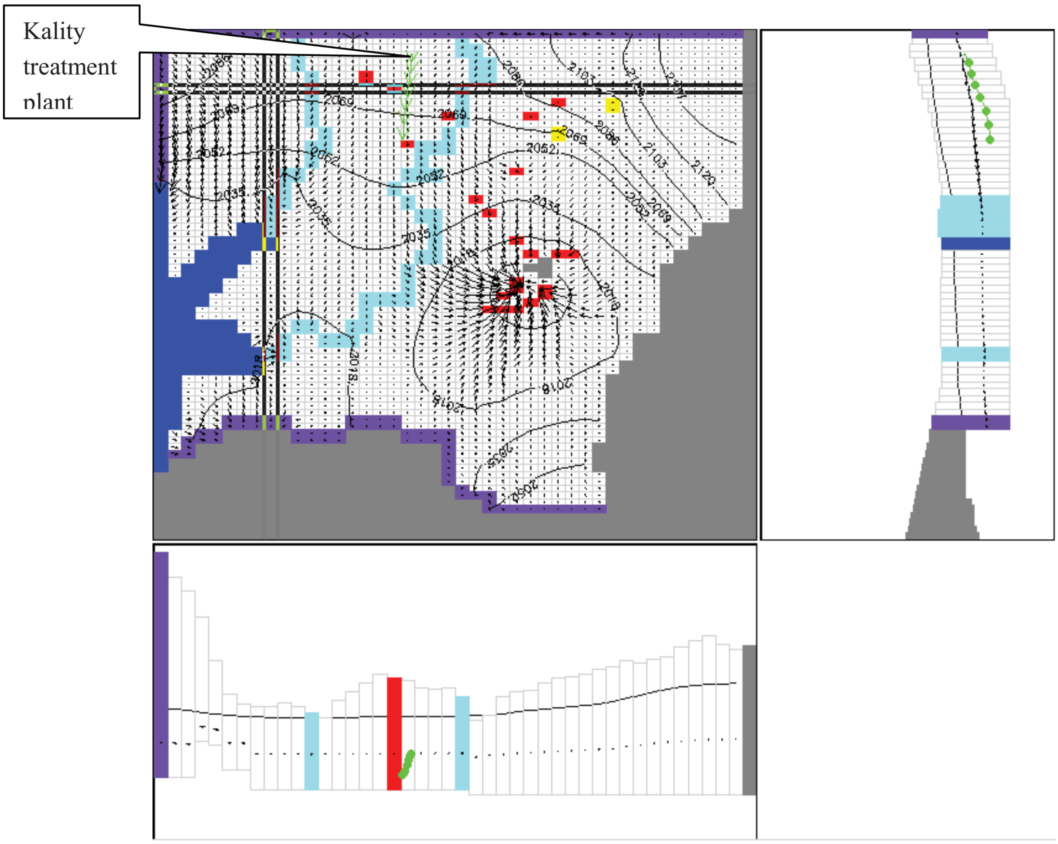


Figure 81. Pollutant migration from Kality treatment plant for 300 years.

The pollutants coming from factories in the Kality area indicates that it does not have much effect to the wellfield contamination if not they are mixed with the surface water from Akaki catchment which pollutes wellfield in about 30 years time.

6.8. Implementation of groundwater protection zoning in Akaki wellfield

Groundwater protection zoning is a supplemental methodology for groundwater protection that includes land use planning in groundwater management. Long-term protection through the use of protection zones will be balanced by the need for economic and social development by allowing more activities outside the protection zones. The delineation of a protection zone is the process that determines the geographical area that should be included in a protection zone program. This area of land is then managed to minimize the potential of groundwater contamination by human activities that occur on the land surface or in the subsurface. Proper implementation of aquifer protection zoning will ensure water quality benefits in the long term. As a result, the unpolluted water sources will aid in good health of the people, animals and ecosystems. Additional secondary benefits are a healthier workforce and living Environment and can add significantly to the economic well-being of the area. Effective and focused protection can be achieved through a differentiated protection approach such as aquifer protection zoning, where the local importance of aquifers is considered (DWAF, 2000). The communication of the benefits must be to communities, interested groups and policy makers for them to start implementing the protection of water resources on all management levels.

Benefits

Proper implementation of aquifer protection zoning will ensure water quality benefits in the long term. As a result, the unpolluted water sources will aid in good health of the people, animals and ecosystems. Additional secondary benefits are a healthier workforce and living environment and can add significantly to the economic benefits. Ecosystem benefits, health benefits to the users and financial savings to the management institutions are some of the benefits of properly implemented protection zoning. These benefits enable the recovery of implementation cost and strengthen the urgency and importance of the implementation of protection zoning. Still, zoning measures need local understanding, acceptance and control to be able to be meaningful. Appropriate participation of the key stakeholders and the general public is a requisite for sustainable development of a scarce resource.

Monitoring of protection zone status

An essential component of any groundwater protection programme is water level and –quality monitoring. This is required to assess the initial conditions and to confirm the effectiveness of the protection measures. A monitoring strategy for an aquifer protection zone is generally designed to perform three functions - source release detection, ambient trend monitoring, and early warning detection (Carter et al., 1987). Verification monitoring is needed to quantify uncertainties in many of the more complex aquifers, especially fractured aquifers (Muldoon. & Bradbury, 2005; Xu and Van Tonder, 2002).

The monitoring within each aquifer protection zone must include (US-EPA, 2004):

1) Monitoring of the chemical composition of the groundwater, including specification of the contributions from human activity.
2) Monitoring of the associated surface systems, including terrestrial ecosystems and bodies of surface water, with which the groundwater body is dynamically linked.

3) Monitoring of the water balance components, which should include water levels, rainfall, discharge and abstraction. These monitoring programmes should be integrated with local protection measures, as in Water Services Plans, Catchment Management Strategies.

Identify potential threats

An inventory of the potential threats to the catchments long-term sustainability needs to be maintained. This must include potential point and non-point sources of contamination as well as activities that impact water quantity, such as urban development. Contamination of groundwater sources has been observed world-wide, and it is becoming self-evident that concentrated human activity will lead to even more groundwater contamination. Groundwater studies in several African countries show that the contamination of water-supply aquifers is mainly due to the improper placement of land-based activities such as agriculture, industries, waste disposal (Banoeng-Yakubo et al., 2006; Boukari et al., 2006; Nkhuwa, 2006; Usher et al., 2004) and excreta disposal (Nkhuwa, 2006; Vogel et al., 2006). In Zambia and Ethiopia the presence of human in the aquifer recharge areas have contaminated groundwater with serious public health implications and risks for users in the future (Nkhuwa, 2006; Tamiru et al., 2005).

Contamination of drinking water occurs when all three the following components exist;

- A potential source of contamination,
- A pathway to an underlying aquifer and
- A potential user of the water.

Groundwater protection zoning is based on the identification and understandings of groundwater flow paths from recharge areas towards potential users. The potential threats can be ranked according to their degree of risk in impairing water sources. Areas in which water sources are vulnerable to these threats can now be identified. Decision makers can use this information to prioritize and decide which threats need to be managed most immediately to prevent, reduce or eliminate risks to water sources.

6.9. Capture zone of the wellfield

The capture zone or contributing area of a ground water extraction well can be defined as that portion of the aquifer from which the well draws its water. Accurate delineation of capture zones is important in many ground water remediation applications and in the definition of wellhead protection areas. The delineation of capture zone is often simplified by using steady-state model based on time-weighted average pumping rates and background hydraulic gradients.

Due to the unique nature of the aquifer type in the area in that it has high ranging between 10 m^2/day to 4200 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 wellfield, major contamination is expected to come from areas outside model domain via Akaki rivers and also from factories nearby. As it can be seen from the figure 82, groundwater is converging towards wellfield from every direction due to higher rate of pumpage from wellfield area. This all areas can be considered as the capture zone of groundwater. This all areas should be protected for safe management of groundwater resource management at the wellfield. Safe capture zone of wellfield without pulling contaminant towards itself is 30 years. After 30 years it starts to suck contaminant from contaminant source particularly from polluted big Akaki river. In figure 82, the green lines indicate that the path lines that contaminant can follow with in 30 years span. This is done by putting particle at the wells in the wellfield and tracking particles backward to see at which time duration contaminants from their source will reach the wells in the wellfield.

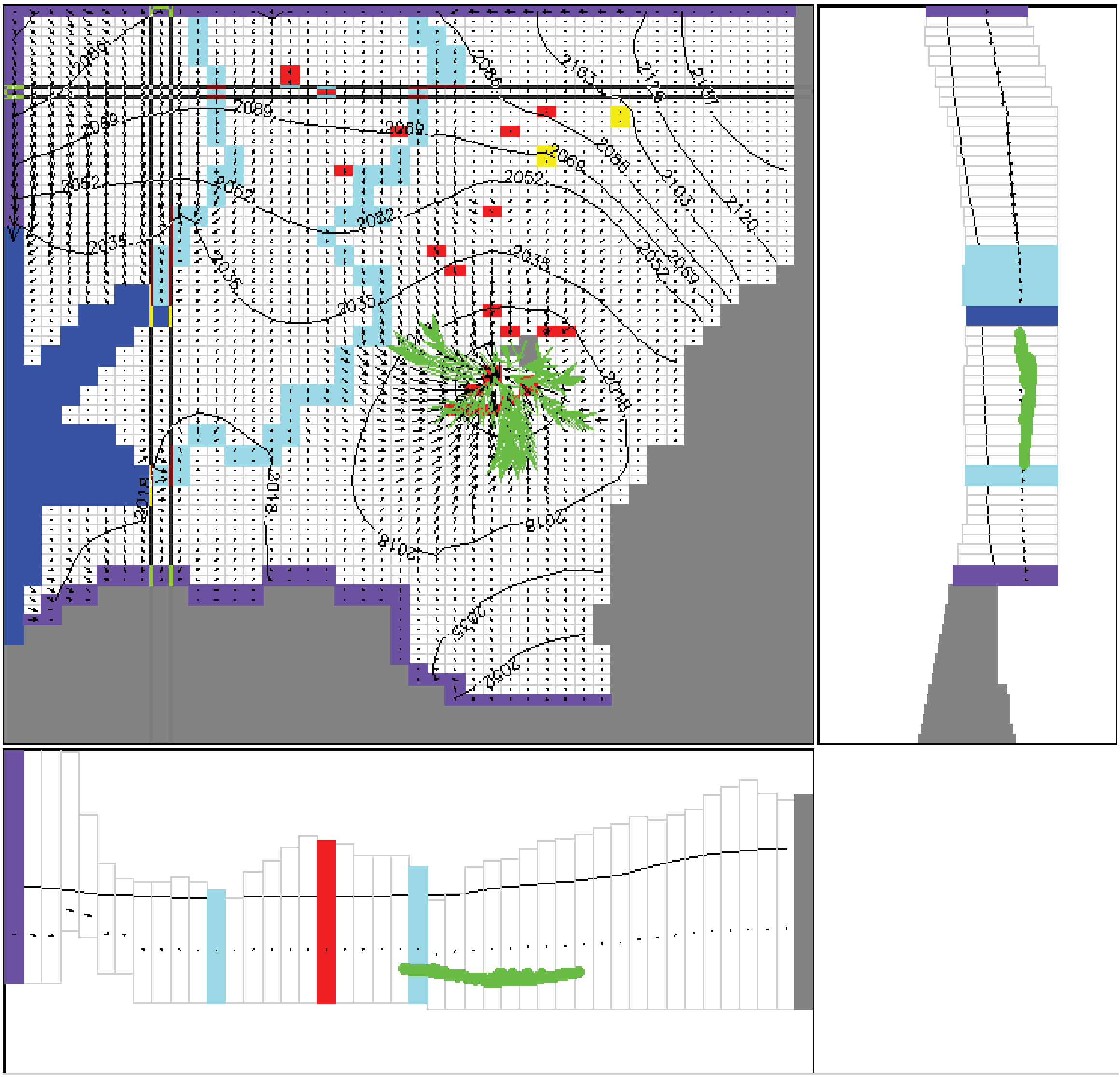


Figure 82. Contamination capture (green) lines of wellfield for 30 years.

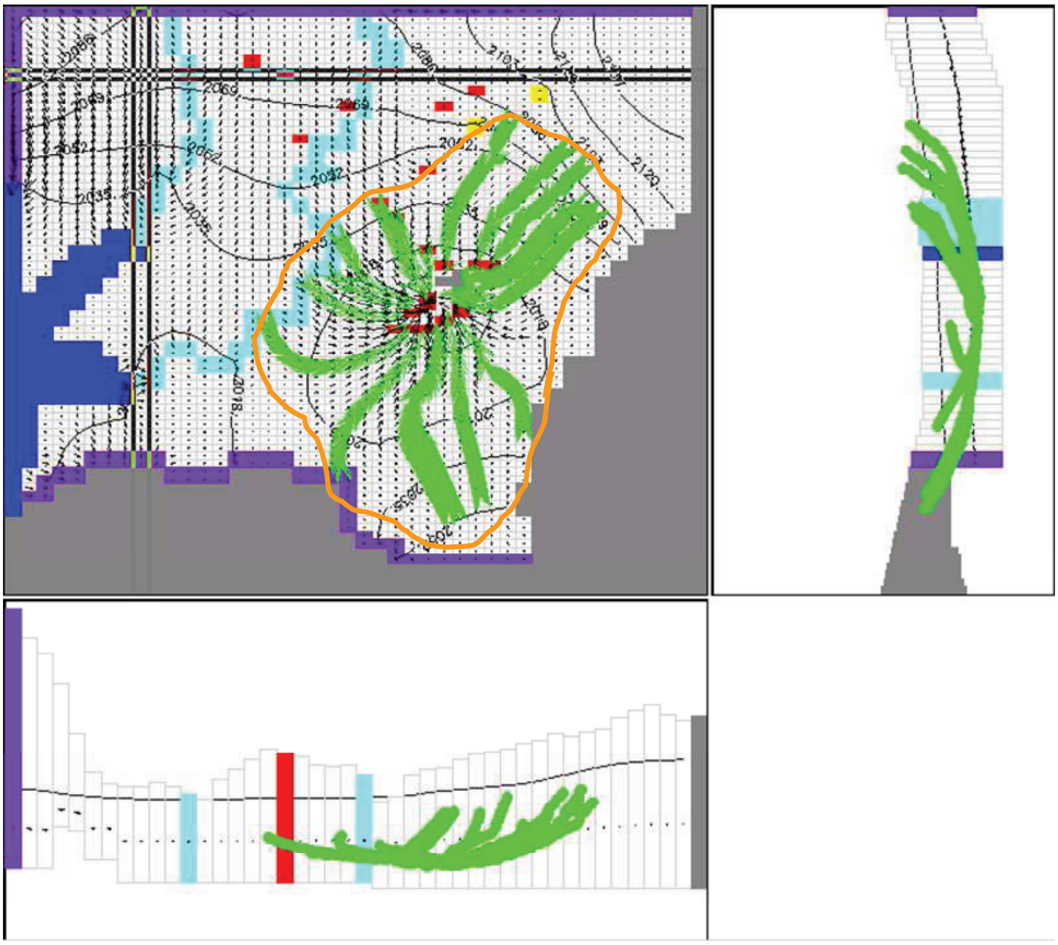


Figure 83. Capture zone of wellfield for 300 years

In this case contaminants from most of the study areas especially from polluted Akaki river and factorie around the wellfield will be captured in the wells. In contrary to this, within 30 years, only areas close to the wellfield are captured.

Protection zone delineation

Many countries world-wide have implemented borehole protection zones, also called groundwater supply protection areas or wellhead protection zones, with the special focus of protecting domestic water supplies against pollution (Foster et al., 2002).

These borehole protection zones have to protect the groundwater from:

- contaminants that decay with time, where subsurface residence time is the best measure of protection; and
- non-degradable contaminants, where flow path-dependent dilution must be provided.

In Ethiopia, particularly in Akaki wellfield aquifers, until today there is no strict zone which is delineated to protect water supply wells against pollution.

6.10. Delineation of a 30 year protection zone of Akaki wellfield

The steady state model is used to delineate a 30 year protection zone, for Akaki wellfield. PMPATH program is employed to simulate path lines by placing particles at borehole sites and tracking them backward over a period of 30 years. The basic assumption regarding this procedure is that the contaminant (example $NO3^{-}$) moves at the velocity of groundwater flow. In addition, major changes in abstraction rates are assumed. This is because great changes in abstraction rates may greatly affect the average seepage velocity of the groundwater, thereby resulting in a different flow pattern and hence the resulting path lines. Figure 84. Shows a 30 year protection zone for boreholes in the wellfield with which a potential source of contaminant should not be placed. The spatial distribution of travel time through the aquifer was obtained by placing particles in appropriate model cells, and tracking their movement backward through time to their point of origin. Generally, the smaller the travel time in a location, the more susceptible is the aquifer to potential contamination at that point.

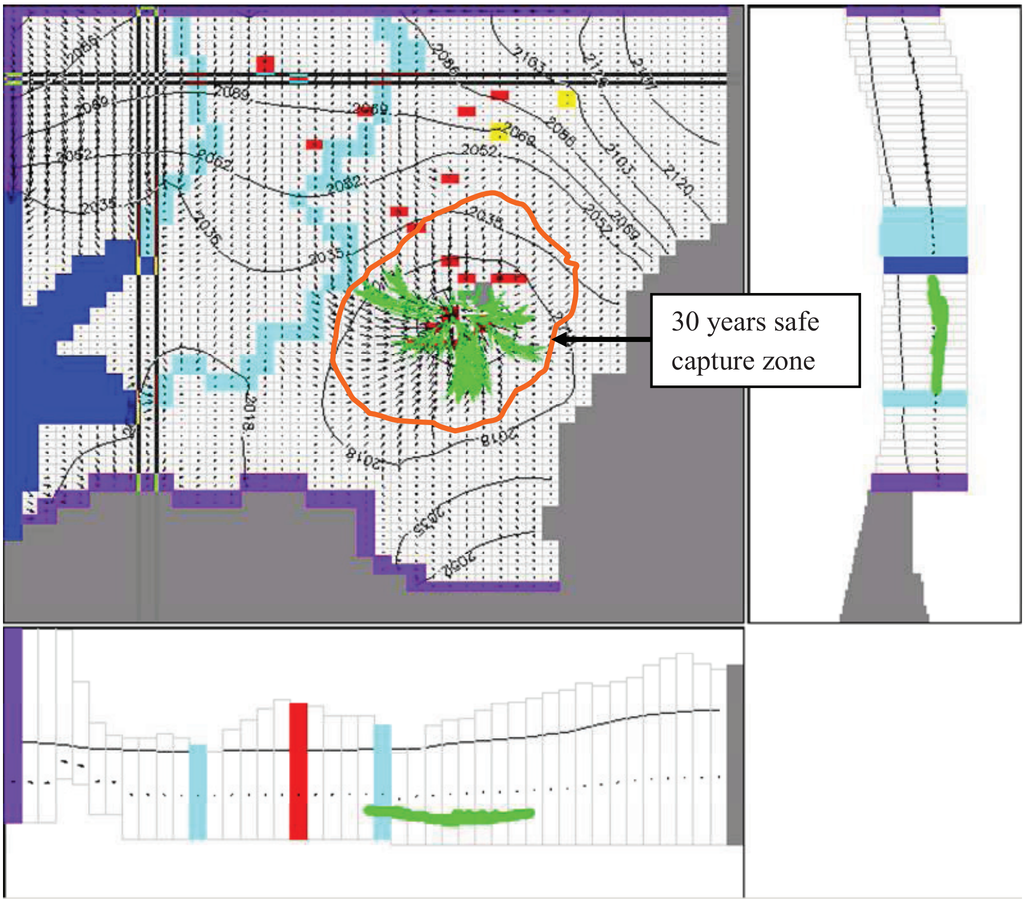


Figure 84. A 30 year protection zone for boreholes in the wellfield

The maximum years that the wellfield can be safe from entering of contaminants from any sources surrounding it with current abstraction rates is 30 years. For more than 30 years duration, contaminants will try to enter in to some of the wells from polluted Akaki river. From other sources of pollution will not pollute for approximately 100 years.

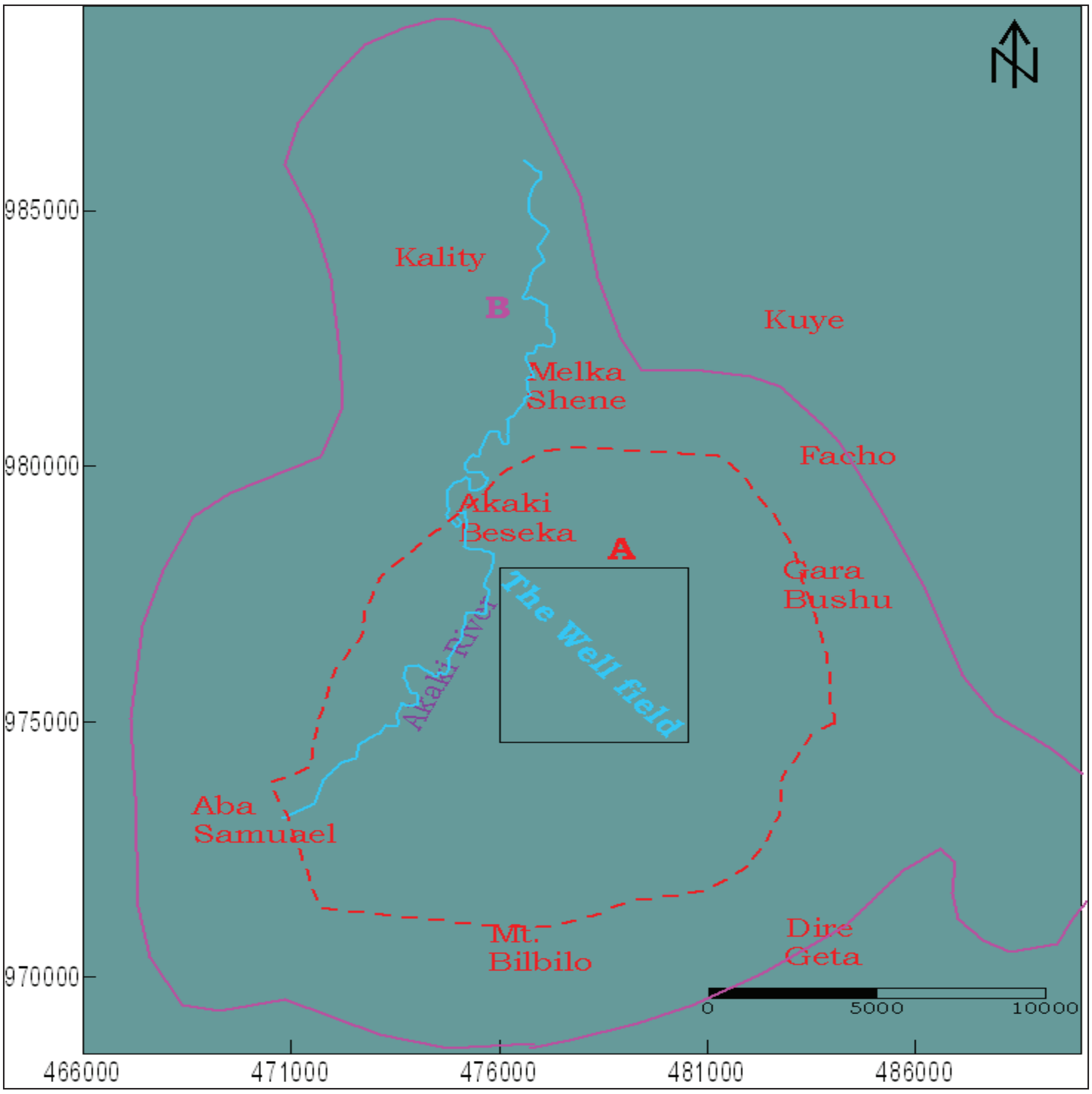


Figure 85. Protection zones delineated around the wellfield.

The protection zones as can be seen in the figure 85, which are represented as zones “A” and “B” should be strictly protected from any pollution sources to the groundwater. Any factories or any pollutant sources should not be constructed in this zone. The upstream of Akaki river should be kept clean to prevent its pollution which can in turn contaminate the wellfield which is operating at pumping rate of more than 46000 m^3/day.

7. Conclusions, discussions and recommendations

7.1. Discussion and conclusions

The Akaki river catchment, which includes the city of Addis Ababa and the Akaki wellfield area, has an extensive drainage system which covers an area of 1500 km2 with an elevation drop of over 1000 m over a distance of about 30 km.

As Addis Ababa is situated at the western shoulder of the main Ethiopian rift, the rocks are strongly affected by the rift tectonics, which is manifested by the number of faults following the general trend of the rift system (NE-SW). The city has a relief of rather flat areas, alternating with volcanic hills and surrounded by trachytic mountains. In general, the Addis Ababa area is underlain by a complex system of aquifers of various size and hydraulic properties, which are mostly hydraulically connected. The aquifer of Akaki wellfield is rather assumed to be made up of many pyroclastic deposits such as scoria, fractured scoraceous and vesicular basalts, ignimbrites, tuff and ashes (AAWSA, 2000).

The annual rainfall values in the catchment are observed to increase with elevation with correlation coefficient of 0.96. Therefore, the hypsometric method is used for rainfall estimation in the catchment. The mean annual rainfall determined by this method is 1224 mm/yr with maximum and minimum RF of 1705 and 970 mm/yr.

The hydrochemical characteristics of groundwater in Akaki catchment volcanic aquifer reflect the interaction of various natural processes and human activities. The overall hydrochemical evolution with in the study catchment is still at early stage, however, because of variations in length of flow path, flow velocity and residence time, a clear evolution from north to south is observed. Less chemically evolved groundwater is represented by a predominant Ca-Na-HCO3 chemical water type dilute system draining from mountainous region of the Intoto silicics, marking typically the initial recharge area. With increased residence times and longer flow paths, groundwater interacts with more aquifer materials and acquires more chemical species with higher concentrations. This is highly reflected by groundwater draining from the young scoria, scoraceous and vesicular basalt located at the south southern part of the catchment (Akaki and Kaliti areas) particularly around the wellfield. Water type around these areas reflects mixed cation bicarbonates with more calcium and magnesium cations indicating much longer residence time and reaction of water with aquifer system. River water samples taken from Akaki bridge reveal Mg-NO3-Cl and other rivers in the area show Ca-Mg-Na-HCO_3 and Ca-Na-HCO_3 type. A shift of water chemistry towards $SO4^{+2}$ Cl and $NO3^{-1}$ is mostly related to the infiltration of contaminants into the rivers or subsurface rather than natural dissolution processes.

The aquifer system is multilayered, but since almost all of the boreholes are screened at more than one aquifer layer, the aquifer parameters reported represent the screened layers all together. Therefore, treatment of each aquifer layer is practically impossible at this stage. Because of this, modeling at the Akaki catchment and wellfield is done taking the screened aquifers as single layer. Well logs are used to assist in the conceptualization of the system prior to accomplish modeling works in wellfield and its catchment.

The area is made up of multi-aquifers having different hydrogeological characteristics and all types of aquifers are found in the area (confined, semic-confined and confined) including perched aquifers.

The Chloride Mass Balance Method (CMB), semi-distributed water balance model and recursive digital filter methods were employed to estimate the recharge in the catchment.
Mean annual groundwater recharge based on CMB is 326 mm year-1 which is 24 % of the average annual rainfall in the area. This figure sets the upper limit to the recharge because effluents from the city are also infiltrating to groundwater elevating the chloride contents. Chloride mass balance assumes that all the rainfall in the catchment infiltrates and contributes to recharge. It also assumes that no additional source of chloride is available besides rain chloride. However, these two assumptions are not valid in this catchment because of a total runoff of about 492 MCM/yr which results from direct runoff and urban water return flow. The city of Addis Ababa is located in the catchment and it has unregulated solid and liquid waste disposal in the catchment leading in elevated chloride concentrations in both groundwater and surface water sources which also falsifies another assumption in to use CMB. As the result of this, recharge is overestimated by this method for this particular catchment. To integrate with CMB, another two methods are adapted in present study to evaluate recharge namely: semi-distributed water balance model and recursive digital filter methods. From the water balance as simulated by the catchment's model, the total average base flow estimated is 92 MCM/yr or 62 mm/yr. From the water balance model described in chapter 3, a base flow and recharge value of 130 MCM/yr or 87 mm/yr is found. Using the digital filter method, the base flow and recharge values are roughly 65 MCM/yr (63mm/yr) indicating good agreement between the models.

The aquifer parameters obtained from the pumping test result show very high contrasting hydraulic properties spatially. There are extremely high and low values of transmissivity and hydraulic conductivity values obtained from nearby wells. The assumptions of homogeneity and infinite horizontal extent of aquifer usually considered in pumping test data analysis are not valid here due the geological heterogeneity of the area. Thus it is tried to optimize the hydraulic properties during the calibration process using the calibration target (hydraulic heads).
The water budget in the catchment model agrees with the modeling results obtained from other models as explained in chapters 3, 4 and 5.
Concerning the modelling works in this study the following issues should be pointed out:

1. The Akaki wellfield 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 wellfield.
2. In the model domain, the groundwater flow lines converge towards Akaki wellfield from all directions, implying that contaminants are carried into the wellfield from all directions.
3. The intensive pumping of groundwater from the Akaki wellfield 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 wellfield.

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 wellfield in less than 30 years time.
5. Flow velocities are different throughout the system. They are more rapid in areas where porosity and transmissivity are high (wellfield and Akaki town) and lower in relatively flat areas (Fanta and Kuye areas).
6. Generally, though urbanization and industrialization are the immediate sources of contamination, the geological and hydrogeological character of the area facilitates contaminant migration.

7.2. Recommendations

Several assumptions had to be made for the hydrological modelling purpose in the present study because of lack of sufficient knowledge about interactions between different hydrological processes. Data inadequacy was also encountered critically. Consequently, further works need to be undertaken in data collection and field investigations, among which the following are worth mentioning:

The gauging station at Aba Samuel has to be calibrated using a wide range of stage and discharge data, as this gauging station is highly important for the study of the Akaki groundwater as well as stream-aquifer interactions. The rating curves of gauging stations on Mutinicha river at the confluence point with Akaki River downstream of Legedadi dam and Little Akaki river at Asco Tunnery should be checked regularly and recalibrated if necessary so that they can produce good quality data over a wide range of stage discharge values.

Recharge mechanisms of Akaki aquifer should be investigated further. This requires a detailed understanding of the hydrogeology of the region. The spatial variation of permeability should also be studied in depth through field and laboratory tests.

Knowledge about stream-aquifer interaction, particularly in the wellfield area, should develop further in order to improve the representation of the actual aquifer by the conceptual model and assess the risk of pollution of the aquifer by Akaki river more accurately. The piezometers planned to be drilled in the wellfield area with the assistance of International Atomic Energy Agency (IAEA) would be of great value in this regard. Integrated surface water – groundwater-modelling approach is expected to give a better representation of the reality. Therefore, attempt should be made to refine the groundwater modelling procedure in that direction.

To model the catchment as well as wellfield with reduced model uncertainties, the following should be recomended first.

- Further work is required to define the thickness of each formation because it has significance in the distribution of hydrogeological properties.
- The clear demarcation between different formations requires further detail study.
- The aquifer geometry and layers need detailed study and investigation.
- Thoroughly understanding of the multi- layer volcanic aquifer in the area, this may be used in the assessment of the extent to which pollutants percolate in the subsurface.

- Further chemical and isotopic analysis has to be adopted for groundwater flow paths and hydrodynamics analysis.
- Application of mass-balance and flow simulation (mixing model) calculations to interpretations of mixing between different water types including surface and ground waters.
- Continuous monitoring of water quality and water level must be conducted so as to determine the groundwater dynamics.

In view of tackling the actual and potential contamination risks of the Akaki wellfield and the Akaki river catchment in general, more effort should be made to address the following points:

- Unless proper groundwater management strategy is implemented, the groundwater resource may become at risk. Presently there is no controlling and management mechanism for the aquifer in the studied area. Therefore, it would be important at this juncture to implement appropriate management and controlling mechanism for the groundwater resource.
- Conduct contaminant transport analysis taking into account chemical reactions, attenuation and multiple layer aquifer structures;
- 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 wellfield;
- 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 wellfield and surrounding areas in addition to the surface waters.

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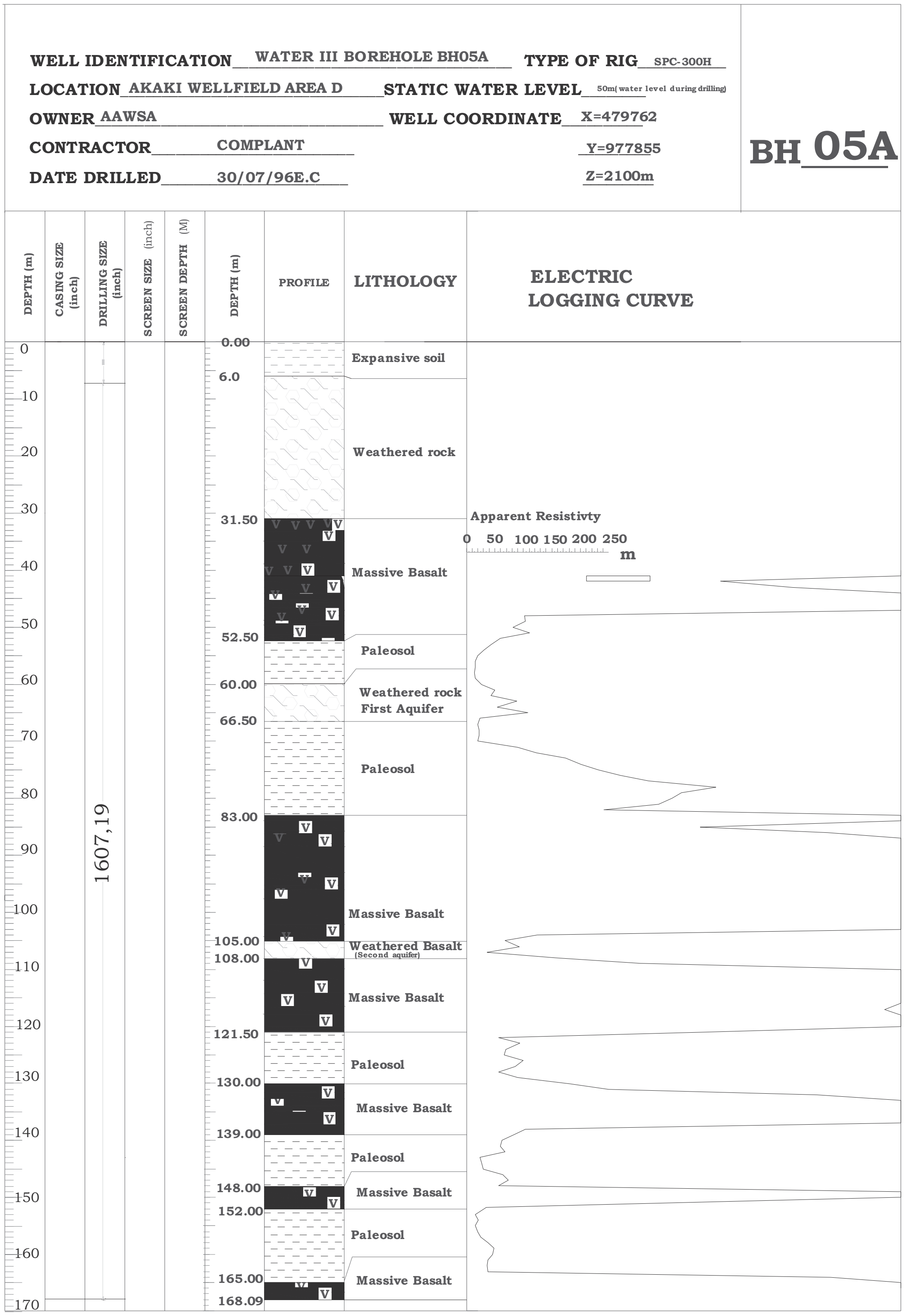
APPENDICES

Appendix 1 Geologic logs, Resistivity logs, and their corresponding values



WELL IDENTIFICATION WATER III BOREHOLE BH17 **TYPE OF RIG** SPC-300H

LOCATION AKAKI WELLFIELD AREA D **STATIC WATER LEVEL** 45.90m

OWNER AAWSA **WELL COORDINATE** X=478204

CONTRACTOR COMPLANT Y=976364

DATE DRILLED 11/11/96/E.C Z=2065.30m

BH 17

DEPTH (m)	CASING SIZE (inch)	DRILLING SIZE (inch)	SCREEN SIZE (inch)	SCREEN DEPTH (M)
0–19	20	24		
19–90	14	17.5		
73–90			14	77.04–89.00
90–142	8	12		
108–136			8	108.47–137.47

DEPTH (m)	PROFILE / LITHOLOGY
0.00–4.00	Expansive soil
4.00–32.00	Weathered rock
32.00–46.00	Massive Basalt
46.00–56.00	Paleosol
56.00–63.00	Weathered rock (First Aquifer)
63.00–68.50	Massive Basalt
68.50–94.00	Weathered rock (Second Aquifer)
94.00–96.00	Paleosol
96.00–110.50	Massive Basalt
110.50–119.00	Weathered rock (Third Aquifer)
119.00–126.00	Massive Basalt
126.00–130.00	Paleosol
130.00–141.50	Weathered rock (Four Aquifer)

LITHOLOGY ELECTRIC LOGGING CURVE

WELL IDENTIFICATION: WATER III BOREHOLE BH23 TYPE OF RIG: SPC-300H
LOCATION: AKAKI WELLFIELD AREA D STATIC WATER LEVEL: 44.00m
OWNER: AAWSA WELL COORDINATE: X=477477
CONTRACTOR: COMPLANT Y=977216
DATE DRILLED: 10/07/97 EC Z=2064.30m

BH 23

DEPTH (m)	CASING SIZE (inch)	DRILLING SIZE (inch)	SCREEN SIZE (inch)	SCREEN DEPTH (M)	DEPTH (m)	PROFILE	LITHOLOGY
0	20	24			0.00 – 5.00		Expansive soil
10					5.00 – 13.00		Weathered rock
20	14	17.5			13.00 – 24.00		Massive Basalt
							Weathered rock
30					26.00 – 33.00		Massive Basalt
40					33.00 – 44.00		Weathered rock
50					44.00 – 49.00		Massive Basalt
60					49.00 – 72.00		Weathered rock (First Aquifer)
70			14	68.91 – 80.51	72.00 – 85.00		Massive Basalt
80					85.00 – 89.00		Weathered rock (Second Aquifer)
90					89.00 – 97.00		Massive Basalt
100	8	12			97.00 – 109.00		Weathered rock (Third Aquifer)
110			8	103.64 – 138.44	109.00 – 112.00		Massive Basalt
120					112.00 – 135.00		Weathered rock (Fourth Aquifer)
130							
140					135.00 – 145.00		Massive Basalt
150							
160							
170							

ELECTRIC LOGGING CURVE

WELL IDENTIFICATION WATER III BOREHOLE BH24 TYPE OF RIG SPC-300H

LOCATION AKAKI WELLFIELD AREA D STATIC WATER LEVEL 42.93m

OWNER AAWSA WELL COORDINATE X=477330

CONTRACTOR COMPLANT Y=976793

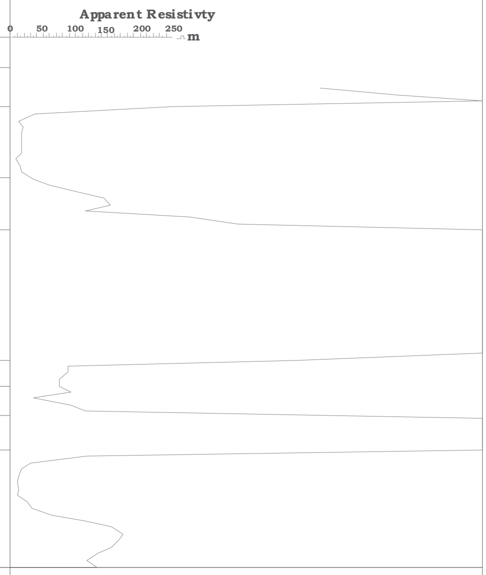
DATE DRILLED 25/10/97 EC Z=2061.6m

BH 24

DEPTH (m)	CASING SIZE (inch)	DRILLING SIZE (inch)	SCREEN SIZE (inch)	SCREEN DEPTH (M)
0 – 15	20	24		
15 – 90	14	17.5		
62.96 – 74.56			14	62.96 – 74.56
90 – 130	8	12		
100.73 – 123.93			8	100.73 – 123.93

DEPTH (m)	PROFILE / LITHOLOGY
0.00 – 7.00	Expansive soil
7.00 – 18.00	Weathered rock
18.00 – 34.00	Massive Basalt
34.00 – 41.00	Weathered rock
41.00 – 48.00	Massive Basalt
48.00 – 53.00	Weathered rock (First Aquifer)
53.00 – 59.00	Massive Basalt
59.00 – 70.00	Paleosol
70.00 – 78.00	Weathered rock (Second Aquifer)
78.00 – 98.00	Massive Basalt
98.00 – 102.00	Paleosol
102.00 – 107.00	Weathered rock (Third Aquifer)
107.00 – 112.00	Massive Basalt
112.00 – 130.00	Weathered rock (Fourth Aquifer)

ELECTRIC LOGGING CURVE



Appendix 2 Electric logging record (resistivity & self potential logging)

BH name: BH5a Depth of Borehole: 168.09m Date:17/11/1997

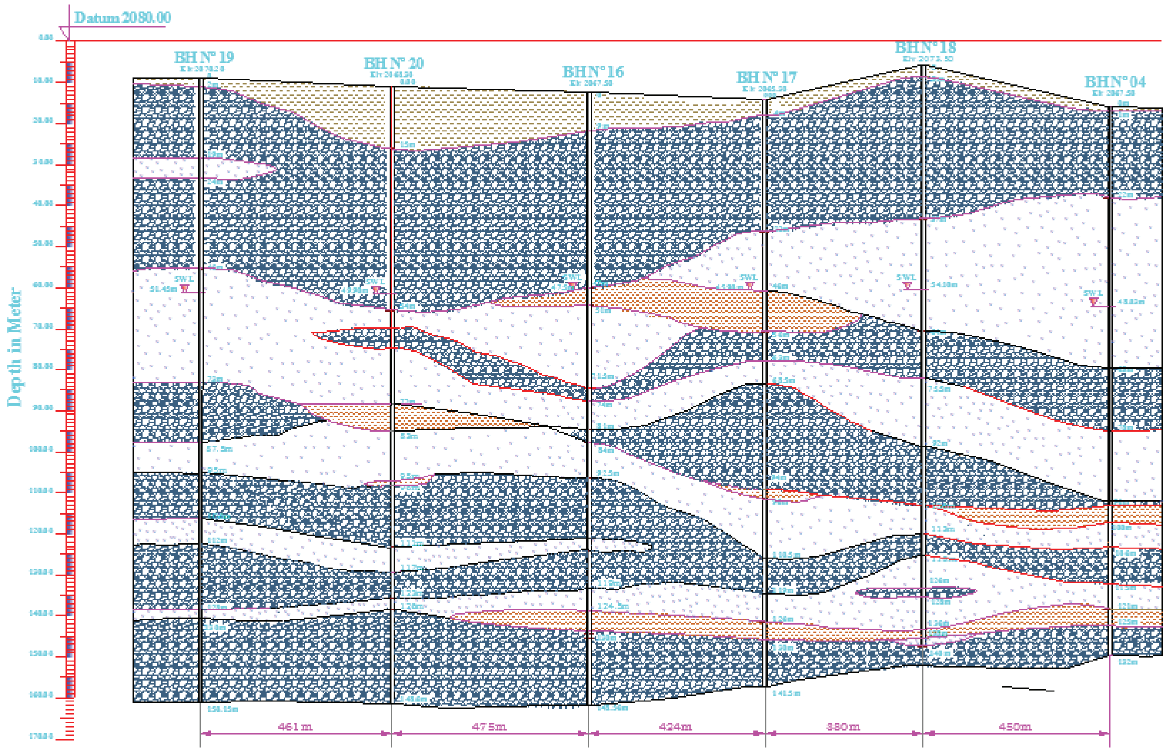
Measurement Method: Apparent Resistively (No.2M 1.9A) Self potential Logging Vsp (mv)

Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)
168	28.2	1042.0	124.0	41.4	69.1	81.0	64.1	360.0
167	26.0	939.5	123.0	43.8	95.2	80.0	53.1	377.0
166	25.7	638.2	122.0	41.6	56.8	79.0	54.6	437.0
165	24.8	36.7	121.0	43.6	418.0	78.0	54.3	319.0
164	23.8	36.3	120.0	87.4	2500.0	77.0	55.1	270.0
163	22.5	36.4	119.0	57.3	1071.0	76.0	55.5	231.0
162	22.3	37.0	118.0	47.6	691.0	75.0	56.8	201.0
161	23.2	45.2	117.0	48.7	733.0	74.0	56.3	1745.0
160	21.3	49.6	116.0	45.4	995.0	73.0	57.7	1237.0
159	23.6	36.8	115.0	45.4	2970.0	72.0	57.2	89.0
158	24.5	24.8	114.0	49.3	2760.0	71.0	58.4	19.2
157	27.2	19.7	113.0	46.8	2440.0	70.0	58.4	22.0
156	24.6	14.8	112.0	50.3	2240.0	69.0	50.7	22.8
155	21.4	20.8	111.0	49.5	1551.0	68.0	60.5	19.7
154	27.4	16.2	110.0	48.5	304.0	67.0	59.8	23.5
153	23.2	35.3	109.0	47.7	1552.0	66.0	60.2	167.3
152	198.9	366.0	108.0	544.0	36.1	65.0	62.6	53.9
151	196.5	1714.0	107.0	47.2	93.0	64.0	61.3	87.8
150	198.8	1461.0	106.0	53.6	66.5	63.0	62.7	42.9
149	197.9	565.0	105.0	53.6	123.8	62.0	60.1	50.4
148	194.7	73.3	104.0	54.4	5150.0	61.0	63.1	27.2
147	25.8	63.2	103.0	47.3	5840.0	60.0	61.3	1511.0
146	25.3	30.0	102.0	53.6	5300.0	59.0	61.0	1436.0
145	22.5	27.0	101.0	56.3	3220.0	58.0	60.9	1626.0
144	26.2	24.0	100.0	56.0	2260.0	57.0	60.5	1627.0
143	25.4	67.5	99.0	56.0	2410.0	56.0	59.7	20.7
142	24.7	60.2	98.0	59.4	3060.0	55.0	61.4	19.6
141	26.9	60.7	97.0	59.1	3430.0	54.0	61.8	31.3
140	30.9	82.7	96.0	58.5	2420.0	53.0	61.8	43.3
139	27.4	104.4	95.0	61.2	2230.0	52.0	60.9	504.0
138	28.5	1221.0	94.0	58.6	2530.0	51.0	59.0	1106.0
137	29.2	1456.0	93.0	58.4	2570.0	50.0	60.2	818.0
136	27.5	847.0	92.0	59.2	2860.0	49.0	63.3	1043.0
135	29.3	1096.0	91.0	60.9	2200.0	48.0	63.2	1025.0
134	30.5	1194.0	90.0	58.9	1732.0	47.0	58.0	244.0
133	34.0	614.0	89.0	60.0	1580.0	46.0	57.3	2130.0
132	30.9	249.0	88.0	63.0	813.0	45.0	55.1	1323.0
131	36.3	180.0	87.0	61.1	632.0	44.0	56.0	1264.0
130	34.9	90.1	86.0	61.1	409.0	43.0	55.3	571.0
129	36.6	56.1	85.0	63.1	1162.0	42.0	55.8	447.0
128	38.5	85.8	84.0	63.9	1055.0	41.0	54.7	1353.0
127	37.6	71.6	83.0	62.5	241.0	40.0	53.2	1647.0
126	38.3	99.3	82.0	62.6	337.0			
125	40.1	66.6						

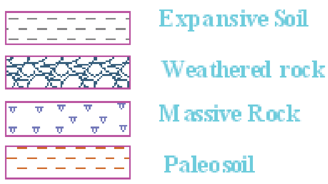
BH Name: BH 17			Depth of Borehole: 141m			Date: 26/10/1996		
Measurement Method: Apparent Resistively (No.2M 1.9A) Self potential Logging Vsp (mv)								
Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)
141	52.7	30.0	111.0	49.8	366.0	81.0	41.1	29.2
140	55.3	30.4	110.0	54.2	2250.0	80.0	29.0	113.7
139	55.1	29.9	109.0	50.6	2150.0	79.0	42.0	108.0
138	57.2	30.7	108.0	47.7	1899.0	78.0	40.2	101.0
137	56.9	24.8	107.0	49.3	1837.0	77.0	41.0	96.2
136	57.1	78.3	106.0	49.0	1605.0	76.0	40.9	92.7
135	56.5	22.0	105.0	47.3	1349.0	75.0	40.4	89.7
134	57.5	86.1	104.0	47.3	1139.0	74.0	39.2	68.4
133	55.4	30.2	103.0	47.1	1057.0	73.0	40.4	55.7
132	53.6	33.1	102.0	46.9	1025.0	72.0	45.6	48.7
131	56.0	30.1	101.0	46.2	1195.0	71.0	37.8	41.4
130	49.3	18.6	100.0	45.2	1222.0	70.0	38.8	91.5
129	54.7	29.0	99.0	45.1	1168.0	69.0	40.3	126.2
128	49.6	42.5	98.0	43.4	672.0	68.0	39.3	270.0
127	52.0	677.0	97.0	41.9	363.0	67.0	40.0	440.0
126	53.6	453.0	96.0	43.8	172.5	66.0	36.5	298.0
125	46.3	1362.0	95.0	45.8	205.0	65.0	37.0	209.0
124	42.7	990.0	94.0	45.7	297.0	64.0	32.8	150.4
123	55.5	914.0	93.0	45.9	450.0	63.0	36.7	88.6
122	55.9	599.0	92.0	44.8	498.0	62.0	35.7	99.5
121	53.0	177.6	91.0	41.0	196.8	61.0	35.2	99.9
120	52.1	73.0	90.0	40.9	112.4	60.0	35.9	83.3
119	54.8	34.4	89.0	43.4	86.1	59.0	35.3	75.1
118	56.0	23.9	88.0	45.2	51.5	58.0	37.9	70.0
117	53.6	14.3	87.0	42.9	35.1	57.0	37.4	76.2
116	54.9	1297.0	86.0	41.5	28.9	56.0	37.4	74.0
115	52.0	685.0	85.0	36.7	79.7	55.0	35.9	50.2
114	45.3	339.0	84.0	43.4	49.0			
113	46.4	218.0	83.0	43.2	32.9			
112	45.8	170.0	82.0	43.3	30.8			

BH Name: BH24		Depth of Borehole: 130m			Date: 28/9/1997			
Measurement Method: Apparent Resistively (No.2M 1.9A) Self potential Logging Vsp (mv)								
Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)	Depth (m)	Vsp (mv)	Ps (Ωm)
130	39.1	132.5	104.0	29.0	34.1	79.0	21.5	1853.0
129	28.1	117.2	103.0	28.2	93.3	78.0	19.0	1025.0
128	37.6	137.6	102.0	29.1	76.3	77.0	19.4	351.0
127	36.5	156.5	101.0	26.6	74.9	76.0	21.0	278.0
126	35.2	168.3	100.0	27.3	87.6	75.0	22.6	16.3
125	34.2	173.2	99.0	27.2	88.6	74.0	23.0	154.2
124	31.9	157.2	98.0	27.1	443.0	73.0	22.4	144.5
123	32.4	115.9	97.0	26.7	1717.0	72.0	25.9	107.2
122	31.4	65.4	96.0	24.3	1766.0	71.0	28.3	59.3
121	32.8	33.1	95.0	23.3	1379.0	70.0	23.4	36.2
120	33.5	25.8	94.0	24.5	2100.0	69.0	21.7	15.5
119	32.1	11.1	93.0	25.6	2400.0	68.0	25.0	15.1
118	30.9	12.8	92.0	23.4	2100.0	67.0	22.3	8.4
117	30.7	10.3	91.0	22.1	1289.0	66.0	21.8	16.3
116	31.1	13.1	90.0	22.7	946.0	65.0	22.0	15.9
115	30.8	18.0	89.0	23.4	1475.0	64.0	22.0	16.4
114	30.1	30.7	88.0	21.8	1512.0	63.0	20.9	18.1
113	30.8	117.0	87.0	21.1	1222.0	62.0	21.1	18.9
112	29.9	3160.0	86.0	22.0	1000.0	61.0	22.4	12.3
111	29.2	1988.0	85.0	22.8	968.0	60.0	22.6	36.9
110	27.2	1835.0	84.0	22.9	2260.0	59.0	22.9	250.0
109	28.9	1362.0	83.0	23.2	3500.0	58.0	19.8	944.0
108	28.2	1018.0	82.0	20.2	2940.0	57.0	20.4	599.0
107	28.5	781.0	81.0	20.4	2480.0	56.0	18.3	479.0
106	28.1	15.5	80.0	21.9	2120.0			
105	27.3	93.4						

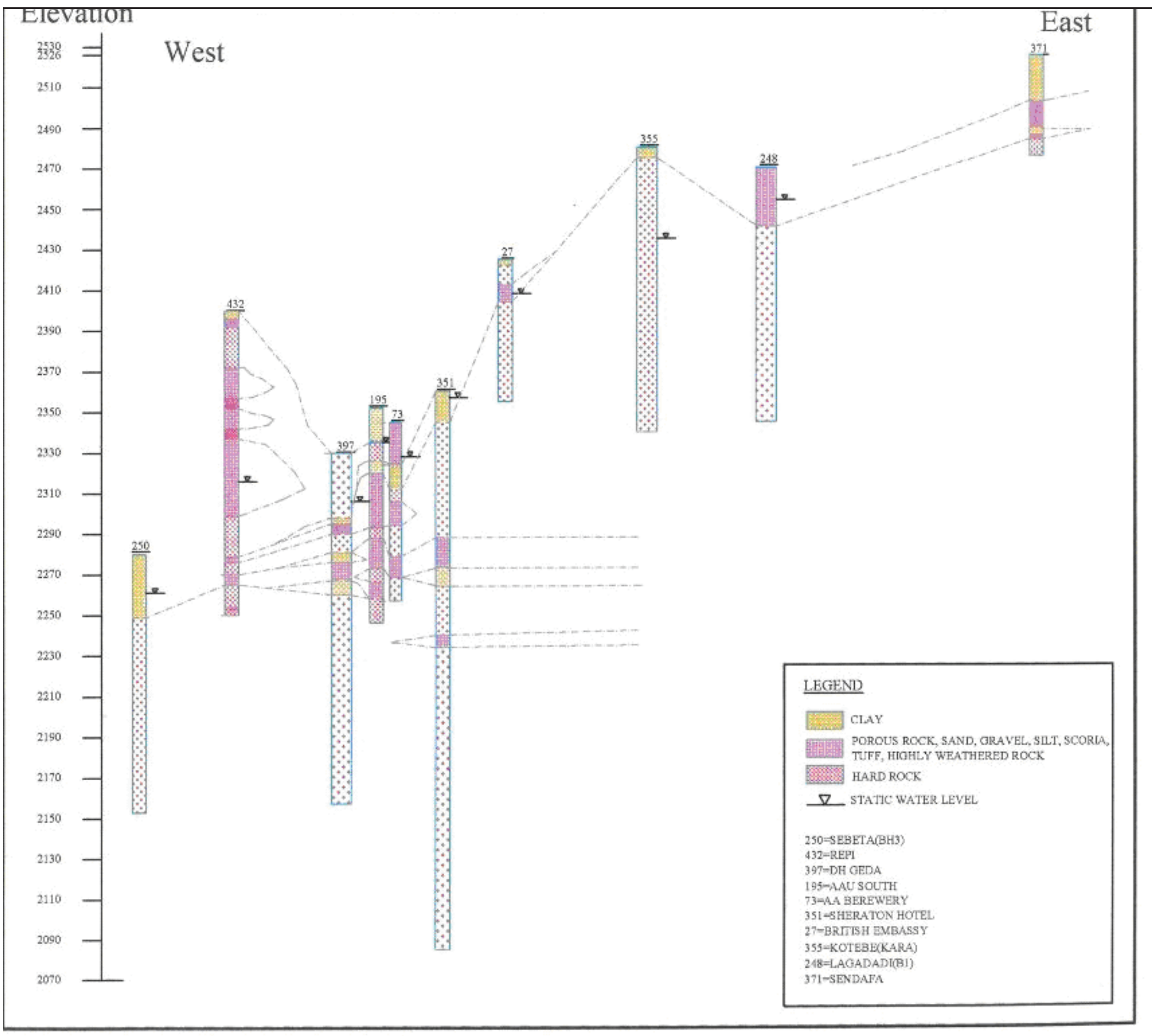
Appendix 3 Hydrostratigraphic cross-section on the wellfield



North-south well log correlation in Akaki wellfield (2.2 km)



Appendix 4 E-W well log correlation of catchment (Dereje Nigusse, 2003)



Appendix 5 How to correct ASTER DEM with topographic map

The relationship between the ground elevation and the elevation from ASTER DEM is shown in figure 2. The elevations from ASTER DEM and those from the topographic map show high correlation with R2 of 0.97. Before applying the elevation extracted from the DEM for further analysis, the elevation is corrected by the regression equation obtained by the built comparison to the ground control point elevations and the extracted elevation. The regression equation obtained from the comparison is $X = (Y- 161.65)/ (0.8992)$, where Y is the elevation from ASTER and X is the elevation from Topomap of the area. The correction process of the elevation from the ASTER is accomplished by applying this formula in the Map calculation of ILWIS. After correction, the required array of elevations at the well locations is extracted by applying the map value function of ILWIS to the ASTER DEM. The following steps illustrate how to correct the digital elevation model before determining rainfall distribution in the catchment

1. **Georeferencing Topo map**

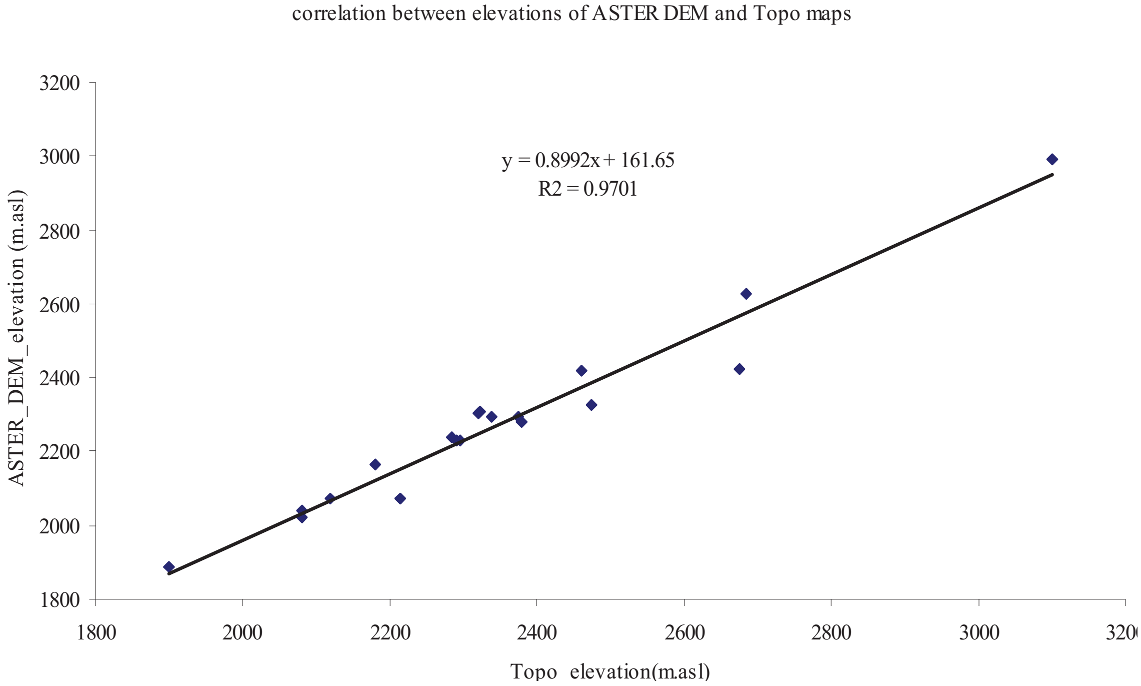
X	Y	Row	Col	Active	DRow	DCol
474000	968000	6965	2603	True	0.15	0.21
490000	990000	1823	6453	True	-0.17	-0.43
499000	968000	7061	8505	True	0.01	-0.06
490000	980000	4188	6420	True	-0.26	-0.16
499000	994000	912	8592	True	0.26	0.44

Sigma = RMSE = 0.402

2. exteraction of elevation from topo map and correcting ASTER DEM with topo map

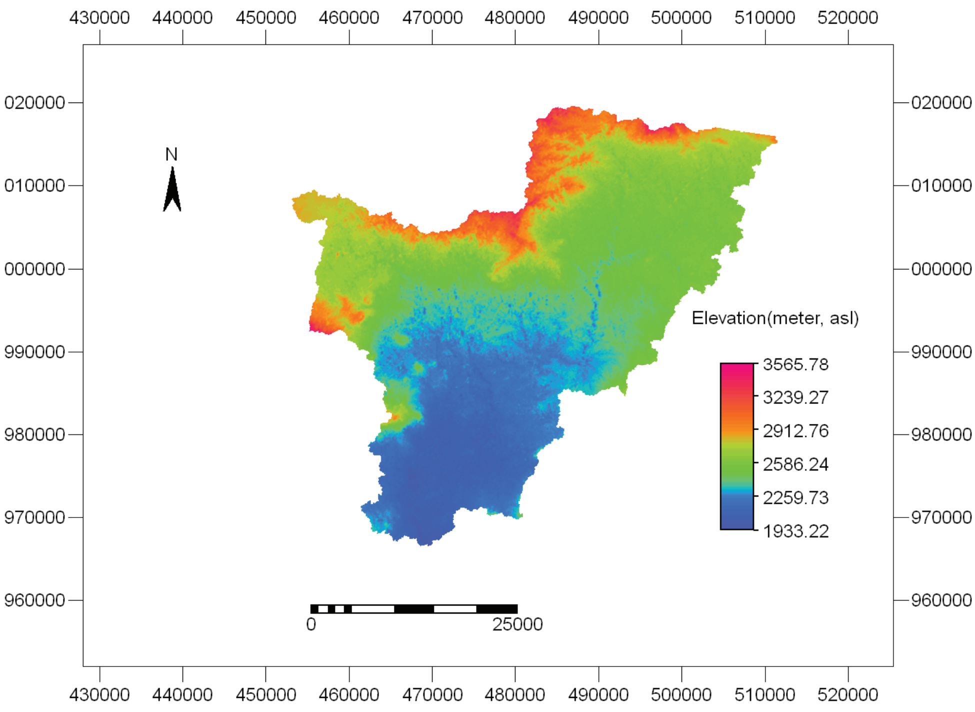
Name	Coordinate	DEM_elevation (m)	TOPO_elevation (m)
1	(491044.00, 973800.00)	2071	2215
2	(492407.00, 979125.00)	2232	2290
3	(495527.00, 983711.00)	2992	3100
4	(493090.00, 984169.00)	2627	2685
5	(492809.00, 983498.00)	2426	2675
6	(489007.00, 981390.00)	2293	2375
7	(484607.00, 984201.00)	2232	2295
8	(482944.00, 986524.00)	2239	2285
9	(476446.00, 991839.00)	2306	2323
10	(476602.00, 994125.00)	2295	2338
11	(477319.00, 981117.00)	2038	2080
12	(478227.00, 975893.00)	2021	2080
13	(477467.00, 970090.00)	2279	2380
14	(480681.00, 969888.00)	2329	2475
15	(484831.00, 967646.00)	1890	1900
16	(491046.00, 973802.00)	2071	2215
17	(498704.00, 981218.00)	2305	2320
18	(498424.00, 993224.00)	2421	2460
19	(481077.00, 988008.00)	2167	2180
20	(474577.00, 971828.00)	2074	2120

Points used to correct the ASTER DEM



Scatter plot of ground elevation vs elevation from ASTER DEM

3. Corrected DEM for Akaki catchment

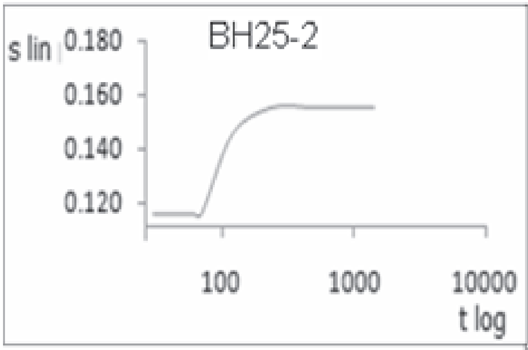


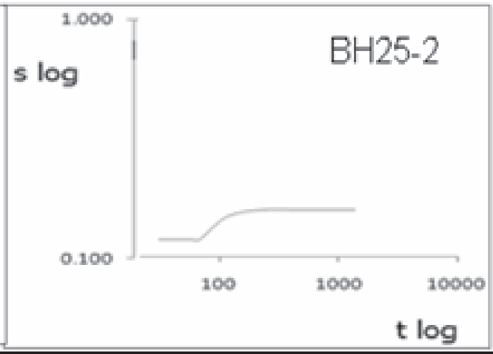
Corrected DEM of Akaki catchment

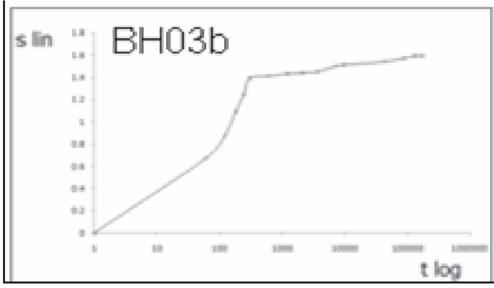
Appendix 6 Chloride concentration in Akaki catchment (2007 – 2008)

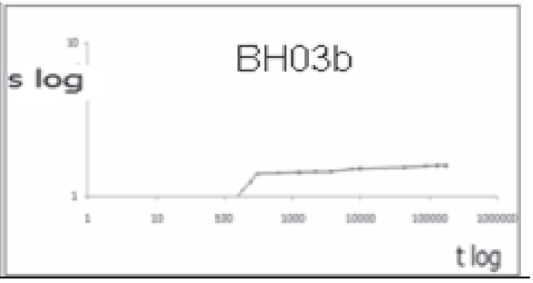
sample ID	X	Y	Groundwater Cl (mg/l)	Average rainfall Cl (mg/l)	Year
G-3	462754	995769	0.6	0.95	2007
G-4	462788	992425	1.3	0.95	2007
G-5	503833	1012823	17.6	0.95	2007
G-6	501208	1013728	1.8	0.95	2007
G-7	503448	1012814	3.2	0.95	2007
G-10	481266	981756	8	0.95	2007
G-11	479544	981260	10.8	0.95	2007
G-13	493917	1005045	1.2	0.95	2007
G-14	493167	1004737	3.5	0.95	2007
G-15	491200	1004464	2.9	0.95	2007
G-18	473369	1005062	1.3	0.95	2007
G-19	456121	1002559	12.7	0.95	2007
G-20	458156	998337	1.5	0.95	2007
G-21	464365	988869	6.7	0.95	2007
G-26	479954	977334	6	0.95	2007
G-27	479700	976927	6.4	0.95	2007
G-28	478347	976750	8.2	0.95	2007
G-42	479031	977601	10	0.95	2007
EP-04	479118.5	977807.4	11.7	0.7	2008
BH-05	476680.7	975819.8	4.9	0.7	2008
BH-01	478061.4	975076.1	3.2	0.7	2008
BH-10	479155.1	976241.9	5.0	0.7	2008
F3	479779.2	981769.5	11.7	0.7	2008
Iron & steel BH	476743.0	980936.4	9.2	0.7	2008
Food Factory BH	476760.5	980804.8	23.7	0.7	2008
Spare Parts BH	478347.8	977935.0	6.6	0.7	2008

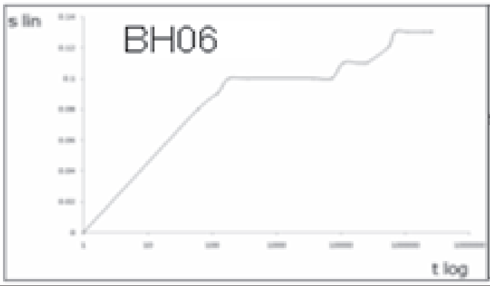
Appendix 7 Plots of time-drawdown curve for selected bore holes

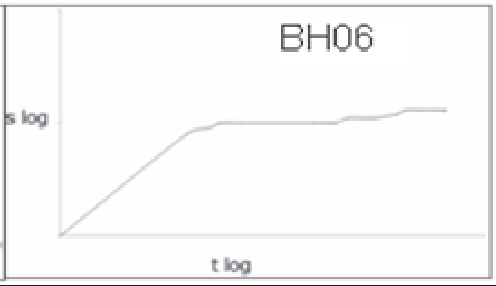


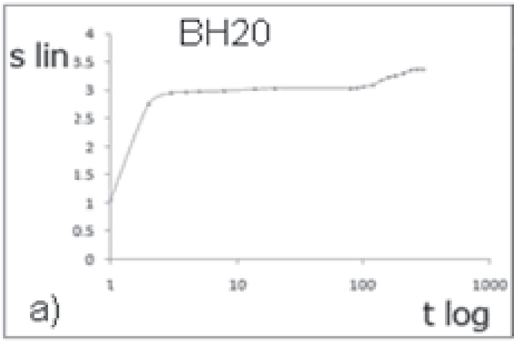


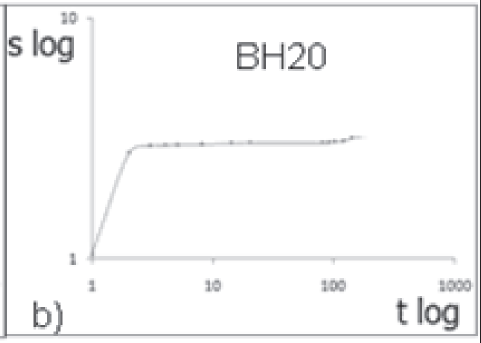


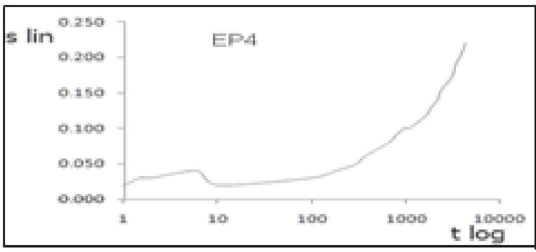


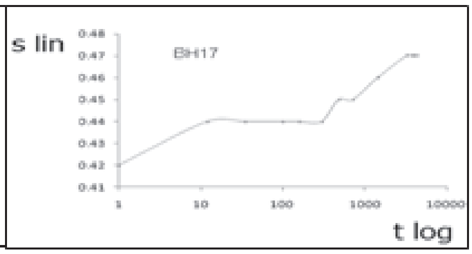




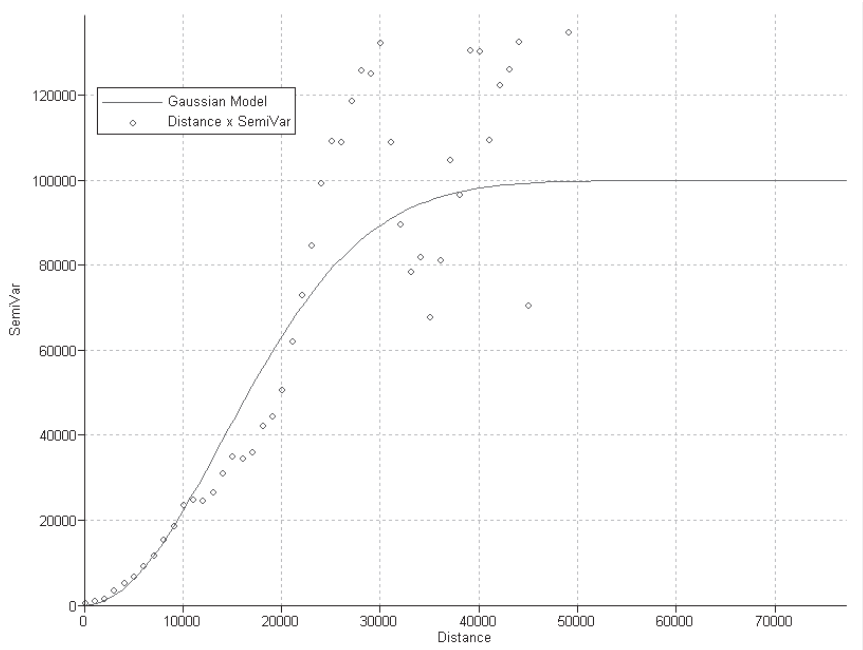




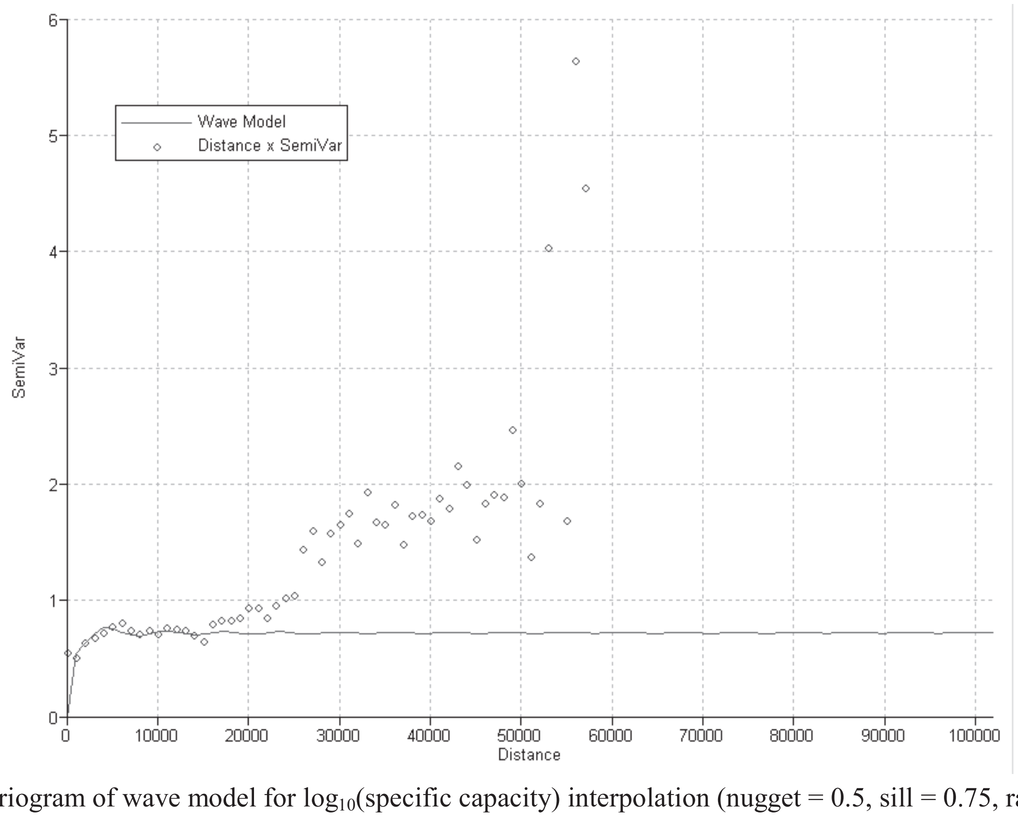




Appendix 8 Semi variogram models for aquifer parameter determination



Semivariogram of Guasian model for water level interpolation (nugget = 0, sill = 10, 0000, range = 20000)



Semivariogram of wave model for $\log_{10}$(specific capacity) interpolation (nugget = 0.5, sill = 0.75, range = 5000)

Appendix 9 Some of model input parameters to Akaki catchment model

Twenty five drains imposed to the model domain

Layer	Row	Col	Elevation	Conductance	Drain no.
1	17	101	2597	560	1
1	18	101	2597	560	2
1	18	102	2597	560	3
1	19	101	2597	560	4
1	19	102	2590	560	5
1	20	102	2597	560	6
1	20	103	2597	560	7
1	21	102	2597	560	8
1	21	103	2597	560	9
1	22	102	2597	560	10
1	33	66	2664	178	11
1	33	69	2658	178	12
1	37	38	2678	20	13
1	38	38	2668	20	14
1	39	49	2634	144	15
1	43	18	2649	500	16
1	43	19	2649	500	17
1	43	29	2642	28	18
1	44	17	2649	500	19
1	44	18	2649	500	20
1	44	19	2640	500	21
1	44	20	2649	500	22
1	45	17	2649	500	23
1	96	72	2113	120	24
1	97	69	2103	76	25

Ninteen head dependent boundary nodes imposed to the Akaki catchment model area

Layer	Row	Col	GHB elevation	Conductance	Bound no.
1	128	31	1938	84	1
1	128	32	1938	84	2
1	129	32	1938	84	3
1	129	33	1938	84	4
1	129	34	1938	84	5
1	129	37	1938	84	6
1	129	38	1938	84	7
1	130	34	1938	84	8
1	130	35	1938	84	9
1	130	36	1938	84	10
1	130	37	1938	84	11
1	130	38	1900	84	12
1	130	39	1938	84	13
1	130	40	1938	84	14
1	131	41	1900	84	15
1	131	45	1900	84	16
1	132	42	1900	84	17
1	132	43	1900	84	18
1	132	44	1900	84	19

One hundred fifty wells applied to the Akaki catchment model

Well No.	Row	Column	Stress rates (m3/day)	Layer
1	16	105	-168	1
2	16	128	-320	1
3	17	97	-108	1
4	18	108	-235	1
5	19	106	-244	1
6	19	108	-345	1
7	19	126	-175	1
8	21	105	-529	1
9	21	125	-231	1
10	22	104	-349	1
11	22	105	-428	1
12	25	118	-210	1
13	25	120	-145	1
14	30	105	-420	1
15	32	104	-420	1
16	35	121	-321	1
17	36	103	-370	1
18	37	94	-315	1
19	37	98	-450	1
20	40	51	-115	1
21	40	109	-425	1
22	41	32	-34	1
23	41	52	-87	1
24	42	33	-36	1
25	43	26	-86	1
26	43	32	-216	1
27	43	89	-560	1
28	43	90	-1321	1
29	44	35	-12	1
30	45	39	-178	1
31	45	53	-42	1
32	46	34	-30	1
33	46	39	-32	1
34	46	40	-54	1
35	46	43	-62	1
36	46	53	-43	1
37	46	54	-104	1
38	46	56	-316	1
39	46	84	-83	1
40	47	36	-40	1
41	47	66	-3	1
42	48	35	-15	1
43	49	59	-56	1
44	49	74	-126	1
45	50	52	-80	1
46	53	18	-65	1
47	53	60	-1700	1
48	53	80	-346	1
49	53	81	-1642	1
50	54	61	-533	1
51	55	17	-1700	1
52	55	47	-48	1
53	55	73	-200	1
54	57	41	-10	1
55	57	54	0	1
56	57	65	-124	1
57	58	36	-50	1
58	58	40	-43	1
59	58	43	-250	1
60	58	50	-90	1
61	59	43	-115	1
62	59	45	-33	1
63	59	47	-101	1
64	59	51	-45	1
65	59	52	-230	1
66	60	47	-340	1
67	60	49	-97	1
68	60	55	-58	1
69	61	28	-108	1
70	61	46	-210	1
71	61	48	-73	1
72	61	78	-87	1
73	62	40	-41	1
74	62	46	-298	1
75	63	63	-12	1

Well No.	Row	Column	Stress rates (m3/day)	Layer
76	64	41	-78	1
77	64	44	-55	1
78	64	46	-20	1
79	64	61	-15	1
80	64	83	-1000	1
81	65	33	-162	1
82	65	43	-47	1
83	65	46	-343	1
84	65	47	-342	1
85	65	58	-45	1
86	66	28	-288	1
87	66	30	-1555	1
88	66	34	-80	1
89	66	39	-90	1
90	66	49	-108	1
91	67	37	-43	1
92	67	51	-129	1
93	67	52	-20	1
94	68	36	-76	1
95	69	41	-45	1
96	70	45	-30	1
97	71	44	-34	1
98	72	30	-99	1
99	73	45	-1440	1
100	74	43	-432	1
101	74	52	-189	1
102	74	53	-227	1
103	74	76	-432	1
104	76	35	-321	1
105	77	29	-332	1
106	77	52	-210	1
107	78	29	-214	1
108	78	47	-583	1
109	78	53	-180	1
110	79	29	-320	1
111	79	36	-312	1
112	80	52	-253	1
113	81	53	-209	1
114	81	54	-216	1
115	84	56	-576	1
116	85	52	-150	1
117	86	57	-176	1
118	87	58	-149	1
119	89	57	-645	1
120	92	54	-176	1
121	93	56	-220	1
122	93	70	-150	1
123	94	68	-150	1
124	95	60	-137	1
125	95	62	-150	1
126	95	72	-547	1
127	96	51	-187	1
128	96	68	-1901	1
129	97	57	-123	1
130	97	60	-250	1
131	99	65	-2400	1
132	101	62	-137	1
133	102	63	-210	1
134	104	64	-137	1
135	105	64	-1340	1
136	105	68	-2500	1
137	105	69	-500	1
138	106	64	-5216	1
139	106	67	-7808	1
140	106	68	-5953	1
141	107	61	-6000	1
142	107	64	-6912	1
143	107	65	-7517	1
144	108	61	-6000	1
145	108	63	-6496	1
146	108	67	-3616	1
147	109	62	-6000	1
148	109	63	-7517	1
149	112	65	-7517	1
150	116	52	-390	1

Appendix 10 Wells, head dependent boundaries, & rivers applied to wellfield

i) well abstructions imposed to welfield model

Well no.	Row	Col	Stress rate (m^3/day)	Layer
1	16	105	-168	1
2	16	128	-320	1
3	17	97	-108	1
4	18	108	-235	1
5	19	106	-244	1
6	19	108	-345	1
7	19	126	-175	1
8	21	105	-529	1
9	21	125	-231	1
10	22	104	-349	1
11	22	105	-428	1
12	25	118	-210	1
13	25	120	-145	1
14	30	105	-420	1
15	32	104	-420	1
16	35	121	-321	1
17	36	103	-370	1
18	37	94	-315	1
19	37	98	-450	1
20	40	51	-115	1
21	40	109	-425	1
22	41	32	-34	1
23	41	52	-87	1
24	42	33	-36	1
25	43	26	-86	1
26	43	32	-216	1
27	43	89	-560	1
28	43	90	-1321	1
29	44	35	-12	1
30	45	39	-178	1
31	45	53	-42	1
32	46	34	-30	1
33	46	39	-32	1
34	46	40	-54	1
35	46	43	-62	1
36	46	53	-43	1
37	46	54	-104	1
38	46	56	-316	1
39	46	84	-83	1
40	47	36	-40	1
41	47	66	-3	1
42	48	35	-15	1

ii) One hundred twelve head dependent boundary nodes used to simulate inflow and out flow flax to and out of model domain of the wellfield

Layer	Row	Column	Elevation (m)	Conductance (m^2/day)
1	1	1	2167	10.00
1	1	2	2164	10.00
1	1	3	2160	10.00
1	1	4	2154	10.00
1	1	5	2147	10.00
1	1	6	2140	10.00
1	1	7	2135	10.00
1	1	8	2128	15.00
1	1	9	2121	15.00
1	1	10	2113	15.00
1	1	11	2107	15.00
1	1	12	2110	15.00
1	1	13	2102	15.00
1	1	14	2100	15.00
1	1	15	2199	15.00
1	1	16	2097	15.00
1	1	17	2096	15.00
1	1	18	2095	15.00
1	1	19	2093	15.00
1	1	20	2093	15.00
1	1	21	2093	15.00
1	1	22	2093	15.00
1	1	23	2093	15.00
1	1	24	2094	15.00
1	1	25	2096	15.00
1	1	26	2098	15.00
1	1	27	2100	15.00
1	1	28	2102	15.00
1	1	29	2104	15.00
1	1	30	2107	15.00
1	1	31	2109	15.00
1	1	32	2112	10.00
1	1	33	2115	10.00
1	1	34	2120	10.00
1	1	35	2126	10.00
1	1	36	2132	1.21
1	1	37	2137	1.21
1	1	38	2142	1.21
1	1	39	2146	1.21
1	1	40	2151	1.21
1	1	41	2155	1.21
1	1	42	2157	1.21
1	1	43	2157	1.04
1	2	1	2167	10.00
1	3	1	2161	10.00
1	4	1	2161	10.00
1	5	1	2154	10.00
1	6	1	2154	10.00
1	7	1	2147	10.00
1	8	1	2147	10.00
1	9	1	2140	10.00
1	10	1	2140	10.00
1	11	1	2132	10.00
1	12	1	2132	10.00
1	13	1	2125	10.00
1	14	1	2125	10.00
1	15	1	2117	10.00
1	16	1	2117	10.00

Layer	Row	Column	Elevation (m)	Conductance (m^2/day)
1	17	1	2109	10.00
1	18	1	2109	10.00
1	19	1	2100	10.00
1	20	1	2100	10.00
1	21	1	2091	10.00
1	22	1	2091	10.00
1	57	6	1988	42.00
1	57	7	1990	42.50
1	57	8	1990	30.00
1	57	9	1990	30.00
1	57	10	1990	30.00
1	57	15	2019	22.00
1	57	16	2020	30.65
1	57	17	2021	18.20
1	57	18	2021	24.30
1	58	6	1988	42.00
1	58	7	1990	42.50
1	58	8	1990	30.00
1	58	9	1990	30.00
1	58	10	1990	30.00
1	58	15	2019	22.00
1	58	16	2020	30.65
1	58	17	2021	18.20
1	58	18	2021	24.30
1	59	4	2000	43.00
1	59	5	1995	42.50
1	59	11	2005	17.25
1	59	12	2005	17.25
1	59	13	2013	14.90
1	59	14	2020	17.95
1	59	19	2022	16.82
1	59	20	2022	16.82
1	59	21	2022	16.82
1	59	22	2023	16.82
1	60	3	2000	43.00
1	60	4	2000	43.00
1	60	5	1995	42.50
1	60	11	2005	17.25
1	60	12	2005	17.25
1	60	13	2013	14.90
1	60	14	2020	17.95
1	60	19	2022	16.82
1	60	20	2022	16.82
1	60	21	2022	16.82
1	60	22	2023	16.82
1	61	3	2000	43.00
1	61	22	2021	16.82
1	62	2	2000	43.00
1	62	3	2000	43.00
1	62	22	2021	16.82
1	63	22	2023	16.82
1	64	22	2023	16.82
1	65	22	2023	16.82
1	66	22	2023	16.82

iii) one hundred twenty two rivers reaches for Akaki wellfield

Layer	Row	Column	River Stage(m)	Conductance(m^2/day)	Bottom Elevation (m).
1	1	11	2104.00	132.50	2103.50
1	1	23	2090.00	45.00	2089.50
1	2	11	2103.00	132.50	2102.00
1	2	23	2089.00	45.00	2088.00
1	3	11	2101.00	132.50	2100.00
1	3	23	2088.00	45.00	2087.00
1	3	24	2086.00	75.00	2085.00
1	4	11	2101.00	132.50	2100.00
1	4	23	2088.00	45.00	2087.00
1	4	24	2086.00	75.00	2085.00
1	5	11	2100.00	110.50	2099.00
1	5	24	2084.00	91.00	2083.00
1	5	25	2081.00	68.00	2080.00
1	6	11	2100.00	110.50	2099.00
1	6	24	2084.00	91.00	2083.00
1	6	25	2081.00	68.00	2080.00
1	7	12	2072.00	136.50	2071.00
1	7	24	2077.00	55.50	2076.00
1	7	25	2079.00	72.50	2078.00
1	8	12	2072.00	136.50	2071.00
1	8	24	2077.00	55.50	2076.00
1	8	25	2079.00	72.50	2078.00
1	9	12	2071.00	68.00	2070.00
1	9	23	2076.00	81.50	2075.00
1	10	12	2071.00	68.00	2070.00
1	10	23	2076.00	81.50	2075.00
1	11	12	2070.00	82.50	2069.00
1	11	23	2075.00	144.50	2074.00
1	12	12	2070.00	82.50	2069.00
1	12	23	2075.00	144.50	2074.00
1	13	12	2059.00	67.00	2058.00
1	13	23	2073.00	115.00	2072.00
1	14	12	2059.00	67.00	2058.00
1	14	23	2073.00	115.00	2072.00
1	15	13	2058.00	73.50	2057.00
1	15	22	2072.00	144.00	2071.00
1	16	13	2058.00	73.50	2057.00
1	16	22	2072.00	144.00	2071.00
1	17	12	2056.00	60.00	2055.00
1	17	13	2057.00	71.50	2056.00
1	17	20	2060.00	73.00	2059.00
1	17	21	2062.00	150.00	2061.00
1	17	22	2064.00	92.00	2063.00
1	18	12	2056.00	60.00	2055.00
1	18	13	2057.00	71.50	2056.00
1	18	20	2060.00	73.00	2059.00
1	18	21	2062.00	150.00	2061.00
1	18	22	2064.00	92.00	2063.00
1	19	12	2054.00	117.50	2053.00
1	19	20	2059.00	110.00	2058.00
1	20	12	2054.00	117.50	2053.00
1	20	20	2059.00	110.00	2058.00
1	21	10	2021.00	120.00	2020.00
1	21	11	2022.00	63.00	2021.00
1	21	19	2055.00	175.00	2054.00
1	21	20	2056.00	142.50	2055.00
1	21	21	2057.00	70.00	2056.00
1	22	10	2021.00	120.00	2020.00
1	22	11	2022.00	63.00	2021.00
1	22	19	2055.00	175.00	2054.00
1	22	20	2056.00	142.50	2055.00
1	22	21	2057.00	70.00	2056.00
1	23	10	2019.00	116.00	2018.00

Layer	Row	Column	River Stage(m)	Conductance(m^2/day)	Bottom Elevation (m).
1	23	18	2054.00	124.00	2053.00
1	24	10	2019.00	116.00	2018.00
1	24	18	2054.00	124.00	2053.00
1	25	9	2017.00	56.00	2016.00
1	25	10	2018.00	52.50	2017.00
1	25	19	2052.00	225.00	2051.00
1	26	9	2017.00	56.00	2016.00
1	26	10	2018.00	52.50	2017.00
1	26	19	2052.00	225.00	2051.00
1	27	9	2015.00	67.00	2014.00
1	27	20	2050.00	190.00	2049.00
1	27	21	2048.00	125.00	2047.00
1	28	9	2015.00	67.00	2014.00
1	28	20	2050.00	190.00	2049.00
1	28	21	2048.00	125.00	2047.00
1	29	9	2014.00	123.00	2013.00
1	29	21	2046.00	183.00	2045.00
1	30	9	2014.00	123.00	2013.00
1	30	21	2046.00	183.00	2045.00
1	31	21	2044.00	151.50	2043.00
1	32	21	2044.00	151.50	2043.00
1	33	20	2040.00	101.50	2039.00
1	33	21	2042.00	169.00	2041.00
1	34	20	2040.00	101.50	2039.00
1	34	21	2042.00	169.00	2041.00
1	35	19	2038.00	165.00	2037.00
1	36	19	2038.00	165.00	2037.00
1	37	19	2036.00	207.00	2035.00
1	38	19	2036.00	207.00	2035.00
1	39	16	2028.00	150.00	2027.00
1	39	17	2030.00	173.50	2029.00
1	39	18	2032.00	160.00	2031.00
1	39	19	2034.00	160.00	2033.00
1	40	16	2028.00	150.00	2027.00
1	40	17	2030.00	173.50	2029.00
1	40	18	2032.00	160.00	2031.00
1	40	19	2034.00	160.00	2033.00
1	41	16	2026.00	241.00	2025.00
1	42	16	2026.00	241.00	2025.00
1	43	11	2010.00	181.00	2009.00
1	43	12	2012.00	197.50	2011.00
1	43	15	2020.00	125.00	2019.00
1	43	16	2024.00	322.00	2023.00
1	44	11	2010.00	181.00	2009.00
1	44	12	2012.00	197.50	2011.00
1	44	15	2020.00	125.00	2019.00
1	44	16	2024.00	322.00	2023.00
1	45	10	2008.00	160.00	2007.00
1	45	13	2014.00	190.00	2013.00
1	45	14	2016.00	160.00	2015.00
1	45	15	2017.00	193.00	2016.00
1	46	10	2008.00	160.00	2007.00
1	46	13	2014.00	190.00	2013.00
1	46	14	2016.00	160.00	2015.00
1	46	15	2017.00	193.00	2016.00
1	47	9	2006.00	263.00	2005.00
1	47	10	2007.00	262.00	2006.00
1	48	9	2006.00	263.00	2005.00
1	48	10	2007.00	262.00	2006.00

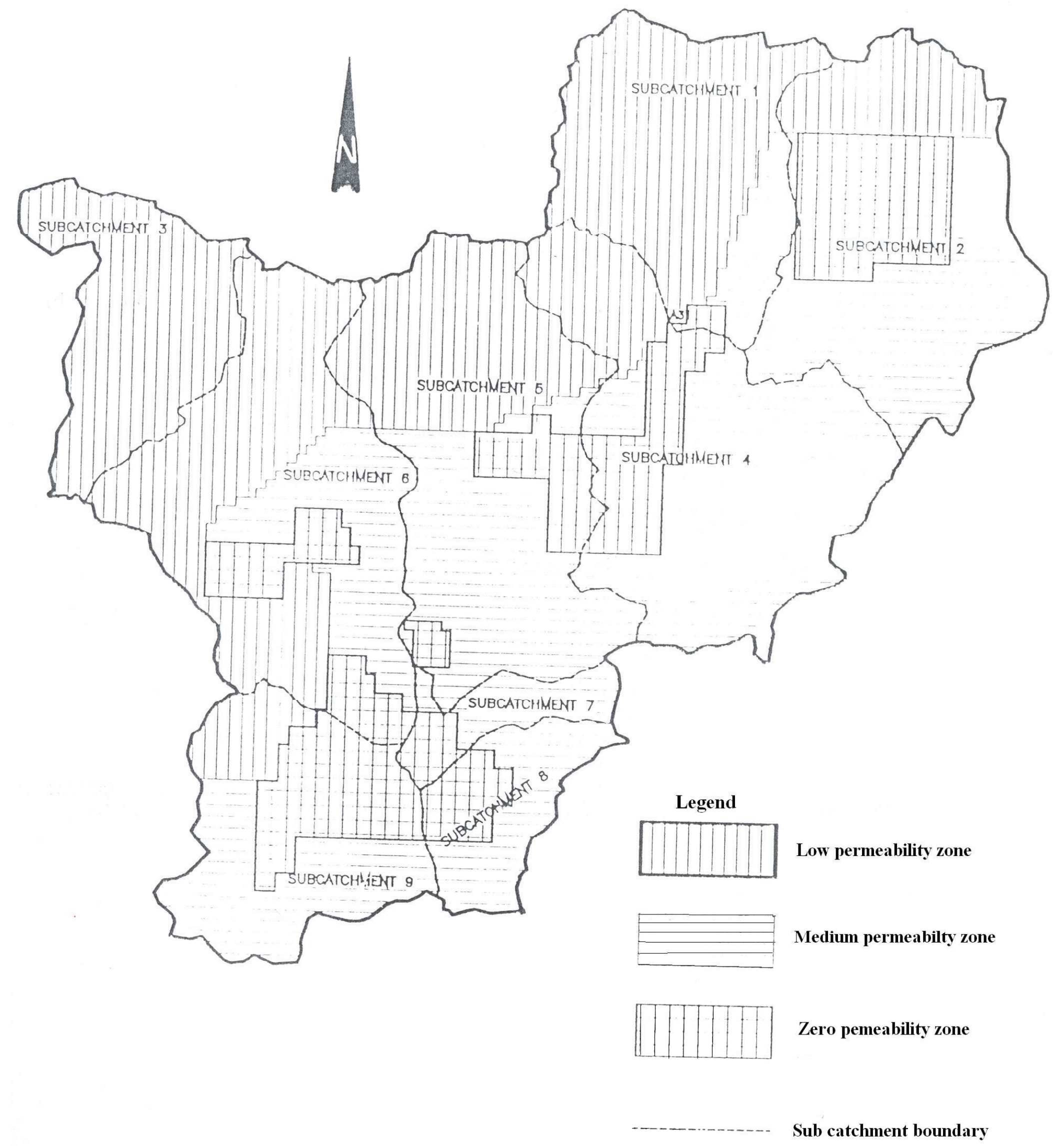
Well abstraction data of the wellfield

BH Name	Depth to top of 14" screen	Depth SWL(m)	Phase	Pump diam	Pump flow (lit./sec.)	well abstractions (m3/day)
BH 6	75	67.82	1	6"	10	720
BH 7	79	67.42	1	6"	10	720
BH 8	83	67.20	1	6"	10	720
BH 9	78	58.70	1	10"	50	3,600
BH12	76	51.53	1	10"	50	3,600
BH14	78	59.18	1	10"	50	3,600
BH16	78	47.98	1	10"	50	3,600
BH17	77	45.94	1	10"	50	3,600
BH18	82	54.08	1	10"	50	3,600
BH21	71	44.68	1	10"	50	3,600
BH22	58	47.90	1	6"	10	720
BH1	69	58.50	2	6"	10	720
BH2	63	52.60	2	6"	10	720
BH3b	63	63.11	2	6"	10	720
BH4	65	47.90	2	6"	10	720
BH5b	75	48.85	2	10"	50	3,600
BH10	76	72.30	2	6"	10	720
BH11	66	61.14	2	6"	10	720
BH13	47	51.17	2	6"	10	720
BH19	71	51.45	2	10"	50	3,600
BH 20	73	50.05	2	10"	50	3,600
BH 23	68	45.02	2	10"	50	3,600
BH 24	62	42.92	2	10"	50	3,600
BH 25	80	41.92	2	10"	50	3,600
BH 26	57	50.95	2	6"	10	720
					Total (m3/day)	55,440

Appendix 11 Akaki wellfield monitoring wells

No	Date	MW-01	MW-02	MW-03	MW-04	P-01	TW-01	time in days
1	8/10/2002	43.9	37.49	43.09	53.69	50.56	51.41	1
2	25/10/2002	43.96	37.56	43.13	53.74	50.59	51.47	17
3	9/11/2002	43.97	37.57	43.16	53.77	50.64	51.47	32
4	5/6/2003	44.82	38.38	43.2	53.82	50.88	51.33	241
5	11/6/2003	44.88	38.43	43.26	53.87	52.43	51.37	248
6	21/06/2003	44.9	38.47	43.3	53.93	51.03	51.4	258
7	28/06/2003	44.94	38.49	43.3	53.93	50.99	51.43	265
8	5/7/2003	44.95	38.52	43.37	54	52.21	51.42	272
9	12/7/2003	45.03	38.61	43.45	54.07	52.25	51.41	279
10	19/07/2003	45.04	38.64	43.47	54.1	52.24	51.48	286
11	26/07/2003	45.08	38.68	43.45	54.15	52.28	51.49	293
12	2/8/2003	45.13	38.73	43.68	54.21	52.31	51.51	300
13	9/8/2003	45.18	38.78	43.66	54.27	52.34	51.55	307
14	16/08/2003	45.23	38.85	43.7	54.33	52.37	51.57	314
15	23/08/2003	45.26	38.88	43.7	54.33	52.3	51.6	321
16	30/08/2003	45.29	38.9	43.7	54.33	51.37	51.6	328
17	6/9/2003	45.31	38.93	43.75	54.38	52.3	51.66	336
18	13/09/2003	45.34	38.97	43.81	54.43	52.3	51.65	343
19	20/09/2003	45.38	39.02	43.88	54.5	51.58	51.7	350
20	18/10/2003	45.54	39.19	44.06	54.69	51.73	51.82	378
21	25/10/2003	45.55	39.21	44.06	54.69	51.76	51.88	385
22	1/11/2003	45.57	39.25	44.1	54.73	51.8	51.88	392
23	8/11/2003	45.62	39.3	44.17	54.78	51.86	51.89	399
24	15/11/2003	45.66	39.34	44.22	54.83	51.88	51.94	406
25	22/11/2003	45.7	39.37	44.23	54.85	51.92	51.98	413
26	29/11/2003	45.73	39.39	44.25	54.86	51.93	52.01	420
27	6/12/2003	45.76	39.42	44.27	54.9	51.95	52.01	427
28	13/12/2003	45.8	39.47	44.3	54.95	51.99	52.01	434
29	20/12/2003	45.84	39.51	44.33	54.99	52.04	52.02	441
30	27/12/2003	45.87	39.56	44.38	55.08	52.13	52.09	448
31	3/1/2004	45.91	39.59	44.46	55.08	52.13	52.13	455
32	10/1/2004	45.93	39.6	44.5	55.1	52.18	52.17	462
33	17/01/2004	45.93	39.6	44.5	55.1	52.18	52.17	469
34	24/01/2004	45.96	39.63	44.55	55.11	52.21	52.16	476
35	31/01/2004	45.98	39.67	44.57	55.13	52.23	52.19	483
36	23/04/2004					54.7	52.6	566
37	24/04/2004	46.48	40.16	45.05	54.68			569
38	16/08/2004					55.27	53.15	683
39	4/10/2004					55.53	53.24	732
40	19/10/2004					55.63	53.32	747
41	14/12/2004	47.54	41.28		55.82	53.96	53.56	803
42	6/3/2005	47.95	41.71	46.66		56.36	53.92	886
43	18/04/2005		41.97	46.85		55.34	54	929
44	12/7/2005		41.76	47.01			53.9	1045
45	26/7/2005	48.69				57.03	54.59	1059
46	2/8/2005	48.67				56.98	54.57	1066
47	11/8/2005	48.71					54.49	1075
48	16/08/2005	48.65				57	54.54	1080
49	23/08/2005	48.71				57.01	54.59	1087
50	30/08/2005	48.61				56.89	54.61	1094
51	6/9/2005	48.71				57.04	54.56	1101
52	15/9/2005	48.59				57.07	54.61	1110

Appendix 12 Subcatchments and soil permeability of Akaki area


SUBCATCHMENT 1
SUBCATCHMENT 2
SUBCATCHMENT 3
SUBCATCHMENT 4
SUBCATCHMENT 5
SUBCATCHMENT 6
SUBCATCHMENT 7
SUBCATCHMENT 8
SUBCATCHMENT 9
A3
N
Legend
Low permeability zone
Medium permeabilty zone
Zero pemeability zone
Sub catchment boundary

Appendix 13 Monthly rainfall data for the water balance model

Intoto Met. Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	14.2	0.0	17.5	96.3	83.7	112.2	270.4	327.7	205.9	58.0	3.3	1.2
1986	0.0	35.7	88.0	197.6	125.4	179.5	180.1	264.2	127.8	36.1	0.0	0.0
1987	0.5	63.4	248.9	82.4	241.3	92.9	196.5	254.4	115.2	21.3	0.8	0.3
1988	9.7	53.4	5.3	144.6	16.6	106.2	277.9	299.3	229.7	59.9	0.0	0.0
1989	4.0	75.8	105.4	133.3	5.8	98.2	409.5	323.4	293.9	11.7	0.0	14.5
1990	0.0	156.6	42.5	117.9	17.6	100.5	325.1	499.7	180.8	32.1	1.5	0.0
1991	12.8	64.9	156.2	37.5	37.0	171.2	258.5	395.2	146.7	1.4	0.0	44.2
1992	52.4	31.5	14.6	42.7	84.6	131.6	247.8	387.0	188.6	42.4	0.0	8.1
1993	15.3	44.6	5.7	147.5	49.0	123.3	266.1	407.6	183.2	28.7	0.0	0.0
1994	0.0	0.0	62.2	56.0	91.0	154.8	336.3	306.9	142.5	0.3	24.4	0.0
1995	0.0	96.3	29.7	186.1	84.0	98.0	291.0	222.1	133.7	5.0	0.2	22.7
1996	31.1	12.2	121.6	78.3	95.2	242.7	387.2	493.9	158.7	1.2	0.6	0.0
1997	21.2	0.0	18.6	77.3	27.4	76.3	256.3	240.8	89.3	88.3	90.0	0.2
1998	25.3	25.3	45.2	47.0	149.5	149.2	369.0	376.3	134.4	44.5	0.0	0.0

Sendafa Met. Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	9.5	0	38.6	158.9	157.9	76.4	394.1	446.1	106	10.8	0	0
1986	0	28.1	117.3	193.7	32.3	164.7	270.9	244.5	143.2	0	0	0
1987	0.2	33.1	128.9	80.5	110.1	55.7	223.6	143.6	105.3	8.7	0	0
1988	0	32.9	0.9	132.3	22.1	104.6	451.1	360.3	198.4	5.2	0	0
1989	18	10.3	43.3	112	21.4	46.3	357.2	339.4	139.9	10.2	0.4	0.6
1990	21.5	190.4	35.7	148.4	38.2	88.5	273.4	470.4	116.3	3.8	2.4	0
1991	15.9	20.5	118.1	0.5	48	94.6	333.4	218.9	134.5	9.4	0	5.6
1992	10.7	46.5	1	29.1	32.5	69.6	257.5	357.9	151.4	55.5	0	0
1993	4.3	105.2	0	78.2	48	94.6	457.2	353	158.4	13.7	0	0
1994	0	0	0	64.1	11	122.7	337.7	184.1	122	0	6.4	0
1995	0	11.4	96.2	116.7	42.4	22.5	230.8	388.8	116.3	0	0	0
1996	69.4	5.6	99.3	78.2	48	180.4	339.2	338.6	111.4	0	0	0
1997	44.5	0	29.4	60	44.8	149.7	303.8	251.1	84.7	72	34.6	0
1998	28.9	23.3	5.8	27	38.2	68.8	359.1	289.7	152	98.9	0	0

Addis Abeba Bole Met. Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1985	35.1	0	49.1	130.3	92.8	110.9	210.3	260.8	168.6	29.8	0	0.4
1986	0	37.6	56.2	216.6	37.7	175.2	167.9	222.3	107.4	31.6	0	2.5
1987	0	49.1	180.1	85.7	154.6	71.9	155.9	98.1	57	16.6	0	0.4
1988	4.7	33.4	6.7	157.9	34.7	93.2	181.4	265.3	187.3	57.3	0	0
1989	3.4	33.7	58.4	143.3	0	88.1	218.1	318.6	150	36.8	0	7.9
1990	3.2	161.1	60.4	144.5	25.2	48.3	204.2	413.4	143	46.1	2.1	0
1991	0.2	29.6	134.1	15	7.7	105.7	279.4	287.9	123.1	4.4	2.1	0
1992	14.5	28	35	58.6	55	82.2	254.8	223.3	157	64.4	2.2	0.4
1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0	0
1994	0	0	52.9	70	29	111.4	242.3	199.3	99.4	0.5	11	0
1995	0	81.3	73.1	133.3	95.9	77.4	165.5	256.9	97	0	0	29.3
1996	19.6	15.8	134.4	96.5	124.6	290.2	346.3	312.7	211.4	0	0.4	0
1997	29.1	0	22.1	66.8	44.8	128	257	160.7	94.7	58.6	3.1	0
1998	63.1	40	43.8	87.8	193.1	111.6	256.8	236.8	185.2	139.5	0	0

Melka Kunture Met. Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	15.8	0	28	36.2	50.2	47.8	270.5	240.2	50.4	19.3	0	0
1986	0	74.6	56	108.8	39.7	136.5	114.5	185.7	84.2	0	0	12.2
1987	0	87.7	132.4	98.3	167.2	74.1	149.5	154	30.5	6.6	0	0
1988	0	26.1	2.7	68.1	10.1	104	189.6	272.3	122.2	8.1	0	0
1989	9.4	44	46.5	73.9	10.8	53.7	272.1	193	66.5	6.5	0	11.7
1990	0	137.2	83.2	125.5	26.6	91.6	292.6	223.7	59.8	0	0	0
1991	0	37.4	131.9	5.3	4.9	132.9	375.1	416.9	129.5	3	0	0
1992	28.4	59.1	14.7	27	74.8	144.3	250.5	223.3	92.8	37	0	4.1
1993	0	72.9	19.8	193.1	70	231.7	491.6	434.6	270.3	50.6	0	0
1994	0	0	125.2	25.7	45.7	70.6	240.2	216.5	132.5	0	8.8	0
1995	11.1	35.4	69.2	74.2	63.5	103.7	250.5	228.3	95.4	19.3	0	0
1996	34.5	0	94.9	113.5	132.9	215	300.8	250.8	91.5	0	0	0
1997	10.5	0	11.6	73.1	24.9	117.8	159.4	139.6	50	66.2	11.1	0
1998	33.3	14.7	109.9	40.9	148.9	103.2	279.1	257.2	133	59.1	0	0

Akaki Besseka Met. Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	3.6	0	32.4	72.4	96.6	93.5	302.7	324.1	164.3	1.6	0	0
1986	0	95.4	66.9	148.7	68.2	143.4	189.4	216.5	86.1	9.4	0	0
1987	0	65.6	181.9	80.7	187.7	69.3	202	246.9	81.7	4.4	0	0
1988	0	44.5	0	96	23.8	124.6	255.9	278.1	254.2	35.4	0	0
1989	2.1	63.8	53.8	226.3	7.1	58.6	264.2	301	170.9	37.9	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
1991	0	37.6	62.4	11.6	45.6	90.4	263.7	308.5	113.3	4.4	0	56.5
1992	34.7	24.2	30.5	15.5	25.6	100.4	218.4	276	86.7	43.3	0.2	0
1993	1.2	53.9	60.1	118.4	62.5	116.5	218	251.5	118.3	20.3	0	0
1994	0	0	62.7	72.2	20.2	125	225.1	168.9	106.8	0	8.1	0
1995	0	25.4	63.7	102.1	20.9	95.7	269.2	242.3	79.5	0	0	4.8
1996	15.3	0.3	79.7	38.8	90.5	240.1	292.5	234.1	119	1.9	0	0
1997	27.6	0	29.5	102.7	25.2	57	203.6	203.4	82.5	114.9	10.3	0
1998	32.7	30.2	19.6	69.3	159.9	116.9	207.8	280	118.5	36	0	0

Monthly Potential Evapotranspiration - Addis Ababa Observatory

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	174.72	171.85	216.95	160.89	178.78	151.43	120.3	126.17	147.51	186.68	171.93	166.98
1986	166.45	154.53	190.67	159.61	184.5	134.58	133.16	133.02	153.57	186.14	182.62	171.96
1987	171.27	161.92	162.89	185.61	169.62	147.67	137.83	158.25	153.82	188.35	173.32	168.35
1988	163.6	180.34	217.7	176.64	201.39	147.79	111.27	131.3	131.29	174.08	164.13	166.25
1989	159.39	158.29	179.67	157.56	196.61	152.74	124.16	142.33	137.63	176.42	168.36	164.54
1990	170.44	136.1	181.81	166.58	184.46	146.28	125.03	127.95	134.43	175.18	158.91	160.25
1991	170.64	159.65	185.52	186.13	195.22	150.02	119.48	128.92	143.8	175.64	158.46	154.09
1992	157.25	159.33	141.77	175.69	184.78	145.61	120.63	110.68	132.46	160.02	149.87	149.97
1993	151.81	139.95	199.45	154.96	165.3	130.27	121.04	126.26	119.15	162.57	157.58	153.01
1994	163.23	165.48	181.47	169.62	184.6	126.07	112.91	114.98	139.19	182.3	153.02	153.09
1995	161.76	158.07	183.33	149.47	180.33	157.18	118.1	123.92	135.68	175.01	160.69	151.85
1996	146.35	169.64	174.83	168.75	169.89	120.48	120.13	125.07	133.91	178.67	153.73	154.58
1997	149.98	167.12	191.26	167.04	196.88	161.22	124.55	133.26	169.84	170.65	147.98	156.03
1998	160.47	157.21	182.89	188.91	171.8	147.82	123.15	127.66	129.16	153.52	160.37	156.45

Derived monthly flow volume (in MCM) of Akaki River at Aba Samuel

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1985	3.7	3.5	3.4	4.2	12.7	7.8	67.9	269.9	88.2	14.7	5.1	6.9
1986	5.4	5.4	9.6	14	7.1	15.5	48.5	119.3	69.5	19.8	8.3	3
1987	3.4	3.7	11.8	18.6	17.6	14	39.2	56.8	15	4.4	3.4	4.7
1988	5.7	6.1	4.9	8.8	5.2	7.4	42.8	136.4	108	20.8	10	5.1
1989	4.4	5.1	4.6	12	7.4	10.6	81.1	253.8	102.4	10.6	6.4	7.3
1990	6.6	14.5	15.2	28.6	8.6	11.5	67.3	292.9	94.1	20.1	7.3	7.1
1991	6.5	7.1	8.7	7	5.2	16.1	96	250.5	189.8	19.5	14.2	15.2
1992	12	13.6	8.3	9.1	9.8	11	62.1	183.6	143.5	18	9	9.7
1993	7.9	10.5	6.7	23.8	17.7	37.9	161	349.5	260.8	27.3	7.7	6.4
1994	5.6	7.1	6.2	6.7	7.7	11.6	66.7	134.4	95.8	12.7	9.4	8.6
1995	8.3	12.6	10.8	20.1	13.4	14.5	56.8	214.4	66.6	9.8	7	7.2
1996	7.4	5.1	10.2	11	16.5	79.5	254	491.3	142	25.4	16.6	15.4
1997	15.5	10.5	11.8	10.5	8.5	14.1	68	133.5	27.5	8.3	5.4	4
1998	5.5	5.1	4.8	5.3	20.8	15.1	140.5	411.6	182.5	43.7	12.2	10.8

Appendix 14 Pictures of the area

Akaki wellfield from Tilu Dimtu Hill

Scoria deposits on wellfield

Cemetery site on Tilu Dimtu Hill

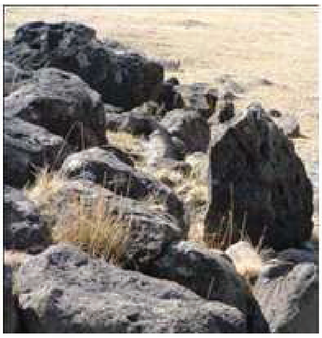
Production well Akaki Wellfield

Food factory at the wellfield

Water point at Fanta Spring

Railway passing through wellfield

Fanta Spring (chlorination tank)



Vesiculated basalt

Polluted Dongora River passing through the wellfield