# GROUNDWATER MODELING

# A CASE STUDY ON

# VOLCANIC WATER SUPPLY AQUIFER /AKAKI WELLFIELD/

# OF

# THE CITY OF ADDIS ABABA

May, 2004
Addis Ababa, Ethiopia

Presented by Yirga Tadesse
Geohydrologist

## Abstract

Addis Ababa is the capital City of Ethiopia and is the seat of International Organisation (UNDP, UNICEF, ECA, AU, etc.), high level of governmental and Non-governmental organisations. The city is expanding from time to time horizontally in the expansion areas in the east, south, west, and in limited extent in the north.

The population of the city have been grown from 443,728 in 1961 to 1,167,315 in 1978 and 2,112,737 in 1994 (CSA, 1999). The population project in the year 2000 is calculated to be 2,495,000.

The water service of the city is from three reservoirs namely Legedadi, Dire and Gefersa which totally produces 175,000m$^3$/d of treated water. The development of groundwater as a source is known to be cheaper and sustainable this time. Water Engineers and Decision Makers are giving focus on the development of urban groundwater sources and/or for the purpose of conjunctive uses. As result of this, 12 wells are developed in the city and 29 wells in Akaki well field to augment the existing surface water sources (the three dams).

The groundwater aquifers in Akaki well field are volcanic rocks. These rocks are scoria deposits, scoriaceous & vesicular basalts. The scoria deposits are loose basic pyroclastic materials. All the above rocks have very high primary porosity which was formerly filled with volatile and hot water. The scoriae deposits, scoriaceous & vesicular basalts behave as granular aquifer mainly due to the primary porosities developed during the genesis of the rocks, and secondary porosities which is developed as a result of faulting, fracturing and fissuring. The tectonic activities in the region developed intensive and network fracturing & fissuring which resulted favourable condition for groundwater circulation and occurrence.

As mentioned above, in Akaki well field 29 production boreholes are found developed to supply water to the city of Addis Ababa and Akaki town. It is obvious that operating 29 wells at one time well produce significant impact in the groundwater resources of the area and the environment. This is the reason which initiate the need for the groundwater modeling and assessment of its impact in the environs.

The Groundwater modeling exercise uses the Processing Mode Flow (Version 5.0.54) software. Different simulation scenarios had been run to provide option of alternatives of abstraction plans to the organisation (AAWSA). The average abstraction rate proposed for long-term exploitation of 20 years is about 32,000m$^3$/day.

Even though there are some limitations in the inputs of the modeling exercise due to lack of enough data acquisition in the modeling area, the present outputs can be tested by start pumping at lower rate for 6 months and increase gradually to the higher rates. Through regular monitoring of discharge and drawdown, re-calibration and post-auditing of the model would improve and make it more valid.


## Table of Contents

## 1. Location and Physiography

Akaki well field is located 23 km south-east of Addis Ababa, in the lower part of Akaki river catchment. The area of the well field is 16 sq. km.

The Akaki river catchment includes the jurisdiction of the city of Addis Ababa and the surrounding Oromiya Region and covers about 1,600$km^2$. The Catchment is dominated by undulated topographic surface with elevation ranging from 1800mals at the mouth of the river to over 3100 masl in the Entoto mountain ranges over a distance of 65km. The well field has more or less flat terrain with ground elevation ranging between 2050-2100masl. The Akaki river catchment is bounded by Mt. Furi (2839masl) in the south-west, Mt. Yerer (3100masl) in the east, Mt. Wochecha in the north-west and of course the Entoto ranges in the north. Some Prominent volcanic peaks in the well field include Grara Bushu (2,346masl) in the north-east, Mt. Guji (2475masl) in the east and Mt. Bilbilo (2,380mals) in the south &south-east.

## 2. Climate

The Climate of Addis Ababa is Woina Dega type (Daniel Gemechu, 1974). The Rainfall has unimodal pattern, one distinct rainy and dry season. The dry season is October through may and the wet one is from June to September being the highest rainfall peak in August. The long-term mean annual rainfall observed at Addis Ababa Observatory is 1254mm. Addis Ababa Observatory is the only gauging station, which has the long-term monitoring in the catchment since the turn of the century except a gap between 1941-1945.

The maximum temperature of Addis Ababa ranges between $20^0$c (in wet season) to $25^0$c (in dry season), while the minimum falls between 7 - $12^0$c in the year. This indicates that daily variation of temperature is highly pronounced.

Wind speed is generally moderate, ranging between 0.5 to 0.9m/s. The average daily sunshine hours are 9.5 hours in November & December, and far low, 3 hours, in July and August.

Pan-evaporation records at Addis Ababa Observatory showed that the average monthly pan-evaporation during dry season (November) is about 180mm and in west season (July) falls to 75mm.

## 3. Hydrology

Akaki River Catchment is mainly drained by two rivers; the Big Akaki river, draining the eastern part and Little Akaki, draining the western portion of the catchment. Both the rivers emerge from Entoto Ranges flowing to south-east and after 95 km joins the Awash river near Dodota. The Big Akaki and Little Akaki joins at Aba-Samuel Lake, man made reservoir just downstream of Akaki well field, about 84km up-stream of the confluence with Awash River.

Since 1981, the Big Akaki River is gauged at Addis -Debrezeit road bridge, commanding a catchment area of 885km$^2$. The station is equipped with an automatic hydrometric record and seven staff gauges to measure manually. The mean annual discharge (from 1981-1998) of the Big Akaki at this point is 9,5171/s or 10.75l/s/km$^2$ which is equivalent to say to annual yield of 339mm.

The discharge records reveal that 82% of the annual run-off is generated in July, August and September only, emphasising that the groundwater contribution to the river is minimum compared to the run-off generated in the west season. An increasing trend of low flow with time is observed on the hydrograph; which is attribute to the waste water contribution from the city of Addis. The increase in the low flow of the Big Akaki as a result of the contribution of waste effluent ranges from 0.5m$^3$/day in early 1980's to 1m$^3$/d to 1.4m$^3$/d in late 80's (Tahal 1992). The low flow of Akaki river (both Big & small) excluding the waste water effluent is estimate to range between 600-1000l/s.

## 4. Groundwater Recharge Estimation

Semi-distributed Water Balance model was developed to estimate the groundwater recharge of the catchment. The model consider three parameters; maximum moisture holding capacity of the unsaturated zone, fraction of soil moisture that percolate to recharge the groundwater and the base-flow recession coefficient. The Akaki catchment is divided to nine sub- catchments based on topography in order to account the spatial variation of input variables and catchment characteristics. Catchment characteristics such as depth to water level, soil permeability, land-use and other parameter values have been established, and accounts for transfer of water from one sub-catchment to another through the hydrological process is made. Taking into consideration of the aerial average monthly rainfall and the potential evapotranspiration for each sub-catchment the model produces monthly runoff at the out let of the catchment and the groundwater recharge. Thus in Akaki river catchment, the mean annual recharge to the groundwater is about 51mm which occurs from June to September, mainly happens in July and August.

## 5. Geology and Geo-structures

The geology of Akaki river catchment briefly look as follows: The north and north eastern area (the Entoto mountain, the northern and north eastern Addis Ababa) is covered with trachytes, rhyolites, basalts and several episodes of pyroclastic materials of older volcanism occur on the upper part and foothill sides of Entoto ridge. Overlying these, younger basaltic rocks (Addis Ababa Basalt) are found covering the central and southern part of the city . Outcrops of ignimbrites north of Bole area (Eastern Addis) and Lideta area (Central Addis) have been observed underlying the Addis Ababa basalt. Younger volcanic of trachy-basalt, trachytes, ignimbrites and tuff belonging to the wochecha, Furi and Yerer volcanoes are recognised overlying un-conformably on the Addis Ababa basalt in the western, south-western and eastern part of the catchment. Akaki (including the well field), Dukem and Debrezeit area are covered with olivine basalt, scoria, scoriaceous basalts and vesicular basalts. In the upper part, in some places, intercalation of tuffs, sand and gravels are also recognised. In north-east, east and in smaller extent in the western part of Debre Zeit, outcrops of trachytes, rhyolitic ignimbrites and tuffs are recognised covering the area.

The overburden covering the bed rocks includes soils, lacustrine & alluvial deposits. Thick insitu soil type cover is found in the centeral, south-eastern, north- eastern, western (kolfie & Keraniyo) and in northern (Gullelie) part of the catchment. The lacustrine covers Bole, Lideta, Mekanisa, Akaki-Aba Samuel area and Dukem-Debre Zeit area. Some alluvial deposit also occur along Big & small Akaki rivers in the southern and south-western part of Addis and minor deposit also accur along Kebena river in the area north-west of Bole.

The Akaki catchment lies at the upper shoulder of the Main Ethiopia Rift System. Therefore, it is highly affected by rift tectonics, which is manifested by numerous faults of the rift trend (NE-SW), and faults and lineaments of E-W, N-W and NE-SE trend. The density of faults increase towards the south-eastern part of the catchment area (where the well field lies) to the direction of the rift floor. In the well field area, some of the cinder cones are aligned along the major NE-SW trending faults which presupposed to be erupted through these faulting process.

## 6. Hydrogeology

The Occurrence of groundwater in Akaki catchment is associated mainly to the volcanic rocks and minor alluvial aquifers do exist along the banks of both Big and Little Akaki rivers. These Volcanic aquifers have primary porosities like vesicles and joints and secondary porosities like faults, fractures & fissures produced as a result of tectonic activities and weathered zones. In the volcanic rocks groundwater circulation and occurrence is associated with these porosities while in the alluvial aquifers, it is in the interstitial spaces in between the sediments.

The geometry of the aquifer systems in the catchment area is highly variable, discontinuous and not well defined. In most area, the volcanic aquifers show semi-confined to unconfined nature which in few area (kerchelie and kality), confined aquifers are penetrated. Correlation of the lith-hydrostratigrahic units is very difficult and yet not established.

The Potentiometric surface indicates that the groundwater is in connection with the surface water of Big & Little Akaki rivers north of Akaki bridge. Thus the base flow of the rivers is contributed from the groundwater. 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.

The piezometric surface constructed from groundwater points inventory made during previous projects showed that the general groundwater flow direction is from north to south in the upper &central part and towards south & south-east in the lower parts of the catchment area.

The aquifers in the well field are scoriae deposits, fractured & jointed scoriaceous basalts, vesicular basalts and basalts. These aquifers in most cases are interlayered and overlay one another. As observed from the geological logs, the occurrence of thicker beds are rear. The vertical and horizontal inhomogenity of the aquifer system is obviously seen on the fence diagram of the well field.

As a result of the variability and complex nature of the volcanic aquifers in the catchment area, the hydraulic properties of the aquifers is also highly variable resulting extremely variable discharges (yields) of boreholes even in close distances unless otherwise it lies on the same fracture/fault zone. However, in Akaki well field variation in hydraulic properties of the aquifer and the yields of boreholes is not so much pronounced.

The transmissivity (T-value) and storativity (S-value) calculated from pumping tests in the well field reveal that it ranges between 1834 $m^2$/d to 105,408 $m^2$/day and from 0.0065 (o.6%) to o.016 (2%) respectively. In the area north of Aba Samuel to Lafto area, the T-values range between 19-117 $m^{2/}$d and the S-values are estimated to range between 0.05 - 0.0001. In Duken area T-values range between 61-153 $m^2$/d. In north of Akaki well field and kality area T-values range from 2.8 - 6,099$m^2$/d. Central part of Addis do have 0.3 - 5,760 $m^2$/d while the northern part of the catchment (Entoto, Gulele and Tatek) have 0.3 - 1,092 $m^2$/d. The western catchment area (woletie Suk - Alem Gena area) have T-values ranging between 9.9 - 95$m^2$/d and the S-values between 0.0004 to 0.013.

From this distribution of hydraulic characteristics of the aquifers, it is clear that aquifer parameters are lower in the upper & western part of the catchment area, relatively higher in the central, southern and south-eastern part and extremely high at Akaki well field and gets lower in the Dukem area south-east of the well field.

## 7. Groundwater Quality

The groundwater quality in Akaki River Catchment is more or less similar and good quality water for domestic & industrial uses except the hot (termal) water in Fluha - Grand Palace - Hilton area where the water is highly mineralized (high TDS). Generally the analytical result showed that all ions in the samples are under the WHO recommended permissible limit for drinking water.
Some wells in the town (specially shallow wells along river banks) show higher Nitrate and chloride concentration which obviously would be due to contamination with waste water from domestic and industrial effluents.

The water group is Ca-Mg bicarbonate type. It is obvious that Ca and Mg is from the weathering and decomposition of the basalts which avail the leaching of ions from (pyroxene, Olivine & plagioclases) and the bicarbonates are from hydration of $CO_2$ gas from the atmosphere and oxidation of the organic matter in the soil.

## 8. Background on Groundwater Modeling

### 8.1 Introduction

Though Ethiopian is presumed to have large quantity of fresh groundwater resources from varies scattered studies and exploration works, the country is still yet not made detail works in studies quantifying and mapping of the groundwater resources in spatial distribution. It is obvious that some works have been done in preparation of river catchment master plans e.g. Awash Catchment Master Plan, Nile Catchment Master Plan, etc.). All these works provide very qualitative information as far as groundwater spatial distribution, potential and the different lith-hydrostratgraphic units in the area.

In such circumstances where a country does not have clear picture in the groundwater resources, development of the resources require prudent action. Development of the resource require either conventionally calculated water balance and come up with the annual groundwater storage (recharge) and the total potential of the area available for exploitation (i.e. with out depletion) and monitoring of the amount of exploitation and water level drop or formulating a correct conceptual model and based on that construction of a numerical groundwater model of the area and evaluate spatial and temporal trends of the hydrological stresses and re-calibrate and post-audit the model for model realization by discharge and drawdown monitoring.

## 8.2 What is groundwater model and why is needed?

Groundwater model is a device that approximates a field situation. There are two approaches: a **physical model** which more or less represent the action field conditions like a laboratory sand tanks to simulate groundwater flow directly. The other is the **mathematical model**, which simulate groundwater flow indirectly by means of a governing equation that are thought to represent the physical process of the system. It considers the equation governing heads or flows along boundary of the system (boundary condition) and for time dependant conditions, equations describing initial heads distribution (initial condition) of the system. Mathematical models can be solved analytically or numerically.

The Purpose of groundwater models aimed at three main objectives:

1. Predictive: Used for prediction of the future of the consequences of proposed works, i.e. say drawdown, discharge, etc. This require calibration.
2. Interpretative Used for gaining insight into the controlling parameters in a site-specific settings or as a frame work for assembling and organising field data and formulating ideas, about system dynamics. It does not necessarily require calibration. Example Regional Aquifer system Analysis.
3. Generic: Used to analyze flow in hypothetical hydrological systems. It also helpful in formulating regional regulation guidelines and screening tools to identify regions suitable or unsuitable for some proposed action. It does necessarily require calibration. Example Model used to study lake-ground water interaction.

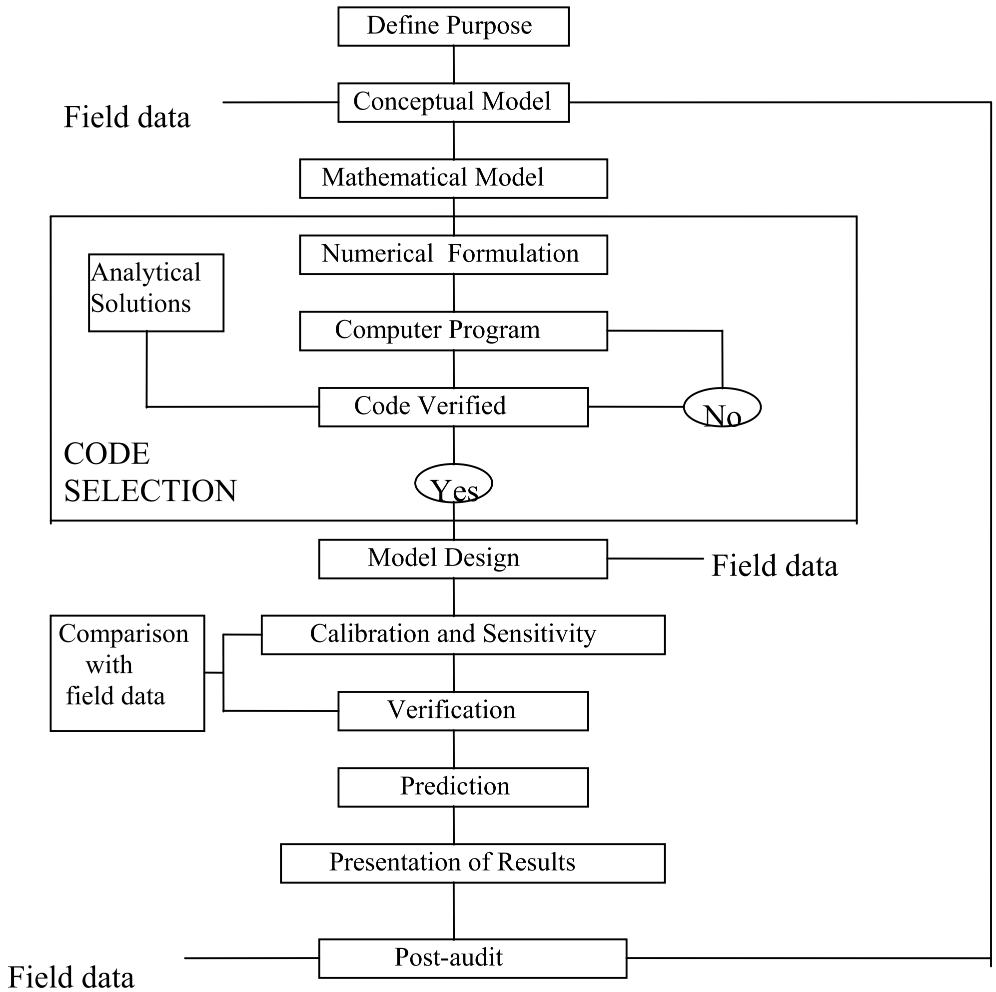
Groundwater modeling is one of the excellent tool to organize and synthesize field data of Hydrogeological assessment. Models require adequate and reliable data to produce useful results. Otherwise inadequate and poor quality data input results unreliable output which would be “garbage in garbage out”.

Groundwater modeling has a paramount importance in assessing the groundwater potential and predicting the possible water level drop in an area as a result of the exploitation of the resource. Single well pumping test or simultaneous group tests of a few wells in a well field would not give sufficient data as pumping on of all the wells in the well field. Running all the wells in the well field would only provide enough data which is by far the most expensive methodology to practice. On the other hand, with limited efforts and expenditure, by constructing a groundwater model, the groundwater potential can be estimated and prediction of amount of abstraction and the consequences of drop of water level as result of pumpage could be predicted.

## 8.3 Modeling protocol

If the purpose of investigation require groundwater modelling, like other assessment methodologies, it has its won steps or protocol to follow. A modeling protocol includes code selection, model design, calibration, calibration sensitivity analysis, verification, prediction, prediction sensitivity analysis and post-audit. Each of these steps builds support in demonstrating that a given site specific model is capable or producing meaningful results, that is the model is Valid. The steps of modeling protocol for application in groundwater model is shown as below.

Figure : 1.1 Flow Diagram of Modeling Protocol




## 9. Purpose or Objectives of the Groundwater Modeling

The purpose of the groundwater modeling exercise are:

- assess the groundwater potential in the well field
- Propose optimum sustainable yield for each well
- Propose different Scenarios of abstraction rates for short-term use in case the organization requires

- Propose groundwater management options.

## 10. Conceptual Model of the Area

Based on the above discussed physiographic, geological, hydrogological & hydrological conditions, the conceptual model of the area is constructed as outline below:

- The model area encompasses the regional flow system of Akaki river catchment and extends to south & south-east up to the confluence with Awash river and the central part of Dukem Plain. Input out of the catchment area is considered to be negligible.
- The source of recharge for all surface and groundwater is the precipitation which only occur in the catchment area.
- The piezometric surface of the groundwater follows the topographic gradient from north to south in the upper catchment and to south and south-east in the lower part, in Akaki & Dukem area.
- As a result of the non-uniformity, highly variable and complex geological setting which reflectes similar hydrogeological conditions, it is not possible to define different model layers. On the other hand, the continuous topographically controlled piezometric surface of the groundwater in the region, and the first instance to simulate flow in such type of complex hydrogeological condtions initiate to considered the aquifer as a single layer system. In addition, the fact that the study is for long term abstraction, the effect of muli-layer system on the out put is negligible. Therefore, considering the upper most aquifer system as a single layered aquifer system would produce valid results.

## 11. Model Characteristics

### 11.1 Model code

The Processing Model Flow (Version 5.0.54) developed by USGS and W.H. Chiang & W.Kinzelbach (1991-1998) was used.

### 11.2 Construction of model grids & boundary conditions

The northern, western and eastern surface water catchment boundaries are taken as no-flow boundary. Since the groundwater leave out the catchment in south-east direction towards Dukem plain, a constant-head boundary was established at 1800masl. This specified head boundary extends from north-east of Dukem down to the confluence of Akaki and Awash rivers.

The Model area is 1862km$^2$. The model grids consists of 94 columns and 116 rows. The grid spacing is 100m in both X and Y directions except in river, well field and spring cells. The river cells and the well field cells have 500m uniform spacing while Fanta spring have 250m uniform spacing.

### 11.3 Groundwater input and output

The recharge to the groundwater is mainly from infiltration and percolation of rainfall and losses from streams in the upper part of the catchment during heavy rains. The result of the hydrogological model of the area showed that an average recharge of 51mm/annum occurs in the catchment area. However, considering the physiographic & hydrogeological conditions of the area, the recharge in the upper mountainous area is taken to have 33m/year and the remaining parts with values of 74mm/year. Recharge is considered negligible in areas where thick clay and lacustrine cover deposits are found.

Groundwater output occur in the form of springs recharging rivers and abstraction through wells. The spring output is simulated with drainage package, the rivers with river package and the wells from their corresponding cells.

Table 11.3.1 : Summary of groundwater outputs

| Out puts | discharge estimated (l/s) |
|---|---|
| Fanta Spring | >22 |
| Aba Samuel gorge Springs | 30 to 60 |
| Rivers | 600 to 1000 |
| Abstraction from wells | 182 |
| Total | 830 t0 1260 |

## 12. Model Calibration

### 12.1 Steady state flow calibration

The Objective of this calibration is to check the overall coherence of the selected assumption of the model at identifying the transmissivity of the aquifer. To carryout the calibration, there has to be stability in time of the piezometric levels, and results an equal amount of inputs and outputs of the aquifer system which leads to a steady state condition.

In the stead state flow calibration, check points of heads in 10 years (1990 & 2000) gap were use. The piezometric levels of all the wells during this time are found almost the same except negligible difference (+o.2 to +0.9m) which might be accounted for climatic variations.

As a result of these, assuming a steady state condition, the calibration of the model is done by comparing the results of calculation with the field observations like piezometric level of the network selected and flows of the river and springs.

#### 12.1.1 Conditions of calibration

The transmissivity values (T-values) estimated from evaluation of pumping test results are classified and taken as input value. Recharge of 33mm/year assigned to the mountainous areas and 77mm/year to the lower flatter zones. The potentiometric map is superimposed on the model to start the flow simulation.

The T- values are adjusted until the model simulate conformable calculated and observed potentiometric surface and until reasonable match is obtained between the observed and simulated discharge of Akaki river, Fanta and Aba-Samuel gorge springs. After many trials satisfactory simulation results is obtained from points of view of flows, piezometric levels and transmissivities.

### 12.1.2 Results of calibration

The simulated potentiometric surface is checked and further calibrated at each well especially in the well field and the surrounding area. Even though the calibration and simulation results showed 1 to 5m difference of piezometric level between close wells due to the available data are not synchronised in time, the result is considered as acceptable (see Table - 12.1.2.1)

Table 11.1.2.1: steady state flow, observed and computed heads (masl)

| Piezometers Name | Observed Head | Calculated Head |
|---|---|---|
| B3 | 2261 | 2262.442 |
| T1 | 2141.9 | 2146 |
| T5 | 2175.3 | 2177.9 |
| B13 | 2130.7 | 2131.7 |
| T2 | 2130.7 | 2131.7 |
| EP1 | 2130.6 | 2131.4 |

| | | |
|---|---|---|
| EP2 | 2170.5 | 2177.8 |
| EP3 | 2130.5 | 2134.9 |
| B15 | 2051.6 | 2048.1 |
| T4 | 2051.2 | 2047.5 |
| EP7 | 2018.47 | 2020.7 |
| BH11 | 2019.5 | 2020.7 |
| BH5b | 2019.5 | 2020.8 |
| MW1b | 2019.7 | 2022.5 |
| BH3b | 2019.7 | 2019.2 |
| BH19 | 2019.5 | 2022.2 |

The computed water balance of the stead state flow is as follows

Table 12.1.2.2: Water balance in steady state flow (l/s)

| Description | Model input/output (l/s) | | Estimate |
|---|---|---|---|
| | Inputs | Outputs | |
| Recharge from precipitation | 2773 | | |
| Discharge of Little Akaki R. | | 86 | |
| Discharge of Big Akaki R. | | 678 | 600 - 1000 |
| Discharge of Kebena R. | | 50 | |
| Discharge of Aba samuel Sping | | 52 | 30 - 60 |
| Discharge of Fanta Sping | | 30 | ✇22 |
| Discharge of South-east limit | | 1695 | |
| Discharge of wells | | 182 | |
| Total | 2773 | 2773 | |

## 12.2 Transient state calibration

Transient state calibration is accomplished by running the model by integrating time and the storage coefficient of the aquifer. This hydrodynamic parameter of the aquifer is produced through calculation of the evolution of observed piezometric level, flows of springs, etc. in a given lapse of time. The transient state calibration was done based on the piezometric variation monitored by Seureca from Nov. 1989 - Oct. 1990 at piezometers B3, B7, B1, B6, B8, B5 and B4.

### 12.2.1 Conditions of calibration

- Initial state : Nov. 1989 water level is assumed to be at steady state condition
- Duration of simulation : 12 months
- Boundary condition, hydrodynamic parameters: Similar to steady state flow condition
- Up take conditions : discharge of the steady state
- Monthly recharge: As computed by he hydrologic model

### 12.2.2 Results of calibration

The storage coefficients estimated from pumping test results were used as first input data. Based on the observed piezometric levels and the recharge values, the storage coefficients have been calibrated to simulate a matching calculated pizometric level to that of the observed one (see Fig. 16)

It shows That the well field has high value with 20% where as in general, the reaming area has very low storage coefficient. Aba-Samuel and the area north of it has 2.5% the area covered with confined aquifers has o.5% and all the reaming catchment area have 4%.

On completion of the calibration processes, the model is now more or less a coherent unit to represent the actual aquifer system on the field.

## 13. Assessment of Discharge of the Well Field

### 13.1 Conditions of simulations

To come up to the sustainable discharge of the well field, eight preliminary simulation had been done. These are:

| | |
|---|---|
| simulation 1: | 30,000$m^3$/d |
| simulation 2: | 40,000$m^3$/d |
| simulation 3: | 50,000$m^3$/d |
| simulation 4: | 60,000$m^3$/d |
| simulation 5: | 72,000$m^3$/d |
| simulation 6: | 82,000$m^3$/d |
| simulation 7: | 92,000$m^3$/d |
| simulation 8: | 102,000$m^3$/d |

On running all these simulations, the general conditions retained are:

- Initial state: actual piezometric situation or steady state flow condition
- Duration of simulation: 20years
- Boundary conditions, hydrodynamic parameters, recharge: similar to steady state flow
- Uptake conditions: discharge of the steady state plus discharge corresponding to the simulation studied

Simulation for the phase-1(11 wells) and for the 25 boreholes including the eleven wells had been run and the impacts of piezometric level and drawdown is observed.

### 13.2 Results of simulations

For characterising the impacts, time steps of 5, 10 and 20 years were considered and the lowering of the water level or the amount of drawdown for the above periods with respect to the pumping rate is observed (see Table 13.2.1 & Fig. 18)

Table 13.2.1: Drawdown in the well field

| Pumping rate, m3/d | DD (m) in 5 years | DD (m) in 10 years | DD (m) in 20 years |
|---|---|---|---|
| 30,000 | 6.80 | 11.30 | 18.10 |
| 40,000 | 9.00 | 14.80 | 23.70 |
| 50,000 | 11.30 | 18.70 | 29.90 |
| 60,000 | 13.50 | 22.20 | 35.60 |
| 72,000 | 16.20 | 26.80 | 42.90 |
| 82,000 | 18.20 | 30.30 | 48.50 |
| 92,000 | 20.70 | 34.20 | 54.80 |
| 102,000 | 22.90 | 37.70 | 60.40 |

The results showed that:

- The drawdowen is high.
- The speed of lowering of the water level decrease very slow with time and the aquifer couldn't form a new equilibrium to stabilize the drawdown because of the low transmissivitly of the aquifers surrounding the well field.
- Fanta spring gradually decrease in discharge and dry out after 10 years; while the Aba-Samuel gorge springs show significant decrease in discharge.

**13.3 Interpretation of the results**

The wells in Akaki well field are telescopic, 14" casings & screens on the upper most and 8" casings & screens in the lower part. The pumps of phase-1 wells are designed be install in the upper casing (14") and the pumps characteristics obliged to be install above the top screen (14").

The simulated drawown in the wells is higher than the available drawdown (head) of the wells for most of the simulated cases except for 30,000m$^2$/d where a few wells have simulated head below the available head specially in 5 & 10 years simulations. Table 13.3.1 shows the available & simulated heads of phase-1 wells at 30,000m$^3$/d.

Table 13.3.1: Available and simulated heads at 30,000m$^3$/day of phase-1 boreholes.

| Well | Available head (m) | Simulated head (m) | | | Remarks |
|---|---|---|---|---|---|
| | | 5 years | 10 years | 20 years | |
| BH 6 | 7.18 | 7.21 | 13.01 | 18.18 | |
| BH 7 | 11.58 | 6.58 | 11.58 | 18.58 | |
| BH 8 | 16.80 | 6.80 | 11.80 | 17.80 | |
| BH 9 | 19.30 | 7.30 | 11.30 | 18.30 | |
| BH 12 | 24.47 | 6.47 | 11.47 | 18.47 | |
| BH 14 | 18.82 | 6.82 | 10.82 | 17.82 | |
| BH 16 | 30.06 | 7.02 | 11.02 | 18.02 | |

| | | | | | |
|---|---|---|---|---|---|
| BH 17 | 31.06 | 7.06 | 11.06 | 18.06 | |
| BH 18 | 27.92 | 6.92 | 10.92 | 17.92 | |
| BH 21 | 26.32 | 6.32 | 11.32 | 18.32 | |
| BH 22 | 10.10 | 7.10 | 12.10 | 18.10 | |

From these data it is obvious to conclude that abstraction from akaki well field can not provide the expected rate of discharge of phase-1 (72,00m$^3$/d) from the eleven wells.

## 14. Proposed Development Plan of the Well Field

### 14.1 Constraint of drawdown

As discussed earlier, most of the wells have short available heads for long-term abstraction rate (☹20 years). Therefore, out of the 25 wells 14 wells and from the 4 Akaki Water Supply wells one well (EP-7) are selected for their higher available head for considering the simulation of sustainable pumping in the well field for 20 years. The smallest available head of these wells is 17m; accounting one meter for well losses, the final drawdown shall not exceed 16 to 18m.

The following four options are selected for simulation of the development alternative plans in the well field:

### 14.2 Simulations

- First simulation: Long-term exploitation of the well field, pumping for 20 years. The objective of the simulation is to find an optimum discharge rate where the drawdown does not exceed 16 to 18m.
- Second simulation: Looking for high discharge rate on maintaining the drawdown constraint (16-18m) for 7 years.
- Third Simulation: Looking for high discharge rate which gives a drawdown of about 16 to 18m after 10 years.
- Fourth Simulation: Looking for high discharge rate which gives a drawdown of about 16 to 18m after 7 years by operating the best 8 wells of phase-1.

#### 14.2.1 Simulation 1 : Long-term exploitation for 20 years:

**Objective:** finding a discharge rate complying with the constraint of drawdown given above. (16 to 18m)

**Conditions of Simulation:**

- Initial state : Actual piezometric condition, stead state flow condition.
- Duration of simulation : 20 years.
- Boundary Condition, hydrodynamic parameters, recharge: similar to steady state flow condition.

- Uptake conditions: discharge of the steady state plus pumping for the simulation.

**Results:**

After several trials, 32,000m$^3$/d has been found to give an admissible drawdown. The total discharge is obtained by taking 15l/s at Ep-7 and 25.3l/s each from 14 other wells. The evolution of drawdown is shown in Figure 23 and it indicates regular piezometric drop in the well field. Figure 24 shows the drawdown map and its extension after 20 years. The drawdown contour map has an elliptical shape oriented in NW-SE direction due to the distribution T-Value.

### 14.2.2 Simulation 2 : High rate of exploitation for 7 years.

**Objective:** Looking for high discharge rate for 7 years complying with the drawdown constraint (16 to 18m). In this case it is assumed that after 7 years another water supply source would be developed for supplement the low discharge rate in the following 13 years.

**Conditions of simulation:**

- initial state : The same as previous simulation (Sim.).
- Duration of simulation : 20 years (7 years at high rate 13 years at low rate).
- Boundary condition : the same as pervious Sim.
- Up take condition: discharge of steady state plus high rate for 7 years and low rate for 13 years.

**Results**

After several trails 58,000m$^3$/d has been found to give an admissible drawdown at the end of the 7$^{th}$ year. This discharge is reduced to 20,000 m$^3$/d for the remaining 13 years and the drawdown after 20 years is found similar. For the first 7 years the total discharge is obtained by pumping 18 l/s from EP-7 and 46.6 l/s from each of the 14 other wells. For the remaining 13 years, EP-7 has to be maintained at 18 l/s and the other wells reduced to 15.2 l/s each. The evolution of drawdown is shown on Figure 23 indicating clearly the change of exploitation after 7 years.

### 14.2.3 Simulation 3: High rate of exploitation for 10 years.

**Objective :** Looking for higher exploitation for 10 years complying with the constraint of drawdown.

**Conditions of simulation:**

- initial state : the same as the previous Sim.

- Duration of simulation : 20 years (10 years at high rate 10 years at low rate).
- Boundary Conditions :- The same as the previous Sim.
- Up take Condition : discharge of steady state flow plus high rate for 10 years and low rate for the remaining 10 years.

**Results:**

After several trails, 43,000 $m^3/d$ has been found to give an admissible drawdown at the end of $10^{th}$ year. Discharge was reduced to 20,000$m^3/d$ for the remaining 10 years and the drawdown has been found similar at the end of $20^{th}$ year. For the first 10 years, the total discharge is obtain by taking 15 l/s from EP-7 and 34.5 each from the 14 wells. For the remaining 10 years, the discharge of EP-7 will be maintained at 18 l/s and the other wells reduced to 15.2 l/s. The evolution of drawdown with time is shown in Figure 23 and it shows clearly the change of exploitation after 10 years.

### 14.2.4 Simulation 4: High rate exploitation from 8 wells of Phase-1

**Objective:** To see the drawdown effect for a discharge rate of 58,000 $m^3/d$ for the 8 best wells of Phase-1, which already connected to CT site (BH-8, 9, 12, 14, 16, 17, 18 & 21).

**Conditions of Simulation:**

- Initial state : the same as previous Sim,
- Duration of simulation : 20 years (7 years at high rate, 13 years at low rate)
- Boundary Conditions : The same as previous Sim.
- Up take Condition : Discharge of steady state plus high discharge rate for 7 years and low rate in the remaining 13 years.

**Results**

Pumping at 58,000 $m^3/d$ has resulted to comply with the constraint of drawown (16 to 18m) at the end of $7^{th}$ year. The discharge is lowered to 20,000 $m^3/d$ for the remaining 13 years, and the drawdown is found similar to the constraint drawdown at the end of 20 years.

For the first 7 years the total discharge is obtain by taking 18 l/s from EP-7 and 81.6 l/s each from the remaining 8 wells. For the remaining 13 years, the discharge of EP-7 will be maintained at 18 l/s and the other wells will be reduced to 28 l/s each. Figure 23 shows the evolution of drawdown in the time of the well field and it is similar with simulation number-2. Therefore, it is possible to pump for the same exploitation rate of the best 8 wells of phase-1.

## 15. Model Limitation and Verification

As discussed earlier, the model area has complex geology and hydrogeology; which ultimately resulted undefined, discontinuous and complex aquifer system. However, in addition to the primary porosity of the volcanic rocks, the intensive faulting, fracturing and fissuring by tectonic activities enhance the transmission and storage capacity of the rocks. Specially at the well field, the primary porosity of the scoria, scoriaceous & vesicular basalts have been interconnected by faulting & fracturing, and thus behaves as primary aquifer system. As a result of this and all others mentioned earlier, the conceptual model assumes that the aquifer is Equivalent Porous Media (EPM) and single layered aquifer system. However, these assumptions would have its own limitations in the model outputs (results).

The data collected in the catchment area as well as in the well field have limitation for proper evaluation of the aquifer hydraulic parameters. The pump tests conducted at the well field do not show sufficient reaction of the aquifer system due to low pumping stress. Thus the drawdowns observed in most wells is less than one meter. It is obvious that estimates of the hydrodynamic parameters (T and S values) from such tests would have significant limitation in the model result.

Although the model has been calibrated with the existing data, because of the above mentioned limitations further verification of the model is required with the actual reaction of the well field to pumping. Further more post-auditing has to be followed during the operation time to adjust the model with time.

## 16. Conclusion and Recommendations

The following conclusion and recommendations have been arrived at the end of the modeling exercise.

◊ Pumping shall be start at lower rate about 30,000 $m^3$/d for about 6 months to monitor the reaction of the aquifer in repose to pumpage. After that, if necessary, re-calibration can be done and abstraction rates can be increased slowly to meet the required discharge.

◊ For reasonable exploitation of the well field over 20 years the abstraction rate shall not exceed 32,000$m^3$/d.

◊ For emergency situations, options of high rate exploitation flowed by reduction of the abstraction rate is possible (simulation 2 to 4). But, AAWSA has to look for new sources in due time to supplement while reducing the abstraction rate.

◊ Pumping at the well field with the above rate would affect the groundwater level in the surrounding Akaki and kality area at the end of 20 years. In Akaki area, water level drop would be about 12m and in kality, about 5m.

◊ Since the well field is downstream of the city and the industrial zone, water quality monitory has be followed regularly while most to full scale operation started.

◊ Monitoring of piezometric level has to be conducted at a regular monitoring schedule. It shall be started 3 to 4 (6) months prior to start pumping to appreciation the impact of pumpage in the well field.