Addis Ababa University

School of Graduate Studies
Addis Ababa Institute of Technology

Aquifer Property Evaluations and Sensitivity Analysis of Akaki well Field, Central Ethiopia

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Thesis Submitted to Addis Ababa Institute of Technology School of Graduate Studies in partial fulfilment of the requirements for the Degree of Masters of Science in Civil Engineering under Hydraulic Engineering

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This is to certify that thesis prepared by Hawi Gudeta entitled: Aquifer property evaluations and sensitivity analysis of Akaki well field, central Ethiopia submitted in partial fulfilment of the requirements for the Degree of Master of Science in **Civil Engineering under Hydraulic Engineering** complies with the regulations of University and meets the accepted standards with respect to originality and quality.

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Date

Declaration

I declare this thesis is my own works which has not been studied in any other university and that all source of material used during the thesis work have been accordingly approved.

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The Thesis has been submitted for the examination with my approval as university advisor.

Dr. Ing. Asie Kemal
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Abstract

Groundwater is essential resource which used in many aspects of life activities. Ethiopia has abundant potential of groundwater resource and in resent two decades the development of this project is increased. Addis Ababa water demand highly increases due to fast population growth, urbanization and industrialization. To supply this need the Akaki ground water well is one of the well field which can meet more than 30% of water supply demands in Addis Ababa. However, a number of wells in Akaki well field get dry and become unproductive. Therefore, this study aims to evaluate and analyses the performance and aquifer parameters (transmissivity and storativity) using the theoretical model: ***Cooper-Jacob method and Theis Recovery method*** with corrected observed time-drawdown, step-drawdown, time-residual drawdown or recovery data. The evaluated result shows, most of aquifer transmissivity is underestimated and few of it overestimated when it compared with WWDSE report. Again, to analysis sensitivity of the aquifer of the study area it modelled by ***MODFLOW*** through different scenarios of-50%, -25% decrement and +25% and +50% increment of discharge and hydraulic conductivity. Also, by discounting general boundary head, constant head, rivers and Akaki well phase IIIA extraction analysis are taken. Accordingly, the aquifer system of Akaki well fields is more sensitive for the probable change of the hydraulic conductivity special during the reduction of ability to permit water through it. Concerning on the water budget of each scenario for ignorance of water packages, the simulated head of area is more sensitive for Akaki river ignorance and as the Akaki well field phase IIIA stop water pumping the other well field phase start to rise, this show the cone of depression is extended up to the phase IIIA field area and this implies there is the well interference between the phases. Those result suggest that un safe yield of water rate costs the high depletion of the water level which cause to the drying of wells and ground water depletion where ground water extracted at rate faster than it can recharge (hydrological imbalance) and sustainability of the resource is under risk.

Key Words: **Groundwater, aquifer, drawdown, safe yield, sensitivity**

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List of Acronyms and Abbreviations

AAWSA	Addis Ababa Water Supply Authority
BH	Bore Hole
BHR	Bore Hole Replaced
BMC	Billion Meter Cubic
DD	Draw down
DEM	Digital Elevation Model
GBH	General Boundary Head
GIS	Geographical Information System
II	Phase 2 Akaki well field
IIIA	Phase 3A Akaki well field
IIIB	Phase 3B Akaki well field
MAE	Mean Absolute Error
Masl	Meter above sea level
ME	Mean Error
NE	North to East
OBS	Observation Wells
REV	Representative Element Volume
RMS	Root Mean Square
SW	South to West
SWAWF	South and western Akaki Well
SWL	Static Water Level
WF1-PW	Well Field 1 of Pumping Well
WF2-PW	Well Field 2 of Pumping Well
WWDSE	Water Works Design and Supervision Enterprise

1. INTRODUCTION

1.1. Background

Groundwater is the most important component of water resource which constitutes about two thirds of the world freshwater resources. In many parts of the world countries, groundwater becomes the first choice since surface water resource such as lakes and rivers are scarce. In the last three decades most water development globally has been from groundwater. At present an estimated 70% of the world's population depends for its basic domestic water services on groundwater. In 51% of countries groundwater withdrawal tops 100m^3 per capital annually (Ethiopia: Strategic Framework for Managed Groundwater Development, 2011).

Groundwater potential in Ethiopia is shaped by complex geological formations and the diversity of the topography, climate and soil. The event of groundwater is mainly influenced by the geophysical climate condition of the area. The geology of Ethiopia is provides usable groundwater and provides good transmission of rainfall to recharge aquifers which produce spring and feed perennial rivers. In many parts of the country ground water is an important source of domestic and industrial water use. With the understanding of the nature of the distribution of the country, it estimated the total ground water reserve of the country as 185BMC, which is distributed in an area of 924,140km^2 made of Sedimentary, Volcanic and Quaternal rocks (B.Berhanu et al, 2014).

In two recent decades there has been an increased interest in ground water resources development especially around Addis Ababa city. This interest has caused due to, an increase of population, industrial activities, agriculture etc. and to achieve the demand required groundwater development needed. Addis Ababa Water Supply Authority (AAWSA) entered a contract agreement with Water Works Design and Supervision Enterprise (WWDSE) to get detailed groundwater investigations studies on five prospective areas and identify well fields. The sites are located in the peripheries of the Addis Ababa city and the surrounding areas: they are: i) Legedadi-Legetafo-Ayat (LLA), ii) South Ayat-North Fanta Well field (SANFWF), iii) South west and west of Akaki well field (SWAWF), iv) Melka Kunture (MK), and v) Sebeta –Tefki (ST) (Addis Ababa groundwater development, design and construction supervision project, 2011). Akaki groundwater wells that are operated by AAWSA used for 30% of public water supply services.

In Akaki River catchment different researchers are asses on different issues to fill the gap they state as a problem. Ground water models provide additional insight into the complex system behaviour and (when appropriately designed) can assist in developing conceptual understanding. Furthermore, once they have been demonstrated to reasonably reproduce past behaviour, they can forecast the outcome of future ground water behaviour, support decision-making and allow the exploration of alternative management approaches. However, there should be no expectation of a single ‘true’ model, and model outputs will always be uncertain. As such, all model outputs presented to decision-makers benefit from the inclusion of some estimate of how good or uncertain the modeler considers the results. (Kumer C.P, 2013).

Groundwater exploitation and management have serious problem when it compared to the surface water due to lack of proper estimation of groundwater potential. For proper estimation of recharge time series data of rainfall, runoff, evaporation, ground water level and hydrodynamic parameters of the aquifers, transmissivity and storativity are required. Akaki groundwater well assessment taken through single well test and partial penetrated well to aquifer for data collection by pumping test in order to estimate the physical hydraulic properties. In this case, we cannot rely on quality of data collected because the method adopted has a limitation to estimate the real values of aquifer hydraulic. Again the silent revolution caused unprecedented increase in groundwater withdrawal of resource. The stress placed on groundwater systems by groundwater abstraction to build up when the ratio of abstraction to mean recharge increases which may cause to imbalances among hydrologic stresses. These indicate excessive pumping and it bring to long term effects. Hence, groundwater flow modelling may project the risk of such uncontrolled withdrawal on the hydrologic system.

Therefore, in this study aquifer properties are evaluated by taking the desired correction (for unconfined aquifer and partial penetration which contains well loss and borehole storage) and using the appropriate theoretical models (i.e. ***Cooper-Jacob method and Recovery method***) evaluation are done. In long terms, extended and uncontrolled withdrawal may result in water level declines, which cause imbalances among hydrologic stresses. In addition this study gives understanding on the response of Akaki well fields for different possibly occurring stress/scenarios (by increasing and decreasing hydraulic conductivity and recharge parameters) and sensitivity analysed to understand the aquifer system. Akaki well fieldsare modelled using ***Groundwater flow modelling, MODFLOW*** model to project the risk/consequences of such uncontrolled withdrawal on the hydrologic system and effects of those scenarios are assessed and predicted.

1.2. Statement of Problem

Ground water is the safest and most reliable water source used for domestic, irrigation, industries, and municipality purposes. However Akaki River catchment is abundant with groundwater due to nature of aquifer and subsurface flow down from the Intoto Mountain, consideration must take for safe yield (withdrawal), well interferences, climate change (i.e. recharge reduction), urbanization, water quality, environmental impacts, hydrological imbalance and related constraints during the expansion of the groundwater development.

Some of Akaki wells are get dry after completion of drilling of the well or after pumping for a short time. Therefore, assessment needed to identify the cause which leads the well to get dry and to remedy the options which can overcome or reduce the effects. That is why this paper investigate on Akaki well fields, evaluate the determined hydraulic properties of the Akaki well field (for the case of phase IIIA) and to analysis the sensitivity of Akaki aquifer depending on the response of aquifer for different scenarios.

1.3. Objectives

The general objective of this study is to ***evaluate and analysis transmissivity and storativity*** *using the recorded pumping test data and* ***analysis sensitivity*** *of Akaki groundwater aquifer* for decline of water table.

1.3.1. Specific Objectives

To achieve the general objectives of this study there are specific objectives which can lead to come with the general one. Those specific objectives are:

- → Evaluate efficiency of the wells which articulates the productivity of wells and determine the safe yield which helps to improve the consistency
- → Determine the accurate values of transmissivity and storativity which tells us the properties of the aquifer by taking the required correction
- → Effect of phase IIIA on the other project of withdrawal will evaluated and interference’s of the wells will be checked
- → Sensitivity of Akaki well field groundwater aquifer will analysing to weigh the response of the aquifer for future numerous probable factors changing

2. LITERATURE REVIEW

2.1. Groundwater

Groundwater is subsurface water which occurs beneath the earth's of saturated surface. In a hydraulic water cycle, groundwater comes from surface waters (precipitation, lake, reservoir, river, sea, etc.) and percolates into the ground beneath the water table. The groundwater table is the surface of the groundwater exposed to an atmospheric pressure under the ground surface (the surface of the saturated zone) and may fluctuate in elevation. On the earth, approximately 3% of the total water is fresh water. Of this, groundwater comprises 95%, surface water 3.5%, and soil moisture 1.5%. Out of all the freshwater on earth, only 0.36% is readily available to use.

There are two principal futures which distinguish the groundwater bodies from the surface water bodies. Firstly, the groundwater movement through the ground is relatively slow which mean that residence times in groundwater's are generally orders magnitude longer than surface waters movement. Secondly, groundwater contains a considerable interdependence between the amount of physic-chemical and chemical materials.

2.1.1. Groundwater Movement

Ground water moves through the sub-surface from areas of greater hydraulic head to areas of lower hydraulic head. The rate of ground water movement depends upon the slope of the hydraulic head or hydraulic gradient, and intrinsic aquifer and fluid properties.

Flow net is a net/graph of stream line curve and equipotential line which described by the Laplace Equation. Stream line is an imaginary line that traces the path that a particle of groundwater would follow as it flows through an aquifer and an equipotential line indicates points/lines which have equal potentiometric head. It is widely used in the groundwater studies to determine quantities, rate and direction of flow. The flow direction of water is perpendicular to the equipotential line.

2.1.2. Groundwater Pumping

Groundwater pumping is an abstraction of water from underground to surface and it requires well informed planning. Well is one of important aspect of hydro-geologist and used for the extraction of groundwater to supply domestic, municipal, industrial, irrigation requires and other uses. Its system can be considered as composed of three elements, the well structure, pump, and discharge piping. The well itself contains an open section through which water enters, screen, with consist of open-ended pipe and a casing to transport or lift the flow to the ground surface.

2.2. Previous Studies

On aquifer parameters evaluation and analysis researches are done especially by Civil and Environmental Engineering department. Saberi Borgaon Assessment on Interpretive Technique of Transmissivity and Storativity on Aquifer: Case of Legedadi Deep Wells, 2016, Dereje Endalkachew Analysis and Evaluation of Hydraulic Parameters in Akaki Well Field of Addis Ababa (case study of phase II), 2016 and Amare Yalew Evaluation Of Hydraulic Parameters In Kobo Irrigation Wells, 2016 are some of recent researcher on evaluation of aquifer properties.

Hydrogeology and Earth science department researcher also investigate and model the Akaki river catchment to evaluate the contamination transport and groundwater flow. Ebisa Oljira Numerical Groundwater Flow Modeling of the Akaki River Catchment2006, Leta Gudissa Analysis of Subsurface Contaminant Transport in Akaki Well Field and surrounding areas, 2007 and Prof. Tenalem Ayenew et al. Integrated Groundwater Modeling and Hydro-chemical Study in Addis Ababa Area: Towards Developing Decision Support System for Wellhead Protection , 2007 are some of them.

2.3. Geological Formation

Groundwater is not usually static but it moves and flows through the pore of rock. The ease with which water and flow through a rock mass depends on a combination of the size of the pores and the degree to which they are inter-connected. This is defined as the permeability or allowance of the rock to pass water through it. Materials which permit water to pass through it easily are said to be permeable and those which permit water to pass only with difficulty, or not at all, are described as impermeable.

2.3.1. Aquifer Rock

An aquifer is defined as a saturated permeable geological unit that is allow significant water toward wells to yield economic rate of quantities and stored. In other words, a layer of rock that is sufficiently porous to store water and permeable enough to transmit water in quantities that can be economically exploited is called aquifer. The most common aquifers are unconsolidated sand and gravels, but permeable sedimentary rocks such as sandstone and limestone, and heavily fractured or weathered volcanic and crystalline rocks can also be classified as aquifers.

2.3.2. Aquitard Rock

An aquitard is a geological unit that is permeable enough to transmit water in significant quantities when viewed over large areas and long periods, but its permeability is not sufficient to justify production wells being placed in it. Clays, loams and shales are typical aquitards.

2.3.3. Aquiclude Rock

An aquiclude is an impermeable geological unit that does not transmit water at all. Dense un-fractured igneous or metamorphic rocks are typical aquicludes. In nature, truly impermeable geological units seldom occur; all of them leak to some extent, and must therefore be classified as aquitards. In practice, however, geological units can be classified as aquicludes when their permeability is several orders of magnitude lower than that of an overlying or underlying aquifer.

2.3.4. Aquifuge Rock

Aquifuge is relatively an impermeable formation property rock, which is neither containing nor transmitting water.

2.4. Aquifer Formation

Aquifers are the most important geological formation for the occurrence of groundwater. This water-bearing formation areal extensive and may be overlain or underline by impermeable or confining bed. In this case aquifer may classify in to four groups.

2.4.1. Confined Aquifer

Confined aquifer or pressure aquifer is when groundwater is trapped or overlain and underlain by low permeable layer or confining bed. Confined aquifers are also characterized by an internal pressure which is always greater than the atmospheric one. In a well penetrating such an aquifer, the water level will rise above the upper confining bed, defining the elevation of the piezometric surface or potential surface which is an imaginary surface coinciding with the hydrostatic pressure head of the water within the aquifer. If the piezometric surface lies above the ground surface, an artesian or flowing well occurs.

2.4.2. Unconfined Aquifer

An unconfined aquifer also is known as phreatic aquifer, is underlain by confining bed and at upper boundary consists of a free groundwater surface at which the pressure equals atmospheric pressure by water table. It characterized by the occurrence of a well-defined water table at atmospheric pressure. Water in a well penetrating an unconfined aquifer is at atmosphere pressure and does not rise above the water table.

2.4.3. Perched Aquifer

Perched aquifer is special type of the unconfined aquifer, which is occurs wherever groundwater body is separated from the main groundwater by a relatively impermeable stratum of small areal extent and by the zone of aeration above the main body of groundwater. Clay lenses in sedimentary deposits often have shallow perched water bodies overlying them. Wells tapping perched aquifers generally yield temporary or small quantities of water.

2.4.4. Leaky Aquifer

Leaky aquifer is known as semi-confined aquifer. It is aquifer which is bounded in upper and lower by aquitards or aquicludes. If leaky aquifer is in hydro-logically equilibrium, the water table in a well tapping it may coincide with the water table. When water is pumped from a leaky aquifer, water moves both horizontally within the aquifer and vertically through the semipermeable layer.

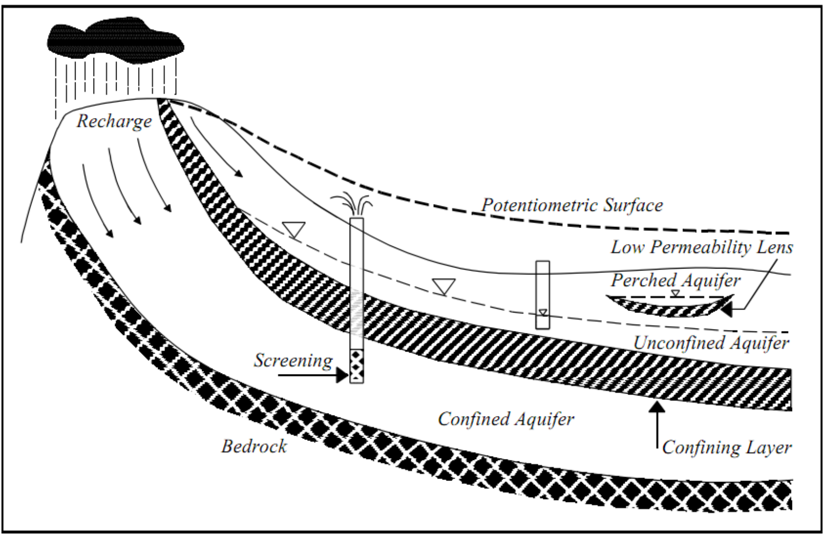

Figure 2-1 Aquifer Formation (source: Engineering and Design GROUNDWATER HYDROLOGY, 1999)

2.5. Hydro-geologic Parameters

Hydro-geologic or physical properties of aquifers porosity and specific yield/storativity express the aquifer storage properties. Hydraulic conductivity (permeability) and transmissivity describe the groundwater transmitting properties.

2.5.1. Porosity

Porosity is a part (pores or voids) of soil and rock which are not occupied by soil matter, but perhaps by water and/or air. Porosity (n) is defined as the volume of the pores of a rock or soil sample (Vp) divided by the total volume (Vt) of both pores and solid material, which shows the percentages of the rock or soil that is void of material. That is

$$n = \frac{Vp}{Vt} \qquad \text{Equation (2.1)}$$

Since these empty spaces serve as water conduits or storages, they are very important when groundwater problems are concerned. Open spaces are characterized by their sizes, shapes, irregularities and distributions, which depend on their origin. In sediments or sedimentary rocks the porosity depends on grain size, the shape of the grains, the degree of sorting and the degree of cementation. In rocks, the porosity depends upon the extent, spacing and pattern of cracks and fractures.

2.5.2. Hydraulic Head

Hydraulic head, h (L): for incompressible fluids (density is a constant), it is the sum of potential energy and pressure energy per unit weight of water. In other word it's the sum of elevation head (z) and pressure head (p/g). Velocity head is ignored due to groundwater velocity is relatively very low and it presented as:

$$h = \frac{p}{\gamma} + z \qquad \text{Equation (2.2)}$$

2.5.3. Hydraulic Conductivity

Co-efficient of permeability, hydraulic conductivity, K is a measure of the ability of a fluid to move through interconnected void spaces in the sediment or rock. Hydraulic conductivity may also be defined as the volume of water that will move through a porous medium, Q in unit time under a unit hydraulic gradient, i through a unit area measured at right angles to the direction of flow, A, is equal to the discharge per unit area of soil mass under unit hydraulic gradient.

$$\mathrm{K} = -\mathrm{Q} * \frac{\mathrm{L}}{\Delta\mathrm{h}} * \mathrm{A} = -\frac{\mathrm{Q}}{\mathrm{iA}} = \mathrm{L/T} \qquad \text{Equation (2.3)}$$

Hydraulic conductivity is a function of both the medium and the fluid properties.

2.5.4. Transmissivity

Transmissivity is the rate at which water flows through a vertical strip of the aquifer at unit width and extending through the full saturated thickness, under unit hydraulic gradient.

It indicates how much water will move through the formation. It can also be defined as the product of the average hydraulic conductivity, K and the saturated thickness, b of the aquifer. It is:

$$\mathrm{T} = \frac{\mathrm{Q}}{\mathrm{wi}} = \mathrm{Kb} \qquad \text{Equation (2.4)}$$

Transmissivity of aquifer is expressed in a unit of L^2/T. It dedicated on the aquifer capability to transmit a water rate.

2.5.5. Aquifer Storage

Storage is one of the significant characteristics of the aquifer because it stored the water. The volume of groundwater stored in an aquifer depends on the porosity, but not all of the water stored in the pore spaces can be extracted, or will drain under the force of gravity. Due to this reason when we define aquifer storage what is really meant is yield.

Specific storage

The specific storage, Ss of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. The specific storage is defined as:

$$\mathrm{Ss} = \frac{\Delta\mathrm{Vwater}}{(\mathrm{Vaquifer} * \Delta\mathrm{h})} \qquad \text{Equation (2.5)}$$

This release of water from storage under conditions of decreasing head h stems from the compaction of the aquifer due to increasing effective stress, σc and the expansion of the water due to decreasing pressure p. Hence, the earlier-defined compressibilities of material and water play a role in these two mechanisms.

Specific yield

Specific-yield, Sy is the ratio of the volume of water , V_w that drains from a saturated rock owing by pumping from wells to the total volume, V of the saturated aquifer. It is defined mathematically by the equation:

$$\mathrm{Sy} = \frac{\mathrm{Vw}}{\mathrm{V}} * 100 \qquad \text{Equation (2.6)}$$

The storativity S is a dimensionless quantity involving a volume of water per volume of aquifer. It should be noted that it is not necessary that soil with high porosity will have high specific-yield because that soil may have low permeability and the water may not easily drain out.

However, this concept of specific yield only applies to unconfined aquifers where changes in storage represent an actual dewatering or drainage of the pore spaces. Unconfined aquifers are not capped and can store and release water by changes in the elevation of the surface of the water table. Unconfined aquifers are more productive for the equivalent fall in aquifer level, and generate effects over a much more localised area than confined aquifers.

In confined aquifers, its storage is referred to as storativity or storage coefficient. This distinguishes it as a secondary effect of aquifer compaction or expansion. A confined aquifer is normally always full of water, even when being pumped, and has very little capacity to store more. This is because groundwater is pressurised by the overlying clay capping layer which acts as a seal, in conjunction with recharge water entering at a higher elevation. Extra water can only enter if the water pressure increases and this has the effect of inflating the aquifer slightly. This is called the elastic storage component and is reversible, meaning a confined aquifer stretches to accommodate extra recharge and relaxes when water is pumped from it.

$$\mathrm{S} = \mathrm{Ss} * \mathrm{b} \qquad \text{Equation (2.7)}$$

Specific retention

All the water stored in a water bearing stratum cannot be drained out by gravity or by pumping, because a portion of the water is rigidly held in the voids of the aquifer by molecular and surface tension forces. Specific retention, Sr is the ratio of the volume of water that cannot be drained out to the total volume of the saturated aquifer.

$$\mathrm{Sr} = \mathrm{n} - \mathrm{Sy} \qquad \text{Equation (2.8)}$$

Since the specific yield represents the volume of water that a rock will yield by gravity drainage or pumping, the remainder is the specific retention. Therefore, porosity can expressed as the sum specific retention and specific yield.

2.5.6. Homogeneity and Isotropy

Homogeneous is uniformity properties (i.e. grain-size distribution, porosity, thickness) at all locations or not depend on position. Again, transmissivity and storativity values are the same wherever present. In other side **Heterogeneous** or non-homogeneous a formation is when the hydraulic properties vary spatially.

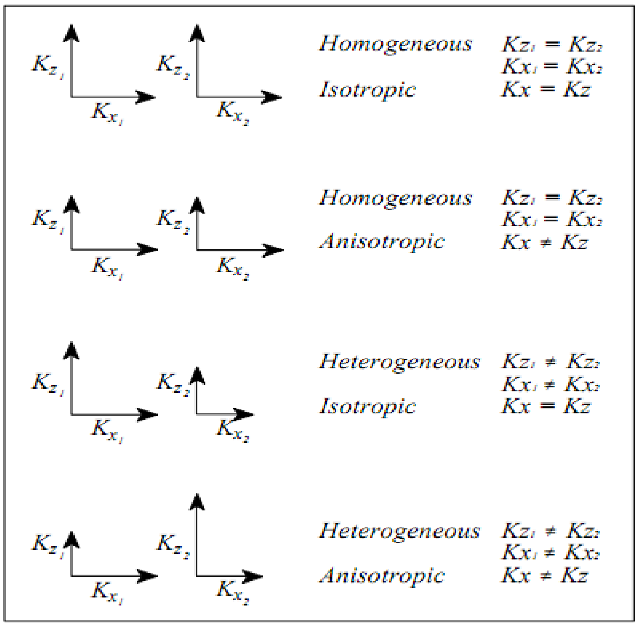

Figure 2-2 Homogeneity and Isotropy (source: Hydrological and Groundwater Lecture Course Material)

Isotropic is one that has the same geological properties (i.e. geometry of the voids, intrinsic permeability) in all directions. But if the geometry of the voids, intrinsic permeability is not uniform in all direction it is called **anisotropy.**

2.6. Aquifer Test

Aquifer test have five objectives to achieve: first to confirm the yield, efficiency and performance of the well, second to investigate water quality, third to assess whether the abstraction can be sustained in terms of yield (and quality), fourth to identify potential environmental impacts and lastly to characterized the aquifer properties (such as transmissivity, hydraulic conductivity and storage) (Bruce M. e.al, 2006).

The principle of pumping test involves applying a stress to an aquifer by extracting groundwater from a pumping well and measuring the aquifer responses during that stress by observing drawdown as a function of time. These measurements are then incorporated into an appropriate well-flow equation to calculate the hydraulic parameters of aquifer.

Determining reliable values of hydraulic characteristics or geological formation of aquifer is critical part of ground water studies. To do so, aquifer test is one of the most effective ways and it is field experiment performance to obtaining there values.

2.6.1. Constant-Rate Test

A constant-rate pumping test consists of pumping a well at constant discharge rate for a set period of time and monitoring the response in at least one observation well. The number and location of observation wells is dependent upon the type aquifer and objectives of the study. It can perform in two ways: single well and observation well test.

1. Observation Well Test

An observation well is a well provided at the well field, additional to the pumped well. Multiple well or observation well test is implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping and subsequent recovery.

This test can be used to know the overall hydro-geologic regime of the studied area; those are transmissivity, T, storativity, S, or specific-yield of a zone. They also can help design municipal well fields, predict rates of ground water flow, determine interconnectivity between saturated zones, and design a remediation system.

2. Single-Well Test

Single well test involves measuring the water level during pumping and recovery is taken in pumping well itself. This indicates there is no observation well or piezometers are used. Again it is a rapid and economical way to evaluate the K and T of the interest area. However it haves those advantages, the drawdown in a pumped well is influenced by well losses and well-bore storage.

Therefore, the effect of the well losses and well bore storage must be considered during the analysis of the drawdown using step-drawdown test. With single-well tests, only a single time–drawdown analysis based on the drawdowns of the pumped well can be made, that is, no comparison of results from different time–drawdown analyses is possible, and no distance–drawdown analysis can be made. Consequently, the results of multiple well tests of aquifer will be more accurate than the results of single-well tests. Moreover, multiple well test results are representative of a larger volume of the aquifer than single-well test results.

2.6.2. Pumping Test Duration

The amount of time the aquifer should be pumped depends on the objectives of the test, the type of aquifer, location of suspected boundaries, the degree of accuracy needed to establish the storage coefficient and transmissivity, and the rate of pumping. The test should continue until the data are adequate to define the shape of the type curve sufficiently so that the parameters required are defined. This may require pumping for a significant period after the rate of water level change becomes small (so called water level “stabilization”).

2.6.3. The Step Discharge Test

The step test is designed to provide measurements of drawdown in the pumping well for a range of yields. This test is taken at single-well and it initially pumped at low rate till the drawdown within the well principally stabilised and for successive series of step by increasing the discharge with near time interval it will continued for other steps. Then for each step the incremental drawdown is determined by extrapolated the drawdown curve to with a slope proportional to the discharge in order to measure the incremental drawdowns.

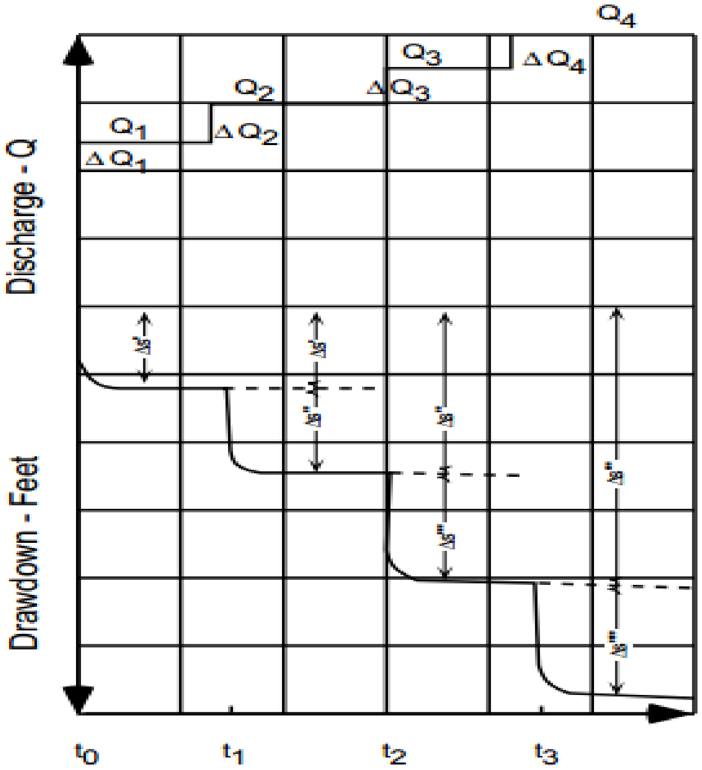

Figure 2-3 Step-drawdown (source: Regional Ground Water Expert, U.S EPA, Region VIII)

2.6.4. Recovery Test

Recovery test is a test taken after the pumping test is stopped or halted, the measurement of the water level of well and piezometers rise are recorded at time, t' after cessation of pumping. This rise of the water level is called the residual drawdowns, s'.

Residual drawdown is the difference between the static water level and water level at the time t'. This data is more reliable than pumping test data because recovery occurs at a constant rate, whereas a constant discharge during pumping is often difficult to achieve in the field. Recovery-test measurements allow the transmissivity of the aquifer to be calculated.

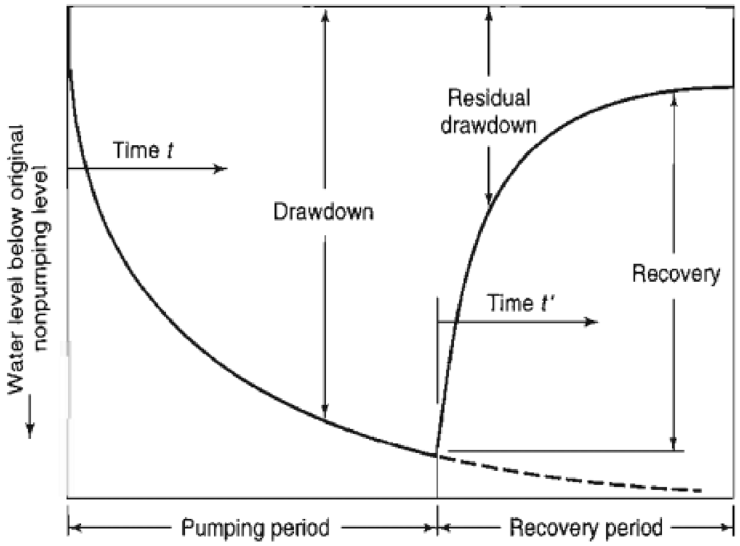

Figure 2-4 Recovery Test Graph (source: David K. Todd et.al, 2005)

2.7. Safe Yield

A yield test performed after the well drilling is completed by aquifer test. Determining the yield of a well involves a test to see the balance between the maximum amount of water that can be pumped out of the well and the amount of water that recharge back into the well.

Therefore, the maximum safe yields of well represents its dependable, continuous output during a long drought and its sustainability.

2.8. Partial Penetration

Partial penetration is an installation of pump or length of water entry is not fully penetrated to the thickness of aquifer. This is occur due to the thickness of aquifer is not justified, the capacity of material we used for drilling or financial problem or scarcity.

Partial penetrations induce vertical flow components in the vicinity of the well. This become cause to additional drawdown due to partial penetration reasons for the flow velocity in the immediate vicinity of the well to be higher than it would be and leading to an extra loss of head.

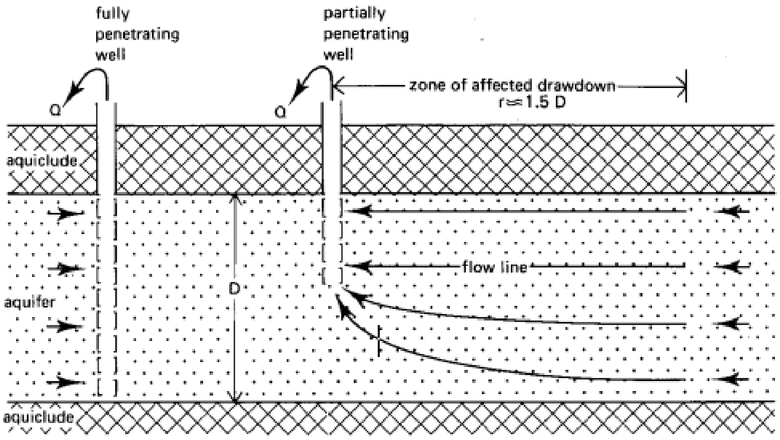

Figure 2-5 Fully and Partially Penetrating Well (source: G.P.Kruseman et.al, 1994)

2.9. Well Performance

A well performance test is conducted to determine total losses; the aquifer losses and the well losses. Aquifer losses, s_1 are the head-losses occur in the aquifer where flow is laminar, and its time dependent and vary linearly with the well discharge. It includes the losses due to partial penetration and it can be expressed as:

$$s_1 = B_{1(r_w,t)}Q$$

Equation (2.9)

Well loss is related with turbulent flow cause by the flow through the well screen and flow inside of the well to the pump intake. It can divide into linear and nonlinear head losses. Linear well losses, s_2 are caused by damaging of the aquifer during drilling and completion of the well. They contain, for example, head losses due to the compaction of the aquifer material during drilling, head losses due to plugging of the aquifer with drilling mud, which reduce the permeability near the bore hole; head losses in the gravel pack; and head losses in the screen. The drawdown s_2 corresponding to this linear well loss can be expressed as:

$$s_2 = B_2Q$$

Equation (2.10)

Non-linear well losses, s_3 are the friction losses that occur inside the well screen and in the suction pipe where the flow is turbulent, and head losses that occur in the zone adjacent to the well where the flow is usually also turbulent. All these losses responsible for the drawdown inside the well-being much greater than one would expect on theoretical grounds. The drawdown s_3 corresponding to this nonlinear well loss can be expressed as:

$$s_3 = CQ^P$$

Equation (2.11)

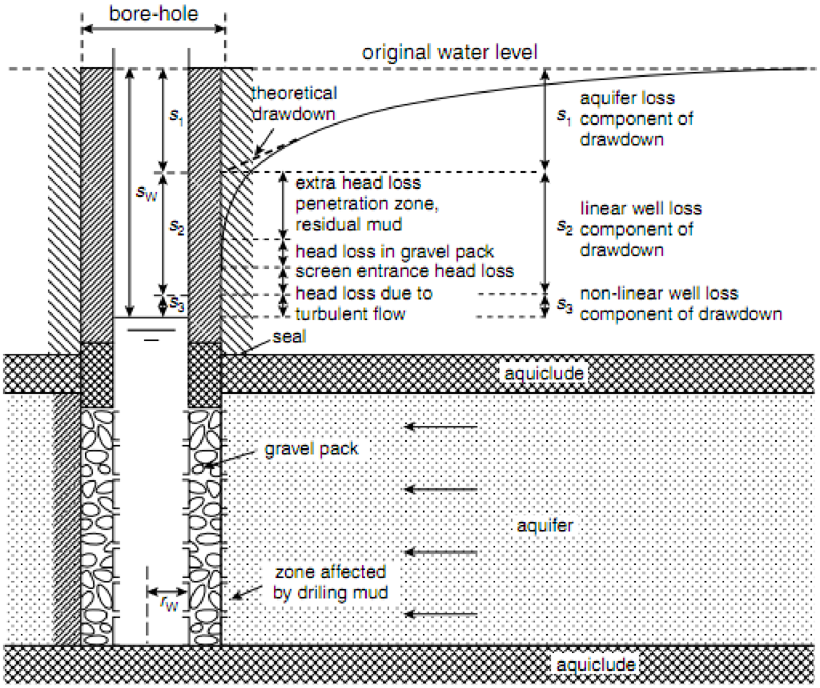

Figure 2-6 Various Head Losses Pumped Well (source: Jacques W. Delleur, 2007)

The general equation describing the drawdown in a pumped well as function of aquifer/well losses and discharge rate, s_w total losses thus reads:

$$s_w = (B_1 + B_2)Q + CQ^P = BQ + CQ^P$$

Equation (2.12)

Which is;

$$s_w = s_1 + s_2 + s_3$$

Equation (2.13)

Where

s_w is total losses

C is the nonlinear well loss coefficient

B is the well-loss coefficient and

Q is discharge rate

2.10. Specific Capacity and Well Efficiency

Specific capacity, Q/s_w is pumping rate divided by the change in well water level or drawdown. This is a measure of the productivity of both the aquifer and the well; the larger the specific capacity, the better the well. Their relationship is expressed that specific capacity decreases with discharge, Q and time, t.

Well efficiency, E_w is stated as the ratio of the aquifer head loss to the total head loss which is include both the aquifer and well losses. To do so step-drawdown of aquifer test are used, for evaluation of the B and C. Step-drawdown tests are analyzed by plotting the reciprocal of specific capacity (s/Q) against the pumping rate (Q).

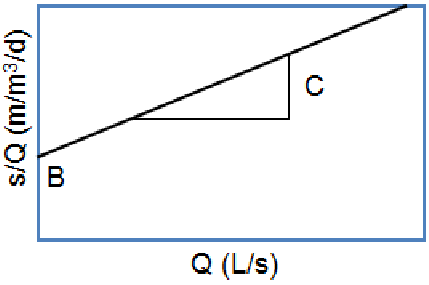

Figure 2-7 Step-drawdown Test Analysis

As you see from the figure above; the intercept of the graph at Q=0 is B = W(u)/4pT, B can also be obtained independently from a Theis or Cooper-Jacob analysis of a pump test, and the slope is the well loss coefficient, C.

Therefore the efficiency of well, E_w termed by percentage as follows:

$$E_w = \left\{\frac{BQ}{BQ+CQ^2}\right\} * 100\% \qquad \text{Equation (2.14)}$$

Another way of for recognizing an inefficient well is to note its initial recovery rate when pumping is stopped.

2.11. Diagnostic and Specialised Plots

Diagnostic plot is a scatter logarithmic derivative plot of drawdown versus time in log–log scale. This plot is used to check the quality of data observed and facilitate the identification of an appropriate conceptual model best suited to interpret the data. In order to identify which model can be used to interpret these data, one needs to compare the diagnostic plot with a set of typical diagnostic plots such as those shown in figure below; it will be used as a catalogue of typical behaviour of aquifer.

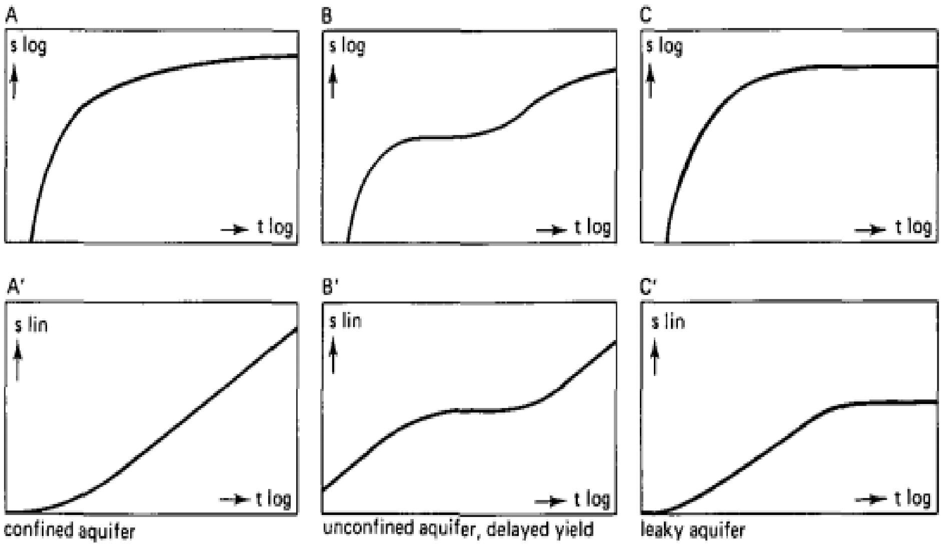

Figure 2-8 Diagnostic and Specialized plots respectively: A) confined aquifer, B) Unconfined aquifer C) Leaky aquifer (Source: G.P.Kruseman et.al, 1994)

Again, specialized plots are semi-log plots of drawdown versus time, or drawdown versus distance to the well; they are specific to a given flow regime above Fig.2.8 A', B' and C'. The characteristic shapes of the curves can help in selecting the appropriate model. In a number of cases, a semi-log plot of drawdown versus time has more diagnostic value than a log-log plot. In this evaluation it is therefore recommend that both types of graphs to be constructed.

2.12. Aquifer Boundary

Aquifer boundary can be classified as; recharging boundary which are river or canal and barrier boundary i.e. block or impermeable. When an aquifer boundary is located within the area influenced by a pumping test, the general assumption that the aquifer is of infinite areal extent is no longer valid.

Boundary conditions of the flow domain must be known prior to the construction of the groundwater flow study. There are three types of boundary conditions: a no-flow boundary (Neumann), a constant-head boundary (Dirichilet), and a water-table boundary. Along a no-flow boundary streamlines will run parallel, and equipotential lines will intersect the boundary at right angles. A constant-head boundary (such as large lake) represents an equipotential line and streamlines will intersect at a right angle while adjacent equipotential lines will run parallel to the boundary and finally the water-table boundary is the water table neither a flow line nor an equipotential line. It is a line where head is known.

2.13. Data Correction

Prior to using the drawdown data collected from a pumping test, it may be necessary to correct for either external sources or effects induced by the test. Corrections to measurements may be needed for unconfined aquifer data due to a decrease in saturated thickness caused by the pumping test. Also, corrections may be necessary if the pumping well only partially penetrates the zone tested.

2.13.1. Data Correction for External Influence

The aquifer may be influenced by natural recharge or discharge, which will result in a rise or a fall in the hydraulic head. By interpolation from the hydrographs of the well and the piezometers, this natural rise or fall can be determined for the pumping and recovery periods. This information is then used to correct the observed water levels.

2.13.2. Rhythmic Fluctuations

In confined and leaky aquifers, rhythmic fluctuations of the hydraulic head may be atmospheric pressure. In unconfined aquifers whose water tables are close to the ground surface, diurnal fluctuations of the water-table can be significant because of the great difference between day and night evapotranspiration. The water-table drops during the day because of the consumptive use by the vegetation and recovers during the night when the plant stomata are closed.

Hydrographs of the well and the piezometers, covering sufficiently long pre-test and post-recovery periods, will yield the information required to correct the water levels observed during the test.

2.13.3. Non-rhythmic Regular Fluctuations

Non-rhythmic regular fluctuations are caused due to changes in atmospheric pressure, can be detected on a hydrograph covering the pre-test period. In wells or piezometers tapping confined and leaky aquifers, the water levels are continuously changing as the atmospheric pressure changes. When the atmospheric pressure decreases, the water levels rise in compensation, and vice versa. By comparing the atmospheric changes, expressed in terms of a column of water, with the actual changes in water levels observed during the pre-test period, one can determine the barometric efficiency of the aquifer.

2.13.4. Data Correction for Well and Aquifer Losses

Data correction for losses (i.e. well and aquifer losses) induced by partial penetration and bore hole storage are determined. The equation is generated using the step-drawdown test and plotting the change in drawdown between each step over discharge of that step versus the step discharge. Then, by fitting the liner line for scatter points the general liner equation developed is used to determine the subtracted drawdown from the observed drawdown to corrected/reduce which induced by the partial penetrating well.

2.13.5. Data Correction for Unconfined Aquifer

The water table in an unconfined aquifer is equal to the elevation head (potential). Since transmissivity in unconfined aquifers is not constant and it will decrease with increasing drawdown, there is no closed solution for this aquifer type. That is why the measured drawdown is corrected, and the pumping test is interpreted as being in a confined aquifer.

For most analysis solutions, the aquifer is assumed to be of constant thickness. This assumption can be accepted if the saturated thickness does not decrease more than 25 percent. If the decrease is greater than 25 percent, then the drawdown data should be corrected prior to analysis (Dawson and Istok, 1991).In an unconfined aquifer, this condition is not met if the drawdown is large compared to the aquifers original saturated thickness. Where this occurs, the Jacob (1944) correction may be applied:

$$s_{cor} = s\left(1 - \frac{s}{2b}\right) \qquad \text{Equation (2.15)}$$

Where: s_{cor}=corrected drawdown

s= observed drawdown

b=initial saturated thickness

2.14. Geologic log

A geological log is constructed from sampling and examination of well cutting collected at frequent intervals during the drilling of a well or test holes. Such logs furnish a description of the geologic character and thickness of each stratum encountered as a function of depth, thereby enabling aquifers to be delineated.

It is good practice to store samples of well cutting systematically. These is not only permit detailed geologic logs to be prepared but also enable grain size analyses and correlation with other nearby wells to be made after drilling is finished.

2.15. Long Period Effect of Groundwater Pumping

Groundwater or subsurface water refers to all water below the surface of the ground including that in the saturated zone and in deep aquifer. An evolution of the population number, industrial development and urbanization are subsequently raising the supply demand. Therefore, the extraction of a large quantity of ground water to reach a demand required for living and industrial purposes without adequate control and management of the state government has caused a drawdown of the water table which damage surface water system that support environmental habitats close to are and have negative environmental impact include continued diminishment of groundwater quality. Those impacts again lead to additional damage.

2.15.1. Overdraft of Aquifer

The slow natural recharge (scarcity of recharge) rate of most aquifers and high rate of pumping or long term groundwater extraction exceeding the aquifer recharge has led to groundwater overdraft problems or in other word hydrologic imbalance is occurred. Overdraft is defined as pumping of water from an aquifer in excess of the supply flowing into the basin. If continued this results in depletion of groundwater that can irreversibly harm the environment. One of the consequences is subsidence or sinking of the land, depletion of surface water and degraded aquifer water quality.

2.15.2. Groundwater Depletion

Depletion of the groundwater level is defined as long term water level declination caused by sustained groundwater pumping over time. Groundwater depletion is a problem that arises mainly due to pumping above the safe yield. It leads to *drying* of wells, reduced surface water flow, subsidence, and deterioration of water quality and subsidence is the downward movement or sinking of the earth’s surface caused by removal of underlying support.

2.15.3. Sustainability of Resource

Pumping of groundwater solves many immediate problems faced by those living in lowly developed and low rainfall regions of the world out. But excessive pumping leads too many negative effects of long term pumping such as effect on sustainability, seawater intrusion, aquifer overdraft, groundwater depletion, land subsidence and so.

2.15.4. Groundwater Mining

The water table drop known as groundwater mining. It occurs when water is withdrawn from an aquifer more rapidly than it is replenished. As the water table drops, water pumping costs increase. Eventually, the users run out of water.

Extensive groundwater mining also may cause subsidence, a lowering of the land surface. Subsidence occurs when the removal of water leaves underground spaces that collapse or when underlying clay shrinks from lack of moisture. The result looks like a cone of depression on the land.

2.15.5. Groundwater Contamination

Lowered in water tables can also lead to greater contamination of ground water. The reduction in surface water lowers the ability of a region’s waterways to filter pollutants from water before it flows in to recharge an aquifer.

Again change in climates is an additional reason which influenced the groundwater level. The uncertainty of future conditions makes this an appropriate juncture to examine the existing literature and identify longer term effects of groundwater pumping. Such a review will provide important implications for cities such as Addis Ababa, where groundwater has the most recently being more relied upon for domestic and household use.

2.15.6. Land Subsidence

During an aquifer is pumped, gradually the water supporting the soil above is removed, affecting the internal structural integrity of the aquifer; this integrity is reduced. In this manner, the land surface begins to settle and compress; such a process called subsidence. Land subsidence is the lowering of the land surface due to changes in subsurface structure in other word subsidence is one of the impacts of groundwater pumping and its defined as the downward movement or sinking of the earth’s surface caused by removal of underlying support.

2.16. Non-Equilibrium Equation

Many aquifer tests will never reach equilibrium; that is, the cone of depression will continue to grow with time. These are known as non-equilibrium or transient flow condition. Analysis of the transient time-drawdown data from an observation well permits determination of the formation constants S and T of an aquifer. If there is no observation well, the time-drawdown data from the pumping well can be used to determine aquifer properties**.**

The non-equilibrium equation is widely applied in practise and is preferred over the equilibrium equation because:

- → S can be determined
- → Only one observation well required
- → Shorter period of pumping is generally necessary
- → No assumption of steady-state flow condition is required (David K. Todd et.al, 2005).

The non-equilibrium method as presented by Theis in 1935 has been used and studied extensively since its development. It has been verified and modified by the leading authorities in groundwater hydrology. When the field conditions approximate the assumptions made in the development of the theory, the results are strikingly reliable.

2.16.1. Groundwater Flow Equations

Flow is a function of several variables and it described by partial differential equation which is governed by laws of physics. The equations are driving by applying the law of conservation of mass and energy with combining to Darcy’s law. The governing flow equations developed under the following common assumptions and conditions.

- → The aquifer has a seemingly infinite areal extent;
- → The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test;
- → Prior to pumping, the hydraulic head is horizontal (or nearly so) over the area that will be influenced by the test;
- → The pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow;
- → The aquifer is pumped at a constant-discharge rate;
- → The water removed from storage is discharged instantaneously with decline of head; and

→ The diameter of the pumped well is small, that is, the storage inside the well can be neglected.

The above mentioned simplifying assumptions and limiting conditions cannot always be fulfilled in the field. In these cases, special well-flow equations for bounded, sloping, or anisotropic aquifers or for large-diameter wells can be used; these can be found in Kruseman and de Ridder (1994).

Finally the governing equation in three dimensions becomes;

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_S \frac{\partial h}{\partial t}-R^*$$

Equation (2.16)

But, if the material is both homogeneous and isotropic, i.e. Kx= Ky= Kz, then the above equation becomes:

$$S_s \frac{\partial h}{\partial t} = K\left[\frac{\partial}{\partial x}\left(\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial h}{\partial z}\right)\right]$$

By combining the partial derivatives:

$$\mathrm{Ss} * \left(\frac{\partial \mathrm{h}}{\partial \mathrm{t}}\right) = \mathrm{K}\left[\frac{\partial^2 \mathrm{h}}{\partial \mathrm{x}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{y}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{z}^2}\right]$$

Or

$$\frac{\partial^2 \mathrm{h}}{\partial \mathrm{x}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{y}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{z}^2}=\frac{\mathrm{S}}{\mathrm{T}}\ \partial \mathrm{h}/\ \partial \mathrm{t}$$

Equation (2.17)

2.16.2. Steady and Un-steady Radial Flow

Steady state is implies when the hydraulic head does not change with time and the general equation becomes:

$$\frac{\partial^2 \mathrm{h}}{\partial \mathrm{x}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{y}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{z}^2}=0$$

Equation (2.18)

When water pumped at constant rate from penetrating well the influence of the discharge extends out ward. As water come from the storage and reduction continue the head also decline with time, is known as unsteady flow. And it described by:

$$\frac{\partial^2 \mathrm{h}}{\partial \mathrm{x}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{y}^2}+\frac{\partial^2 \mathrm{h}}{\partial \mathrm{z}^2}=\frac{\mathrm{S}}{\mathrm{T}}\partial \mathrm{h}/\ \partial \mathrm{t}$$

Equation (2.19)

2.17. Analytical Method

To determine the exact solution for differential equations the classical mathematical approaches is analytical method. Analytical solutions provide quick result with assumption required which is homogeneity and limited to 1D and 2Dproblems.

Analyzing and evaluating pumping test data is as much an art as a science. It is a science because it is based on analytical/theoretical models that the geologist or engineer must understand and on thorough investigations that he must conduct into the geological formations in the area of the test. It is an art because different types of aquifers can exhibit similar drawdown behaviours, which demand interpretational skills on the part of the geologist or engineer (G.P. Kruseman et.al, 1994).

2.17.1. Theis Method

Theis method is one of the widely applied methods in groundwater hydrology to determine S and T. Theis was the first formula developer for unsteady state flow that introduces the time factor and storativity. However, this method requires curve matching of a type-curve and time-drawdown data from a pumping well test. Typically, this is done using a type-curve (W(u) Vs u) plotted on a logarithmic graph paper and the drawdown(s) data curve plotted on another transparent logarithmic graph paper (s Vs r2/t) with the same scale, and superimposing and sliding the transparent one over the other to get the best possible match while keeping the coordinate axes of two plots parallel. Obviously this is a tedious approach. Based on the coordinates of a matching point from both plots (W(u), u, s, and r2/t) in the matched position, the values of S and T can be determined using Theis non-equilibrium equation.

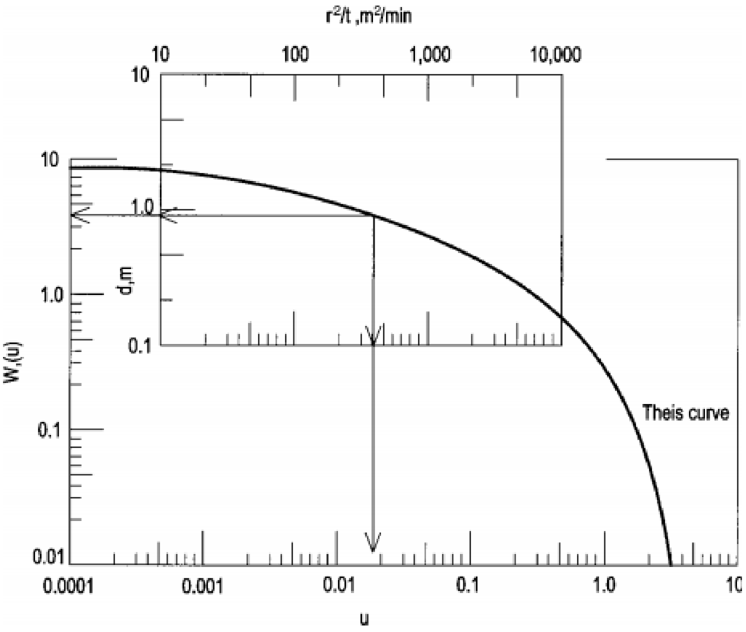

Figure 2-9 Theis Type-curve and Data-curve graph (source: Groundwater ppt chp3,)

The advantage of this method is used to improve the calculation accuracy and it has also disadvantages. That is when the r is small and T is large, the steep part of observation curve appears in the first two min, which is difficult to measure. While the part that is easy to measure is too gentle to fit accurately and these all lead to low accuracy of parameters.

2.17.2. Cooper-Jacob Method

The Jacob method (Cooper and Jacob 1946) is developed as a based the Theis formula. From $u = r^2S/4KDt$, it will be seen that u decreases as the time of pumping t increases and the distance from the well r decreases. Accordingly, for drawdown observations made in the near vicinity of the well after a sufficiently long pumping time, the terms beyond ln u in the series become so small that they can be neglected. So for small values of u ($u < 0.01$), the drawdown can be approximated by,

$$s = \frac{Q}{4\pi KD} W(u) = \frac{Q}{4\pi KD}\left(-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - ....\right)$$

to

$$s = \frac{Q}{4\pi KD}\left(-0.5772 - \ln \frac{r^2S}{4KDt}\right)$$

with

an error less than	1%	2%	5%	10%
for u smaller than	0.03	0.05	0.1	0.15

After being rewritten and changed into decimal logarithms, this equation reduces to:

$$s = \frac{2.3Q}{4\pi KD}\log(\frac{2.25KDt}{r^2S}) \qquad \text{Equation (2.20)}$$

When the values of KD and S are determined, they are introduced into the equation $u = r^2S/4KDt$ to check whether $u < 0.1$, which is a practical condition for the applicability of the Jacob method.

There are many advantages of linear graphic method of Cooper-Jacob. In this case all test data can be used and the randomness of curve fitting method can be avoided to determine the aquifer properties. But, the pumping time needs to be long to meet the requirement of $u \leq 0.01$, especially when T is small and r is large. Besides, the long pumping time may leads to the deviation of intercept and gradient, which will result in larger T and smaller S.

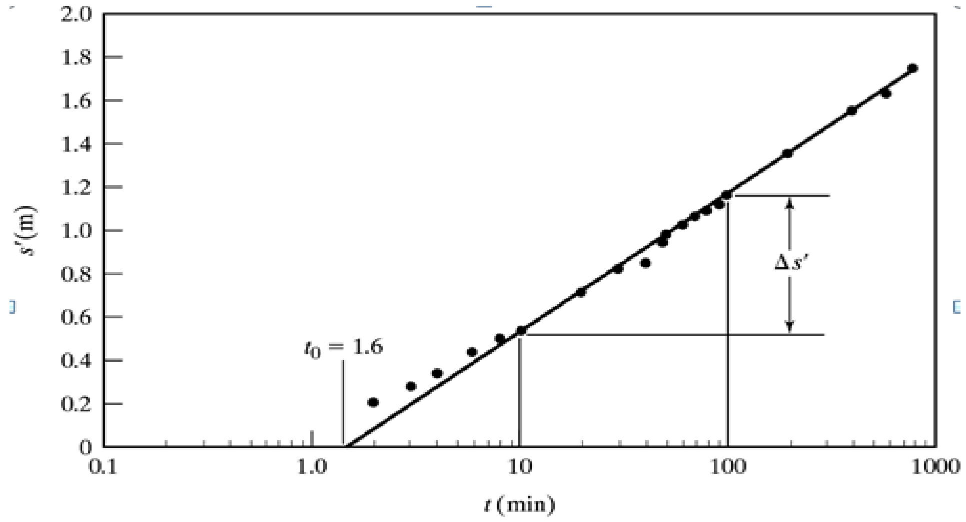

Figure 2-10 Cooper-Jacob method analysis (source: Philip B. Bedient)

2.17.3. Theis Recovery Method

The recovery method developed by Theis (1935) and analysis taken based on the superposition principle. The principle assumes that, after the pump is stopped, the pumping continue at the same discharge as earlier, and that an imaginary discharge, equal to discharge, is injected into the well. Then, the recharge and the discharge cancel each other's, resulting in well as is required for the recovery period.

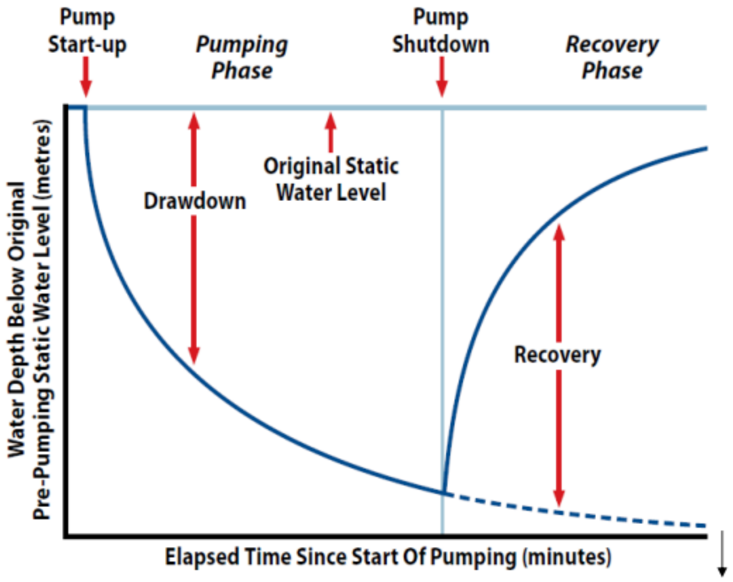

Figure 2-11 Time-drawdown and Residual Drawdown (source: Groundwater Concept and Methods for Assessing Sustainability Nanoose Community Workshop, 2015)

The Theis recovery method has proved useful option for determining the coefficient of transmissibility of an aquifer if the storage co-efficient remains virtually constant throughout both the period of pumping and the subsequent period of recovery. For residual drawdown, Δs and discharge, Q during recovery it given by,

$$T = \frac{Q}{4\pi\Delta(s - s')} = \frac{-Q}{-4\pi\Delta s_r} = \frac{Q}{4\pi\Delta s_r}$$ Equation (2.21)

2.18. Groundwater Model

Groundwater model are an attempt to represent the essential features of the actual groundwater system by means of mathematical counterpart. The underlying philosophy is that an understanding of the basic laws of physics, chemistry, and biology that described groundwater flow and transport and an accurate description of the specific system under study will enable a quantitative representation of the cause and effect relationships enables forecasts to be made for any set of conditions (David. K.Todd et.al, 2005).

Therefore, groundwater model can be categories into two. The first one is groundwater flow models which solve the head distribution of the structure and secondly, solute transport models solve concentration of solute as affected by advection or movement of solute with the average groundwater flow, dispersion which is spreading and mixing of the solute and chemical reactions, which slow down or transform solutes.

Groundwater flow model is a mathematical model simulation by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flow along the boundaries of the area. It haves basic components to model a project area:

- → A statement of objectives
- → Data describing the physical system
- → A simplified conceptual representation of the system
- → Data processing and modelling software
- → A report containing written and graphical presentation

2.18.1. Governing Equation

Governing equation is derived or developed from Darcy's and conservation of mass (water balance) equation. Darcy's law state that, the flow rate, Q through porous media is proportional to head loss, h_L and inversely proportional to the length, L of the flow path. Therefore, Darcy's measurement showed that the proportionalities Q~h_L and Q ~1/L then by introducing a proportionality constant, K:

$$Q = -KA\frac{h_L}{L} \quad \text{Or} \quad Q = -KA\frac{\partial h}{\partial l} \qquad \text{Equation (2.22)}$$

Water balance of conservation of mass state that:

Inflow-Outflow= Change in Storage

The derivation done by referring to a cube of porous material (representative element volume, REV) which is enough to representative of properties of the porous medium with a volume of Δx, Δy, Δz. Finally, after arrangement, the total change inflow rate is equal to the change in storage and it expressed as:

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)\Delta x\Delta y\Delta z = Change\ in\ Storage \qquad \text{Equation (2.23)}$$

If there is a possibility of sink (i.e. pumping well) or source (i.e. an injection of well or recharge) within the REV, it represented by the R*ΔxΔyΔz. R is positive when it is source of water and it subtracted from left hand side. It become:

$$\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - R\right)\Delta x\Delta y\Delta z = Change\ in\ Storage \qquad \text{Equation (2.24)}$$

Now, by consider the right-hand side of the above equation, change in storage is represented by specific storage, Ss, which is defined as it is the volume of water released from storage per unit change in head, h per unit volume of aquifer:

$$S_s = -\frac{\Delta V}{\Delta h \Delta x \Delta y \Delta z} \qquad \text{Equation (2.25)}$$

and the rate of change in storage in the REV is

$$\frac{\Delta V}{\Delta t} = -S_s \frac{\Delta h}{\Delta t} \Delta x \Delta y \Delta z \qquad \text{Equation (2.26)}$$

Finally, by combining the above two equations and replaced the Darcyy's flux, qx, qy and qz by Darcy's equation and it became *General flow equation*.

$$\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{K_{xx}} \frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(\mathrm{K_{yy}} \frac{\partial \mathrm{h}}{\partial \mathrm{y}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mathrm{K_{zz}} \frac{\partial \mathrm{h}}{\partial \mathrm{z}}\right) = \mathrm{S_s} \frac{\partial \mathrm{h}}{\partial \mathrm{t}} - \mathrm{R}$$

Equation (2.27)

Darcy's law and the law conservation of mass is solution techniques based upon either finite element or finite difference approximation. Where the finite difference used a rectangular element shaped technique to discretization of aquifer and the finite element used the triangular or quadrilateral shape to discretization.

2.18.2. MODFLOW 2000

MODFLOW was first published by McDonald and Harbaugh. MODFLOW-2000 is the fourth version, documented in Harbaugh et al. MODFLOW-2000 is a computer program that simulates one, two or three-dimensional groundwater flow using a finite difference solution of the model formulation.

A computer code solves a set of algebraic equations generated by approximating the partial differential equations i.e. governing equation, boundary conditions, and initial conditions (which expressed as s matrix equations and solver by numerical method) that form the mathematical model. Finite difference and finite element are techniques which operate on the mathematical model and solve by computer.

MODFLOW-2000 can simulated steady and unsteady flow in an irregular shaped flow system in which aquifer layers can be confined, unconfined or combination of confined and unconfined. Flow from external stresses, such as flow to well, areal recharge, evapotranspiration, flow to drain and flow through river beds, can be simulated. The hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage co-efficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux cross the model's outer boundary, which allows water to be supplied by a boundary block in the modelled area at a rate proportional to the current head difference between a source of water outside the modelled area and the boundary block. MODFLOW-2000 has been expanded to simulate solute transport and parameter estimation (David. K.Todd et.al, 2005).

3. METHODOLOGY

3.1. Descriptions of Study Area

The groundwater component includes the development of an aquifer in the Akaki area south of Addis Ababa. The potential of this aquifer was identified in 1991 when drilling a testing program for the Akaki town water supply project was carried out.

3.1.1. Location of Akaki Well Fields

Akaki groundwater prospective sites are in the upper part of Awash River Basin and distributed in the suburb of Addis Ababa city and adjacent Oromiya Regional State within 10 to 40 km from the centre of the city. The south-eastern, central and eastern parts are flat and undulating lands covered with thick quaternary alluvial and lacustrine deposits (AAWSA, 2000). Akaki well fields contain four phases: Existing (old), Phase II, Phase IIIA and Phase IIIB which covers 101.2km^2 area with Lat. 80 47’25.50” - 80 53’6.23”N, Lon. 380 44’00” - 380 49’18.79”E and Elev. 2110 – 2050masl. Evaluation and analysis of aquifer properties: transmissivity and storativity are taken for Akaki well fields of phase IIIA. Phase IIIA of well field covers area of 24km^2 and have twenty wells.

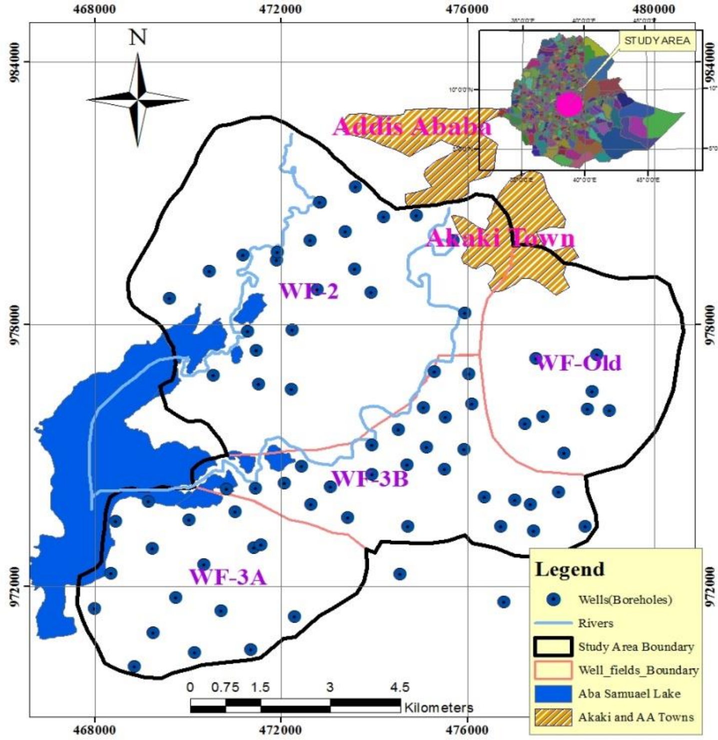

Figure 3-1Akaki Groundwater Well Fields Map, 2018

3.1.2. Climate

Based on Rainfall, the climate of the study area can be categorized in to two broad seasons: the dry season (winter) which covers the period from October to May and the wet season extends from June to September, with slight rainfall during autumn and spring. This seasonal variation of rainfall distribution with in the study area is due to the annual migration of the inter-tropical convergence zone, a low-pressure zone marking the convergence of dry tropical easterlies and moist equatorial westerlies across the catchment (Ebise Oljira, 2006).

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

3.1.3. Land Use / Land Cover

The general land use pattern of the area, though very diverse, was broadly classified into forest, urban, agricultural and open areas with rock exposures (grazing site). Akaki town and Kality areas represent the urban part, which is characterized by paved. In this part of the area, most of the rainwater is converted into surface runoff and drained into network of streams and rivers with little water infiltrating into the ground.

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

3.1.4. Local Geology

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

3.2. Data Collection

In this study both data collecting techniques: primary and secondary method from site and respective organization that has a great responsibility for groundwater well development. Secondary data are collected through literature studies and document analysis from those concerning organizations.

Data required for the evaluation of the aquifer properties are:

- → Discharge/yield from each wells
- → Constant discharge time-drawdown test data
- → Step-drawdown test data
- → Recovery test data. All those data are collected from Ethiopia Water Works design and Supervision Enterprise (WWDSE).

Data required for the groundwater flow model (MODFLOW)

- → Digital elevation model
- → Geographic map and areal cross section (Ministry of Water Irrigation and Electric, MoWIE)
- → Hydraulic conductivity/transmissivity data
- → Initial condition water head data
- → Groundwater pumping/extraction data
- → Groundwater recharge rate of area and surface water interaction (collected from WWDSE)

Furthermore, several books, journal, reports and Google are instrument to access government documents, guidance and manuals are used to this investigation.

3.3. Data Analysis

Analysis are started by evaluation of aquifer properties for Akaki well phase IIIA which have 20 wells and all Akaki well fields are (Existing, phase II, phase IIIA and phase IIIB) modelled subsequently. Before discussing the evaluation of aquifer parameters, data quality check and the aquifer formations are identified. Then, the necessary correction is taking to account the partial penetration and single well effects, which have substantial effect on the drawdown data collected from certain wells and finally hydraulic properties are determined.

3.3.1. Aquifer Property Evaluation

The first aim of this study is to determine the correct aquifer properties (storativity, S and transmissivity, T) and that can represent the real system. Therefore, the accuracy of result always depends on the reliability of the input data. So, the data quality management is one of the devices to control and judge our input data.

3.3.1.1. Data Quality Check

Before all the progress of aquifer parameters evaluation, data quality check takes place. This is done, by preparing a graph for the drawdown verse time on log-log paper then using grasped correlation values and the judgment will be take on quality of data collected. The regression correlation coefficient standard values must be $R^2>\mathbf{0.5}$ and as it's closed to one it indicates the correlation is perfect. Akaki phase IIIA well field contains 20 wells and all their pumping test data quality will be checked.

Again an external influence are checked, those are not related to pumping including groundwater level changes due to recharge or discharge sources such as rainfall or river flow for all wells. These are done by comparing the water level before the pumping test and the water level after recovery period. Then, if the same or relatively the same constant water level is observed as during the pre-testing period and after the recovery period, it can safely be assumed that no external events influenced the hydraulic head during the test. Beside if the water level is subject to unidirectional or rhythmic changes, correction will be taking.

Well-bore storage effect is an effect induced due to single well test. This effect is appear at early pumping times, and may last from a few minutes to many minutes. Its effect is depending on the storage capacity of the well or diameter of the well. In a log-log plot of drawdown versus time, the effect of well-bore storage is reflected by a straight-line segment with a slope of unity. Therefore using the diagnostic plot for early drawdown data and if the trend line becomes straight line with unit slope, it indicates there is a bore storage effects and correction will be take.

3.3.2. System Identification

The first step in aquifer-test data interpretation is to analyse the relationship of drawdown to time while considering the hydro-geologic setting. The characteristic shape of the curves generated by plotting drawdown versus elapsed time using log-log scale and log-linear scale provides clue about the aquifer flow characteristics. Categorizing aquifer system is fundamental to my correction of the time-drawdown data.

3.3.3. Data Correction

Data correction are occupied for time-drawdown data test due to drawback of method adopted during the data collection or pumping test (i.e. single well test, casing, partial penetration) and model assumption (i.e. the aquifer is confined). As discussed in the literature review chapter, the well loss and aquifer loss is determined using step dawn test to take correction for the observed drawdown and for wells which doesn't have step draw down test data, Kozeny, 1933 will used for correction of partial penetrating well losses.

1. Partial penetration correction

All Akaki groundwater wells are partially penetrated wells to aquifer thickness. With a partially penetrating well, the condition of horizontal flow of water to well is not satisfied, at least not in the vicinity of the well and vertical flow components induced in the aquifer. In this case it accompanied by extra head losses in and near the well. Consequently, the draw down in partially penetrating well is greater than the drawdown in a fully penetrating well.

i. Step-drawdown correction

In step–drawdown analyses, the so-called diagnostic plots are used, values of sw/Q vs. Q are therefore plotted on arithmetic paper where sw represents the drawdown difference at the end of each step of step tests for increased discharge, Q test.

$$s_w = BQ + CQ^2$$

This equation is known as the Jacob's equation. Based on this equation, Jacob (1947) developed an analysis method to calculate the values of B and C directly from the diagnostic plot of sw/Q vs. Q itself; it will yield a straight line whose slope is equal to C; the value of B can be found by extending the straight line till it intercepts the Q = 0 axis. Therefore, s_w is subtracted from observed drawdown to correct.

ii. Kozeny correction factor

Kozeny (1933) provides a practical method to estimate the change in specific capacity (Q/s). He gives the approximate reduction factor to correct specific capacity (Q/s) for partial penetration effects. Correction factor:

$$F = \frac{L}{b}\left[1 + 7\cos\left(\frac{\pi L}{2b}\right)\sqrt{r/2L}\,\right] \qquad \text{Equation (3.1)}$$

Therefore, F is multiplied with the specific capacity of each collected or observed constant discharge drawdowns, then corrected drawdown are determined.

2. Unconfined correction

The saturated thickness of an unconfined zone decreases during pumping tests; however, most conceptual models are based on the assumption that it remains constant (like in case of confined aquifers). This assumption can be accepted if the saturated thickness does not decrease more than 25%. If the decrease is greater than 25 %, then the drawdown data should be corrected prior to analysis. Using equation 2.15 which presented in literature review for s (drawdown which corrected for partial penetrating case) of unconfined aquifer correction is apply.

$$\mathrm{s_{cor}} = \mathrm{s}\left(1 - \frac{\mathrm{s}}{\mathrm{2b}}\right)$$

3.3.4. Efficiency and Productivity Aquifer

The relationship between drawdown and discharge can be expressed as the specific capacity of a well, Q/sw, which describes the productivity of both the aquifer and the well. The specific capacity is not a constant but decreases as pumping continues and also decreases with increasing Q. The well efficiency, Ew, is defined as the ratio of the aquifer head loss to the total head losses; it reads when expressed as a percentage.

$$E_w = \left\{\frac{BQ}{BQ + CQ^2}\right\} * 100\%$$

Safe yield of the well productive is determined depending on the efficiency. The higher the efficiency indicates the safest the well yield.

3.3.5. Analysis Methods

In this study under non-equilibrium method for evaluation and analysis of aquifer properties two techniques are selected: Cooper-Jacob and Theis Recover method. Theis Curve Fitting method is dropped due to difficulty to rely on the result obtained because it is random curve fitting. In this case the results are varying from users to users. Therefore it is difficult to be assure the determine result is the corrected one.

3.3.5.1. Cooper-Jacob Method

Cooper-Jacob is a graphical (semi-log) method to determine transmissivity and storativity of aquifer for small u. After plotting on Excel spread sheet 2010, corrected drawdown vs. time on semi-log the straight line added which fit the point. Therefore, by extending this straight line to cross the log-t axis at s=0, t_0 determined or using the generated equation for fitted straight line it can be determine.

Finally, using Cooper-Jacob formulated formula of straight line fit, and for constructed equation by inserting the values of discharge and the slope of one log or the change in the drawdown, physical properties of aquifer (transmissivity and storativity) are determine.

3.3.5.2. Theis Recovery Method

The analysis of recovery test is based on the principle of superposition. Applying this principle is by assuming that after the pump has been shut down, the well continues to be pumped at the same discharge as before, and that an imaginary recharge, equal to the discharge, is injected into well. The recharge and discharge are cancelled each other, resulting in an idle well as required for the recovery period. Recovery method is applied only for wells that have a recover data which is collected after the pump shutdown. It is developed by Theis and more reliable than other methods due to no variance of discharge.

Transmissivity is evaluated from a Recovery semi-log graph constructed on Excel spread sheet 2010: residual drawdown (the difference between the original water level before the start of pumping and the water level measured at a time t’ after the cessation of pumping) vs. log t/t’ and introducing straight trend line care to obtained the slope, interception point and delta of residual drawdown for one log-cycle. Finally it calculated by Theis Recovery formula (equation 2.21).

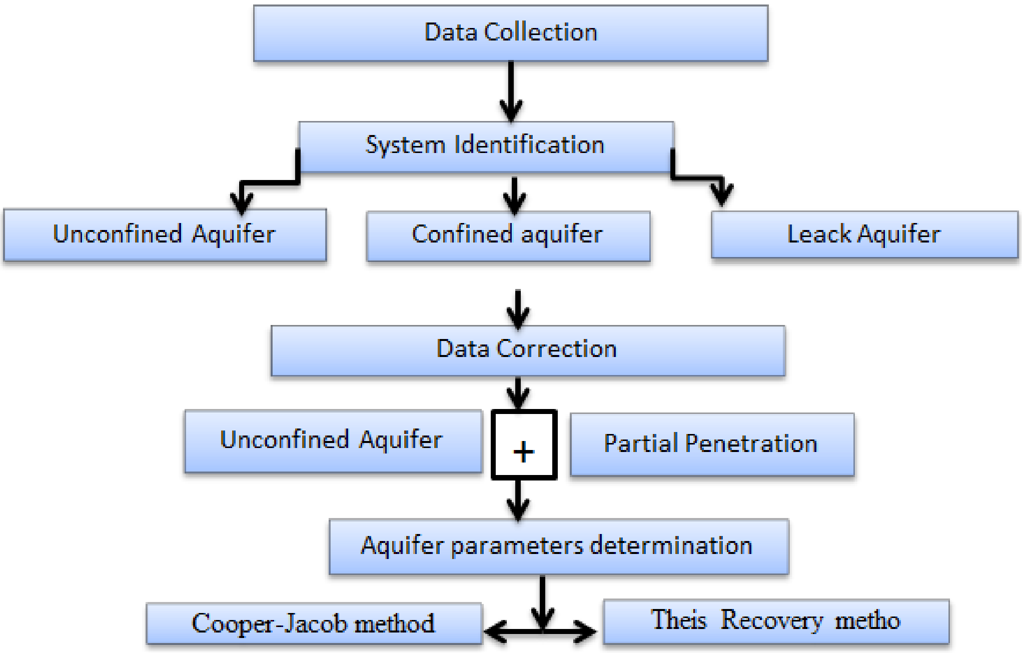

Figure 3-2 Data analysis frame work for aquifer parameter evaluation

3.6. MODFLOW (2000) Model

A groundwater model is a replica of some real-world groundwater system. The term 'modeling' refers to the formation of conceptual models and manipulation of modelling code to represent a site-specific groundwater system.

Most groundwater models in use today are deterministic mathematical models. Deterministic models are based on conservation of mass, momentum, and energy and describe cause and effect relations. MODFLOW is one of the tools of computer simulation model for analysing flow and solute-transport in groundwater systems.

Numerical methods yield approximate solutions to the governing equation (or equations) through the discretization of space and time. Within the discretized problem domain, the varying internal properties, boundaries, and stresses of the hydro-geologic system are approximated. Deterministic, distributed-parameter, numerical models can relax the rigid idealized conditions of analytical models or lumped-parameter models, and they can, therefore, be more realistic and flexible for simulating field conditions (if applied properly). This approach constitutes a numerical model.

Two major classes of numerical methods have come to be the most widely used and accepted for solving the groundwater-flow equation. These classes are finite-difference and finite-element methods. Each of these two major classes of numerical methods includes a variety of subclasses and implementation alternatives.

In this paper the finite-difference methods are selected to conceptualize the Akaki well fields. This method approximates the first derivatives in the partial differential equations as difference quotients (the differences between values of the independent variable at adjacent nodes with respect to the distance between the nodes, and at two successive time levels with respect to the duration of the time-step increment). Advantages of the finite-difference methods are conceptually and mathematically simpler, and are easier to program. The finite-difference equations typically are derived for a relatively simple, rectangular grid, which also eases data entry.

Again, the construction of a rectangular finite-difference grid have two possible modes of grid construction are illustrated in two dimensions the calculation points (or nodes) are located at the centers of the blocks (or cells) formed by the grid lines. This type of grid is commonly called a block-centered grid. In the other hand, the grid nodes are considered to be located at the intersections of the grid lines. This type has been variously called a point-, node-, mesh-, or lattice-centered grid. Although there is no overall inherent advantage of one type over the other, there will be some operational differences between the two approaches in the treatment of boundaries and in areas of influence around nodes. Most, but not all, finite-difference groundwater models are based on the use of block-centered grids. In this study finite difference technique of block-centered used to model the drawdown of the water table that occurs when water is pumped from aquifers.

General protocol for performing modelling studies is follows a process steps:

→ Determination of modelling objectives
→ Data gathering and organization
→ Development of a conceptual model
→ Numerical code selection
→ Assignment of properties and boundary conditions to a grid
→ Calibration and sensitive analysis
→ Model execution and interpretation of results
→ Recommendations for future monitoring.

3.6.1. Model Conceptualization

Due to complexity of the groundwater nature its simplification is essential to reproduces system behaviour. Establishing conceptual model of system is aimed to simplify this complexity. Anderson and Woessner (1992) stated that, a conceptual model is a pictoral representation of the groundwater flow system, frequently in the form of a block diagram or cross section. The nature of the conceptual model will determine the dimensions of the numerical model and design of the grid.

Understanding of hydrogeological and geological is required to conceptualizing the field situation to build a frame work. It needs an expression of fact in very simple but still best approximation of major field situation according to the scope of the purpose. The conceptual model also understands the mathematical constraints of numerical modeling despite the profound fact of almost every field situation can be represented mathematically.

Conceptualization is start with delineating (using GIS) the Akaki well field area and identifying the boundary conditions. It intend to maintain the mathematical representation by identifying the available major system, the possible boundaries and aquifer characteristic which results an input data base, cross section and simplified map for the modeling.

Nature of Akaki Aquifer

Hydro-stratigraphy helped to understanding the nature of Akaki well field aquifers. According to the report prepared by WWDES to AAWSA for each wells, most of Akaki River Catchment is made up of both inter granular and fracture type aquifers. Alluvial sediments and pyroclastic rocks are inter-granular porosity aquifers, and volcanic rocks such as weathered or fractured basalts, ignimbrites, trachytes, welded tuffs and rhyolites are fractured aquifer types. From this analysis major nature of the study area is categorized as unconfined aquifer and its model with unconfined aquifer.

For unconfined aquifer simulated Dupuit assumption is horizontal flow by no change in head with depth. Simulation involving an unconfined aquifer arrays specifying hydraulic conductivity, specific yield and the elevation of the datum.

Flow System

Topography, geology and structures are the primary controlling factors on the flow system of the groundwater. The alluvial deposits mainly composed of clay are found along Akaki Rivers and its tributary. After potentiometer head data distribution from various deep wells drilled in the aquifer system are collected, potentiometer contour map has been constructed to now the groundwater flow direction by Arc GIS tool. Therefore, by converting this contour using Surfer to make the data compatible for calling in the MODFLOW and the general boundary conditions can be realized.

Again, the high elevation, ridges and steep sloped areas of the city are covered by thin layer of residual clay soils while watershed divide and plain areas of the town (central and upper part of the town) are covered by thick residual clay soils and the southern parts of town (Akaki and Abba Samuel area) are covered dominantly with very thick lacustrine deposits. These indicate local groundwater flow direction in the well field is from NE towards the SW where natural springs exist in the Aba Samuel Gorge.

Boundary Condition

Identifying the boundary condition of the study area is mandatory for groundwater modelling. To have a good conceptualization of a hydrologic system, it is essential to identify and assign system boundaries appropriately. Because groundwater flow modelling is influenced by the boundary conditions which the extent of the flow domain to be analyzed or simulated process. Therefore, correct conceptualization of boundary is important to select an appropriate mathematical representation in the model so that the effect of the boundary on flow can be correctly understood.

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

Akaki well fields (the existing BH, phase II WF01, phase IIIA WF02 and phase IIIB SL wells) contains constant head, general head boundary and barrier (no-flow) boundary conditions. From the upper part (North) of the Akaki wells there is inflow which comes from Intoto Mountain and at the down (South-East and South-West) of well field there is an outflow from the catchment which are represented by general head boundary of head dependent. Again Aba Samuel reservoir is model in constant head boundary. The final boundary condition is no-flow boundary are the left (West) and the right (East) of Akaki well fields.

During model conceptual boundary condition cells are grouped as constant head cells and inactive (or no-flow) cells. Constant head cells have a specified value through all time steps of simulation and it assigned by -1. Inactive cells do not allow flow into or out of the cells and it assigned by zero, 0. Therefore both constant head and no-flow cells are used to represent the condition of various hydrologic conditions along the boundary.

Water Budget Preparing

1. Distribution of recharge

Recharge is the rate of infiltrated water that passes through the water table and joins the groundwater flow system. However, the recharge determined have met with limed success, spatial uniform distribution of recharge volume assumed a cross the water table equal to some percentages of average annual precipitation. The major recharge to the Akaki aquifer comes from precipitation and river channel losses. Main direct recharge is assumed to take place in all areas except where low permeable lacustrine soils exist. The recharge has been assigned in the model in a distributed manner by varying in a wide range from 0.00007 to 0.0005 m/day (Tenalem A. et.al, 2007). This value of recharge rate is often adjusted during calibration.

2. Groundwater discharge

Water may enter or leave a model in one of two ways: through the boundaries which can as determined by the boundary conditions, or through source and sink within the interior of the grid. Akaki well fields contain 77 wells which discharge or abstracted with different rate. Therefore, using Surfer different maps of segment, polygon and point were overlaid for differentiating zonation of hydrogeological parameters, location and distribution of observation wells, model boundaries, water point alignment with respect to structures, model boundaries and for other analysis using as background during the construction of the numerical model and in different variations of the conceptual model for the period of calibration process by importing it to MODFLOW.

Finally, the features of conceptual model are transferred as input to MODFOLW model through GIS, Global mapper and Surfer software which is presented in two-dimensional grid. This grid is superimposed on a site map which aided to wells, constant head and rivers locations.

3.6.2. Numerical Model

Governing Equations

General flow equation is derived by in view of flow through control volume or by taking the rectangular element. Then using both Darcy's law and continuity equation to each side of the element and it describes the conservation of fluid mass during flow through a porous medium.

1. Darcy's law

Darcy's law relates the Darcy flux, v to the rate of head-loss per unit of length of porous medium, $\frac{\partial h}{\partial l}$. Considering two-dimensional flow through a rectangular control volume, the flow components for four side of element are expressed using Darcy's law:

$$q_{1=} - T_{xi-1\ j} \Delta y_j \left(\frac{\partial h}{\partial x}\right)_1 \qquad \text{Equation (3.2a)}$$

$$q_{2=} - T_{xi\ j} \Delta y_j \left(\frac{\partial h}{\partial x}\right)_2 \qquad \text{Equation (3.2b)}$$

$$q_{3=} - T_{yi\ j+1} \Delta x_i \left(\frac{\partial h}{\partial x}\right)_3 \qquad \text{Equation (3.2c)}$$

$$q_{4=} - T_{yi\ j} \Delta x_i \left(\frac{\partial h}{\partial x}\right)_4 \qquad \text{Equation (3.2d)}$$

Where, q=vA

q- is flow rate from four sides

v- Darcy's flux which is v= T/b* $\left(\frac{\partial h}{\partial l}\right)$

h- hydraulic gradient

b- thickness of aquifer

A-area of control volume A= Δx.b

T-transmissivity x and y flow directions

2. Conservation of mass

Water balance of conservation of mass state that: Inflow-Outflow= Change in Storage. The derivation done by REV to representative of properties of the porous medium with a volume of Δx, Δy, Δz. Then, the total change inflow rate is equal to the change in storage and it expressed as:

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)\Delta x\Delta y\Delta z = Change\ in\ Storage \qquad \text{Equation (3.3a)}$$

If there is a possibility of sink (i.e. pumping well) or source (i.e. an injection of well or recharge) within the REV, it represented by the R*ΔxΔyΔz. R is positive when it is source of water and it subtracted from left hand side. It become:

$$\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}-R\right)\Delta x\Delta y\Delta z = Change\ in\ Storage \qquad \text{Equation (3.3b)}$$

Now, by consider the right-hand side of the above equation, change in storage is represented by specific storage, Ss, which is defined as it is the volume of water released from storage per unit change in head, h per unit volume of aquifer:

$$S_s = -\frac{\Delta V}{\Delta h\Delta x\Delta y\Delta z} \qquad \text{Equation (3.3c)}$$

and the rate of change in storage in the REV is

$$\frac{\Delta V}{\Delta t} = -S_s\frac{\Delta h}{\Delta t}\Delta x\Delta y\Delta z \qquad \text{Equation (3.3d)}$$

Finally, by combining the above two equations (Equation (3.3b) and Equation (3.3d)) and replaced the qx, qy and qz by Darcy's equations and it became *General flow equation*.

This partial differential equation for transient three dimensional groundwater flow in heterogonous and anisotropy medium, for a confined or unconfined is expressed as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t}-R \qquad \text{Equation (3.4)}$$

Where,

Kxx , Kyy and Kzz -are values of hydraulic conductivity in the x, y and z directions of Cartesian Coordinate Axes and which are represent directions of hydraulic conductivity (L/T)

h- is hydraulic head (L)

W- is a volumetric flux per unit volume and represents sinks and/or sources (1/T),

S_s -is the specific storage of the porous material (1/L), and

t- is time (T).

This equation together with the specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial head conditions constitutes a mathematical representation of groundwater flow system. The solution of this equation requires the use of a numerical method such as the finite difference method (David K. Todd et.al, 2005).

Finite difference

Finite difference is replaces the continuous system described by above equation (general groundwater flow equation) with a finite set of discrete points in space and time. A two dimensional finite difference grid is generated by specifying arrays of values for Δx and Δy for horizontal plane and in this study the grid designed by 200m X 200m cell. Finite difference may categorize in to two. In block-centered approach, which is flux boundaries located at the edge of block, and mesh-centered grid which is the boundary coincides with node.

Akaki well field represented by finite difference grid, which covers about 101.km^2 with 80 rows, 75 columns and one layer unconfined aquifer. A node is a point within each cell (grid) where the head are calculated. IBOUND establishing the lateral extent of the formations in each layer using the catchment boundary map and assigned a cell as active if the formation covered more than 50 percent of the cell area, inactive and constant head.

Top Layer

Surface elevation is occupied as top of aquifer layer. It is prepared by Global Mapper using 30m×30m DEM and processed to generate in grid format which is compatible to load on MODFLOW with Surfer again.

Bottom Layer

Bottom layer indicates the foot of aquifer. Akaki aquifer thickness are varies between 300m to 600m values and this makes it difficult to allocate the bottom layer. In order to avoid drying of cells during simulations elevated zones. Therefore, 550m takes which is relatively higher thickness at the cells.

Initial and Prescribed Hydraulic Head

Initial hydraulic head at constant head cells are used as specified head values of those cells and remain constant throughout the flow simulation. For transient flow simulation, the initial head must be the actual values since they are account for the storage terms. For steady-state flow simulation, the initial head are used as starting values for the iteration equation solvers. The initial head at the constant head cells must be the actual values while all other values can be set at an arbitrary level.

The static water levels of Akaki aquifer are not uniform which helps to get an initial hydraulic head. Therefore, by taken the average of the range of the SWL, 52m the initial hydraulic head of a constant head cell are determine by subtracting the SWL from the surface elevation and it should be higher than the elevation of the bottom.

Horizontal Hydraulic Conductivity

Horizontal hydraulic conductivity is the hydraulic conductivity along model rows. In this model groundwater flow within the layer was assumed to be horizontal and it uses the spatial distribution of the hydraulic map described in the conceptual model to begin the model simulation.

Flow Packages

a. General Head Boundary

General Boundary Head (GBH) package is used to simulate head-dependent flow boundary condition, flow in or out of a general boundary head from an external source is provided in proportion to the difference between the head in the cell and the head assigned to the external source. This visualization is set by flow pattern or flow direction of the area. Using the data editor, a general-head boundary is defined by using the cell-by cell or polyline input methods to assigning parameters to vertices of the polylines along the trace of boundary. The input parameters are assumed to be constant during a given stress period.

The flow Q into or out of a cell from an external source with a known head is proportional; to the difference between the head in the cell, h_{ijk}, and the head assigned to the external source, h_{bijk} as

$$Q_{bijk} = C_{bijk}(h_{bijk} - h_{ijk}) \qquad \text{Equation (3.5)}$$

Where

C_{bijk}- is conductance between the external source and cell (i, j, k)

Hence, topographical nature of Akaki well fields is flat, to identify the hydraulic boundaries which is regional groundwater divide are typically found near topographic highs and may from beneath partially penetrating surface water bodies. Therefore, in this study area almost there is no groundwater divide.

b. Recharge

The recharge package is designed to simulate distributed recharged to the groundwater system of the study area. In MODFLOW, the recharge rate Qr is applied to a single cell within a vertical column of cells. In the simplest situation, the water table is located in the top layer of the model, the top layer is designated as unconfined and an array of recharge flux is specified for that layer.

c. River

The purpose of the River package is to simulate the effect of flow between groundwater systems and surface-water features. In this study area both Little (Tinishu) Akaki and Big (Tiliku) Akaki rivers are considered.

The two main Akaki river branches are confluence of which is at the Aba-Samuel reservoir. The western branch of the river, the Little Akaki, raises north-west of Addis Ababa on the flanks of Wechacha Mountain and flows for 40 km before it reaches the reservoir. The eastern branch of the river, the big Akaki, rises north-east of Addis Ababa and flows into the Aba-Samuel reservoir after 53 km flow. In the Addis Ababa city, there are dissimilar perennial and intermittent streams which are tributaries of the little or Big Akaki rivers, and towards the south approximately all streams/or big tributaries crossing the city in different direction join either of the rivers. The two rivers flow on either side of Addis Ababa - Debrezeit road and end up at the artificial lake Aba Samuel (Tsinat Tsegaye, 2017).

Along the rivers path line, for each cells conductance, C are determined for hydraulic conductivity, K, length of the river through the cell, L, width of the river, W and the thickness accumulated sediment of the river bed, M.

$$C = \frac{K*L*W}{M} \qquad \text{Equation (3.6)}$$

The accumulated formations include alluvial, residual, and lacustrine deposits. The thickness varies between 5 m and 50 m in the south (AAWSA, 2000).

d. Well

A well package designed to simulate features such as wells that withdrawal water from or add to the aquifer at a constant rate during a stress period, where the rate is independent of both area and the head in the cell.

Akaki well fields have three phases (phase I, phase IIIA and phase IIIB) and the existing one with having a total of 77 wells are used for modeling and wells that are owned at household levels have a lower withdrawal rates so, it will not considered in the simulation. Those wells are abstracted or pumping for the sake of water supplies to achieve the required demand. Negative values are used to indicate pumping or discharge wells. The input parameters are assumed to be constant during a given stress period. But for transient flow simulations involving several stress periods, the input parameters can be different from period to period.

3.6.3. Calibration and Sensitive Analysis

After conceptual model, grid design, input parameters to the cells, boundary and initial condition task done; model calibration, sensitivity analysis and prediction are take place. Calibration of a flow model refers to a demonstration that the model is capable of producing field-measured heads and flows which are the calibration values. Calibration is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error.

Finding this set of values amounts to solving known as the inverse problem. In an inverse problem the objective is to determine value of parameters and hydrologic stresses from information about heads, whereas in the forward problem system parameters such as hydraulic conductivity, specific storage and hydrologic stresses such as recharge area are specified and the model calculates heads. In this paper the calibration will take in manual trial-error adjustment of parameters.

Therefore, to afford a complete indication of the quality of the calibration, summary statistics on the difference between simulated and measured water levels were calculated after model calibration. The mean error (ME), mean absolute error (MAE) and root mean squared error (RMS) are common ways to express the average difference between simulated and measured water levels (Mary P. Anderson et.al, 1992). The objective of the calibration is to minimize these error values.

1. The mean error is the mean difference between measured heads (hm), simulated heads (hs) and number of calibration values, n.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(hm - hs)i$$

2. The mean absolute error (MAE) is the mean of the absolute value of the differences in the measured and simulated heads.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(hm - hs)i|$$

3. The root mean squared error (RMS) is the average of the squared differences in measured and simulated heads.

$$RMS = [\frac{1}{n}\sum_{i=1}^{n}(hm - hs)i]\hat{}0.5$$

The above error measures can only be used to evaluate the average error in the calibrated model. The RMS is usually thought to be the best measure of error if errors are normally distributed. The maximum acceptable value of the calibration criterion depends on the magnitude of the change in heads over the problem domain (Mary P. Anderson et.al, 1992).

Model sensitivity analysis is performed to quantify the uncertainties in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Mary P. Anderson et.al, 1992). To test the response of the calibrated model to a range of values for various input parameter, a sensitivity analysis is done. Sensitivity analysis help to determine which model parameters have the greatest effect on a model. Results of the analysis can guide future data collection efforts that will reduce model errors. It is done by varying the values of one input parameter while keeping all others constant.

Sensitivity is a relative rate change of selected output caused by unit change in the input. The more change in output caused by the input; the model is more sensitive to that input. In fact the model make up also determine how sensitive to an input parameter.

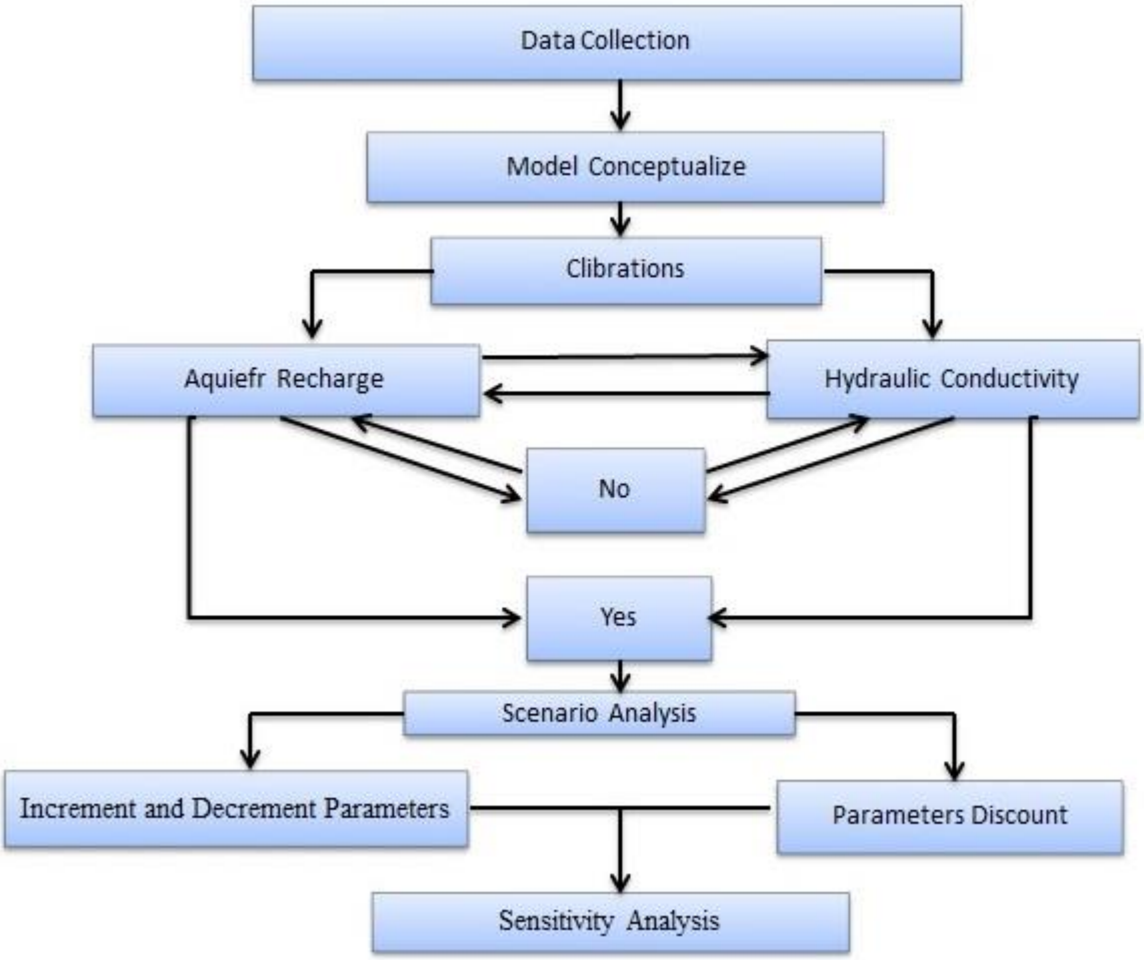

Figure 3-3 Data analysis frame work of MODFLOW for sensitivity analysis

4. RESULT AND DISCUSSION

4.1. Aquifer Parameters Evaluation Analysis Result

4.1.1. Pre-Results

Data Quality Check Result

Data quality checked is the first action taken to collected constant discharge pumping test data and the result show that, among 20 wells of Akaki phase IIIA six wells (WF02-PW04, WF02-PW06, WF02-PW07, WF02-PW08 WF02-PW15 and WF02-PW19) are failed data quality checks where R^2 or correlation-coefficient becomes < 0.5. This indicates that those wells have poor data quality and due to this reason they doesn’t used for the aquifer parameters evaluation. In addition, WF02-PW10, WF02-PW11 and WF02-PW14 do not pass the step-drawdown configuration for correction process (the slope, B become –ve) and WF02-PW02 and WF02-PW010 of step-drawdown data have up and down values so, they are ignored. Again, WF02-PW03 and WF02-PW20 have no documented data at all. Finally, the results for external influence test and borehole storage (test for early 30min and 60min check) are shows that, the study area is free from external and borehole storage influences. Therefore, data correction for both effect doesn’t needed.

Correction for Unconfined Aquifer and Partial Penetration Well

WF02-PW01, WF02-PW05, WF02-PW09, WF02-PW012, WF02-PW013, WF02-PW016, WF02-PW017 and WF02-PW018 are the last wells arrived for correction of drawdown data of partial penetrating wells. For partial penetrating well effect s_w which determined through well-performance or step-drawdown techniques subtracting from observed drawdown data. Also, Kozeny’s correction factor, F method is adapted only for WF02-PW05 due to the well doesn’t have a step-drawdown test data. Then, by multiplied the intended Kozeny’s correction factor to observed drawdown, s the correction is taken. The analyses used for the determination of the s_w and correction factor for seven and one wells respectively attached in the appendix-A part of this document.

Once more, unconfined aquifer correction, for WF02-PW01, WF02-PW09, WF02-PW12, WF02-PW16, WF02-PW17 and WF02-PW18 wells aquifer formation are categorized as unconfined aquifer and correction is applied. This indicates those wells are corrected for both constraints.

4.1.2. Efficiency and Productivity of Wells

Both well efficiency and the well-losses or well performance are determined by using the step-discharge test data. An efficiency of the well helps to decide the save yield of the well and well-losses are determine a losses (well and aquifer losses) induced due to the partial penetration.

Figure 4.1. show a graph (drawdown for increasing discharge vs. time since pumping started) of step-drawdown for four steps with 60l/s, 75l/s, 90l/s and 108l/s discharges seccussively pumping in constant time interval of 120min of PW01.

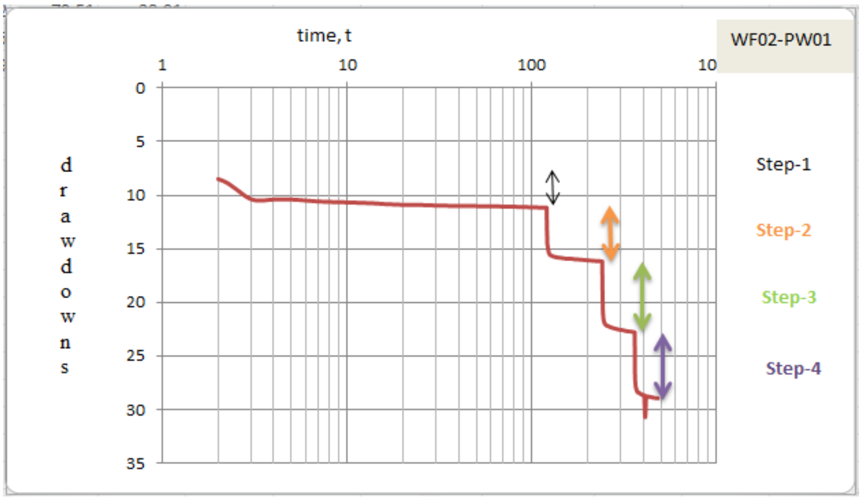

Figure 4-1 Step-drawdown curve of WF02-PW01

Therefore, computing the change in drawdown for each steps and plot the graph sw/Q vs. Q in linear graph and adding best straight line trade/fit, the well-loss coefficient and non-linear well loss coefficient, Fig.4.2., can determined which are used for efficiency and correction calculation.

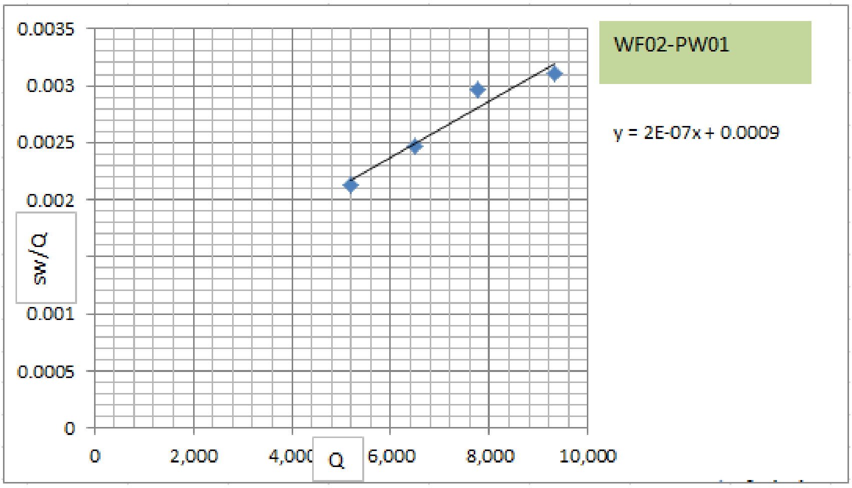

Figure 4-2 sw/Q vs. Q plots for WF02-PW01

Now, by taking the evaluated B and C values: the well-loss coefficient and non-linear well loss coefficient, the efficiency can determined as below table for each step-drawdown pumping discharges.

Table 4-1 Efficiency and productivity of WF02-PW01

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW01		0.0009	2	
Discharge, Q (L/s)	step 1	60		46.47%
	step 2	75		40.98%
	step 3	90		36.65%
	step 4	108		32.54%

The above table 4-1 illustrate that the efficiency of the WF02-PW01 for step increased discharge of drawdown test. The remaining wells result (i.e. PW-09, PW-13, PW-16, PW-17 and PW-18) of step-drawdown plot, sw/Q vs. Q plots and efficiency obtained are included on Appendix A.

Since, efficiency is the ration of aquifer head losses to the total head losses and assessed by step-drawdown data test, it tells about the efficiency of well within the extracting water rate of wells. The standard efficiency for the productive wells are 65% and above. However, in our country Ethiopia it’s not applicable in this efficiency bound. The result obtained from this evaluation also reflects this limitation.

The general equation generated from the sw/Q vs. Q graph for each wells are helpful to obtain the safe yield of that aquifer with adequate efficiency. Therefore, table 4-2 specifies the calculated maximum safe yield of each well with sufficient efficiency 65%.

Table 4-2 Efficiency and Productivity of wells

Well Index	Current yield, Q (L/s)	Efficiency of well for Q			Max. safe yield (L/s)	sw	Productivity, Q/sw mxa.
		B	C	E %			
PW01	102	0.0009	2.00E-07	33.8	28.04	29.24	301.36
PW09	70	0.0003	3.00E-07	14.2	6.23	10.39	581.93
PW12	46	0.0036	1.00E-06	47.5	22.44	32.31	123.01
PW13	61	0.0004	1.00E-07	43.1	24.93	6.21	849.35
PW16	83	0.0015	2.00E-07	51.1	46.74	25.53	280.90
PW17	81	0.0004	4.00E-07	12.5	6.23	26.668	262.43
PW18	77	0.0028	5.00E-07	45.7	34.90	42.06	158.18

All the wells remarked in the table above suggests that the Akaki phase IIIA well field extract water under poor efficiency. Due to this reason the well perform with excessive yield and poor productivity which induced the excessive energy cost to yield water.

The productivity of aquifer and wells described by the specific capacity of well which is the relationship between discharge over drawdown. The high specific capacity is the high aquifer productivity. Therefore, the above table gives the summery of both the efficiency and productivity of wells.

4.1.3. Aquifer Parameters Evaluation Result

One of the main objectives of this study is the evaluation of aquifer parameters which are transmissivity and storativity for Akaki well field (case study of Akaki well phase IIIA) after the required correction are taken. This is due to, linear and non-linear well losses, the water levels inside the pumped well it self are generally lower than those directly outside the well screen. This implies that drawdown data from the pumped well cannot be used for analysis unless corrected. Therefore, using the corrected data evaluation is done as follows in: Cooper-Jacob and Theis recovery method.

4.1.3.1. Cooper-Jacob Method Result

Constant rate test is conducted persistently with a constant discharge rate and the main purpose of constant rate test is to determine sustainable abstraction rate, aquifer parameters and the physical limitation of the aquifer. Therefor using the constant pumping test data collected by WWDSE the aquifer parameters, transmissivity and storativity are determined.

Cooper-Jacob, straight line fitting, analytical method developed for the late time-drawdown data. This is because; the early time data may affect by casing (volume of water stored in borehole) and cause the point to deviate from straight line fitting. Hence, for all evaluated wells the early time data are ignored to overcome on the effect of the casing and the late time data used which can obtain the best straight line fit to the scatter data of corrected drawdown. Some of the graph fitted by more than one straight line this is due to change in slope from one portion to the other.

The evaluation results for the eight wells using Cooper-Jacob method obtained presented below for each well and summarized in table 4-3 for all wells.

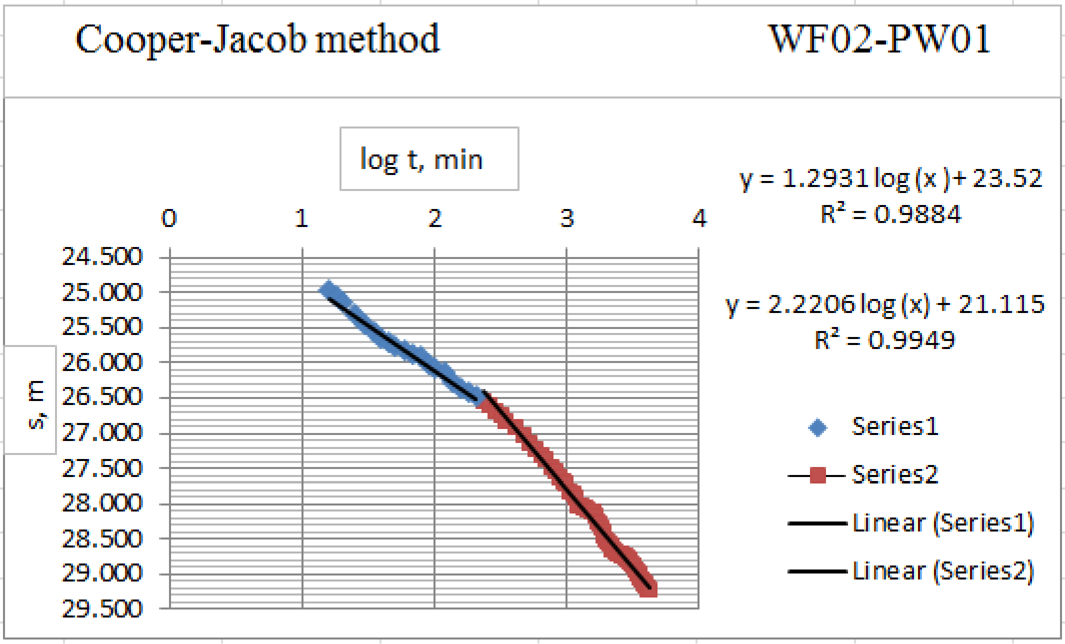

Figure 4-3 Cooper-Jacob straight line of well PW01

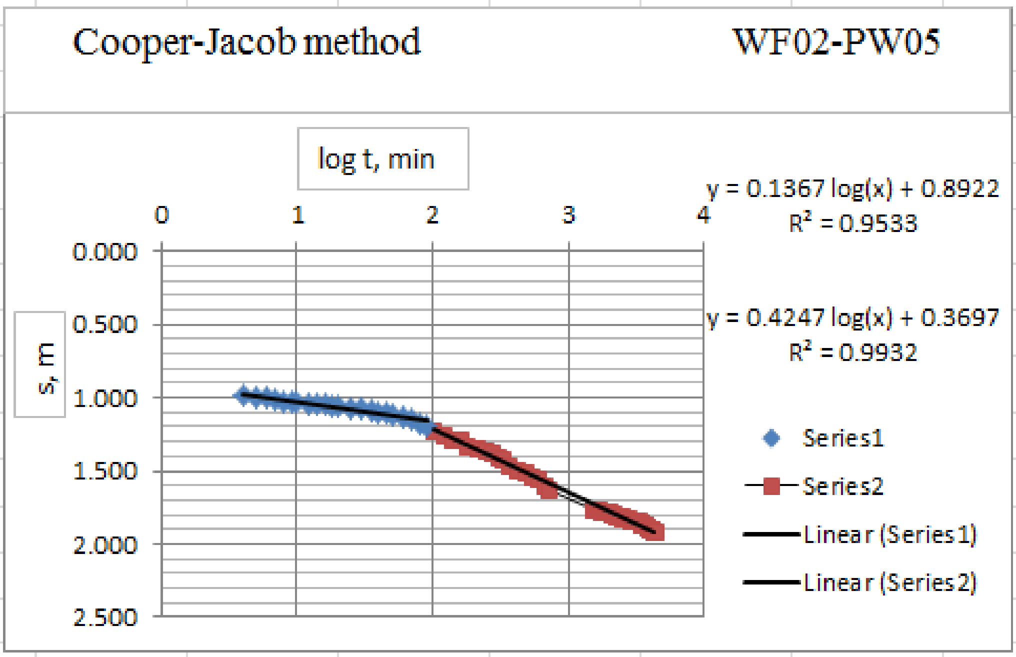

Figure 4-4 Cooper-Jacob straight line of well PW05

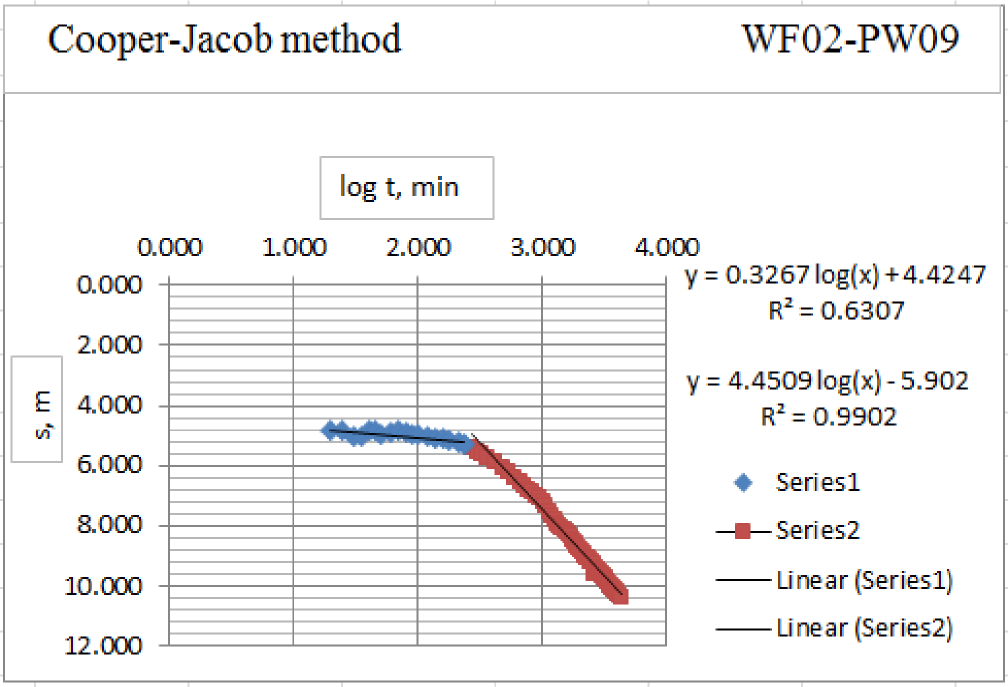

Figure 4-5 Cooper-Jacob straight line of well PW09

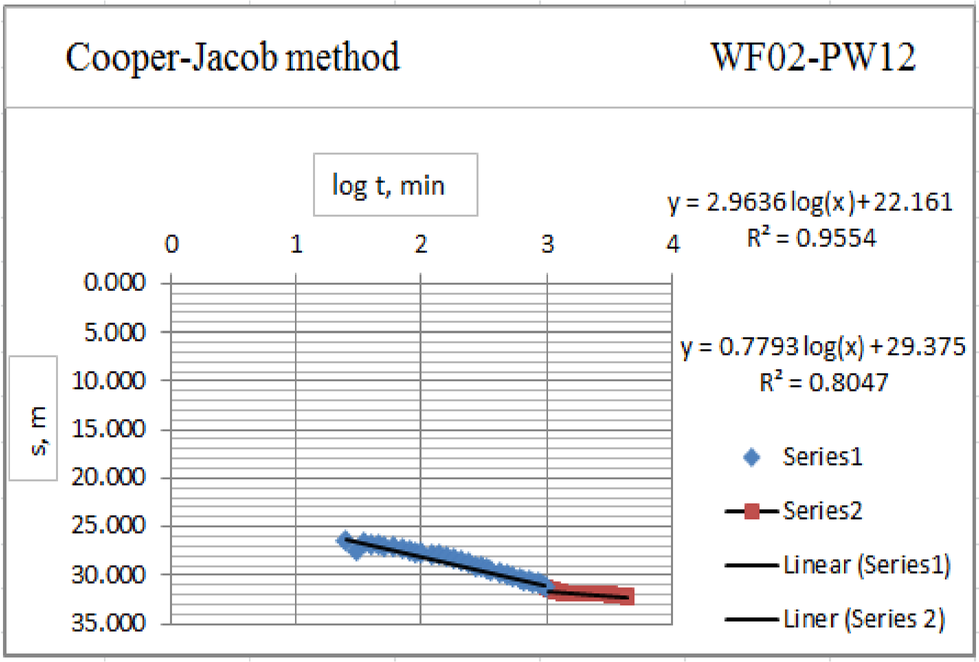

Figure 4-6 Cooper-Jacob straight line of well PW12

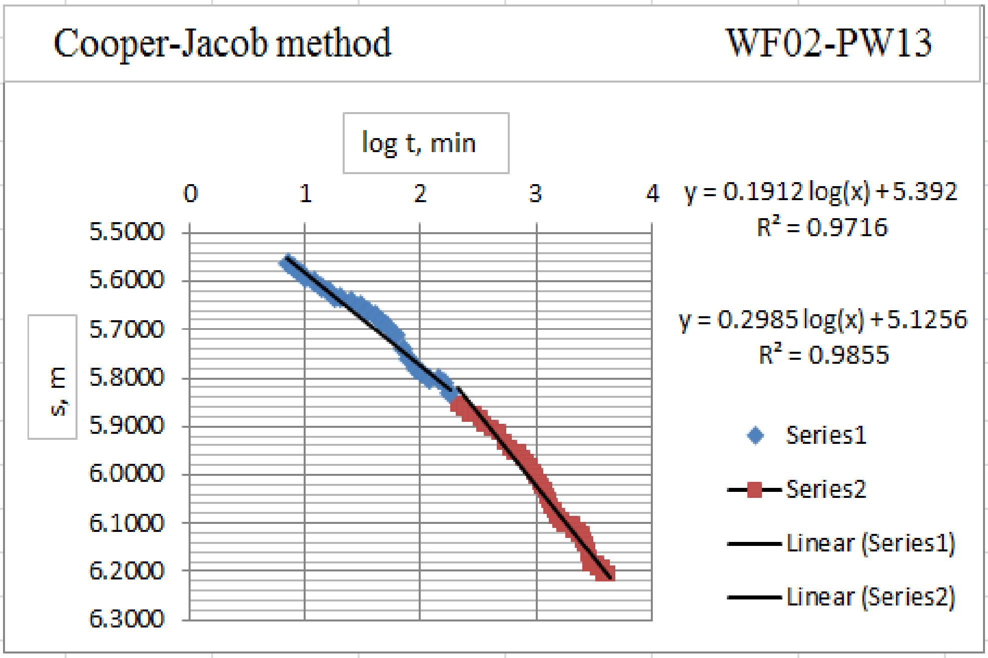

Figure 4-7 Cooper-Jacob straight line of well PW13

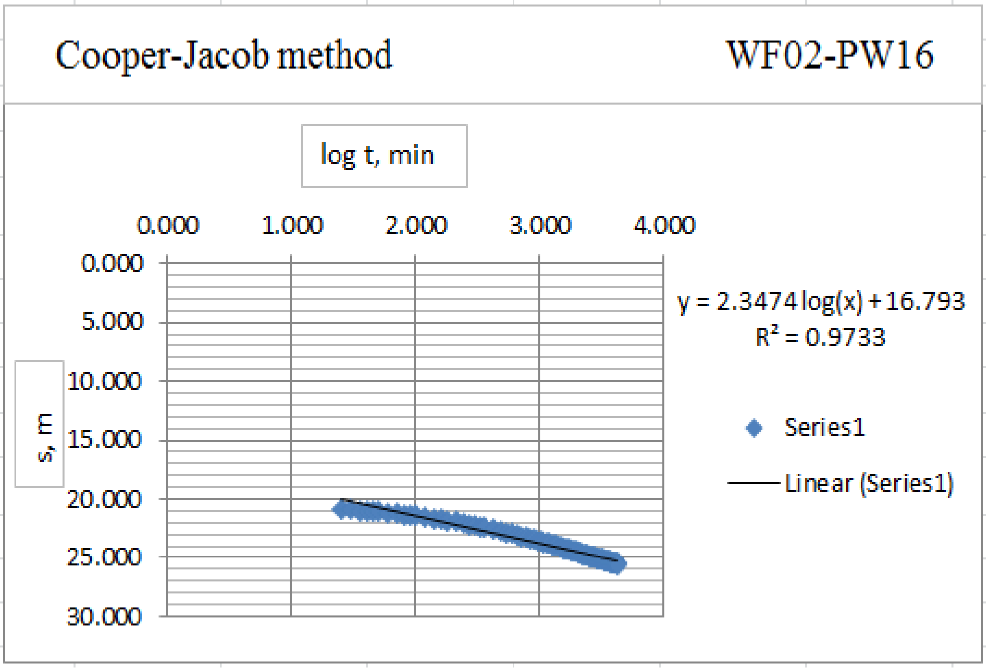

Figure 4-8 Cooper-Jacob straight line of well PW16

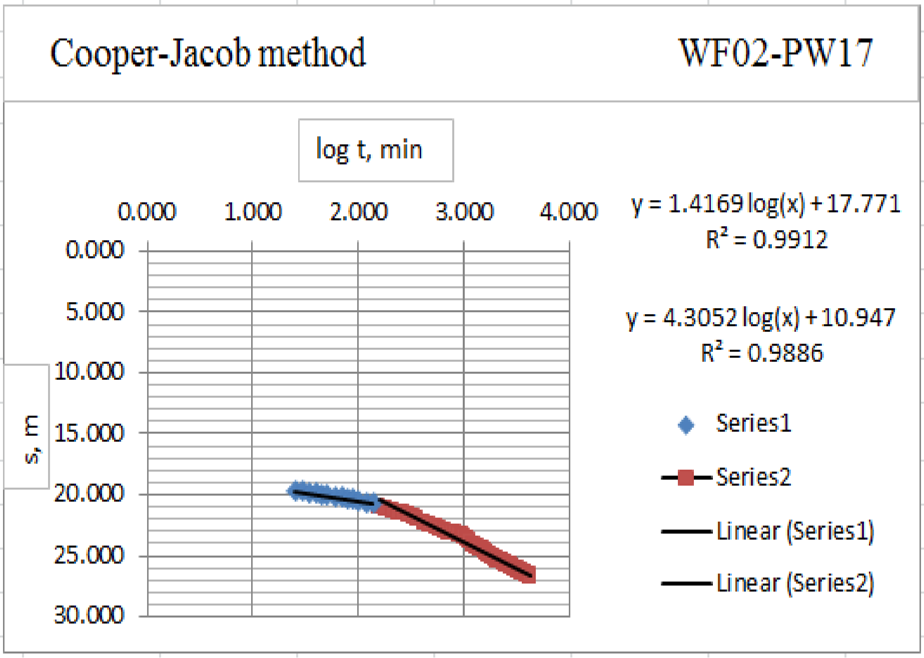

Figure 4-9 Cooper-Jacob straight line of well PW17

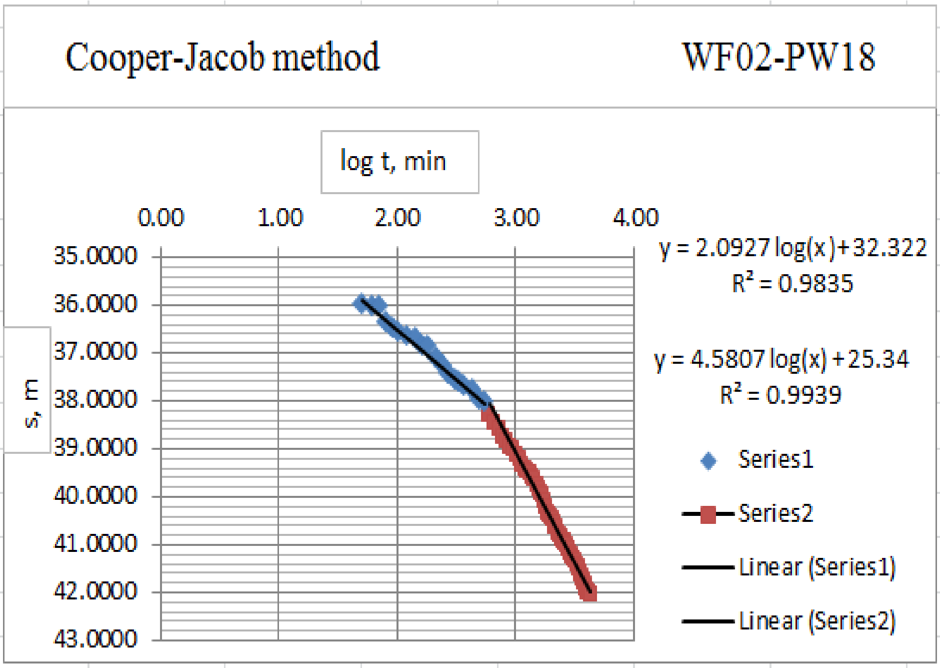

Figure 4-10 Cooper-Jacob straight line of well PW18

The entire correlation-factor of the straight line fit are between 0.6307-0.9949 values and the scatter points are pretty fit the straight line. As semi-logarzmic equations developed for each wells it helps to determine the aquifer parameters. Then, all above figures of Cooper-Jacob summary and evaluated transmissivity and storativity values of eight wells are tabulated in table below with WWDSE document result of physical properties of the study area aquifer.

Table 4-3 Cooper-Jacob straight line evaluation summery

		Straight line fit		**Cooper-Jacob evaluation**		WWDSE document	
Well Index	Q, L/s	t_o	Δs	Transmissivity	Storativity	Transmissivity	Storativity
PW01	102	4.496E-22	1.695	952.37	7.618E-18	886	3.71E-12
PW05	50	2.07E-10	0.241	3283.22	1.64E-05	1600	91.7
PW09	70	1.99E-17	1.206	918.45	3.25E-13	115	168
PW12	46	2.312E-11	1.520	478.90	4.15E-07	398	-
PW13	61	4.373E-32	0.239	4039.88	6.161E-27	3840	-
PW16	83	4.873E-11	2.347	559.43	7.857E-07	520	-
PW17	81	1.993E-16	2.470	518.88	3.61E-12	321	-
PW18	77	2.492E-19	3.096	393.48	2.83E-15	663	-

Transmissivity is widely used in groundwater hydraulics to understand of the aquifer properties. It is defined as the rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. The comparisons between Cooper-Jacob transmissivity evaluated analysis of the Akaki well and the WWDSE documented value summarized at above table and point out the variation. This variation characterized the values as under and over the corrected intended parameters.

The transmissivity result interpreted as most of the WWDSE record under estimate the aquifer transmissivity when it compared with corrected evaluation. However, WWDES of the storativity result is not given for some wells the comparison is taken for WF02-PW01, WF02-PW05 and WF02-PW09 and its over-estimated.

4.1.3.2. Theis Recovery Curve Fitting Method

Recover data are observed after pumping test halt and the water level of the aquifer start recover. Residual drawdown, the difference between static water level and recovery water level after pumping test, data are more reliable than pumping test data because recovery occurs at a constant rate, whereas a constant discharge during pumping is often difficult to achieve in the field. It allows measurements of transmissivity of the aquifer to be calculated.

However, most of the wells are failed in drawdown data quality check; recovery data gives another chance to determine the transmissivity. Therefore, PW08, PW10, PW11, PW12, PW14, PW16, PW17, PW18 and PW19 of phase IIIA wells have an acceptable recovery data to determine the transmissivity. But PW03 and PW05 have no recovery data as well as PW01, PW02, PW04, PW06, PW07, PW09 and PW13 have unacceptable recovery data and they are dropped.

Therefore, once necessary correction taken for recovery data by Kozeny’s correction factor (Appendix-B) for those having an acceptable recovery data, evaluation are done. In some case of the graphs are fitted with straight line by more than ones. This is due to change in slope from one portion to the other.

Transmissivity values obtained by using Theis Recovery method are presented as below figures (Fig.4.11- Fig.4.19).

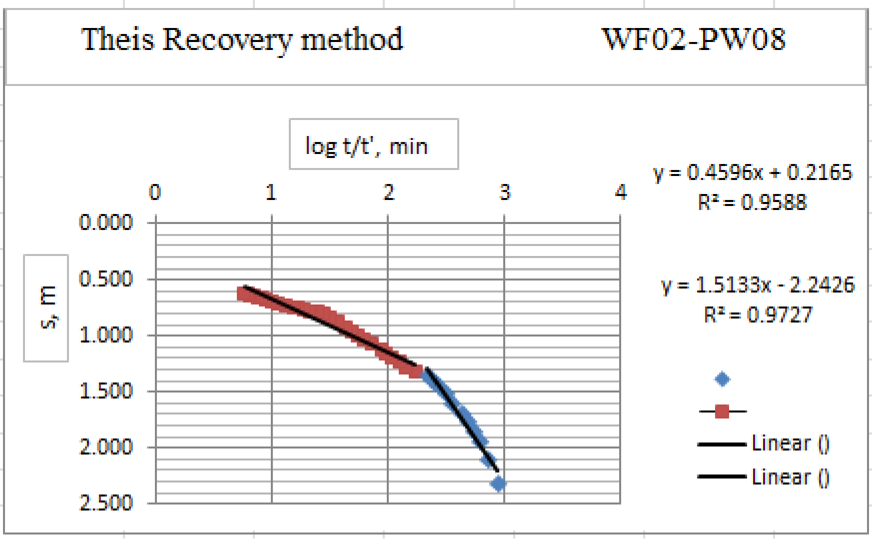

Figure 4-11 Theis Recovery of PW08

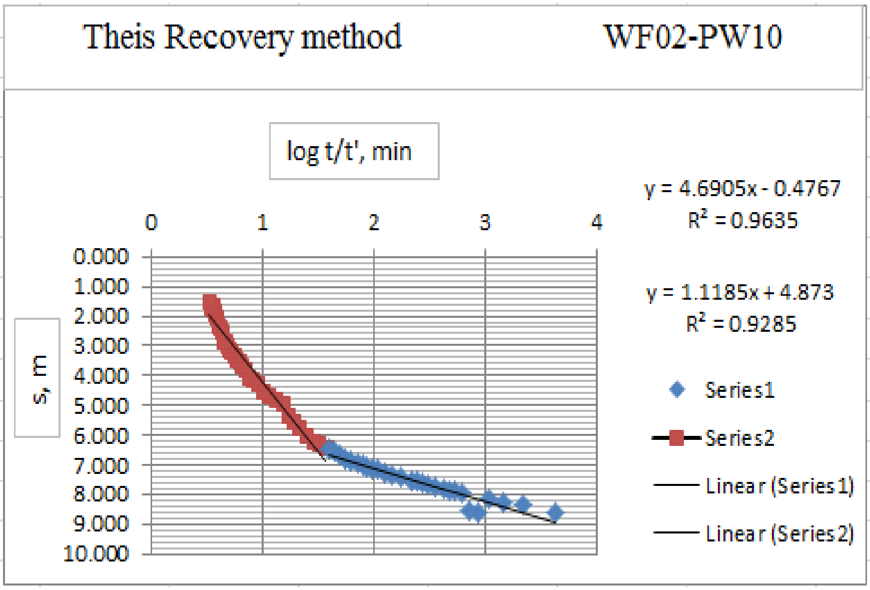

Figure 4-12 Theis Recovery of PW10

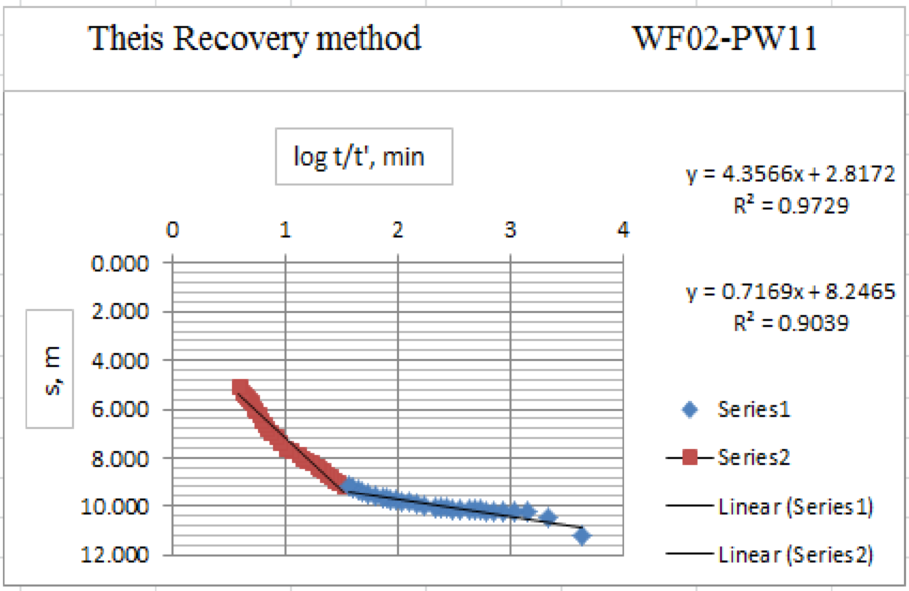

Figure 4-13 Theis Recovery of PW11

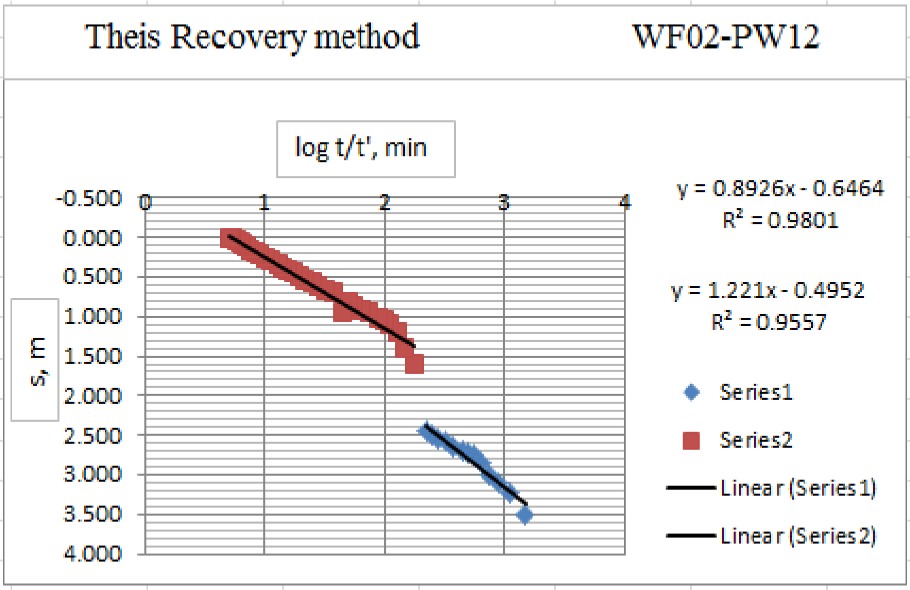

Figure 4-14 Theis Recovery of PW12

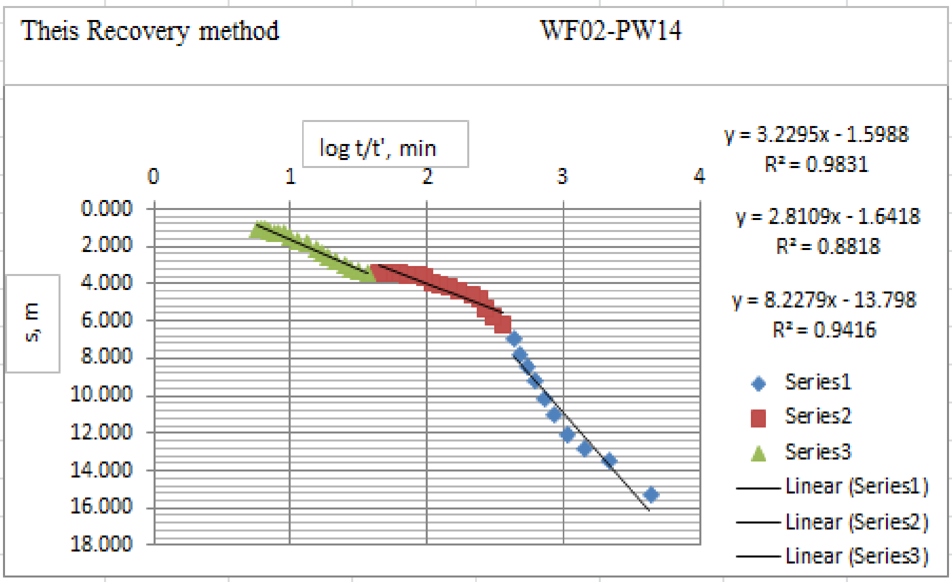

Figure 4-15 Theis Recovery of PW14

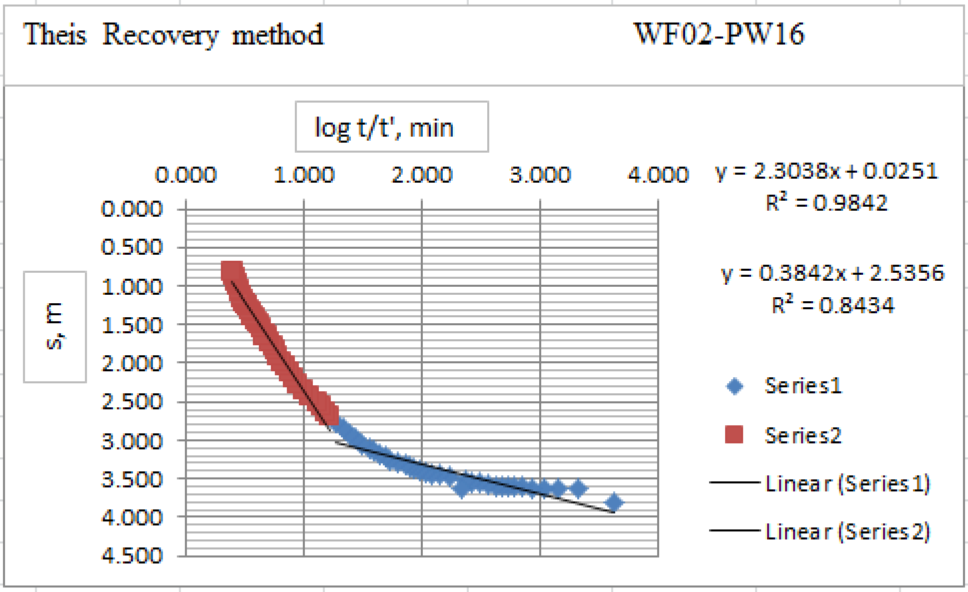

Figure 4-16 Theis Recovery of PW16

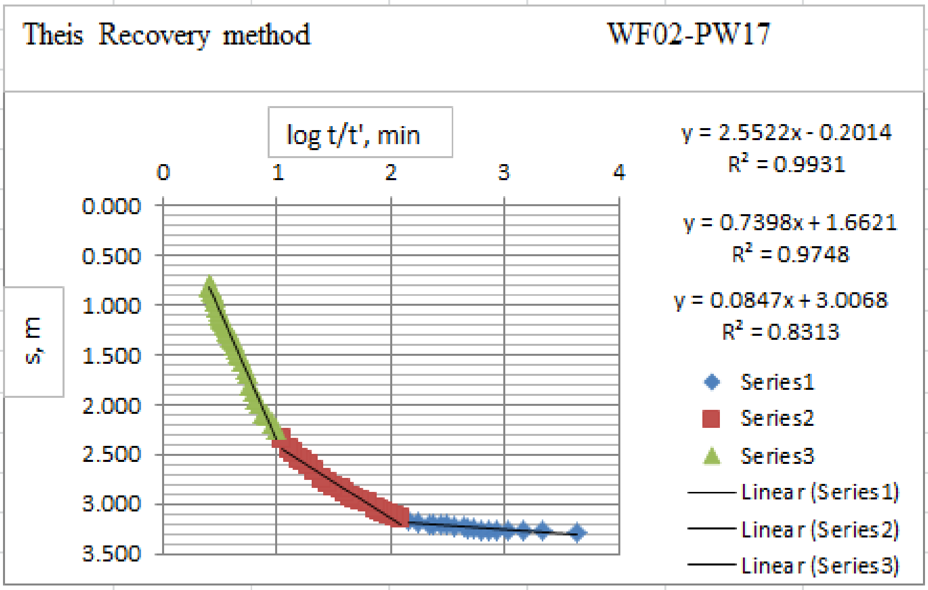

Figure 4-17 Theis Recovery of PW17

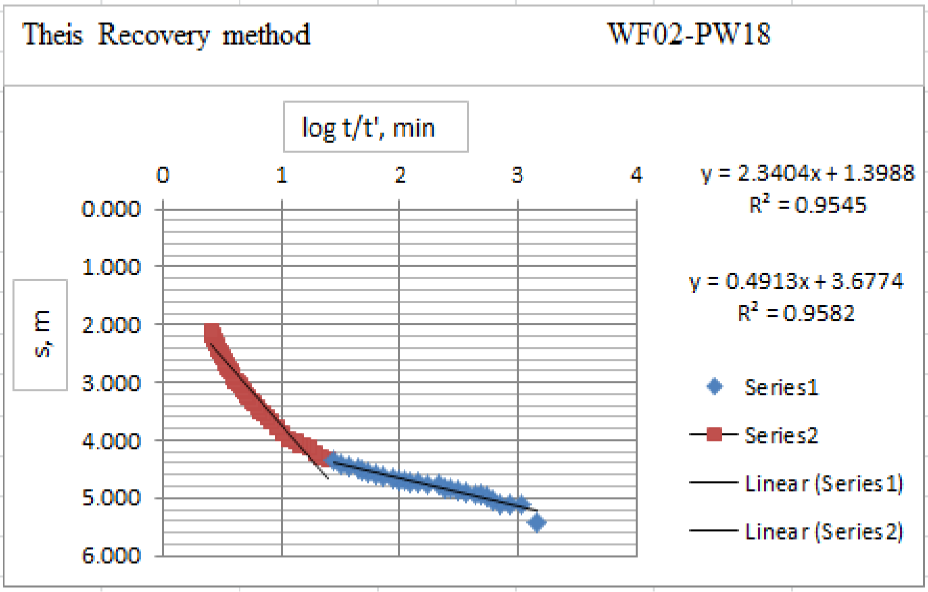

Figure 4-18 Theis Recovery of PW18

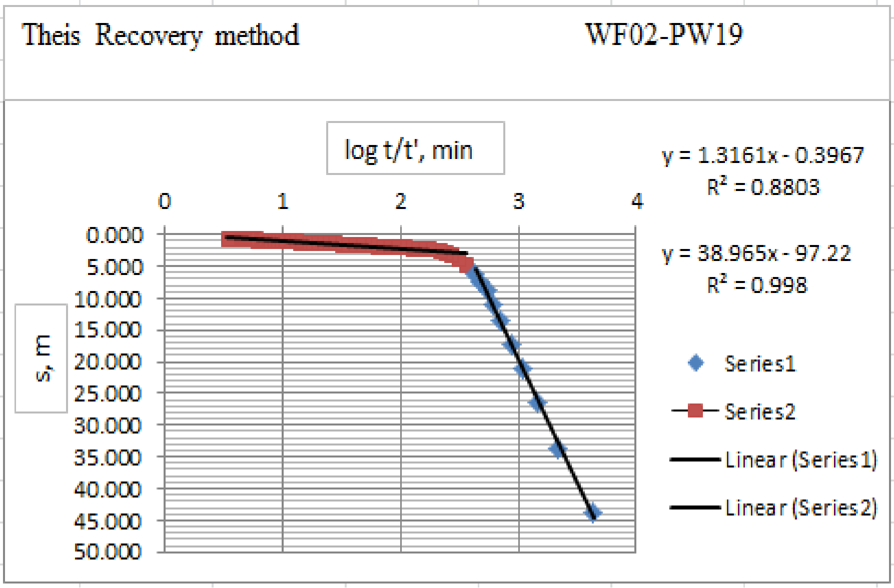

Figure 4-19 Theis Recovery of PW19

The determined transmissivity of the above wells are arranged as below table. The result show that the difference between data corrected and uncorrected (by WWDSE) used for evaluation of transmissivity. Then, for PW08, PW10, PW18, and PW19 over-estimate and PW11, PW12, PW14 and PW17 under-estimated from the corrected data transmissivity evaluated.

Table 4-4 Theis Recovery evaluated transmissivity

			Theis Recovery		WWDSE document
Well Index	Q, m^3/d	F	Δs'	Transmissivity,T	Transmissivity,T
PW08	4320	0.566	0.834	948.57	1250
PW10	3706.58	0.576	2.290	296.34	454
PW11	6048.04	0.523	1.767	626.69	104
PW12	3974.4	0.571	1.044	697.15	398
PW14	5184.03	0.602	4.211	225.41	194
PW16	7171.2	0.661	0.941	1395.82	-
PW17	6998.4	0.684	0.543	2361.02	321
PW18	6652.8	0.611	1.072	1136.12	1260
PW19	2274.05	0.683	7.161	58.15	167

As a final point, transmissivity values described the capacity of an aquifer to transmit water. This means high transmissivity is high ability of aquifer to transmit water and for low transmissivity vies versa. Accordingly, for corrected drawdown, lower transmissivity evaluated values indicate the aquifer is over-estimated and higher transmissivity evaluated values show that the aquifer is under-estimated. The transmissivity and storativity evaluated by analytical method: Cooper-Jacob and Theis Recovery method are taken through geometrical mean are summarized as below table.

Table 4-5 Summary of aquifer parameters evaluation

		For Corrected Drawdown			WWDSE document		Remark for T
Well Index	Method	Transmissivity	Storativity	Geo. Mean T	Transmissivity	Storativity	
PW-01	**Cooper-Jacob**	952.366	7.618E-18	952.366	886	3.71E-12	Under-estimted
	Theis Recovery	-	-				
PW05	**Cooper-Jacob**	3283.215	1.64E-05	3283.215	1600	91.7	Under-estimted
	Theis Recovery						
PW-08	**Cooper-Jacob**	-		948.570			
	Theis Recovery	948.57					
PW-09	**Cooper-Jacob**	918.447	3.25E-13	918.447	115	168	Under-estimted
	Theis Recovery						
PW-10	**Cooper-Jacob**			296.336			
	Theis Recovery	296.34					
PW-11	**Cooper-Jacob**			626.685			
	Theis Recovery	626.69					
PW-12	**Cooper-Jacob**	478.903	4.15E-07	577.811	398		Under-estimted
	Theis Recovery	697.15					
PW-13	**Cooper-Jacob**	4039.880	6.161E-27	4039.880	3840		Under-estimted
	Theis Recovery	-					
PW-14	**Cooper-Jacob**	-	-	225.415			
	Theis Recovery	225.41					
PW-16	**Cooper-Jacob**	559.426	7.857E-07	883.662	520		Under-estimted
	Theis Recovery	1395.82					
PW-17	**Cooper-Jacob**	518.884	3.61E-12	1106.841	321		Under-estimted
	Theis Recovery	2361.02					
PW-18	**Cooper-Jacob**	393.481	2.83E-15	668.611	663		Under-estimted
	Theis Recovery	1136.12					
PW-19	**Cooper-Jacob**	-	-	58.151			
	Theis Recovery	58.15					

4.2. Model Result Analysis

In this study finite difference technique MODFLOW is used to simulate the head of the water level to that of observed head of Akaki well fields. This simulation are helped reproduce the system then to apply different scenarios and observe the response of the aquifer for this change which able us to understand the aquifer system of the field and analysis the sensitivity.

The conceptualized model with delineating (using GIS) the Akaki well field area and identifying the boundary conditions shown in the figure below. It intend to maintain the mathematical representation by identifying the available major system, the possible boundaries and aquifer characteristic which results an input data base, cross section and simplified map for the modeling.

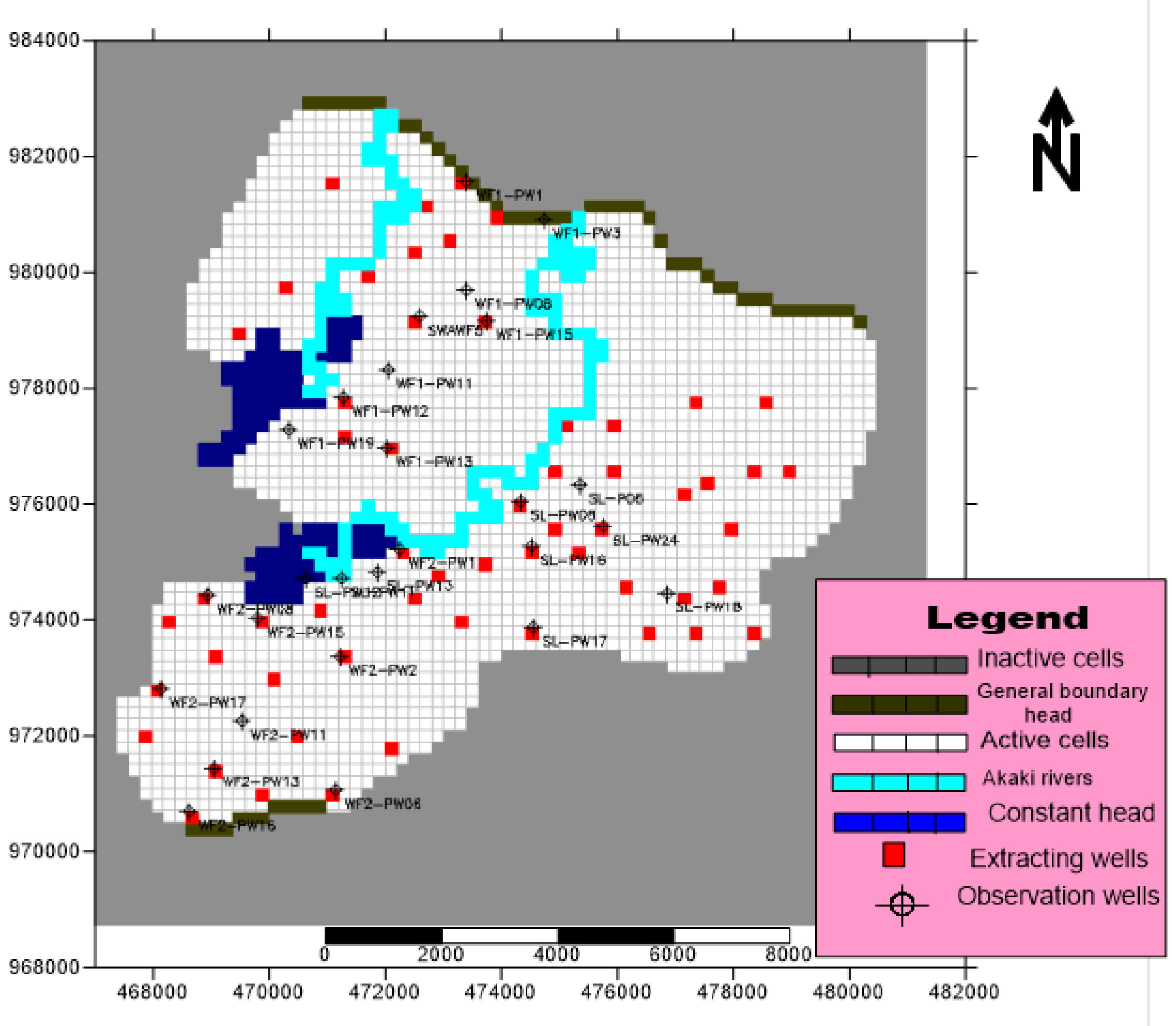

Figure 4-20 Akaki Well Fields Conceptualized Grids

4.2.1. Calibrated Parameters

Calibration is an essential activity in modelling to simulate the calculated values with the observed one by adjusting and refining the values of parameters reasonable. During trial-error calibration, parameter values are assigned to each node element and also by making zoned polygon in grid. Then for each adjusted parameter (i.e. hydraulic conductivity and recharge) values model runs and try to the simulated head and flux until match with measured data.

4.2.1.1. Aquifer Hydraulic Conductivity

One of the major parameters used for calibration action is the hydraulic conductivity of aquifer. According to Ayinalem Ali (1999), the hydraulic conductivity of the Akaki well field aquifers lies in the range of 7.4 to 674.8 m/day (Ebasa Oljira June, 2006). Depending on the nature of the borehole geophysical logging structure flow the aquifer classified for the calibration zone. Therefore, in this study at the time of calibration hydraulic conductivity are zoned with the value between 0.2952 m/day – 2.5149 m/day. Figure4-20 shows the hydraulic conductivity simulated zoned values.

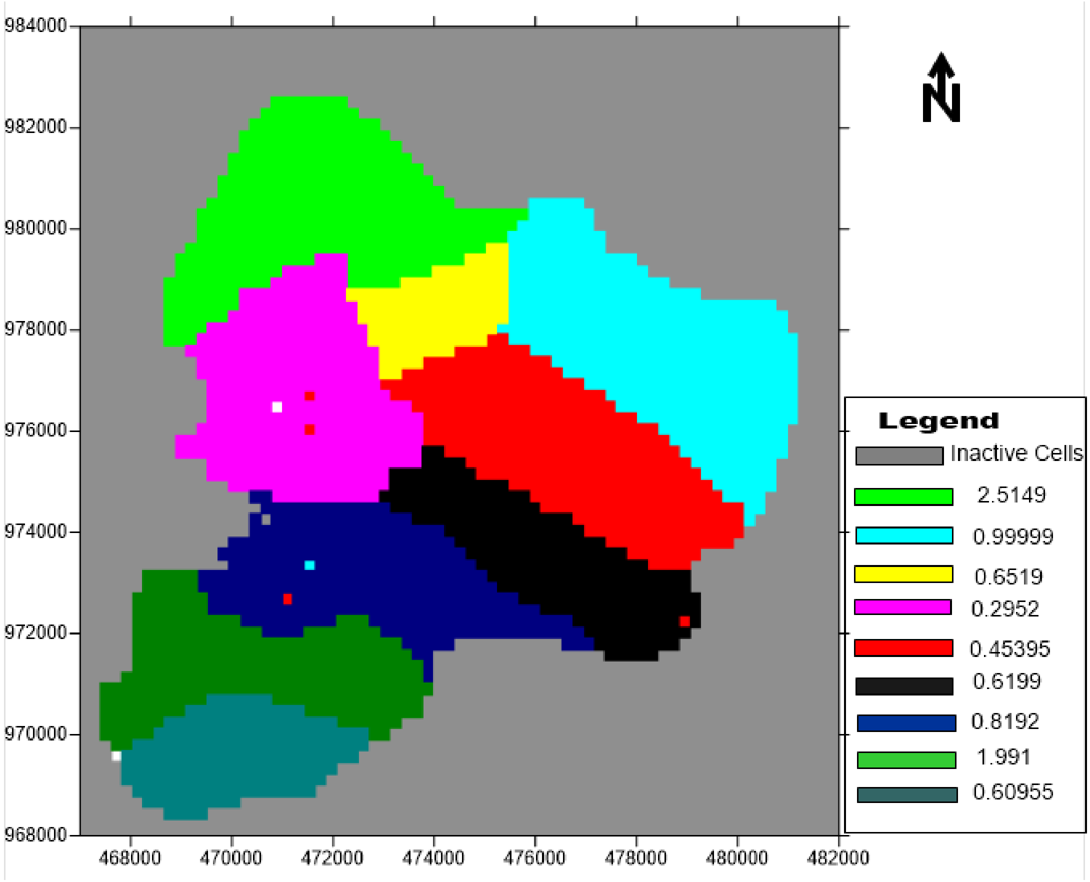

Figure 4-201 Simulated Hydraulic Conductivity Zone Map of Akaki Well Fields

4.2.1.2. Groundwater Recharge of Aquifer

The groundwater recharge varies in a wide range governed by the rainfall distribution, topography, land use and geology. The major recharge to the aquifer comes from precipitation and river channel losses. Main direct recharge is assumed to take place in all areas except where low permeable lacustrine soils exist. The recharge has been assigned in the model in a distributed manner by varying in a wide range from 0.00007 to 0.0005 m/day (Tenalem A. et.al, 2007).

Also, WWDSE document indicates that the average recharge of the Akaki river catchment is 74mm/year. Therefore by taking those materials as reference of the recharge estimated data, the calibration and the area is modelled with values between 0.0001 m/day to 0.000399m/day and it showed at below figure.

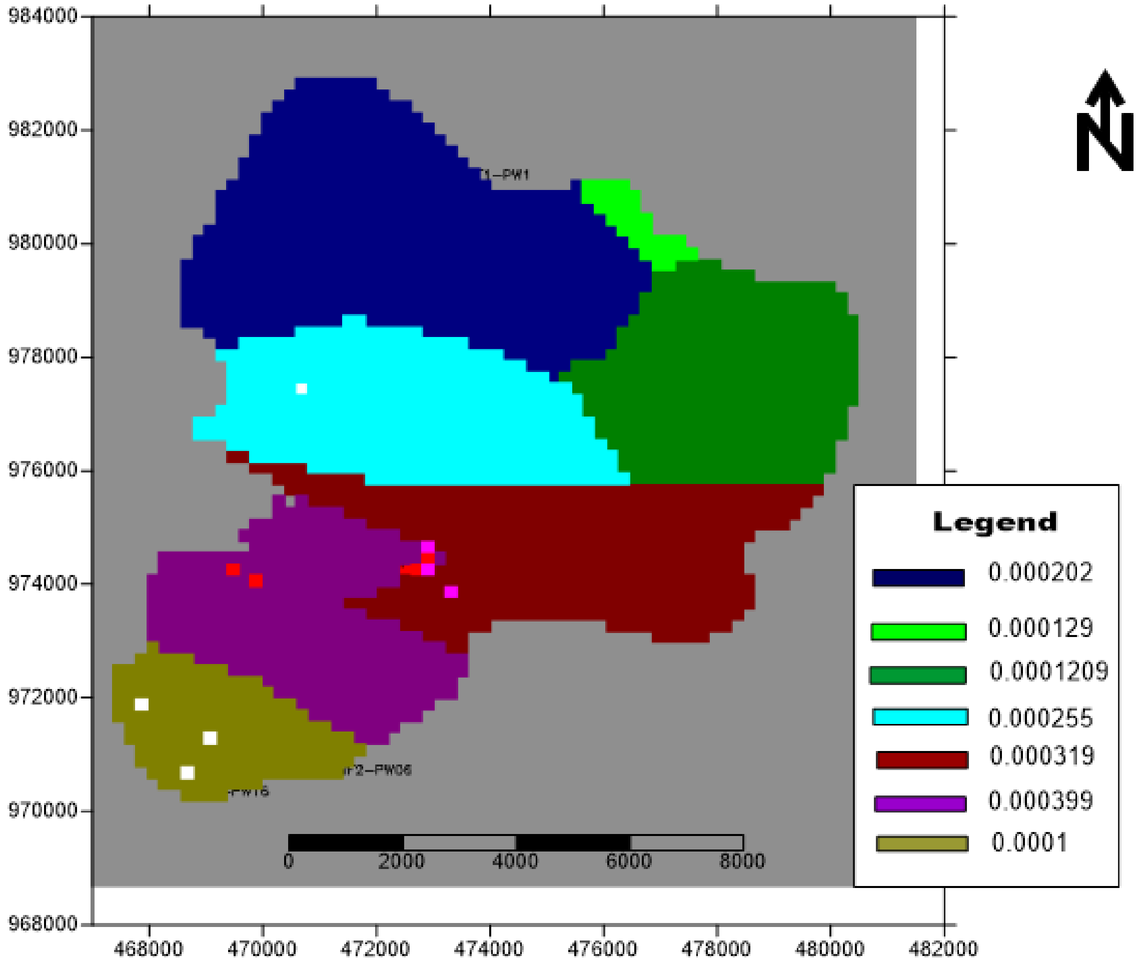

Figure 4-212 Simulated Recharge Zone Map of Akaki Well Fields

4.2.2. Calibration Result

The result of the calibration evaluated both quantitatively and qualitatively. Comparison of contour map and scatter plot between measured and simulated head are used to evaluate the qualitative calibration result. Again, the quantitative calibration result evaluated by measuring the error between simulated and the measure head.

4.2.2.1. Contour Map Matching

Generating contour of calibrated or simulated head and the observed head contour map and by simple observation and comparing, judgement can be taken depending on the similarity of pattern. It is a qualitative measure of the similarity between patterns of simulation and the observed head and giving some idea of the spatial distribution of error in the calibration. Figure4-22 and figure4-23 of below are model simulated and measure hydraulic head contour which is compared.

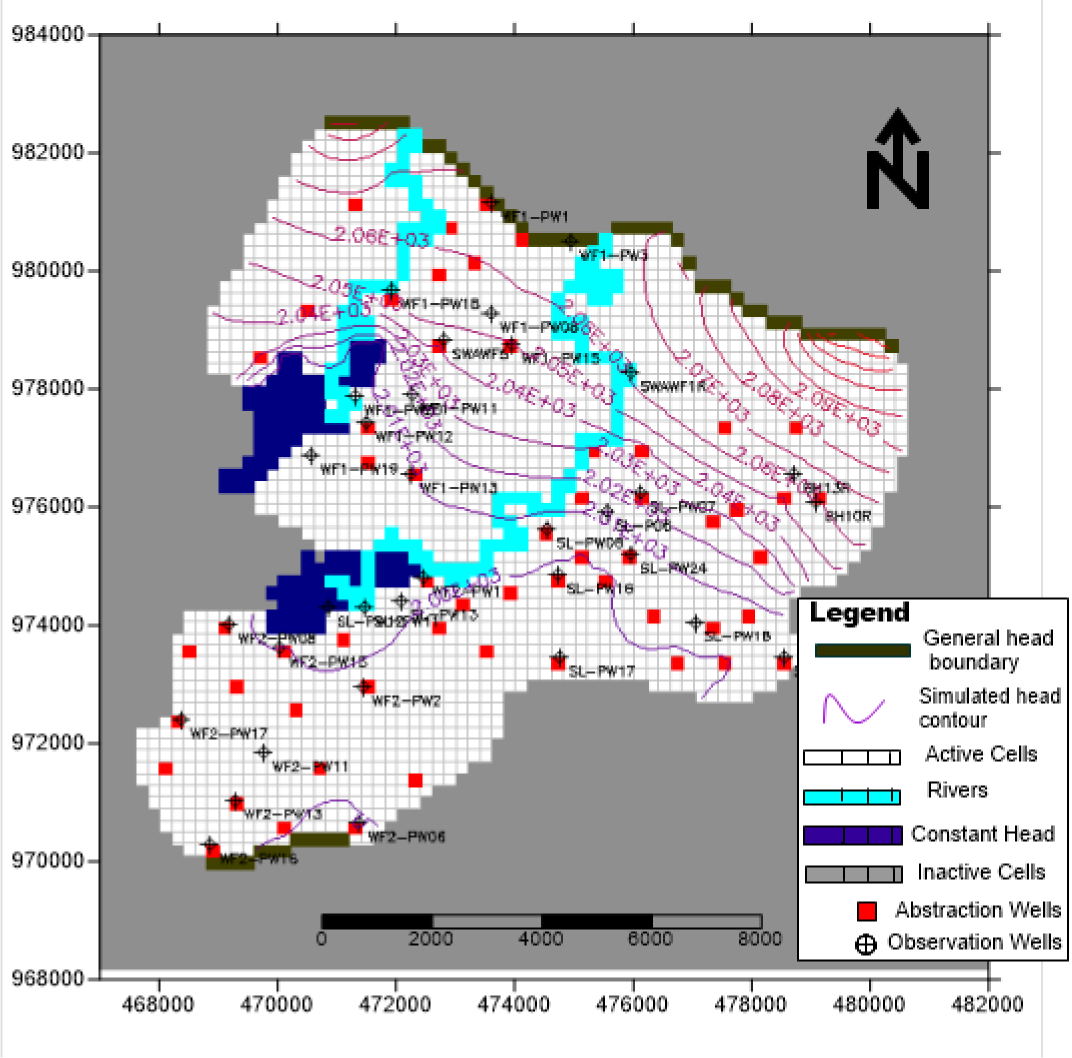

Figure 4-223 Contour Comparison of Model-simulated

After calibration is done, the MODFLOW tools icon for two-dimensional displayed the generated contour for the simulated hydraulic head of the conceptualized modelled. This prepared map (figure 4-22) used to comparisons. In other hand, hydraulic head contour for observed GWL by the WWDSE is generating by using GIS is presented as below figure.

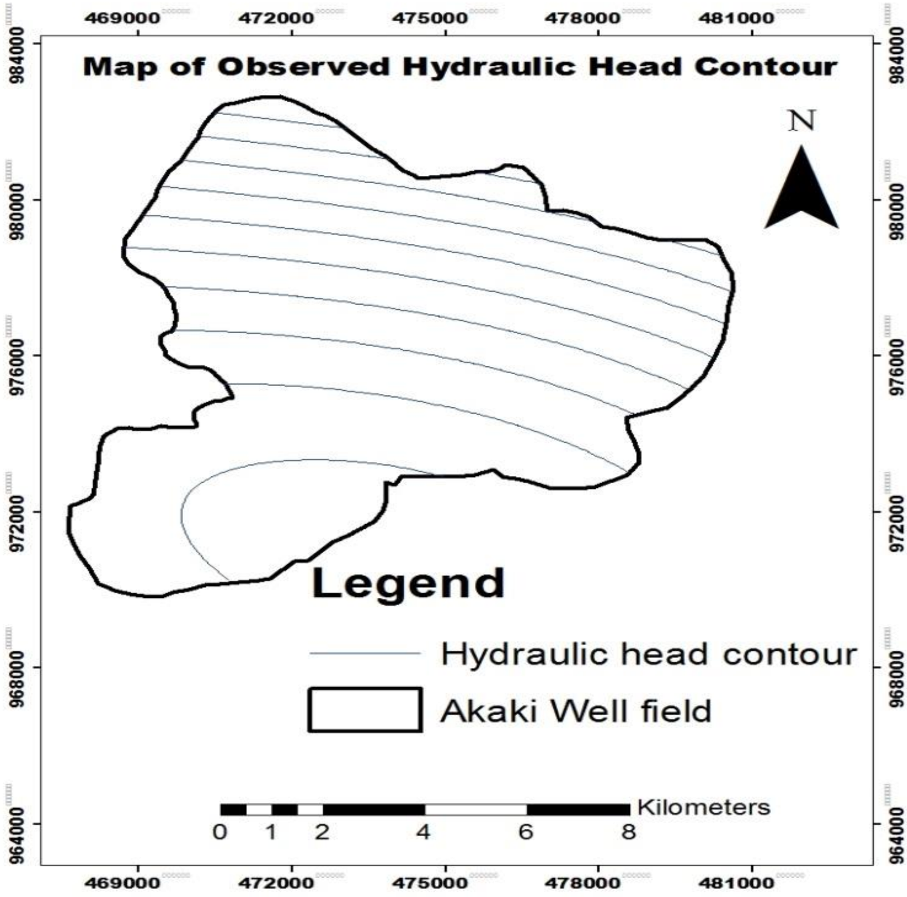

Figure 4-234 Observed Hydraulic Head Contour

It's very difficult to come with the overlay contour due to so many reasons: data quality, model limitation, complexity of aquifer (heterogeneity), etc. are affects their trend or path. Therefore, contour maps of field data include errors introduced by contouring it should not be used as the only proof of calibration. Therefore, other calibration evaluation techniques are taken to verification.

4.2.2.2. Scatter Plot of Observed and Simulated Head

Model generated scatter diagram showing the calibrated fit between the observed and simulated heads. It is examined whether the scatter points lay on the straight line or relatively closed to it or not. If the points are far away from the straight line it continued with additional parameter adjustment and try till it close to line.

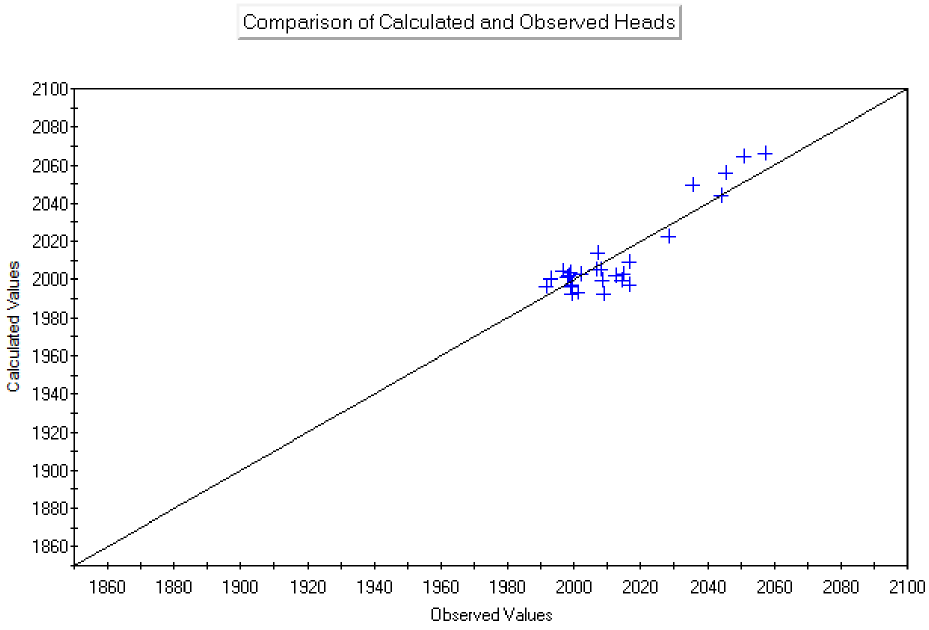

Figure 4-245 Comparison of Calculated and Observed head

Therefore, the above scatter plot has a correlation coefficient of 0.8548 on liner paper and it acceptable value.

4.2.2.3. Calibration Statistics

The three statistic calibration techniques measure a quantitative error between the measured and simulated head data. Those are mean error (ME), mean absolute error (MAE) and rout mean squared error (RMS). After many manual tries for calibration procedures and the head simulated, the statistics of average error between measured and calibrated head determined. ME, MAE and RMS become 1.71, 6.79 and 8.09 respectively.

4.2.3. Scenario Analysis

The calibrated flow model helps as a tool to evaluate the response of an aquifer system to probable future stresses. Sensitivity parameters analyzed after calibration are done by taking different scenarios or stresses applied to simulated value obtained. Those, scenarios are taken by changing the quantity of hydraulic conductivity and recharge rate that may resulted by climate change, from land use, pore configuration change and demand supply.

Therefore, in this study for hydraulic head and recharge the scenario applied for +25%, +50% increment and -25%, 50% decrement of the parameters values.

4.2.4. Sensitive Analysis Result

The purpose of a sensitive analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimate of aquifer parameters, stresses and boundary conditions (Mary P. Anderson et.al, 1992). This, means it clarify the respond of calibrated model for which model parameters it is sensitive or which one is have more effect on the model futures. It analysed by varying the parameters with different situations or values while keeping all other parameters constant and sensitivity is realised subjected on change in output which caused by change in input. Sensitivity of model for those particular parameters is ranked depending on the output or the model response due to change in input parameter.

The below graph described the sensitivity analysis for different scenarios of increment in +25%, +50% and decrement in -25%, -50% for recharge and hydraulic conductivity of aquifer. Calibrated head of aquifer is compared with the head of each scenario of parameters and the mean absolute error calculated. Plotting the scenario effect percent and mean absolute error for each variation of parameters abled to sensitive analysis taken. The result of the sensitivity analysis is reported as change in parameter affects the groundwater system of Akaki well fields aquifer on the spatial distribution of head.

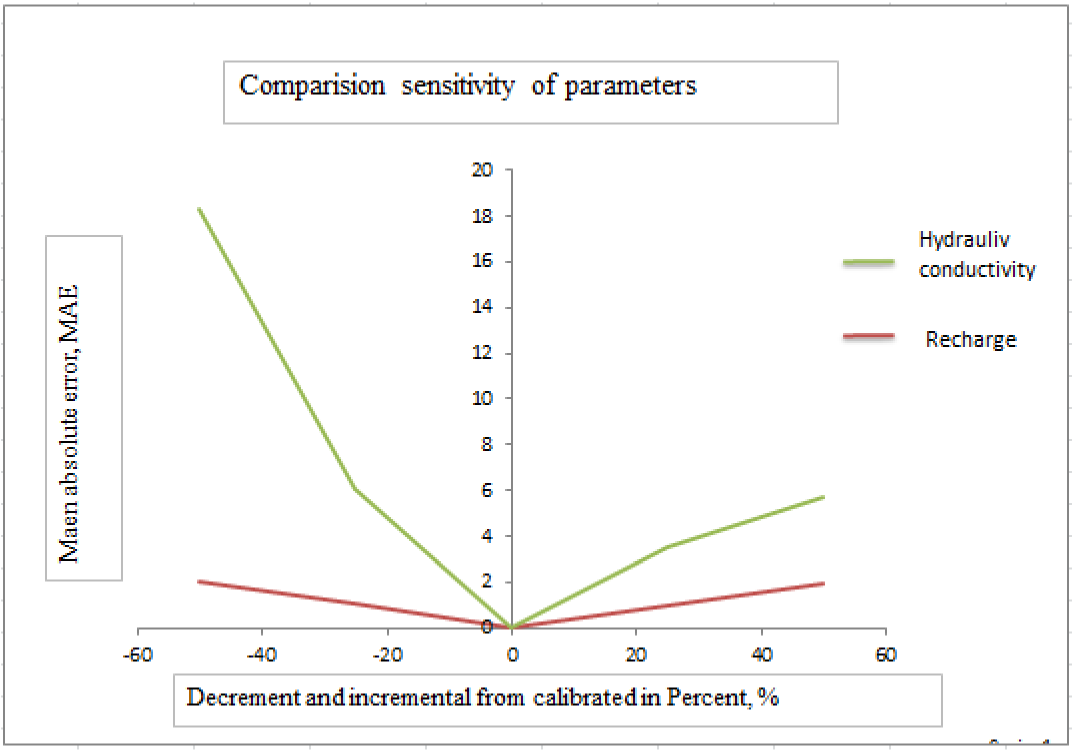

Figure 4-256 Model Sensitivity to Recharge, Hydraulic-conductivity and Abstraction

The objective of this paper is modeling Akaki groundwater flow to understand the aquifer system and its response for the different probable stresses and it’s analysed through a sensitivity analysis of its aquifer parameters. Therefore, from result obtained of different parameters change of scenario which presented in above figure4-25 helps to realized the sensitivity of Akaki aquifer system. Accordingly, the aquifer system of Akaki well fields is more sensitive for the probable change of the hydraulic conductivity special during the reduction of ability to permit water through it. Again, changes in the recharge on the area also have significant effect on the groundwater flow of field and sensitive parameters for the calibrated model.

Additionally, sensitivity of groundwater aquifer of Akaki well fields are analyzed through rivers (Tiliku and Tinishu Akaki), constant head (Abba Samuel reservoir) and general head boundary ignorance scenarios. Their sensitivity evaluated by water budget calculated of calibrated model and their result after ignorance applied. Water budget is described the inflow, out flow and the net flows of water through the model area boundaries. The summery of each discounting scenarios are tabulated as below and the model water budge run recorded of them are presented in appendix D.

Table 4-6 Summery of water budget run record of scenarios

		Net water budget	Change	% Incre. or Decr.	Remark
	Simulated	-4.23E-01			
Scenarios					
Rives ignorance		-7.13E-02	3.52E-01	83.1	Decreases
Constant head ignorance		-3.30E-01	9.28E-02	21.94	Increases
General head boundary ignorance		1.60E-01	2.63E-01	62.24	Increases

The change in water budget from the simulated of rivers, constant head and general head boundary condition ignorance are 0.352, 0.0928 and 0.263 respectively. It can interpret as the ignorance of the Akaki Rivers decreases the net water budget which indicate both rivers feeds the Akaki groundwater aquifer. The ignorance of the constant head (Abba Samuel reservoir) increases the net water budget which mean out flow from aquifer to the reservoir is greater than in flow from reservoir. Lastly, the ignorance of the general head boundary increases the net budget of the water which means there is out flow across the boundary.

Finally, to answer the question of ‘does Akaki well phase IIIA have effect on drawdown of the other phases?’ evaluation taken by considering the phase IIIA wells as no extraction/pumping and model the area. Considering the phase IIIA well field as observation well and pumping the other phase is done to measure the effects.

Table 4-7 Comprising of water head between no pumping and pumping

OBS Wells	**Simulated**	**No pumping**
WF2-PW1	2001.825	2006.1
WF2-PW2	1999.281	2010.758
WF2-PW06	1999.921	2017.587
WF2-PW08	1996.766	2011.729
WF2-PW11	1996.419	2014.671
WF2-PW13	1993.037	2017.616
WF2-PW15	1999.434	2010.832
WF2-PW16	1992.705	2019.771
WF2-PW17	1992.5	2014.326

Therefore, the result conveys that, table 4-7 the observed wells of hydraulic head are rise. This directs the aquifer is starting to recovered and recharge from Akaki Rivers.

On the other hand, the assigned observed wells for the phase II, phase IIIB and the existing well water head increased. This can interpret, as the Akaki well field phase IIIA stop water pumping the other well field phase start to rise, the cone of depression is extended up to the phase IIIA field area which implies there is the well interference between the phases.

Table 4-8 Head of simulated and the no pumping of phase IIIA Akaki well field

OBS Well Index	**Simulated**	**Observed**	**Discount phase IIIA**
SL-06	2013.736	2007	2017.195
SL-PW08	2004.983	2006.8	2009.147
SL-PW11	2000.748	1998	2003.328
SL-PW12	2004.486	1996.55	2004.789
SL-13	2002.015	1998.4	2005.268
SL-16	1996.753	1999	2002.588
SL-PW17	1997.368	1999.46	2004.19
SL-PW18	2002.663	2002.15	2006.654
SL-PW24	2003.179	1999	2007.286
WF1-PW08	2055.417	2045.521	2055.694
WF1-PW11	2022.517	2028.5	2023.106
WF1-PW12	2002.728	2014.9	2003.055
WF1-PW13	2008.96	2016.6	2010.291
WF1-PW15	2049.458	2035.7	2050.023
WF1-PW19	2004.746	2008.11	2004.842
SWAWF5	2043.56	2044.3	2043.93

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This investigation intensive on the Akaki well fields area which is part of Akaki river catchment, to evaluate and analysis the aquifer parameters and to simulate the groundwater flow for analyzing sensitive parameter. Pumping test are essential activity to determine in-situ properties of water bearing formation, aquifer properties (i.e. transmissivity, storativity, hydraulic conductivity), identification of boundary condition, the cone of influence of a pumping well in a ground water extraction system and overall hydro-geologic regime.

Ground-water analysing is difficult phenomenon where hydraulic testing is limited to an isolated well. These problems include well-known and quantifiable effects such as borehole head loss during pumping, as well as much more difficult to quantify factors such as lateral and vertical anisotropy. Many effects could only be quantified with reasonable accuracy using multiple observation wells or flow logs. Installing single well test and partial penetration well induced additional headache on the reliability of data observed which are used to determine the aquifer properties.

For evaluation analysis: data collection, quality check, system identification, data correction are done and finally transmissivity and storativity are determined by Cooper-Jacob and Theis Recovery methods. Among twenty wells of Akaki phase IIIA wells only eight, in case of Cooper-Jacob and seven, in case of Theis Recovery of them are passes for aquifer parameters evaluation. This shows in addition to the limited method adapted to data collection there is also uncontrolled data gathering and it’s collected by unskilled persons.

Efficiency clarified that the productivity of the abstracted well and transmissivity is illustrated the ability of the aquifer productivity or transmissivity. Therefore, from the result obtained all Akaki wells are performing below minimum standard adequate efficiency, 65%. Another method for recognizing an inefficient well is to note it is initial recovery rate when pumping is stopped. Where the well loss is large, this drawdown component recovers rapidly by drainage into the well from the surrounding aquifer. A rough rule of thumb for this purpose is if a pump is shut off after one hour of pumping and 90 percent or more of the drawdown is recovered after five minutes, it can be concluded that the well is unacceptable inefficient. Again, from evaluated result transmissivity of aquifer is underestimated and overestimated when it compared with WWDSE report.

Akaki well field groundwater flow are simulated using the MODFLOW model. This is by constructing the study area conceptualizing, numerical and calibrating the regional steady-state. In this study finite difference technique used to model hydraulic water head that occurs when water is pumped from aquifers with different scenarios and simulated to data observed by the WWDSE. Comparisons are made of the drawdown of the water table when well pumped and not pumped and it is effects on sustainability and it is shown that reasonable predictions can be made of field behaviour.

The area is conceptualized in one layer and unconfined aquifer which is display on the 200m×200m of grid cells size with a total volume of 4.930121E+10 active cells. The Akaki well field area boundary of active cell represented by one and inactive cells are which is out of boundary are assigned in zero. Also, Abba Samuel reservoir is taken as a constant head and it assigned by negative one value and both Tinishu and Tiliku Akaki rivers and 77 wells are considered in river and well packages of model. Bottom layer of aquifer and initial and prescribed hydraulic head are introduced by subtracting the aquifer thickness (300m-600m) and the static water level (18m to 80m) from top elevation of surface area respectively.

Calibration, iteratively running the model and comparing the output to observed site condition by adjusting inputs within specified range, was continued until the computed heads and boundary flows matched field conditions. Then, the model calibration evaluated through contour among simulated and observed hydraulic head and scatter plot for qualitative assessment. The statistics error difference between calibrated and measure head evaluated through ME=1.71, MAE=6.79 and RMS=8.09 for quantitate evaluation are resulted.

Sensitivity analysis performed by changing the calibrated parameters to identify the most important parameters for conceptual model development. Therefore, to recognise and assess the response of aquifers with respect to various scenarios of groundwater condition are applied for -50%, -25%, +25% and +50% decrement and increment in recharge and hydraulic conductivity. Also, model is run to assess the effects in the state of rivers, constant head and general head boundary ignored on the aquifer and the sensitivity is identified. Finally, in the state of no pumping for phase IIIA scenario is taken to determine the effects on the further phases and check the existence of well interference.

It determined that the conceptualized model area is more sensitive for the reduction of hydraulic conductivity. Also, recharge parameter change have a significant effect on the system. Concerning on the water budget of each scenario for ignorance of water packages, the simulated head of area is more sensitive for Akaki river ignorance and it reduced by 83.1%. Finally, Akaki well phase IIIA has effects on the other phase wells of drawdown and there is well interferences between the well fields.

The result obtained can concluded from this study of evaluation and modelling of Akaki well field under different scenarios discover that the inefficient well pumping (above safe yield) and change in parameters results considerable groundwater level decline. Efficiency and pumping rate have direct and strong bond relationship to each other to clarify the productivity and certainty of wells. So, it can say all, Akaki well fields operated with poor efficiency, pump beyond the safe yields and with the existence of well interference (which increased the drawdown of the water level). Therefore, this will cause to the drying of wells and ground water depletion where ground water extracted at rate faster than it can recharge (hydrological imbalance) and sustainability of the resource is become under risk.

5.2. Recommendation

Generally the result of this study helps to identifies the cause of well dry, evaluate the correct aquifer parameters, analysis sensitivity, assess impacts and forecast the future changes in ground water caused by pumping rate, reduction in recharge and etc. and interpreted in a compatible manner with groundwater level depletion and forward the recommendation.

Finally, the followings are recommended:

- → Farther assessment and budget of groundwater vulnerability based on relevant monitoring (i.e. observation well) data have to take to observe the periodical situations and evaluate accurate aquifer properties.
- → The standard well efficiency is mandatory to groundwater management and for operation cost of pumping operated. So, the wells have to operate by the standard acceptable efficiency of wells law to improve the productivity and certainty of the demand supply also the resources.
- → Safe yield (discharge with adequate efficiency of well) have a great role on the sustainability of the Groundwater resource. So, it must be work on the reliable data collected, determine accurate values and good care on management.
- → Superintend the groundwater potential resource periodically to recognize and control the impacts cause by changes.
- → The Akaki river catchment have abundant groundwater potential and to use this properly and to supply the growth demand it have drilled with sufficient deep of well across the aquifer thickness to rise the transmissivity.
- → As far as urbanization of city expanded, climate change and the resource is under risk therefore protection and additional treatment is required. The area is sensitive for the recharge increment so, spread the artificial recharge and protect the existing recharging (i.e.Tinishu and Tiliku Akaki, Abba Samuel reservoir those feed the Akaki well fields) mechanisms have plan to improve the sustainability of resource.
- → The success of a groundwater study not limited and relies only on the technical activities, but also on the effectiveness and efficiency of project management. So, management of groundwater must be strength up to controlling the privacy and individual organization shallow and deep well drilling without assessment and measurement taking and legal frame work must be established.

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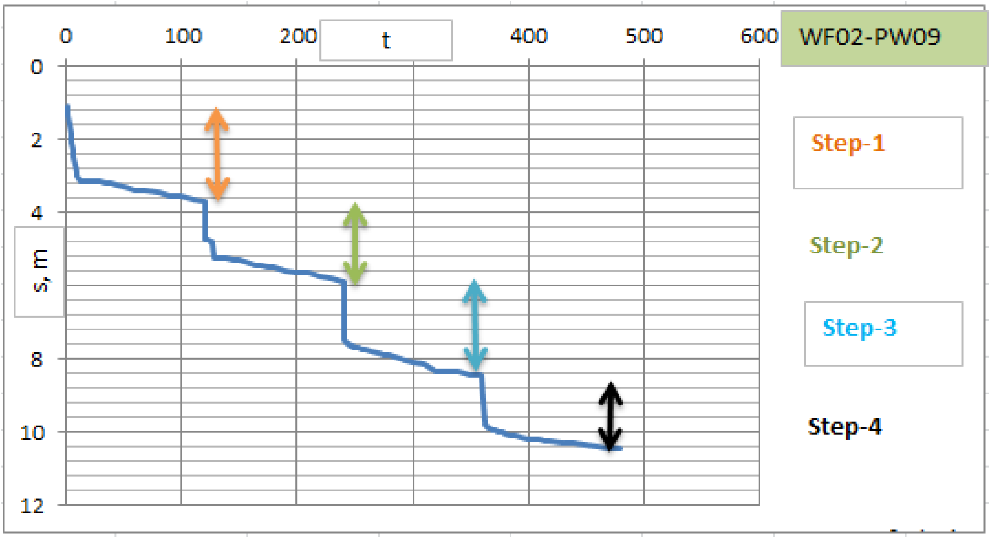
Appendix- A

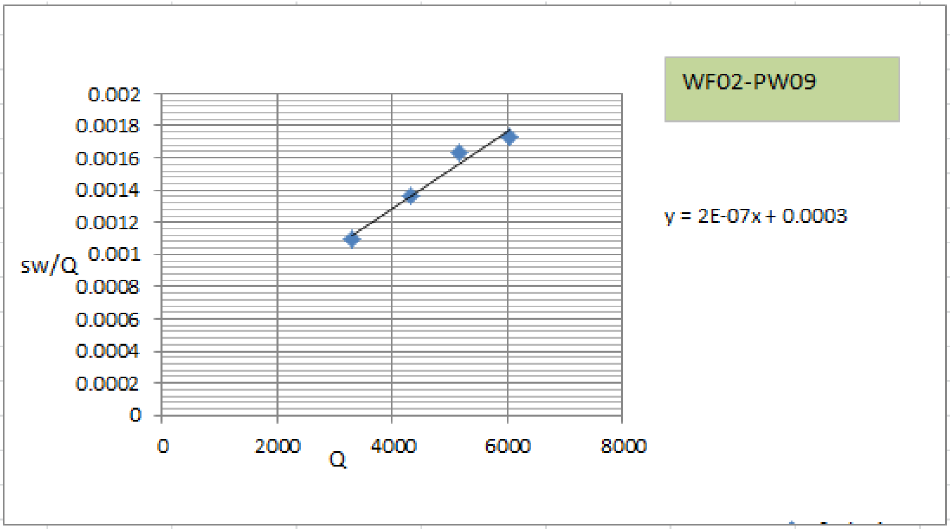
Data Analysis for Aquifer Test

This appendix presents details of the analysis method adapted to the eight constant-rate pumping test (described in efficiency and productivity of well section) performed in the Akaki well fields. The appendix discusses the calculation necessary to account for partial penetration effects using step-drawdown test then, discusses the efficiency for each wells. Also for WF02-PW05 the Kozeny's reduction factor determined is tabulated.

Pumping well 09



Appendix A-1 Step-drawdown curve of WF02-PW01

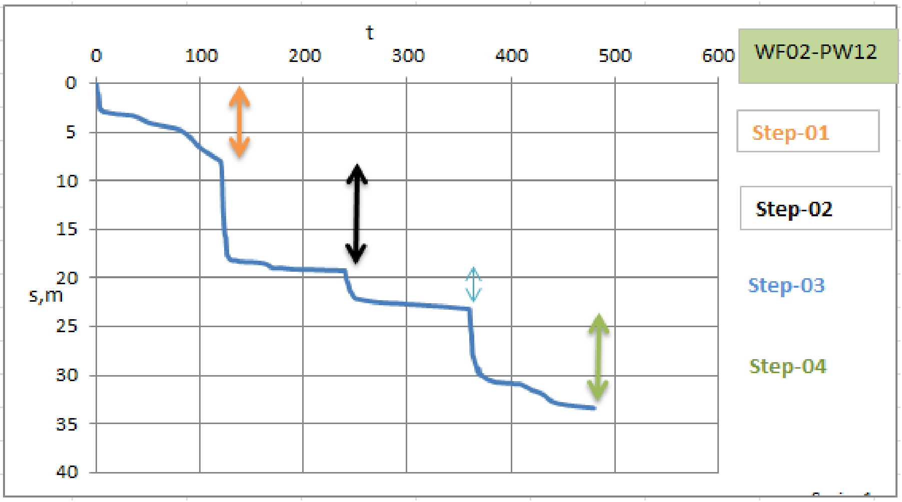


Appendix A-2 sw/Q vs. Q plots for WF02-PW01

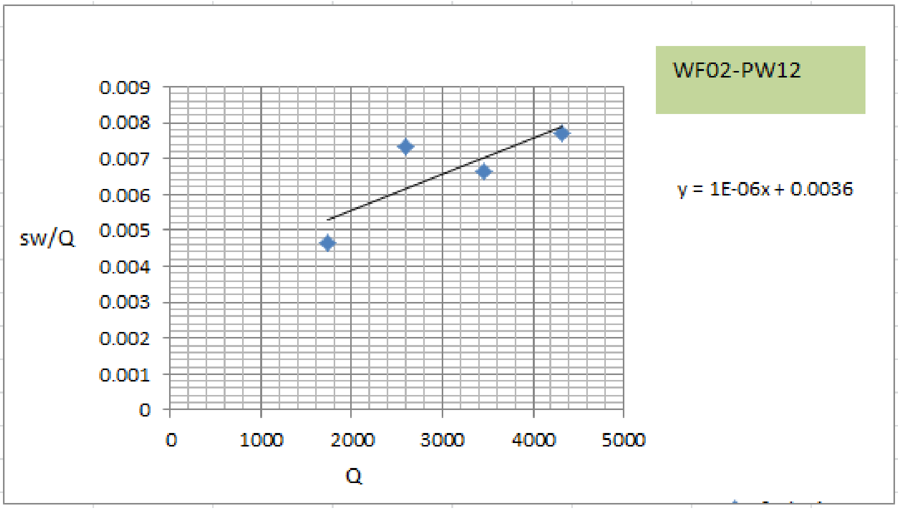
Appendix A-1 Efficiency and productivity of WF02-PW01

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW09		0.0003	3	
Discharge, Q (L/s)	step 1	38.28		23.21%
	step 2	50.13		18.75%
	step 3	59.65		16.25%
	step 4	70		14.19%

Pumping well 12



Appendix A-3 Step-drawdown curve of WF02-PW12

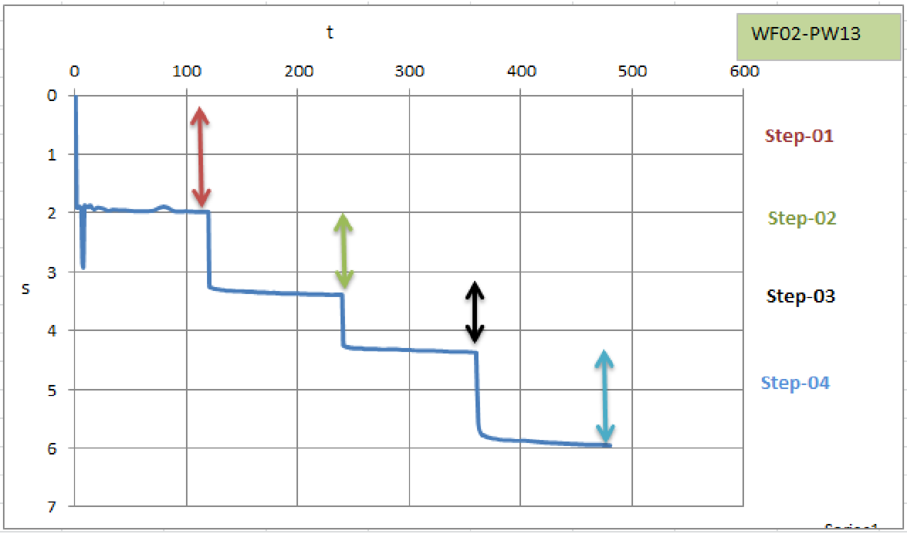


Appendix A-4 sw/Q vs. Q plots for WF02-PW12

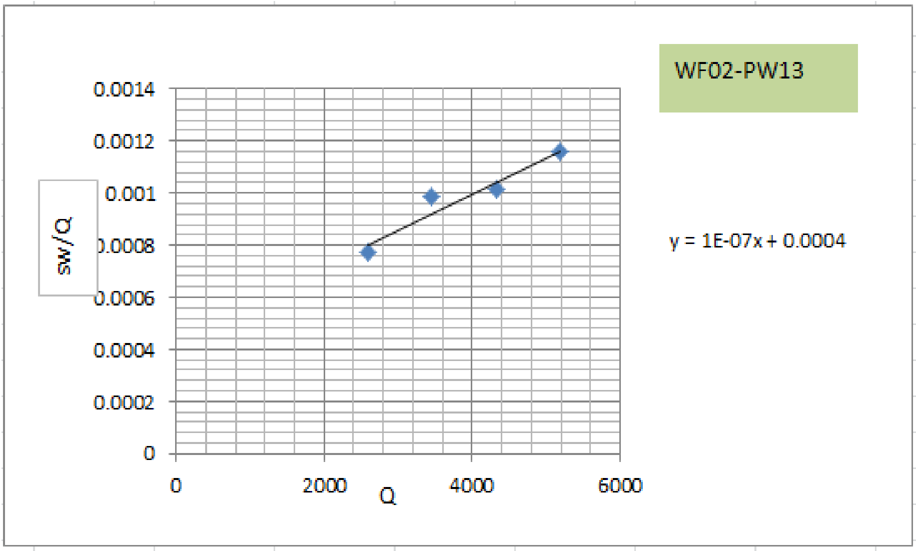
Appendix A-2 Efficiency and productivity of WF02-PW12

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW12		0.0036	10	
Discharge,Q(L/s)	step 1	20		67.57%
	step 2	30		58.14%
	step 3	40		51.02%
	step 4	50		45.45%

Pumping well 13



Appendix A-5 Step-drawdown curve of WF02-PW13

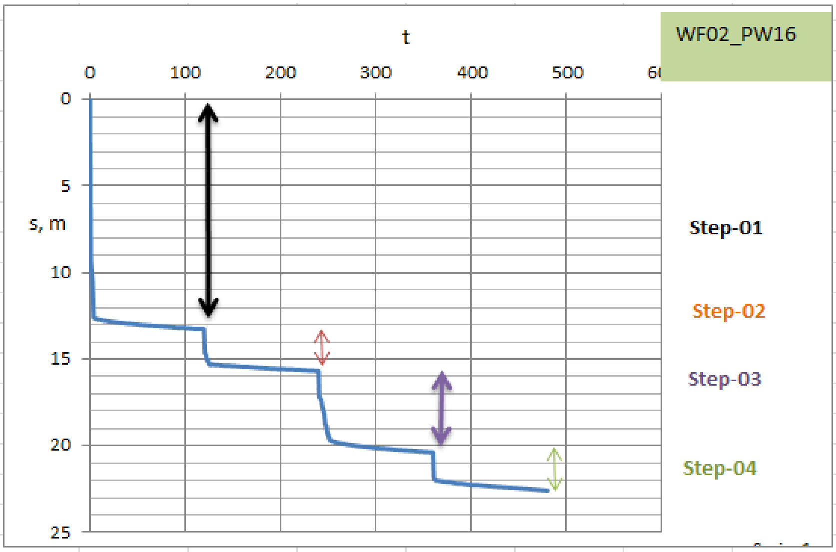


Appendix A-6 sw/Q vs. Q plots for WF02-PW12

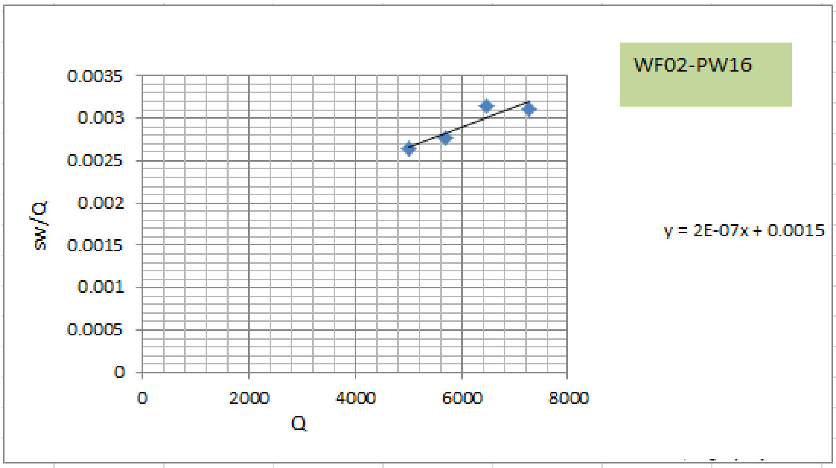
Appendix A-3 Efficiency and productivity of WF02-PW13

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW13		0.0004	1	
Discharge, Q(L/s)	step 1	30		60.68%
	step 2	40		53.65%
	step 3	50		48.08%
	step 4	60		43.55%

Pumping well 16



Appendix A-7 Step-drawdown curve of WF02-PW16

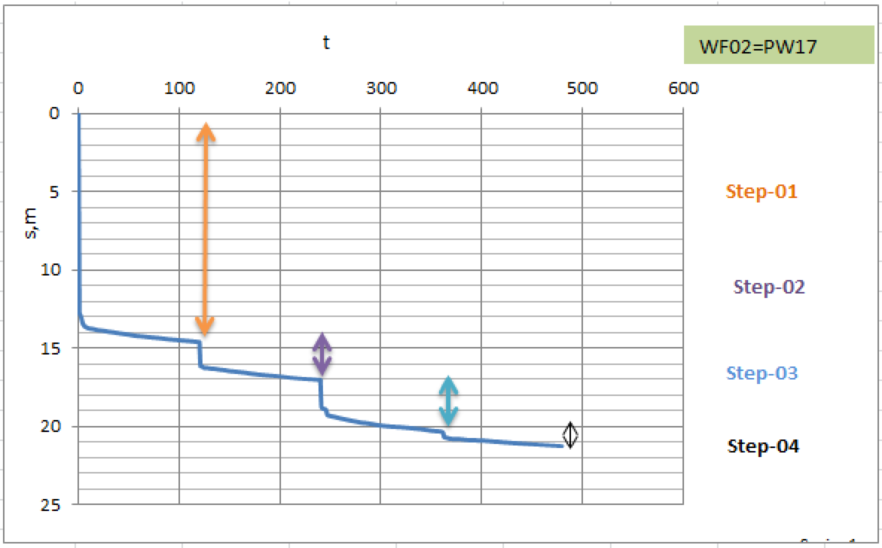


Appendix A-8 sw/Q vs. Q plots for WF02-PW16

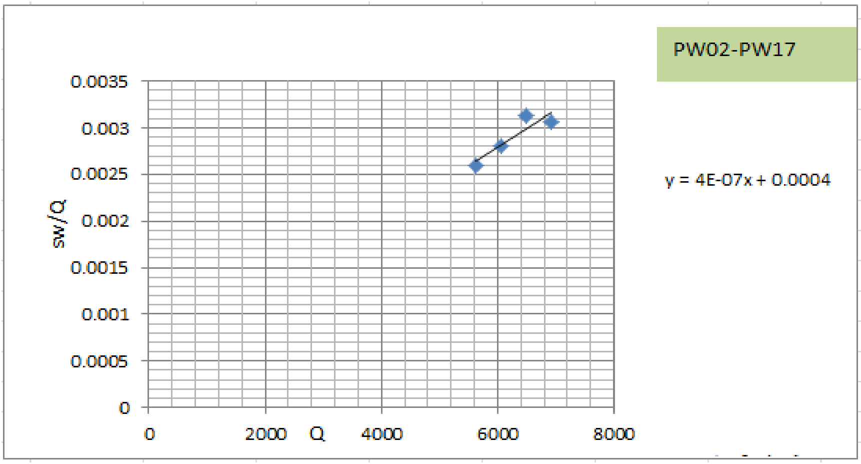
Appendix A-4 Efficiency and productivity of WF02-PW16

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW16		0.0015	2	
Discharge, Q(L/s)	step 1	58		59.95%
	step 2	66		56.81%
	step 3	74.9		53.68%
	step 4	84.3		50.73%

Pumping well 17



Appendix A-9 Step-drawdown curve of WF02-PW17

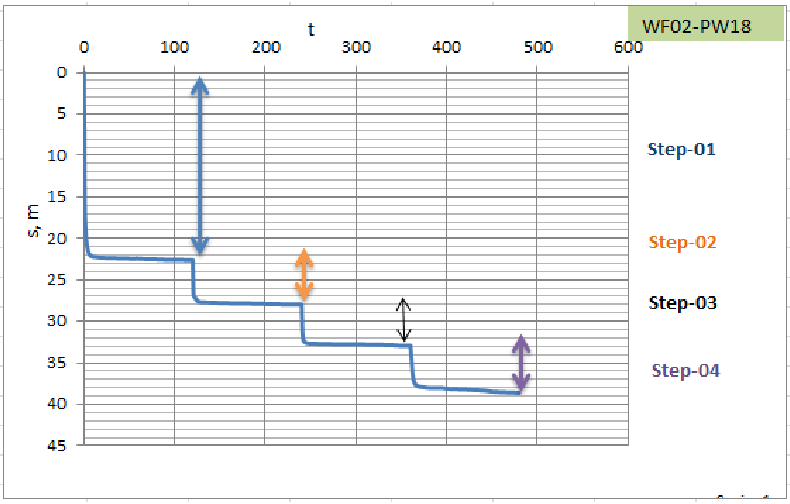


Appendix A-10 sw/Q vs. Q plots for WF02-PW17

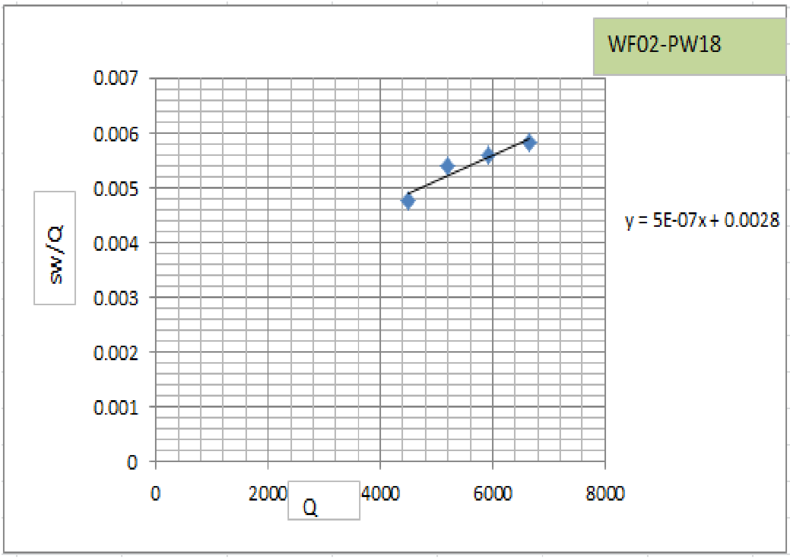
Appendix A-5 Efficiency and productivity of WF02-PW17

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW17		0.0004	4	
Discharge, Q(L/s)	step 1	65		15.11%
	step 2	70		14.19%
	step 3	75		13.37%
	step 4	80		12.64%

Pumping well 18



Appendix A-11 Step-drawdown curve of WF02-PW18



Appendix A-12 sw/Q vs. Q plots for WF02-PW18

Appendix A-6 Efficiency and productivity of WF02-PW18

Pumping well		B	C 10^-7	Ew=[BQ/BQ+CQ^2]*100%
PW18		0.0028	5	
Discharge, Q(L/s)	step 1	52		55.48%
	step 2	60		51.92%
	step 3	68.5		48.62%
	step 4	77		45.70%

Appendix- B

Kozeny’s Correction Factor for Recovery Data Correction

After pumping test is end the water level in the well start to rise. The difference between the static water level and the measured rise water level is called residual drawdown, s’. Therefore, this recorded data are allowed to calculate the aquifer transmissivity.

The analysis of partial penetrating well to aquifer is provides by Kozeny (1933) which is approximate reduction factor for partial penetrating well. All below table illustrated the calculation of reduction factor of Kozeny to correct the recovery data of the wells.

WF02-PW08

Appendix B-1 Kozeny's correction factor for recovery data correction of WF02-PW08

From	To	Length, B	Blind length	Screen length, L	r	2l/r	L/B	[7COS(πL/2B)]	√(r/2L)		F	Arthimethi mean
0+1	130.9	131.9	130.9									0.702
130.9	148.45	17.55		17.55	0.3556	98.7064	0.11822	6.879769672	0.10065	1.69247	0.20009	
148.45	154.3	5.85	5.85									
154.3	166	11.7		11.7	0.3556	65.8043	0.66667	3.503217823	0.12327	1.43186	0.95457	
166	171.85	5.85	5.85									
171.85	189.4	17.55		17.55	0.3556	98.7064	0.75	2.682646026	0.10065	1.27002	0.95251	
189.4	195.25	5.85	5.85									
195.25	201	5.75	5.75									
201	206.75	5.75		5.75	0.2032	56.5945	0.5	4.951717884	0.13293	1.65822	0.82911	0.579
206.75	218.25	11.5	11.5									
218.25	224	5.75		5.75	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	
224	241.25	17.25	17.25									
241.25	252.75	11.5		11.5	0.2032	113.189	0.4	5.664429267	0.09399	1.53242	0.61297	
252.75	270	17.25	17.25									
270	275.75	5.75		5.75	0.2032	56.5945	0.25	6.467689896	0.13293	1.85973	0.46493	
275.75	281.5	5.75	5.75									
281.5	287.25	5.75		5.75	0.2032	56.5945	0.5	4.951717884	0.13293	1.65822	0.82911	
287.25	298.75	11.5	11.5									
298.75	304.5	5.75		5.75	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	
304.5	316	11.5	11.5									
316	321.75	5.75		5.75	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	
321.75	333.25	11.5	11.5									
333.25	339	5.75		5.75	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	
339	356.25	17.25	17.25									
356.25	362	5.75		5.75	0.2032	56.5945	0.25	6.467689896	0.13293	1.85973	0.46493	
362	379.25	17.25	17.25									
379.25	385	5.75		5.75	0.2032	56.5945	0.25	6.467689896	0.13293	1.85973	0.46493	
385	413.75	28.75	28.75									
413.75	425.25	11.5		11.5	0.2032	113.189	0.28571	6.307472939	0.09399	1.59286	0.4551	
425.25	448.25	23	23									
448.25	454	5.75		5.75	0.2032	56.5945	0.2	6.65774004	0.13293	1.88499	0.377	
454	465.5	11.5	11.5									
465.5	471.25	5.75		5.75	0.2032	56.5945	0.3343	6.063106661	0.13293	1.80595	0.60373	
471.25	482.75	11.5	11.5									
482.75	488.5	5.75		5.75	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	
488.5	5002	11.5	11.5							**Geo. Mean**		0.566

WF02-PW10

Appendix B-2 Kozeny's correction factor for recovery data correction of WF02-PW10

Depth interval in (m)		Length (m)		Diameter								
From	To	Blind	Screen	of casing	r	2l/r	L/B	[7COS(πL/2B)]	√(r/2L)		F	Arthimethi mean
0	151.6	152.6		14"								0.635036951
151.6	163.73		12	14"	0.3556	67.4916	0.07329	6.953709265	0.12172	1.8464	0.1353	
163.73	175.77	12.04		14"	0.3556							
175.73	187.74		12	14"	0.3556	67.4916	0.49917	4.958176228	0.12172	1.6035	0.8004	
187.74	199.73	12		14"	0.3556							
199.73	211.73		12	14"	0.3556	67.4916	0.50083	4.945229486	0.12172	1.602	0.8023	
211.73	223.73	12		14"	0.3556							
223.73	235.7		12	14"	0.3556	67.4916	0.50063	4.946854413	0.12172	1.6021	0.8021	
235.7	241.7	6		14"	0.3556							
241.7	252.85	12		8"	0.2032							
252.85	264.88		12	8"	0.2032	118.11	0.41124	5.590971405	0.09201	1.5145	0.6228	0.615143522
264.88	275.92	12		8"	0.2032							
275.92	287.45		12	8"	0.2032	118.11	0.53168	4.699611582	0.09201	1.4324	0.7616	
287.45	304.75	18		8"	0.2032							
304.75	316.29		12	8"	0.2032	118.11	0.41609	5.558749363	0.09201	1.5115	0.6289	
316.29	333.59	18		8"	0.2032							
333.59	345.11		12	8"	0.2032	118.11	0.41638	5.556820092	0.09201	1.5113	0.6293	
345.11	362.42	18		8"	0.2032							
362.42	373.98		12	8"	0.2032	118.11	0.41566	5.561636121	0.09201	1.5118	0.6284	
373.98	391.23	18		8"	0.2032							
391.23	402.75		12	8"	0.2032	118.11	0.4171	5.551980164	0.09201	1.5109	0.6302	
402.75	425.79	24		8"	0.2032							
425.79	431.55		6	8"	0.2032	59.0551	0.20833	6.628884106	0.13013	1.8626	0.388	
431.55	454.55	24		8"	0.2032							
454.55	465.94		12	8"	0.2032	118.11	0.33333	6.063106661	0.09201	1.5579	0.5193	
465.94	477.44	12		8"	0.2032							
477.44	488.97		12	8"	0.2032	118.11	0.5	4.951717884	0.09201	1.4556	0.7278	
488.97	5001	12.5		8"	0.2032					**Geo.Mean**		**0.576**
Total Blind casing length		**242**										
Total Screen casing Length			260									
Total length Blind Screen Casing		**502**										

WF02-PW12

Appendix B-3 Kozeny's correction factor for recovery data correction of WF02-PW12

Interval(m)		Type of	Length(m)		Diamet								
From	To	Casing	Blind	Screen	er of	r	2l/r	L/B	[7COS(πL/2B)]	√(r/2L)		F	Arthimethi mean
1	113.06	Blind	114.06		12	0.3048							0.608284097
113.06	147.76	Screen		34.7	12	0.3048	227.69	0.23484	6.529578516	0.06627	1.43273	0.33646	
147.76	159.84	Blind	12.08		12	0.3048							
159.84	182.99	Screen		23.15	12	0.3048	151.903	0.66332	3.534975974	0.08114	1.28682	0.85358	
182.99	207.12	Blind	24.13		12	0.3048							
207.12	224.4	Screen		17.28	12	0.3048	113.386	0.41729	5.55071245	0.09391	1.52128	0.63481	
224.4	230.43	Blind	6.03		12	0.3048							
224.4	242.81	Blind	18.41		8	0.2032							
242.81	248.59	Screen		5.78	8	0.2032	56.8898	0.23894	6.513198223	0.13258	1.86353	0.44527	0.584724866
248.59	260.15	Blind	11.56		8	0.2032							
260.15	265.94	Screen		5.79	8	0.2032	56.9882	0.33372	6.060995097	0.13247	1.80288	0.60165	
265.94	300.69	Blind	34.75		8	0.2032							
300.69	312.2	Screen		11.51	8	0.2032	113.287	0.24774	6.477149492	0.09395	1.60855	0.3985	
312.2	323.75	Blind	11.55		8	0.2032							
323.75	335.31	Screen		11.56	8	0.2032	113.78	0.50022	4.950036939	0.09375	1.46406	0.73235	
333.31	352.65	Blind	17.34		8	0.2032							
352.65	364.22	Screen		11.57	8	0.2032	113.878	0.40021	5.663088891	0.09371	1.53068	0.61259	
364.22	381.52	Blind	17.3		8	0.2032							
381.52	398.82	Screen		17.3	8	0.2032	170.276	0.5	4.951717884	0.07663	1.37947	0.68974	
398.82	416.06	Blind	17.24		8	0.2032							
416.06	427.55	Screen		11.49	8	0.2032	113.091	0.39993	5.664878723	0.09403	1.53269	0.61297	
427.55	433.31	Blind	5.76		8	0.2032							
433.31	450.63	Screen		17.32	8	0.2032	170.472	0.74653	2.717791303	0.07659	1.20816		
											Geo. Mean		**0.5711**

WF02-PW14

Appendix B-4 Kozeny's correction factor for recovery data correction of WF02-PW14

Interval(m)		Type of Casing	Diameter of Casing	Length(m)								
From	To				r	2l/r	L/B	7COS(πL/2B)	√(r/2L)		F	Arthimethi mean
1	124.43	Blind	14"	124.43	0.3556							0.620973717
124.43	141.98	3Screen	14"	17.55	0.3556	98.7064	0.12361	6.868597448	0.10065	1.69135	0.2091	
141.98	153.68	2Blind	14"	11.7	0.3556							
153.68	171.23	3Screen	14"	17.55	0.3556	98.7064	0.6	4.117202112	0.10065	1.41441	0.8486	
171.23	182.93	2Blind	14"	11.7	0.3556							
182.93	194.63	2Screen	14"	11.7	0.3556	65.8043	0.5	4.951717884	0.12327	1.61042	0.8052	
194.63	200.48	1Blind	14"	5.85	0.3556							
200.48	212	2Blind	8"	11.52	0.2032							
212	235.04	4Screen	8"	23.04	0.2032	226.772	0.57016	4.377841034	0.06641	1.29071	0.7359	0.633
235.04	258.08	4Blind	8"	23.04	0.2032							
258.08	275.36	3Screen	8"	17.28	0.2032	170.079	0.42857	5.474309563	0.07668	1.41976	0.6085	
275.36	292.64	3Blind	8"	17.28	0.2032							
292.64	304.16	2Screen	8"	11.52	0.2032	113.386	0.4	5.664429267	0.09391	1.53196	0.6128	
304.16	321.44	3Blind	8"	17.28	0.2032							
321.44	332.96	2Screen	8"	11.52	0.2032	113.386	0.4	5.664429267	0.09391	1.53196	0.6128	
332.96	350.24	3Blind	8"	17.28	0.2032							
350.24	361.76	2Screen	8"	11.52	0.2032	113.386	0.39291	5.709883293	0.09391	1.53623	0.6036	
361.76	379.04	3Blind	8"	17.28	0.2032							
379.04	390.56	2Screen	8"	11.52	0.2032	113.386	0.4	5.664429267	0.09391	1.53196	0.6128	
390.56	402.08	2Blind	8"	11.52	0.2032							
402.08	413.6	2Screen	8"	11.52	0.2032	113.386	0.5	4.951717884	0.09391	1.46503	0.7325	
413.6	430.88	3Blind	8"	17.28	0.2032							
430.88	442.4	1Screen	8"	11.52	0.2032	113.386	0.4	5.664429267	0.09391	1.53196	0.6128	
442.4	459.68	3Blind	8"	17.28	0.2032							
459.68	465.44	1Screen	8"	5.76	0.2032	56.6929	0.25308	6.454685862	0.13281	1.85726	0.47	
465.44	476.96	2Blind	8"	11.52	0.2032							
476.96	488.48	2Screen	8"	11.52	0.2032	113.386	0.5	4.951717884	0.09391	1.46503	0.7325	
488.48	500	2Blind	8"	11.52	0.2032					**Geo. Mean**		**0.602**

WF02-PW16

Appendix B-5 Kozeny's correction factor for recovery data correction of WF02-PW16

epth interval in (n		Type of casing	Length (m)		Diameter of casing								
From	To		Blind	Screen		r	2l/r	L/B	OS(πL/2	√(r/2L)		F	Arthimethi mean
490	484.2	Blind	5.8		8"								
484.2	466.86	Screen		17.34	8"	0.2032	170.669	0.60167	4.10238	0.07655	1.31402	0.7906	0.731
466.86	455.38	Blind	11.48		8"	0.2032							
455.38	437.98	Screen		17.4	8"	0.2032	171.26	0.50245	4.93261	0.07641	1.37692	0.69184	
437.98	420.75	Blind	17.23		8"	0.2032							
420.75	409.21	Screen		11.54	8"	0.2032	113.583	0.40014	5.66353	0.09383	1.53141	0.61278	
409.21	391.91	Blind	17.3		8"	0.2032							
391.91	380.41	Screen		11.5	8"	0.2032	113.189	0.4	5.66443	0.09399	1.53242	0.61297	
380.41	363.16	Blind	17.25		8"	0.2032							
363.16	351.61	Screen		11.55	8"	0.2032	113.681	0.40014	5.66353	0.09379	1.53118	0.61269	
351.61	334.42	Blind	17.19		8"	0.2032							
334.42	322.92	Screen		11.5	8"	0.2032	113.189	0.66667	3.50322	0.09399	1.32928	0.88619	
322.92	317.17	Blind	5.75		8"	0.2032							
317.17	311.41	Screen		5.76	8"	0.2032	56.6929	0.25087	6.46402	0.13281	1.8585	0.46624	
311.41	294.21	Blind	17.2		8"	0.2032							
294.21	276.98	Screen		17.23	8"	0.2032	169.587	0.74946	2.68816	0.07679	1.20642	0.90416	
276.98	271.22	Blind	5.76		8"	0.2032							
271.22	254.03	Screen		17.19	8"	0.2032	169.193	0.7803	2.37219	0.07688	1.18237	0.9226	
254.03	248.28	Blind	5.75		8"	0.2032							
248.28	231.09	Screen		17.19	8"	0.2032	169.193	0.62741	3.86985	0.07688	1.29751	0.81407	
231.09	225.67	Blind	5.42		8"	0.2032							
225.67	219.75	Blind	5.92		14"	0.2032							
219.75	196.11	Screen		23.64	14"	0.2032	232.677	0.67083	3.46354	0.06556	1.22706	0.82315	0.666
196.11	184.51	Blind	11.6		14"	0.2032							
184.51	166.96	Screen		17.55	14"	0.2032	172.736	0.60226	4.09705	0.07609	1.31173	0.79001	
166.96	155.37	Blind	11.59		14"	0.2032							
155.37	137.83	Screen		17.54	14"	0.2032	172.638	0.74989	2.68373	0.07611	1.20425	0.90306	
137.83	131.98	Blind	5.85		14"	0.2032							
131.98	120.26	Screen		11.72	14"	0.2032	115.354	0.0888	6.93208	0.09311	1.64543	0.14612	
120.26	1	Blind	121.26		14"	0.2032							
Total Blind casing length			**282.35**									**Geo. Mean**	**0.661**
Total Screen casing Length				208.65									
Total length Blind Screen Casing			**491**										

WF02-PW17

Appendix B-6 Kozeny’s correction factor for recovery data correction of WF02-PW17

epth interval in (n		Type of casing	Length (m)		Diameter of casing								
From	To		Blind	Screen		r	2l/r	L/B	[7COS(πL/2B)]	√(r/2L)	[ ]	F	Arthimethi mean
0.75	127.5	Blind	128.25		14"	0.3556							
127.5	145.1	Screen		17.6	14"	0.3556	98.9876	0.1213	6.873455002	0.10051	1.69085	0.20509	0.661
145.1	150.95	Blind	5.85		14"	0.3556							
150.95	168.5	Screen		17.55	14"	0.3556	98.7064	0.75	2.682646026	0.10065	1.27002	0.95251	
168.5	186.05	Blind	17.55		14"	0.3556							
186.05	191.9	Screen		5.85	14"	0.3556	32.9021	0.25	6.467689896	0.17434	2.12755	0.53189	
191.9	197.75	Blind	5.85		14"	0.3556							
197.5	221.15	Screen		23.65	14"	0.3556	133.015	0.80855	2.077851469	0.08671	1.18016	0.95422	
221.15	227	Blind	5.85		14"	0.3556							
227	232.75	Blind	5.75		6"	0.3556							
232.75	244.25	Screen		11.5	6"	0.3556	64.6794	0.49784	4.968503132	0.12434	1.61779	0.80539	0.75
244.25	250	Blind	5.75		6"	0.3556							
250	267.25	Screen		17.25	6"	0.3556	97.0191	0.75	2.682646026	0.10152	1.27235	0.95427	
267.25	278.25	Blind	11		6"	0.3556							
278.25	284.5	Screen		6.25	6"	0.3556	35.1519	0.36232	5.897682487	0.16867	1.99473	0.72273	
284.5	296	Blind	11.5		6"	0.3556							
296	313.25	Screen		17.25	6"	0.3556	97.0191	0.6	4.117202112	0.10152	1.418	0.8508	
313.25	336.25	Blind	23		6"	0.3556							
336.25	347.75	Screen		11.5	6"	0.3556	64.6794	0.33333	6.063106661	0.12434	1.7539	0.58463	
347.75	359.25	Blind	11.5		6"	0.3556							
359.25	365	Screen		5.75	6"	0.3556	32.3397	0.33333	6.063106661	0.17585	2.06617	0.68872	
365	376.5	Blind	11.5		6"	0.3556							
376.5	388	Screen		11.5	6"	0.3556	64.6794	0.5	4.951717884	0.12434	1.61571	0.80785	
388	405.25	Blind	17.25		6"	0.3556							
405.25	411	Screen		5.75	6"	0.3556	32.3397	0.25	6.467689896	0.17585	2.13732	0.53433	
411	428.5	Blind	17.5		6"	0.3556							
428.5	445.5	Screen		17	6"	0.3556	95.613	0.49275	5.007686137	0.10227	1.51213	0.74511	
445.5	457	Blind	11.5		6"	0.3556							
457	468.5	Screen		11.5	6"	0.3556	64.6794	0.5	4.951717884	0.12434	1.61571	0.80785	
468.5	480	Blind	11.5		6"								
Total Blind casing length			**301.1**								**Geo. Mean**		**0.684**
Total Screen casing Length				**179.9**									
Total length Blind Screen Casing			**481**										

WF02-PW18

Appendix B-7 Kozeny’s correction factor for recovery data correction of WF02-PW18

Depth interval in (m		Type of casing	Length (m)		Diameter								
From	To		Blind	Screen	of casing	r	2l/r	L/B	7COS(πL/2B	√(r/2L)	[ ]	F	Arthimethi mean
496	484.48	Blind	11.52		8"	0.2032							
484.48	478.73	Screen		5.75	8"	0.2032	56.5945	0.33333	6.063106661	0.13293	1.80595	0.60198	0.670
478.73	467.17	Blind	11.56		8"	0.2032							
467.17	455.69	Screen		11.48	8"	0.2032	112.992	0.49826	4.9651856	0.09408	1.4671	0.731	
455.69	438.43	Blind	17.26		8"	0.2032							
438.43	426.97	Screen		11.46	8"	0.2032	112.795	0.39903	5.670717684	0.09416	1.53394	0.61208	
426.97	409.71	Blind	17.26		8"	0.2032							
409.71	398.27	Screen		11.44	8"	0.2032	112.598	0.39861	5.673414901	0.09424	1.53466	0.61173	
398.27	380.95	Blind	17.32		8"	0.2032							
380.95	363.67	Screen		17.28	8"	0.2032	170.079	0.49942	4.956206023	0.07668	1.38004	0.68922	
363.67	340.56	Blind	23.11		8"	0.2032							
340.56	323.31	Screen		17.25	8"	0.2032	169.783	0.4274	5.482300646	0.07675	1.42074	0.60723	
323.31	294.39	Blind	28.92		8"	0.2032							
294.39	282.91	Screen		11.48	8"	0.2032	112.992	0.28416	6.31486959	0.09408	1.59407	0.45297	
282.91	277.13	Blind	5.78		8"	0.2032							
277.13	265.64	Screen		11.49	8"	0.2032	113.091	0.66532	3.516065154	0.09403	1.33063	0.88529	
265.64	254.1	Blind	11.54		8"	0.2032							
254.1	225.32	Screen		28.78	8"	0.2032	283.268	0.71379	3.045682273	0.05942	1.18096	0.84296	
225.32	208.25	Blind	17.07		8"	0.2032							
215	209.35	Blind	5.65		14"	0.2032							0.60
209.35	203.5	Screen		5.85	14"	0.2032	57.5787	0.26897	6.385109989	0.13179	1.84147	0.49529	
203.5	191.78	Blind	11.72		14"	0.2032							
191.78	168.34	Screen		23.44	14"	0.2032	230.709	0.66667	3.503217823	0.06584	1.23064	0.82043	
168.34	162.48	Blind	5.86		14"	0.2032							
162.48	144.94	Screen		17.54	14"	0.2032	172.638	0.74957	2.686983423	0.07611	1.2045	0.90286	
144.94	139.09	Blind	5.85		14"	0.2032							
139.09	121.5	Screen		17.59	14"	0.2032	173.13	0.12649	6.862416371	0.076	1.52154	0.19246	
121.5	1	Blind	122.5		14"						Geo. Mean		0.611
Total Blind casing length			312.92										
Total Screen casing Length				190.83									
Total length Blind Screen Casing			503.75										

WF02-PW19

Appendix B-8 Kozeny’s correction factor for recovery data correction of WF02-PW19

Interval(m)		Type of Casing	Length(m)		Diameter of Casing								
From	To		Blind	Screen		r	2l/r	L/B	[7COS(πL/2B)]	√(r/2L)		F	Arthimethi mean
550	538.4	Blind	11.6		8 "	0.2032							
538.4	521.08	Screen		17.32	8"	0.2032	170.472	0.60076	4.110416773	0.07659	1.31482	0.78989	0.611
521.08	509.57	Blind	11.51		8 "	0.2032							
509.57	492.28	Screen		17.29	8"	0.2032	170.177	0.59931	4.123361204	0.07666	1.31608	0.78874	
492.28	480.72	Blind	11.56		8 "	0.2032							
480.72	469.17	Screen		11.55	8"	0.2032	113.681	0.5	4.951717884	0.09379	1.46442	0.73221	
469.17	457.62	Blind	11.55		8 "	0.2032							
457.62	446.1	Screen		11.52	8"	0.2032	113.386	0.39917	5.669794024	0.09391	1.53246	0.61171	
446.1	428.76	Blind	17.34		8 "	0.2032							
428.76	417.2	Screen		11.56	8"	0.2032	113.78	0.40028	5.662640109	0.09375	1.53087	0.61277	
417.2	399.88	Blind	17.32		8 "	0.2032							
399.88	388.3	Screen		11.58	8"	0.2032	113.976	0.40028	5.662643202	0.09367	1.53041	0.61259	
388.3	370.95	Blind	17.35		8 "	0.2032							
370.95	359.35	Screen		11.6	8"	0.2032	114.173	0.5	4.951717884	0.09359	1.46342	0.73171	
359.35	347.75	Blind	11.6		8 "	0.2032							
347.75	341.95	Screen		5.8	8"	0.2032	57.0866	0.16715	6.760353738	0.13235	1.89475	0.3167	
341.95	313.05	Blind	28.9		8 "	0.2032							
313.05	301.43	Screen		11.62	8"	0.2032	114.37	0.50086	4.945016792	0.09351	1.46239	0.73246	
301.43	289.85	Blind	11.58		8 "	0.2032							
289.85	278.3	Screen		11.55	8"	0.2032	113.681	0.49978	4.953398258	0.09379	1.46458	0.73197	
278.3	266.74	Blind	11.56		8 "	0.2032							
266.74	249.4	Screen		17.34	8"	0.2032	170.669	0.59938	4.122730191	0.07655	1.31558	0.78853	
249.4	243.81	Blind	5.59		8 "	0.2032							
243.81	237.81	Blind	6		14"	0.2032							
237.81	220.26	Screen		17.55	14 "	0.2032	172.736	0.7484	2.698870373	0.07609	1.20535	0.90208	0.66
220.26	214.36	Blind	5.9		14"	0.2032							
214.36	202.63	Screen		11.73	14"	0.2032	115.453	0.66686	3.501414617	0.09307	1.32587	0.88416	
202.63	196.77	Blind	5.86		14 "	0.2032							
196.77	185.05	Screen		11.72	14"	0.2032	115.354	0.4983	4.964911117	0.09311	1.46227	0.72865	
185.05	173.25	Blind	11.8		14"	0.2032							
173.25	161.55	Screen		11.7	14 "	0.2032	115.157	0.28495	6.311116523	0.09319	1.58811	0.45253	
161.55	132.19	Blind	29.36		14"	0.2032							
132.19	126.33	Screen		5.86	14"	0.2032	57.6772	0.5	4.951717884	0.13167	1.65201	0.826	
126.33	120.47	Blind	5.86		14 "	0.2032							
120.47	108.77	Screen		11.7	14"	0.2032	115.157	0.09712	6.918784362	0.09319	1.64474	0.15974	
108.77	1	Blind	109.77										
Total Blind casing length 14” = 174.55 , 8” =					**342.01**						**Geo. Mean**		**0.68**
Total Screen casing Length 14 “ = 70.26 , 8 “ = 138.73					**208.99**								
Total Length of Blind & Screen casing					**551**								

Appendix-C

Wells used by well packages

Akaki well field have four phases with the 101.1 km^2 of area and totally the model is constructed for the 77 wells. This table explained the Longitudinal, Latitudinal, Elevation and the discharge rate of the wells. Surfer software used this data and generates grid point which is input to the location of wells in the MODFLOW.

Appendix C-1 Akaki well field casing wells

		Geographical Co-ordinate			
Well Field	**Well Index**	**X**	**Y**	**Z**	**Q, m^3/d**
AKWF-01	SWAWF1R	475945	978251	2060	1045.4
AKWF-01	SWAWF2	475697	979915	2055	4708.8
AKWF-01	SWAWF4A	472846	980785	2180	2592.0
AKWF-01	SWAWF4B	472836	980785	2058	7776.0
AKWF-01	SWAWF5	472779	978788	2054	7776.0
AKWF-01	WF01-PW1	473597	981135	2079	907.2
AKWF-01	WF01-PW2	474204	980459	2069	5400.0
AKWF-01	WF01-PW3	474918	980486	2073	2419.2
AKWF-01	WF01-PW4	471185	979580	2061	10540.9
AKWF-01	WF01-PW5	470469	979211	2050	12096.1
AKWF-01	WF01-PW6	472630	979912	2058	6806.6
AKWF-01	WF01-PW7	471909	979461	2055	626.4
AKWF-01	WF01-PW8	473583	979260	2063	4320.0
AKWF-01	WF01-PW9	469612	978592	2054	6048.0
AKWF-01	WF01-PW11	472245	977865	2056	5369.8
AKWF-01	WF01-PW12	471476	977396	2049	8640.1
AKWF-01	WF01-PW13	472233	976508	2057	1900.8
AKWF-01	WF01-PW14	471521	976630	2050	6592.4

AKWF-01	WF01-PW15	473944	978722	2066	3456.0
AKWF-01	WF01-PW16	473386	980122	2062	2702.6
AKWF-01	WF01-PW18	471918	979657	1969	12096.1
AKWF-01	WF01-PW19	470557	976837	1972	5788.8
AKWF-01	WF01-PW20	471289	977837	1978	3456.0
AKWF-01	WF02-PW10 ANBG	474558	972286	2112	3706.6
AKWF-02	WF02-PW1	472446	974756	2089	
AKWF-02	WF02-PW2	471426	972883	2066	1728.0
AKWF-02	WF02-PW3	470352	972510	2081	777.6
AKWF-02	WF02-PW4	470717	971442	2064	950.4
AKWF-02	WF02-PW5	476795	971654	2090	4320.0
AKWF-02	WF02-PW6	471351	970556	2067	2592.0
AKWF-02	WF02-PW7R	471566	972956	2060	6480.0
AKWF-02	WF02-PW8	469163	973946	2063	4320.0
AKWF-02	WF02-PW9	473955	974576	2064	6048.0
AKWF-02	WF02-PW10	469239	972866	2071	4320.0
AKWF-02	WF02-PW11	469738	971752	2075	6048.0
AKWF-02	WF02-PW12	470153	970500	2048	4320.0
AKWF-02	WF02-PW13	469257	970946	2066	5270.4
AKWF-02	WF02-PW14	468453	973497	2062	5184.0
AKWF-02	WF02-PW15	470022	973535	2061	12268.9
AKWF-02	WF02-PW16	468849	970179	2064	7171.2
AKWF-02	WF02-PW17	468353	972311	2061	6998.4
AKWF-02	WF02-PW18	468006	971498	2066	6652.8
AKWF-02	WF02-PW19	472286	971308	2067	2272.3
AKWF-02	WF02-PW20	471027	973709	2056	7776.0

AK-Old -WF	BH10R	479055	976033	2096	12960.1
AK-Old -WF	BH11R	478780	977307	2088	13132.9
AK-Old -WF	BH13R	478679	976462	2080	4752.0
AK-Old -WF	BH14R	478585	976053	2079	12096.1
AK-Old -WF	BH22R	477628	975889	2074	8640.1
AK-Old -WF	BH1R	478074	975053	2089	10886.5
AK-Old -WF	BH26R	477246	975731	2077	7776.0
AK-Old -WF	BH23R	477479	977222	2065	4118.7
AKWF-03	WF03-PW1	477362	973887	2068.00	5616.0
AKWF-03	SL-PW3	475288	976908	2058	6518.1
AKWF-03	SL-PW4	476037	976861	2068	7603.2
AKWF-03	SL-PW5	475058	976100	2062	7862.5
AKWF-03	SL-PW6	475528	975870	2059	7257.6
AKWF-03	SL-PW7	476098	976183	2055	4017.6
AKWF-03	SL-PW8	474528	975585	2056	8153.6
AKWF-03	SL-PW9	475128	975184	2068	6085.2
AKWF-03	SL-PW10	473954	975244	2053	4752.0
AKWF-03	SL-PW11	471453	974241	2048	9737.3
AKWF-02	SL-PW12	470835	974233	2046	9804.7
AKWF-03	SL-PW14	472640	973882	2072	7344.0
AKWF-03	SL-PW15	473428	973584	2078	2764.8
AKWF-03	SL-PW16	474702	974792	2069	8508.7
AKWF-03	SL-PW17	474733	973382	2078	2953.2
AKWF-03	SL-PW18	477023	973986	2087	5717.1
AKWF-03	SL-PW19	476375	974046	2112	2916.0
AKWF-03	SL-PW21	477959	974168	2091	7795.9
AKWF-03	SL-PW22	475507	974679	2070	6250.2

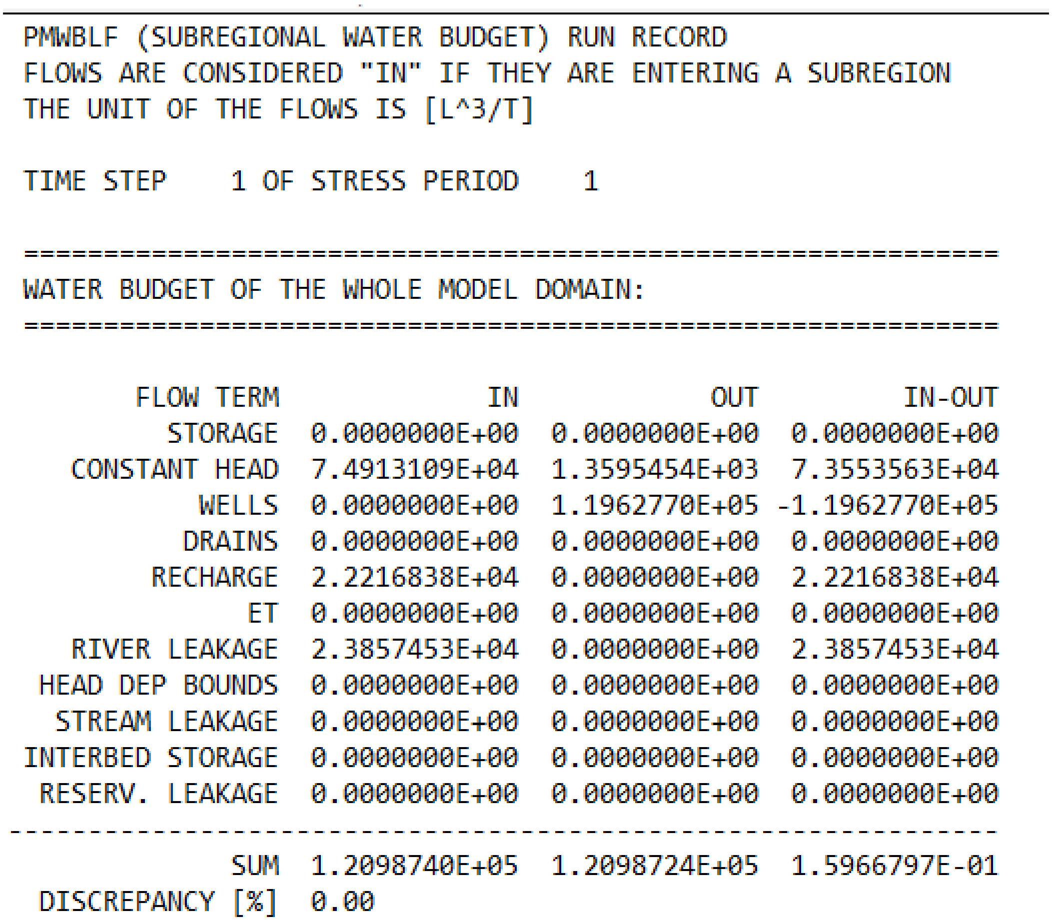
AKWF-03	SL-PW24	475941	975137	2064	8812.9
AKWF-03	SL-PW25	473071	974284	2060	9331.3
AKWF-03	SL-PW30	478528	973384	2113	3998.6
AKWF-03	SL-PW32	476717	973370	2121	4199.1
AKWF-03	SL-PW33	477434	973280	2114	3196.8
AKWF-03	WF02-PW1	472446	974756	2053	8812.9

Appendix–D

Water Budget Record

Water budget run record described inflows and outflows for flow terms which are generated by model. This used for the comparison of sensitivity analysis for different scenarios.

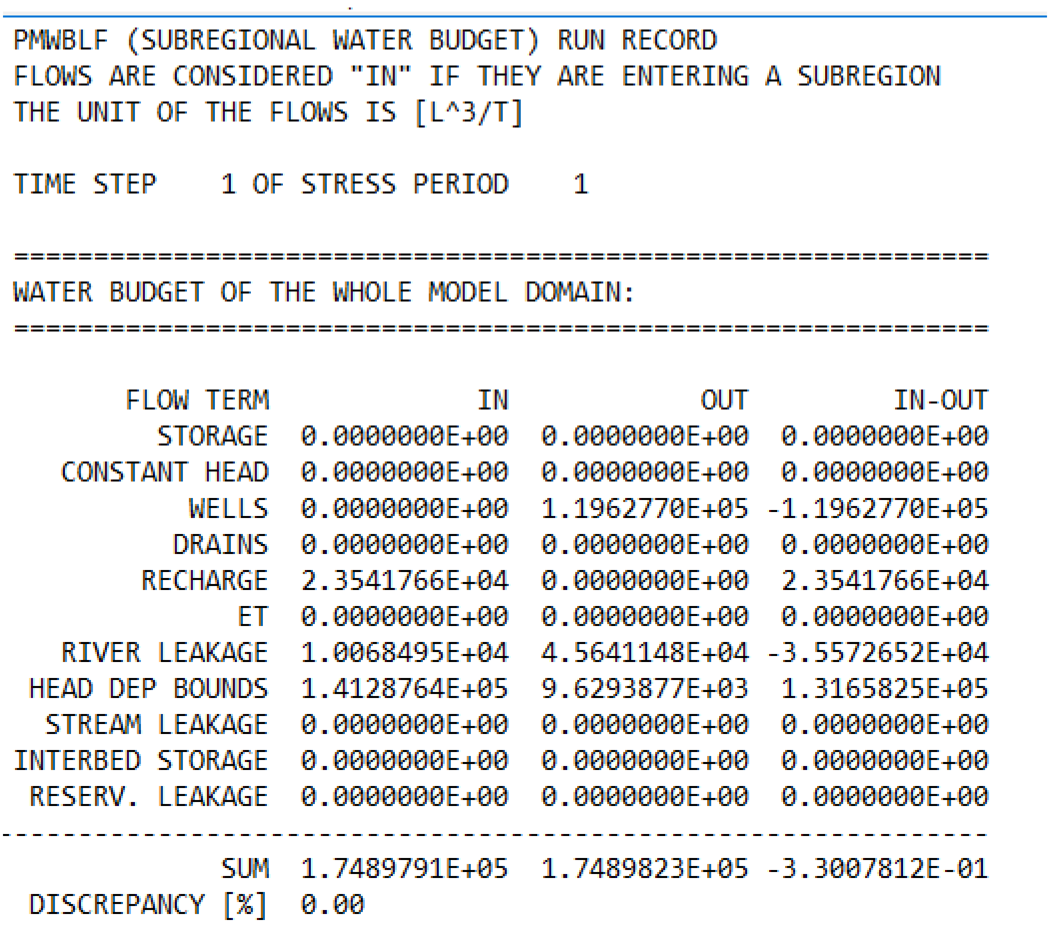
General boundary head ignorance



```
PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    1

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM            IN             OUT          IN-OUT
         STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   CONSTANT HEAD  7.4913109E+04  1.3595454E+03  7.3553563E+04
           WELLS  0.0000000E+00  1.1962770E+05 -1.1962770E+05
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  2.2216838E+04  0.0000000E+00  2.2216838E+04
              ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
   RIVER LEAKAGE  2.3857453E+04  0.0000000E+00  2.3857453E+04
 HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
-------------------------------------------------------------
             SUM  1.2098740E+05  1.2098724E+05  1.5966797E-01
 DISCREPANCY [%]  0.00
```

Appendix D-1 Water budget run record during general boundary head ignorance

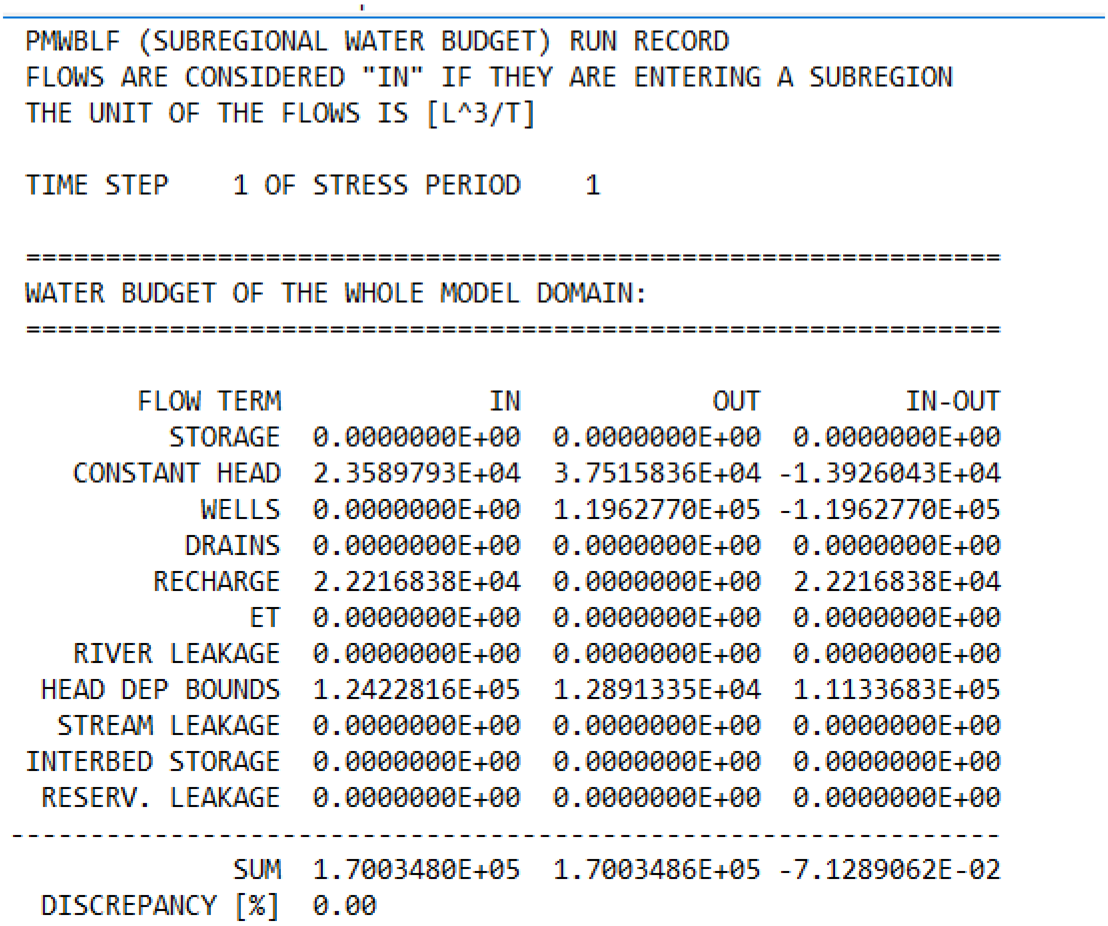
Constant head ignorance



```
PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    1

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM             IN             OUT           IN-OUT
         STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   CONSTANT HEAD  0.0000000E+00  0.0000000E+00  0.0000000E+00
           WELLS  0.0000000E+00  1.1962770E+05 -1.1962770E+05
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  2.3541766E+04  0.0000000E+00  2.3541766E+04
              ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
   RIVER LEAKAGE  1.0068495E+04  4.5641148E+04 -3.5572652E+04
 HEAD DEP BOUNDS  1.4128764E+05  9.6293877E+03  1.3165825E+05
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
---------------------------------------------------------------
             SUM  1.7489791E+05  1.7489823E+05 -3.3007812E-01
 DISCREPANCY [%]  0.00
```

Appendix D-2 Water budget run record during constant head ignorance

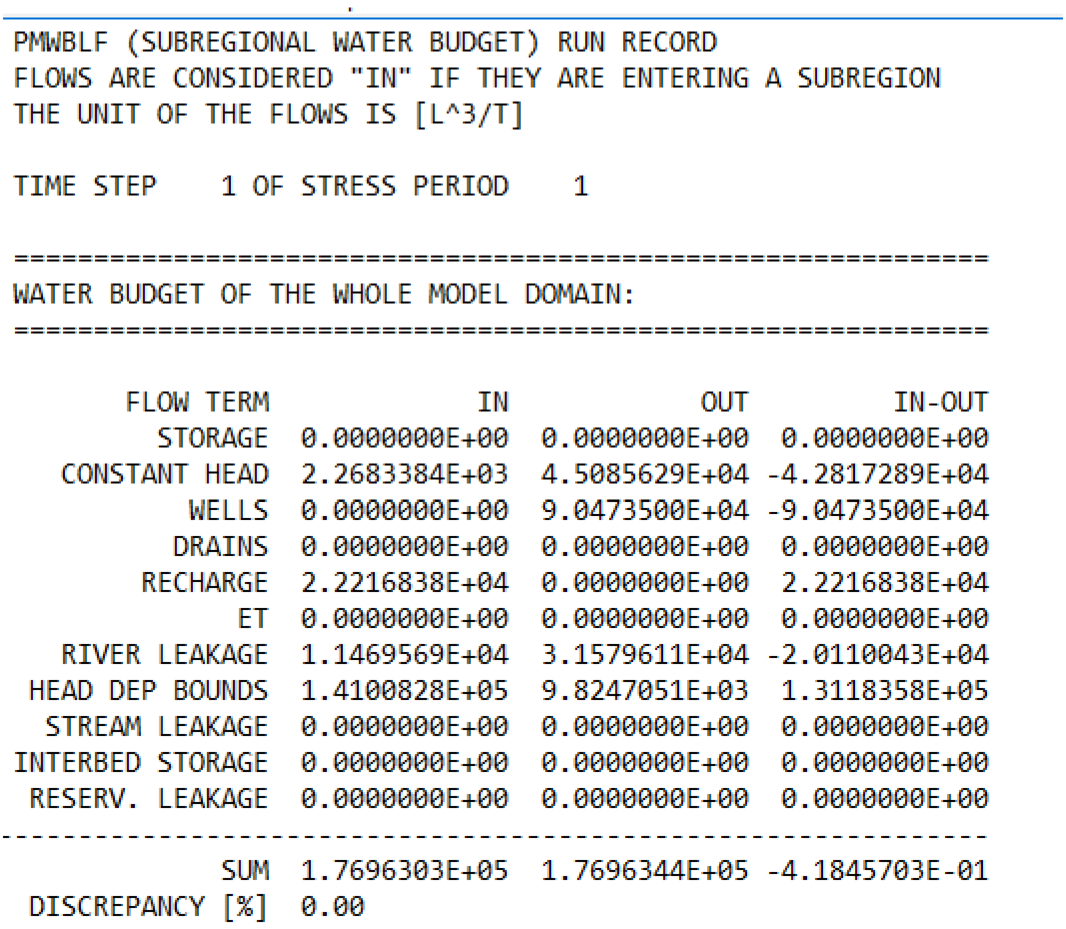
Tinishu and Tiliku Akaki rivers ignorance



```
 PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
 FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
 THE UNIT OF THE FLOWS IS [L^3/T]

 TIME STEP    1 OF STRESS PERIOD    1

 ==============================================================
 WATER BUDGET OF THE WHOLE MODEL DOMAIN:
 ==============================================================

        FLOW TERM             IN             OUT          IN-OUT
          STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
    CONSTANT HEAD  2.3589793E+04  3.7515836E+04 -1.3926043E+04
            WELLS  0.0000000E+00  1.1962770E+05 -1.1962770E+05
           DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
         RECHARGE  2.2216838E+04  0.0000000E+00  2.2216838E+04
               ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
    RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  HEAD DEP BOUNDS  1.2422816E+05  1.2891335E+04  1.1133683E+05
   STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
---------------------------------------------------------------
              SUM  1.7003480E+05  1.7003486E+05 -7.1289062E-02
  DISCREPANCY [%]  0.00
```

Appendix D-3 Water budget run record during Akaki rivers ignorance

Discounting Akaki well phase IIIA



```
PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP    1 OF STRESS PERIOD    1

=============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
=============================================================

       FLOW TERM            IN             OUT           IN-OUT
         STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   CONSTANT HEAD  2.2683384E+03  4.5085629E+04 -4.2817289E+04
           WELLS  0.0000000E+00  9.0473500E+04 -9.0473500E+04
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  2.2216838E+04  0.0000000E+00  2.2216838E+04
              ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
   RIVER LEAKAGE  1.1469569E+04  3.1579611E+04 -2.0110043E+04
 HEAD DEP BOUNDS  1.4100828E+05  9.8247051E+03  1.3118358E+05
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
 RESERV. LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
--------------------------------------------------------------
             SUM  1.7696303E+05  1.7696344E+05 -4.1845703E-01
 DISCREPANCY [%]  0.00
```

Appendix D-4 Water budget run record during Akaki well phase IIIA ignorance