ADDIS ABABA UNIVERSITY

INSTITUTE OF TECHNOLOGY SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

HYDRAULIC ENGINEERING

MASTER THESIS

ON

REAL-TIME PERFORMANCE: THE CASE OF AKAKI PHASE IIIB WELL FIELD

PREPARED BY:-SHEMSU ABDELA

ID No. GSE/1354/06

Tel. 0921610384

ADVISOR:-Dr MEBRUK MOHAMMED

Sponsor: Ethiopian Roads Authority

June 2020

ABSTRACT

Groundwater is an important source of water supply throughout the world. Its use in irrigation, industries, municipalities, and rural homes continues to increase. There is a tendency to think of groundwater as being the primary water source in arid regions and of surface water in humid regions.

In Addis Ababa for the first time, the modern water supply provision was introduced 15 years after the establishment of the city. At that time the source selected is groundwater and served the city for almost 58 years. At the moment the largest volume of the daily production of water in Addis Ababa is groundwater that accounts for 65% of total daily production.

The vast expansion of the city increases the shortage of water and Addis Ababa Water and Sewerage Authority have implemented the short-term and medium-term plan to overcome the deficit that occurred in the city. The plans implemented are the development of groundwater and the expansion of Legedadi Dam. Even if these projects are functional the shortage of potable water has not yet been solved. Many of the developed groundwater have a failure problem and have shown a decline in the yield. This research, with the help of understanding the real-time performances of the wells, found out the reason for the malfunction and the decline of the yield of the developed groundwater of the Akaki phase IIIB project. The efficiency and the yield of each well were worked out from step drawn down test and the hydraulic parameters were worked out from time draw dawn and recovery test conducted during the well study. These values were compared with values assigned for the welll operation.

From the analysis of this thesis,, many of the wells were failed during the study time. Among 24 wells in the well field, the efficiency obtained for nine wells from the step drawdown test was found to be less than the standard value expected for the production well and it tells that the well failed before construction.

The Transmissivity values of the developed well is also computed by three method using Excel-2013 and the value obtained is compared with the values used during the study and design document and the result tell transmissivity estimates is again found to have errors at design and study.

Keywords:- Groundwater, Transmissivity, Akaki phase IIIB, Efficiency and Step drawdown test.

ACKNOWLEDGMENTS

First of all, I would like to give our endless thanks to the almighty God who gave us health and effort from early beginning to the end. Then I would like to thank greatly indebted my advisor Dr. Mebruk Mohammed, for his excellent guidance, encouragement and unreserved advice throughout my research work. I highly appreciate his constructive comments and advice in every aspect of my thesis which helped me to come up with the right direction for the research.

Secondly thanks to the Ethiopian Road Authority for providing the financial support and for providing the opportunity of postgraduate program of Addis Ababa Institution of Technology (AAIT). I am also thanks to waterworks Design and Supervision Enterprises (WWDSE) and Addis Ababa water and sewerage Authority (AAWSA) for relevant data offering.

Finally thanks to all my dear friends and my wife zebiba nuredin for deep Supporting and sharing ideas during my thesis preparation.

List of Acronyms and Abbreviations

AAWSA	Addis Ababa Water & Sewerage Authority
WWDSE	Water Works Design and Supervision Enterprises
L/S	Liter per second
M3/S	Cubic meter per second
M2/s	meter Square per second
MASL	Meters above sea level
PW	Pumping Well
PP	Partial Penetration
SWL	Static water level
WF	Well field
K	Hydraulic Conductivity
DD	Drawdown
B	Saturated aquifer thickness
Q	Average Pumping Rate
S	Storativity
S_a	Observed Drawdown
S_C	Corrected Drawdown
T	Transmissivity
SL-PW	soft loan production Well

Addis Ababa Institute of Technology

Thesis proposal Submitted to Addis Ababa Institute of Technology, School of Graduate Studies in partial fulfillment of the requirements for the Degree of Masters of Science in Civil Engineering with Hydraulic Engineering.

Date defended--------------------

Members of Examining Board

-- --------------------------

(Chairman) (Signature)

-- --------------------------

(Advisor) (Signature)

-- -------------------------

(Internal examiner) (Signature)

--------------------------------------- ------------------------

(External examiner) (Signature)

Table of Contents

CHAPTER ONE 1
1 INTRODUCTION 1
1.1 Statement of the problem 2
1.2 The objective of the research 3
1.2.1 General objective 3
1.2.2 Specific objective 3
CHAPTER TWO 4
2 LITERATURE REVIEW 4
2.1 Groundwater 4
2.2 AQUIFERS 4
2.3 Types of Aquifer 4
2.3.1 Confined aquifer 4
2.3.2 Unconfined aquifer 5
2.3.3 Leaky aquifer 6
2.4 Aquifer Parameters 6
2.4.1 Transmissivity 7
2.4.2 Specific storage 8
2.5 Pump Test 9
2.5.1 Single well pumping tests 9
2.5.2 Multiple well pumping tests 11
2.6 Duration and types of the pumping test 11
2.6.1 Preliminary Pump Test 12
2.6.2 Step-Drawdown Pumping Test 13
2.6.3 Constant-Rate Pumping Test 13
2.6.4 Recovery Test 14
2.7 Correction of Pump Test Data 15
2.7.1 Correction for Unconfined aquifer 15
2.7.2 Well Efficiency and Correction for Well Loss 16
2.7.3 Well Efficiency 20
2.7.4 Correction for Partial Penetration 22
2.8 Estimate Aquifers Parameters and Pumping test Analysis 23
2.9 Causes of well failure 26
2.10 WELL REHABILITATION 29

CHAPTER THREE 30
3 RESEARCH METHODOLOGY 30
  3.1 Description of the Study area 30
  3.2 Basic Description of each of the Wells 30
  3.3 General Approach 35
    3.3.1 Data collection 35
    3.3.2 Data quality checking 35
    3.3.3 Data analysis method 35
    3.3.4 Estimation of Aquifers Parameters and Pumping test Analysis 37
    3.3.5 Estimation of operational drawdown range 38
    3.3.6 Result and interpretation 38
CHAPTER FOUR 39
4 RESULT AND DISCUSSION 39
  4.1 Data analysis 39
    4.1.1 Pumping Test 39
    4.1.2 Well Efficiency 39
    4.1.3 Partial penetration 41
  4.2 Transmissivity and Storativity result for Akaki phase IIIB wells 43
  4.3 Pumping and recovery time 46
  4.4 Causes of well failure 47
  4.5 Maximum Expected Yield 52
CHAPTER FIVE 53
5 CONCLUSION AND RECOMMENDATION 53
  5.1 Conclusion 53
  5.2 Recommendation 54
REFERENCES 55

List of Figures

Figure 1: confined aquifer..5

Figure 2: unconfined aquifer...6

Figure 3.leaky aquifer 6

Figure 4Various components of head losses in a pumped well. 17

Figure 5: components of drawdown recorded at the end of each step showing errors made if drawdown's s1,s2, and s3 where used directly to draw graph Q versus S/Q 20

Figure 6Partial Penetration (a) when the aquifer is not fully drilled (b) due to Blind and Screen section of the well. 22

Figure 7 : Cooper-Jacob method for solution of non-equilibrium equation 24

Figure 8: the drawdown and recovery curves near observation well near a pumping well.....26

Figure 9: Location of bore holes drilled at Akaki ground water prospective area (Source WWDSE July 2014), ...34

Figure 10 step draw down test graph of well ID SL -PW -07 41

Figure 11Time versus drawdown cooper-Jacob graph of well ID SL – PW-07.......................44

Figure 12.Sw/Q vs Q plot for SL-PW 10...56

Figure 13.Sw/Q vs Q plot for SL-PW 14...56

Figure 14.Sw/Q vs Q plot for SL-PW 18...56

Figure 15.Sw/Q vs Q plot for SL-PW 21...57

Figure 16.Sw/Q vs Q plot for SL-PW 33...57

Figure 17 Plot for Efficiency corrected drawdown for SL-PW-07...62

Figure 10Plot for Efficiency corrected drawdown for SL-PW-10..62

Figure 19Plot for Efficiency corrected drawdown for SL-PW-14..63

Figure 20Plot for Efficiency corrected drawdown for SL-PW-21..63

Figure 21Plot for Efficiency corrected drawdown for SL-PW-25..64

Figure 22Plot for Efficiency corrected drawdown for SL-PW-30..64

Figure 23 Plot for Efficiency corrected drawdown for SL-PW-33.......................................65

Figure 24 Plot for kozeny corrected drawdown for SL-PW-07..66

Figure 25 Plot for kozeny corrected drawdown for SL-PW-10..66

Figure 26 Plot for kozeny corrected drawdown for SL-PW-11..67

Figure 27 Plot for kozeny corrected drawdown for SL-PW-14..67

Figure 28 Plot for kozeny corrected drawdown for SL-PW-18..68

Figure 29 Plot for kozeny corrected drawdown for SL-PW-21..68

Figure 30 Plot for kozeny corrected drawdown for SL-PW-25..69

Figure 31 Plot for kozeny corrected drawdown for SL-PW-30..69

Figure 32 Plot for kozeny corrected drawdown for SL-PW-33.. **Error! Bookmark not defined.**

List of Tables

Table 1.Relation of well loss coefficient to well condition (after Walton). 19

Table 2 : Akaki phase IIIB well project information 32

Table 3Well efficiency of Akaki phase IIIB Deep Wells. 40

Table 4.Values of B, C and well efficiency calculated for SL -PW -07 based on figure 10. 40

Table 5kozeny correction factor for partial penetration of nine well 42

Table 6Summery of Transmissivity 42

Table 7Pumping and recovery time 46

Table 8 Rang of operational drawdown between analysis and reference drawdown 48

Table 9 Operational Efficiency 50

Table 10 Efficiency Of The Well For The Discharge Of Completion Report 50

Table 11 Difference between Design and Pumping Discharge 51

Table 13Efficiency and yield of 65% for 10 well 52

Table 13 values of E, Q, B, and C for WWDSE and analyzed SL-PW-10 58

Table 14 values of E, Q, B, and C for WWDSE and analyzed SL-PW-14 59

Table 15 values of E, Q, B, and C for WWDSE and analyzed SL-PW-18 59

Table 16 values of E, Q, B, and C for WWDSE and analyzed SL-PW-21 60

Table 17 values of E, Q, B, and C for WWDSE and analyzed SL-PW-33 61

CHAPTER ONE

1 INTRODUCTION

Water is essential for life on Earth, and the largest source of freshwater lies under the Earth's surface. Groundwater constitutes one portion of the earth's water circulatory system known as the hydrologic cycle. Water-bearing formations of the earth's crust act as conduits for transmission and as a reservoir for the storage of water. Practically all groundwater originates as surface water. The source of natural recharge includes precipitation, stream flow, lakes, and reservoir. Other contributions for groundwater recharge are artificial recharge occurs from execs irrigation, seepage from canal water. Groundwater is the sub-surface water that occurs beneath the water table in soils and geologic formations that are fully saturated (Freeze and Cherry, 1979). It is one of the most valuable natural resources, which supports human health, economic development, and ecological diversity. Because of its several inherent qualities (e.g., consistent temperature, widespread and continuous availability, excellent natural quality, limited vulnerability, low development cost, drought reliability), it has become an important and dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries (Todd, 2005). Of the 37 Mkm3 of freshwater estimated to be present on the earth, about 22% exist as groundwater, which constitutes about 97% of all liquid freshwater potentially available for human use (Foster, 1998). Groundwater resource management of an aquifer system involves developing a quantitative understanding of the flow processes that operate within the aquifer. Three main futures must be considered: how water enters the aquifer system how water passes through the aquifer system and how water leaves the aquifer system. Groundwater regime forecasting involves a study of modifications to the flow processes due to changes in any of these futures induced by natural and/or manmade processes.

Addis Ababa is the capital city of Ethiopia and Africa. Therefore, the city consists of governmental and non-governmental organization offices, different institutions, and public and private health centers and several commercial and industrial companies. For the first time, the modern water supply provision was introduced 15 years after the establishment of the city. Then the first surface water development with treatment plant at Gefersa has been established in 1930 with the increased demand of its population (PLAN, 2011).

At present Addis Ababa City is supplied with surface water from the Legedadi (180,000m3/day), Dire(no treatment plant contain raw water to feed Legedadi) and Gefersa reservoirs(30,000m3/day), and groundwater have been pumped from the Akaki well field located to the south of Addis Ababa(243,000m3/day) and Legedadi deep well (40,000m3/day) and other wells located within the city(810,000m3/day). The current total daily production is estimated to be 574,000m^3/day. (Henok M, 2018).

A current report on groundwater availability shows the decline in water levels in the well area as the rate of withdrawal of water in the area has increased and failure problems of the developed groundwater occurred. To overcome this problem safe groundwater generalization study of the aquifer is fundamental for the sustainability of the resource in the city.

The study area of this research is under development in Akaki area is located south of the city of Addis Ababa about 20km from the city center. The proposed source for the water supply project is groundwater, According to the latest hydro geological study result, the well field's yield capacity is estimated to be around 70,000m^3/d (Henok M, 2018).

1.1 Statement of the problem

Globally, demands for water supplies are significantly increasing along with drastic population growth, conflicts over agricultural land and pastures, change of climate, environmental protection, and governing laws and regulations for water use and allocations (Henok M, 2018).

Addis Ababa is the capital city of Ethiopia and Africa. At present Addis Ababa City Administration is supplied with surface water from the Legedadi, Dire, and Gefersa reservoirs and groundwater has been pumped from the Akaki well field located to the south of Addis Ababa and other wells and springs located within the city. The current total daily production is estimated to be 574,000m3/day but the demand was 930,000m3/day (Henok M, 2018).

So AAWSA can't fulfill the demand of the city. To meet this demand for safe and clean water supply the Addis Ababa City through Addis Ababa Water Supply and Sewerage Authority (AAWSSA) has embarked on groundwater development around the Addis Ababa area. One of these groundwater developments is that of 24 deep well developments in the Akaki area. The project intends to supply from twenty-four deep wells of Akaki phase IIIB Well field which can provide 70,000m3/day. Currently, the well field is not working up to its expectation. Such failure to attain the expected yield can be due to improper operation and maintenance of the wells. This research is thus trying to identify the problems related to operation and maintenance important in delivering the optimum yield from the wells in Akaki phase IIIB.

1.2 The objective of the research

1.2.1 General objective

The general objective of this research is to evaluate the real-time performance Akaki phase IIIB well field for possible operation and maintenance problem identification.

1.2.2 Specific objective

- Interpreting the existing well data by using standard methods
- Determining the properties of the aquifer from the pumping test data
- Determine the efficiency of the well both for operational and pumping test data.
- Identify the cause of possible operational and maintenance problems.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Groundwater

Water is essential for life on Earth, and the largest source of fresh water lies under the Earth's surface. Groundwater is an important source of water supply throughout the world. Wells drilled into the saturated zone are pumped and groundwater extracted for different purposes. Regularly most of the water pumped for the purposes of irrigation, water supply, and industrial uses. Freshwater makes up only 2.5% of all the water on earth, but not all of this water is available for human use. The water in polar ice caps, other forms of ice and snow, soil moisture, marshes, biological systems, and the atmosphere are not readily available. As a result, only the 10,530,000 km3 of groundwater, 91,000 km3 of fresh water in lakes, and the 2,120 km3 of water in rivers are considered attainable for use and comprise a total of 10,623,120 km3. Consequently, groundwater comprises 99% of the earth's available freshwater. It is uncertain when mankind first started extracting groundwater by artificial means such as wells or infiltration galleries. Early humans most likely drank from surface streams. They may also have discovered groundwater through the discharge of natural springs in some parts of the world and used this source in addition to surface streams. As streams dried up in hot weather, people learned to dig into the alluvium to find water below the surface (W.Delleur, 2007).

2.2 AQUIFERS

A permeable stratum or geological formation of permeable material, which is capable of yielding appreciable quantities of groundwater under gravity, is known, as an aquifer. The term "appreciable quantity" is relative (Kruseman, 2000).

2.3 Types of Aquifer

Depending upon the availability of groundwater, there are three main types of aquifer. Those are confined, unconfined and Leaky (Kruseman, 2000).

2.3.1 Confined aquifer

A confined aquifer is bounded above and below by an aquiclude. In a confined aquifer, the pressure of the water is usually higher than that of the atmosphere, so that if a well taps the aquifer, the water in it stands above the top of the aquifer, or even above the ground surface. We then speak of a free-flowing or artesian well (Kruseman, 2000).

Artesian or confined aquifers are common in glaciated regions of the world where a body of outwash sand and gravel may have been covered by clay-rich till or lacustrine sediments from subsequent glaciations. Along the way, it is sandwiched between impermeable or slightly permeable shale's which maintain its confined and artesian condition. Wells drilled into this aquifer, even hundreds of miles from its recharge area, often flow from the pressure within the aquifer(Jacques W.Delleur. et al.(2007))

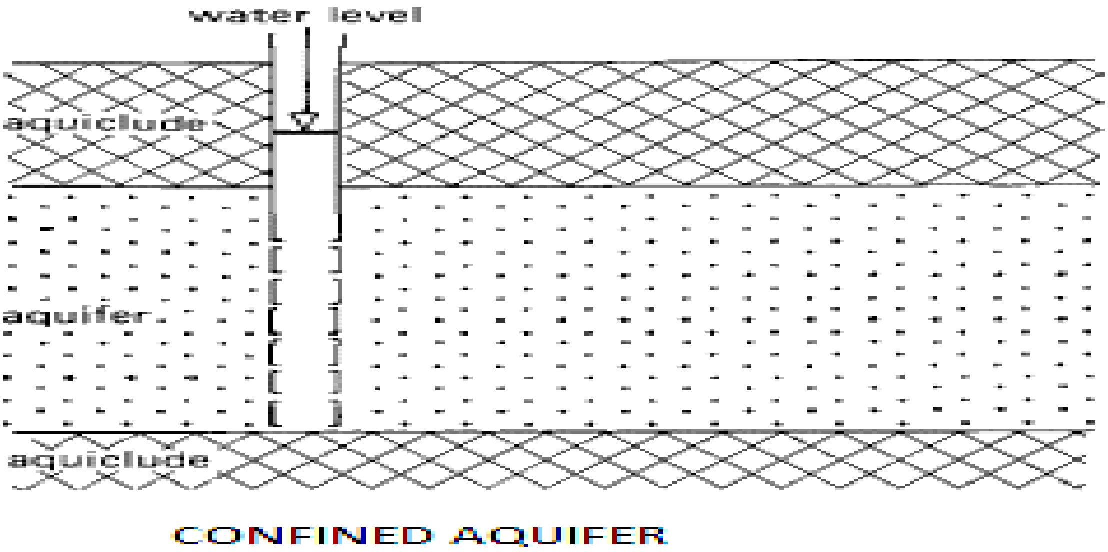


Figure 1: confined aquifer

2.3.2 **Unconfined aquifer**

An unconfined aquifer is also known as a water table aquifer, is bounded below by an aquiclude, but is not restricted by any confining layer above it. Its upper boundary is the water table, which is free to rise and fall. Water in a well penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the water table (Kruseman, 2000).

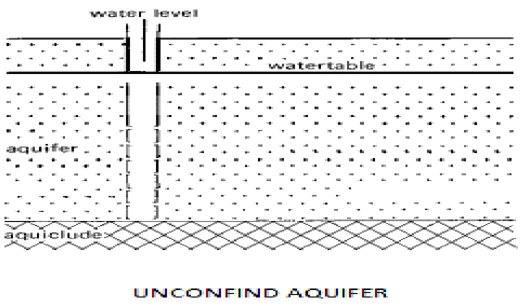


Figure 2: unconfined aquifer

2.3.3 Leaky aquifer

A leaky aquifer is also known as a semi-confined aquifer, is an aquifer that’s upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquiclude. Water is free to move through the aquitards, either upward or downward. If a leaky aquifer is in hydrological equilibrium, the water level in a well tapping it may coincide with the water table. The water level may also stand above or below the water table, depending on the recharge and discharge condition (Kruseman, 2000).

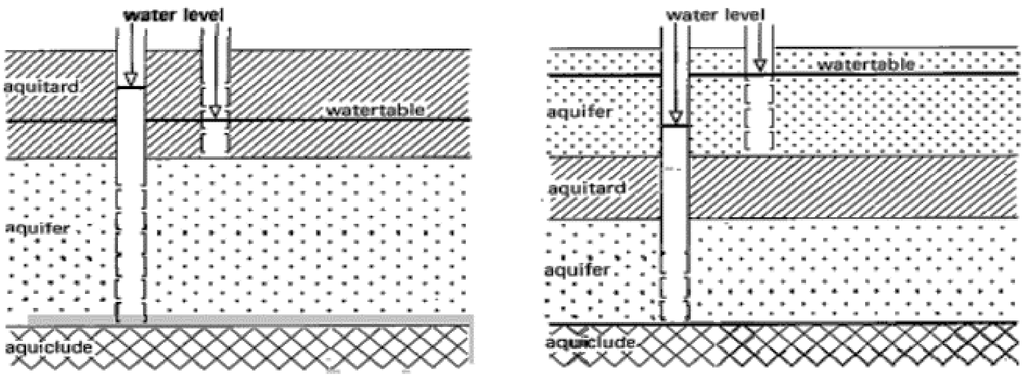


Figure 3.leaky aquifer

2.4 Aquifer Parameters

As groundwater becomes more important as a source of uncontaminated water, improved hydrogeological knowledge, new groundwater exploration technologies and data processing methods must be efficient to facilitate investigations and evaluation of groundwater resources. Many investigation techniques are commonly employed with the aim of estimating the spatial distribution of aquifer parameters such as hydraulic conductivity, transmissivity, and storativity and aquifer depth. Unfortunately, the conventional methods for the determination of hydraulic parameters such as pumping tests, and grain size analysis are invasive, relatively expensive and either integrate over the largest volume of data or provide information only to a small section of the aquifer in the surrounding area of the borehole. Accordingly, interpolating aquifer properties between boreholes is often difficult with little or no data in which to base these extrapolations. Therefore, in areas with little pumping test information, the spatial distribution of aquifer properties cannot be confidently calculated.

2.4.1 **Transmissivity**

Transmissivity is the product of the average hydraulic conductivity K and the saturated thickness of the aquifer D. Consequently, transmissivity is the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated Thickness of the aquifer.

Transmissivity is an essential hydraulic property of aquifers and water-bearing materials. In common with permeability, transmissivity provides a representation about the water-bearing features of hydro geological bodies. Transmissivity values enable us to assess possibilities of groundwater abstraction, in the first approximation. Therefore, knowledge of transmissivity distribution helps us to draw important conclusions from hydrogeological studies, and for this reason, prevailing transmissivity values are often represented in hydrogeological maps. They provide a basis for future groundwater exploration, development, abstraction and protection.

By definition, Transmissivity (T) is a measure of the amount of water that can be transmitted horizontally through a unit width by the fully saturated thickness of an aquifer under a hydraulic gradient equal to 1. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer and is given by:

$$T = Kb$$

Where;

K = hydraulic conductivity [LT-1]

b = saturated thickness of the aquifer [L]

The statistical distribution and prevailing values of permeability and transmissivity strongly depend on the relation of the magnitude of the elements of the heterogeneity of the rock to the extent of the studied area (Rats, 1967). Since transmissivity depends on hydraulic conductivity and saturated thickness, its value will differ at different locations within aquifers comprised of heterogeneous material, bounded by sloping confining beds, or under unconfined conditions where the saturated thickness will vary with the water table.

Despite the quantitative nature of transmissivity and its importance for quantitative appraisals, no objective classification of transmissivity has been introducing until Jiri Krasny published it on 1993 (Vol. 31 No. 2- GROUNDWATER- March- April 1993). Before this, quantitative or semi-quantitative terms describing transmissivity are often used, denominating different grades or classes as large, small, etc., but without strictly stating limits between them. This is the current case with hydrogeological maps where the inexactly defined term ‘’productivity’’ is sometimes used (cf.eg, IAH et al., 1983). Even if transmissivity is expressed numerically the verbal designation of the numerical classes might involuntary reflect the relation between hydrogeological condition and water demand. In areas where yields of the water well are sufficient to cover limited water consumptions transmissivity may be designated as high. On the other hand where well yields do not suffice for the large requirements transmissivity might be designated as low. Such a subjective approach prevents the objective comparison of the transmissivity at both local and regional scales, including vales represented on the hydrogeological maps.

As stated above pumping tests are the most frequent procedures used to determine transmissivity values that are often available as extensive data populations that may be used to characterize hydrogeological environments. Thus, the classification of transmissivity magnitudes and variation was proposed with the intention of expressing, representing and comparing available transmissivity data in a more objective manner.

2.4.2 **Specific storage**

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

$$S_s = \rho g(\alpha + n\beta)$$

Where p is the mass density of water (M/L3), g is the acceleration due to gravity (N/L3), and the other symbols are as defined earlier. The dimension of specific storage is Length-'(Kruseman, 2000)

2.5 Pump Test

In any given well filed, the aquifer system has to be, as much as possible, accurately known so that hydraulic parameters can be determined without any confusion. One way of knowing the aquifer system whether it is bounded or unbounded or if the system is being recharged from a nearby river or stream is to conduct pumping tests. The principle of a pumping test involves applying stress to an aquifer by extracting groundwater from a pumping well and measuring the aquifer response to that stress by monitoring drawdown as a function of time. These measurements are then incorporated into an appropriate well-flow equation to calculate the hydraulic parameters of the aquifer.

Ideally, an aquifer test should be performed under the natural conditions of a stable water table. This is, however, not always possible. Water tables rise and fall due to natural recharge and discharge of the groundwater reservoir (precipitation and evaporation), manmade recharge and discharge of the groundwater reservoir (irrigation losses and pumping from wells), changes in barometric pressure, and tidal movements in coastal aquifers. Such short-term variations of the water table have an adverse effect on the drawdown and recovery of the water table during testing. In well-filed pumping test principles Pumping tests can be single well and multiple well.

2.5.1 **Single well pumping tests**

A single well pumping test involves pumping at a constant or variable rate and measuring changes in water levels during pumping and recovery. Such tests are used to determine T and K when water level recovery is too rapid for slug tests and no observation wells or piezometers are available.

The drawdown in a pumped well is influenced by well loss and well-bore storage. Well loss is responsible for drawdown being greater than expected from theoretical calculations and can be classified as linear or non-linear. Linear loss is caused by compaction and/or plugging of subsurface material during well construction and installation and head loss in the filter pack and screen. Non-linear loss includes head loss from friction within the screen and suction pipe. Since well-bore storage is large when compared to an equal volume of formation material, it must be considered when analyzing drawdown data from single-well pumping tests (Kruseman and de Ridder, 1991). However, Papadopoulos and Cooper (1967) observed that the influence of well-bore storage on drawdown decreases with time (t) and becomes negligible at $t > 25rc^2$, where rc is the radius of the unscreened part of the well where the water level is changing. The effects of well-bore storage on early-time drawdown data can be determined by a log-log plot of drawdown (sw) versus time (t). Borehole storage effects exist if the early-time drawdown data plots as a unit-slope straight line (Kruseman and de Ridder, 1991).

General Assumption of Single Well Test

- The aquifer has an apparently infinite areal extent.
- The zone is homogeneous and of uniform thickness over the area influenced by the test
- Prior to the test, the water table or piezometric surface is (nearly) horizontal over the area influenced and extends infinitely in the radial direction.
- The head in the well is changed instantaneously at time to = 0.
- The inertia of the water column in the well and the linear and non-linear well losses are negligible (i.e, well installation and development process are assumed to have not changed the hydraulic characteristics of the formation).
- The well diameter is finite; hence storage in the well cannot be neglected.
- Groundwater density and viscosity are constant.
- No phases other than water (such as gasoline) are assumed to be present in the well or saturated portion of the aquifer.
- Groundwater flow can be described by Darcy's Law.
- Water is assumed to flow horizontally

Single well tests are more common than aquifer tests using monitoring wells due to the obvious advantage that only one well is needed. However, in practice, only transmissivity can be estimated, due to the high sensitivity of the (effective) well radius.

Some of the disadvantages of single-well tests are:

- Well construction (e.g. partial penetration) can lead to an underestimation of aquifer transmissivity.
- Storativity cannot be reliably determined; and
- Single well test analyses typically make no allowance for leakage, or other recharge/no-flow boundaries (SMITH, 2008).

2.5.2 Multiple well pumping tests

In Multi-Well aquifer test observation of the drawdown are recorded at some distance from the pumping well. In this case, drawdowns are measured against time in the observation wells. Hear the recorded data are more reliable since the drawdown measured in the observation well is more or less has laminar flow in the observation well. Multiple well tests is implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping or subsequent recovery. Properly designed and conducted multiple-well tests can be used to define the overall hydrogeologic regime of the area being investigated, including T, S and/or specific yield of a zone. They also can help design municipal well fields, predict rates of groundwater flow, determine interconnectivity between saturated zones, and design a remediation system. Two basic types are constant discharge and variable discharge. The former is performed by pumping at a constant rate for the duration of the test, while the latter is distinguished by changes in rate. Measurements obtained from the pumping well generally are less desirable for calculating hydraulic properties because of the irregularities induced from the operation of the pump and well bore storage. Obtaining data from observation well(s) allows for characterization of the pumped zone over a larger area (strickland, 2006).

General assumption of multiple well tests

- The aquifer is infinite in a real extent.
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test.
- Prior to pumping, the piezometric surface is horizontal, or nearly so, over the area to be influenced by the test.
- The well penetrates the entire thickness of the aquifer and, thus, receives water by horizontal flow.
- The water removed from storage in the aquifer is discharged instantaneously
- With decline of head.
- Non-linear well losses are negligible

2.6 Duration and types of the pumping test

The question of how many hours to pump the well in a pumping test is difficult to answer because the period of pumping depends on the type of aquifer and the degree of accuracy desired in establishing its hydraulic characteristics. Economizing on the period of pumping is not recommended because the cost of running the pump a few extra hours is low compared with the total costs of the test. Besides, better and more reliable data are obtained if pumping continues until steady or pseudo-steady flow has been attained. At the beginning of the test, the cone of depression develops rapidly because the pumped water is initially derived from the aquifer storage immediately around the well. But as pumping continues, the cone expands and deepens more slowly because, with each additional meter of horizontal expansion, a larger volume of stored water becomes available. This apparent stabilization of the cone often leads inexperienced observers to conclude that steady state has been reached. Inaccurate measurements of the drawdown in the piezometers - drawdown that are becoming smaller and smaller as pumping continue - can lead to the same wrong conclusion. In reality, the cone of depression will continue to expand until the recharge of the aquifer equals the pumping rate. In some tests, steady-state or equilibrium conditions occur a few hours after the start of pumping; in others, they occur within a few days or weeks; in yet others, they never occur, even though pumping continues for years. It is our experience that, under average conditions, a steady-state is reached in leaky aquifers after 15 to 20 hours of pumping; in a confined aquifer, it is good practice to pump for 24 hours; in an unconfined aquifer, because the cone of depression expands slowly, a longer period is required, say 3 days. It is not absolutely necessary to continue pumping until a steady-state has been reached, because methods are available to analyze unsteady-state data. Nevertheless, it is good practice to strive for a steady-state, especially when accurate information on the aquifer characteristics is desired, say as a basis for the construction of a pumping station for domestic water supplies or other expensive works. If a steady-state has been reached, simple equations can be used to analyze the data and reliable results will be obtained. Besides, the longer period of pumping required to reach steady-state may reveal the presence of boundary conditions previously unknown, or in cases of fractured formations, will reveal the specific flows that develop during the test. Preliminary plotting of drawdown data during the test will often show what is happening and may indicate how much longer the test should continue (Kruseman, 2000).

2.6.1 **Preliminary Pump Test**

Before implementing a constant-rate or step-drawdown pumping test, the well should be developed adequately to reduce the influence of well construction on aquifer response. Preliminary pumping test are usually the first tests that are performed during well-pumping tests. They are implanted so that the well can settle. This provisional pumping test is commonly conducted for 2 hours prior to step drawdown test;

- to check the possible discharge of the well,
- to check the maximum anticipated drawdown,
- To decide the pump position for the step drawdown test.

2.6.2 Step-Drawdown Pumping Test

Step drawdown tests are normally conducted to assess well/aquifer-loss performance and for guidance in selecting an optimum pumping rate for a subsequent, longer-duration, constant-rate pumping test. The test is conducted as a series of sequential, short-duration constant-rate pumping tests, with each step conducted of uniform duration and at progressively higher pumping rates. Step-drawdown tests are nowadays quite popular, they are the most frequently performed tests in the case of single well (Kawecki 1995). There are various reasons why they are performed: in the case of exploration wells, they allow to determine the proper discharge rate for the subsequent aquifer test, to understand the behavior of the well during the pumping, to determine the optimum production capacity and to analyses the well performance over time (Boonstra and Kselik 2001). This test is also used in determining efficiency of the well.

2.6.3 Constant-Rate Pumping Test

The constant-rate test is the most common type of pumping test performed, and its concept is very simple: the borehole is pumped at a constant rate for an extended period (from several hours to several days or even weeks) while the water levels and pumping rates are monitored. During constant-rate pumping tests, groundwater is extracted from the aquifer and regulated to maintain a constant, uniform rate. The pressure response within the pumped well is monitored during the active withdrawal (drawdown) phase. Ideally, a constant-rate test should be long enough for the water level to reach or at least approach equilibrium. How long it takes to do this depends on the hydraulic properties of the aquifer. Usually, the drawdown against time is recorded a period of 72 hours by keeping the discharge at a uniform rate.

Maintaining a steady pumping rate during a constant rate test is sometimes a problem, especially if the chosen pumping rate results in a large drawdown. This is because for centrifugal pumps (the most commonly used type of pump) there is a relationship between pumping rate and pumping head. Incidentally, the pump must be set at a depth that is several meters below the deepest water level expected during the test. During a constant-rate test, it is worth roughly plotting the data in the field as the test proceeds, in case these deviations are observed. Decisions can then be made about extending or shortening the planned test length, or trying a different pumping rate.

2.6.4 Recovery Test

When the pump is shut down after a pumping test, the water levels in the well and the piezometers will start to rise. This rise in water levels is known as residual drawdown**.** It is expressed as the difference between the original water level before the start of pumping and the water level measured at a time after the cessation of pumping. The recovery test is not strictly a pumping test, because it involves monitoring the recovery of the water level after the pump has been switched off. Recovery tests are valuable for several reasons:

- They provide a useful check on the aquifer characteristics derived from pumping tests, for very little extra effort – just extending the monitoring period after the pump has been switched off.
- The start of the test is relatively ‘clean.’ In practice, the start of a constant-rate test, for example, rarely achieves a clean jump from no pumping to the chosen pumping rate. Switching a pump off is usually much easier than starting a pump, and the jump from a constant pumping rate to no pumping can be achieved fairly cleanly.
- Similarly, recovery smoothes out small changes in the pumping rate that occurred during the pumping phase, and there is no problem with well losses from turbulent flow. This results in more reliable estimates of aquifer properties when the recovery data are analyzed.

Ideally, the duration of the recovery test should be as long as is necessary for the water to return to its original level, which, theoretically, would be as long as the duration of the pumping phase of the test program. In practice, however, the recovery test is often shorter, partly for reasons of cost (keeping equipment and personnel on the site). In theory, the recovery curve should be a mirror image of the drawdown curve, as long as it is measured from the extension to the drawdown curve. However, In practice, the water level may not actually recover to the original rest level for a variety of reasons, such as

- The aquifer might be of limited extent with no recharge having taken place, in which case the recovered rest water level may be lower than the original one (conversely, if recharge occurs during the test, recovery may occur sooner than expected).
- Some confined aquifers are not perfectly elastic, so they behave differently on recovery (they have a different storage coefficient).

- In unconfined aquifers, air may be trapped in pore spaces on rewetting of the dewatered portion of the aquifer.

2.7 Correction of Pump Test Data

Pumping tests are used to determine in-situ properties of water-bearing formations and define the overall hydrogeological regime. Such tests can determine transmissivity (T), hydraulic conductivity (K), storativity (S), connection between saturated zones, identification of boundary conditions, and the cone of influence of pumping well in a groundwater extraction system.

The water-level data collected before, during, and after the test must be converted to drawdowns by subtracting the static water from the measured water level and should be expressed in appropriate units. Before being used in the analysis, the observed water levels may have to be corrected for external influences (i.e. those not related to the pumping). To find out whether this is necessary, one has to analyze the local trend in the hydraulic head or water table. The most suitable data for this purpose are the water level measurements taken. If, after the recovery period, the same constant water level is observed as during the pre-testing period, it can safely be assumed that no external events influenced the hydraulic head during the test. If, however, the water level is subject to unidirectional or rhythmic changes, it will have to be corrected. Unidirectional variation is when the aquifer is 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. Rhythmic fluctuations of the hydraulic head may be atmospheric pressure. 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.

2.7.1 **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 by 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 aquifer's original saturated thickness. Where this occurs, the Jacob (1944) correction may be applied:

$$Scor=s(1-S/2D) \quad (2.3)$$

Where; Scor is the corrected drawdown,

s is observed drawdown and

D is the original saturated aquifer thickness.

However, this correction is based on the Dupuit-Forchheimer assumption (groundwater flows horizontally and hydraulic gradient is equal to the slope of the water table). Neuman (1975) showed that this assumption is not valid for an unconfined aquifer until the later portion of the test when the drawdown matches the Theis type curve. Therefore, the correction is not recommended with early and intermediate data (Dawson and Istok, 1991).

2.7.2 **Well Efficiency and Correction for Well Loss**

The drawdown in a pumped well consists of two components: the aquifer losses and the well losses. Aquifer losses are the head losses that occur in the aquifer where the flow is laminar. They are time-dependent and vary linearly with the well discharge. Well loss is associated with turbulent flows caused by flow through the well screen and flow inside of the well to the pump intake.

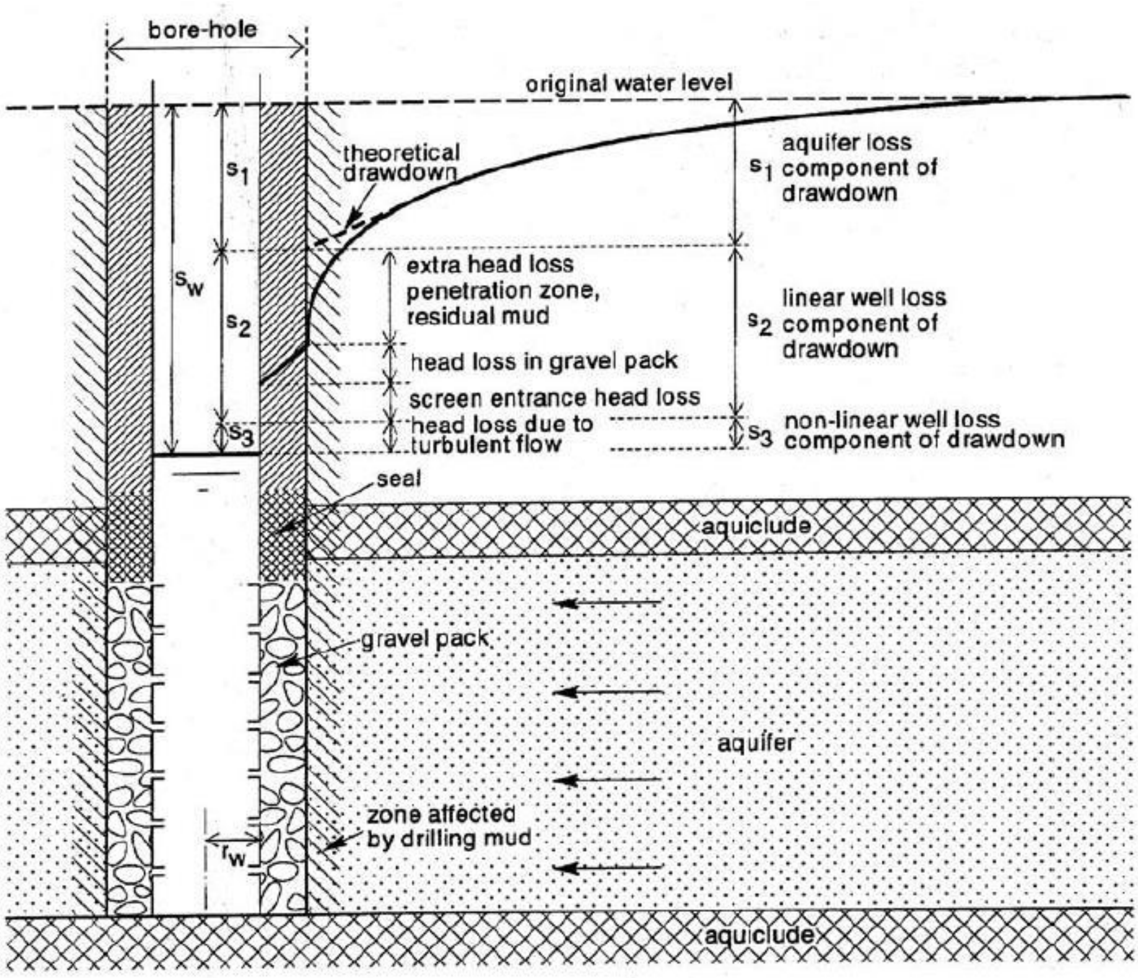


Figure 4 Various components of head losses in a pumped well.

Well loss is the difference between the actual measured drawdown in the pumping well and the theoretical drawdown due to groundwater flow through the aquifer's porous media. This theoretical drawdown is also called the formation loss. Equations of theoretical drawdown should be applicable to the actual aquifer (formation) conditions, such as confined, unconfined, leaky, with delayed gravity response, quasi-steady-state, or transient. Well loss is the result of various factors, such as an inevitable disturbance of the porous medium near the well during drilling, an improper well development (e.g., drilling fluid is left in the formation and mud cake along the borehole is not removed), a poorly designed gravel pack or well screen, and turbulent flow through the gravel pack and the well screen. Well loss is always present in pumping wells, and its evaluation is an important part in deciding if the well performance is satisfactory or not. All wells will experience a decrease in well efficiency sooner or later, as indicated by an increased well loss. Three-step pumping test is the only reliable means of quantifying the well loss, and it should be performed not only after well completion but also periodically during well exploitation to evaluate the well performance and needs for possible well rehabilitation (kersic, 2009).

The total measured drawdown (sw) at well is a combination of the linear losses and turbulent losses:

$$\mathbf{sw = AQ + BQ^2}$$

Where A= coefficient of the linear losses,

B = coefficient of turbulent losses, and

Q = pumping rate

The turbulent losses are usually assumed to be quadratic, but other powers may be used to describe it. The linear losses (A) include both the formation loss (A0) and the linear loss (A1) in the near-screen zone:

$$\mathrm{A = A0 + A1}$$

For practical purposes, A1 can usually be ignored. The formation loss or the theoretical drawdown in the well (s0) is determined by using the appropriate equation for the specific flow condition. For example, in the case of a quasi-steady-state flow in a confined aquifer, the equation is as follows:

$$\mathrm{so} = \frac{\mathrm{Q}}{2\pi\mathrm{T}} \ln \frac{\mathrm{R}}{\mathrm{rw}}$$

Where s0= drawdown due to groundwater flow through the aquifer porous media

T = transmissivity

R = radius of well influence

rw= well radius

The coefficient of linear formation loss (A0) can be calculated as follows:

$$\mathrm{Ao} = \frac{1}{2\pi\mathrm{T}} \ln \frac{\mathrm{R}}{\mathrm{rw}}$$

The general equation describing the drawdown in a pumped well as function of aquifer/well losses and discharge rate can be written as

S= (B1+B2) Q + CQp(2.4)

Or

S=BQ+CQP **(2.5)**

Where;

S is the total drawdown

Q is the discharge

C is the non- liner well loss coefficient

P is exponent

B is the liner well loss coefficient

Values of the three parameters B, C, and P in the above equation can be found from the analysis of so-called step-drawdown tests. Jacob (1947) used a constant value of 2 for the exponent P. According to Lennox (1966), the value of P can vary between 1.5 and 3.5, its value may be even higher in fractured rock aquifers. The value of P = 2 as proposed by Jacob is, however, still widely accepted.

well loss can be a substantial fraction of the total drawdown when pumping rates are large. With proper design and development of new well, well losses can be minimized. Clogging or deterioration of well screens can also increase well losses in old wells. Based on field experiences, Welton suggested criteria for the non-linear well loss coefficient C as shown in Table 1.

Table 1.Relation of well loss coefficient to well condition (after Walton).

Well lose coefficient (C)min2/m5	Well conditions
< 0.5	Properly designed and developed
0.5 to 1.0	Mild deterioration or clogging
1.0 to 4.0	Severe deterioration or clogging
>4.0	Difficult to restore well to original capacity

Knowing B and C, we can predict the drawdown inside the well for any realistic discharge Q at a certain time t (B is time-dependent). We can then use the relationship between drawdown and discharge to choose, empirically, an optimum yield for the well, or to obtain information on the condition or efficiency of the well. We can use it to express the relationship between drawdown and discharge as the specific capacity of a well (Q/s) which describes the productivity of both the aquifer and the well. The specific capacity is not constant but decreases as pumping continues (discharge is constant), and also decreases with increasing discharge.

2.7.3 Well Efficiency

Well efficiency is the ratio between the theoretical drawdown and the actual drawdown measured in the well. It is expressed in percent:

$$\text{Well Efficiency} = \frac{\text{Theoretical Drawdown (s0)}}{\text{Measured Drawdown (sw)}} * 100\%$$

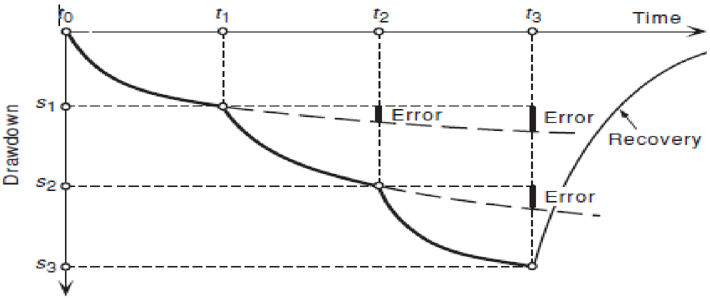


Figure 5: components of drawdown recorded at the end of each step showing errors made if drawdown's s1,s2, and s3 were used directly to draw graph Q versus S/Q

$$\mu = \frac{S_t}{S_a}$$

Where: $S_{a=S_t+S_w}$

$$\mu = \frac{S_t}{S_{t+}S_w}$$

$$\mu(S_{t+}S_W) = St$$

$S_{W=}(\frac{1-\mu}{\mu})S_t$ Or $S_{t=}(\frac{\mu}{1-\mu})S_t$

$$S_{a=}(\frac{\mu}{1-\mu} + 1)S_W$$

$$S_{a=}(\frac{1}{1-\mu})S_W$$

$$S_{W=}(1-\mu)S_a$$

As explained earlier, the theoretical drawdown is determined by applying an appropriate equation of groundwater flow toward a well (theoretical drawdown equals the formation loss). It can also be found graph analytically as explained earlier. In general, the difference between the theoretical drawdown and the measured drawdown increases with increasing pumping rate as shown in Fig. 4. Consequently, well efficiency decreases with an increased pumping rate. Determining well efficiency and well loss is highly recommended because it provides valuable information about the well performance and can be used to make an informed decision regarding the well pumping rate, maintenance, and rehabilitation.

A well efficiency of 70 percent or more is usually considered acceptable. If a newly developed well has less than 65 percent efficiency, it should not be approved without a thorough analysis of the possible underlying reasons. This may include well redevelopment followed by new performance testing(kersic, 2009).

The relationship between drawdown and discharge can be expressed as the specific capacity of a well, $\frac{Q}{S_W}$, which describes the productivity of both the aquifer and the well. The specific capacity is not 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.

$$E_w = \left\{ \frac{B_1 Q}{BQ + CQ^P} \right\}$$

The well efficiency according to the Equation above can be assessed when both the results of a step-drawdown and those of an aquifer test are available. The former is needed for the values of B, C, and P and the latter for the value of B1.

In practice, only the results of a step-drawdown test are usually available. The substitution of the B, C, and P values into the Equation above would overestimate the well efficiency because of B >B1. For these cases, Driscoll (1986) introduced another parameter, Lp, being the ratio of the laminar head loss to the total head losses; it reads when expressed as a percentage (W.Delleur, 2007)

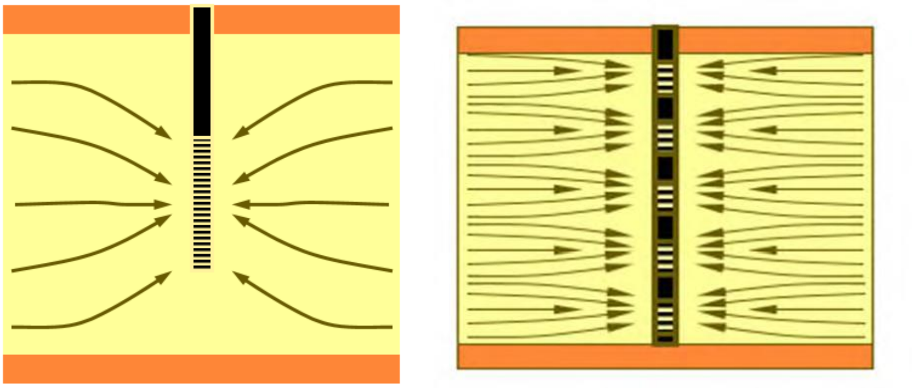
$$L_P = \left\{ \frac{B_1 Q}{BQ + CQ^P} \right\} * 100$$

2.7.4 Correction for Partial Penetration

It is quite common in developing aquifer drilling, entire aquifer thickness cannot be drilled, and the thickness is not known. But most analysis for aquifer properties considers/assumes the well to penetrate the aquifer fully and this assumption does not satisfy pumping tests. Therefore, it is necessary to consider the effects of partial penetration.

There are two cases where partial penetration may occur. The first case is when the aquifer is not fully penetrated and the second case arises from the casing arrangement of the well. These two cases are shown below in figure 9.

Partial penetration of the well into the aquifer causes the vertical component flow to happen in the vicinity of the well and which in turn causes a head loss in the pumping well. When the well only partially penetrates the aquifer, the average flow path length is increased so that greater resistance to flow is encountered.



(a) (b)

Figure 6 Partial Penetration (a) when the aquifer is not fully drilled (b) due to the Blind and Screen section of the well.

Kozeny (1933) contributes the following approximate reduction factor to correct specific capacity (Q/s) for the effects of partial penetrations.

$F=L/b[1+7\cos(\pi L/(2b))\sqrt{(r/2L)}]$

Where

b = is the total aquifer thickness (m)

r = is the well radius (m); and

L = is screen length (m).

The equation is valid for L/b < 0.5 and L/r > 30. Accordingly the required correction for the possible effect of partial penetration is conducted by considering the geometric mean

2.8 Estimate Aquifers Parameters and Pumping test Analysis

It is relatively easy to calculate hydraulic characteristics if the aquifer system (i.e. aquifer plus well) is precisely known. This is generally not the case, so interpreting a pumping test is primarily a matter of identifying an unknown system. System identification includes the construction of diagnostic plots and specialized plots. Diagnostic plots are log-log plots of the drawdown versus time since pumping started. Specialized plots are semi-log plots of drawdown versus time or drawdown versus distance to the well; they are specific for a given flow regime. Both plots must be constructed because the diagnostic value lies in the typical combination of the log-log and semi-log plots. The choice of a theoretical model is a crucial step in the interpretation of pumping tests. If the wrong model is chosen, the hydraulic characteristics calculated for the real aquifer will not be correct. Unfortunately, the theoretical solutions of well flow problems are not unique. Some models developed for different aquifer systems, yield similar responses when required to handle given stress. This means that besides the log-log and semi-log plots of the drawdown versus time, all other relevant hydrogeological information, e.g. lithology, boundary conditions, should be taken into account(v.s.kovalevsky, 2004).

In this thesis, the method used for the determination of the aquifer parameters areTheis curve-matching method, Cooper-Jacob straight-line method and residual/recovery drawdown vs time method is used to determine the hydraulic parameters of the aquifer by analyzing aquifer test data.

Cooper-Jacob Method

It was observed by Cooper and Jacob (1946) that for small values of r and large values of t, u is so small, that the series of W (u)in Eq.$S = \frac{Q}{4\pi T} W(u)$ to becomes negligible after the first two terms. Therefore, for small values of u (u < 0.01) the drawdown can be approximated by using the following relationship:

$$S = \frac{Q}{4\pi T}\left(-0.5772 - \log e \frac{r^2 S}{4Tt}\right)$$

$$= \frac{Q}{4\pi T}\left(\log_e \frac{4Tt}{r^2 S} - 0.5772\right)$$

This reduces to $S = \frac{2.30Q}{4\pi T}\log_{10}(\frac{t_2}{t_1})$

If s1 and s2 are the drawdowns at time t1 and t2 since pumping started

$S2 - S1 = \frac{2.30Q}{4\pi t}\log 10(\frac{t2}{t1})$

If the time-drawdown data on a pumping well is plotted on a semi-log paper (Fig. 2.10) and for convenience t1 and t2are chosen one log cycles apart,

$$\log 10\frac{t_2}{t_1} = 1, \text{and if } S_{2\_}S_{1=}\Delta S, \text{then}$$

$$\Delta S = \frac{2.30Q}{4\pi T}$$

$$T = \frac{2.30Q}{4\pi\Delta S}$$

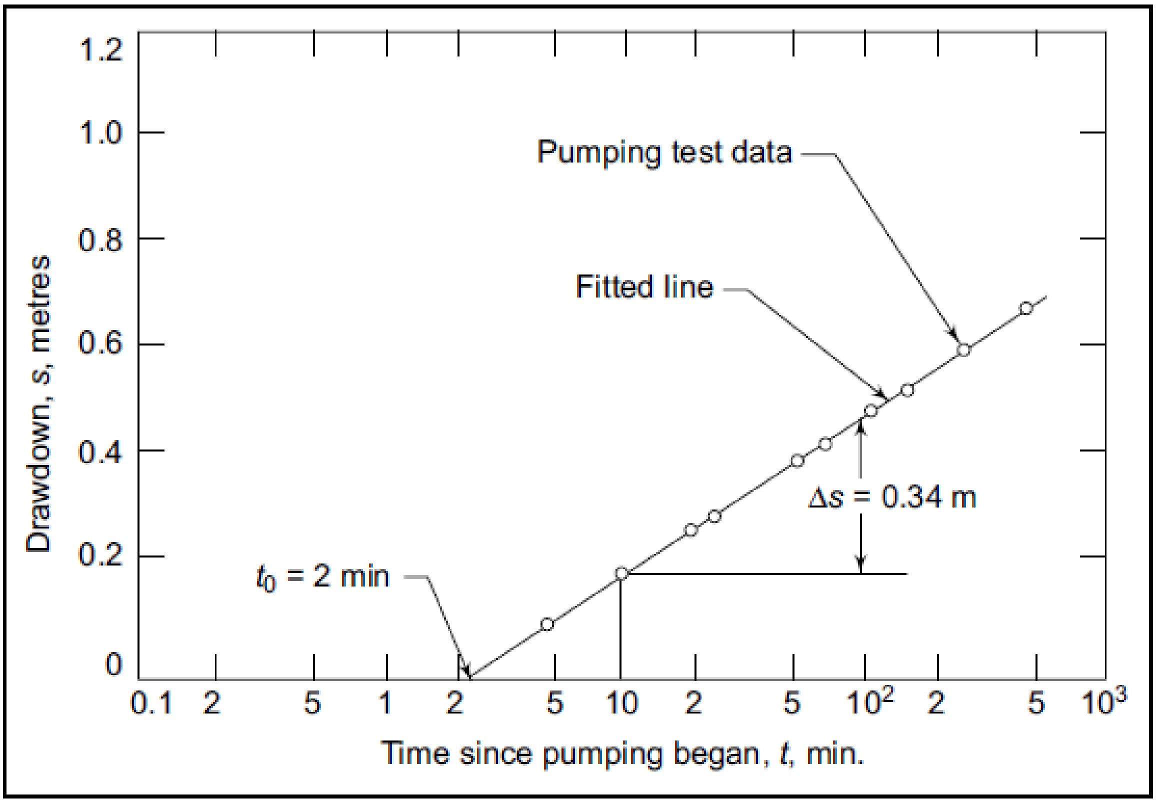


Figure 7: Cooper-Jacob method for the solution of a non-equilibrium equation

From equation $S = \frac{2.30Q}{4\pi T}\log_{10}(\frac{t_2}{t_1})$

$$S = 0 \text{ when} \log_{10}\frac{2.25Tt}{r^2S} = 0$$

i.e. when $\frac{2.25Tt}{r^2S} = 1$

Therefore, a plot of drawdown s versus the logarithm of t forms a straight line. Projecting this line to s = 0, where t = t0, the time for s = 0 can be noted and S can be computed as

$$S = \frac{2.25Tt_0}{r^2}$$

Recovery Test

When the pump is stopped at the end of a pumping test; the water level in the well and in the observation well start rising. This is referred to as the recovery of groundwater level. The fall in water level (drawdown) below the original static water level (before pumping) and during the recovery period is known as residual drawdown. Figure 2.13 shows a schematic diagram of change in water level with time during and after pumping.

The transmissibility of the aquifer can be calculated by analyzing the residual drawdown, which will provide an independent check on pumping test results. The rate of recharge to the well during the recovery period is assumed to be constant, whereas it becomes difficult to control the pumping rate in the field. Moreover, in the case of a recovery test, measurements of recovery can also be made in the well in the absence of an observation well. The residual drawdown s_ can be calculated as follows (Theis, 1935):

$$S' = \frac{Q}{4\pi T}(\,W(u) - W(u'))$$

Where,

Su $= \frac{r^2S}{4Tt}$Andu$' = \frac{r^2S}{4Tt'}$

Figure 12 defines t and t’. For small value of r and large values of t’

Equation can$S' = \frac{Q}{4\pi T}\big(W(u) - W(u')\big)$be approximated as

$$S' = \frac{2.30Q}{4\pi T}\log\frac{t}{t'}$$

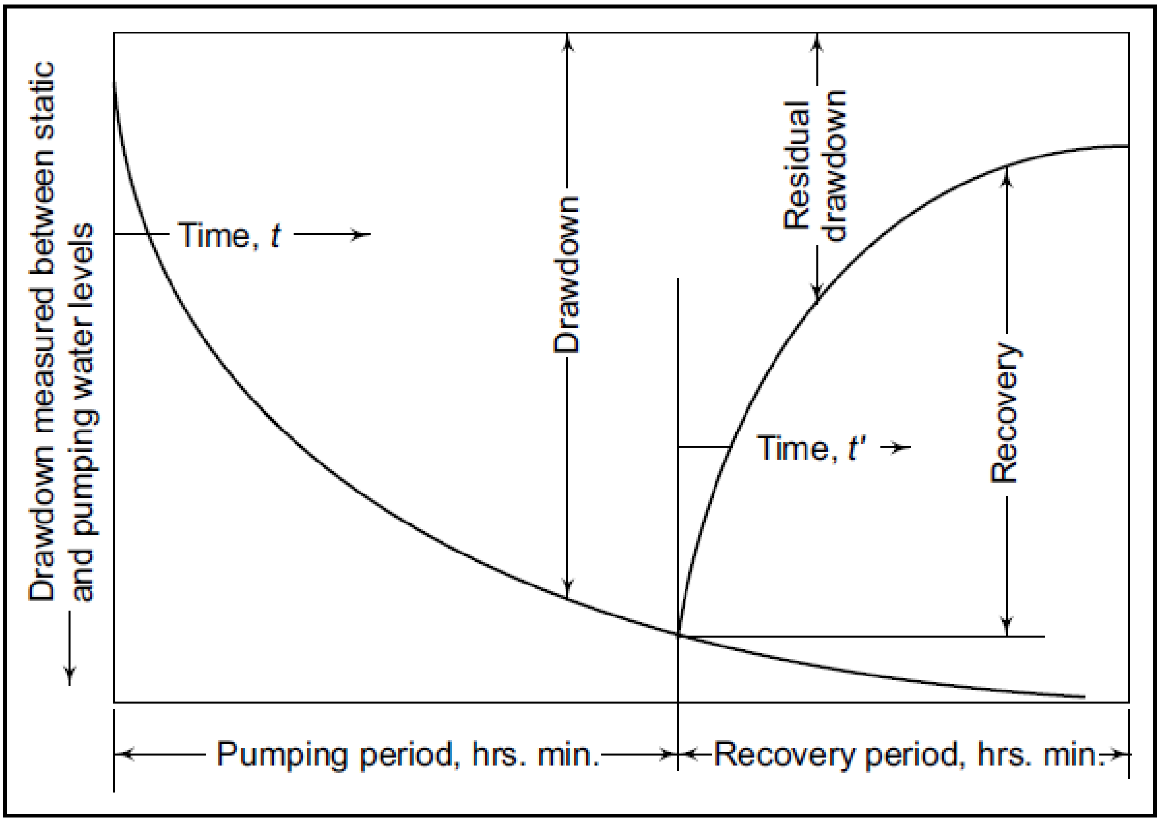


Figure 8: the drawdown and recovery curves near observation well near a pumping well

The residual drawdown S' versus $\frac{t}{t'}$ are plotted on a semi-logarithmic paper. The slope of the straight line so plotted equals 2.30Q/4πT, so that for $\Delta S'$, the residual drawdown per log cycle of t/t', the transmissibility becomes

$$T = \frac{2.30Q}{4\pi\Delta S'}$$

The recovery test method cannot be used to determine the comparable value of S (A.M.MICHAEL, 2008)

2.9 Causes of well failure

Water well problems result from many causes including equipment failure, depletion

of the aquifer, corrosive qualities of the water, and improper well design and construction.

There are several basic causes of well failure

- Design stage
- construction
- Aquifer characteristic estimation/analysis
- During operation (yield and time of operation)

- Maintenance

Design and construction stage

- Improper well design and construction
- Incomplete well development

Improper well design and construction

When designing a well, the licensed water well contractor must match the type of well Construction with the characteristics of the producing aquifer. Decisions must be made about:

- Perforated well casing/liner vs. well screen
- Slot size of well screen
- Placement of well screen or perforated liner
- Size and amount of sand pack around the well screen (if required)
- Location of the pump in the well.

If poor choices are made, you may experience problems with sediment in your water or reduced well yield. Provincial regulations require that a well must be completed to ensure no damage will be incurred to the pumping system, plumbing, or fixtures due to sediment in the water.

Incomplete well development

During drilling, mud and borehole cuttings can partially plug the aquifer. This material must be fully removed by the licensed water well contractor to allow water to freely enter the well. This procedure is part of well development. If the well has not been fully developed, you may experience problems with sediment in your water or low well yield.

Aquifer characteristic

- Borehole stability problems
- Incrustation build-up
- Corrosion
- Aquifer problems

Borehole stability problems

Borehole stability problems can result from damaged casing and screens, borehole wall collapse, corrosion, or excessive water velocities into the well. High water velocity can cause formation particles, like sand, to flow into the well, causing the eventual collapse of the borehole wall. The proper materials must be selected and installed to avoid such problems.

A combination of poor materials, improperly placed screens, and a poor well seal make it uneconomical to maintain and restore such a well. Often the most cost-effective solution is to drill a new well that is properly designed and constructed.

Aquifer problems

While most well problems are related to the construction, development or operation of the well, the formation can also be a source of problems. Reduced aquifer yield can be caused by a lack of recharge. For example, the amount of water withdrawn can exceed the recharge from rain and snowmelt. This is referred to as "mining the aquifer". Sometimes the decline in water level is seasonal. Typically water levels are higher in spring and lower in the fall. Extended dry periods can also impact water levels, especially in shallow water table-type aquifers.

Checking the water level in your well is an important maintenance procedure. You will be able to identify water level trends and identify well problems or aquifer depletion before the problem becomes serious.

Now go back to the exercise at the start of this module. Try to identify possible causes for each problem you identified.

Over-pumping

A well is over-pumped if the water is withdrawn at a faster rate than the well was designed for or the aquifer can produce. Over-pumping is the most common well problem that leads to premature well failure. Over-pumping not only depletes the groundwater aquifer (or source), but it rapidly increases the rate of corrosion, incrustation, and befouling related problems.

Over-pumping also increases the rate of sediment particles moving toward the well, causing plugging of the perforated area where water flows into the well. It can also cause the aquifer to settle and compact which further restricts water flow to the well.

There are four common symptoms associated with most water well problems:

- Reduced well yield
- Sediment in the water
- Change in water quality
- Dissolved gas in the water.

2.10 WELL REHABILITATION

A new well, properly drilled, cased, and developed, will give years of satisfactory service with little attention. Many wells fail, however; that is, they yield decreasing quantities of water with time. Well rehabilitation refers to the treatment of a production well by mechanical, chemical, or other means to recover as much as possible of the lost production capacity.

One case of failure is the depletion of the groundwater supply. Not a fault of the well, this trouble can sometimes be remedied by decreasing pumping drafts, resetting the pump, or deepening the well. The second cause of well trouble results from faulty well construction. Such items as poor casing connections, improper perforations or screens, incomplete placement of gravel packs, and poorly seated wells are typical of difficulties encountered. Depending on the particular situation as determined from television or photographic survey of the well. It may be possible to repair the well, but sudden failures involving the entrance of sand or collapses of a casing often require the replacement of the entire well.

The third and most prevalent cause of well failure results from corrosion or incrustation of well screen. Corrosion may result from the direct chemical action of the groundwater or electrolytic action caused by the presence of two different metals in the well. The effects of corrosion can be minimized by selecting nonmetallic well screens or ones of corrosion-resistant metal (such as nickel, copper, or stainless steel), and by providing cathodic protection. If the damage is localized, it may be possible to insert a liner inside the screen to prevent excessive sand pumping (Todd, 2005).

CHAPTER THREE

3 RESEARCH METHODOLOGY

3.1 Description of the Study area

Akaki well field is located south of the city of Addis Ababa about 20km from the city center. Addis Ababa deep wells water supply of phase III B project lies within the UTM coordinates of (475965, 480234) East and (974672, 978362) North and the average elevation is about2,070m a.s.l. There are twenty-four wells develop in the Akaki phase III B project which covers 14.5 km^2 area.

The average target depths intended to drill at the site under the contract agreements was 500m production wells however there was a possibility of increasing or decreasing the drilling depth by 10% production wells under the contract Agreements. It was arranged and managed to drill to the maximum depth up to 623m to get more information about the extent of the aquifer, water quality variation, and the aquifer thickness (WWDSE, 2015).

3.2 Basic Description of each of the Wells

As per the contract agreement between Addis Ababa Water and Sewerage Authority (AAWSA) and Water Works Design and Supervision Enterprise (WWDSE) on Nov 28/2008 for detailed study, investigation, supervision of drilling and testing of test wells, pilot production wells and production wells has been carried out, to evaluate groundwater potential and safe yield of boreholes in selected groundwater prospective sites around Addis Ababa City and its surroundings. Drilling and testing of water wells were carried out by many drilling Contractors, who have signed separate contractual agreements with Addis Ababa Water and Sewerage Authority.

Akaki phase IIIB is one of the water supply projects implemented to alleviate the prevailing unsatisfactory water supply situation at the capital city, which is an important service for one of the most water deficit areas of the city-western & central Addis Ababa. The project is based on groundwater sources, specifically of 24 deep wells in the Akaki well field with a discharge of 70,000m3/day. Out of 24 deep wells 14, deep wells have no operational SCADA data which means that their sensors were damaged. Those wells are SL-PW-03, SL-PW-04, SL-PW-05, SL-PW-06, SL-PW-08, SL-PW-09, SL-PW-12, SL-PW-13, SL-PW-15, SL-PW-16, SL-PW-17, SL-PW-19, SL-PW-20, and SL-PW-22. The rest 10 wells have operational (scada) data. Those wells are SL-PW-07, SL-PW-10, SL-PW-14, SL-PW-18, SL-PW-21, SL-

PW-33, SL-PW-11, and SL-PW-24. From 10 deep wells which have operational data all of them, operational draw dawn are out of analysis draw dawn and referenced draw dawn.

Table 2: Akaki phase IIIB well project information

No	Prospective site/well field	Well Index	Well type	Coordinate UTM Zone 37 Adindan		Elev, m	Depth, m	Static water level, m	Dynamic water level, m	Drawdown, m	Q, test, (l/S)
				UTM east	UTM north						
1	Akaki	SL-PW-03	production well	475276	976930	2052	582	54.32	128.99	74.67	75.44
2	Akaki	SL-PW04	production well	476037	976861	2068	595	55.18	91.25	36.07	88
3	Akaki	SL-PW-05	production well	475058	976100	2062	502	48.79	68.99	20.2	91
4	Akaki	SL-PW-06	production well	475528	975870	2059	600	52.02	86.4	34.38	86.5
5	Akaki	SL-PW-07	production well	476098	976183	2076	550	53.52	131.03	77.51	46.7
6	Akaki	SL-PW-08	production well	474528	975585	2057	569	49.06	73.5	24.44	95
7	Akaki	SL-PW-09	production well	473954	975244	2068	600	64.54	78.72	14.18	70.43
8	Akaki	SL-PW-10	production well	473954	975244	2053	591	49.28	133.39	84.11	55
9	Akaki	SL-PW-11	production well	471453	974241	2048	335	50.04	63.35	13.31	112.7
10	Akaki	SL-PW-12	production well	475507	974697	2046	320	49.45	55.95	6.5	113.48

11	Akaki	SL-PW-13	Production well	472078	974359	2050	319	51.65	57.57	5.92	106
12	Akaki	SL-PW-14	Production well	472640	973882	2072	518.5	70.25	98.33	28.08	84.9
13	Akaki	SL-PW-15	Production well	473428	973584	2078	623	70.55	134.5	63.95	32.35
14	Akaki	SL-PW-16	production well	474702	974792	2069	595	69.98	97	27.02	98
15	Akaki	SL-PW-17	Production well	474733	973382	2072	501	78.54	124.67	124.67	34.55
16	Akaki	SL-PW-18	production well	477023	973986	2090	503	84.85	114.61	29.76	66.17
17	Akaki	SL-PW-19	production well	476375	974046	2091	568	90.5	147.06	56.56	27
18	Akaki	SL-PW-21	production well	477959	974168	2103	501	98.47	108.3	9.83	90.23
19	Akaki	SL-PW-22	Production well	475507	974679	2070	515	76.65	120.13	43.48	72.34
20	Akaki	SL-PW-24	Production well	475941	975137	2063	551	65	71.67	6.67	102
21	Akaki	SL-PW-25	Production well	473071	974284	2060	552	56.08	61.61	5.53	109
22	Akaki	SL-PW-30	Production well	478528	973384	2113	518	132.4	133.72	1.32	46
23	Akaki	SL-PW-32	Production well	476725	973381	2111	170	110	149.74	39.74	47.67
24	Akaki	SL-PW-33	Production well	477415	973284	2112	453	116.38	139.69	23.31	37.34

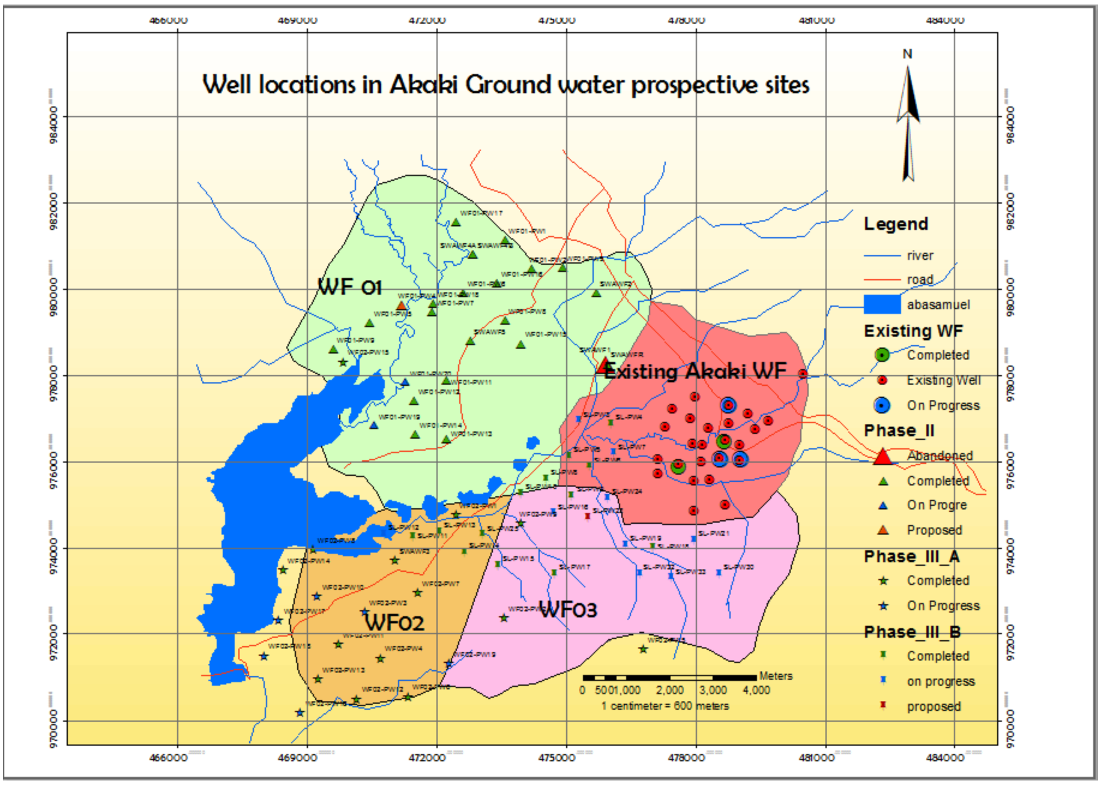


Figure 9: **Location of boreholes drilled at Akaki groundwater prospective area (Source WWDSE July 2014),**

3.3 General Approach

The study involves data collection from relevant offices, for which a data quality check was first conducted. Since the data collected is from the well test and during real-time operation of the wells it is vital to correct the data for partial penetration and the possibility of taping in an unconfined aquifer. This can be done using the Kozeny factor as discussed in the literature review and well efficiency analysis. After such correction is made transmissivity of the aquifer is estimated for both time drawdown data and recovery data collected during the study and design phase. The same but time drawdown analysis was done for real-time operation data collected.

3.3.1 **Data collection**

A successful groundwater investigation depends on field data. However, to minimize additional fieldwork each groundwater study should start with the collection and analysis of the available information and documentation. These researches primarily focus on primary data collected while the pump test was conducted in the Akaki phase IIB wells and data during its operation. Hence the primary pump test data like the step drawdown test data, constant pumping test data, recovery test data, and the coordinate of each well were collected from Waterworks Design and Supervision Enterprise (WWDSE). The well operational data also collected from Addis Ababa Water and Sewerage Authority (AAWSA) on the SCADA system report.

3.3.2 **Data quality checking**

The quality of data collected from Waterworks Design and Supervision Enterprise (WWDSE) and Addis Ababa Water and Sewerage Authority (AAWSA) on the SCADA system were checked for possible data collection errors. The quality of the data can be checked by visualization where un-recorded and outliers were easily removed from further analysis. Outliers on pumping rate can be identified as values larger than 3 times the average pumping rate during the pumping duration.

3.3.3 **Data analysis method**

After the raw pumping test data and operational data were collected analysis was made for the determination of the real-time performance of the well.

3.3.3.1 Adjustment of Pump Test Data

Due to economic reasons, most of the groundwater developed in the city is a single well test system aquifer property determination do not represent real aquifer characteristics of the study area which is seen in the analysis of this documents and over and underestimation of transmissivity.

The two-components of drawdown in the pumped well are the aquifer losses and the well losses. The drawdown is corrected for the entire well by using well efficiency. The corrected drawdown data is used to estimate the hydraulic parameters in the cooper Jacob standard methods.

Adequate and reliable estimates of aquifer parameters are most important for the proper management of vital groundwater resources. The pumping (aquifer) test is the standard technique for estimating various hydraulic properties of aquifer systems, transmissivity (T), and storage coefficient (S), for which the graphical method is widely used. And also data from the recovery phase are available to interpret the well parameters.

In this study, before the interpretation of each pumping well is done for the determination of the aquifer parameters, adjustment to the data was conducted in two ways:-

3.3.3.2 Correction on drawdown using the efficiency of the well,

Here correction was conducted for wells SL-PW-07, SL-PW-10, SL-PW-14, SL-PW-18, SL-PW-21, and SL-PW-33 using the step drawdown data collected from WWDSE.

From the step drawdown test for each well the efficiency of the wells was calculated and from the well efficiency the drawdown caused by well loss by determined and subtracted from the observed drawdown and the actual drawdown is tabulated and analyzed.

3.3.3.3 Correction on drawdown for partial penetration,

Here correction was conducted for well SL-PW-07, SL-PW-10, SL-PW-11, SL-PW-14, SL-PW-18, SL-PW-21, SL-PW-25, SL-PW-30, and SL-PW-33 using the casing arrangement data collected from WWDSE.

By using the casing arrangement for each well the effect of partial penetration on the drawdown is determined by using a factor developed by Kozeny’s correction factor. Kozeny’s correction factor is obtained by calculating the geometric mean of each screen and blind length combination. By multiplying the correction factor to the observed drawdown the actual drawdown is obtained as if the well was a fully penetrating well.

After the correction for the drawdown was done for each well by using an appropriate method from the above-stated methods correction was also applied to unconfined aquifers. Thus, the measured drawdown data, observed in individual single well pumping test data are corrected.

3.3.4 Estimation of Aquifers Parameters and Pumping test Analysis

The proposition that the wells might fail during the study time can be verified by carefully analyzing the pump test data collected. Pump tests can be analyzed based on the type of test conducted. In Akaki well field three types of tests have been conducted (the step drawdown, the constant discharge, and recovery tests). Except for the step drawdown analysis, the two tests can be analyzed based on the cooper Jacob method. Many analytical solutions are available for interpreting aquifer pumping test data. The assumptions incorporated within each solution must be evaluated for consistency with site conditions including the type of pumping and observation wells (fully- or partially-penetrating); the pumping rate (constant versus variable); and aquifer conditions (confined or unconfined). The physical characteristics of the aquifers, the necessary parameters such as the aquifer's design discharge, transmissivity, and storage coefficient are computed.

3.3.4.1 Cooper and Jacob methods

Cooper and Jacob (1946) attempted to simplify Theis's equation, such that a solution using a single sheet of semi-log graph paper was possible. Is based on the Theis formula from u = r2S/4KDt, it will be seen that u decreases as the time of pumping t increases and the distance from the well decreases. Accordingly, for drawdown observations made in the near vicinity of the well after a sufficiently long pumping time, the terms beyond in u in the series become so small that they can be neglected. So for small value of u($u < 0.01$).

It was noted by Cooper and Jacob that for small values of r and large values of t, u is small the straight-line approximation for this method should be restricted to small values of u ($u<0.01$) to avoid large errors. The major advantage of this method is its simplicity. It only requires semi-log graph paper or a standard software spreadsheet package. It suffers from the same limitations and assumptions as to the Theis method, however, and one major assumption besides the Cooper–Jacob approximation is only valid for a situation where u is small (say, $u < 0.05$); that is, where r is small and/or t is large. In practice, however, this condition is often satisfied (and at small values of t, the time–drawdown response is often swamped by well-bore storage effects in any case).

3.3.5 Estimation of operational drawdown range

The object of this study is to evaluate the real-time performance Akaki phase IIIB well field for possible operation and maintenance problem identification.

There are several basic causes of well problems.

- Improper well design and construction
- Incomplete well development
- Borehole stability problems
- Over-pumping

To identify the Akaki phase IIIB well problem out of the above causes of well problems calculate the range of operational drawdown by using analysis and reference transmissivity and compare the result and state percent of each cause of failure for the Akaki phase IIIB well field.

3.3.6 Result and interpretation

The final step is to interpret the results obtained which involves comparing the hydro-geologic parameters and well efficiency and well yields with the design as existing in the well completion reports) for possible failure in the design and study and/or post-construction failure. The interpretation will suggest possible learning outcomes for future understanding of failures.

Out of the ten well-developed in Akaki phase IIIB for 10 well the standard method of aquifer analysis by cooper Jacob methods is performed to obtain the hydraulic parameter of the aquifer and also to compare the result with the completion report. These results help to know if the well is failed due to the design or day-to-day operation.

CHAPTER FOUR

4 RESULT AND DISCUSSION

This paper intends to find out the real-time performance of wells developed in Addis Ababa in the area of Akaki project phase IIIB. Out of the twenty-four well-developed in Akaki phase IIIB, 10 wells were selected for analysis because they are the only wells that this research has obtained real-time operational data.

4.1 Data analysis

4.1.1 **Pumping Test**

Due to economic reasons most of the groundwater developed in the city is a single well test system aquifer property determination do not represent exacts aquifer characteristics of the study area which is seen in the analysis of this documents and over and underestimation of transmissivity.

The two components of drawdown in the pumped well are the aquifer losses and the well losses. The drawdown is corrected for the entire well by using well efficiency. The corrected drawdown data is used to estimate the hydraulic parameters in the cooper Jacob standard methods.

4.1.2 **Well Efficiency**

Determining well efficiency and well loss is highly recommended because it provides valuable information about the well performance and can be used to make an informed decision regarding the well pumping rate, maintenance, and rehabilitation.

Step drawdown tests are usually leading us to assess well/aquifer-loss performance and for guidance in deciding on optimum pumping rate for a later constant-rate pumping test. Since raw step drawdown data was available for six-well in the Akaki phase IIIB Deep Well project, the well efficiency of these wells have been determined and a comparison was done with the result collected from WWDSE.

A well efficiency of 65 percent or more is usually considered acceptable. If a newly developed well has greater than 65 percent efficiency, it should be accepted to operate. A step drawdown test is performed to see the design of the well and also to test out 80% and 65% efficiency of the project and try to evaluate the result obtained from the step drawdown and compute it with the data of the completion report. Such an approach will tell if the failure has resulted during the study phase rather than during operation.

Out of the six-well of the Akaki phase IIIB project which was shown in the table below five of the well are below 65% (table 3). This efficiency result tells us the well has already failed during the design time and the remaining well is accepted because the efficiency is greater than 65% could be considered fit for operation with the suggested discharge.

Table 3Well efficiency of Akaki phase IIIB Deep Wells.

well name	Well Efficiency	
	From WWDSE	Calculated
SLPW07	42.9	14.67
SLPW10	16.40	27.46
SLPW14	67.93	40.51
SLPW18	93.32	76.13
SLPW21	76.85	5.71
SLPW33	45.84	35

Step drawdown test was performed on SL -PW -07 using discharges of 25.22lit/s, 33.85lit/s, 42.71lit/s, and 50.49lit/s. The liner well loss coefficient (B) and the non-liner well loss coefficient (C) were determined from this step drawdown test was calculated to be 0.0061 and 0.000188 respectively. Using these values the efficiency was determined for each of the corresponding discharges. A constant pumping rate of 50.49 lit/s for SL -PW -07 was used as pumping rate, which resulted in a well efficacy of 14.67%. This low well efficiency could have been avoided with a low discharging rate as can be observed in table 4 below.

Table 4.Values of B, C, and well efficiency calculated for SL -PW -07 based on figure 10.

from this research

	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.003	4.00E-06	2261.088	0.0090	0.01204	0.25	24.91
Step2	0.003	4.00E-06	2957.472	0.0118	0.01483	0.20	20.23

Step3	0.003	4.00E-06	3667.68	0.0147	0.01767	0.17	16.98
Step4	0.003	4.00E-06	4362.336	0.0174	0.02045	0.15	14.67
from WWDSE							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.00614	1.88E-06	2261.088	0.004251	0.010391	0.5909048	59
Step2	0.00614	1.88E-06	2957.472	0.00556	0.0117	0.5247842	52.4
Step3	0.00614	1.88E-06	3667.68	0.006895	0.013035	0.4710309	47.1
Step4	0.00614	1.88E-06	4362.336	0.008201	0.014341	0.429	42.9

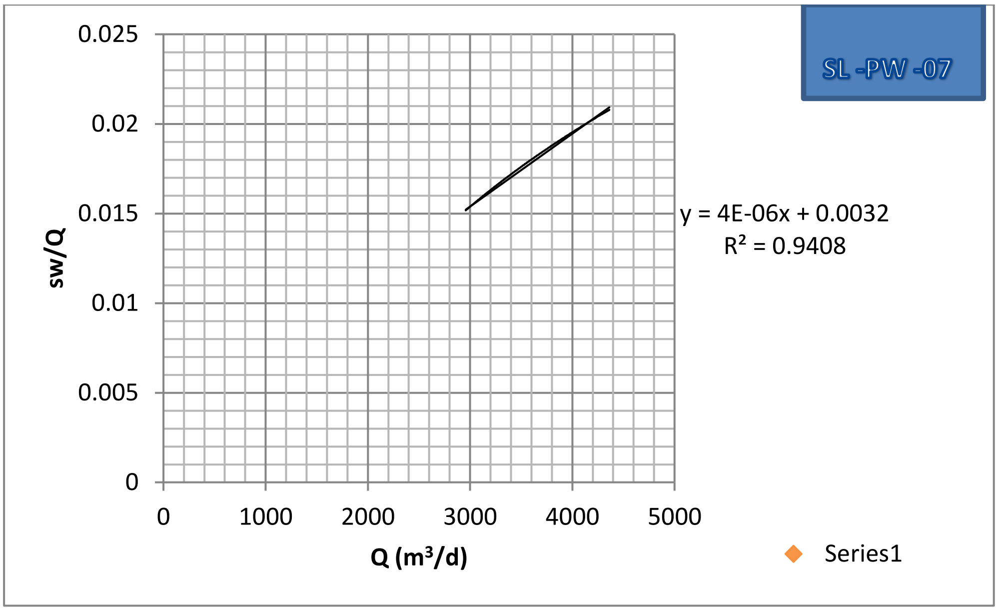


Figure 10 step drawdown test graph of well ID SL -PW -07

The well efficiency, liner well loss coefficient (B), and non-liner well loss coefficient (C) analysis of the remaining wells are included in the annexed figure 12 to 16 and table 19 to 23 with the raw step drawdown test table 13 to 19.

4.1.3 **Partial penetration**

Out of ten well-developed in Akaki phase IIIB project nine of the well need kozeny correction factor to correct the measured drawdown for the head loss caused by partial penetration. The step drawdown test data are not included in the WWDSE report for well SL-

PW-11, SL-PW-24, SL-PW-25, and SL-PW-30. To compute the hydraulic parameter, the partial penetration correction is performed. By arranging the blind and screen for each of the four well the observed drawdown has adjusted the arithmetic and geometric mean values are obtained from the casing arrangement of blind and screen but for the correction of the drawdown we use the geometric mean as a Kozeny correction factor. List of the correction factor is shown in the Table 5 below.

The casing arrangement collected from WWDSE and the analyses calculated for the correction is attached in annex -4 for the five well of Akaki phase IIIB.

Table 5 kozeny correction factor for partial penetration of nine well

Well ID	Geometric mean	Well ID	Geometric mean
SL-PW-07	0.6	SL-PW-21	0.5
SL-PW-10	0.58	SL-PW-24	0.14
SL-PW-11	0.68	SL-PW-25	0.599
SL-PW-14	0.62	SL-PW-30	0.62
SL-PW-18	0.65	SL-PW-33	0.678

- $F = L/b[1+7COS(\prod L/2B)\surd(r/2L)]$

Below table show for SL-PW-07 kozeny correction factor calculation

Interval(m)		Length (m)	Length (m)							r of well =0.24 given
From	To		Blind	Screen	L/r > 30	L/b ≤0.5	remark	πL/2b	SQRTr/2L	F = L/b[1+7COS(3.1L/2B)SQRTr/2L]
0.7	116.3	117	117							
116.3	133.85	17.55		17.55	73.125	0.6	rejected	0.785	0.08269	0.845674005
133.85	157.25	23.4	23.4							
157.25	168.95	11.7		11.7	48.75	0.363636	accepted	0.848649	0.101274	0.534033795
168.95	186.5	17.55	17.55							
186.5	209.9	23.4		23.4	97.5	0.666667	rejected	1.350538	0.071611	0.739680522
209.9	215.75	5.85	5.85							
215.75	239.15	23.4		23.4	97.5	0.727273	rejected	1.243564	0.071611	0.844453173
239.15	250.85	11.7	11.7							
250.85	262.55	11.7		11.7	48.75	0.444444	accepted	0.872222	0.101274	0.647077169

262.55	280.1	17.55	17.55							
280.1	285.95	5.85		5.85	24.375	0.25	rejected	0.592453	0.143223	0.457924478
285.95	303.5	17.55	17.55							
303.5	315.2	11.7		11.7	48.75	0.4	accepted	0.860274	0.101274	0.584950867
315.2	332.75	17.55	17.55							
332.75	338.6	5.85		5.85	24.375	0.25	rejected	0.592453	0.143223	0.457924478
338.6	356.15	17.55	17.55							
356.15	367.85	11.7		11.7	48.75	0.4	accepted	0.860274	0.101274	0.584950867
367.85	385.4	17.55	17.55							
385.4	397.1	11.7		11.7	48.75	0.444444	accepted	0.996825	0.101274	0.615520718
397.1	408.8	11.7	11.7							
408.8	414.65	5.85		5.85	24.375	0.285714	rejected	0.603846	0.143223	0.521504507
414.65	432.2	17.55	17.55							
432.2	443.9	11.7		11.7	48.75	0.5	accepted	1.184906	0.101274	0.633412774
443.9	449.75	5.85	5.85							
449.75	461.45	11.7		11.7	48.75	0.571429	rejected	1.029508	0.101274	0.780150268
461.45	473.15	11.7	11.7							
473.15	479	5.85		5.85	24.375	0.333333	rejected	0.747619	0.143223	0.578395873
479	490.7	11.7	11.7							
490.7	496.55	5.85		5.85	24.375	0.285714	rejected	0.603846	0.143223	0.521504507
496.55	514.1	17.55	17.55							
514.1	519.95	5.85		5.85	24.375	0.285714	rejected	0.730233	0.143223	0.499122046
519.95	531.65	11.7	11.7							
									F GEO MEAN	0.599991032

4.2 Transmissivity and Storativity result for Akaki phase IIIB wells

The objective of this thesis is to evaluate the real-time performance Akaki phase IIIB well field for possible operation and maintenance problem identification. The transmissivity and Storativity values both for observed and corrected drawdown are shown by the cooper Jacob and the result are compared with the results obtained from documents of WWDSE. Most of the well developed in our city are single well test due to economic reason and has no observation well and it is difficult to calculate Storativity from the single well test by using cooper Jacob method.

Transmissivity and Storativity values using Cooper-Jacob method

The cooper-Jacob method is the simplest method than Theis method and the method is applied for the Akaki deep well in the semi-log plot of the drawdown vs. time the best fit line is done using the Trend line tool which gives the equation of the line and R2 values. The Cooper-Jacob method is applied for all of the ten wells in Akaki phase IIIB well fields. The plots for all of ten well are shown in figure 17 to figure 23 in the annex part.

According to the pumping test data in the study area, the equation obtained and the plot is as shown the figure 11 below.

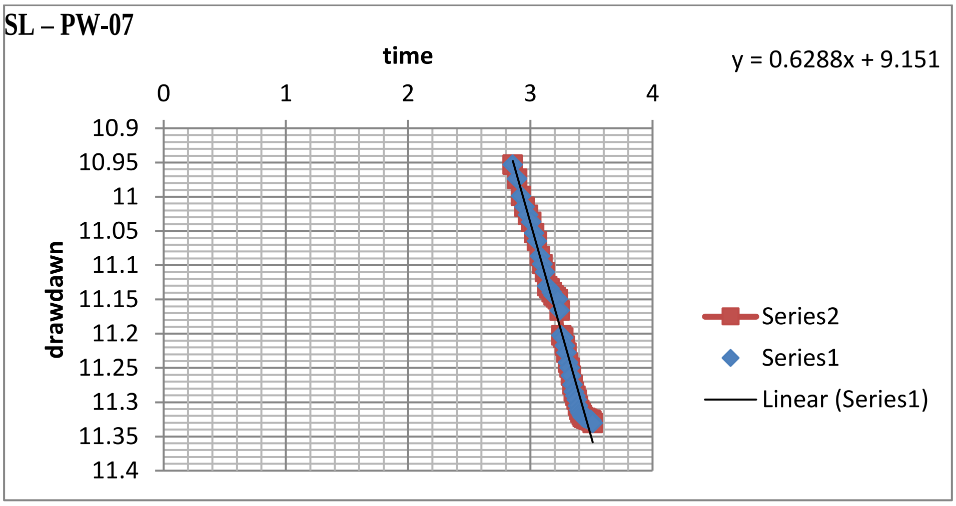


Figure 11Time versus drawdown cooper-Jacob graph of well ID SL – PW-07

The obtained values of the measured parameters are substituted in the equations the required parameters transmissivity computed by (Cooper and Jacob 1946)

- $T = \frac{2.30Q}{4\pi\Delta S}$

Table 6 Summary of Transmissivity

Well index	Transmissivity m2per day		
	WWDSE	Kozeny Corrected	Efficiency Corrected
SL-PW-07	309	127.43	521.54
SL-PW-10	255	82.69	294.69
SL-PW-14	1010	770.82	1205.74
SL-PW-18	1020	423.63	296.27
SL-PW-21	4040	2519	2537.74

SL-PW-33	224	115.44	152.98
SL-PW-11	635	1080.56	No step draw dawn test
SL-PW-24	1310	No kozeny correction	No step draw dawn test
SL-PW-25	757	792.63	No step draw dawn test
SL-PW-30	165000	12730.66	No step draw dawn test

Summary of hydraulic parameters by using Excel-spread sheet is calculated both for the uncorrected and corrected drawdown data estimation of Transmissivity are performed and the geometric mean result obtained by copper Jacob methods is compared with the result of WWDSE. The 10 well-calculated transmissivity values as shown in table 10 of this thesis has variation from the one in the designed documents of WWDSE the percent increase and decrease of transmissivity is also calculated and these results tell us if the transmissivity is overestimated or underestimated. This over and underestimation of the hydraulic parameter of the Akaki phase IIIB well is one of the failure reasons due to design and study AAWSA facing it at the moment. The exaggerated result of the transmissivity doesn’t stand for the aquifer characteristic of the study area.

4.2.1.1 Over-pumping

A well is over-pumped if the water is withdrawn at a faster rate than the well was designed for or the aquifer can produce. Over-pumping is the most common well problem that leads to premature well failure. Over-pumping not only depletes the groundwater aquifer (or source), but it rapidly increases the rate of corrosion, incrustation, and befouling related problems.

Over-pumping also increases the rate of sediment particles moving toward the well, causing plugging of the perforated area where water flows into the well. It can also cause the aquifer to settle and compact which further restricts water flow to the well.

4.3 Pumping and recovery time

According to Akaki phase IIIB well field SCADA data pumping hour and recovery hour are out of reality because submersible pump working 16 hours to 18 hours but SLPW10, SLPW11, SLPW21, SLPW24, and SLPW33 are out of this hour.

Table 7Pumping and recovery time

well name	Average pumping hour	Average pumping rate during pumping m3/hr	Average pumping rate during pumping m3/day	Average recovery time in hour
SLPW07	14.8269	120.8782	1792	1.0192
SLPW10	19.1121	117.4894	2245	1.0259
SLPW11	21.4286	130.7719	2802	1
SLPW14	17.8684	109.1369	1950	1.0263
SLPW18	17.8269	173.9098	3100	1.0192
SLPW21	19.0154	248.9491	4734	1
SLPW24	19.2807	274.1636	5286	1.0526
SLPW25	15.831	337.8749	5349	1
SLPW30	16.9928	158.6428	2696	1
SLPW33	21.0678	117.7193	2480	1.0339

4.4 Causes of well failure

Water well problems result from many causes including equipment failure, depletion

of the aquifer, corrosive qualities of the water, and improper well design and construction.

There are several basic causes of well failure

- Design stage
- construction
- Aquifer characteristic estimation/analysis
- During operation (yield and time of operation)
- Maintenance

Based on operational draw dawn and referenced draw dawn calculation above causes of well failure for each well percent of failure, which is listed below, and their values are summarized Table 8 below.

- In the case of well SL-PW-07 27% is caused by all failure causes while 15% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-10 11% is caused by all failure causes while 31% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-14 30% is caused by all failure causes while 65% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-18 54% is caused by all failure causes while 53% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-21 78% is caused by all failure causes while 81% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-33 96% is caused by all failure causes while 100% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-11 4% is caused by all failure causes while 22% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-24 12% is caused by all failure causes.
- In the case of well SL-PW-25 85% is caused by all failure causes while 100% is mainly caused by design, operation, and aquifer character.
- In the case of well SL-PW-30 96% is caused by all failure causes while 100% is mainly caused by design, operation, and aquifer character.

Table 8 Rang of operational drawdown between analysis and reference drawdown

well index	analysis DD	reference DD
SL-PW-07	88%	73%
SL-PW-10	15%	83%
SL-PW-14	14%	49%
SL-PW-18	14%	82%
SL-PW-21	19%	22%
SL-PW-33	0%	4%
SL-PW-11	41%	63%
SL-PW-24	_	83%
SL-PW-25	0%	21%
SL-PW-30	0%	4%

Below table show how to get percent for the range of operational drawdown between analysis and reference drawdown.

Drawdown(S) =24*2.3*Q/(4∏*T)*LOG10(2.25*T*t/(0.24*0.24*24*St))

Op Static water level = 72.7

SL-PW-07						**Analyzed**		**References**		**Op Static water level = 72.7**						
					T	**521.5400000000**	**127.4300000000**	**181350.00000**	**1.81350E-06**	**Drawdown(S) = =24*2.3*Q/(4∏*T)*LOG10(2.25*T*t/(0.24*0.24*24*St))**						
					St	**0.00100**	**0.00001**	**0.00100**	**0.00001**			**Analyzed**			**References**	
R NO	DATE	time	Level (m)	operation DD	Flow (m3/h)	Analyzed DDmin	Analyzed DDmax	References DDmin	Observation DDmax	Analyzed Rnagmin	Analyzed Rnagmax	88%	References Rang min	References Ran max	73%	EFF
1	06/08/09	1	28.8	29.53	125	6.241961301	31.52752967	0.025645341	-1.604513E+08	1	1	1	1	0	0	0.2
1	06/08/09	2	28.8	29.53	125	6.558889861	32.82464118	0.026556788	-69306567.02	1	1	1	1	0	0	0.2
1	06/08/09	3	28.8	29.53	124	6.690326934	33.31473556	0.026873231	-15862410.34	1	1	1	1	0	0	0.2
1	06/08/09	4	28.8	29.53	124	6.820811872	33.84877868	0.027248489	21663431.94	1	1	1	1	1	1	0.2
1	06/08/09	5	28.8	29.53	123	6.866201081	33.98670007	0.027317469	50361295.13	1	1	1	1	1	1	0.2
1	06/08/09	6	28.8	29.53	123	6.948230387	34.32242607	0.027553375	73951901.12	1	1	1	1	1	1	0.2
1	06/08/09	7	28.8	29.53	123	7.017585176	34.60627836	0.027752831	93897474.28	1	1	1	1	1	1	0.2
1	06/08/09	8	28.8	29.53	124	7.135205003	35.13551331	0.028152645	112078978.4	1	1	1	1	1	1	0.2
1	06/08/09	9	28.9	29.43	124	7.188628256	35.35416169	0.028306283	127442840.2	1	1	1	1	1	1	0.2
1	06/08/09	10	28.9	29.43	124	7.236416985	35.54974934	0.028443718	141186283	1	1	1	1	1	1	0.2
1	06/08/09	11	29.1	29.23	123	7.220940316	35.43856149	0.028337655	152379878.4	1	1	1	1	1	1	0.2
1	06/08/09	12	29.1	29.23	123	7.260088089	35.59878381	0.028450239	163638289.9	1	1	1	1	1	1	0.2
2	06/08/09	15	28.9	29.43	120.8	7.228832914	35.36560366	0.028224934	189067574.6	1	1	1	1	1	1	0.2
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
260	10/04/10	6	33.2	25.13	118	6.665781997	32.9272055	0.026433319	70945726.28	1	1	1	1	1	1	0.2
260	10/04/10	7	33.3	25.03	119	6.789371024	33.48087093	0.0268503	90843897.88	1	1	1	1	1	1	0.2
260	10/04/10	8	32.7	25.63	120	6.9050371	34.00210965	0.027244495	108463527.5	1	1	1	1	1	1	0.2

Out of the six-well of the Akaki phase IIIB project which was shown in the table below five of the well are below 65% (table9). This efficiency result tells us except for SL-PW-18 the rest well efficiency is less than 65% so operational well efficiency is not accepted.

Table 9 Operational Efficiency

R NO	**well index**	**operational Efficiency based on operational discharge**	
		min Efficiency (E=B/(B+CQ)	**max Efficiency (E=B/(B+CQ)**
1	**SL-PW-07**	**14%**	**22%**
2	**SL-PW-10**	**15%**	**28%**
3	**SL-PW-14**	**48%**	**79%**
4	**SL-PW-18**	**93%**	**97%**
5	**SL-PW-21**	**6%**	**7%**
6	**SL-PW-33**	**39%**	**49%**
7	**SL-PW-11**	**no step dd test**	
8	**SL-PW-24**	**no step dd test &kozeny**	
9	**SL-PW-25**	**no step dd test**	
10	**SL-PW-30**	**no step dd test**	

Depending on recommended discharge and analysis B and C the efficiency of the whole well below 65% except SL-PW-18 which tell tell us during designing the recommended discharge are not properly designed the result tabulated in table 10 below

Table 10 Efficiency of the Well for the Discharge of Completion Report

R NO	**well index**	**DESIGN DISCHARG (m3perday)**	**analysis B**	**analysis C**	**Efficiency due to design Q and analysis B and C %** **E=B/(B+CQ)**
1	**SL-PW-07**	**3974**	**0.003**	**4E-06**	**15.9**
2	**SL-PW-10**	**4752**	**0.004**	**4E-06**	**17.4**
3	**SL-PW-14**	**7258**	**0.002**	**4E-07**	**40.8**
4	**SL-PW-18**	**5717**	**0.005**	**6E-08**	**93.6**
5	**SL-PW-21**	**7776**	**9E-05**	**2E-07**	**5.5**
6	**SL-PW-33**	**3197**	**0.008**	**3E-06**	**45.5**
7	**SL-PW-11**	**8640**	**no step dd test**		
8	**SL-PW-24**	**8813**	**no step dd test &kozeny**		
9	**SL-PW-25**	**9331**	**no step dd test**		
10	**SL-PW-30**	**3974**	**no step dd test**		

The difference between recommended discharge and pumping discharge tell us during designing the recommended discharge are not properly designed the result tabulated in table 11 below

Table 11 Difference between Design and Pumping Discharge

well name	Average pumping hour	Average pumping rate during pumping m3/day	Recommended discharge m3/day	Difference m3/day
SLPW07	14.8269	1792	3974	2182
SLPW10	19.1121	2245	4752	2507
SLPW11	21.4286	2802	8640	5838

SLPW14	17.8684	1950	7258	5308
SLPW18	17.8269	3100	5717	2617
SLPW21	19.0154	4734	7776	3042
SLPW24	19.2807	5286	8813	3527
SLPW25	15.831	5349	9331	3982
SLPW30	16.9928	2696	3974	1278
SLPW33	21.0678	2480	3197	717

4.5 Maximum Expected Yield

The well efficiency computed for the 6 wells for their expected yield estimated in their study and design document is as shown in table 13.

Table 12Efficiency and yield of 65% for 10 well

Well name	B	C	Q[1](l/s)	Q[4](m3/day)
SL-PW-07	0.003	4.00E-06	46	403.8
SL-PW-10	0.004	4.00E-06	55	538.5
SL-PW-14	2.00E-03	4.00E-07	84	2692.3
SL-PW-18	5.00E-03	6.00E-08	66.17	44,871.79
SL-PW-21	9.00E-05	2.00E-07	90	242.31
SL-PW-33	8.00E-03	3.00E-06	37	1435.9
SL-PW-11	**No step draw dawn test**		100	
SL-PW-24			102	
SL-PW-25			108	
SL-PW-30			46	

[1]Yield as indicated in the well completion report and [4]Expected Yield for 65% efficiency

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

According to the analysis of Akaki phase IIIB well the following conclusions are reached.

Well efficiency in turn tells us whether the design and construction of the well is done perfectly or not. For some well in the Akaki deep well major mainly focused on getting a high well yield with no consideration on the well efficiency. Such consideration of efficiency may be excess pumping which led to groundwater depletion where groundwater is extracted at a rate faster than it can be replaced. This makes the developed well to fail without completing its lifetime.

The hydraulic parameter is calculated both for observed and corrected drawdown by using Excel spared sheet after the correction is performed for both uncorrected and corrected drawdown of the developed well of AAWSA the transmissivity of the well is calculated by the cooper Jacob method and the Geometric mean values of transmissivity is obtained and compared the result obtained with the one in the designed documents of WWDSE.

The transmissivity values obtained in this thesis have great variation from the study of WWDSE these variations are shown in the table of this document. The percent increase and decrease of transmissivity are presented in the table we see the over and underestimation of transmissivity in the study area. These exaggerated transmissivity results inform us one of the well failure reasons due to the design of the developed well which AAWSA is facing it now.

The exact hydraulic characteristic of the area is not obtained due to over and underestimation of the transmissivity. Most of the well are over-pumped beyond their capacity and there is also a problem of water level drop this together shorten the life of the motor and the well face failure problem.

The referenced draw dawn and analysis draw dawn values obtained in this thesis from 0% to 96% beyond operational draw dawn, the operation of AAWSA well values are shown in table 16 of this document. Some percent of operational draw dawn beyond referenced and analyzed draw dawn result tell us one of the well failure reasons due to design, construction, and operation of the developed well. The percent of failure due to design, construction, and operation listed above result part.

5.2 Recommendation

Based on analysis AAWSA has some gap in the operation and management of groundwater because as we have seen from the analysis part some well working without given by the consultant pumping hour. Due to this, some well can't do the whole lifetime. So AAWSA planned implementation of groundwater schemes supported through long term master plan and lack of systematic monitoring of the well field aquifer characteristic either through the test wells and/or through the production wells the study has given some advice about the operation and management of groundwater AAWSA have to implement the advice given by the consultant.

Due to economic reason, most of the groundwater developed in the city is a single well test system aquifer property determination do not represent exacts aquifer characteristics of the study area which is seen in the analysis of this documents and over and underestimation of transmissivity. The development well should be standardized to obtain the exact hydraulic characteristic of the area.

During the development of groundwater, attention has to be given to the efficiency of the well and the hydraulic characteristic of the well. The discharge and the borehole performance are also estimated from the step draw-down pumping test of the developed groundwater. Source of water in Addis Ababa is surface water and groundwater as we now some part of the city water source is only groundwater this groundwater dependence results in potable water shortage in the city AAWSA has to study the alternative source of water development for that particular area and use conjugate use of water to overcome the shortage of water occurred in the city.

The groundwater sources of the study area need proper management and operation of the well. The developed groundwater has to be standardized to reduce the failure of the well.

REFERENCES

A.M.MICHAEL, S. (2008). water welsl and pumps. UNITED STATES: TATA MCGRAW- HILL.

BANKS, D. (2006). Chesterfield, UK: Holymoor Consultancy.

Borga, S. (2016). Assessment on Interpretive Technique of Transmissivity and Storativity on Aquifers: the case of Legedadi deep wells. Addis Ababa.

ENGINEERING, A. (1984). ADDIS ABABA WATER RESOURCES RECONNAISSANCE STUDY. ADDIS ABABA: DEVELOPMENT PROJECTS STUDY AGENCY.

enterprise, w. w. well accomplishment report. Addis Ababa.

enterprise, w. w. (2015). well, accomplishment report. Addis Ababa.

Fetter, C. (. (1988,1980). Applied hydrogeology. United states of America: Merrill Publishing company.

kersic, N. (2009). Groundwater resources Sustainability, management, and restoration. New York,Chicago.

Kevin, M. (2005). Hydrogeology principles and practice.

Kruseman, E. G. (2000). Analysis and Evaluation of Pumping Test Data. Netherlands: Veenmandrukkers.

Michel Vermersch, f. c. (2013). umbrella technical Assistance. Addis Ababa.

paul Pavelic, m. G. (2012). Groundwater Availability and use in sub-Saharan Africa A Review of 15 countries. India: International water management.

PLAN, A. A. (2011). ADDIS ABABA WATER AND SEWERAGE AUTHORITY BUSINESS PLAN 2011-2020 FINAL. ADDIS ABABA: ADDIS ABABA WATER AND SEWERAGE AUTHORITY.

prise, w. w. (2015). well, accomplishment report. Addis Ababa.

Smith, P. A. (2008). Aquifer Test Guidelines.

SMITH, P. A.-E. (2008). AQUIFER TEST GUIDELINES.

Strickland, T. (2006). TECHNICAL GUIDANCE.

Todd, D. K. (2005). Groundwater hydrology. United States of America: Arizona state university.

v.s.kovalevsky, G. R. (2004). An international guide for hydrological investigations. Unesco.

W.Delleur, J. (2007). The Handbook of Groundwater Engineering. Indiana: Delleur School of Civil Engineering Purdue University West Lafayette.

Water Works Design and Supervision Enterprise Addis Ababa Groundwater Development, D. a. (2014).

WWDSE. (2015). well completion report. Addis Ababa.

Annex 1 Sw/Q vs Q plot

Figure 12.Sw/Q vs Q plot for SL-PW 10.

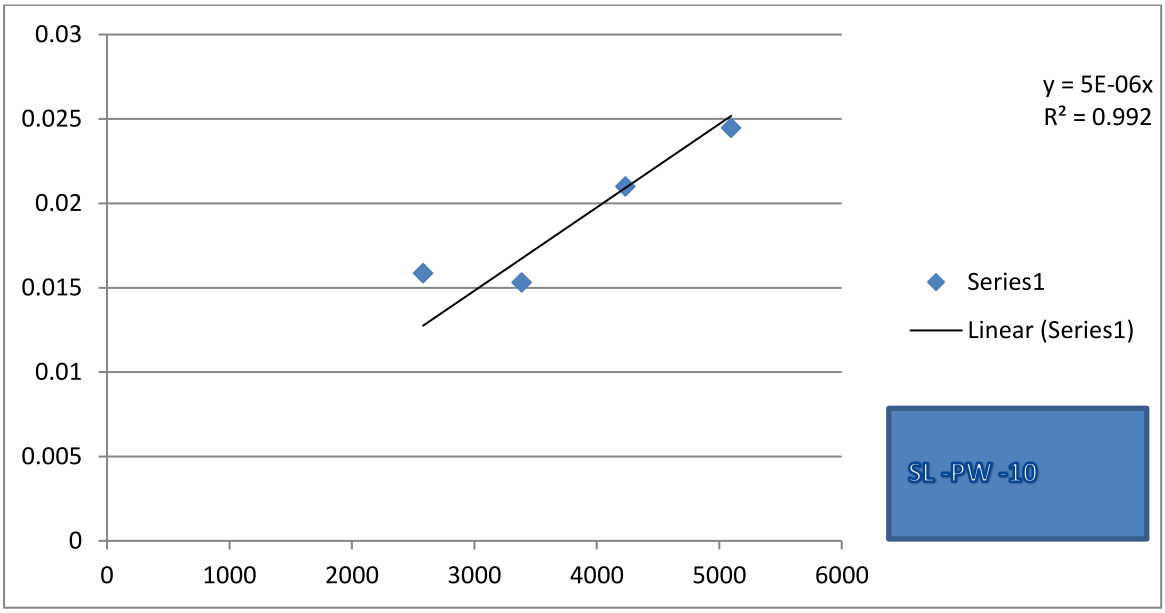


Figure 13.Sw/Q vs Q plot for SL-PW 14.

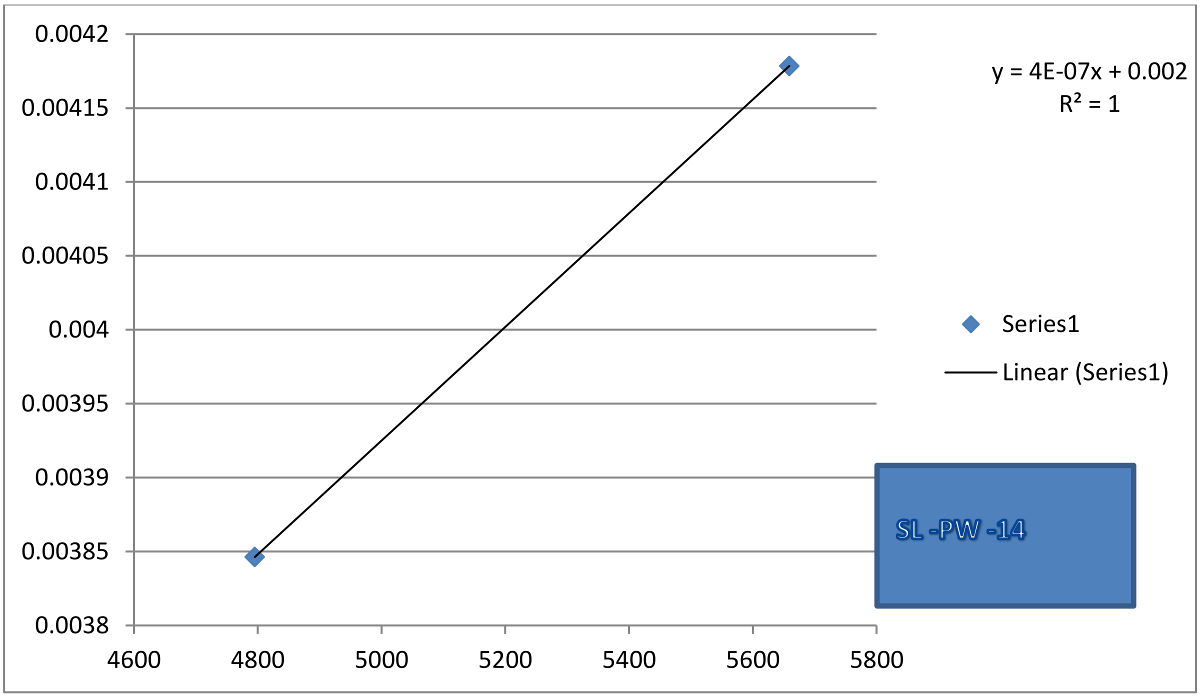


Figure 14.Sw/Q vs Q plot for SL-PW 18.

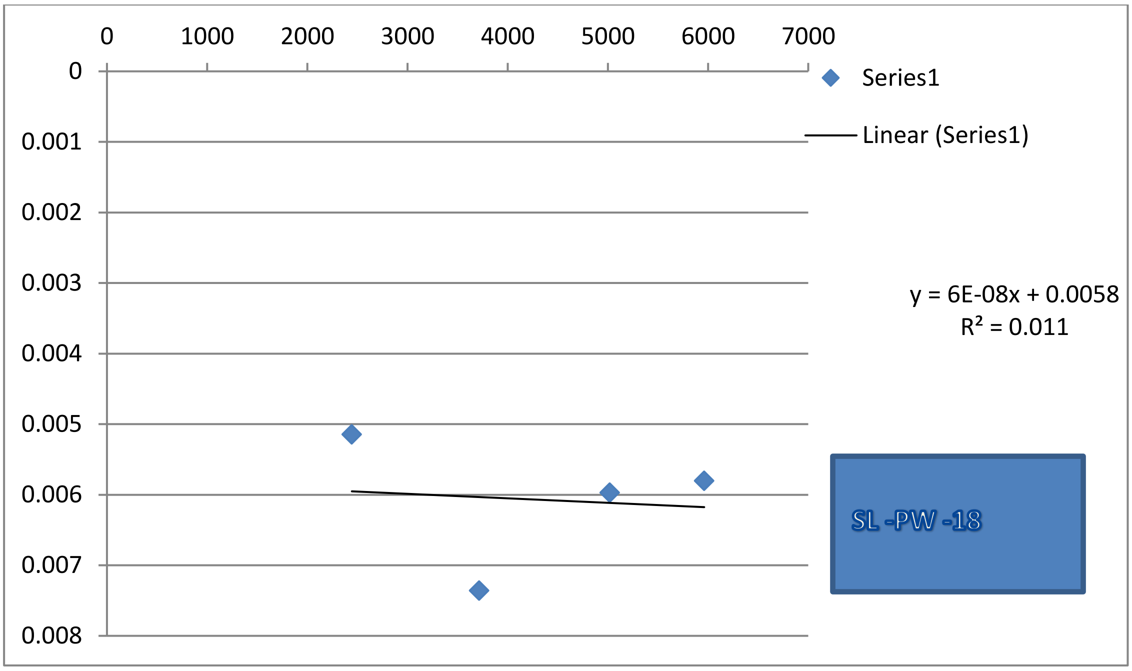


Figure 15.Sw/Q vs Q plot for SL-PW 21.

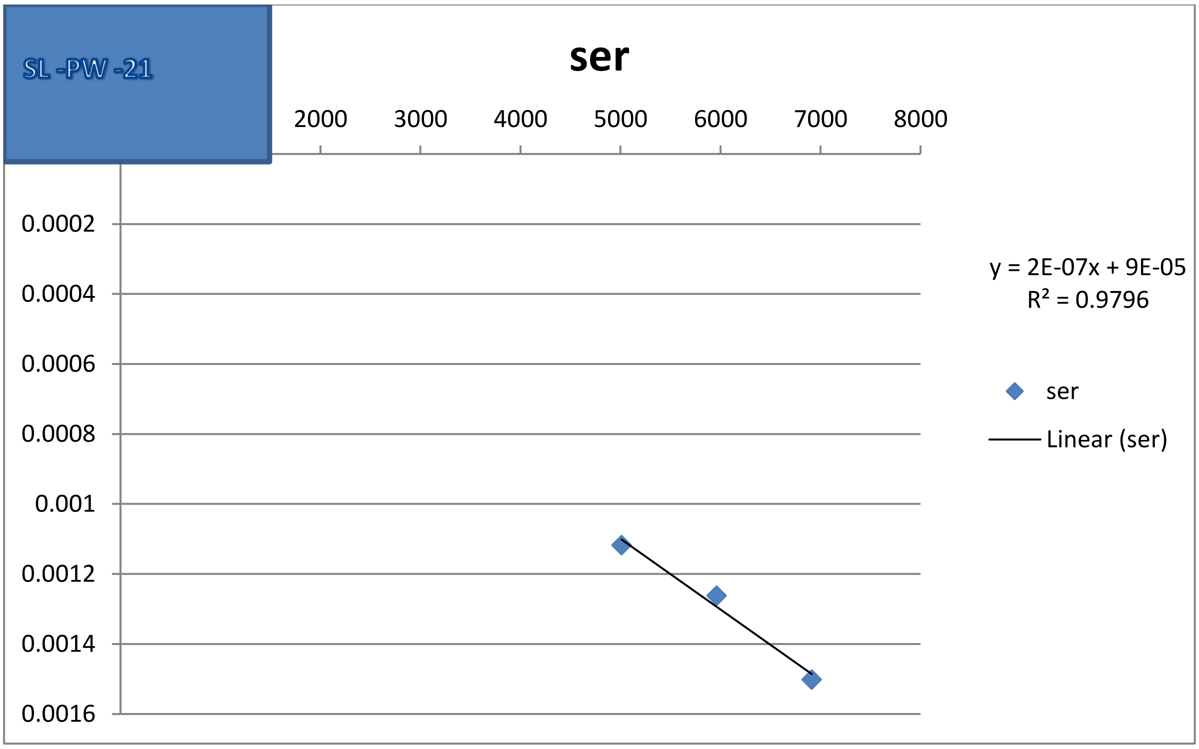
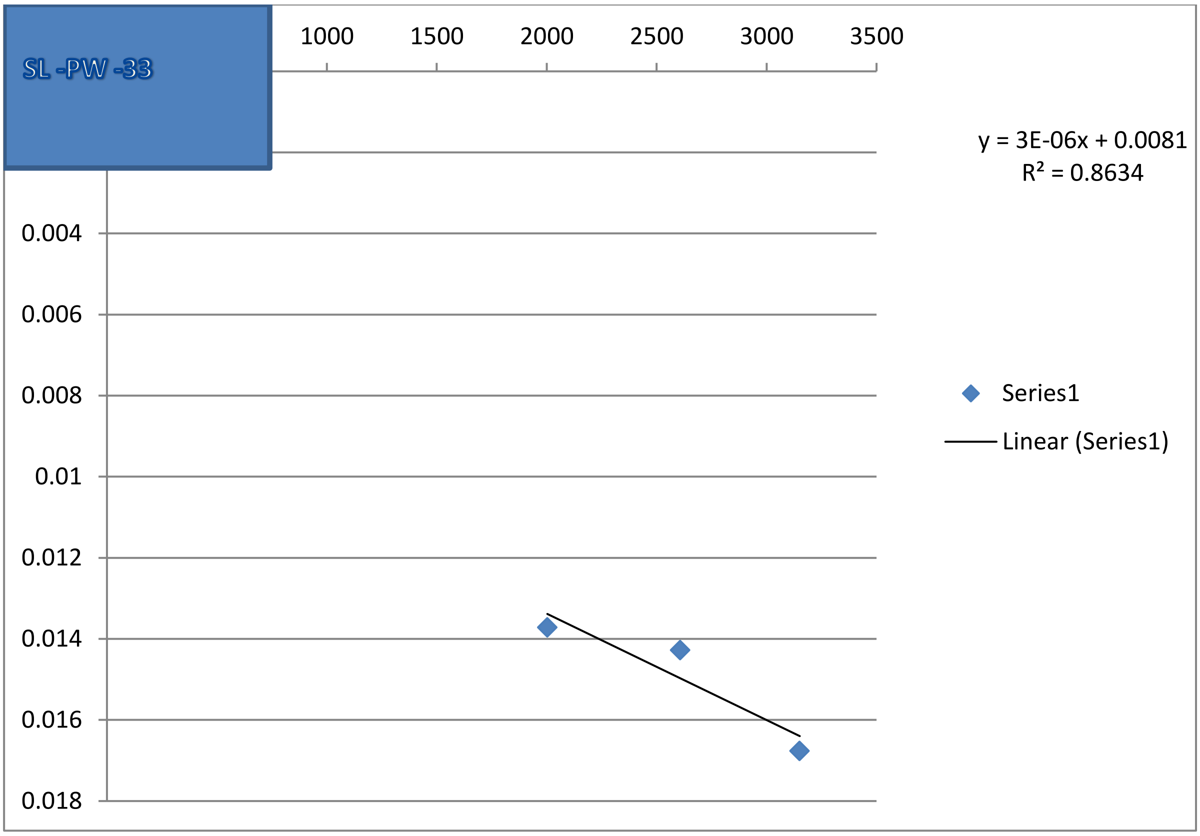


Figure 16.Sw/Q vs Q plot for SL-PW 33.



Annex 2 VALUES OF E, Q, B, AND C FOR WWDSE AND ANALYZED

Table 13 values of E, Q, B, and C for WWDSE and analyzed SL-PW-10

from calculated

	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.004	4.00E-06	2581.632	0.0103	0.01433	0.28	27.92
Step2	0.004	4.00E-06	3388.608	0.0136	0.01755	0.23	22.79
Step3	0.004	4.00E-06	4233.6	0.0169	0.02093	0.19	19.11
Step4	0.004	4.00E-06	5097.6	0.0204	0.02439	0.16	16.40

from WWDSE

	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.0044	2.28E-06	2581.632	0.005886	0.010286	0.427761	42.77
Step2	0.0044	2.28E-06	3388.608	0.007726	0.012126	0.362856	36.28

Step3	0.0044	2.28E-06	4233.6	0.009653	0.014053	0.313109	31.31
Step4	0.0044	2.28E-06	5097.6	0.011623	0.016023	0.274613	27.46

Table 14 values of E, Q, B, and C for WWDSE and analyzed SL-PW-14

from calculated							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	2.00E-03	4.00E-07	4795.2	0.0019	0.00392	0.51	51.05
Step2	2.00E-03	4.00E-07	5659.2	0.0023	0.00426	0.47	46.91
Step3	2.00E-03	4.00E-07	6480	0.0026	0.00459	0.44	43.55
Step4	2.00E-03	4.00E-07	7344	0.0029	0.00494	0.41	40.51
from WWDSE							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.00224	1.44E-07	4795.2	0.000691	0.002931	0.7643724	76.43
Step2	0.00224	1.44E-07	5659.2	0.000815	0.003055	0.7332423	73.33
Step3	0.00224	1.44E-07	6480	0.000933	0.003173	0.7059298	70.59
Step4	0.00224	1.44E-07	7344	0.001058	0.003298	0.6792951	67.93

Table 15 values of E, Q, B, and C for WWDSE and analyzed SL-PW-18

from calculated							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	5.00E-03	6.00E-08	2444.256	0.0001	0.00515	0.97	97.15
Step2	5.00E-03	6.00E-08	3715.2	0.0002	0.00522	0.96	95.73
Step3	5.00E-03	6.00E-08	5018.112	0.0003	0.00530	0.94	94.32

Step4	5.00E-03	6.00E-08	5961.6	0.0004	0.00536	0.93	93.32
from WWDSE							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.00409	2.15E-07	2444.256	0.0005255	0.0046155	0.8861416	88.6
Step2	0.00409	2.15E-07	3715.2	0.0007988	0.0048888	0.8366116	83.66
Step3	0.00409	2.15E-07	5018.112	0.0010789	0.0051689	0.7912718	79.12
Step4	0.00409	2.15E-07	5961.6	0.0012817	0.0053717	0.7613915	76.13

Table 16 values of E, Q, B, and C for WWDSE and analyzed SL-PW-21

from calculated							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	9.00E-05	2.00E-07	4171.392	0.0008	0.00092	0.10	9.74
Step2	9.00E-05	2.00E-07	5055.264	0.0010	0.00110	0.08	8.17
Step3	9.00E-05	2.00E-07	6085.152	0.0012	0.00131	0.07	6.89
Step4	9.00E-05	2.00E-07	7430.4	0.0015	0.00158	0.06	5.71
from WWDSE							
	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.00296	1.20E-07	4171.392	0.000501	0.003461	0.855351	85.5
Step2	0.00296	1.20E-07	5055.264	0.000607	0.003567	0.829915	82.99
Step3	0.00296	1.20E-07	6085.152	0.00073	0.00369	0.802121	80.2
Step4	0.00296	1.20E-07	7430.4	0.000892	0.003852	0.768502	76.85

Table 17 values of E, Q, B, and C for WWDSE and analyzed SL-PW-33

from calculated

	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	8.00E-03	3.00E-06	1323.684	0.0040	0.01197	0.67	66.83
Step2	8.00E-03	3.00E-06	2002.752	0.0060	0.01401	0.57	57.11
Step3	8.00E-03	3.00E-06	2607.552	0.0078	0.01582	0.51	50.56
Step4	8.00E-03	3.00E-06	3151.008	0.0095	0.01745	0.46	45.84

from WWDSE

	B	C	Q	CQ	B+CQ	E=B/B+CQ	%
Step1	0.00108	6.36E-07	1323.684	0.000842	0.00192	0.561955	56.19
Step2	0.00108	6.36E-07	2002.752	0.001274	0.00235	0.458842	45.88
Step3	0.00108	6.36E-07	2607.552	0.001658	0.00274	0.39439	39.43
Step4	0.00108	6.36E-07	3151.008	0.002004	0.00308	0.35019	35

Annex 3 Drawdown–Time Plots for Efficiency Corrected Drawdown

Figure 17 Plot for Efficiency corrected drawdown for SL-PW-07

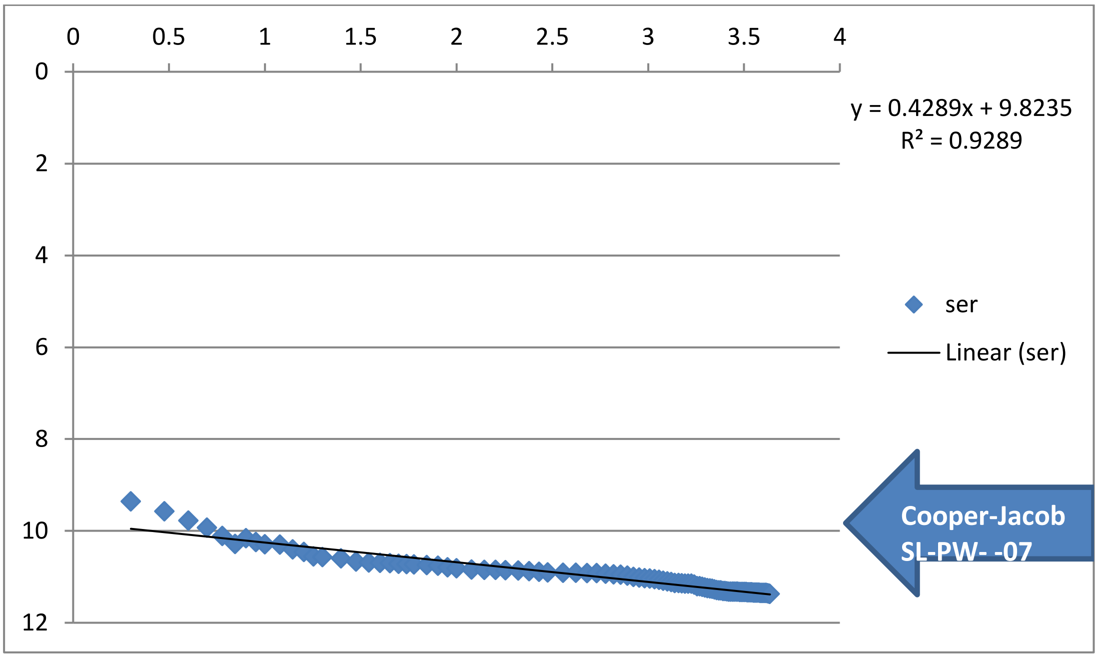


Figure 18Plot for Efficiency corrected drawdown for SL-PW-10

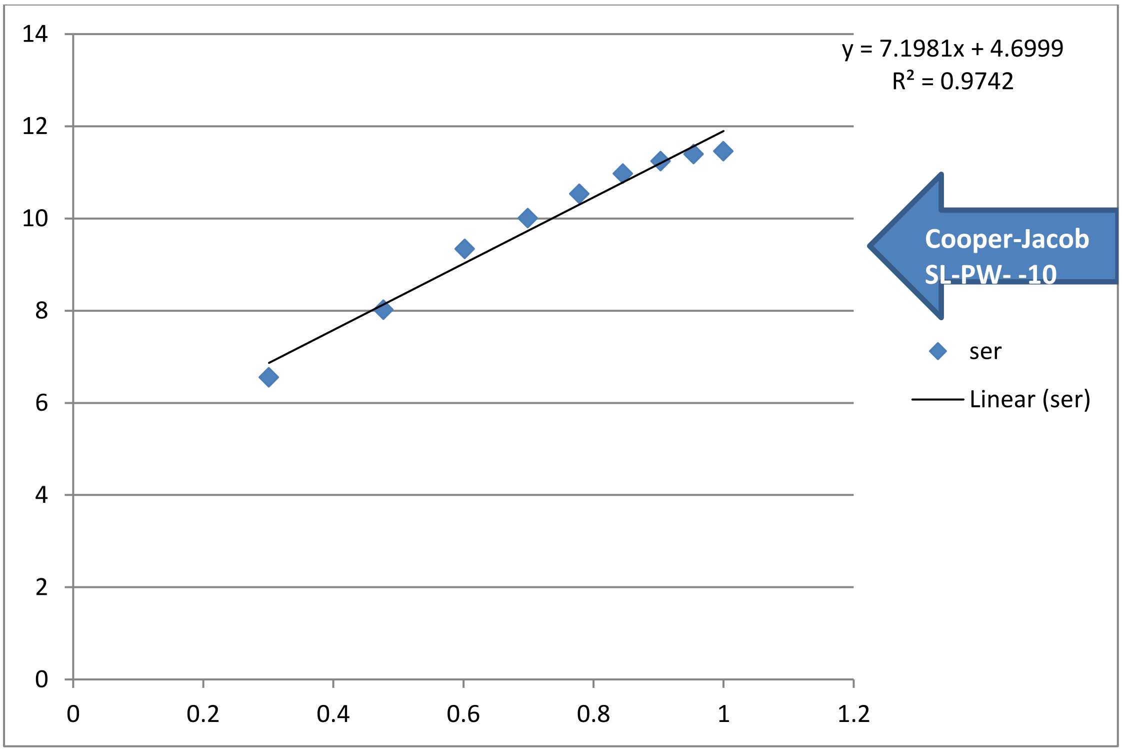


Figure 19Plot for Efficiency corrected drawdown for SL-PW-14

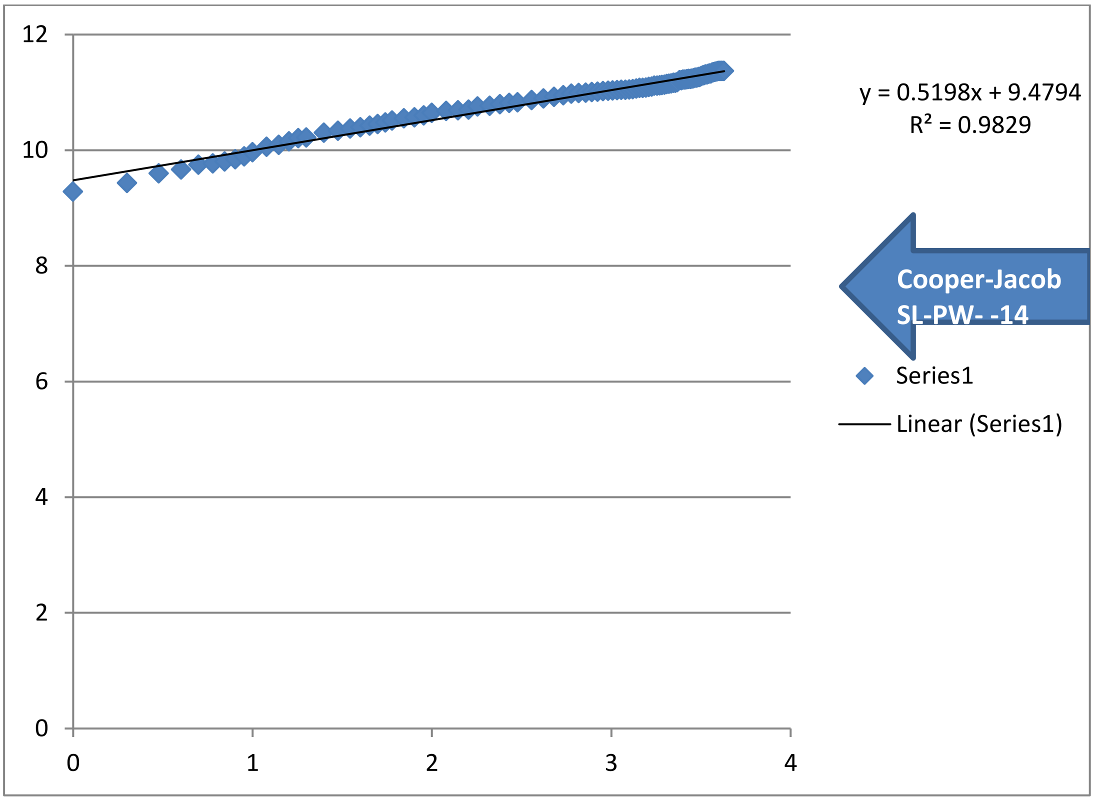


Figure 20Plot for Efficiency corrected drawdown for SL-PW-21

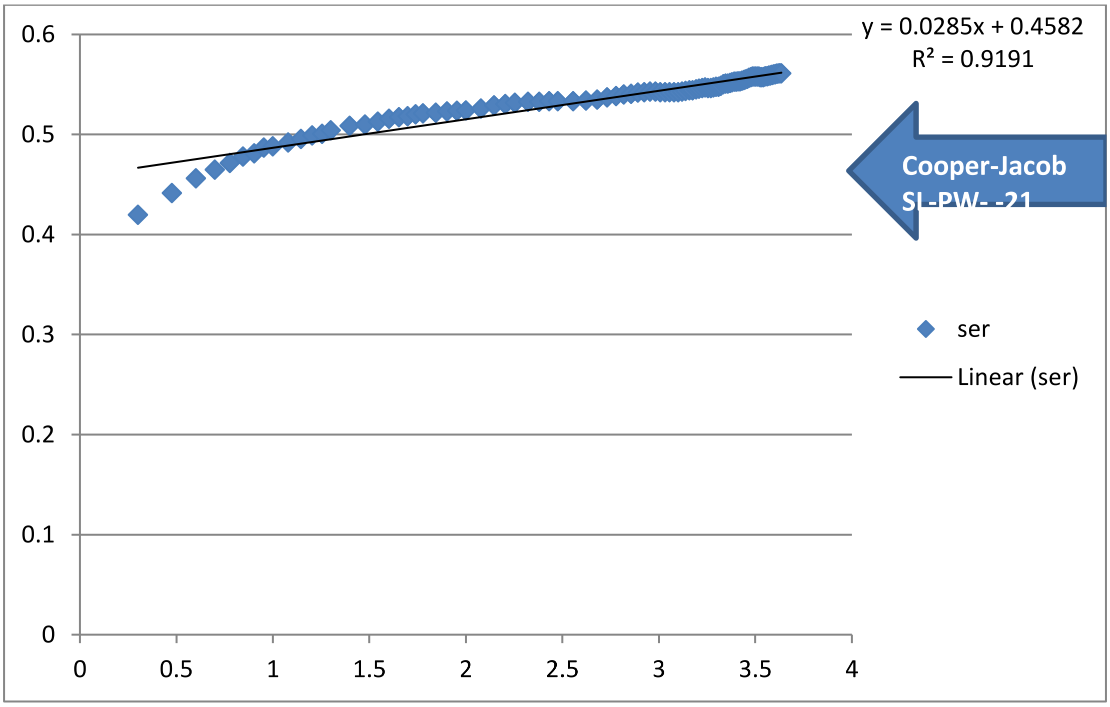


Figure 21Plot for Efficiency corrected drawdown for SL-PW-25

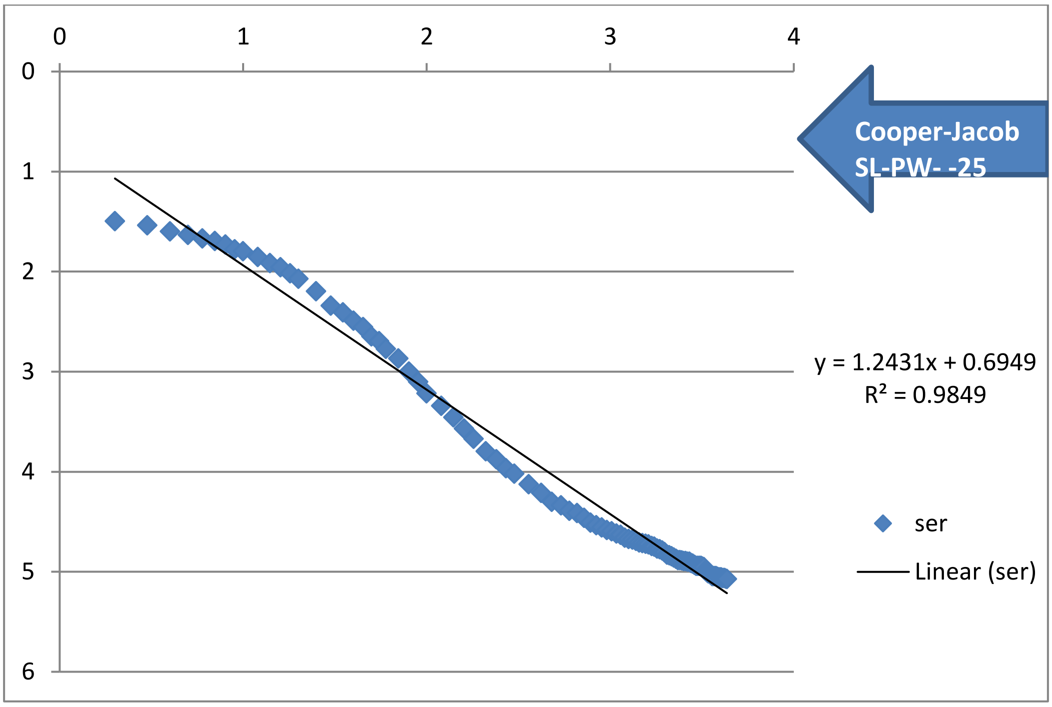


Figure 22Plot for Efficiency corrected drawdown for SL-PW-30

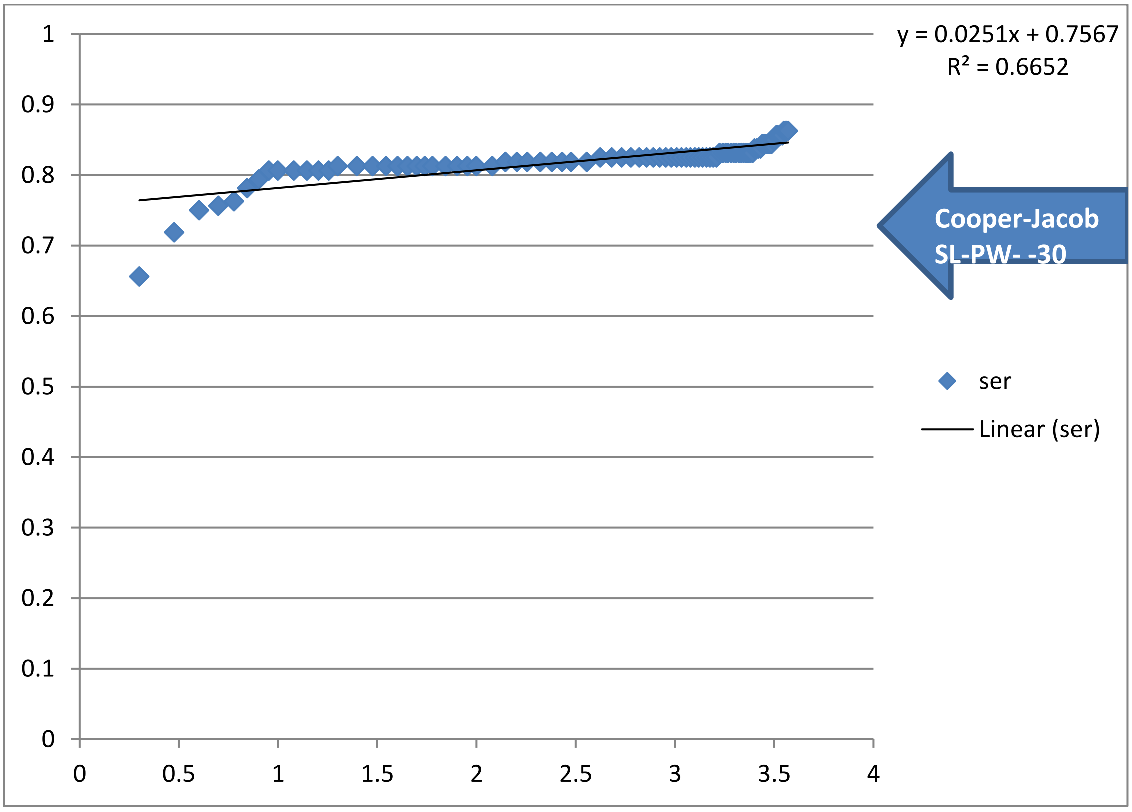
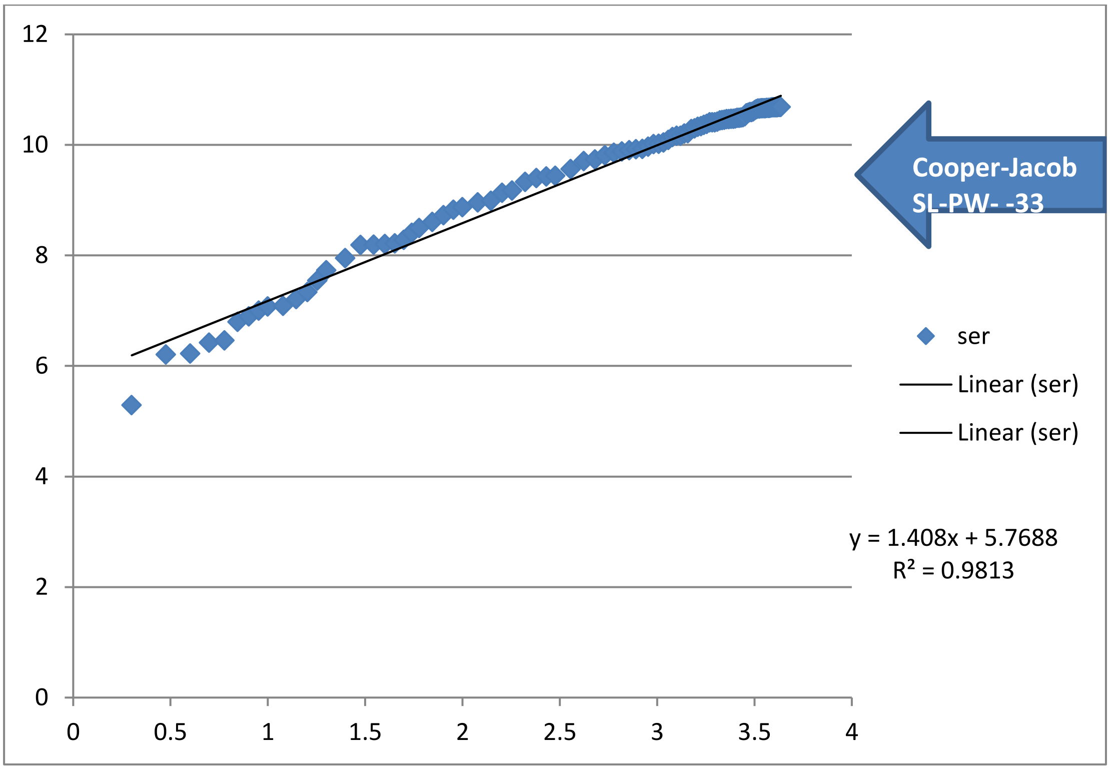


Figure 23 Plot for Efficiency corrected drawdown for SL-PW-33



Annex 4 Drawdown–Time Plots for kozeny Corrected Drawdown

Figure 24 Plot for kozeny corrected drawdown for SL-PW-07

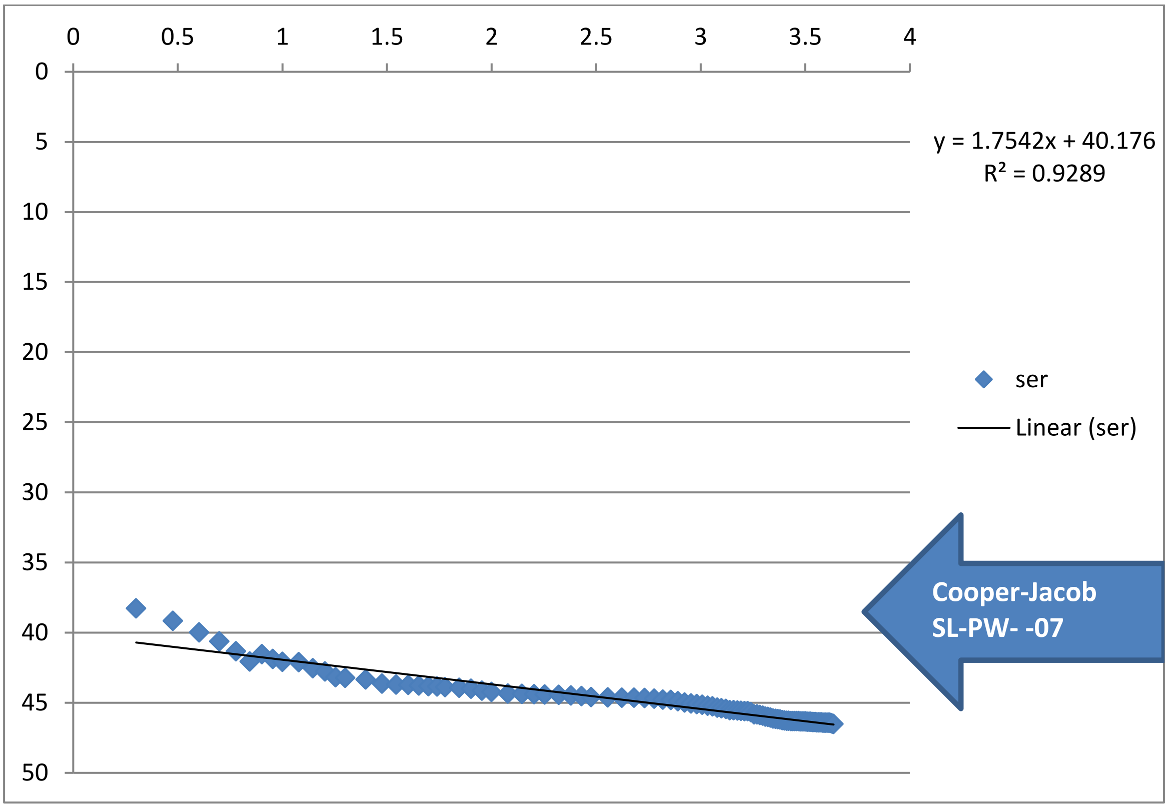


Figure 25 Plot for kozeny corrected drawdown for SL-PW-10

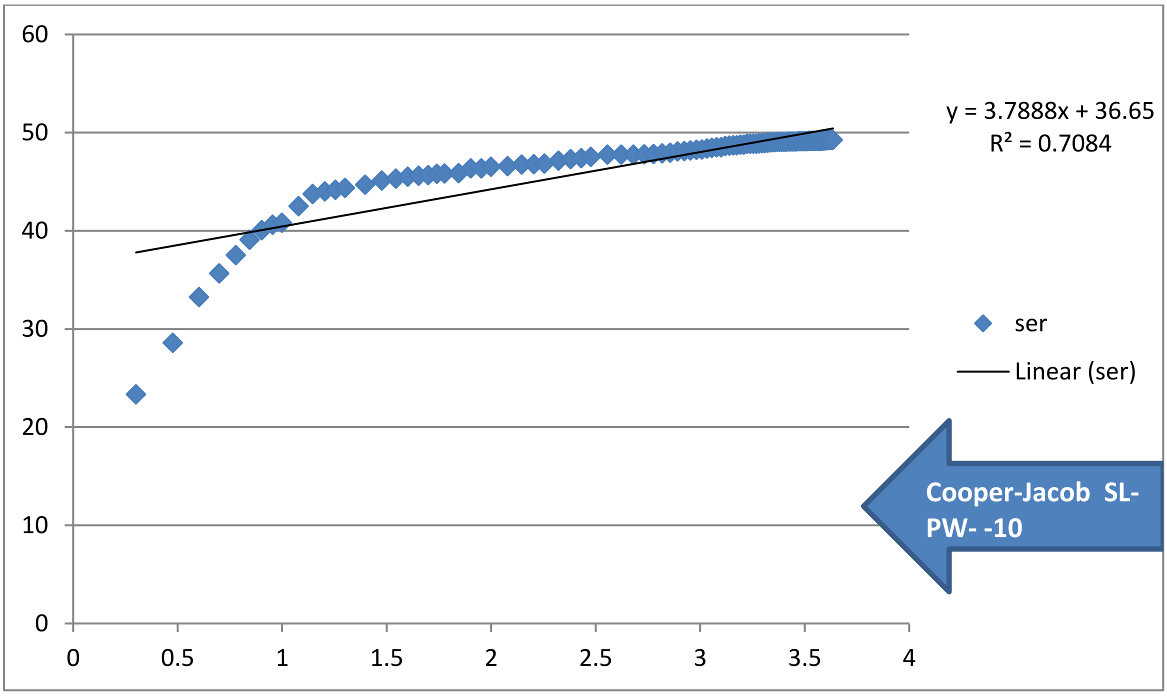


Figure 26 Plot for kozeny corrected drawdown for SL-PW-11

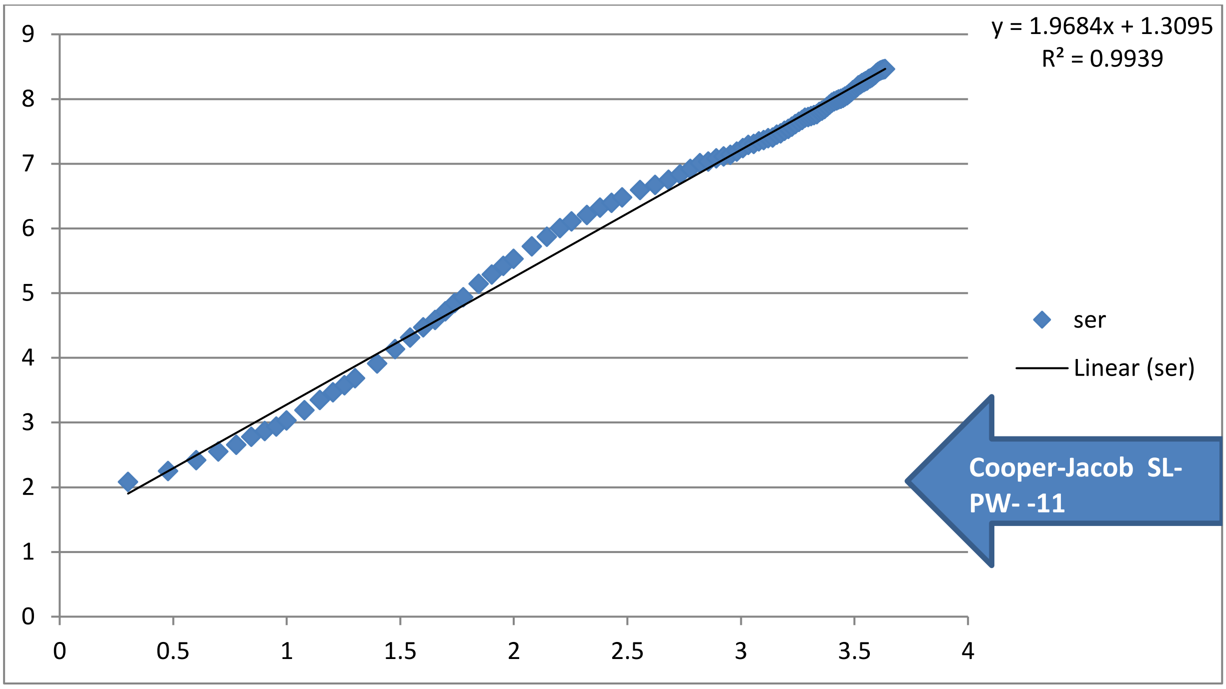


Figure 27 Plot for kozeny corrected drawdown for SL-PW-14

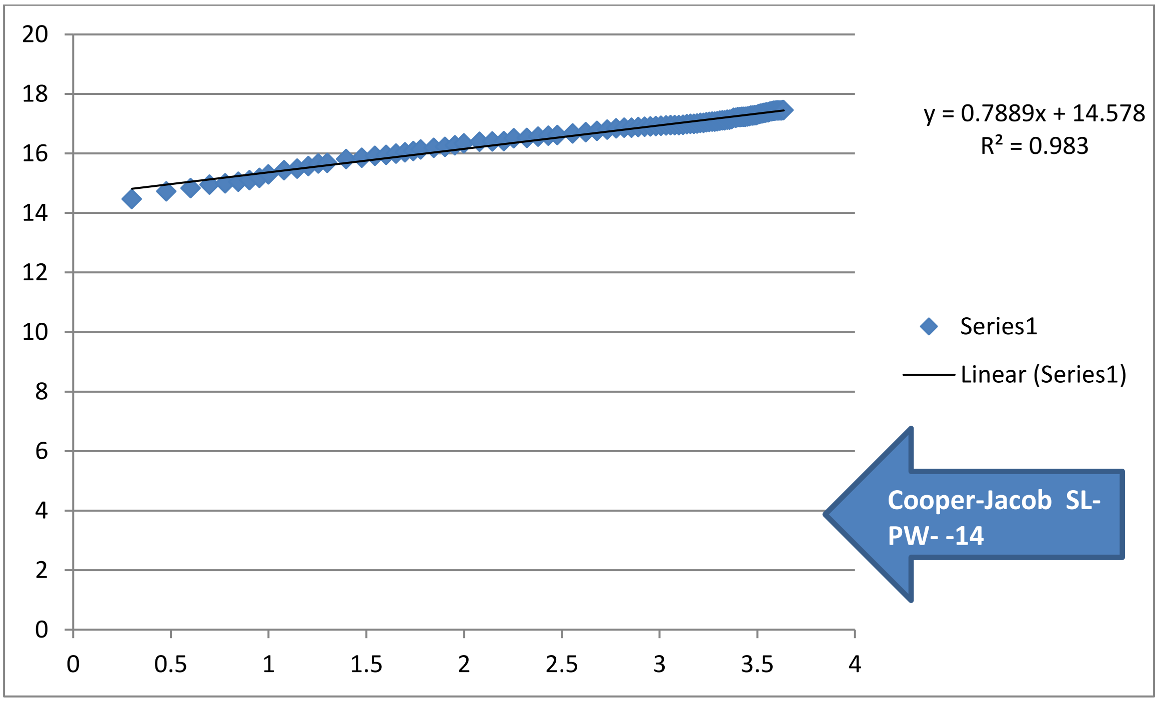


Figure 28 Plot for kozeny corrected drawdown for SL-PW-18

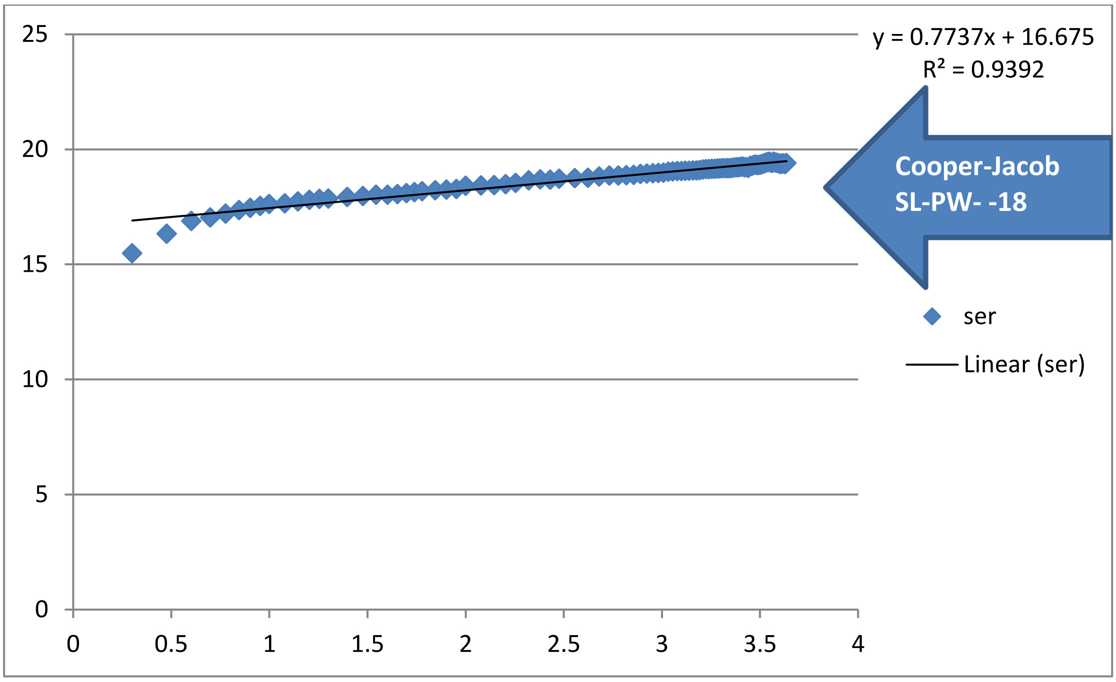


Figure 29 Plot for kozeny corrected drawdown for SL-PW-21

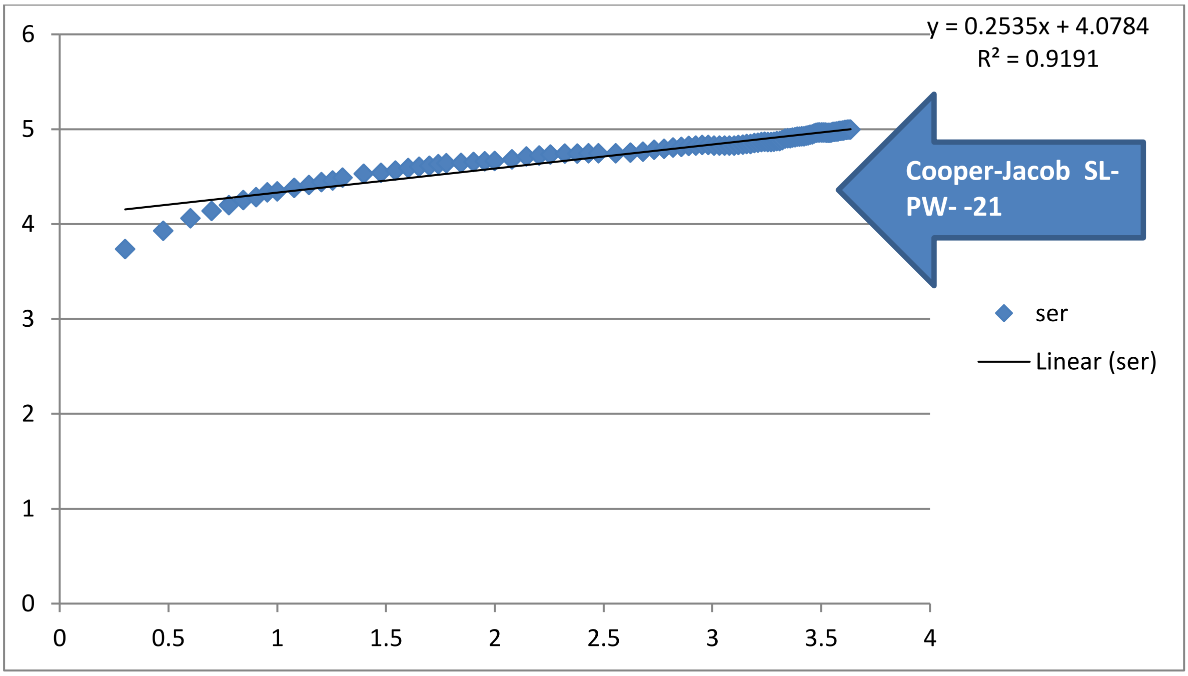


Figure 30 Plot for kozeny corrected drawdown for SL-PW-25

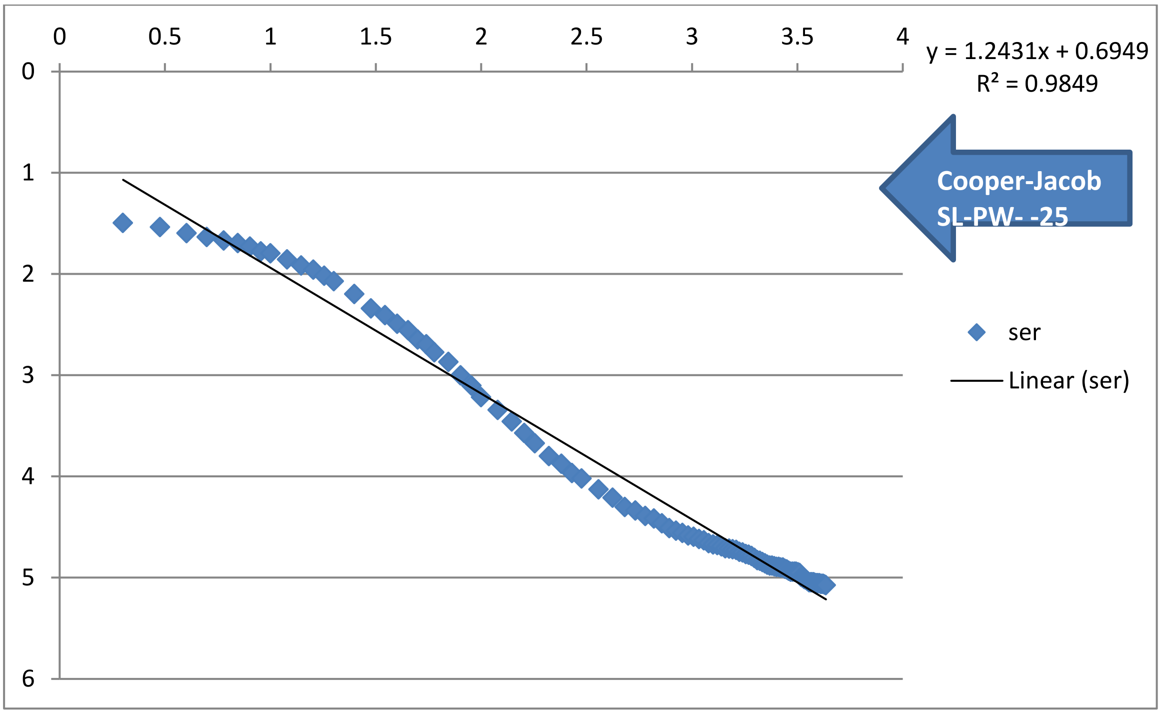
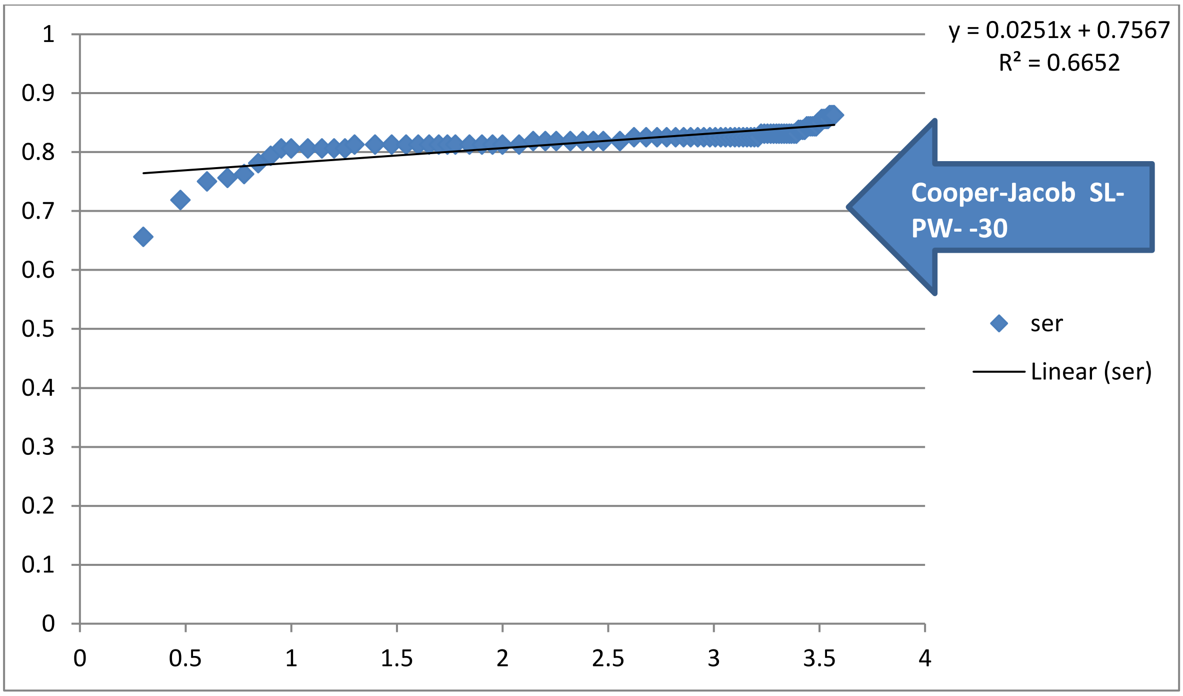


Figure 31 Plot for kozeny corrected drawdown for SL-PW-30



Annex 5 Summary of the well completion report

No	Prospective site/well field	well field	Well Index	Well type	Coordinate UTM Zone 37 Adindan		Elev, m	Contractor	Depth, m	Static water level, m	Dynamic water level, m	Draw down, m	Q, test, (l/S)	Transmis. (m2/day)	Specific well yield, l/s/m	Status
					UTM east	UTM north										
1	Akaki	Well field 02	SL-PW-03	production well	475276	976930	2052	CGCOC	582	54.32	128.99	74.67	75.44	448	1.01	Completed
2	Akaki	Well field 02	SL-PW04	production well	476037	976861	2068	CGCOC	595	55.18	91.25	36.07	88	150	2.44	Completed
3	Akaki	Well field 02	SL-PW-05	production well	475058	976100	2062	CGCOC	502	48.79	68.99	20.2	91	822	4.5	Completed
4	Akaki	Well field 02	SL-PW-06	production well	475528	975870	2059	CGCOC	600	52.02	86.4	34.38	86.5	747	2.51	Completed
5	Akaki	Well field 02	SL-PW-07	production well	476098	976183	2076	CGCOC	550	53.52	131.03	77.51	46.7	309	0.6	Completed
6	Akaki	Well field 02	SL-PW-08	production well	474528	975585	2057	CGCOC	569	49.06	73.5	24.44	95	138	3.88	Completed
7	Akaki	Well field 02	SL-PW-09	production well	473954	975244	2068	CGCOC	600	64.54	78.72	14.18	70.43	1000	4.966	Completed
8	Akaki	Well field 02	SL-PW-10	production well	473954	975244	2053	CGCOC	591	49.28	133.39	84.11	55	255	0.65	Completed
9	Akaki	Well field 02	SL-PW-11	production well	471453	974241	2048	CGCOC	335	50.04	63.35	13.31	112.7	635	8.467	Completed
10	Akaki	Well field 02	SL-PW-12	production well	475507	974697	2046	CGCOC	320	49.45	55.95	6.5	113.48	140	17.458	Completed

No	Prospective site/well field	well field	Well Index	Well type	Coordinate UTM Zone 37 Adindan		Elev, m	Contractor	Depth, m	Static water level, m	Dynamic water level, m	Draw down, m	Q, test, (l/S)	Transmis.	Specific well yield, l/s/m	Status
11	Akaki	Well field 02	SL-PW-13	Production well	472078	974359	2050	CGCOC	319	51.65	57.57	5.92	106	1020	17.9	Completed
12	Akaki	Well field 02	SL-PW-14	Production well	472640	973882	2072	CGCOC	518.5	70.25	98.33	28.08	84.9	1010	3.02	Completed
13	Akaki	Well field 02	SL-PW-15	Production well	473428	973584	2078	CGCOC	623	70.55	134.5	63.95	32.35	85.6	0.51	Completed
14	Akaki	Well field 02	SL-PW-16	production well	474702	974792	2069	CGCOC	59.5	69.98	97	27.02	98	761	3.62	Completed
15	Akaki	Well field 02	SL-PW-17	Production well	474733	973382	2072	CGCOC	501	78.54	124.67	124.67	34.55	90.7	0.8	Completed
16	Akaki	Wellfield 02	SL-PW-18	production well	477023	973986	2090	CGCOC	503	84.85	114.61	29.76	66.17	1020	2	Completed
17	Akaki	Well field 02	SL-PW-19	production well	476375	974046	2091	CGCOC	568	90.5	147.06	56.56	27	32.5	0.477	Completed
18	Akaki	Well field 02	SL-PW-21	production well	477959	974168	2103	CGCOC	501	98.47	108.3	9.83	90.23	4040	9.179	Completed
19	Akaki	Well field 02	SL-PW-22	Production well	475507	974679	2070	CGCOC	51.5	76.65	120.13	43.48	72.34	1020	1.66	Completed
20	Akaki	Well field 02	SL-PW-24	Production well	475941	975137	2063	CGCOC	551	65	71.67	6.67	102	2450	15.3	Completed
21	Akaki	Well field 02	SL-PW-25	Production well	473071	974284	2060	CGCOC	552	56.08	61.61	5.53	109	792	19.7	Completed
22	Akaki	Well field 02	SL-PW-30	Production well	478528	973384	2113	CGCOC	518	132.4	133.72	1.32	46	18700	34.848	Completed

No	Prospective site/well field	well field	Well Index	Well type	Coordinate UTM Zone 37 Adindan		Elev, m	Contractor	Depth, m	Static water level, m	Dynamic water level, m	Draw down, m	Q, test, (l/S)	Transmis.	Specific well yield, l/s/m	Status
23	Akaki	Well field 02	SL-PW-32	Production well	476725	973381	2111	CGCOC	170	110	149.74	39.74	47.67	438	1.2	Completed
24	Akaki	Well field 02	SL-PW-33	Production well	477415	973284	2112	CGCOC	453	116.38	139.69	23.31	37.34	242	1.6	Completed