ADDIS ABABA UNIVERSITY
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SCHOOL OF GRADUATES STUDIES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Assessment of reasons for yield decrease of water wells in Akaki well field based of Design, Construction and Operation

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil and Environmental Engineering
(Water Supply and Environmental Engineering)

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This is to certify that the thesis prepared by Bethelhem Kena, titled: "Assessment of reasons for yield decrease of water wells in Akaki well field based of design, construction and operation" submitted in partial fulfillment of the requirements for the degree of masters of science in Civil and Environmental Engineering (Water Supply and Environmental Engineering) that complies with the regulations of the university to meets the accepted standards concerning originality and quality.

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DECLARATION

I hereby declare that this thesis represents my own work and has not been submitted to this or other institutions for a degree or master's program previously.

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This thesis has been submitted for examination with my approval as a university advisor.

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ABBREVIATION AND ACRONYMS

AAWSA: Addis Ababa Water and Sewerage Authority

CCTV: Closed Circuit Television

CSA: Central Statistical Agency

DD: Drawdown

Eh: Redox potential

GI: Galvanized Iron

GIS: Geographic Information System

L/S: Litre per second

m: Meter

m^2/min: meter square per minute

m^3/min: meter cube per minute

m^3/day: meter cube per day

NE: North East

PH: Potential of Hydrogen

PVC: Polyvinyl Chloride

Q: Pumping rate

s: Drawdown

S: Storativity

SW: South West

t: time

T: Transmissivity

UTM: Universal Transverse Mercator

WWDSE: Water Works Design and Supervision Enterprises

ABSTRACT

Groundwater is of paramount importance for the city of Addis Ababa and the majority of the groundwater supplied to the city comes from drilled wells in and around Akaki-Kality sub city. Even though numerous water wells are built over the years, the majority of the wells fell to provide anticipated design yield. The study mapped 70 wells found in Akaki Phase I, Akaki Phase II, Akaki Phase IIIA & Akaki Phase IIIB on ARCMAP to see the spatial distribution of wells and their performance over the years. From the map, some wells were observed to perform better than their neighboring wells and some wells were found to perform worse than the neighboring wells. Therefore the research engrossed in understanding the reason behind this phenomenon mainly by focusing on the design, construction, and operation of selected wells from all phases of Akaki well field.

The selected 35 wells were grouped in accordance with their performance. Data from the well-completion report was organized and analyzed to identify the possible reason for the decrease in yield. Parameters used to compare the grouped wells were depth, elevation, screen arrangement, geologic medium, filter material used, construction process, year of construction, and the drilling contractor. The result showed bottom elevation of some better performing wells is deeper than those in a worse condition which means they are tapping water from a deeper aquifer. Another finding was 60% of the study wells have 30-50% of their casing screened. Some wells perform worse than their surrounding wells because their screened section is lower. For these wells, it can be suggested to increase the screen section in accordance with the water-bearing formation.

From the analysis done using the Cooper Jacob method, it was found that the majority of the wells are developed within the radius of influence of one another meaning pumping water from one well is affecting the neighboring wells. Another finding of the research is the drawdown result from single and multiple well tests which showed 100% of the wells are being affected by the surrounding wells which supports the result obtained on the radius of influence of those same wells.

Keywords: ***Akaki Phase I, Akaki Phase II, Akaki Phase IIIA, Akaki Phase IIIB, drawdown, radius of influence, well performance, well yield***

1. CHAPTER ONE: - Introduction

1.1. Background

Around 70% of the earth's surface is covered with water. Only 2.8% is fresh and the rest is saline. Thirty percent of the earth's freshwater is assumed to be a groundwater source (Gleick, 1993). Openings in subsurface formations that are adequate to give water in a usable amount to wells and springs are found nearly everywhere on the land surface which makes groundwater one of the most widely available natural resources. Groundwater represents the largest reservoir of fresh usable water that can be used by humans and considering its obvious value to the economy and human welfare makes groundwater the most valuable resource on earth (Heath, 1982).

Effective and sustainable water resource usage is vital in addressing the issues that arise when dealing with access to a clean water supply. Even though groundwater is a profoundly useful and plentiful asset, extreme or overuse of this resource can pose serious difficulties to human beneficiaries and the environment. Water table, over the years, is lowering beyond the reach of existing water wells necessitating the drilling of deeper wells to access groundwater sources (Driscoll, 1986).

Groundwater has become increasingly vital for both urban and rural areas in the past few decades and there are few explanations for this. Compared to other resources, groundwater typically costs less to develop; the natural protection provided by aquifers is capable of preventing contamination, and groundwater provides reliable supply and drought protection. In arid and semi-arid regions of Ethiopia, groundwater provides the only practical way to meet the needs of rural communities, and note that groundwater also supplies many urban centers including the capital city Addis Ababa. In such a manner, future advancement of settlements and urban areas development in Ethiopia is exceptionally reliant upon the capability of adjacent aquifers to truly satisfy the expanding need of the population increase and industry expansion (Seifu, 2013).

The town of Addis Ababa gets water from ground and surface water sources but this research focuses on the groundwater source obtained and supplied to the city. Akaki well field is considered as the primary groundwater source for Addis. There are plenty of water wells drilled and developed to supply clean & potable water for the city. Although a lot of investments are put in this study wells most of the wells' current condition are deteriorated in terms of yield decrease from their intended designed production rate which raises a big question as to why this is happening. The increase in the population of Addis Ababa over the years and the unmet water demand of the population require us to use the already existing water source infrastructures to their fullest capacity.

The proper design and construction of water well is highly required in order to maximize the benefits from water wells (Naggar, 2005). Water well is said to be it has failed if it no longer gives water or has shown a drastic decrease in production rate. Many water wells in and around Addis are observed to give lower yield than was initially designed for.

Previous research done in Akaki well fields showed that there is a possibility of overestimation of design production yield of wells and state that as the reason of well yield decrease. The groundwater sources of the Akaki Phase II have wrong assumptions in the design phase since it did not give major stress to the well drawdown loss. It was also found that there is a great variation of values of transmissivity and storativity (Lidiya, 2020). The same is true for Akaki Phase IIIB where the recommendation in the design report for the values of production yield, transmissivity & storativity values were found to be inaccurate and do not represent the capacity of the well (Sofia, 2017). Another researcher, (Yimer,2018) explained groundwater extraction greater than the replenish capacity of the well is one of the main factors that affect the groundwater potential of the Akaki catchment. He identified deforestation and over-pumping of groundwater as the primary cause for the depletion of groundwater.

However most wells in Akaki well field display a decrease in production yield over the years, it was observed that some wells perform better than the neighbouring wells and some wells perform worse than the neighbouring wells. This research will try to find reasons as to why this is happening and later will try to suggest alternative measures that can restore yield and revive the wells.

1.2. Problem Statement

The city of Addis Ababa uses a combined system of groundwater and surface water sources to supply water to the residents of the town. Even if the city is also supplied by surface water sources, the majority of the contribution to the supply system is from shallow & deep water wells excavated in and nearby the city.

Akaki well field is one of the sources of water for the city of Addis Ababa acquiring water from the deep wells developed in that area. Although it is the main source of water supply, various problems are observed in the functionality and sustainability of developed water wells. Over the years of service of these drilled wells, it was seen that there is a significant decline in the production capacity of the wells. Some wells are even left abandoned due to this problem before giving service to their intended design period.

Groundwater source, by contrast, is considered as the best means of a source of potable water as it often requires no treatment and can be realized reliable during times of drought or limited rainfall. But this method of extracting water by drilling underground is an expensive process. In addition to cost, also considering the unsatisfied water need of the people of Addis, different rehabilitation measures have to be employed to restore or improve water yield and maximize the performance of failed wells.

Performance decline (decrease in discharge) in a well can be categorized in two ways, aquifer problem or well problem. Over the years wells in Akaki well field showed a variety of performances. Some wells showed a great decline in yield while the neighboring wells were performing better whereas in some areas of the well field some wells were found to perform better than the surrounding wells. This brought the idea that some wells perform worse than their neighboring wells not because there is no water in the aquifer but due to well problems. Well problem in this research is defined as problems caused during the design, operation, or construction of the well. The study will focus on selected water wells that showed yield decrease over the years and the problems are highly related to the well itself (well problem).

1.3. Objective of the research

1.3.1. General Objective

The main objective of this research is to identify reasons for the performance decline of water wells found in Akaki well field.

1.3.2. Specific Objective

In order to achieve the main goal, the study will specifically focus on the following

- To map and identify wells that have shown performance decline in Akaki well field
- To assess and understand reasons for the decrease in yield over the years
- To recommend possible rehabilitation measures that can restore yield in the wells

1.4. Research Questions

The research will try to answer the following questions

- Which wells are in good condition and which aren't?
- What are the major reasons for the decrease in water well yield found in Akaki well field?
- What are the possible rehabilitation measures that can revive yield in those wells that are showing lower performance?

1.5. Scope of the study

The study aims on finding reasons for the decrease in the yield of water wells found in Akaki well fields; Akaki Phase I, Akaki Phase II, Akaki Phase IIIA, and Akaki Phase IIIB. Study wells are selected based on the relative performance rating of wells as compared to one another. That is a single well could be performing better than the neighboring wells or a single well could perform worse than the surrounding wells. 35 water wells were selected from different phases of the well field for detailed study. These wells have shown a decrease in yield and also are assumed to have a problem in the design, construction, and operation. Well-completion reports of the study wells were gathered and deeply studied under different circumstances.

1.6. Structure of the study

The research constitutes five chapters. The first chapter discusses the general content of the research starting from background information, states the problem, scope of the study, and specifies the objectives to be achieved at the end of the research.

The second chapter is the literature review section that discusses in detail by capturing contents from different previous researchers that will give a general image of the concept of subsurface water and provide the reader with the existing knowledge.

The third chapter deals with the methods followed to do this research. It consists of information about the study area, the data used, the materials and tools used to do the research.

The fourth chapter is the result and discussion part which points out findings from the research, gives descriptive information of results acquired, and interpretation of the results obtained are deeply discussed.

The fifth or last chapter of the study holds the conclusion and recommendation parts. The conclusion sums out the key findings obtained from the research and the recommendation points out possible investigation information for future researchers on the topic by mentioning limitations on the research.

2. CHAPTER TWO: - Literature Review

2.1. Water sources

Water is the most plentiful substance on the planet, the vital constituent of every living thing, and a significant power continually forming the outer layer of the earth. It is likewise a critical component in cooling the earth for human life and in affecting the advancement of progress. Hydrology, which treats all phases of the world's water, is a subject critical for individuals and their current circumstances (Chow, Maidment & Mays, 1988). Among the present, generally intense and complex issues are water issues identified with the appropriate use and safeguard of water sources. Related to water issues is the need to supply man-kind with satisfactory, clean freshwater (Gleick, 1993). Water can have many purposes amongst which are for cleaning, drinking, bathing, industry use, Irrigation, etc.

All water underneath the land surface is referred to as under-ground water (or subsurface water). The term used for water on the land surface is surface water (Heath, 1982).

2.1.1. Groundwater sources

The ground-water environment is deposited away from view besides in caverns and mines, and the thinking that we gain even from these are, generally, deceptive (Heath, 1982). Infiltration is the course of water entering starting from the surface into the underground soil formation. Many elements impact the invasion rate, including the state of the soil surface and its vegetative cover, the properties of the dirt, for example, its porosity furthermore pressure-driven conductivity, and the current moisture content of the soil (Chow, Maidment & Mays, 1988). Dependent upon the proportion of infiltration and the genuine properties of the soil, the wetting front may enter from a couple of centimeters to a couple of meters into a soil (Hillel, 1980).

Groundwater can be tapped from two sources namely shallow and deep water sources.

2.1.1.1. Shallow groundwater

Water that can be reached through hand digging of wells in areas where water has been trapped in the underground, for instance, in valleys, downstream of earth dams and near swamps, incidental watercourses, streams, and lakes (USBR,1964).

2.1.1.2. Deep groundwater

Water that has permeated/percolated underground for years or centuries is kept somewhere down in the surface and is referred to as deep groundwater sources. These aquifers of water are reached by drilling deep boreholes utilizing distinctive boring systems and are pumped out of the ground surface to be used (USBR, 1964).

2.1.2. Groundwater sources in Ethiopia

The volume of groundwater in the subsurface is determined by the number of open gaps in rocks and their spatial expanse. Volcanic rocks cover two-thirds of Ethiopia. The rest of Ethiopia is covered by Sedimentary and metamorphic aquifers. Volcanic rocks are the most accessible aquifers in central Ethiopia due to their stratigraphic position. Aquifers are formed in regions where sedimentary rock is exhumed by volcanic cap erosion or where volcanic materials did not exist previously. The rock type, the extent of the rocks, the recharge rates and such conditions affect and create a difference in the groundwater potential between continents, regions, and countries. By surface area, volcanic rocks are the biggest, while loose sediments are the biggest aquifers by groundwater storage. There are an estimated 640 billion cubic meters of fresh water and 540 million cubic meters of saline water in Ethiopia (Seifu, 2013).

2.1.3. Groundwater sources in Addis Ababa/Akaki

In addition to surface water resources, groundwater is highly used as a source of drinkable water in Addis Ababa. Large levels of stored groundwater give you a higher chance of getting good-quality and high-yielding water. Groundwater is found in scoriaceous layers and flow contact zones of the town (Seifu, 2013). The lithological stratigraphy and tectonics of the area determine the basin's overall hydrogeological configuration. The primary aquifers were divided into three categories. a) Shallow aquifers: formed by worn volcanic rocks and alluvial deposits along river channels, b) Deep aquifers: formed by cracked volcanic rocks that access fresh groundwater, and c) Thermal aquifers: found at depths more than 300 meters (Leta, 2014).

Previous research by Shaqa determined the regional groundwater flow direction, which is thought to be north-south from Addis Ababa to the Akaki well field. The well fields subsurface flow conditions are assumed to be from the NE to the SW (Wang, 2001). High flow abounds in and around the Akaki well field, according to Tenalem (2008) where scoria and fractured basalts offer the most productive aquifer.

The extraction of subsurface resources in the Akaki catchment's well fields is presently not based on a thorough understanding of drawdown levels and the area's prospective groundwater resources. Meanwhile, in the Akaki watershed, maladministration of subsurface resources and misuse has continued (Tenalem, 2006).

2.2. Groundwater hydrology

Hydrology, which treats all times of the world's water, is a subject basic for people and their momentum situation (Dawei, 2010). Ground-water hydrology manages the event of underground water yet additionally with its development. Subsurface openings are adequately huge to yield water in a usable amount to wells and springs underlie practically every spot on the land surface and in this way make groundwater quite possibly the most generally accessible regular resource. At the point when this reality and the way that groundwater additionally addresses the biggest supply of freshwater promptly accessible to man are thought of as together, clearly the worth of groundwater, as far as both financial aspects and human government assistance, is limitless. Accordingly, its sound turn of events, tenacious preservation, and steady insurance from contamination are significant worries of each one. These worries can be converted into viable activity exclusively by expanding our insight into the fundamental parts of ground-water hydrology (Heath, 1982).

Investigation of hydrogeology helps for the groundwater advancement for which information on the hydrogeology of the space, i.e., of the arrangement soil, re-energize offices like streams and repositories, downpour fall design, environment, and so forth are required (Raghunath, 2006).

Underground water happens in two distinct zones. One zone, which happens quickly beneath the land surface in many regions, contains both water and air and is alluded to as the unsaturated zone. The unsaturated zone is perpetually underlain by a zone wherein all interconnected openings are loaded with water. This zone is alluded to as the soaked zone. Water in the soaked zone is the main underground water that is accessible to supply wells and springs and is the main water to which the name groundwater is accurately applied. Saturated zone recharge happens by permeation of water from the land surface through the unsaturated zone. The unsaturated zone is, consequently, vital to ground-water hydrology (Heath, 1982).

2.2.1. Aquifer

An aquifer can be defined as a formation, group of formations, or part of a formation that comprises adequate saturated previous material to produce significant quantities of water to springs and wells. An aquifer from a geological concept as defined by (Meinzer, 1928) in which water bodies are classified in accordance with stratigraphy. Meinzer clearly intended that an aquifer include the unsaturated part of the permeable unit. An aquifer is chosen based on conditions of quality, quantity, and location of it. Water sources in the aquifer are primarily from infiltration and follow the horizontal flow (Ojha, Berndtsson & Bhunya, 2008).

2.2.1.1. Confined aquifer

A rock unit having extremely low pressure-driven conductivity that confines the development of ground water either in or out of nearby springs is termed as confined aquifer. Water is said to be confined when water fully fills an aquifer that is overlain by a confining bed (Ralph C. Heath, 1982). Water in a confined aquifer or artesian aquifer is under pressure just like a conduit flow as the aquifer is sandwiched underlain and overlain between two impermeable layers (Ojha, Berndtsson & Bhunya, 2008).

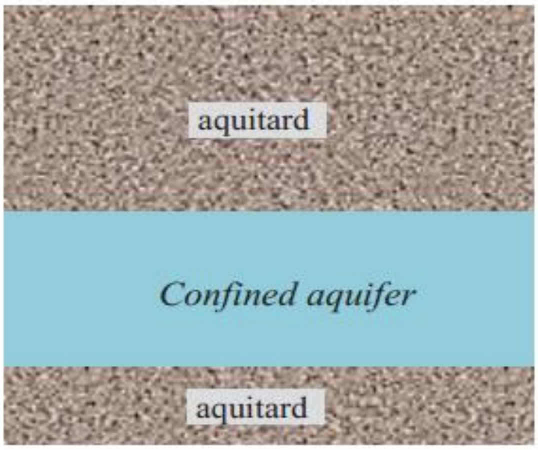

Figure 2. 1: Confined Aquifer (source: (Dawei, 2010)

2.2.1.2. Unconfined aquifer

Where water just somewhat fills a spring, the upper surface of the saturated zone is allowed to rise and drop. The water in such aquifers is called unconfined, and the aquifers are termed as unconfined aquifers (Heath, 1982). In an unconfined aquifer, groundwater has a free surface open for movement and is also termed as a water table aquifer. The zone that overlain the aquifer is referred to as water table or groundwater table (Ojha, Berndtsson& Bhunya, 2008).

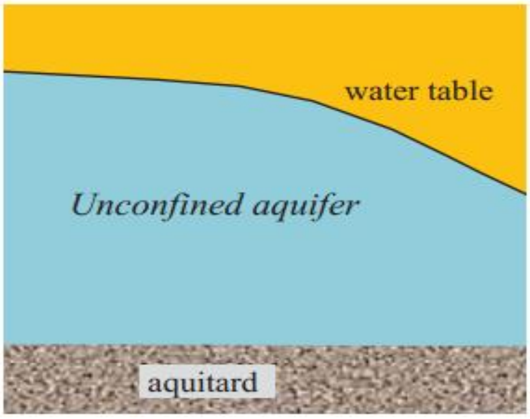

Figure 2. 2: Unconfined Aquifer (source: (Dawei, 2010)

2.2.2. Aquifer properties

2.2.2.1. Storativity

The volume of water released from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface is known as storativity. Storativity doesn't have dimension. It has a value that ranges between 0.00005 and 0.005 in most confined aquifers. For unconfined aquifers, the storativity or storage coefficient is the same as the specific yield and may range between 0.05 and 0.30 (Ojha, Berndtsson & Bhunya, 2008).

2.2.2.2. Transmissivity

Transmissivity is the term used to describe the ability of water to move through an aquifer. It is the rate at which water of the prevailing kinematic viscosity is conveyed through a unit width of the aquifer under a unit hydraulic gradient. It is considered as a property of the aquifer, which is transmissive, whereas the contained liquid is transmissible. However, though spoken of as a property of the aquifer, it embodies also the saturated thickness of the aquifer and the properties of the contained liquid. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow path (Gutentag, 1992).

2.2.2.3. Hydraulic Conductivity

Assuming a permeable medium is isotropic and the liquid is homogeneous, the hydraulic conductivity of the formation is the volume of water at the current kinematic thickness that will move in unit time under a unit hydraulic gradient through area measured at right angles to the direction of flow (Gutentag, 1992).

The factors controlling ground-water movement were first explained by French Engineer Henry Darcy, in 1856. Darcy's law is

$$Q = KA\left(\frac{dh}{dl}\right) \quad \text{……………………………………………………………………} \quad (1)$$

Where Q is the quantity of water per unit of time; K is the hydraulic conductivity and depends on the size and arrangement of the water-transmitting openings (pores and fractures) and the dynamic characteristics of the fluid (water) such as kinematic viscosity, density, and the strength of the gravitational field; A is the cross-sectional area, at a right angle to the flow direction, through which the flow occurs; and dh/dl is the hydraulic gradient.

Since the amount of water (Q) is directly proportional to the hydraulic gradient (dh/dl), the flow of ground-water flow is considered laminar-meaning, water particles tend to follow discrete streamlines and not to mix with particles in adjacent stream-lines (Heath, 1982).

2.2.2.4. Porosity

Porosity is a measure of the water-bearing capacity of the formation, and all this water cannot be released by gravity or pumping from wells. The porosity of the grain size is determined by its shape, size, and packing. The volume of voids in a rock or soil can be expressed quantitatively as a percentage of the total volume of the rock or soil (Ojha, Berndtsson & Bhunya, 2008). It could be expressed as a decimal division or as a rate.

$$n = \frac{V_v}{V_T} \qquad (2)$$

Where n is the porosity, V_v is the volume of void, V_T is the total volume of aquifer formation, S_r is specific retention and S_y is the specific yield.

Porosity can also be determined by adding values of specific retention and specific yield (Gutentag, 1992).

$$n = S_r + S_y \qquad (3)$$

S_r = Specific retention

S_y = Specific Yield

2.3. Water well design and construction

2.3.1. Well Design

Proper well design is an important factor for a sustainable facility. Specifying the materials and dimensions of a well is what we call well design (Driscoll, 1986). However different design standards have been articulated every once in a while by those working in the field of well plan, a point has now been achieved at feasible design plan for an ideal well for practically all aquifer conditions found within nature. When designing a well one should focus on the efficient utilization of the aquifer, proper initial cost, long life span, operation, and maintenance cost must be low (Garge,1987).

An assessment of records from existing wells in the surrounding area must be made to decide yield, depth, and attributes of the aquifers utilized. Local well drillers are also a valuable source of information. If sufficient records are not available, test holes should be drilled to allow for the selection of the site with the highest potential for water production and to aid in the formulation of the production well design for the selected site. The well designer should estimate the yield and specific capacity of a full-sized production well based on the completed test holes' aquifer thickness, aquifer depth, and static water level. To determine the corrosion and/or incrustation characteristics of the water, a water sample should be collected and analyzed (Boman, Shukla, and Hardin, 2006).

2.3.1.1. Well depth

During drilling of well samples are taken out at every depth going down. Well depth depends on the soil and rock samples taken during the drilling of a test borehole. A gamma-ray log in the test hole can provide more precise information about the bore log (Sharm El-Sheikh, 2005).

2.3.1.2. Casing diameter

The pipe is used to support the hole during drilling or to complete the well assembly afterward. The diameter of the casing pipe is determined by the size of the hole and must be large enough to house the pump while allowing the water to flow upwards within a certain limit (Sharm El-Sheikh, 2005).

2.3.1.3. Well casing and screen

The length of the screen is an important design consideration. A well screen that is too short has a negative impact on well efficiency, whereas a well screen that is too long has issues such as cascading water, entrained air, and accelerated corrosion and/or incrustation. The optimal length of the well screen is determined by the aquifer thickness, available drawdown, and stratification of the aquifer. Depending on the preliminary investigation results, the well screen should be made of materials that are as corrosion resistant as possible. Sand and/or gravel will enter the well if the screen corrodes, necessitating either the replacement of the screen or the drilling of a new well. The material of the well screen is sometimes selected based on the strength requirements for load expected from the borehole and collapse pressure. Stainless steel provides the best corrosion resistance and strength for most fresh groundwater environments. Galvanized steel, GI, is appropriate for many irrigation wells where the water is not corrosive. It has the same strength as stainless steel. PVC well screens are corrosion-resistant and are commonly used in shallow wells. However, only a limited amount of open space can be provided while maintaining strength requirements. As a result, non-metallic well screens are typically insufficient for deep wells (Boman, Shukla, and Hardin, 2006).

2.3.1.4. Filter pack

Gravel-packed wells have a larger borehole through the water-bearing formation than the well screen. By filling the space between the face of the borehole and the well screen with graded sand or gravel that is coarser than the formation, the adjacent zone directly surrounding the well screen is made more permeable than the aquifer. The design of gravel pack includes gradation, thickness, and quality specifications for the gravel pack material. The samples collected during the test hole drilling should be examined to determine a portion of the aquifer thickness to be screened. A uniform gravel pack has much higher permeability and is much easier to install without segregation. The gravel pack material should be composed of clean, well-rounded, smooth grains. These characteristics improve the gravel pack's permeability and porosity. (Boman, Shukla and Hardin, 2006).

2.3.2. Well Construction

2.3.2.1. Drilling methods

Different geological conditions and subsurface formation, different drilling mechanisms are available. Certain drilling methods are preferred in certain areas because they are efficient and cost-effective. The best drilling mechanism for a specific drilling job necessitates a good knowledge of the geologic conditions as well as the physical limitations of the drilling rig (Driscoll, 1986).

The drilling diameters chosen should allow for not only the installation of the final well casing but also the installation of adjusted gravel pack and the necessary sealing to ensure effective contamination prevention (Guedes, Gomes, Almeida, Cortez, 2013)

The following few sections explain some methods of drilling mechanisms including their application and limitation.

2.3.2.1.1. Direct Rotary Drilling

In most formations, the direct rotary drilling method was developed to increase drilling speeds and depths. Cuttings are removed by continuous circulation of drilling fluid as the bit enters the rock, and the borehole is bored by rotating a bit. The viscosity and uphole velocity of the drilling fluid is the governing elements in properly eliminating cuttings indirect rotary drilling. Direct rotary has the following advantages: high penetration rates in all types of materials, minimal casing is required throughout the drilling operation, efficient rig mobility and demobilization, and well screens can be simply installed as part of the casing installation. Even though this method has many benefits it also has some disadvantages, such as the cost of drilling rigs are high, the high level of maintenance required by drilling rigs, the collection of accurate samples necessitates special procedures, and the use of drilling fluids may root plugging of some formations. Drilling cannot proceed unless cuttings can be removed. Most direct rotary machines used to drill water wells are limited to boreholes with a maximum diameter of 22 to 24 inches due to pump capacity limits and, ineffective cuttings removal (Driscoll, 1986).

Drilling underground can be done in a variety of ways, including mud rotary and air rotary. Mud rotary drilling incorporates bentonite clay or other elements into the jetting water to boost its ability to lift cuttings. Mud rotary drilling benefits include keeping the borehole open and avoiding the need for drives casings, as well as being faster than cable tool and jetting methods. The constraints of this method are observed during drilling through rock can only be done with larger rigs, numerous motors cost more fuel per hour than cable tool rigs, and huge rigs require support vehicles to transport water and drill pipe (Aller, Bennett &Hackett, 1989)

An air rotary drill rig is mechanically comparable to a mud rotary drill rig. The main distinction is that instead of drilling mud, cuttings are removed using compressed air. The advantages of this method include the fact that it is the fastest drilling method and takes less time to set up than other ways. However, it is the costliest approach, uses the most fuel, and necessitates the use of backup vehicles and a big air compressor (Aller, Bennett &Hackett, 1989)

2.3.2.1.2. Reverse Circulation Rotary Drilling

The rate of penetration by direct rotary machinery becomes less desirable as hole diameters exceed 24 inches. Reverse circulation machines were created to overcome the limitations of hole diameter and drilling velocity. The drilling fluid flow is reversed in reverse circulation rotary drilling, and the drilling fluid travels upward inside the drill pipe before discharging at the surface, often into one or more settling pits. Where the static water level is less than 3m below the surface, reverse circulation drilling is not often used. It is recommended that you use at least three times the amount/volume of material removed during the drilling process (Driscoll, 1986).

2.3.2.1.3. Jetting

Because of its simplicity and low cost of equipment, jetting remains a preferred method for drilling small-diameter wells. The jetting procedure includes breaking up the formation material and washing the cuttings away with a high-speed spray of water. On the end of a string of hollow drill pipe, a chisel-shaped bit with holes for nozzles is attached. A high-pressure pump is used to give water pressure to the nozzles. The nozzles emit water, which loosens the material being drilled out while also keeping the bit tidy. Typically, the casing is added as the drilling progresses. In caving formations, the drilling/driving sequence is particularly time-consuming, especially at deeper depths, because the drill string must be disassembled and removed from the well before driving casing, and then reassembled before drilling can resume. This approach just requires a few people for digging operations, and the only tools needed are a pump and pipe that can provide enough pressure. But this method only works in soft, fine-grained sediments, and installing a sanitary seal to protect against surface contamination is challenging (Aller, Bennett &Hackett, 1989)

2.3.2.2. Well development

Well-development is the process of repairing destruction to the formation caused by the drilling operation and removing the finer material next to the screen or filter pack using a range of mechanical and chemical means. The procedure cleanses or broadens channels in the water-bearing sand and gravel, allowing water to readily enter the well. (Boman, Shukla ,and Hardin, 2006).

To produce sand-free water at the maximum specific capacity, all new wells should be developed before starting production or giving service. Keeping the well's specific capacity high ensures that it will be energy efficient (Driscoll, 1986).

Another aspect that contributes to well inefficiency is poor well development once drilling is completed. Wells that are not properly developed will not reach optimal efficiency, resulting in higher pumping costs during the system's lifetime. Although it is critical to correctly design and construct the well using high-quality materials, it is also critical to complete full well development (Boman, Shukla, and Hardin, 2006).

2.3.2.2.1. Over pumping

Over-pumping is the simplest and most cost-effective approach; however, it is ineffective for high-capacity wells (extra water is required). Due to the non-reversal of flow, the approach is unable to break tiny particle bridging. It is pumping at a faster pace than when the well is placed into operation (Driscoll, 1986).

2.3.2.2.2. Backwashing

Backwashing is a simple and low-cost method that can produce good results. It is not recommended if there is a risk of sinking owing to the removal of too much fine material from the overlying strata. For the alternating washing and cleaning, the process needs a huge volume of water. The approach caused the aquifer to vibrate violently, and it should not be utilized where there are weak sandy clay formations (Sharm El-Sheikh, 2005).

2.3.2.2.3. Mechanical Surging

In sand and gravel formations, surging is one of the most prominent and widely utilized ways of producing wells. A fast up and down movement of a plunger creates surging, which is a development approach. This fast movement dislodges fine particulates from their bridging and drags them into the well (Sharm El-Sheikh, 2005).

2.3.2.2.4. Compressed air method

The compressed air approach is both fast and efficient. It is widely utilized and can be used in a variety of situations. There is little need for specialized equipment, and there is little risk of overdevelopment (Sharm El-Sheikh, 2005).

2.3.2.2.5. High velocity jetting

In the event of a big open screen area, high velocity jetting is the most successful way of well development. This strategy may be used to cover every portion of the screen (Sharm El-Sheikh, 2005). Water or air can be used for high-velocity jetting development. Air jetting is another alternative method to water jetting. Air jetting is a practical approach that gives good results if water is not easily available (Driscoll, 1986).

2.4. Analysis of pumping test data

During a pumping test, the flow in the aquifer is regarded to be the unsteady-state condition. The unsteady-state data is analyzed using one of the three methods: (1) Theis curve matching, (2) the Cooper–Jacob straight-line method, and (3) The distance–drawdown approach method. The three approaches for analyzing pumping test data mentioned here are mostly for confined aquifers (Kuo, 2014).

2.4.1. Theis method

Theis(1935) was the first to solve the drawdown for confined aquifers under unsteady-state pumping. Specifically, the drawdown of the piezometric surface is a function of the constant flow rate (Q), the transmissivity of the aquifer (T), the radial distance from the pumping well to the observation well (r), the aquifer storativity (S), and the time from the start of pumping (t).

The Thesi equation is:

$$S = \frac{Q}{4\pi t}[-0.5772 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \ ....] \quad ....\ (4)$$

Where the argument u is dimensionless and given as

$$U = \frac{r^2 S}{4Tt} \quad ....\ (5)$$

Where, s = drawdown at time t (m)

Q = constant pumping rate (m^3 /day)

r = radial distance from the pumping well to the observation well (m)

S = aquifer storativity (dimensionless)

T = aquifer transmissivity (m^2 /day)

t = time since pumping started (in days)

For small u values, the third and later terms in the well function can be truncated without causing a significant error.

2.4.2. Cooper and Jacob method

The (Cooper-Jacob, 1946) method is a simplification of the Theis method valid for greater time values and decreasing distance from the pumping well (smaller values of *u*). This method involves truncation of the infinite Taylor series that is used to estimate the well function W(u). Due to this truncation, not all early time measured data is considered to be valid for this analysis method. He pointed out that, for small u values, the Theis equation can be modified to the following form without significant errors: The resulting equation is:

$$S = \frac{2.3Q}{4\pi T} log_{10} \frac{2.25Tt}{Sr^2} \quad \text{.....} \quad (6)$$

Where, s = drawdown at time t (m)

Q = constant pumping rate (m3 /day)

r = radial distance from the pumping well to the observation well (m)

S = aquifer storativity (dimensionless)

T = aquifer transmissivity (m2 /day)

t = time since pumping started (in days)

This solution is appropriate for the conditions shown in the following figure.

The Cooper-Jacob Solution assumes the following:

•The aquifer is confined and has an “apparent” infinite extent

•The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping

•The piezometric surface was horizontal before pumping

•The well is pumped at a constant rate

•The well is fully penetrating

•Water removed from storage is discharged instantaneously with a decline in head

•The well diameter is small, so well storage is negligible

•The values of *u* are small (rule of thumb $u < 0.01$)

2.4.3. Distance-drawdown method

(Fetter, 1980) Based on the relationship *(Equation (6))* and simultaneous drawdown measurements in at least three observation wells, each at a different distance from the pumping well, a semi-log distance–drawdown graph can be constructed. From the plot, the slope, Δs, and the intercept, r_0, of the straight line at zero drawdowns can be derived. The following relationships can then be used to determine the transmissivity and storativity of the aquifer:

$$T = \frac{0.366Q}{\Delta s} \quad (7)$$

$$S = \frac{2.25Tt}{r_0^2} \quad (8)$$

Where, s = drawdown at time t (m)

Q = constant pumping rate (m3 /day)

r_0 = intercept (m)

S = aquifer storativity (dimensionless)

T = aquifer transmissivity (m2 /day)

t = time since pumping started (in days)

Δs = slope (m)

2.4.4. Drawdown

The depth to which the water level in a well is dropped below the static level during pumping is termed drawdown. The difference between the static water level and the water level during pumping is measured in meters of water. This word refers to the hydraulic head (measured in meters of water) required to induce water to flow through the aquifer and into the borehole at the same rate as water is extracted from it (Boman, Shukla, and Hardin, 2006). In general, the total drawdown in the water well is related to head losses in the aquifer formation, damage zone, filter pack or filter pack envelope, well screen, wellbore, and well casing.

One of the most important reasons for measuring drawdown is to make sure that your source is adequate and not being depleted. The data you collect to calculate drawdown can tell you if your supply is slowly declining. Early detection of this can give you time to explore alternative sources (Lytle & Markowski, 1989)

2.4.5. Radius of Influence

The radius of influence, r_0, represents the distance to the outer edge of the cone of depression. The zone of effect is the area near the well where the piezometric head surface shows a detectable drop. The aquifer's decline is insignificant outside the radius of impact meaning it has no influence (Heath, 1982)

2.5. Well Failure

Water well systems have several identified reasons that frequently interact to generate the circumstances seen at well locations (Driscoll 2008; Borch, 1993; Alford, 2000; Smith and Comeskey 2009). A common problem in predicting or assessing causes of well performance decline is attempting to define the problem too narrowly. For example, is it a well problem or an aquifer problem? Wells and their performance must be understood in terms of the aquifer conditions in which they are created in (Ahmed, Taylor, and Sheng, 2014).

The incorrect choice of gravel pack and screen slot opening size is frequently linked to early well failure. Excessive sand pumping might lead to the complete collapse of a well. Installing low-quality screening equipment, on the other hand, results in more well failures. The rate of corrosion or incrustation at the screen and inside the formation or gravel pack around the bore hole rises as the velocity of water traveling into the well increases. Poorly built and constructed wells have greater maintenance expenses. (Boman, Shukla, and Hardin, 2006)

When a well's condition may be rectified, rehabilitation may be expected or required. This will mostly include fixing issues with poor hydraulic performance that have developed as a result of fouling or silting. Through excellent design, installation, development & sampling methods, the need for rehabilitation may frequently be minimized or eliminated. The original structure, particularly its diameter, strength, & screen length, might restrict rehabilitation possibilities. However, owing to natural variability or the use of different materials, creating a new borehole may result in changes in important parameters, and a new borehole may require time to readjust. It is thus preferable to keep an existing borehole wherever possible (Fretwell, Short, and Sutton, 2006).

2.6. Rehabilitation of water well

Good design, selection of the right materials, frequent inspection, repair, and treatment of well systems, and early warning identification of symptoms of issues, all of which are made systematic by excellent record keeping, are all necessary for maintaining well performance and preventing failure. To measure and understand the well's performance over time, a minimum of baseline data is required for each well. The goal of maintaining a well is to prolong its service life and give representative levels and samples of the groundwater in the area around it. Proper documenting of elements that can be utilized as standards for data comparison at a later time is part of the maintenance process (Ahmed, Taylor, Sheng, 2014).

Chemical and mechanical approaches, which are sometimes combined for better effectiveness, are more conventional maintenance procedures used to recover yields of water in supply wells. Over-pumping, surging, jetting, and air development are all examples of mechanical rehabilitation. These are the same techniques that are utilized in well development, and they are discussed in detail in the section headed "Well Development Methods." Acids, biocides, and surfactants are the three types of chemicals utilized in conventional chemical well rehabilitation. Chemical treatment has three primary goals: 1) dissolve incrust-ants accumulated on the well intake or in the surrounding geologic formation, 2) kill bacteria in the well or surrounding formation, and 3) scatter clay and other debris so they may be removed. Chemicals have a significant impact on the well environment. These modifications might endure a long time or be permanent. Parameters such as Eh, pH, temperature, and conductivity should be monitored if chemical rehabilitation is undertaken. These measures can be used to compare the quality of water before and after well rehabilitation. The external components of the well need to be maintained as well which includes components such as well casing, protective casing, and a well cap (Aller, Bennett and Hackett 1989).

3. CHAPTER THREE: - Research Methodology

Groundwater is considered as one of the sources that supply the city of Addis Ababa. Many water wells; shallow and deep, are developed in or near to the city. One of the main potential sources of groundwater is found in Akaki sub-city. Although these wells are built they show deterioration in their performance over the years. This study mainly focuses on finding out reasons for the well's performance decrease and suggests possible remedial measures that can alleviate problems regarding well efficiency.

3.1. Study area description

Addis Ababa, the capital city of Ethiopia is the largest city in the whole country. The population of the town is estimated to be around 5,006,000(Population stat, 2021). The city also constitutes different institutions, organizations both national and international.

The location of the city is at 8°50′ N to 9°5′ N & 38°38′ E to 38°54′ E and found at an elevation of 2355meters according to (NGA: Country files, 2012). Up until recently the city of Addis Ababa was divided into 10 sub-cities namely Arada, Addis Ketema, Lideta, Kirkos, Yeka, Bole, Akaki-Kality, Nefas Silk-Lafto, Kolfe-Keranyo, and Gullele. In 2020, an eleventh sub-city was added by the name Lemi Kura (Addis Ababa City Website, 2013).

Akaki-Kality sub-city is one of the sub-cities of Addis as mentioned above and is where the study wells are situated in. It is located at 8°53′40.92″N 38°46′23.52″E and an elevation of 2139. It covers an area of 118.08km^2 and has a population of 195,273 (City government of Addis Ababa, 2011).

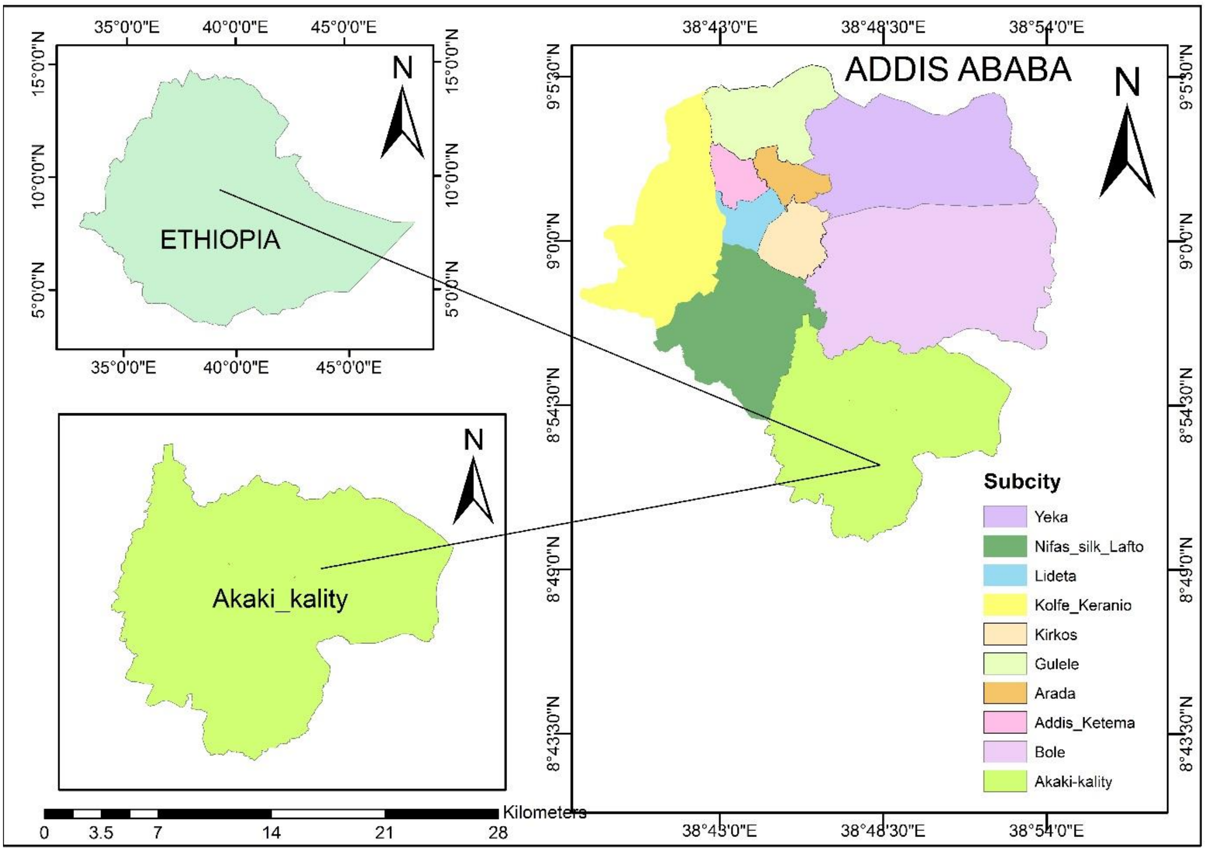

Figure 3. 1. Map of the study area

Akaki- Kality sub-city is found in the southern part of the city of Addis Ababa as shown in Figure 3.1. The area is considered a potential source of groundwater that is mainly used to supply the need for potable water to the town of Addis.

Akaki well field is selected for this study purpose because most deepwater wells that supply water to the capital city are situated in that area. Currently there are around four well fields namely Akaki Phase I, Akaki Phase II, Akaki Phase IIIA and Akaki Phase IIIB.

Figure 3.2 shows the spatial distribution of water wells found in Akaki well fields developed over the years in each phase of construction. The wells are mapped based on their geographical location to have a clear image of the location to one another. In addition to that, mapping the wells will also help identify which areas to focus on in other words narrow down the focus of the study area & study wells.

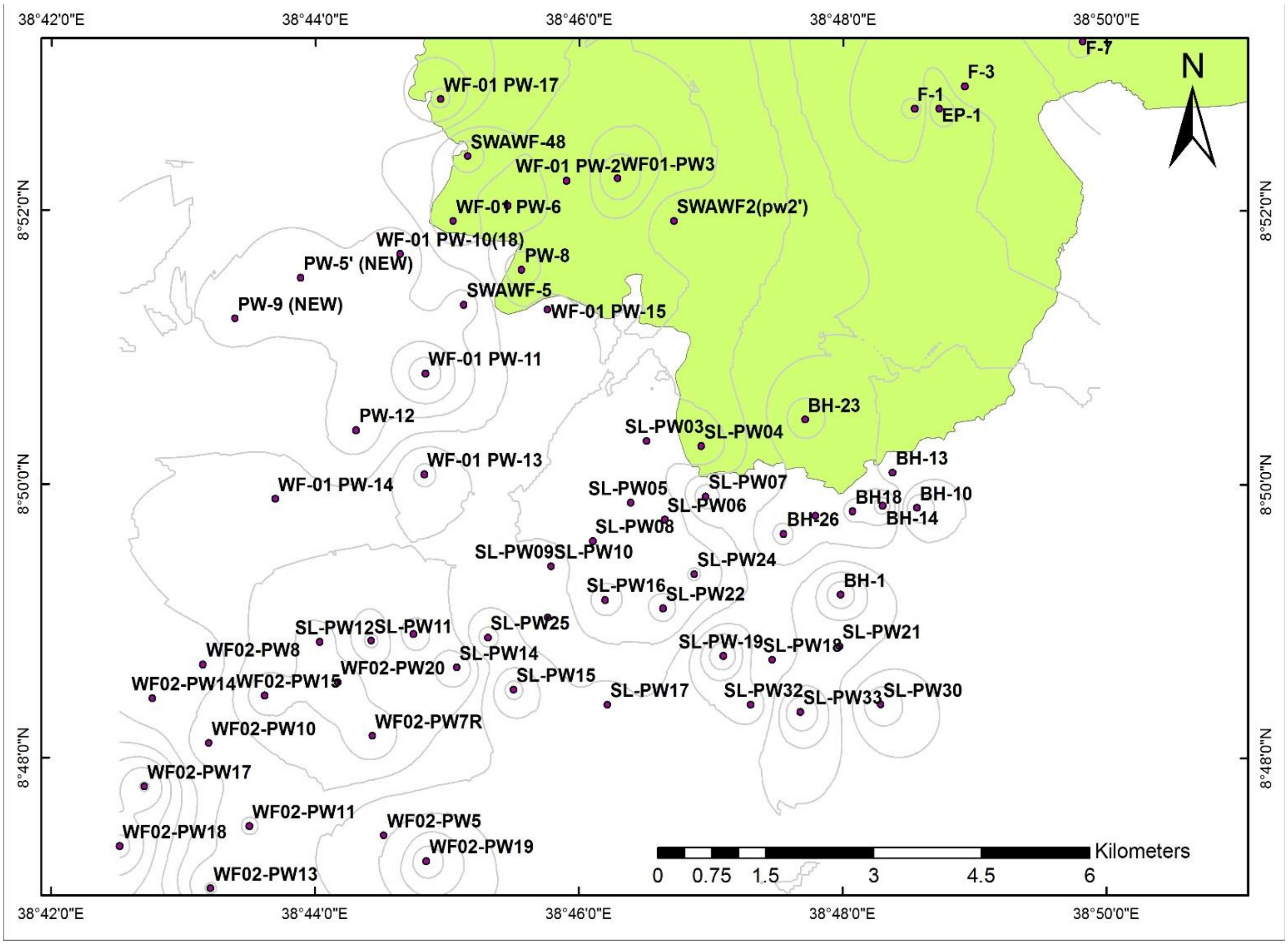

Figure 3. 2. Map showing wells found in Akai well field

3.1.1. Climate

In Ethiopia, climate is studied and data regarding it is stated at a city level which is very coarse as climate changes based on geographic location even within the city especially for a city as big as Addis Ababa.

The climate in Addis Ababa is warm and temperate. The annual average temperature of the city is 15.6^0. December is considered the driest month of the year but also when the lowest average temperature occurs. The warmest month is April. Rainfall patterns are seasonal in the country. The time from June to September is the season where rain is highly prevalent (Climate-Data.org, 2015).

3.1.2. Lithology of the area

As from observation of the lithological and geophysical reports of most wells, during drilling, it can be said that Akaki well field area is mainly covered by fresh, moderately fractured, and highly fractured volcanic rocks but varying in thickness from well to well. The main geological formations include Scoria, ignimbrite, Basalt & Scoracious basalt, Clay, fractured rock, and pyroclastic material. The water-bearing formations are volcanic rocks that are weathered and fractured.

Table 3.1 and Figure 3.3 show sample descriptions of the lithological distribution of earth materials penetrated during the development of wells for SL-PW-33. This data is obtained from samples taken during the drilling process of SP-PW-33 in the Akaki Phase IIIB well field.

Table 3. 1: Lithological description of SL-PW-33

No	Depth, m		Lithological description
	From	To	
1	0	16	Top soil
2	16	28	Highly weathered Basalt
3	28	44	Pyroclastic material
4	44	54	Slightly weathered and fractured basalt
5	54	84	Scoracious Basalt
6	84	96	Moderately weathered & Fractured basalt
7	96	114	Scoria
8	114	146	Highly weathered & Fractured basalt
9	146	148	Pyroclastic material
10	148	200	Highly fractured &moderately weathered basalt
11	200	298	Highly weathered and fractured Basalt
12	298	400	Highly weathered and fractured Ignimbrite
13	400	418	Moderately weathered and fractured basalt
14	418	424	Slightly weathered and fractured basalt
15	424	430	Moderately weathered & Fractured Ignimbrite
16	430	453	Samples are not taken properly

Source: AAWSA well completion report of well index SL-PW33, 2014

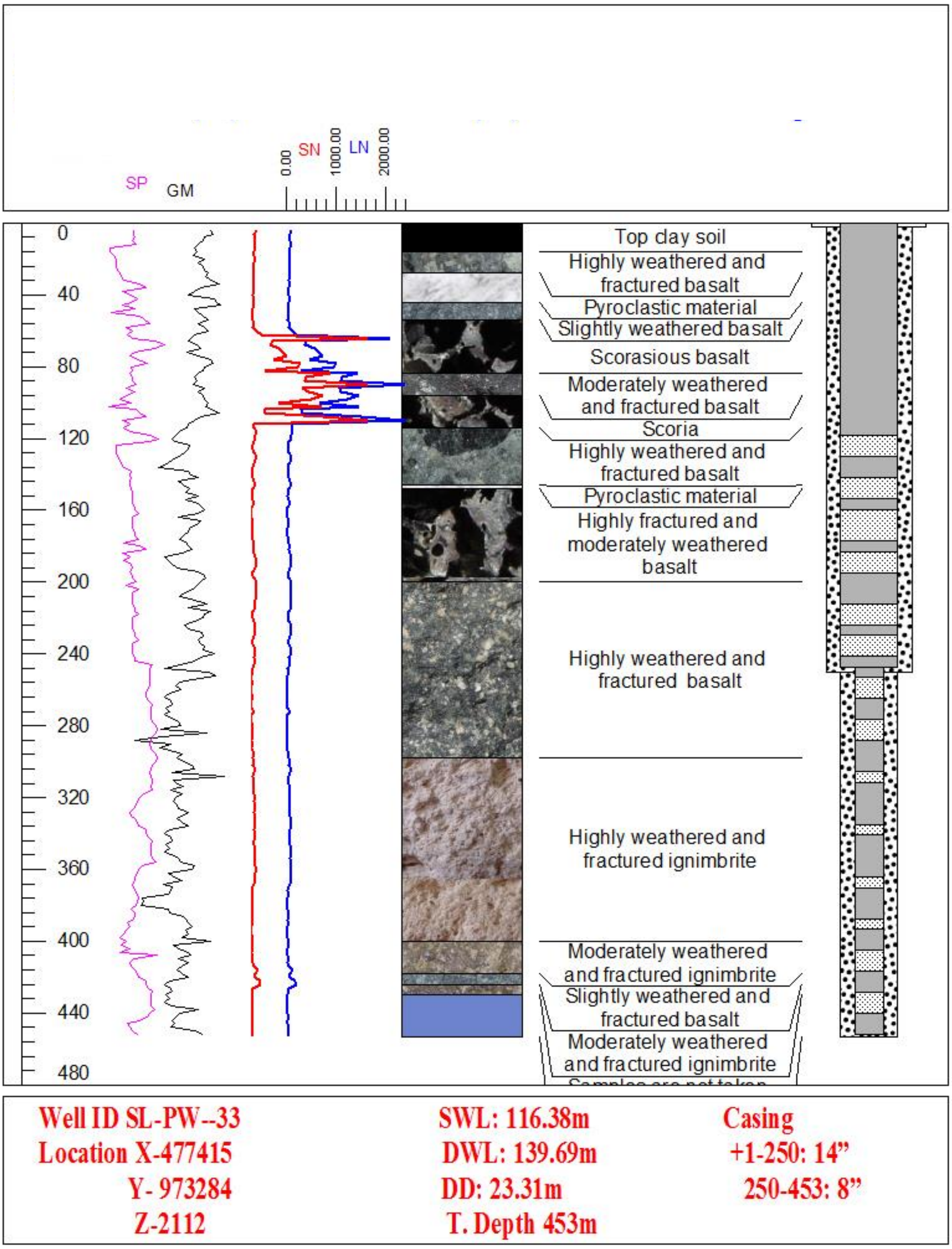

Figure 3. 3. As-built drawing of the well construction, geophysical logs and lithological description of SL-PW-33

(Source: well completion report of well index SL-PW33, 2014)

3.2. Research Design

Many water wells are drilled and developed in and around Akaki sub-city to supply water for the town of Addis Ababa but the majority of the wells are observed to decrease in production rate over the years. So this research will try to find out the reasons for yield decrease in Akaki well fields (Akaki Phase I, Akaki Phase II, Akaki Phase IIIA, and Akaki Phase IIIB). A set of steps were followed to achieve the objective of the study and can be seen in Figure 3.4.

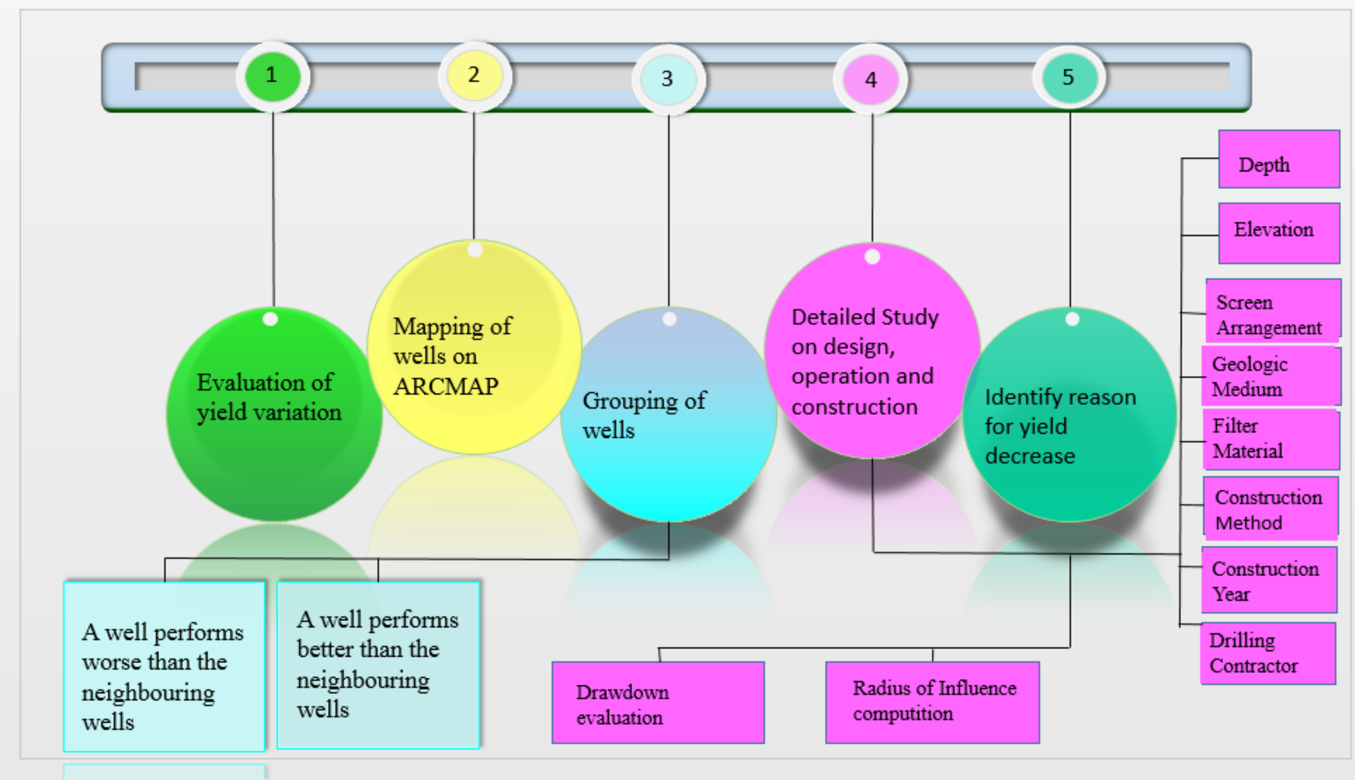

Figure 3. 4. Process map of the research

First is identifying and arranging all wells in Akaki well fields with their perspective geographic location, designed yield, and current yield. Based on the current and design yield information, how much in percent each well has shown a decrease in yield since they started giving service was computed. This information is the main foothold to pursue with the research because the main reason for doing this research is to identify if in fact, yield decrease is a problem in wells found in Akaki well field and how wells found in the field are being affected by this problem.

Second is all 70 wells in Akaki well field well mapped on ARCMAP 10.3 to have a clear view of where each well is located. In addition to mapping the water wells, clustering of wells with their perspective yield variation was executed. Looking at the map in accordance with variation in yield created a better level of understanding of which areas are affected by yield decrease and to narrow down the focus to a few selected wells.

The third step followed was grouping the wells based on the clustered yield data into two groups and later into seven sub-sections. The first group holds five sub-sections. This group represents a situation where one well performs a lot lower than its neighboring wells. The second group holds two sub-sections and shows a situation where a well performs better than the neighboring surrounding wells. These groupings of wells created a deeper understanding of the study not just in the selection of several wells that showed a decrease in yield but the performance of wells regarding yield as compared to the neighboring wells.

The fourth step was doing a detailed study for the selected 35 wells under the seven sections; 22 wells from group one and 13 wells from group two. The study wells selected are BH-10R, BH-13R, BH-14R, BH-1R, BH-22R, BH-26R, SL-PW21, SL-PW18,SL-PW-33, SL-PW-30, SL-PW-32, WF01-PW3, WF01-PW2, SWAWF2(PW2'), WF02-PW12, WF02-PW5, WF02-PW6, WF02-PW8, WF02-PW10, WF02-PW11, WF02-PW13, WF02-PW14 in group one and SL-PW-11, SL-PW-12, SL-PW-13, WF02-PW7R, WF02-PW15, WF-01 PW-11, SWAWF-4B, WF-01 PW-6, WF-01 PW-13, WF-01 PW-14, WF-01 PW-15, WF-01 PW-16, WF-01 PW-17 in group two. A Well-completion report of each of the wells was collected from Addis Ababa Water and Sewerage Authority, AAWSA, and a detailed study was done on the design and construction of each well. Each selected well was compared based on their depth, elevation, screen depth, geological medium, filter material, construction method, year of construction, and well-drilling contractor to identify the gap/difference. Here we are assuming that there is water in the aquifer as our study wells were selected based on the better performance of the neighboring wells or vice versa.

The reason for the selection of these comparison criteria is as follows. Depth and elevation of the well are selected as comparison criteria to identify where the bottom elevation of each well ends. This is to identify if the reason for the yield decrease comes from the fact that the well is developed at a shallower depth than the neighboring wells. Screen depth is the length of the opening area that lets water into the well and is used as one contrasting criterion to identify two things. One is to check if some of the wells are performing because they have a larger screen depth than the wells that have lower performance. The second point is to check the design document with the arrangement of the screened area with its perspective water-bearing aquifer. Geological medium is compared for each well because since the study wells are found at close distance with each other in each section this information helps see the similarity of the formation in each borehole and to match this information with the perspective screen length/ screen arrangement. The filter material used to fill between the wall of the well and the casing was also compared based on the size of the granular material used and the volume of it. Another factor considered was the year of construction of each well to check if the wells have exceeded their intended design life and to see if the problem for yield decrease might have arisen from that. The construction method of the well is also studied in accordance with each contractor's method of developing a well. The different methods of drilling of a well are studied and compared between wells in each section.

The last step in the research is identifying reasons as to why the wells are showing a decrease in production rate over the years. Each well has a different reason for yield reduction and different solutions are suggested for each for better performance of it.

3.3. Data Collection

To achieve the objective of identifying reasons for yield decrease in Akaki well field, design documents of wells from each phase of well field were collected from Addis Ababa Water and Sewerage Authority, AAWSA, and Water Works Design and Supervision Enterprises, WWDSE. The well completion report incorporates general information about the well that includes diameter, depth, aquifer properties, drilling information, screen/blind arrangement, filter pack arrangement, year of construction, and other important information that are input for this research. In addition to the design documents of the wells, the current production yield and operation hours of each well are obtained from the data collected by experts in AAWSA.

Wells in Akaki well field was built in four phases; Phase I, Phase II, Phase IIIA, and Phase IIIB. A total of seventy water wells design documents and current status were gathered from all phases found in the well field. From the data it was found that there are 13 wells under Phase I, 17 of the wells belong to Phase II, another 17 belong to Phase IIIA and there are 23 wells under Phase IIIB.

All wells under Phase I are operational however all wells have shown a decrease in production rate from their designed discharge. The current average daily production rate of wells under Phase I is 474.00 l/s. Operation hour of wells under this phase ranges from 10 hours to 22hours per day.

From 17 wells found in Akaki Phase II well field. The current average daily production rate of wells under Phase II is 696.10 l/s. Operation hour of wells under this phase ranges from 5 hours to 24 hours per day.

In Akaki Phase IIIA well field there are 17 wells. The current average daily production rate of wells under Phase IIIA is 574.05 l/s. Operation hour of wells under this phase ranges from 0 hours to 24 hours per day.

The last phase is Phase IIIB having 23 wells. The current average daily production from these wells is estimated at 864.00 l/s. All wells under this group showed a decrease in production rate from their designed yield value. The minimum and maximum operation hour recorded was 22 hours and 24 hours consecutively.

Below here are lists of wells found in Akaki Phase I, Akaki Phase II, Akaki Phase IIIA and Akaki Phase IIIB. A list of 70 wells and their design and current production rate are organized in Table 3.2 below.

Table 3. 2: Location, design & current production capacity of wells

Akaki Well field water wells										
			Coordinate UTM Zone 37 Adindan							
No	Well Index	Well field	UTM East	UTM North	Elevation, m	Design Q, l/s	current Q, l/s	Difference, l/s	Current Wellfield production rate, l/s	Current Wellfield production rate, m3/day
1	BH18	Akaki phase I	478139	975983	2077	28	23	-5		
2	EP-1	Akaki phase I	479340	981400	2128	25	15	-10		
3	EP-2	Akaki phase I	481600	982850	2211	4	5	1		
4	F-1	Akaki phase I	479000	981400	2125	17	16	-1		
5	F-3	Akaki phase I	479700	981700	2141	7	6	-1		
6	F-7	Akaki phase I	481337	982304	2199	25	22	-3		
7	BH-1R	Akaki phase I	478074	975053	2089	100	32	-68		
8	BH-10R	Akaki phase I	479001	976028	2097	150	60	-90		
9	BH-13R	Akaki phase I	478695	976503	1874	55	37	-18		
10	BH-14R	Akaki phase I	478583	976056	2079	100	96	-4		
11	BH-22	Akaki phase I	477628	975889	2067	100	70	-30		
12	BH-23	Akaki phase I	477477	977217	2068	20	17	-3		
13	BH-26R	Akaki phase I	478074	975053	2089	90	75	-15	474.00	40,953.6
14	SWAWF-2 (pw2')	Akaki phase II	475697	979915	2062	55	30	-25		
15	WF-01 PW-2	Akaki phase II	474204	980459	2077	50	25	-25		
16	SWAWF-5	Akaki phase II	472738	978761	2059	80	59	-21		
17	WF-01 PW-6	Akaki phase II	472589	979885	2063	80	32	-48		
18	WF-01 PW-10(18)	Akaki phase II	471853	979443	2060	120	96	-24		
19	WF-01 PW-11	Akaki phase II	472204	977838	2061	50	48	-2		
20	PW-12	Akaki phase II	471243	977076	2055	80	60	-20		
21	WF-01 PW-14	Akaki phase II	470717	976149	2055	100	56	-44		
22	WF-01 PW-15	Akaki phase II	473903	978695	2068	50	26	-24		

23	SWAWF-4B	Akaki phase II	472795	980758	2062	80	27	-53		
24	WF-01 PW-16	Akaki phase II	473345	980095	2066	30	18	-12		
25	PW-5' (New)	Akaki phase II	470472	979124	2055	100	75	-25		
26	PW-8	Akaki phase II	473542	979233	2066	50	16	-34		
27	PW-9 (New)	Akaki phase II	469559	978576	2056	70	50	-20		
28	WF-01 PW-13	Akaki phase II	472191	976481	2060	50	19	-31		
29	WF-01 PW-17	Akaki phase II	472419	981526	2064	60	49	-11		
30	WF01-PW3	Akaki phase II	474918	980486	2081	50	10	40	696.10	60,143.04
31	WF02-PW5	Akaki phase III-A	471628	971625	2072	50	35	-15		
32	WF02-PW6	Akaki phase III-A	471206	970331	2059	30	17	-13		
33	WF02-PW9	Akaki phase III-A	473904	974552	2064	80	45	-35		
34	WF02-PW10	Akaki phase III-A	469194	972866	2073	40	22	-18		
35	WF02-PW11	Akaki phase III-A	469759	971750	2073	70	34	-36		
36	WF02-PW12	Akaki phase III-A	470118	970468	2049	50	24	-26		
37	WF02-PW13	Akaki phase III-A	469221	970912	2057	70	34	-36		
38	WF02-PW14	Akaki phase III-A	468416	973467	2055	70	47	-23		
39	WF02-PW15	Akaki phase III-A	469835	978303	2064	100	34	-66		
40	WF02-PW16	Akaki phase III-A	468799	970195	2045	40	45	5		
41	WF02-PW17	Akaki phase III-A	468302	972283	2055	45	50	5		
42	WF02-PW18	Akaki phase III-A	467956	971481	2060	30	34	4		
43	WF02-PW19	Akaki phase III-A	472218	971279	2069	26	25	-1		
44	WF02-PW20	Akaki phase III-A	470985	973682	2055	100	30	-70		
45	WF02-PW7R	Akaki phase III-A	471576	972958	2057	75	25	-50		
46	WF02-PW8	Akaki phase III-A	469116	973925	2054	50	33	-17		
47	SL-PW12	Akaki phase III-A	470835	974233	2046	112	40	-72	574.05	49,597.92
48	SL-PW03	Akaki phase III-B	475276	976930	2059	70	33	-37		
49	SL-PW04	Akaki phase III-B	476037	976861	2068	88	35	-53		

50	SL-PW05	Akaki phase III-B	475058	976100	2062	91	38	-53		
51	SL-PW06	Akaki phase III-B	475528	975870	2059	86	35	-51		
52	SL-PW07	Akaki phase III-B	476098	976183	2055	46	35	-11		
53	SL-PW08	Akaki phase III-B	474528	975585	2056	95	40	-55		
54	SL-PW09	Akaki phase III-B	473954	975244	2068	70	40	-30		
55	SL-PW10	Akaki phase III-B	473954	975244	2053	50	25	-25		
56	SL-PW11	Akaki phase III-B	471453	974241	2048	112	70	-42		
57	SL-PW14	Akaki phase III-B	472640	973882	2072	80	24	-56		
58	SL-PW15	Akaki phase III-B	473428	973584	2078	30	25	-5		
59	SL-PW16	Akaki phase III-B	474702	974792	2069	98	34	-64		
60	SL-PW17	Akaki phase III-B	474733	973382	2078	30	19	-11		
61	SL-PW18	Akaki phase III-B	477023	973986	2087	66	40	-26		
62	SL-PW21	Akaki phase III-B	477959	974168	2103	90	50	-40		
63	SL-PW22	Akaki phase III-B	475507	974679	2070	98	35	-63		
64	SL-PW24	Akaki phase III-B	475941	975137	2064	102	40	-62		
65	SL-PW25	Akaki phase III-B	473071	974284	2060	108	80	-28		
66	SL-PW30	Akaki phase III-B	478528	973384	2113	46	40	-6		
67	SL-PW32	Akaki phase III-B	476717	973381	2111	46	35	-11		
68	SL-PW33	Akaki phase III-B	477434	973370	2112	102	30	-72		
69	SL-PW-13	Akaki phase III-B	472078	974359	2050	100	36	-64		
70	SL-PW-19	Akaki phase III-B	476340	974040	2112	25	25	0	864.00	74,649.6
								Total	**2608.15**	**225,344.16**

The total current production rate from all phases in Akaki well field is estimated as 225,344.16 m^3/day.

3.4. Sample selection

Data gathered from AAWSA on the current discharge rate was first arranged and analyzed in excel. For further clearance, all wells on all phases were mapped on ARC MAP 10.3.

Almost all wells found in Akaki well field show a decrease in yield from their intended design production rate. For this study 35 water wells from all phases of the well field are selected based on the following criteria.

- A Well shows a decrease in yield from the design yield/discharge
- A Well is either performing better or worse than its neighboring wells

Based on this criteria water wells in Akaki well field are categorized in two groups and again in two 7 sub-sections as shown in the table below.

Table 3. 3: Study wells in their perspective group and sub-section

Group	Sub-Section	No	Well Name	Design discharge, l/s	Current discharge, l/s	% difference
1	1	1	BH-10R	150	60	-60
		2	BH-13R	55	37	-33
		3	BH-14R	100	96	-4
	2	1	BH-1R	100	32	-68
		2	BH-22R	100	70	-30
		3	BH-26R	90	75	-17
		4	SL-PW21	90	50	-44
		5	SL-PW18	66	40	-39
	3	1	SL-PW-33	102	30	-71
		2	SL-PW-18	66	40	-39
		3	SL-PW-21	90	50	-44
		4	SL-PW-30	46	40	-13
		5	SL-PW-32	46	35	-24
	4	1	WF01-PW3	50	10	-80
		2	WF01-PW2	50	25	-50
		3	SWAWF2(PW2')	55	30	-45
	5	1	WF02-PW12	50	24	-52
		2	WF02-PW5	50	35	-30

		3	WF02-PW6	30	17	-43
		4	WF02-PW8	50	33	-34
		5	WF02-PW10	40	22	-45
		6	WF02-PW11	70	34	-51
		7	WF02-PW13	70	34	-51
		8	WF02-PW14	70	47	-33
		1	SL-PW-11	112	70	-38
		2	SL-PW-12	112	40	-64
		3	SL-PW-13	100	36	-64
		4	WF02-PW7R	75	25	-67
	6	5	WF02-PW15	100	34	-66
		1	WF-01 PW-11	50	48	-4
		2	SWAWF-4B	80	27	-66
		3	WF-01 PW-6	80	32	-60
		4	WF-01 PW-13	50	19	-62
		5	WF-01 PW-14	100	56	-44
		6	WF-01 PW-15	50	26	-48
		7	WF-01 PW-16	30	18	-40
2	7	8	WF-01 PW-17	60	49	-18

3.5. Data Analyses

Well physical and aquifer properties were captured from well completion report of each well used for this research. Wells in each section are compared to one another to identify gaps in the design documents. Comparisons were made based on diameter, well depth, bottom elevation, screen length, screen/blind arrangement, gravel pack material & volume, geologic medium, and well drilling method used. This information of the wells is arranged & analyzed in an excel sheet and compared to one another to find out if the gap arises from differences in the design or construction procedures of the wells.

The expected result from this is finding bottom elevation which will tell us if the well is built at a shallower depth in other words water is being tapped from the shallow aquifer. Other information expected to acquire is the screen to total area which tells us if the screened section of the casing is what is causing some wells to perform better than the other neighboring wells. The gravel pack material, the drilling method used, and approaches different contractors to use to construct are observed.

Overuse or over-pumping of wells is pretty common in Akaki well field to satisfy the increasing need of users of Addis Ababa. Due to that most wells are giving service for many hours leaving less time for the well to recover or revive and is creating a drop in the level of water in the wells. Early detection in well performance decline can give time to explore alternative sources, establish conservation measures or obtain any special funding needed to get a new water source. Measurements of drawdowns provide crucial information about the operation and efficiency of wells. To analyze a well's efficiency and performance, drawdown data with well yield is combined.

The Cooper and Jacob equation was used to compute drawdown in multiple wells and the radius of influence. Storativity (S), Transmissivity (T), discharge (Q), and current hour (t) of wells are used to calculate drawdown values. Radial distance (r) between wells is measured from ARCMAP and used for the calculation of drawdown.

$$S = \frac{2.3Q}{4\pi T} log_{10} \frac{2.25Tt}{Sr^2} \qquad (6)$$

A single well and multiple wells analysis is implemented to identify the effect of one well on others when water is discharged from it. Current operation discharge and operation hour data were used to calculate the drawdown effects on one another.

It is an obvious phenomenon to observe water level decline in surrounding wells when water is pumped from one well. This usually happens when water wells are drilled close to each other. Many times, when two or more wells are located in the same aquifer then it is possible that their cones of depression may intersect. When such a situation exists, the wells are said to interfere with one another because the zone of influence of one well overlaps the zone of influence of the other well. The radius of Influence is computed using the following formula to check if this phenomenon is true in each study well and is contributing to the efficiency decline of the wells.

$$R(t) = \frac{1.5\sqrt{Tt}}{S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

R(t) = Radius of Influence (meter) t = operation hour (minute)

T = Transmissivity (m^2/min)

S = Storativity

3.6. Assumption

The assumption made for this study is that there is potential groundwater or enough water is available in the aquifer. This assumption is made because of the method of selection of the sample wells for this study. All wells selected for research are in comparison with their neighboring wells either performing better or worse.

4. CHAPTER FOUR: - Result and Discussion

The study tried to identify the main reasons for the decrease in the yield of water supplying wells found in Akaki well field for the city of Addis Ababa. From the data collected from AAWSA, a total number of 70 water wells were mapped on ARCGIS based on their variation from the designed discharge rate to identify wells with severe yield decrease problems.

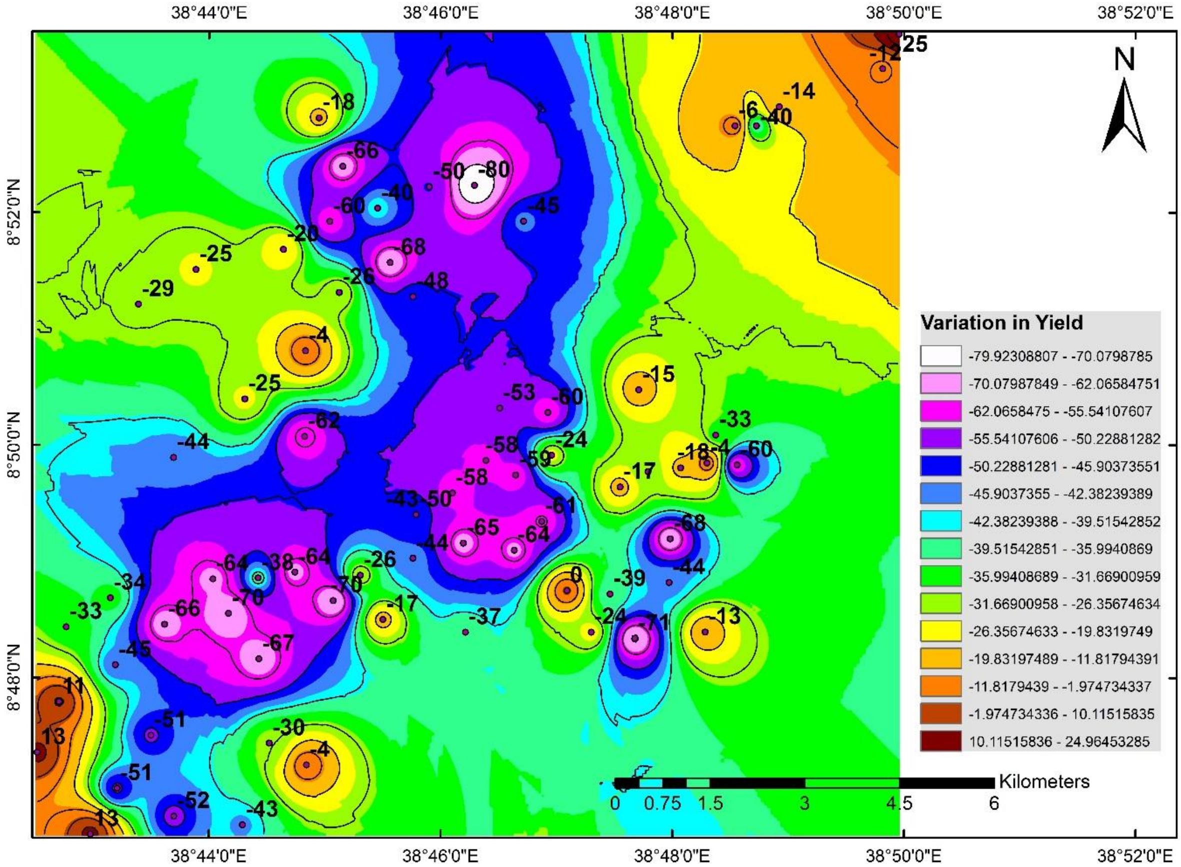

Figure 4. 1. Akaki well field variation in yield from designed production rate

As the map shows almost all wells show a yield decrease meaning they are not performing to their fullest capacity. Even though most wells are constructed around the same year, amongst all mapped wells, it was observed that some wells function better than the neighboring boreholes whereas the contrary is observed; that is a single well performs a lot less than the neighboring wells.

For further study of the relation between boreholes, seven sub-sections were developed. The grouping of wells was developed by considering the main factor of performance decrease in yield from the initially designed production rate.

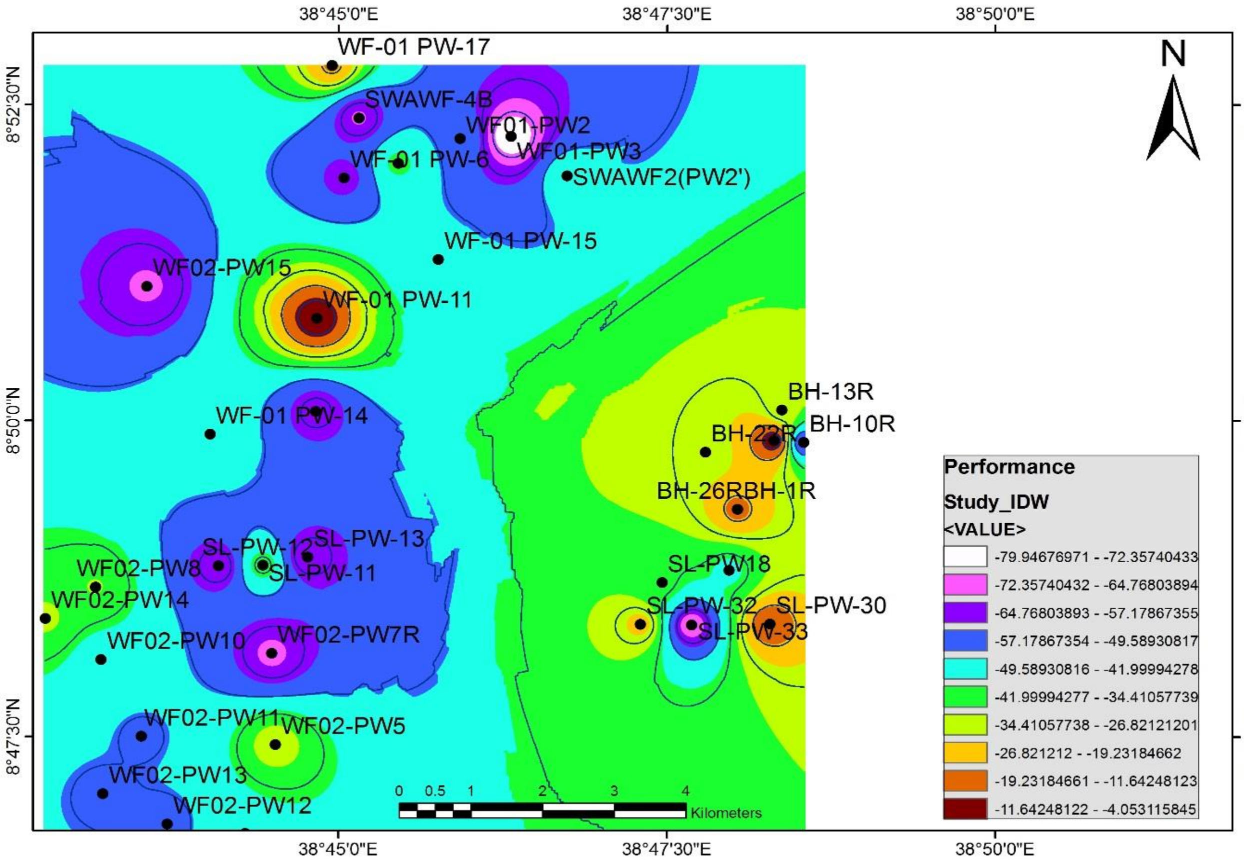

Figure 4. 2: Akaki study wells

The wells in each group have similarities in terms that either one well is performing worse than the neighboring wells or one well is performing a lot better than the neighboring wells. In sub-sections one to five, a well performs a lot less than the neighboring wells whereas in sub-section 6 & 7 one well is found in good condition as compared to the neighboring surrounding wells in the study field.

The approach followed to answer the reason for the decrease in yield from the expected production discharge rate by considering factors in the design, operation, and construction of individual wells in each section.

4.1. Design and construction

Design document of 70 water wells in Akaki well field was collected and further detailed study was done on selected 35 water wells. From what can be observed in the current production rate of the study wells over the years from their designed yield, all wells show a decrease in discharge from their expected yield estimated during the designed period. With the rate most wells are decreasing over the years, it can be said that many wells can go out of service before serving their intended design period. As discussed above some wells clearly have well yield reduction caused majorly by the well's design and construction ineffectiveness. The majority of the wells, however, besides design and construction ineffectiveness, their performance decline due to other well interferences.

Deterioration in well performance in this study is computed using a reference that is the initial well yield which is expected in the design life of the well and is obtained from the well completion report. To detect the amount of decrease and have a clear understanding of the well current production status the difference in the drop of yield is computed in Table 4.1. As can be seen, a significant change in production rate is observed. This major change in the production rate calls for attention that must be given to sustain the functionality of the wells.

The design discharge column represents the design yield of the wells and this data is captured from the well completion report of each well. The current discharge column represents the current operation discharge rate of the wells. The yield variation column represents the difference of production rate from the design yield and is put in percentile format.

$$\%yield\ variation = \frac{Current\ Discharge - Design\ Discharge}{Design\ discharge}\ x\ 100 \quad .... (10)$$

Table 4. 1: Variation of yield from design yield

Group	Sub-Section	No	Well Name	Design discharge, l/s	Current discharge, l/s	Yield Variation (%)
1	1	1	BH-10R	150	60	-60
		2	BH-13R	55	37	-33
		3	BH-14R	100	96	-4
	2	1	BH-1R	100	32	-68
		2	BH-22R	100	70	-30
		3	BH-26R	90	75	-17
		4	SL-PW21	90	50	-44
		5	SL-PW18	66	40	-39
	3	1	SL-PW-33	102	30	-71
		2	SL-PW-18	66	40	-39
		3	SL-PW-21	90	50	-44
		4	SL-PW-30	46	40	-13
		5	SL-PW-32	46	35	-24
	4	1	WF01-PW3	50	10	-80
		2	WF01-PW2	50	25	-50
		3	SWAWF2(PW2')	55	30	-45
	5	1	WF02-PW12	50	24	-52
		2	WF02-PW5	50	35	-30
		3	WF02-PW6	30	17	-43
		4	WF02-PW8	50	33	-34
		5	WF02-PW10	40	22	-45
		6	WF02-PW11	70	34	-51
		7	WF02-PW13	70	34	-51
		8	WF02-PW14	70	47	-33
2	6	1	SL-PW-11	112	70	-38
		2	SL-PW-12	112	40	-64
		3	SL-PW-13	100	36	-64
		4	WF02-PW7R	75	25	-67
		5	WF02-PW15	100	34	-66
	7	1	WF-01 PW-11	50	48	-4
		2	SWAWF-4B	80	27	-66
		3	WF-01 PW-6	80	32	-60
		4	WF-01 PW-13	50	19	-62
		5	WF-01 PW-14	100	56	-44
		6	WF-01 PW-15	50	26	-48
		7	WF-01 PW-16	30	18	-40
		8	WF-01 PW-17	60	49	-18

From the table, we can understand that all wells show a decrease in production rate since they were first developed. The highest record is for well WF01-PW3 which is an 80% drop from the designed discharge and the lowest 4% is observed on BH-14R & WF-01PW-11.

Considering sub-section three wells, the largest decrease in production is observed on well SL-PW-33 for which the initial discharge was supposed to give 102l/s but now only giving 30l/s signifying 71% loss from its production capacity. SL-PW32 performs better as compared to values of the other wells though it has shown a 24% decrease from the designed rate. From this analysis, we can understand that there is a clear drop-in production rate from the initial estimated discharge rate or an exaggerated yield is fixed for the wells during the design phase.

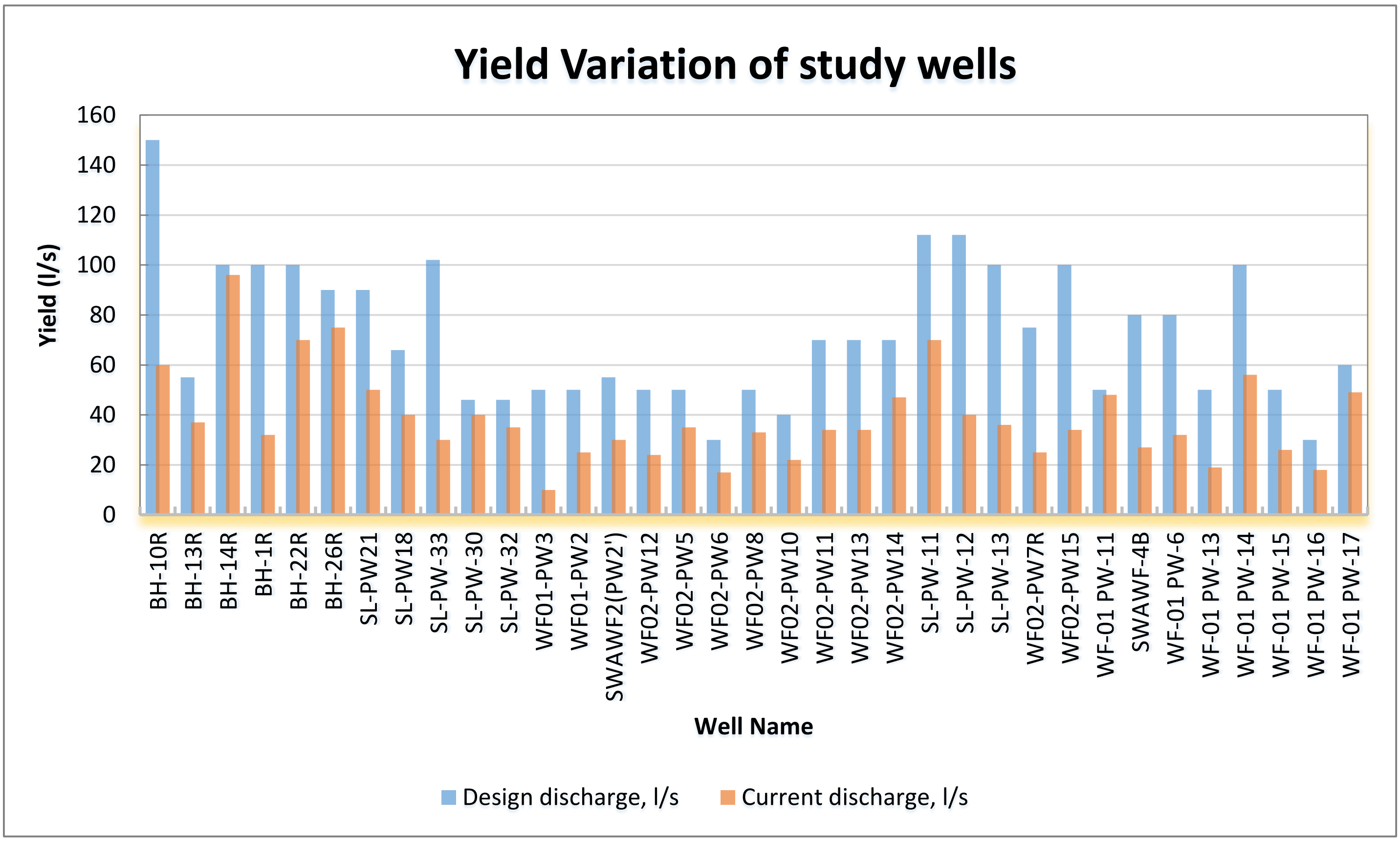

Figure 4. 3: Yield variation

To identify reasons for the hydraulic failure of wells as compared to neighboring wells, a comparison of design properties amongst grouped wells was done by considering factors of well bottom elevation, well depth, well diameter, screen area, filter material used, geologic medium of the area and drilling method used for each well.

4.1.1. Well bottom elevation

As described at the beginning of this chapter, seven sub-sections of wells were established for further study and analysis in identifying the main reasons for the decrease in well yield of Akaki well field.

Grouped wells were compared based on the depth of excavation to identify if the drilled depth is in fact the reason the wells are decreasing in production rate. The depth and elevation values of the wells are taken from the well design documents for each well. In the last column in Table 4.2, the bottom elevation of individual wells is computed by subtracting the depth from the elevation values and the result is as stated.

$$Well\ bottom\ elevation(meter) = Well\ Elevation(m) - Well\ Depth(m) \quad \ldots\ldots\ldots \quad (11)$$

From the previous analysis done for Section three wells, well SL-PW33 has the highest drop in discharge when compared with other wells in that same section. It can be understood from Table 4.2 that this well is developed at a shallower depth which is 1659meter compared with other wells. The higher the bottom elevation value the shallower the pump location meaning water tapped from the well is found at the surface of the aquifer and increasing the depth of the well might increase the production rate of the well.

Well SL-PW32 showed a 24% drop in production rate from the design discharge and it can be seen on Table 4.2 that the well is drilled deeper than the rest of the wells under section three. This could be one of the reasons the well is performing better than other neighboring wells. A similar interpretation can be done for the rest of the groups as well.

Table 4. 2: Well bottom elevation of study wells

Group	Sub-Section	No	Well Index	Depth, m	Elevation, m	Bottom Elevation, m
1	1	1	BH-10R	551	2097	1546
		2	BH-13R	550	2060	1510
		3	BH-14R	550	2079	1529
	2	1	BH-1R	520	2089	1569
		2	BH-22R	462	2067	1604
		3	BH-26R	500	2089	1589
		4	SL-PW21	501	2103	1602
		5	SL-PW18	503	2087	1584
	3	1	SL-PW-33	453	2112	1659
		2	SL-PW-18	503	2087	1584
		3	SL-PW-21	501	2103	1602
		4	SL-PW-30	533	2135	1602
		5	SL-PW-32	602	2111	1509
	4	1	WF01-PW3	482	2081	1599
		2	WF01-PW2	250	2077	1827
		3	SWAWF2(PW2')	448	2062	1614
	5	1	WF02-PW12	520	2049	1529
		2	WF02-PW5	499	2072	1573
		3	WF02-PW6	500	2059	1559
		4	WF02-PW8	502	2054	1552
		5	WF02-PW10	480	2073	1593
		6	WF02-PW11	341	2073	1732
		7	WF02-PW13	342	2057	1715
		8	WF02-PW14	500	2055	1555
2	6	1	SL-PW-11	335	2048	1713
		2	SL-PW-12	320	2046	1726
		3	SL-PW-13	319	2050	1731
		4	WF02-PW7R	550	2057	1507
		5	WF02-PW15	550	2064	1514
	7	1	WF-01 PW-11	500	2061	1561
		2	SWAWF-4B	480	2062	1582
		3	WF-01 PW-6	532	2063	1531
		4	WF-01 PW-13	400	2060	1660
		5	WF-01 PW-14	552	2055	1503
		6	WF-01 PW-15	492	2068	1576
		7	WF-01 PW-16	550	2066	1516
		8	WF-01 PW-17	477	2064	1587

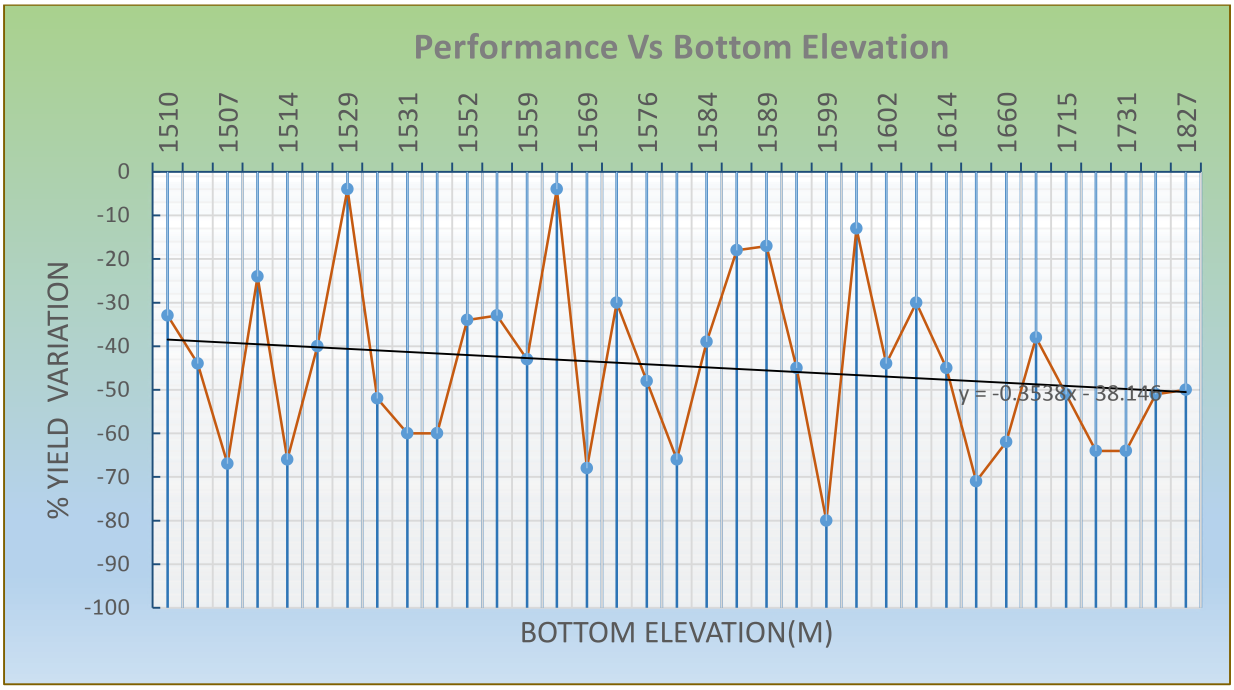

Figure 4. 4. Performance of study wells with perspective bottom elevation

Generally, for the majority of the wells, the trend line of the graph shows there is a decrease in performance as the bottom elevation is shallower. Considering the extreme values, well with better performance with 4% yield variation (BH-14R) and the well with the worst yield variation of 80% drop (WF01-PW3); the bottom elevation values are 1529m and 1599m respectively.

The expectation is, as the bottom elevation value increases, the yield variation increases. But this is not the case for some of the wells which indicate the bottom elevation isn’t the only factor contributing to the well's performance drop. This will require us to see other factors of design appearances which will take us to the next comparison parameter, screen length.

4.1.2. Screen area

As the screen area is considered the most important part of the well that has a big role in well performance and sustainability rate. It is the section of the well that permits water to enter the well, gives structural support for the aquifer material, and blocks sediments from entering the well.

The screen area column represents the surface area of the screened section of the well computed for different sizes of diameter & depth that each well has. The blind area column represents the section of the well that is kept blind and is computed the same way as screened section but with its respective depth & diameter.

$$Surface\ Area\ A = 2\pi rh + 2\pi r^2 \quad \text{..} \quad (12)$$

A = Surface area, m^2

r = radius of the well, m

h = depth of the well, m

The last column in Table 4.3 represents the ratio of screen to the total area to have a clear understanding of the screened section of the well as compared to the total area. All calculations done are in meter.

$$\frac{Screen\ Area}{Total\ Area}(\%) = \frac{Screen\ Area}{Screen\ Area + Blind\ Area}\ x\ 100 \quad \text{..................................} \quad (13)$$

If screen area per total area coverage was to be considered for wells under sub-section 6, for well SL-PW-11 which is performing better than the neighboring wells has 49.40% of the total area covered with screen. While the rest in the group has a lower value of screen coverage with values 30.27%, 41.74%, 33.11%, and 30.42%. From this, it can be suggested that a decrease in screen area might be a possible reason for yield decrease so increasing screen length across the aquifer zone could result in better performance of wells.

Table 4. 3: Screen to total area of study wells

Group	Sub-Section	No	Well Name	Screen Area,m2	Blind Area, m2	Screen area/Total area (%)
1	1	1	BH-10R	159.678	174.205	47.82%
		2	BH-13R	141.024	301.966	31.83%
		3	BH-14R	245.452	285.986	46.19%
	2	1	BH-1R	165.228	282.743	36.88%
		2	BH-22R	144.941	264.422	35.41%
		3	BH-26R	148.331	291.785	33.70%
		4	SL-PW21	141.240	295.178	32.36%
		5	SL-PW18	134.162	307.799	30.36%
	3	1	SL-PW-33	130.036	278.306	31.84%
		2	SL-PW-18	134.162	307.799	30.36%
		3	SL-PW-21	141.240	295.178	32.36%
		4	SL-PW-30	152.443	305.413	33.29%
		5	SL-PW-32	163.647	340.172	32.48%
	4	1	WF01-PW3	257.032	187.360	57.84%
		2	WF01-PW2	80.064	203.291	28.26%
		3	SWAWF2(PW2')	227.188	142.139	61.51%
	5	1	WF02-PW12	164.400	266.814	38.12%
		2	WF02-PW5	323.034	204.115	61.28%
		3	WF02-PW6	330.668	167.347	66.40%
		4	WF02-PW8	111.276	303.195	26.85%
		5	WF02-PW10	258.277	189.560	57.67%
		6	WF02-PW11	172.705	222.598	43.69%
		7	WF02-PW13	93.118	106.362	46.68%
		8	WF02-PW14	133.441	282.258	32.10%
2	6	1	SL-PW-11	178.809	183.188	49.40%
		2	SL-PW-12	131.337	302.556	30.27%
		3	SL-PW-13	144.840	202.179	41.74%
		4	WF02-PW7R	154.786	312.694	33.11%
		5	WF02-PW15	139.754	319.676	30.42%
	7	1	WF-01 PW-11	553.585	223.975	71.20%
		2	SWAWF-4B	89.235	209.740	29.85%
		3	WF-01 PW-6	94.039	265.249	26.17%
		4	WF-01 PW-13	100.726	348.665	22.41%
		5	WF-01 PW-14	230.971	216.361	51.63%
		6	WF-01 PW-15	323.809	230.026	58.47%
		7	WF-01 PW-16	375.910	236.181	61.41%
		8	WF-01 PW-17	329.893	191.095	63.32%

Reviewing the result of yield reduction of wells under sub-section three (Table 4.3), almost all wells have a similar screen to total area ratio. The well's 30.36 to 33.30 percent of the total area is screened. This signifies the section of the casing that permits water to enter each well is of similar capacity. Therefore, the problem in yield decrease could be blockage of the screen slot (clogging).

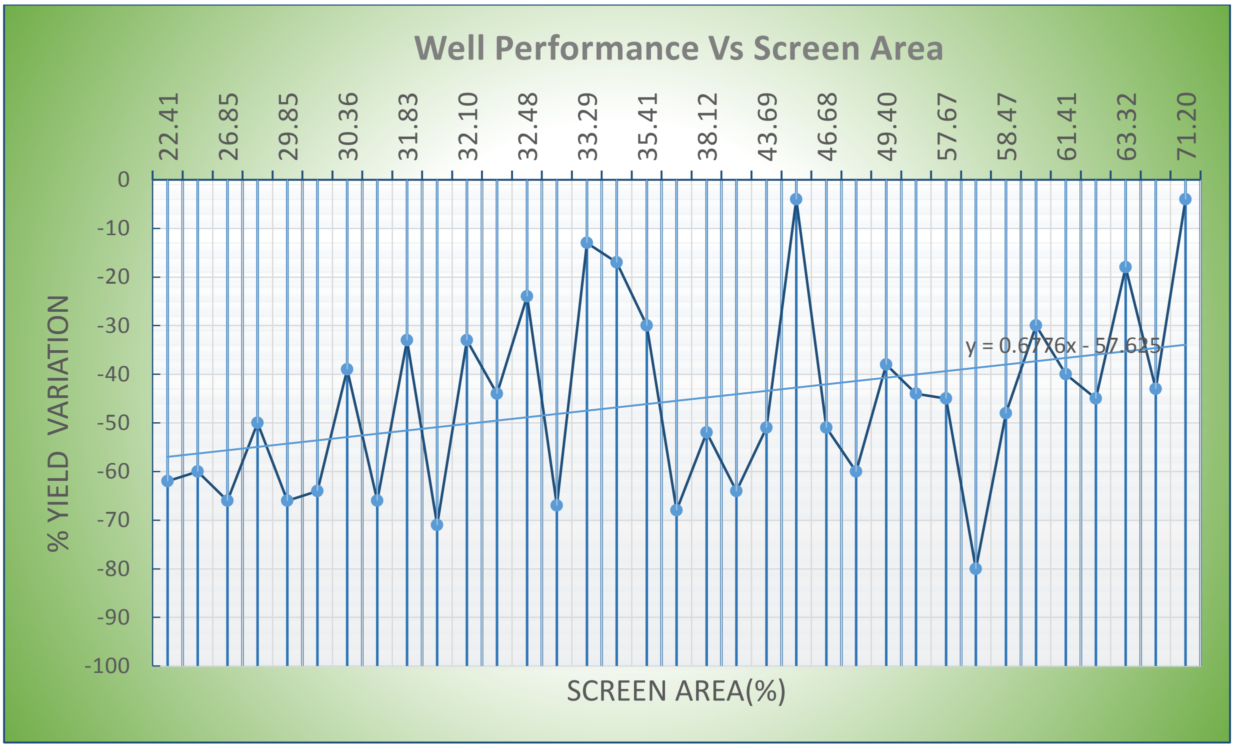

Figure 4. 5. Performance of study wells with a perspective Screen area

The trend line for the majority of the wells shows that there is an increase in performance as the screened area section increases. Just like results in the bottom elevation result we can see here also that it is not the case for all wells which implies that yield decrease of wells does not only relate to screen length but rather the contribution of other factors as well. This will lead us to the next comparison factors down below.

4.1.3. Filter material, Geologic medium, and well construction

From the well completion report, observing the geophysical well log it can be seen that the major aquifer system of the study wells are found to be weathered & fractured basalt and Scoracious basalt, and screens are arranged accordingly. So comparison cannot be done regarding this matter as it is similar between neighboring wells. Wells around the center of Figure 4.1 shows a higher level of yield decline that can be related to ground water depletion in that area. Further detailed study of the aquifer property and hydrological factors of this area could result in some interesting outcome.

Gravel packing was placed based on the geological condition of the wells to obtain clean and load-free water. The common drilling mechanism used for most wells is mud rotary. For some well in addition to mud rotary; air rotary, reverse circulation, and rimming by rock bit is used.

4.2. Well interference

From the radius of influence calculation done using the Cooper and Jacob method, it can be said that most wells are developed within the radius of influence of one another. Each well is constructed very close to each other so much so that when water is discharged from the wells their radius of influence overlaps. Due to this problem most wells are not giving expected design yield because a high volume of water appropriation is taking place.

Table 4. 4: Distance between boreholes of sub-section three

Distance between boreholes r, meter					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**0**	696	804	1037	1117
SL-PW32	696	**0**	674	1463	1803
SL-PW18	804	674	**0**	953	1620
SL-PW21	1037	1463	953	**0**	968
SL-PW30	1117	1803	1620	968	**0**

Table 4.4 represents wells under section three and the distance between each well is put in the table. As can be seen from the Table, the maximum and the minimum distance between two neighboring boreholes developed is 1803meter and 674meter respectively. The longest distance which is 1803meter is the distance between SL-PW32 and SL-PW30 and the shortest amongst the group which is 674meter is the distance between SL-PW18 and SL-PW32. The space between the rest of the wells in the group is between the values of 674 and 1803metes.

From this table, we can understand that the distance between each neighboring well is different from one another. The same is true for the rest of the groups of study wells selected for the assessment of yield decrease in Akaki well field.

The Cooper and Jacob equation was used to compute the radius of influence of each well. The formula used Storativity(S), Transmissivity (T), and time of operation (t) parameters to calculate the radius of influence. The values of these parameters are taken from the well completion report of each well. The operation time taken is the current operation hour of each well.

$$R(t) = \frac{1.5\sqrt{Tt}}{S} \quad \text{.....................(9)}$$

R(t) = Radius of Influence (meter)   S = Storativity

T = Transmissivity (m^2/min)   t = operation hour (min)

Table 4. 5: Radius of Influence of wells of sub-section 3

Well Id	Radius of Influence, meter
SL-PW33	1519.87
SL-PW32	2219.80
SL-PW18	3387.48
SL-PW21	6741.66
SL-PW30	13886.82

The radius of influence of each study well was calculated and the result was obtained as can be seen in Table 4.5. For example, if we consider well SL-PW33, it has a radius of influence of 1519.9 meters meaning any well developed within this radial distance of the well probably is going to interfere with the discharge expected from SL-PW33.

As can be seen from Table 4.4, the horizontal distance of each well in sub-section three is within this distance meaning there is definitely an interference between each borehole in the group. The same is true for the rest of the wells in this group as well because the maximum distance measured in the group was 1803meter which is less than the radius of influence of SL-PW32, SL-PW18, SL-PW21, and SL-PW30 (Table4.5).

Table 4. 6: Drawdown of wells under sub-section three

Drawdown, meter					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**15.823**	1.437	1.171	0.703	0.567
SL-PW32	1.273	**10.353**	1.308	0.458	0.228
SL-PW18	0.775	0.870	**5.308**	0.683	0.397
SL-PW21	0.318	0.260	0.332	**1.792**	0.329
SL-PW30	0.074	0.060	0.063	0.078	**0.331**

The matrix under Table 4.6 represents digits of expected drawdown observed in different wells in the row for the pumping taking place in the wells in the column of the table. The cooper and Jacob method is used to compute the drawdown of each well. The discharge (Q) and operation hour (t) used to compute the drawdown is the current discharge and operation hour of the wells. Storativity (S), Transmissivity(T), and radial distance (r) values were taken from the well completion report of each well.

$$S = \frac{2.3Q}{4\pi T} log_{10} \frac{2.25Tt}{Sr^2} \qquad (6)$$

The well SL-PW33 initially was designed to give a yield of 102 L /sec but currently, it is only giving 30 L/s which is a large decrease from the intended designed yield. The same holds true for the other wells in the group as well as there is a decrease in yield from the design assumption.

From the single well test, water is pumped from the well at the column header and drawdown results (stated in diagonal cells of the table) are observed on that same well. When 30l/s of water is drawn from SL-PW33 well, the drawdown expected on the well itself is 15.823 meters, as far as the hydrogeological parameters stated in the corresponding well design reports are true.

From the multiple-well test, water is pumped from SL-PW33, and drawdown is computed on the rest of the wells. When 30l/s of water is pumped from SL-PW33 the drawdown it caused on the other wells in this section was found to be 1.437, 1.171, 0.703, and 0.567 meters. From the well analysis results, we can observe that as the distance from the pumping well increases drawdown decreases. Wells closer to the pumping well is highly affected and are susceptible to a decrease in yield.

The other finding from the drawdown matrix in Table 4.6, when water is pumped from SL-PW32 the drawdown caused on SL-PW32 is greater than the drawdown on the neighboring wells. If we consider well ID SL-PW32 as the pumped well, when water is drawn from this well the drawdown observed on wells SL-PW33, SL-PW18, SL-PW21 & SL-PW30 is 1.273, 1.308, 0.458 & 0.228 meters respectively. This shows the draw-down result of the pumped well, 10.353 meters is much greater than the rest. All results in the matrix are positive emphasizing every well affecting one another in the sub-section.

Table 4. 7: Drawdown effects of each well on one another under sub-section three

Drawdown, meter					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**15.823**	1.437	1.171	0.703	0.567
SL-PW32	1.273	**10.353**	1.308	0.458	0.228
SL-PW18	0.775	0.870	**5.308**	0.683	0.397
SL-PW21	0.318	0.260	0.333	**1.792**	0.330
SL-PW30	0.074	0.060	0.063	0.078	**0.331**
DD of pumped well	15.823	10.353	5.308	1.792	0.331
∑ DD of all wells	18.263	12.979	8.184	3.715	1.853
% of DD caused by nearby wells	**13.36%**	**20.23%**	**35.14%**	**51.75%**	**82.14%**

To understand how each well affects one another a simple calculation was done on the drawdown result found in previous calculations. This helps to realize how the operation of one well is affecting the surrounding wells and to come up with a solution that will result in a better yield conservative method.

Drawdowns shown in Table 4.7 are the same as Table 4.6 calculated using Cooper and Jacob method. The additional feature shown in Table 4.7 here is collective drawdown caused on each well by the neighboring wells which are stated on the last row of the table.

$$\%DD\ caused\ by\ nearby\ wells = 1 - \left(\frac{DD\ of\ pumped\ well}{\sum DD\ of\ all\ wells}\right) \quad \text{.................. (14)}$$

‘‘% of dd caused by nearby wells’’ represents the percent of the contribution of neighboring wells to the drawdown of the study well (pumped well).

As can be seen in Table 4.7 all wells are affected by one another when water is pumped from each well. The difference is the amount of influence each well faces. From this section of wells, well SL-PW30 is the most influenced well in the group with 82.14% of the drawdown on the well being caused by the other four wells in the section. It can be said that the decrease in discharge of this well is due to the influence of the neighboring wells.

Another result observed from this table is for well SL-PW33 whereby the percent of the contribution of drawdown by the neighboring wells is 13.36% which is the lowest amongst the wells under section three. From this, we can understand that majority of the drawdown is caused by the well itself and can be said that there is a problem in the design or construction of this well. The same goes for well SL-PW32 whereby around 80% of the drawdown caused on the well is by the well itself.

From Table 4.8 it can be seen that 100% of the wells are influenced by the neighboring wells in each section but the magnitude ranges from 0.38%-94.55%.

From the result of drawdown calculations done in all seven sub-sections of study wells, it can definitely be said that well interference is highly prominent in Akaki well field. It can be considered as the leading factor for the decrease in the yield of water wells.

Table 4. 8. Drawdown effect of wells on one another

Group	Sub-Section	No	Well Name	Drawdown caused by the neighboring wells (%)
1	1	1	BH-10R	40.56%
		2	BH-13R	3.11%
		3	BH-14R	74.94%
	2	1	BH-1R	63.05%
		2	BH-22R	45.18%
		3	BH-26R	14.67%
		4	SL-PW21	8.33%
		5	SL-PW18	33.75%
	3	1	SL-PW-33	13.36%
		2	SL-PW-18	20.23%
		3	SL-PW-21	35.14%
		4	SL-PW-30	51.75%
		5	SL-PW-32	82.14%
	4	1	WF01-PW3	35.39%
		2	WF01-PW2	1.92%
		3	SWAWF2(PW2')	0.38%
	5	1	WF02-PW12	11.82%
		2	WF02-PW5	13.90%
		3	WF02-PW6	11.53%
		4	WF02-PW8	43.97%
		5	WF02-PW10	8.26%
		6	WF02-PW11	3.96%
		7	WF02-PW13	58.02%
		8	WF02-PW14	6.26%
2	6	1	SL-PW-11	17.15%
		2	SL-PW-12	9.24%
		3	SL-PW-13	32.12%
		4	WF02-PW7R	27.10%
		5	WF02-PW15	7.68%
	7	1	WF-01 PW-11	0.43%
		2	SWAWF-4B	65.70%
		3	WF-01 PW-6	12.56%
		4	WF-01 PW-13	0.92%
		5	WF-01 PW-14	0.63%
		6	WF-01 PW-15	1.55%
		7	WF-01 PW-16	1.65%
		8	WF-01 PW-17	0.62%

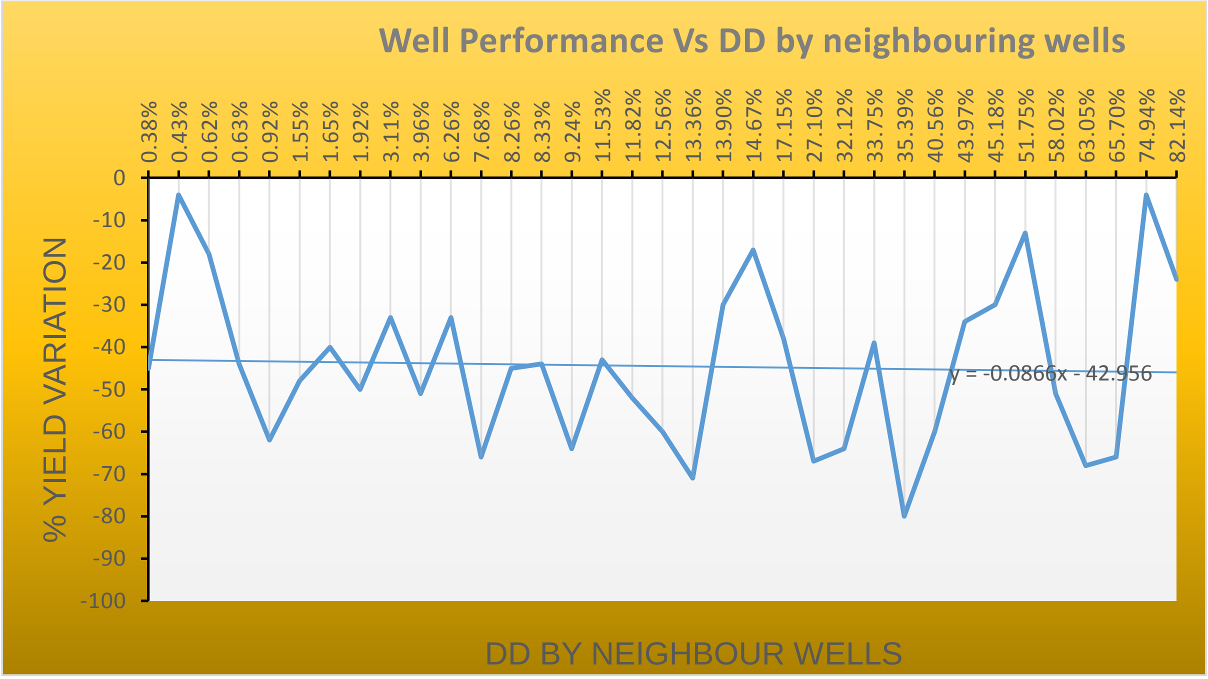

Figure 4. 6. Performance of study wells with the perspective effect of DD by neighboring wells

The general trend line from the graph shows that there is a decrease in performance as the drawdown effect of neighboring wells increases. This phenomenon is true for most of the study wells. Even if the DD effect of other wells has a high contribution to well yield decline, it is not the only determinant or cause for the performance drop of wells. That's why in the graph we see some wells having a low dd effect by other wells but still have a higher level of yield decline over the years.

4.3. Operation hour and discharge rates

To address the demand of the beneficiaries of the town most wells are operating more than 16hours per day. This increased operation hours of each well might have resulted in insufficient recovery time for the wells to replenish.

The Cooper and Jacob equation is used to compute for an ideal operation hour where the drawdown expected is zero. Rearranging the formula and computing for the time where drawdown (s) is zero gives us the following formula.

$$t = \frac{r^2 S}{2.25T} \quad \text{...} (15)$$

t = time, hr S = Storativity

r = radial distance between wells, meter T = Transmissivity, m^2/min

Table 4. 9: Ideal operation hour for sub-section three wells

Operation hour per day, hr (s=0, Q = current discharge)					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	-	4.61	6.16	10.24	11.88
SL-PW32	2.36	-	2.21	10.42	15.83
SL-PW18	1.35	0.95	-	1.90	5.49
SL-PW21	0.57	1.13	0.48	-	0.49
SL-PW30	0.14	0.37	0.30	0.11	-

If the wells were to keep giving service with the current yield they are working and were to show zero drawdowns, the value of operation hour as shown in the matrix of Table 4.9 has to be followed.

Considering the current operation hour of the wells under section three SL-PW33, SL-PW32, SL-PW18, SL-PW21, and SL-PW30 which is 22hrs, 24hrs, 24hrs, 24hrs, and 22hrs respectively; the ideal operation hour resulted under Table 4.9 is far-fetched. The values in Table 4.9 obtained indicate the duration (in hr) of pumping the wells in the first column of the table (keeping the current design discharge) need to operate before any drawdown is observed in the wells indicated in the header row.

Depending on the pump's capacity, initial design production rate and current recovery time of the well operation hour of each well have to be fixed and the wells to operate based on that fixed time of operation.

Another phenomenon considered is the well's discharge rate by keeping the drawdown level almost zero and the well is operated at the current operation hour. The matrix under Table 4.10 was computed to show the results obtained.

The Cooper and Jacob equation was used to compute the results of the pumping rate of the wells. For this calculation Storativity (S), Transmissivity (T), radial distance (r), current operation hour (t), and a very small amount of drawdown (s=0.1) were used.

Table 4. 10: Ideal pumping rate for wells under sub-section three

Pumping Rate Q , L/hr (s=0.1, t = constant)					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**11.38**	125.28	153.66	255.95	317.71
SL-PW32	164.96	**20.28**	160.52	458.90	920.01
SL-PW18	309.79	275.95	**45.21**	351.32	604.02
SL-PW21	942.73	1155.09	902.02	**167.38**	909.28
SL-PW30	3241.12	4001.29	3801.97	3066.90	**725.08**

Comparing results seen in Table 4.10 with the current production yield of wells in section three (Table 4.1), it can be seen that the wells are overworked and discharge rates have to be minimized to ensure the sustainability and lifespan of water wells.

5. CHAPTER FIVE: - Conclusion and Recommendation

5.1. Conclusion

Groundwater is considered as one of the sources of water for the city of Addis Ababa and the main supply of groundwater mainly comes from Akaki well field. The wells in Akaki well field are deep and are built in different phases.

Although a certain designed amount of water is expected from this well field most wells are deteriorating and are giving a lower yield than expected. The main aim of this research is to find a possible reason why these water wells are showing a decrease in production rate.

Although there was a decrease in yield in most of the wells in Akaki well field, it was also observed that some wells perform better than the neighboring surrounding wells. This led to the thinking that there is potential groundwater but due to the design, construction, or operation of the well the yield couldn't be maintained up to the designed standard. To achieve the goal, 35 water wells were selected based on their performance in relation with their neighbors for a detailed study of the behavior of the wells during design, construction, and operation.

From the 70 water wells found in the well field, 93% of the wells have shown a reduction in yield from their initial designed well yield. This loss of performance of most wells found in the field is not only compromising the service to the beneficiary of the town but must be seen also as a sign that the resource is not being utilized to its fullest potential.

Based on the calculation of the radius of influence of selected 35 water wells using the Cooper and Jacob method, it was found that the majority of the wells are developed within the radius of influence of one another. This means when water is pumped from one well the capacity of the surrounding well is highly affected and might be considered as one reason for yield decrease in the Akaki well field.

Results from the drawdown calculation of wells in each section using the Jacob and Cooper method, it was found that most of the results were positive which signifies that drawdown is prevalent in most of the wells. Further analysis was done in each section to see the effect of drawdown on one another. It was seen that 100% of the study wells are influenced by the neighbouring wells in each section meaning majority of the drawdown comes from the neighboring wells which emphasise more that there is well interference and can be put as a reason for yield decrease.

To come up with a reason for the yield decrease of the selected wells a detailed study was done based on depth, elevation, screen arrangement, geological medium, filter material, construction process, year of construction, and the drilling contractor. The decrease in yield could be a compilation of reasons stated above and the study tried to bring that to attention.

From the 35 wells design document it was found that some wells are developed at a shallower depth when compared with the surrounding wells (better performing wells). Increasing depth to these wells could result in better performance of the wells. Another finding is that 60% of the wells have 30-50% of the screened area. In some sections, it was seen that the screened area of the well that has lower performance is smaller than the surrounding wells and it can be suggested to increase screen depth in accordance with its perspective geologic medium.

The geologic medium, the filter material, and the drilling mechanism of all wells were found similar except for volume differences. Though we cannot see how the wells are developed, reading from the well completion report it can be said that the well building process followed standard procedures when drilling, selecting water-bearing formation, and also filling the open space with the appropriate gravel material. The Year of construction of the study wells is from 2009-2015 G.C. implying it has only been 7-13 years since the wells come to service which is lower than the expected service life of developed wells in Akaki well field which is 20-25 years.

Results also showed that most wells are being over-pumped for a longer period leaving less time to recover. Majority of the wells in the well field are operating for more than 16 hours per day. Through time this phenomenon causes yield decrease and in the end failure of the wells.

5.2. Recommendation

Given this research is done using data collected in 2020 as the current discharge rate, more recent use of data must be used by future researchers. Observing the trend of the performance of study wells over the years it is likely that the discharge rate will keep decreasing and well performance will deteriorate.

Due to lack of information on the aquifer property, for storativity values, this research assumed a value of 0.0002 for all of the wells but using actual values could result in a different result of drawdown values.

Including additional study wells could enrich the results obtained in this research. The more data/information on the well field the broader the sense of the results and findings in this research will become.

Investigation of the subsurface features of wells using CCTV, land use and land coverage of the study area to see contribution of this factors for yield decline in Akaki well field. Also to come up with a more precise solution/suggestion eliminating guesswork.

Further investigation on the quality of water from the wells to see the occurrence of Incrustation or chemical build up that could be put as a possible reason for blockage of screened section.

To over see the replenshing capacity of the wells after being pumped for longer hours and use of this information to fix the production rate and operation hour of wells in that area.

Study on hydrogeological component of the well field may answer why majority of the wells that are in close distance have declined in performance.

Findings from this research give a good insight into the operation of water wells and a possible reason for yield decrease in the Akaki well field. This information could be used by future researchers or AAWSA and could be considered as a baseline for expansion of projects in the well field.

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ANNEX

Annex 1: Lithological data and design characteristics of boreholes of some selected wells

Table 1: Well Index WF01-PW3

Well Index	WF01-PW3
Well depth, m	481.6
Static water level ,m	21.83
Pumping test Pump position, m	114
Pumping test discharge ,l/s	28
Maximum drawdown, m	68.65
Dynamic Water level ,m	90.48
Maximum discharged Water temperature during pump test	27 °C
Transmissivity ,m^2/day	5.75×10^2
Specific capacity, l/s/m	0.408
Safe Yield , l/s	35
Well Type	Test well
Main Aquifer	Weathered & Fractured vesicular basalt and Scoracious basalt

Table 2: Description of drilled cuttings of WF01-PW3

Depth interval (m)		Lithologic description
From	to	
0	10	Top soil
10	40	Massive Basalt
40	44	Scoraceous Basalt
44	58	Vesicular Basalt
58	70	Highly weathered Scoria
70	92	Moderately weathered vesicular basalt
92	100	Scoria
100	122	Massive Basalt
122	130	Slightly weathered basalt
130	134	Massive Basalt
134	230	slightly weathered vesicular basalt
230	258	slightly fractured basalt
258	266	highly fractured Scoraceous basalt
266	274	Slightly weathered basalt
274	464	Scoraceous Basalt
464	481	weathered vesicular basalt

Table 3: Well Index SWAWF2

Well Index	**SWAWF2**
Well depth, m	448
Static water level,m	9.45
Pumping test Pump position, m	110
Pumping test discharge,l/s	54.45
Maximum discharged water temp	23.6oc
Maximum drawdown, m	89.39
Dynamic Water level ,m	98.84
Transmissivity ,m2/day	5.83 x 101
Specific capacity, l/s/m	0.61
Safe Yield , l/s	56
Well Type	Test well
Main Aquifer	Highly weathered & Fractured basalt and Scoriaceous basalt

Table 4: Description of drilled cuttings of SWAWF2

Depth interval (m)		**Lithologic description**
From	to	
0	8	Reddish-brown clay
8	30	Highly weathered and fractured basalt almost decomposed to soil
30	44	Massive fresh basalt (very fine cutting material
44	60	Moderately weathered and fractured basalt
60	68	Highly weathered and fractured basalt
68	72	Moderately fractured basalt
72	216	Moderately weathered and highly fractured basalt(vesicular)
216	250	Slightly fractured basalt
250	308	Fractured fresh basalt
308	376	Highly fractured and slightly weathered scoriaceous basalt
376	380	Highly fractured fresh basalt
380	410	Highly weathered and fractured scoriaceous basalt with scoria
410	430	Highly fractured and slightly weathered basalt
430	448	Highly fractured and slightly weathered vesicular basalt with some mineral filling (qtz)

Annex 2: Distance between boreholes

Table 5: Distance between wells under Sub-section one

Distance between boreholes r, meter			
	BH-10R	**BH-13R**	**BH-14R**
BH-10R	**0**	580	475
BH-13R	580	**0**	462
BH-14R	475	462	**0**

Table 6: Distance between wells under Sub-section two

Distance between boreholes r, meter					
	BH-1R	**SL-PW21**	**SL-PW18**	**BH-26R**	**BH-22R**
BH-1R	**0**	692	1290	1140	1117
SL-PW21	692	**0**	953	1700	1785
SL-PW18	1290	953	**0**	1701	2025
BH-26R	1140	1700	1701	**0**	501
BH-22R	1117	1785	2025	501	**0**

Table 7: Distance between wells under Sub-section three

Distance between boreholes r, meter					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**0**	696	804	1037	1117
SL-PW32	696	**0**	674	1463	1803
SL-PW18	804	674	**0**	953	1620
SL-PW21	1037	1463	953	**0**	968
SL-PW30	1117	1803	1620	968	**0**

Table 8: Distance between wells under Sub-section four

Distance between boreholes r, meter			
	WF01-PW3	**WF01-PW2**	**SWAWF2(PW2')**
WF01-PW3	**0**	716	962
WF01-PW2	716	**0**	1589
SWAWF2(PW2')	962	1589	**0**

Table 9: Distance between wells Under Sub-section five

Distance between boreholes r, meter								
	WF02-PW12	**WF02-PW5**	**WF02-PW6**	**WF02-PW8**	**WF02-PW10**	**WF02-PW11**	**WF02-PW13**	**WF02-PW14**
WF02-PW12	**0**	1902	1096	3599	2569	1331	1000	3448
WF02-PW5	1902	**0**	1362	3406	2733	1874	2510	3702
WF02-PW6	1096	1362	**0**	4157	3236	2026	2068	4197
WF02-PW8	3599	3406	4157	**0**	1061	2268	3014	836
WF02-PW10	2569	2733	3236	1061	**0**	1250	1954	983
WF02-PW11	1331	1874	2026	2268	1250	**0**	995	2179
WF02-PW13	1000	2510	2068	3014	1954	995	**0**	2678
WF02-PW14	3448	3702	4197	836	983	2179	2678	**0**

Table 10: Distance between wells Under Sub-section six

Distance between boreholes r, meter					
	SL-PW-11	**SL-PW-12**	**SL-PW-13**	**WF02-PW7R**	**WF02-PW15**
SL-PW-11	**0**	715	599	1280	1642
SL-PW-12	715	**0**	1303	1459	1049
SL-PW-13	599	1303	**0**	1484	2222
WF02-PW7R	1280	1459	1484	**0**	1590
WF02-PW15	1642	1049	2222	1590	**0**

Table 11: Distance between wells Under Sub-section Seven

Distance between boreholes r, meter								
	WF-01 PW-11	**SWAWF-4B**	**WF-01 PW-6**	**WF-01 PW-13**	**WF-01 PW-14**	**WF-01 PW-15**	**WF-01 PW-16**	**WE-01 PW-17**
WF-01 PW-11	**0**	2979	2082	1357	2684	1902	2529	3694
SWAWF-4B	2979	**0**	1357	4319	5330	2341	861	855
WF-01 PW-6	2082	1357	**0**	3427	4479	1772	784	1649
WF-01 PW-13	1357	4319	3427	**0**	2100	2798	3793	5050
WF-01 PW-14	2684	5330	4479	2100	**0**	4562	5098	5849
WF-01 PW-15	1902	2341	1772	2798	4562	**0**	1507	3196
WF-01 PW-16	2529	861	784	3793	5098	1507	**0**	1704
WE-01 PW-17	3694	855	1649	5050	5849	3196	1704	**0**

Annex 3: Well Interference of Study wells

Table 12: Wells under Sub-section one

Well name	Radius of Influence,m
BH-10R	3464.78
BH-13R	1031.08
BH-14R	9011.71

Table 13: Wells under Sub-section two

Well Id	Radius of Influence, m
BH-1R	4638.49
SL-PW21	6741.66
SL-PW18	3387.48
BH-26R	1666.33
BH-22R	3101.41

Table 14: Wells under Sub-section three

Well Id	Radius of Influence, m
SL-PW33	1519.87
SL-PW32	2219.80
SL-PW18	3387.48
SL-PW21	6741.66
SL-PW30	13886.82

Table 15: Wells under Sub-section Four

Well Id	Radius of Influence, m
WF01-PW3	2489.82
WF01-PW2	1446.87
SWAWF2(PW2')	809.86

Table 16: Wells under Sub-section Five

Well Id	Radius of Influence, m
WF02-PW12	2116.01
WF02-PW5	4242.64
WF02-PW6	1723.37
WF02-PW8	4767.07
WF02-PW10	1142.37
WF02-PW11	1358.31
WF02-PW13	6572.67
WF02-PW14	2214.72

Table 17: Wells under Sub-section Six

Well Id	Radius of Influence, m
SL-PW-11	2672.78
SL-PW-12	1086.85
SL-PW-13	2765.86
WF02-PW7R	2502.12
WF02-PW15	1840.18

Table 18: Wells under Sub-section Seven

Well Id	Radius of Influence, m
WF-01 PW-11	1040.58
SWAWF-4B	10997.16
WF-01 PW-6	4229.36
WF-01 PW-13	1308.39
WF-01 PW-14	2392.37
WF-01 PW-15	1411.12
WF-01 PW-16	857.76
WE-01 PW-17	895.82

Annex 4: Drawdown of Study wells

Table 19: Wells under Sub-section one

Drawdown, meter			
	BH-10R	**BH-13R**	**BH-14R**
BH-10R	**3.943**	0.748	0.831
BH-13R	2.321	**34.952**	3.238
BH-14R	0.370	0.373	**1.360**
DD of study well	3.943	34.952	1.360
∑ DD of all wells	6.633	36.073	5.430
% of DD caused by nearby wells	**40.56%**	**3.11%**	**74.94%**

Table 20: Wells under Sub-section two

Drawdown, meter					
	BH-1R	**SL-PW21**	**SL-PW18**	**BH-26R**	**BH-22R**
BH-1R	**1.675**	0.328	0.221	0.242	0.245
SL-PW21	0.387	**1.792**	0.333	0.234	0.226
SL-PW18	0.520	0.683	**5.308**	0.371	0.277
BH-26R	1.089	0.000	0.000	**26.243**	3.449
BH-22R	0.861	0.466	0.360	1.538	**8.237**
DD of study well	1.675	1.792	5.308	26.243	8.237
∑ DD of all wells	4.533	3.269	6.221	28.628	12.434
% of DD caused by nearby wells	**63.05%**	**45.18%**	**14.67%**	**8.33%**	**33.75%**

Table 21: Wells under Sub-section Three

Drawdown, meter					
	SL-PW33	SL-PW32	SL-PW18	SL-PW21	SL-PW30
SL-PW33	**15.823**	1.437	1.171	0.703	0.567
SL-PW32	1.273	**10.353**	1.308	0.458	0.228
SL-PW18	0.775	0.870	**5.308**	0.683	0.397
SL-PW21	0.318	0.260	0.333	**1.792**	0.330
SL-PW30	0.074	0.060	0.063	0.078	**0.331**
DD of study well	15.823	10.353	5.308	1.792	0.331
∑ DD of all wells	18.263	12.979	8.184	3.715	1.853
% of DD caused by nearby wells	**13.36%**	**20.23%**	**35.14%**	**51.75%**	**82.14%**

Table 22: Wells under Sub-section four

Drawdown, meter			
	WF01-PW3	WF01-PW2	SWAWF2(PW2')
WF01-PW3	**2.173**	0.298	0.227
WF01-PW2	1.190	**15.231**	0.000
SWAWF2(PW2')	0.000	0.000	**59.541**
DD of study well	2.173	15.231	59.541
∑ DD of all wells	3.363	15.529	59.768
% of DD caused by nearby wells	**35.39%**	**1.92%**	**0.38%**

Table 23: Wells under Sub-section Five

Drawdown, meter								
	WF02-PW12	WF02-PW5	WF02-PW6	WF02-PW8	WF02-PW10	WF02-PW11	WF02-PW13	WF02-PW14
WF02-PW12	**7.398**	0.088	0.545	0.000	0.000	0.384	0.621	0.000
WF02-PW5	0.241	**3.029**	0.341	0.066	0.132	0.246	0.158	0.041
WF02-PW6	0.400	0.208	**8.119**	0.000	0.000	0.000	0.000	0.000
WF02-PW8	0.063	0.075	0.031	**2.288**	0.337	0.167	0.103	0.391
WF02-PW10	0.000	0.000	0.000	0.192	**22.841**	0.000	0.000	0.391
WF02-PW11	0.058	0.000	0.000	0.000	0.237	**25.461**	0.886	0.000
WF02-PW13	0.229	0.117	0.141	0.095	0.148	0.230	**1.279**	0.109
WF02-PW14	0.000	0.000	0.000	1.443	1.203	0.024	0.000	**13.963**
DD of study well	7.398	3.029	8.119	2.288	22.841	25.461	1.279	13.963
∑ DD of all wells	8.390	3.518	9.176	4.084	24.897	26.511	3.047	14.895
% of DD caused by nearby wells	**11.82%**	**13.90%**	**11.53%**	**43.97%**	**8.26%**	**3.96%**	**58.02%**	**6.26%**

Table 24: Wells under Sub-section Six

Drawdown, meter					
	SL-PW-11	SL-PW-12	SL-PW-13	WF02-PW7R	WF02-PW15
SL-PW-11	**13.879**	1.997	2.265	1.115	0.738
SL-PW-12	1.643	**34.214**	0.000	0.000	0.139
SL-PW-13	0.742	0.365	**4.679**	0.302	0.106
WF02-PW7R	0.310	0.250	0.242	**4.421**	0.210
WF02-PW15	0.177	0.872	-0.293	0.227	**14.343**
DD of study well	13.879	34.214	4.679	4.421	14.343
∑ DD of all wells	16.751	37.697	6.893	6.064	15.536
% of DD caused by nearby wells	**17.15%**	**9.24%**	**32.12%**	**27.10%**	**7.68%**

Table 25: Wells under Sub-section seven

Drawdown, meter								
	WF-01 PW-11	**SWAWF-4B**	**WF-01 PW-6**	**WF-01 PW-13**	**WF-01 PW-14**	**WF-01 PW-15**	**WF-01 PW-16**	**WE-01 PW-17**
WF-01 PW-11	**54.469**	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SWAWF-4B	0.038	**0.317**	0.060	0.027	0.021	0.044	0.073	0.073
WF-01 PW-6	0.196	0.314	**2.786**	0.058	0.000	0.240	0.466	0.260
WF-01 PW-13	0.000	0.000	0.000	**13.998**	0.000	0.000	0.000	0.000
WF-01 PW-14	0.000	0.000	0.000	0.045	**3.294**	0.000	0.000	0.000
WF-01 PW-15	0.000	0.000	0.000	0.000	0.000	**18.117**	0.000	0.000
WF-01 PW-16	0.000	0.000	0.340	0.000	0.000	0.000	**32.063**	0.000
WE-01 PW-17	0.000	0.293	0.000	0.000	0.000	0.000	0.000	**53.622**
DD of study well	54.469	0.317	2.786	13.998	3.294	18.117	32.063	53.622
∑ DD of all wells	54.702	0.925	3.186	14.128	3.315	18.402	32.603	53.956
% of DD caused by nearby wells	**0.43%**	**65.70%**	**12.56%**	**0.92%**	**0.63%**	**1.55%**	**1.65%**	**0.62%**

Annex 5: Performance of study wells with respect to bottom elevation

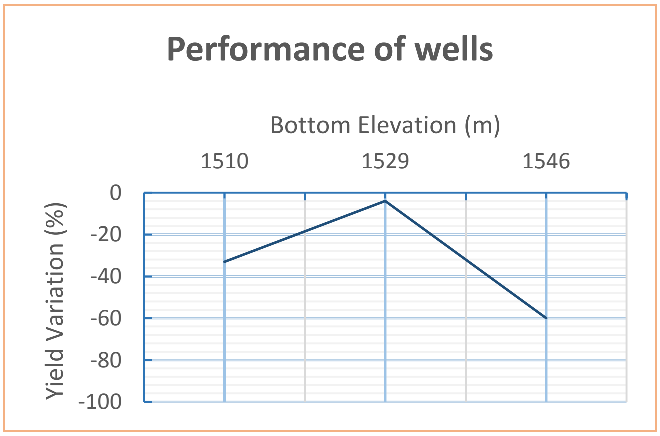

Figure 1: Wells under Sub-section one

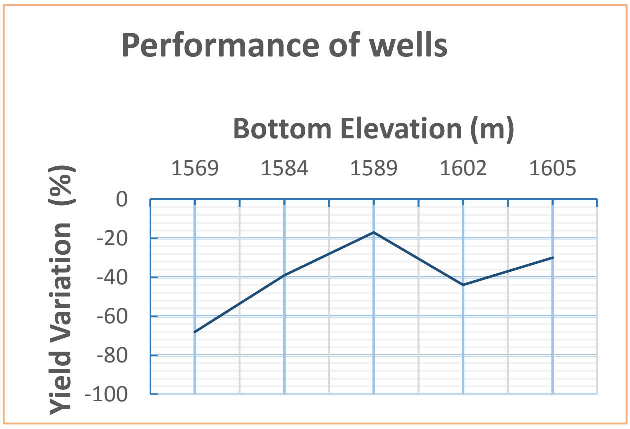

Figure 2: Wells under Sub-section two

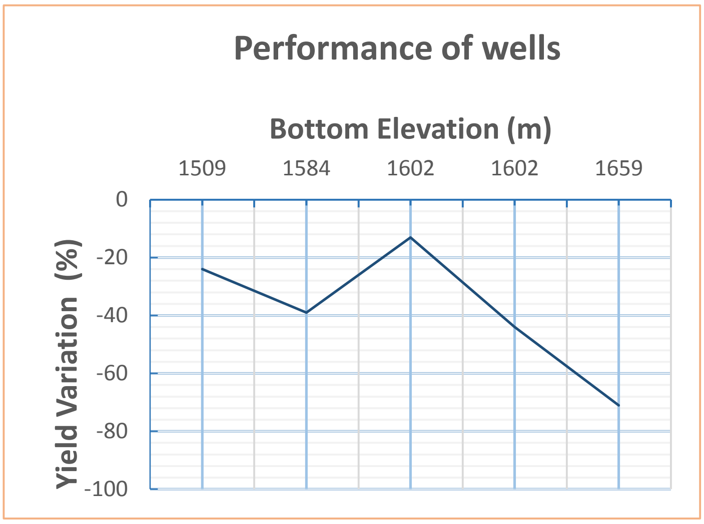

Figure 3: Wells under Sub-section three

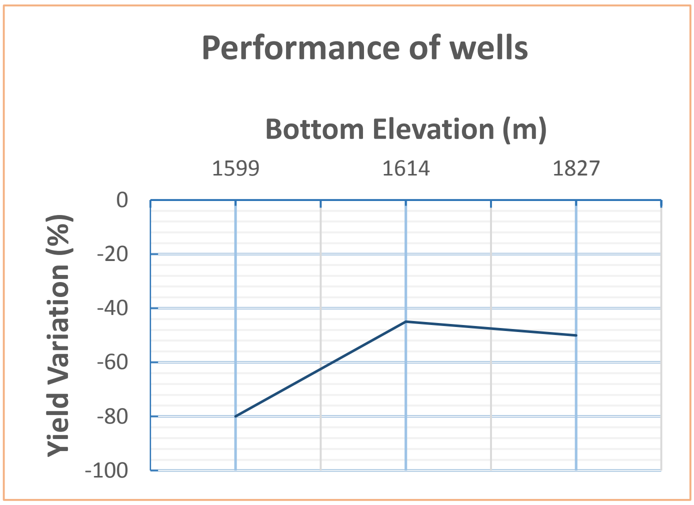

Figure 4: Wells under Sub-section Four

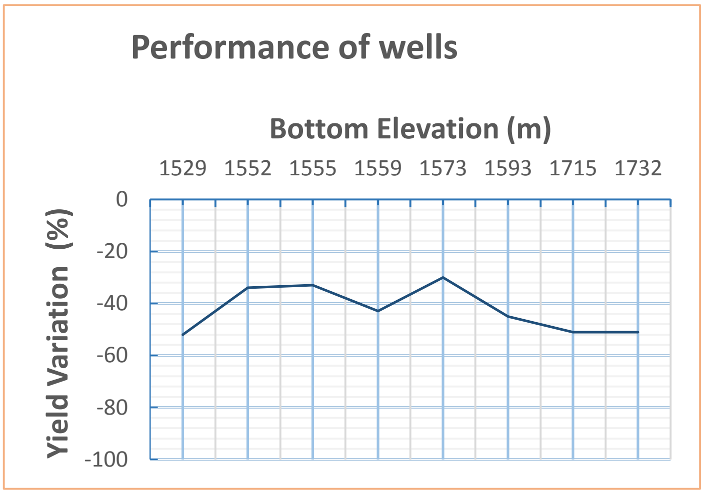

Figure 5: Wells under Sub-section Five

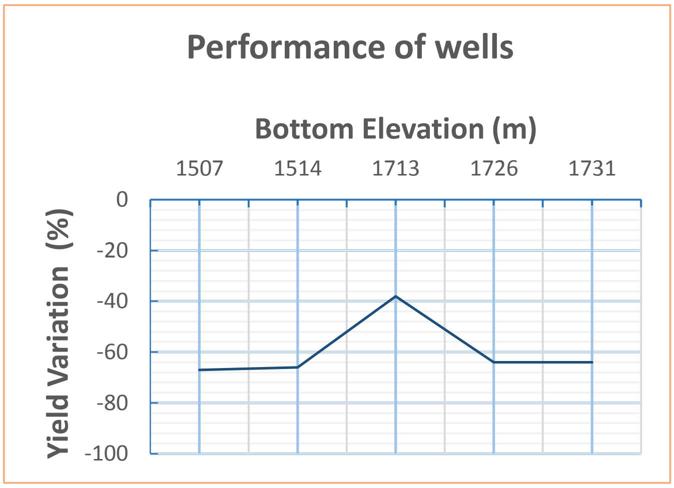

Figure 6: Wells under Sub-section Six

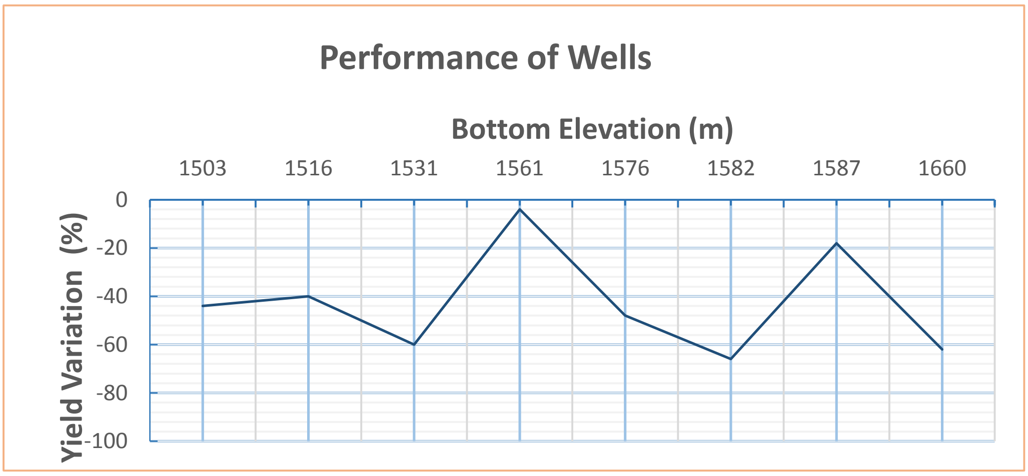

Figure 7: Wells under Sub-section Seven

Annex 6: Performance of study wells with respect to Screen Area

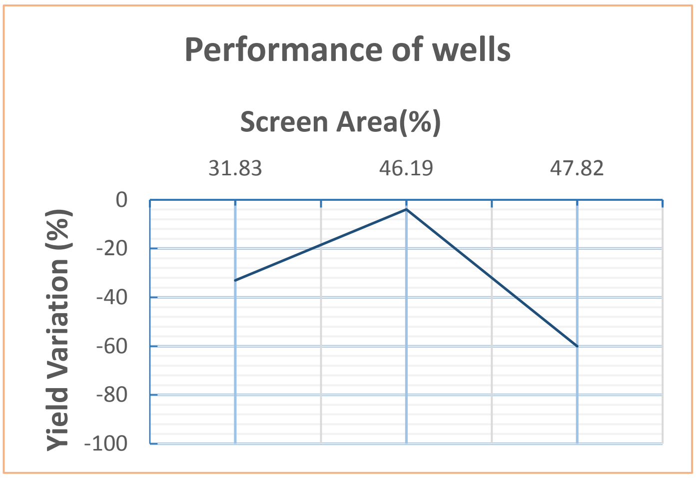

Figure 8: Wells under Sub-section One

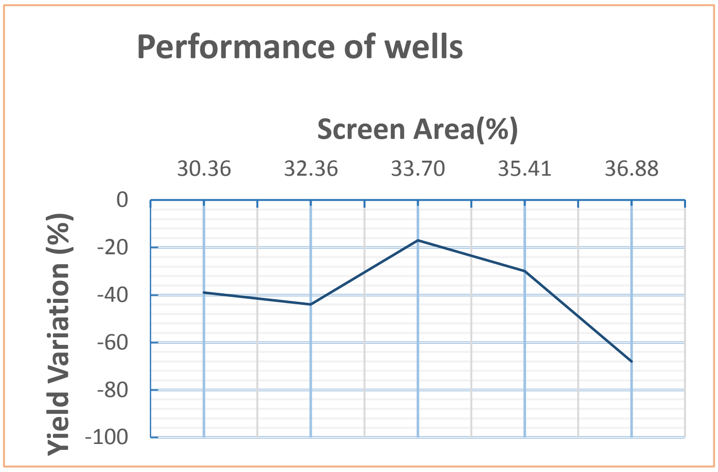

Figure 9: Wells under Sub-section Two

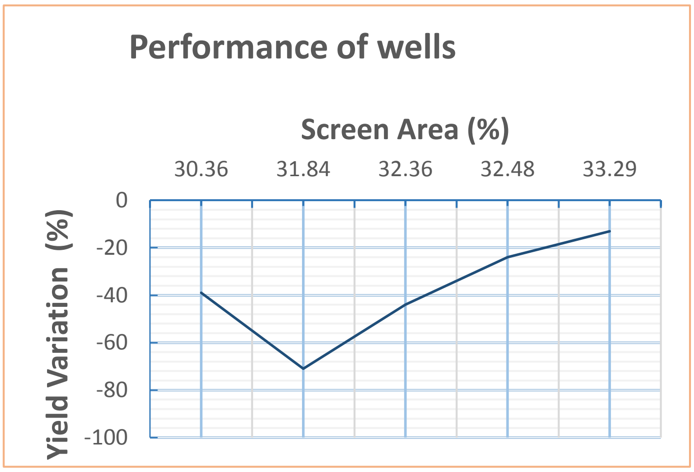

Figure 10: Wells under Sub-section Three

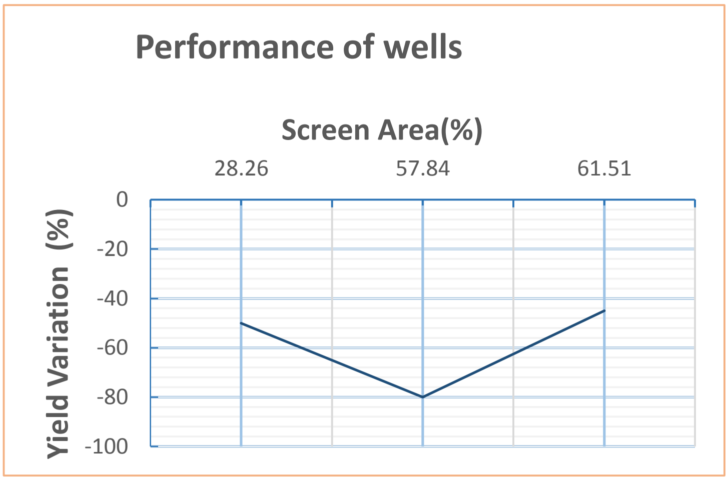

Figure 11: Wells under Sub-section Four

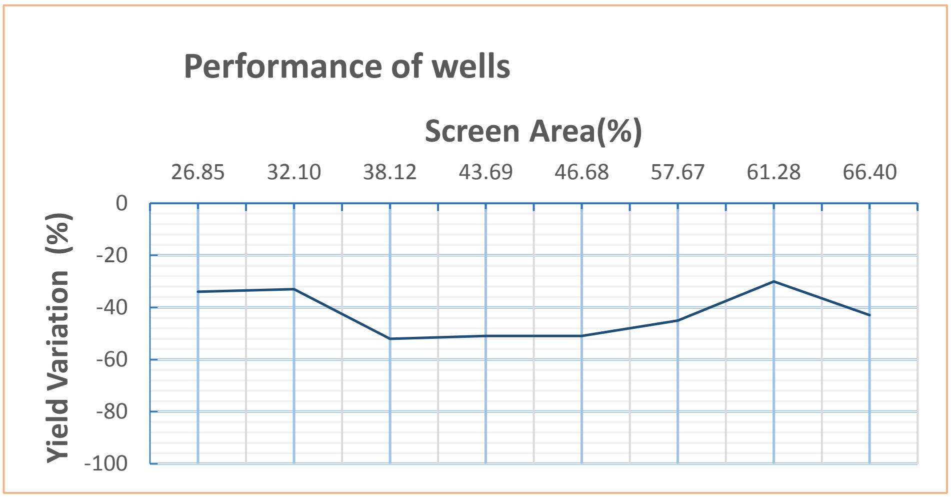

Figure 12: Wells under Sub-section Five

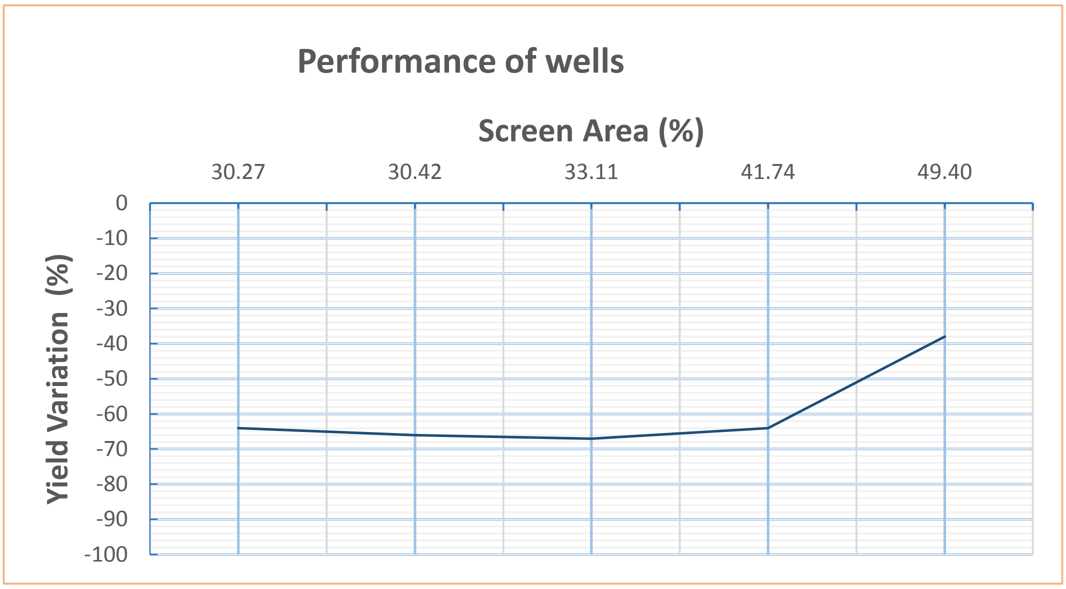

Figure 13: Wells under Sub-section Six

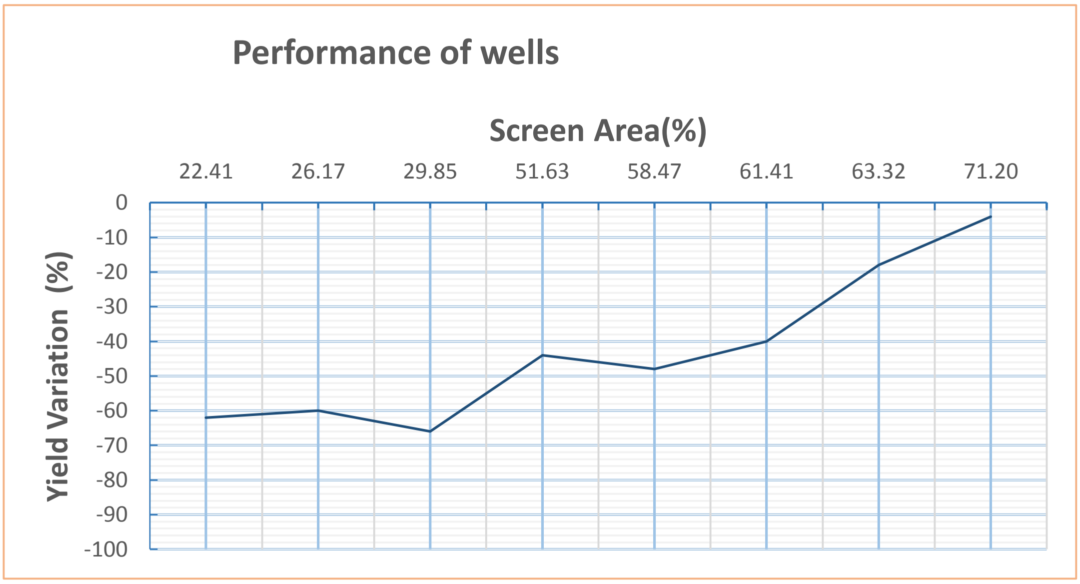

Figure 14: Wells under Sub-section Seven

Annex 7: Ideal operation hour of study wells for zero DD

Table 26: Sub-section one

Operation hour, hr *(s=0, Q = current pumping rate*)			
	BH-10R	**BH-13R**	**BH-14R**
BH-10R	**0.00**	0.36	0.24
BH-13R	5.70	**0.00**	3.61
BH-14R	4.58E-02	0.04	**0.00**

Table 27: Sub-section two

Operation hour, hr (*s=0, Q = current pumping rate*)					
	BH-1R	**SL-PW21**	**SL-PW18**	**BH-26R**	**BH-22R**
BH-1R	**0.00**	0.40	1.39	1.09	1.04
SL-PW21	0.25	**0.00**	0.48	1.53	1.68
SL-PW18	3.48	1.90	**0.00**	6.05	8.58
BH-26R	7.72	17.17	17.19	**0.00**	1.49
BH-22R	2.33	5.96	7.67	0.47	**0.00**

Table 28: Sub-section three

Operation hour, hr(*s=0, Q = current pumping rate*)					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**0.00**	4.61	6.16	10.24	11.88
SL-PW32	2.36	**0.00**	2.21	10.42	15.83
SL-PW18	1.35	0.95	**0.00**	1.90	5.49
SL-PW21	0.57	1.13	0.48	**0.00**	0.49
SL-PW30	0.14	0.37	0.30	0.11	**0.00**

Table 29: Sub-section Four

Operation hour, hr(*s=0, Q = current pumping rate*)			
	WF01-PW3	**WF01-PW2**	**SWAWF2(PW2')**
WF01-PW3	**0.00**	1.90	3.43
WF01-PW2	5.39	**0.00**	26.53
SWAWF2(PW2')	3E+01	92.39	**0.00**

Table 30: Sub-section Five

Operation hour, hr (*s=0, Q = current pumping rate*)								
	WF02-PW12	**WF02-PW5**	**WF02-PW6**	**WF02-PW8**	**WF02-PW10**	**WF02-PW11**	**WF02-PW13**	**WF02-PW14**
WF02-PW12	**0.00**	19.39	6.44	69.43	35.38	9.50	5.36	63.73
WF02-PW5	4.82	**0.00**	2.47	15.47	9.96	4.68	8.40	18.27
WF02-PW6	9.71	14.99	**0.00**	139.64	84.62	33.17	34.56	142.34
WF02-PW8	13.68	12.25	18.25	**0.00**	1.19	5.43	9.59	0.74
WF02-PW10	121.37	137.37	192.58	20.70	**0.00**	28.74	70.22	17.77
WF02-PW11	23.04	45.68	53.39	66.91	20.33	**0.00**	12.88	61.76
WF02-PW13	0.56	3.50	2.38	5.05	2.12	0.55	**0.00**	3.98
WF02-PW14	58.17	67.06	86.19	3.42	4.73	23.23	35.09	**0.00**

Table 31: Sub-section six

Operation hour, hr (*s=0, Q = current pumping rate*)					
	SL-PW-11	**SL-PW-12**	**SL-PW-13**	**WF02-PW7R**	**WF02-PW15**
SL-PW-11	**0.00**	1.72	1.21	5.50	9.06
SL-PW-12	7.79	**0.00**	25.87	32.44	16.77
SL-PW-13	0.75	3.55	**0.00**	4.61	10.33
WF02-PW7R	4.71	6.12	6.33	**0.00**	7.27
WF02-PW15	19.11	7.80	34.99	17.92	**0.00**

Table 32: Sub-section Seven

Operation hour, hr (*s=0, Q = current pumping rate*)								
	WF-01 PW-11	**SWAWF-4B**	**WF-01 PW-6**	**WF-01 PW-13**	**WF-01 PW-14**	**WF-01 PW-15**	**WF-01 PW-16**	**WE-01 PW-17**
WF-01 PW-11	**0.00**	180.31	88.07	37.41	146.36	73.50	129.95	277.24
SWAWF-4B	1.47	**0.00**	0.30	3.08	4.70	0.91	0.12	0.12
WF-01 PW-6	5.82	2.47	**0.00**	15.76	26.92	4.21	0.82	3.65
WF-01 PW-13	23.67	239.73	150.93	**0.00**	56.67	100.61	184.89	327.74
WF-01 PW-14	6.92	27.30	19.28	4.24	**0.00**	20.00	24.97	32.88
WF-01 PW-15	43.60	66.05	37.85	94.36	250.84	**0.00**	27.37	123.11
WF-01 PW-16	208.63	24.18	20.05	469.30	847.78	74.08	**0.00**	94.72
WE-01 PW-17	272.06	14.57	54.21	508.46	682.08	203.65	57.89	**0.00**

Annex 8: Ideal pumping rate of study wells for minimum DD

Table 33: Sub-section one

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)			
	BH-10R	**BH-13R**	**BH-14R**
BH-10R	**0.304**	1.605	1.444
BH-13R	0.002	**0.000**	0.001
BH-14R	0.026	0.026	**0.007**

Table 34: Sub-section two

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)					
	BH-1R	**SL-PW21**	**SL-PW18**	**BH-26R**	**BH-22R**
BH-1R	**0.002**	0.010	0.014	0.013	0.013
SL-PW21	0.013	**0.003**	0.015	0.021	0.022
SL-PW18	0.008	0.006	**0.001**	0.011	0.014
BH-26R	0.007	0.000	0.000	**0.000**	0.002
BH-22R	0.008	0.015	0.019	0.005	**0.001**

Table 35: Sub-section three

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)					
	SL-PW33	**SL-PW32**	**SL-PW18**	**SL-PW21**	**SL-PW30**
SL-PW33	**0.000**	0.002	0.003	0.004	0.005
SL-PW32	0.003	**0.000**	0.003	0.008	0.015
SL-PW18	0.005	0.005	**0.001**	0.006	0.010
SL-PW21	0.016	0.019	0.015	**0.003**	0.015
SL-PW30	0.054	0.067	0.063	0.051	**0.012**

Table 36: Sub-section four

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)			
	WF01-PW3	**WF01-PW2**	**SWAWF2(PW2')**
WF01-PW3	**0.000**	0.003	0.004
WF01-PW2	0.002	**0.000**	0.000
SWAWF2(PW2')	0.000	0.000	**0.000**

Table 37: Sub -section five

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)								
	WF02-PW12	**WF02-PW5**	**WF02-PW6**	**WF02-PW8**	**WF02-PW10**	**WF02-PW11**	**WF02-PW13**	**WF02-PW14**
WF02-PW12	**0.000**	0.027	0.004	0.000	0.000	0.006	0.004	0.000
WF02-PW5	0.015	**0.001**	0.010	0.053	0.026	0.014	0.022	0.085
WF02-PW6	0.004	0.008	**0.000**	0.000	0.000	0.000	0.000	0.000
WF02-PW8	0.052	0.044	0.107	**0.001**	0.010	0.020	0.032	0.008
WF02-PW10	0.000	0.000	0.000	0.011	**0.000**	0.000	0.000	0.006
WF02-PW11	0.059	0.000	0.000	0.000	0.014	**0.000**	0.004	0.000
WF02-PW13	0.015	0.029	0.024	0.036	0.023	0.015	**0.003**	0.031
WF02-PW14	0.000	0.000	0.000	0.003	0.004	0.195	0.000	**0.000**

Table 38: Sub-section six

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)					
	SL-PW-11	**SL-PW-12**	**SL-PW-13**	**WF02-PW7R**	**WF02-PW15**
SL-PW-11	**0.001**	0.004	0.003	0.006	0.009
SL-PW-12	0.002	**0.000**	0.000	0.000	0.029
SL-PW-13	0.005	0.010	**0.001**	0.012	0.034
WF02-PW7R	0.008	0.010	0.010	**0.001**	0.012
WF02-PW15	0.019	0.004	0.000	0.015	**0.000**

Table 39: Sub-section seven

Pumping Rate, Q,m3/min (*s=0.1, t = constant*)								
	WF-01 PW-11	**SWAWF -4B**	**WF-01 PW-6**	**WF-01 PW-13**	**WF-01 PW-14**	**WF-01 PW-15**	**WF-01 PW-16**	**WE-01 PW-17**
WF-01 PW-11	**8.81E-05**	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SWAWF -4B	0.072	**0.009**	0.045	0.100	0.130	0.061	0.037	0.037
WF-01 PW-6	0.016	0.0102	**0.001**	0.055	0.000	0.013	0.007	0.012
WF-01 PW-13	0.000	0.000	0.000	**0.000**	0.000	0.000	0.000	0.000
WF-01 PW-14	0.000	0.000	0.000	0.124	**0.002**	0.000	0.000	0.000
WF-01 PW-15	0.000	0.000	0.000	0.000	0.000	**0.000**	0.000	0.000
WF-01 PW-16	0.000	0.000	0.005	0.000	0.000	0.000	**0.000**	0.000
WE-01 PW-17	0.000	0.017	0.000	0.000	0.000	0.000	0.000	**0.000**