ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

ASSESSMENT OF WATER WELL DRILLING CHALLENGES IN ETHIOPIA

BY

GASHAW SIMENEH HAILEMARIAM

A thesis submitted to the School of Earth Sciences, graduate program, Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Sciences in Engineering Geological Sciences (Hydrogeology)

June 30/2018
Addis Ababa, Ethiopia

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Approved by the Examining Committee:

Head, School of Earth Sciences Signature Date

Advisor Signature Date

Examiner Signature Date

Examiner Signature Date

Declaration for Originality

I declare that this thesis is my original work for the requirement of master‘s degree accomplished under the supervision of Dr. Tilahun Azagegn, School of Earth Sciences, Addis Ababa University, during the year 2017/18. My further declaration is that this work has not been presented and/ or submitted to any other college, institution, or university for the award of any degree or diploma. All secondary data, sources and materials used in the thesis work have duly cited and acknowledged.

Gashaw Simeneh Hailemariam (MSc candidate)

Signature _______________ Date ______________

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Tilahun Azagegn (Advisor)

Signature _______________ Date______________

TABLE OF CONTENTS

Figures

Tables

Table 1. Frequency of drilling challenge among sampled wells

Annexes

216 sample collected field borehole data

Abstract

The purpose of this study is to identify the main water well drilling and completion problem and explore viable solutions, in Ethiopia. The scope is limited to literature review, data from private and governmental drilling and consulting companies, technical training institutions and discussion with senior drilling professionals.In general 216 selected boreholes with the typical drilling problem were identified throughout the country with their GPS coordinates, target drilling depth and aquifer type. Analysis was made to categorize which kind of structural and hydrogeological setting is most vulnerable for the recorded well drilling challenge. The most prevalent drilling problems happened in Ethiopia include Well caving, drillpipe stacking, lost circulation, hole deviation, drillpipe failures, hole cleaning and personnel and equipment related problems.

Among the problems investigated in this paper, the main Ethiopian rift valley and the Tana basin are the areas with highest frequency of drilling challenges are encountered. Among the drilling challenges, well caving stands out as the major drilling challenge with 26.3% of the total occurrence. The frequency of lithology also clearly showed that 45% of drilling problems happening in Fractured and weathered basalt aquifer. Moreover, discussions with chief drillers and hydro-geologists in the field also unveiled the most of the drillers operating in the field lack basic standard training on the drilling of boreholes with various methods of drilling, using appropriate drilling fluids and troubleshooting when the major drilling challenges encountered on the field.

Hence, water well drilling crew and supervising hydro-geologists must have a proper acquaintance with different kinds drilling system. Furthermore, typical drilling fluid consumables which are highly recommendable for drilling of wells in different geologic and structural settings must be identified and accepted by the clients. The water well drilling firms and their technical staffs must also be familiar and willing to apply drilling fluids and polymers in order to minimize the risk of abandoning and failure of borehole construction. Selection of quality casings and screens are also crucial to minimize drilling challenges such as casing and well collapse. The technical specifications of drilling projects must also incorporate consideration of local hydrogeology and geological structures to prepare well designs and to select drilling methods and consumables.

CHAPTER ONE
INTRODUCTION

1.1 Background

Drilling of water wells needs high investment cost, purchasing drilling machine tools, construction materials and employing of high skill man power. The Government of Ethiopia with the support of international bilateral and multilateral Aid agencies allocates huge amount of capital every year to fulfill the demand of water. Groundwater investigation and identification of the resource is also a big task and needs skilled man power and investment. For a successful completion of groundwater developments projects both feasibility study and water well construction management is mandatory.

According to the UN hydrogeological map of Africa (UNESCO, 2006), the hydrogeology of the volcanic rocks covering the great East African rift valley is classified as “the most complex and least understood”. This is due to the presence of variable groundwater flow patterns, chemistry, groundwater depths, occurrences, and discharge mechanisms. Hydraulic conductivity and water table depth vary significantly among water wells at only a few hundred meters distance from each other (TesfayeChernet, 1982). In addition, The geologyisoften heterogeneous due to different geological settings and tectonic movement. Furthermore, there is also largeshort fall in the number of well-trained drillers, sufficient drilling rigs and knowledge and willingness to use drilling fluids and consumables among the professionals. Reliable comprehensive statistics on ground water use in Ethiopia do not exist but there is very high dependence for domestic water supply, rural livelihood and livestock rearing, and increasingly for urban water supply. Although the distribution of aquifers is now reasonably mapped over large areas, quantitative information on aquifer characteristics recharge rates, ground water flow regimes abstraction rates and quality control is uneven and generally incomplete in Ethiopia. Every year at least hundreds of water wells are drilled. The occurrence of drilling and well completion problems are a day to day appearances. Causes of drilling problems vary from place to place depending on the hydro-geological and structural factors and the drilling methods.

Efforts made on this paper to reviewing of water well drillers note, well completion reports and discussion with senior hydro-geologists, chief drillers and drilling super-intendants, data collection of drilling challenges, Drilling history of boreholes in different regions and geologic settings of the country. This paper assesses the practical problems in water well drilling in Ethiopia in order to propose appropriate solution on the identified problems, point out different approaches which are believed would help to improve the prevailing conditions and assist in achieving future prospective i.e., lesser drilling and completion problems with decreasing abandoned wells and more safe and potable water supply to the community with more economic benefit with respect to time, cost, yield and sustainability of boreholes.

1.2 Objective

In light of the current theories and experience indicating the means and ends how to minimize the common drilling and well completion problems and thereby improving the results of drilled wells which would apparently maximize the amount of safe and clean potable water is the target of the study. To realize this objective effort has been made to scrutinizing the drilling and well completion problems through reviewing different literature’s. Besides, close examinations on actual field experiences have also been made to identify the causes of the problems in order to be in a better position to achieve the envisaged objective.

1.2.1 General Objective

General objective of this paper to identify the main water well drilling and completion problem and explore viable solutions, in Ethiopia

1.2.2 Specific Objective

The specific objective of this research is includes

- Identify the common drilling problems that have been occurring in the country
- Identify the major cause of each problem
- Describe the Geological and hydrological condition of the wells
- General considerations managing drilling and completion problems proper mitigating measures and solutions to minimize the risk

1.3 Scope of the study

The paper will attempt to address the practice of well drilling and development including well designing, methods of drilling and concept of drilling fluids and capacity of the drillers and site supervising Engineers in Ethiopia that may be resulted due to different geological, hydrogeological and structural conditions, topographic settings, and manmade problems.

The scope of the study is limited to literature review, information from technical training institutions such Ethiopian Water technology Institute, discussion with senior hydro-geologists, supervising geologist, drillers and Governmental and private water well drilling companies and consultant. The researcher's self-experience and testimonials also included in the identification of the problems and propose appropriate solutions based on the findings.

1.4 Methodology

The research on drilling problems basically should be focused on well drilling completion reports, however many daily drilling notes, published and unpublished reports could not able to reflect the actual drilling challenges, cause of the problems and the mitigation measured on the. Hence the methodology focused on the following:

- Gathering of data from previous publication research and literatures made specifically in the drilling challenges and also review case studies
- Data collection from governmental and private drilling companies, from water technology institute on drilling challenges encountered from different regions of the country.
- Discussion with senior drilling super intendants, Hydro-geologists and chief drillers and review their daily drilling reports
- Data processing and analyze using special geo-statistics software proper data manipulation and summarize to generate important information
- Identification and correlating field borehole data including location, depth and lithology with possible drilling challenge using Arc GIS software.

1.5 Literature Review

Literature review showed that, only little effort, have been made to identify the water well drilling challenges and the mitigation measures in Ethiopia. AbebeG.Hiwot in his case study submitted on 25th WEDC conference for integrated development of water supply and Sanitation showed major causes of borehole drilling challenges in Ethiopia. Msc Thesis done by Tesfaye&Eleni also showed the challenges on drilling and pumping test in the sector.

Furthermore, Getachew,2004 showed the crucial benefits for proper Borehole designs and drilling technology for better prediction of drilling depth and access to advances in drilling technology and the need for the technical staffs such as drillers and supervising engineers training by focusing on extending access to relevant stakeholders and the private sector.

According to Carter et al, 2003, Wells should be designed so that they are *fit for their intended purpose.* This means that the diameter, depth, casing type and backfill materials, screen open area and other design features should be well-matched to need specifically water demand, longevity, hydraulic efficiency and cost of the project. Furthermore, Danert et al. 2007, mentioned on the article paper, cost effectiveness of borehole in sub-

Saharan African countries unveiled that cost of drilling well in Africa is higher than India.

SeifuKebede 2013, on his book ground water in Ethiopia mentioned the history, occurrence, development and storage of ground water potential in regions and basins including aquifer types and classifications. Furthermore, in Africa ground water Atlas, SeifuKebede et.al. 2018, mentioned briefly the hydrogeology of Ethiopia with aquifer type classification and occurrence.

Wogayehu 2017, in his Msc. Thesis showed the drilling challenges and possible geologic and technical solution focusing on Tana basin and its surrounding area.

1.6 Statement of the problem

Water well drilling is a disruptive process. Reactive and non-reactive, fractures, cavities, loose, hard, permeable and semi-permeable formations can be encountered. Water-based drilling fluids are the predominant circulating medium used in the drilling industries. Well design and maintenance of the drilling fluid system is critical to borehole stability and success. Contaminants can also be encountered in the sub-surface. The single largest contaminants are the drilled cuttings produced by the drilling process itself.

The study paid modest attention to the problems in groundwater resource development mainly to the common challenges in water well construction and well completion activities. In the drilling world the huge challenge is the nature of the job itself. Thus, the major problem emanates from the nature of the job. Due to lack of necessary data base and skillful management, do not know the deep knowledge about the kind of drilling method proposed and the proper and quality consumables such as drilling fluids and well casings.

Due to such reasons many drilling projects either failed or serve the beneficiaries for short period of time. Moreover, the well designs mostly did not consider the specific characteristics of local geology and hydrogeology. The problems enhanced by inexperienced technical performances of the well drillers and their supervisors are also notable.

The number of abandoned and short lived wells due to the above noted problems is increasing from time to time and it is believed to aggravate the overall delivery of potable water supply in Ethiopia.

It is almost certain that problems will occur while drilling a well, even in very carefully planned wells. For example, in areas in which similar drilling practices are used, hole problems may have been reported where no such problems existed previously because formations are both geologically, hydro geologically and structurally heterogeneous. Therefore, two wells near each other may have totally different hydrogeological and structural conditions.

In well planning, the key to achieving objectives successfully is to design drilling programs on the basis of anticipation of potential hole problems rather than on caution and containment. Understanding and anticipating drilling problems, understanding their causes, and planning solutions are necessary for overall-well-cost control and for successfully reaching the target depth. This chapter addresses major water well drilling challenges in Ethiopia based on the actual field observation and experiences, with possible solutions, and, in some cases, preventive measures.

Drilling problems depending on the actual site condition can be very costly. In general, towards the main Ethiopian rift valley system well drilling becoming more and more challenging. As the one drill deeper the formation becomes loose and in some instances hydrothermal water encountered. The most prevalent drilling problems happened in Ethiopia include pipe sticking, lost circulation, hole deviation, pipe failures, borehole instability, mud contamination, formation damage, hole cleaning and personnel and machinery related problems.

CHAPTER TWO

2. Ethiopian Geology

The Geological units in Ethiopia fall into one of the following three major categories: Precambrian Basement, Late Paleozoic to early Tertiary sediments and Cenozoic volcanic and associated sedimentary rocks. In a generalized summary the extent of coverage of the different rock groups may be presented as follows. Precambrian rocks with associated intrusives occupy some 23% of the total surface area, Paleozoic and Mesozoic sediments 25% Cenozoic sedimentary rocks 20% and Cenozoic volcanic rocks 32% (Tesfaye, 1993)

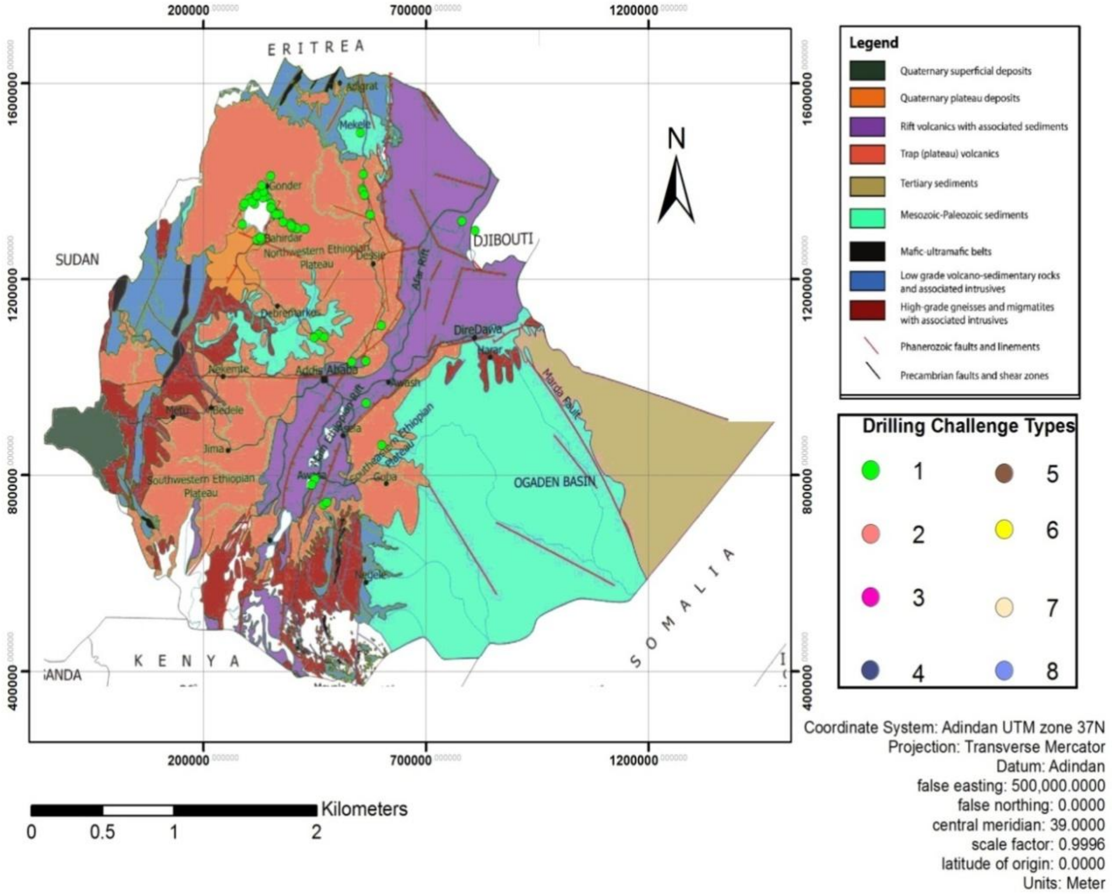


Figure 1- Modified Geological Map of Ethiopia. (Geological Survey of Ethiopia, EIGS)

The following section provides summary of Ethiopian geology (Kebede et.al 2018):

2.1 Igneous- volcanic Geologic Environment

Rift volcanic,extends through Ethiopia and dying out in Mozambique. Rift related consolidated and unwedded pyroclastic deposits and basalts. The major compositions are volcanic ash, pumice, ignimbrite and pyroclastic deposits. Multiple sets of tectonic structures such as faults, fractures, volcanic landforms, isolated volcanoes and cones, calderas and craters are found richly. (Kebede, 2018)

Plateau basalts, It is mostly vesicular and scoraceous basalt with a limited extent laterally. Volcanic center on the plateau associated with central eruptions and mainly associated with shields. (Seifu Kebede, 2018)

Shield volcanics, Minor acid volcanic rocks such as Trachytes and Rhyolites intercalated with Basalt having a wider based shields dotting the plateau of Ethiopian. (Seifu Kebede, 2018)

Upper and Lower Basalts,are typical transitional basalts, very homogenous in composition. They are generally aphyric and compact in places showing clear stratification and contain rare basic tuffs (Kazmin et al., 1980; Kazmin, 1979)

2.2 Sedimentary- Geologic Environment

It is largely consolidated and associated unconsolidated sediments. Alluvial sediments namely fluvial deposits, diatomites, red beds, and paleosols.Alluvio-lacustrine sediments, river terraces, volcano clastics, colluvial and delta formed sediments, elluvials and soils. In Central, southern and north western Ethiopia localized sediment deposits are richly found. (Seifu Kebede, 2018)

Carbonate, Evaporite and Sandstone rocks,Interbedded limestone, evaporite and shale and karst features are observed as an important structural feature. Detrital, poorly cemented sandstone also formed having poor surface drainage and plain forming extends south up to Mokadishu in Somalia. Limestone dominantly with shale, marl and gypsum intercalations.horizontally bedded and characterized by karst features. (Seifu Kebede, 2018)

Upper & lower Sandstone ,Highly cemented , the top part has been transformed higher temperature generated by Cenozoic volcanism. The thickness is estimated around 700 meter. (Seifu,Kebede, 2018)

2.3 Precambrian/ Orogenic belt

In south and western Ethiopia, Metamorphosed sediments, gneiss and tectonic granites are richly found. High grade metamorphic rocks are interbedded with low grade metamorphosed rock generally.

In northern part of the country, low grade Arabian Nubian shield with low grade transition zone volcano sedimentary succession. Mafic and ultra mafic complexes also found in the region. metamorphosed volcanic sedimentary rocks and post tectonic granite intrusive igneous rocks are richly found. (SeifuKebede, 2018)

CHAPTER THREE

3. Hydrogeology of Ethiopia

The most important aquifers in Ethiopia are formed by unconsolidated sediments; volcanic rocks; and consolidated sedimentary rocks. Basement aquifers are also important locally. (Kebede, 2018)

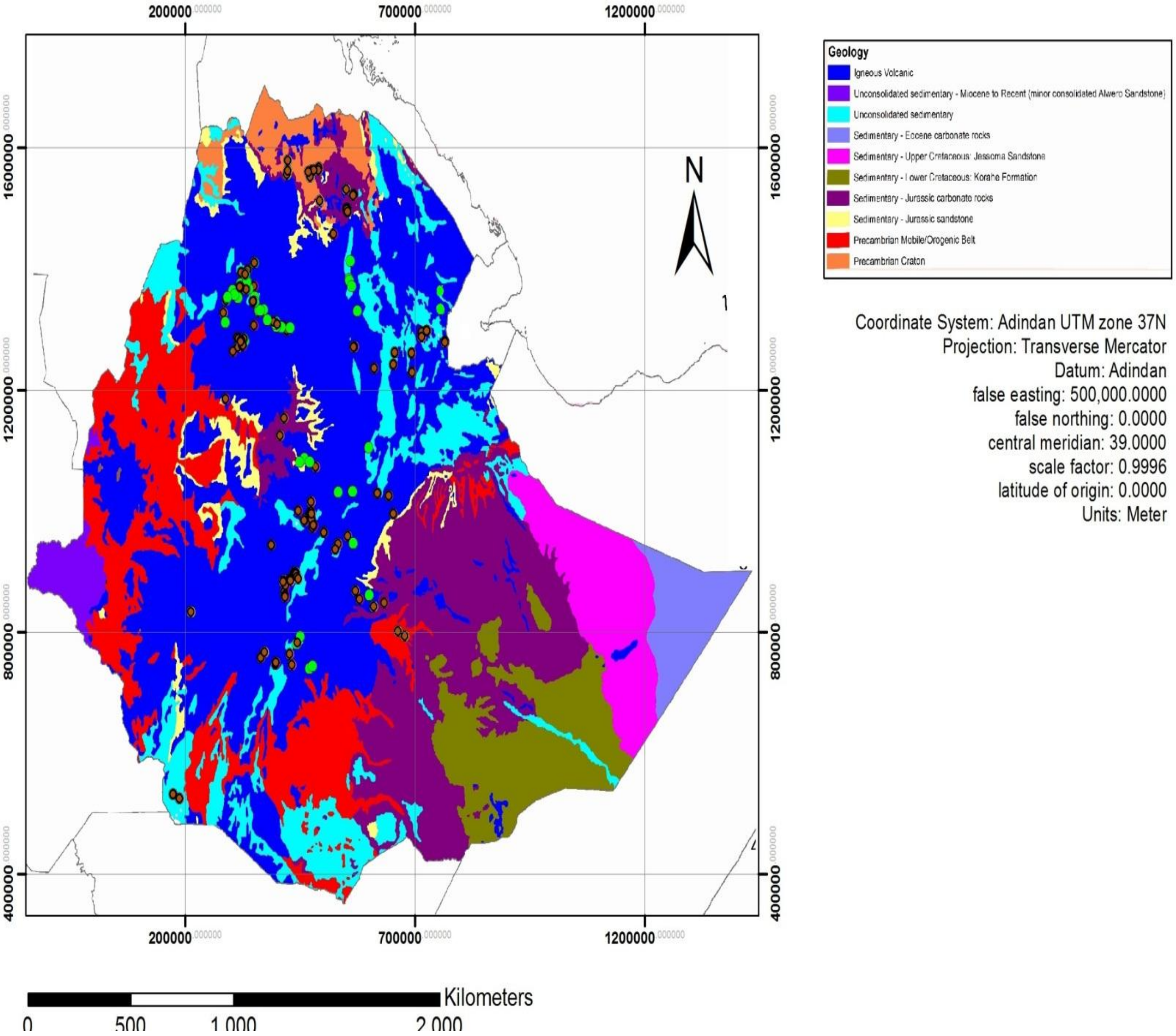


Figure 2- Modified Hydro- Geological Map of Ethiopia

3.1 Unconsolidated Aquifers in Ethiopia

Alluvial Deposits, in Afar has higher yield, in floodplains, have moderate to high permeability, with measured transmissivity from 1-500 m^2/day and having a discharge upto 20 lit/sec. These aquifers can be both confined and unconfined; the thickness ranges from 0 - 400 meters; salinity is very variable. However, Alluvial deposit in northern Ethiopia has a relatively low yield. Overlying basement rocks can store a good amount of water and have characteristics of high permeability and water infiltration capability. Typically are shallow in depth and have laterally limited extent, and form perched aquifers. Manual hand dug wells and flowing springs are common. (Seifu Kebede, 2018)

Alluvio-lacustrine sediments, are permeable with high variability. Deposits of Fine sand have the highest permeability. Higher transmissivities have been noted in several places. These aquifers can also be both confined and unconfined.

Alluvial Aquifers within Lake Tana basin, occurs richly in the eastern part of the basin following the lower margin and rib of Fogera and Gumera plain. They also cover a significant area of the north part of the basin at the lower part of the Megech and Western shore of Lake Tana. The intergranular permeability of the consolidated gravels, sand and clay controlled the yield of this. They are typically have high yield aquifers.

Wadi bed aquifers, Although it is localized, these intergranular aquifers have substantial potential of ground water in water scarce desert and arid settings. Wadi bed extends 30 000 km across the country, and total groundwater reserve in these aquifers could be as much as 3 billion M3. The most significant wadi aquifers, found in Ogaden, Lower Omo, Borena, in the Afar depression and the Western Lowlands bordering Sudan. The most dynamic wadi bed aquifers are those dominated by gravelly and sandy sediment deposits with a low proportion of clay.

3.2. Igneous Volcanic Aquifers in Ethiopia

Rift volcanics, have low productivity with low borehole discharge, from 1 to 5 lit/sec. In some cases the aquifer is found to be confined, leading to artesian well with low borehole discharge and high salinity and fluoride content.(Seifu Kebede, 2018)

Plateau basalts' most extensive existence is in the Lake Tana Basin, where these form a highly productive, fractured aquifer, with borehole discharge reaching 20 l/s, and groundwater discharge to springs and rivers. The Quaternary volcanics in other part of the country are highly productive but have dual fracture-intergranular porosity.(Seifu Kebede, 2018)

Shield volcanics, aquifer can reach up to 500 m thick. Groundwater discharge happens through springs, which are common at the foot of the shield of volcanics. The intercalation of basalt with volcanic ash forms a ground water system with dual porosity and permeability. Groundwater storage is focused in ash layers, while groundwater flow is focused through fractured layer of basalt. Acidic volcanic rocks show lower groundwater potential in the areas dominated by Shield volcano. The aquifer is naturally semi-confined to unconfined. The depth of water table ranges from 5 to 60 m, and well depths are typically 60 to 150 metres.(Seifu Kebede, 2018)

Upper and Lower basalt aquifer forms the most productive of the volcanic aquifers in the country of Ethiopia. It is normally semi-confined to unconfined and often found to be artesian wells. Groundwater discharge occurs to springs and to wetlands on cliffs. The average thickness of aquiver ranges 50 to 1000 m. The depth to water table varies from 0 to 250 metres. Borehole discharges reach up to 20 l/s. These rocks are characterized by uneven topography with dissected and irregular morphology. The rocks are deformed, and in their northern section dip at up to 40°. They are thinly bedded, and in several areas are brecciated. Field evidence shows that the brecciated parts are characterized by lower permeability. The rocks are normally highly weathered, found red in colour and have low permeability in general. Both primary (vesicle) porosity and secondary (fracture) porosity have been modified and reduced by secondary mineralization such as by calcite, zeolite and silica.(Seifu Kebede, 2018)

3.3 Consolidated sedimentary Aquifers with fracture and Intergranular flow

These aquifers characterized by karst features, including caves. The limestones of the Sofomar caves region have the highest degree of karstification of Ethiopia's carbonate rocks. The aquifer has moderate productivity and permeability. Evidence from water wells in midland and highlands areas, where the aquifer crops out, shows that groundwater levels can be deeper. Where the water table is shallower, it forms relatively high yield aquifers. In general, these aquifers are typically 500 to 1000 m thick, and are semi-confined to unconfined. (Seifu Kebede, 2018)

The highly cemented sandstone named Adigrat formation has low primary porosity, and the top part has been transformed by heating volcano. Fracturing has created secondary porosity and permeability. The emergence of springs at the contact of the sandstone and the overlying volcanic rocks is indicative of the low permeability of the formation.This aquifer is normally 200 to 1000 m thick and is semi-confined to unconfined. (Seifu Kebede, 2018)

Karst is a geomorphologic name of landscape shaped by the dissolution of layers of soluble bedrocks usually limestone, carbonates or dolomites. It can also be developed in sandstones, evaporates, Marbles, and volcanic rocks. Karistified rocks occur in three regions, including, the north eastern plateau-Ogaden, Mekele region and the Blue Nile gorge and the Afar depression. (Seifu Kebede 2013)

3.4 Precambrian basements in Ethiopia

The productivity of basement aquifers in Ethiopia largely depends of the development of weathered rock or regolith amid the density of fractures. In turn, these are partly controlled by the grade or type of metamorphic rock formation that forms the basement. Less important controls on groundwater existence are the recharge of sustainability and topography. Groundwater in the basement aquifers found in shallow regolith or weathered rock basins.

Borehole yields from the most productive boreholes in basement aquifers are generally less than 0.1 lit/sec. Basement aquifers in western and south-central parts of Ethiopia are productive, and the lowest productivity basement aquifers are found in the Borena lowlands near the border of Kenya and northern Ethiopia. The basement aquifers are unconfined. Aquifer (regolith) thickness varies from 0 to 60 m, thinner in northern Ethiopia and thicker in western Ethiopia.(Seifu Kebede, 2018)

The basement rocks of Northern Ethiopia have low groundwater potential. Groundwater occurs generally in fractures in the upper few metres of the unweathered rocks; in very thin regolith layers; and in patches of overlying alluvial sediments in river valleys.(Seifu Kebede, 2018)

Groundwater in the basement rocks is stored in, and transmitted through, both regolith layers and fractures. There is variable fracturing and regolith development. Borehole yields range from 0.13 to 0.33 l/s.

The crystalline basement aquifers of Western Ethiopia have better groundwater storage than in other areas. This higher groundwater potential is related to high rainfall that supports high recharge; to a relatively thick regolith which favours groundwater storage; and to rugged undulating topography which favours accumulation of weathering products in depressions and flat plains allowing groundwater storage and circulation.(Seifu Kebede, 2018)

CHAPTER FOUR

4 Major Drilling Challenge

Water well drilling problems occurred depending on the actual hydro-geologic and structural settings of specific water well drilling site conditions. In general, towards the main Ethiopian rift valley system, water well drilling becoming more and more complicated and challenging. Furthermore as the drilling depth is increased the formation becomes loose and fractured and in some instances hydrothermal water encountered and the drilling task will be complicated.

The most prevalent drilling challenges happened and recorded in Ethiopia include, Borehole instability or well caving, Drill pipe stacking, Circulation loss, drill pipe broken and failure, hole deviation, casing and well collapse, mud contamination, personnel and equipment related problems.

4.1 Borehole Instability/Well caving

Borehole instability is the adverse condition of an open borehole interval that does not maintain its gauge shape and size and/or its structural integrity. The major causes are, mechanical failure, caused by in-situ stresses, and chemicals caused by interaction of borehole fluid with the geologic formation and erosion triggered by fluid circulation. (Larry, 2006)

Mechanical Rock-Failure Mechanisms: Mechanical borehole failure encountered when the stress acting on the rock surpasses the compressive or the tensile strength of the rock. Shear stresses as a result of low mud weight causes compressive failure, while normal stresses as a result of excessive mud weight bring tensile failure.

In order to forecast the borehole-instability challenges the failure criteria are served as the optimum-normal-stress criterion for tensile failure and the supreme strain energy of distortion criterion for compressive failure. In the maximum-normal-stress criterion, failure is said to happen when, under the action of collective stresses, one of the acting principal stresses reaches the failure value of the rock tensile strength. In the optimum of energy distortion criterion, under the action of combined stresses, failure is said to happen when the energy of distortion reaches the same energy of failure of the drilled rock under pure tension. (Larry, 2006)

Mechanical Instability can occur because the in-situ stress state of equilibrium has been disturbed after drilling. The mud in use with a certain density may not bring the transformed stresses to the original state; therefore, shale and other metamorphosed rocks such as schist and slate may become mechanically instable while the borehole is being drilled.

Chemical Instability. Chemical-induced shale instability is produced by the drilling-fluid/shale interaction, which changes the shale pore pressure in the vicinity of the borehole walls as well as shale mechanical strength. The mechanisms that contribute to these challenges are: osmotic and capillary pressure diffusion in the vicinity of the borehole walls, and borehole-fluid invasion into the shale when borehole drilling overbalanced (Larry, 2006).

> The most difficult formation to drill is shale. Depending on mud weight and mud composition, shale can slough in or plastically flow inward, which can cause mechanical pipe stacking. In almost all lithology types, the application of little drilling mud in quantity can lead to the collapse of the borehole, which can ultimately issue mechanical pipe stacking. Also, when drilling through anhydrite rich area such as Afdera, in Afar region it can exhibit plastic behavior under overburden pressure, if mud weight is not high enough. The anhydrite rich rock has the trend of flowing inward, which causes mechanical pipe stacking. Indications of a potential pipe-stacking problem caused by borehole instability are a rise in drill pipe pressure circulation, an increase in torque, and, rarely, no fluid return to the surface.

Principles of Borehole Instability

Before the drilling activity started, the in-situ rock stresses at some depth are in equilibrium with the strength of the rock. While a borehole is being drilled, however, the balance between the rock strength and the in-situ stresses is disturbed. Moreover, foreign fluids are introduced, and an interaction process begins between the borehole fluids and the geologic formation.

Borehole-Instability Prevention

Total prevention of borehole instability is unrealistic because restoring the chemical and physical in-situ situations of the rock is impossible. However, the drilling engineer or the supervising Hydrogeologist can mitigate the problems of borehole instabilities by adhering to good field practices. These practices include selection of site specific drilling method, proper mud-weight selection and maintenance especially for direct mud rotary and reverse circulation drilling system, proper borehole-trajectory selection, and the use of borehole fluid such as Bentonite, foam, polymers additives and water compatible with the formation being drilled will minimize the risk of well caving and borehole instability.

4.2 Drill Pipe Stacking

During drilling operations, a drill pipe is considered stuck if it cannot be freed and pulled out of the hole without damaging the drillpipe and without exceeding the drilling rig’s maximum allowed hook load and pull back capacity. In this section among the common drill pipe stacking problems occurred in Ethiopia, differential pressure pipe stacking and mechanical pipe stacking problems are discussed. (Larry, 2006)

Differential-Pressure Pipe Stacking:occurs when a portion of the drill string becomes embedded in a mud cake or an impermeable film of fine drilled cuttings. It also formed on the wall of a permeable formation primarily on fractured and weathered part of the rock units during drilling. The drillpipe is said to be differentially stuck, if the mud pressure, which acts on the outside wall of the drillpipe, is greater than the formation-fluid pressure, which generally is the case with the exception of underbalanced drilling. The differential pressure acting on the portion of the drill pipe that is embedded in the mud cake can be expressed as some of the indicators of differential-pressure-stuck drillpipe while drilling permeable zones or known depleted-pressure zones are increased in torque and drag; an inability to interchange the drill string and, in some cases, to rotate it; and uninterrupted drilling-fluid circulation. Differential-pressure drillpipe stacking can be prevented or at least its occurrence mitigated if some or all of the following precautions are taken:

- Supervise and maintain the lowest constant fluid loss adhering to the borehole drilling system.
- Maintain the lowest level of drilled cuttings in the mud system, or, if economical, eliminate all drilled cuttings as much as possible.
- Select a good quality bentonite mud with relevant polymer system that will yield smooth mud cake having a low coefficient of friction.
- Maintain drill string rotation at all times, if possible.

Mechanical Pipe Stacking: **caused by inadequate removal of drilled cuttings from the annulus; borehole instabilities, such as hole caving and collapse. This is prominent in plastic clay and anhydrite rich rock formation units found in different parts of the country Ethiopia.**

For example, Danakil depression, and Afdera area, in Afar Regional state.

*Drilled Cuttings are e***xcessive accumulation of mud or drilled rocks mixed with drilling fluids in the annular space caused by improper and inadequate cleaning of the borehole. This can cause mechanical drillpipe stacking. The settling of a large amount of suspended cuttings to the bottom when the drilling section cylinder pump is shut down causes drillpipe stacking. Increases in torque or drag and sometimes in circulating drill pipe pressure are indications of large accumulations of cuttings in the annulus and of potential drillpipe-stacking problems. The rock strength at some depth should be in equilibrium with the in-situ rock stresses before borehole drilling started, while a well is being drilled, however, the balance between the in-situ stresses and the rock strength will eventually be disturbed. In addition, foreign fluids are introduced, and an interaction process begins between the formation and borehole fluids.(Larry, 2006)**

4.3 Loss of circulation

Loss of circulation is defined as the uncontrolled flow of mud into a drilled rock formation, sometimes referred to as thief zone. In general loss of circulation can be classified in three subsequent stages based on the seriousness of its risk. (Larry, 2006)

Seepage loss is a condition when the mud volume loses into formation at very minimal rate and this will have no or little effect for a water well drilling operation.

Partial loss is a condition when some volume of drilling fluid (Bentonite mixed with water) loses into the well and the drillers get some drilling mud volume back on the surface. In partial lost circulation, mud continues to flow to surface with some loss to the formation. However, this type of fluid loss will not lead to well control situation because the total hydrostatic pressure does not decrease.

Total loss is the worst condition with highest consequence of bringing other problems. Because there is no mud returning back to surface and the mud level will drop to any level down hole. Losing a lot of fluid into the well will directly affect hydrostatic pressure at the bottom. Total lost circulation, occurs when all the mud flows into a formation with no return to surface. If drilling continues during total lost circulation, it is referred to as blind drilling. This can be very dangerous and can cause permanent pipe stuck, well collapse and loss of drilling accessories and tools (Larry, 2006).

Zones of circulation loss and Its Causes

Geologic drilled formations that are inherently having a nature of volcanic fractured rocks such as basalt, rhyolite, ignimbrite and trachyte found in the central part of Ethiopia and, cavernous and Karst formation found in the Eastern part of the country having high permeability and discharge have higher potential zones for loss of circulation. Furthermore, under certain improper drilling conditions, induced fractures can also become another source for potential zones of lost circulation. In addition, excessive mud weight and improper annular hole cleaning can cause loss of circulation.

Prevention of Lost Circulation

The complete prevention of lost circulation is impossible because of the nature of some geologic formations, such as inherently fractured, cavernous, or high-permeability zones of aquifers are not avoidable, in order to reach the targeted depth of wells. However, limiting and minimizing circulation loss is possible if certain safety measures are taken, especially those related to weathered and fractured and Karst rock formations. If lost-circulation zones are anticipated, preventive measures should be taken by the following precautions include:

- Applying and treating the mud with lost-circulation materials such as relevant drilling fluids such as bentonite, drilling foam and recommended type polymers.
- Maintaining proper mud weight,
- Minimizing annular-friction pressure losses during drilling
- Adequate borehole cleaning,
- Installing temporary surface casing to protect collapse from upper weaker rock formations within a transition lithologic layer zone,
- Updating formation pore pressure and fracture gradients for better accuracy with lithologic well log and well drilling data.

Remedial Measures

When loss of circulation happens, sealing the zone with proper type of drilling fluid namely sealant polymers is necessary unless the geological conditions allow blind drilling, which is unlikely in most cases. The common drilling fluid polymers that generally are mixed with the Bentonite mud to seal loss zones may be grouped as fibrous, flaked, granular, and a combination of fibrous, flaked, and granular materials. These materials are available in course, medium, and fine grades for an attempt to seal low-to-moderate lost-circulation zones. In the case of severe lost circulations, the use of various plugs to seal the zone becomes mandatory. It is important, however, to know the location of the lost-circulation zone before setting a plug.

4.4 Borehole Deviation

It is the unintentional departure of the drillpipe with drill bit from a preselected borehole route. Whether drilling curved-hole section or straight the inclination of the bit to walk away from the anticipated path can lead to higher drilling costs and will create a huge problem to install permanent productive well casings and ease-boundary legal problems especially in industrial and urban areas. (Larry,W.L.2006)

The cause of hole deviation is not exactly known however, generally the drilling professionals agreed that one or a combination of several of the following factors may be responsible for the deviation:

- Heterogeneous nature of formation and dip angle.
- The drilling string characteristics, material made etc…
- Absence of drilling Stabilizers (location, number, and clearances).
- Total applied weight on the bit and the target drilling depth
- The instability and loose surface condition of drilling sites
- Hole-inclination angle from vertical.
- Drill-bit type and its basic mechanical design.
- Improper borehole cleaning and development of wells

It is also known that some resultant force acting on a drill bit causes hole deviation to occur. The mechanics of this resultant force is complex and is governed mainly by the mechanics of the bottom hole assembly (BHA), rock/bit interaction, bit operating conditions, and, to some lesser extent, by the drilling-fluid hydraulics. The forces imparted to the drill bit because of the bottom hole assembly are directly related to the makeup of the assemble such as, stiffness, stabilizers, and reamers. The buckled shape of a given designed bottom hole assembly depends on the amount of applied Weight on bit. The significance of the bottom hole assembly buckling is that it causes the axis of the drill bit to misalign with the axis of the intended borehole track, thus causing the deviation. Pipe stiffness and length and the number of stabilizers, that is, their location and clearances from the wall of the wellbore are two major parameters that govern bottom hole assembly buckling behavior. The contribution of the rock/bit interaction to bit deviating forces is governed by rock properties such as bedding or dip angle, cohesive strength, internal friction angle and drill-bit design features such as bit size, tooth angle, bit type.

The mechanics of rock and bit interaction in general is a very complex topic and it is the least understood in regard to borehole deviation complications. Fortunately, the initiation of down hole measurement while drilling tools that allow monitoring the advance of the drill bit along the desired path makes our lack of understanding of the mechanics of borehole deviation more acceptable.

4.5 Drill pipe broken/Failures

Drill pipe broken or failures can be put into one of the following categories:

- Twist off caused by excessive torque;
- Drill pipe parting because of excessive tension;
- Drill pipe burst or collapse because of excessive external or internal pressure;
- Exhaustion as a result of mechanical cyclic loads with or without corrosion.

Drill Pipe broken or failure as a result of twist off occurs when the induced shearing stress caused by high torque surpasses the drillpipe-material ultimate shear stress. In general, excessive torques are not encountered under normal drilling practices in vertical water well drilling. Excessive torque can easily cause twist off to improperly selected drill string components. Also when the induced tensile stress exceeds the drillpipe-material ultimate tensile stress drillpipe breakage might be happened. This condition may arise when drillpipe stacking occurs, and an over pull is applied in addition to the effective weight of suspended pipe inside borehole above the stuck point (Larry,2006). This phenomenon common in urban water supply projects such as deep borehole drilling in Akaki well fields and some suburb of Addis Ababa where the drilling depth reached up to 500 meter depth and above.

Pipe breakage or failure as a result of collapse or burst is rare; however, under extreme conditions of high mud weight and complete loss of circulation, drillpipe might be burst. This is common in Main Ethiopian rift valley where the areas are rich in un-welded and welded pyroclastic, ash, pumice alluvial and reworked materials of quaternary rift volcanics.

Drill Pipe-Failure/Breakage Prevention

Although pipe failure cannot be eliminated totally, there are certain measures that can be taken to minimize it. Fatigue failures can be mitigated by diminishing induced cyclic stresses and insuring a noncorrosive environment during the drilling operations. Cyclic stresses can be reduced by controlling dogleg severity and drill string vibrations. Corrosion can be mitigated by corrosive scavengers and controlling the mud pH in the presence of H_2S. The proper handling and inspection of the drill string on a routine basis are the best measures to prevent drill pipe failures and breakage (Larry, 2006).

4.6 Mud Contamination

A mud is said to be contaminated when a foreign material such as undesired drilled cuttings joins the mud system and causes undesirable changes in mud properties, such as viscosity, density and filtration capacity. Water-based mud systems, in general, are highly vulnerable to contamination. Mud contamination can also result from drilling cuttings entering the mud during water well drilling or overtreatment of the mud system with additives such as excess bentonite (Larry,W.L.2006)

Common Mud Contaminants, Sources, and Treatments

The most common mud contaminants to water-based drilling mud systems are solids such as

- Gypsum/anhydrite;
- Cement/lime;
- Makeup water rich in (Ca++, Mg++);
- Soluble bicarbonates and carbonates (HCO_3^-, CO_3^{--});
- Soluble sulfides (HS^-, S^{--});
- Salt/saltwaterflow(Na+,Cl^-).

Solids Contaminants are materials that are added to make up a mud system or bentonite and drilled cuttings that are drilled. Excess solids of any type are the most undesirable contaminant to the drilling consumables and fluids. Solid contaminants affect all kinds of mud properties. It has been shown that fine solids, micron and submicron sized, are the most detrimental to the overall drilling efficiency and must be eliminated if they are not found to be essential part of the mud make up. The elimination of drilled solids is attained through the use of mechanical separating equipment such as shakers, desanders, desilters, and centrifuges.

- Shakers eliminate solids in the size of cuttings (around 140μ).
- Desanders eliminate solids in the size of sand (down to 50μ).
- Desilters eliminate solids in the size of silt (down to 20μ).
- When solids become smaller than the drilled cutoff point of desilters, centrifuges may have to be used.

Chemical flocculants are also sometimes used to flocculate fine solids into a bigger size so that they can be eliminated by solids-removal equipment.

- Differentiation of total flocculant from various types of solids is difficult, while selective flocculants will flocculate drilled solids but not the added polymers and drilling fluids.
- Lastly, dilution sometimes can be applied to lower solids concentration.

4.7 Equipment and Personnel-Related Problems

Equipment

The integrity of drilling equipment and its maintenance are major factors in minimizing drilling problems. Proper rig hydraulics or pump power for efficient bottom and annular bore hole development, and cleaning are essential. Furthermore, proper hoisting power, derrick design loads and drilling line tension load allow safe over pull in case of a drill pipe and casing stacking problems. Well-control systems such as ram, internal and annular preventers are all necessary for reducing the risk of drilling challenges. Proper monitoring and recording systems of the drilling rig also crucial to monitor trend changes in all drilling parameters and can retrieve drilling data at a later date, proper tubular hardware specifically suited to accommodate all anticipated drilling conditions. Effective drilling fluid and consumable handling and maintenance equipment will also enhance the function of drilling rigs with accessories and extend year of service and help to acquire quality and timely completion of drilling projects.

Personnel

In Ethiopia, most of the drillers found in the water well drilling industry and currently operating in the field lack basic standard training on the drilling of water wells with various methods of drilling, using appropriate drilling fluids and trouble shooting when the major drilling challenges encountered on the field. The most important thing is that in order to have effective and efficient performances one has to believe in the requirements of different types of training programs and attitudinal changes to the workers and the management group and skill training's which would help to minimize the above noted technical problems. During drilling and completion operations, qualified personnel are crucial and key to the success of those drilling operations. Drilling technology training centers should continue training and education for drilling personnel and supervisors both formally and informally to successful drilling and well completion practices. In general, all the problems related to manpower are the results of poor planning, lack of experience and skill deficiency can be improved through appropriate training field exposure and awareness of drilling fluids and consumables.

CHAPTER FIVE

5.DRILLING PROBLEM ANALYSIS

Water well drilling, well development, pumping test and well construction completion activities should be made in planned, scheduled and organized manner. Recording and documentation of all activities including well drilling and related challenges are essential in order not to make same mistakes again and again. Furthermore, thelithologic information and borehole history will be an input for future designing and drilling of water wells in similar geologic and structural settings of well sites.

In the country of Ethiopia, with some exceptions, water well drilling challenges and their mitigation measures and entire well history are not documented. Hence crucial information was missed and similar drilling problems occurred repeatedly in different parts of the country.

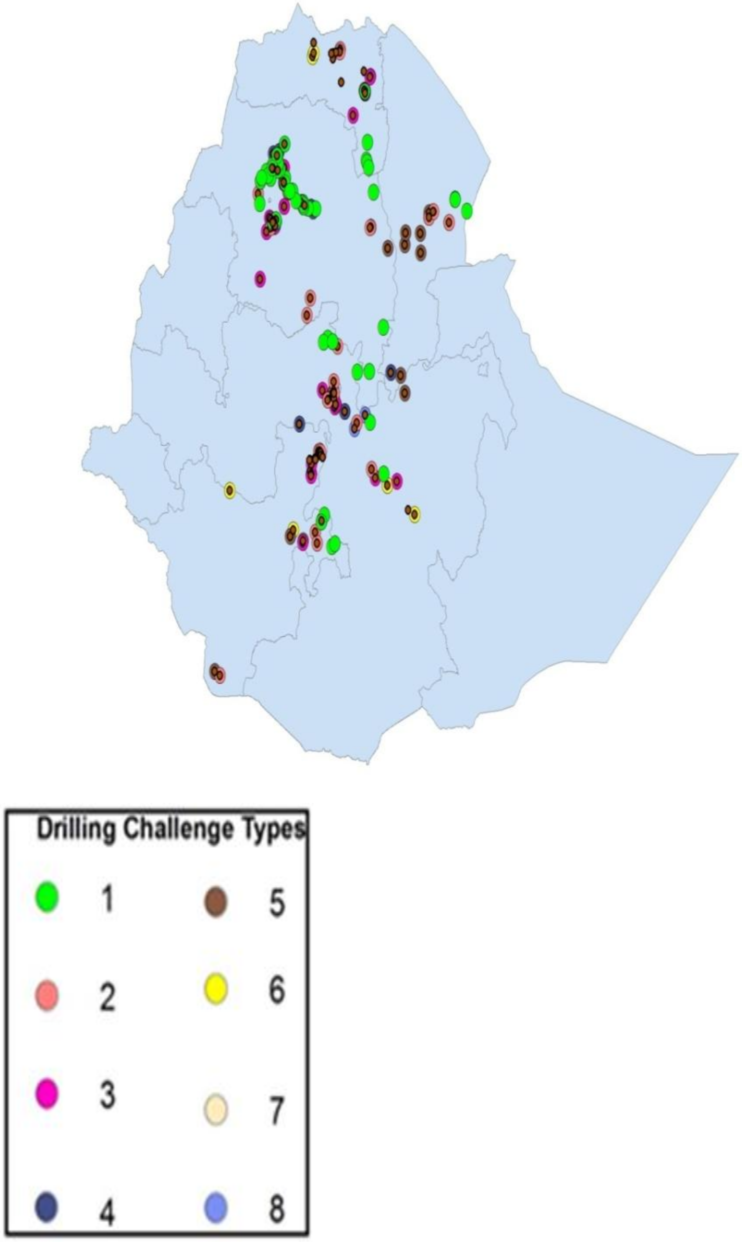


Figure 3.Drilling challenge types and occurence with regional administrations. Drilling challenge types were given from 1-8. Challenge number 1 typify well caving, 2 drillpipe stack, 3. Loss of circulation, 4. Caving and drill pipe stack 5. Drill pipe broken, 6. Well collapse, 7. Casing collapse and 8. Caving and loss of circulation

Most of the drilling challenge information with some exceptions however exist and gathered as unwritten history in individual operators and geologist working with water well drilling contractors, consultants, regional water work construction Enterprises and Regional water bureaus .These information has to be collected to investigate the root cause of the drilling problems. Discussion were made in simple, easy, understandable ways to identify major drilling challenges, lithologies, targeted depth and specific location of wells. The objective was to identify the major type of drilling problem and lithology with frequency of occurrence and mitigation measure if any.

In general 216 selected boreholes with the typical drilling problem were identified throughout the country with their GPS coordinates, target drilling depth, aquifer type. As it is shown below using Arc-GIS software the selected borehole site data were merged with modified hydrogeologic map of the country to identify and ensure which kind of structural and hydrogeological setting is most vulnerable for the recorded drilling challenge.

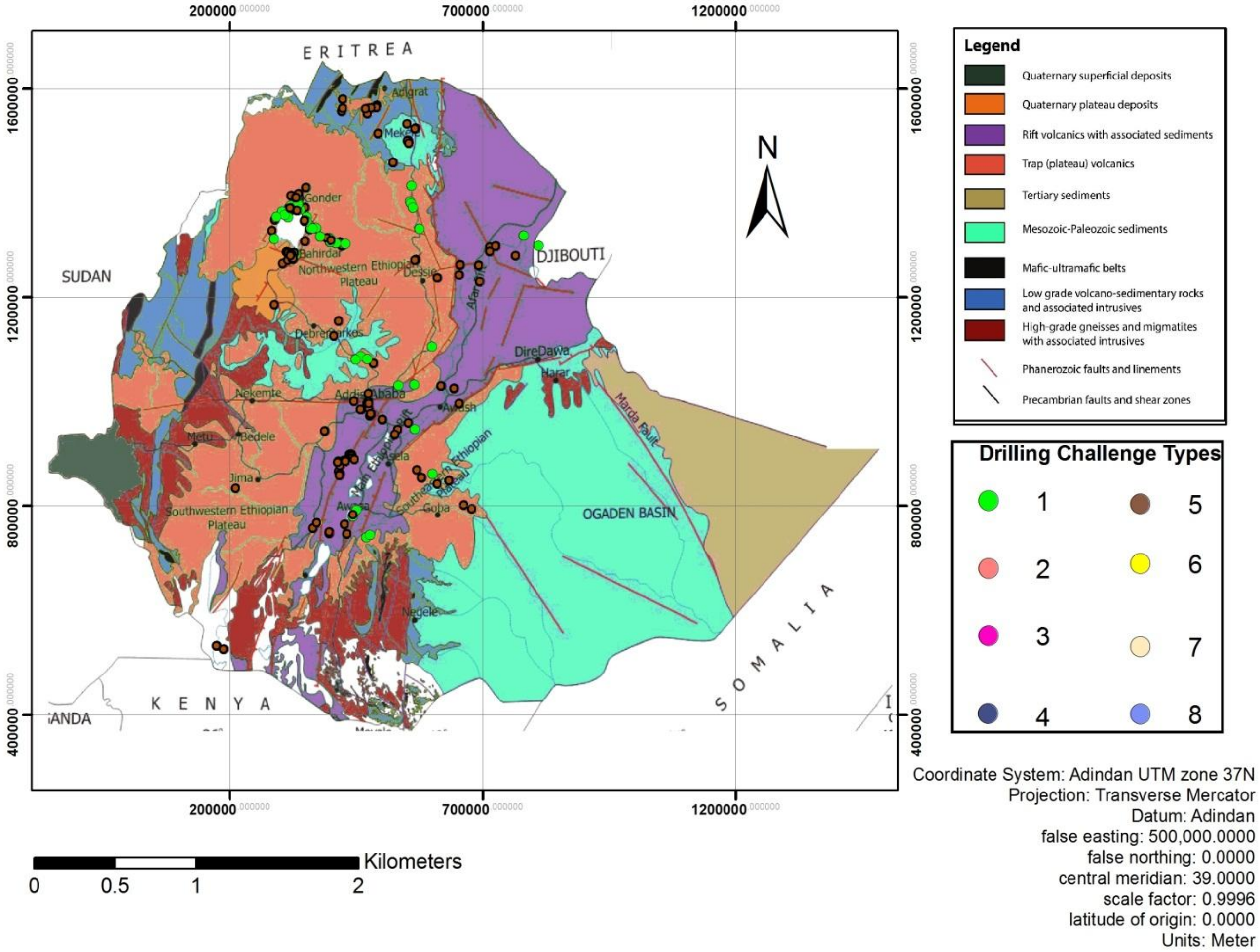
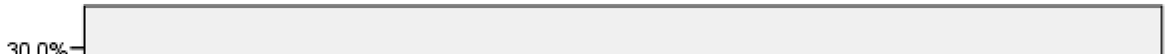


Figure 4.Modified Hydro-geologic map of Ethiopia with merged borehole data. Drilling challenge types were given from 1-8. Challenge number 1 typify well caving, 2 drillpipe stack, 3. Loss of circulation, 4. Caving and drill pipe stack 5. Drill pipe broken, 6. Well collapse, 7. Casing collapse and 8. Caving and loss of circulation

5.1 Area Charts for the frequency of Drilling Challenge

Figure 5. Area Chart for Dilling challenge frequency table

Area Charts for the frequency of Drilling Challenge



Water Well Drilling Challenge

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Caving	57	26.3	26.3	26.3
	Drill Pipe Stacking	40	18.4	18.4	44.7
	Circulation Loss	47	21.7	21.7	66.4
	Caving & Drill Pipe Stacking	20	9.2	9.2	75.6
	Drill Pipe Broken	12	5.5	5.5	81.1
	Well Collapse	9	4.1	4.1	85.3
	Casing Collapse	22	10.1	10.1	95.4
	Caving & Circulation loss	10	4.6	4.6	100.0
	Total	216	100.0	100.0	

Table 1. Frequency of drilling challenge among sampled wells

Among the samples collected in this specific research well caving stands first with 26.3 % of frequency of occurrence during drilling of boreholes. It happened due to the undesirable condition of a drilled open hole that cannot obtain its structural integrity. This drilling challenge can be mitigated with the mud drilling or reverse circulation drilling method and appropriate drilling fluids and polymers.

The second major drilling challenge observed on the samples taken is loss of circulation with 21.7% rate of occurrence. Even though the degree of the uncontrolled flow of whole mud into a formation or a thief zone varies from well to well the case studies and interviews of drillers revealed that the mitigation measure usually taken by the drillers is either using excessive bentonite or introducing foreign materials like, red clay, plywood and mattress inside the borehole to plug the source of the circulation loss area. The traditional approaches mostly aggravate the situation.

The Third major problem identified from the analysis was drill pipe sticking with total percentage 18.43%. It occurs when inadequate removal of drilled cuttings from the annulus or borehole instabilities such as caving and collapse

The fourth problem was casing collapse. It is an immediate issue of unintentional departure of the drill bit from a preselected borehole trajectory. After the completion of the drilling activity, a huge problem might be happened during the installation of the productive casings encountered and eventually the casing itself will be collapsed. This phenomenon is also common in PVC productive casings. In this specific study 10.2% of the investigated wells encounter case collapse.

Drill pipe sticking and loss of circulation were also treated together with caving and analyzed on this thesis. Accordingly, caving with drill pipe sticking occurred 9.2% and caving with loss of circulation occurred 4.6% respectively

Drill pipe breakage and well collapse are the least likely occurred recorded 5.5% and 4.1% respectively. Pipe breakage or failure usually happened by applying excessive torque. If the torque exceeds the pipe material ultimate shear stress pipe breakage can be happened.

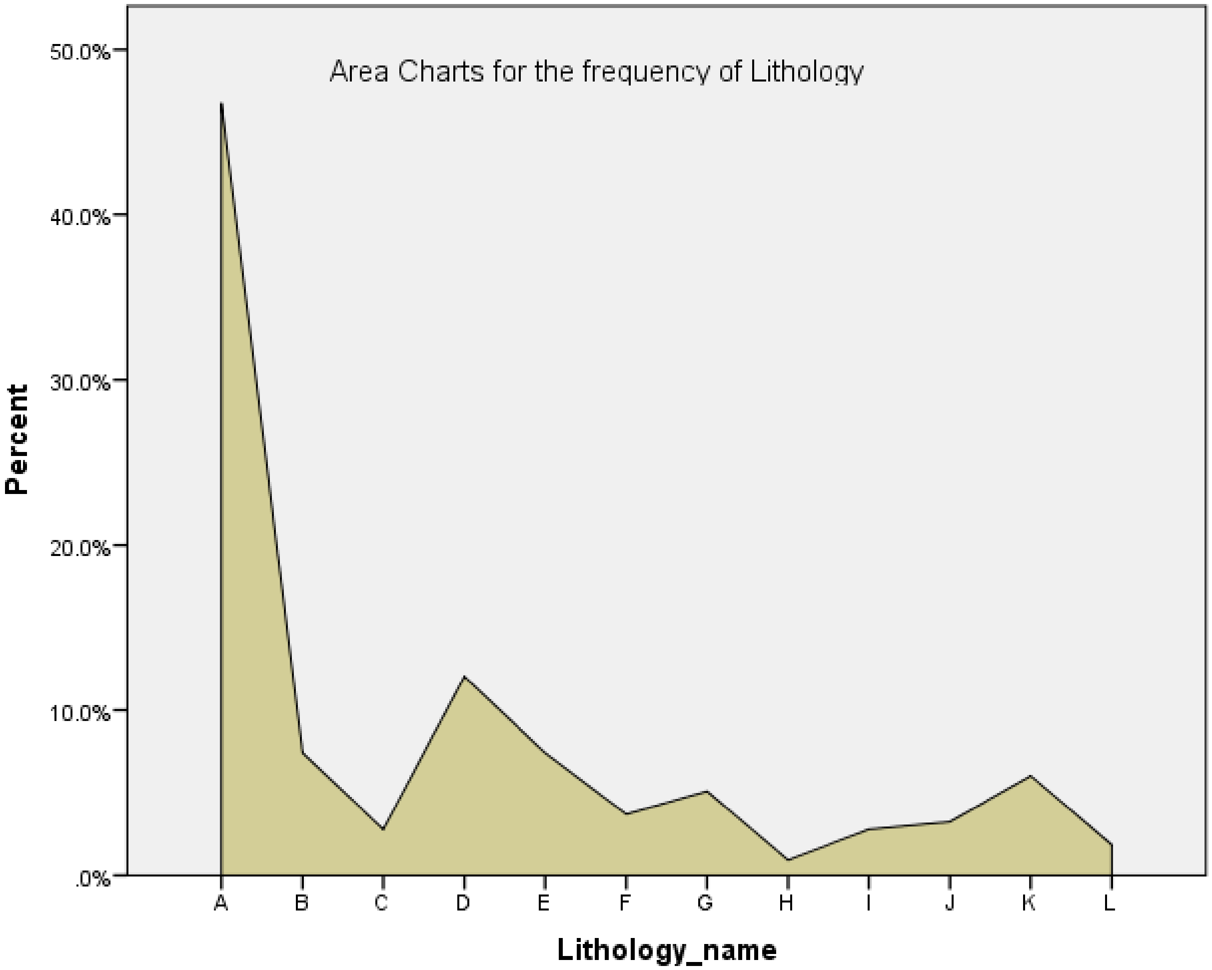


Figure 6.Area chart of lithology. Aquifer, lithology types were given from A-L. Lithology code symbolize Fractured and weathered Basalt, B symbolize fractured basalt and ignimbrite, C symbolize Rhyolite, Trachyte and fractured basalt, D symbolize, Moderately fractured Scoraceous basalt, E symbolize Alluvial, lacustrine deposits, F symbolize, Quaternary basalts and alluvial lacustrine deposit. G symbolize, Pyroclastic ash. H symbolize Fractured Limestone. I symbolize,Fracturedkaristic formation. J symbolize, Weathered Meta sediment. K symbolize , fractured and weathered granite. L symbolize, fractured and moderately weathered Ignimbrite.

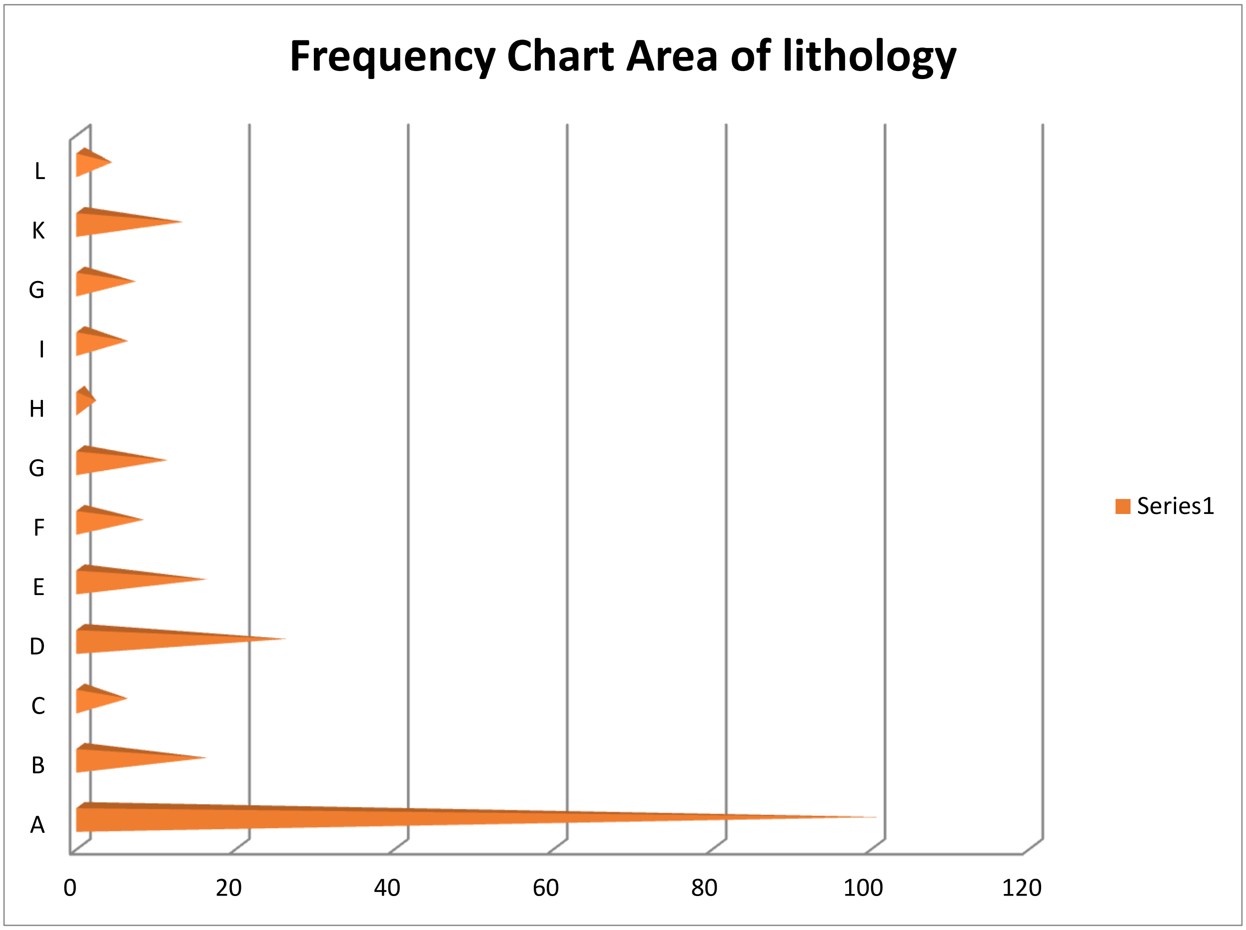


Figure 7. Frequency chart Area of lithology which are vulnerable for the drilling challenges

According to the selected samples 45% of drilling problems happened on Fractured and weathered basalt aquifer. The frequency of lithology also clearly showed that consolidated and unconsolidated sedimentary rocks, meta sediments and basement rocks has a lowest frequency of drilling challenge.

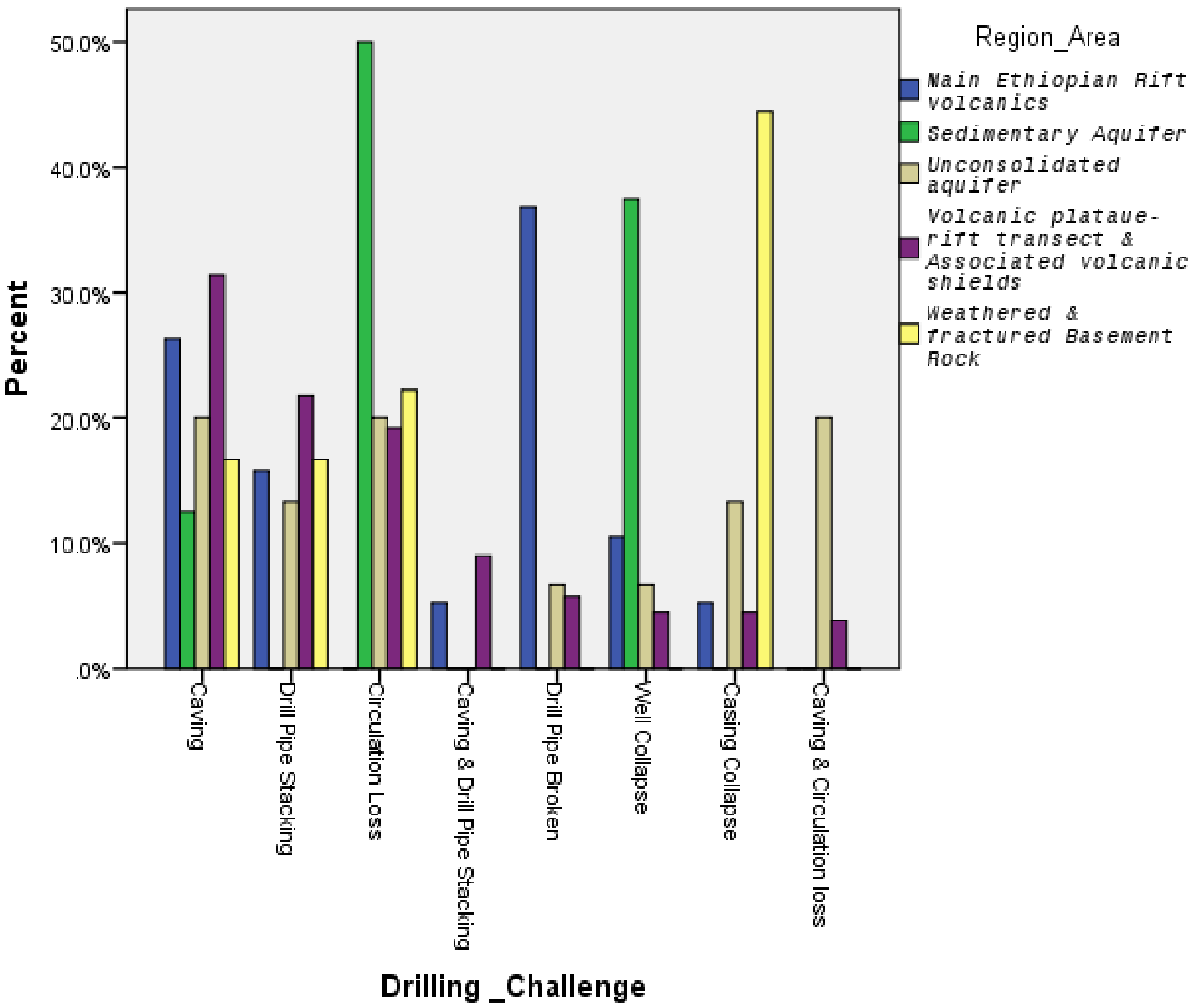


Figure 8. Bar chart for Main Geologic areas compared with the drilling challenges

The summary analysis of drilling challenge versus major lithologies from sampled wells is shown in the above bar chart. After statistical analysis of drilling problem of each sub areas, well caving and borehole instability problem found in all major geological regions of the country namely main Ethiopian Rift system, sedimentary consolidated rocks and unconsolidated sediment areas.

5.3 Degree of Vulnerability of rock formations for drilling challenges

The graph below defined the type of lithology and degree of vulnerable to the drilling challenges.

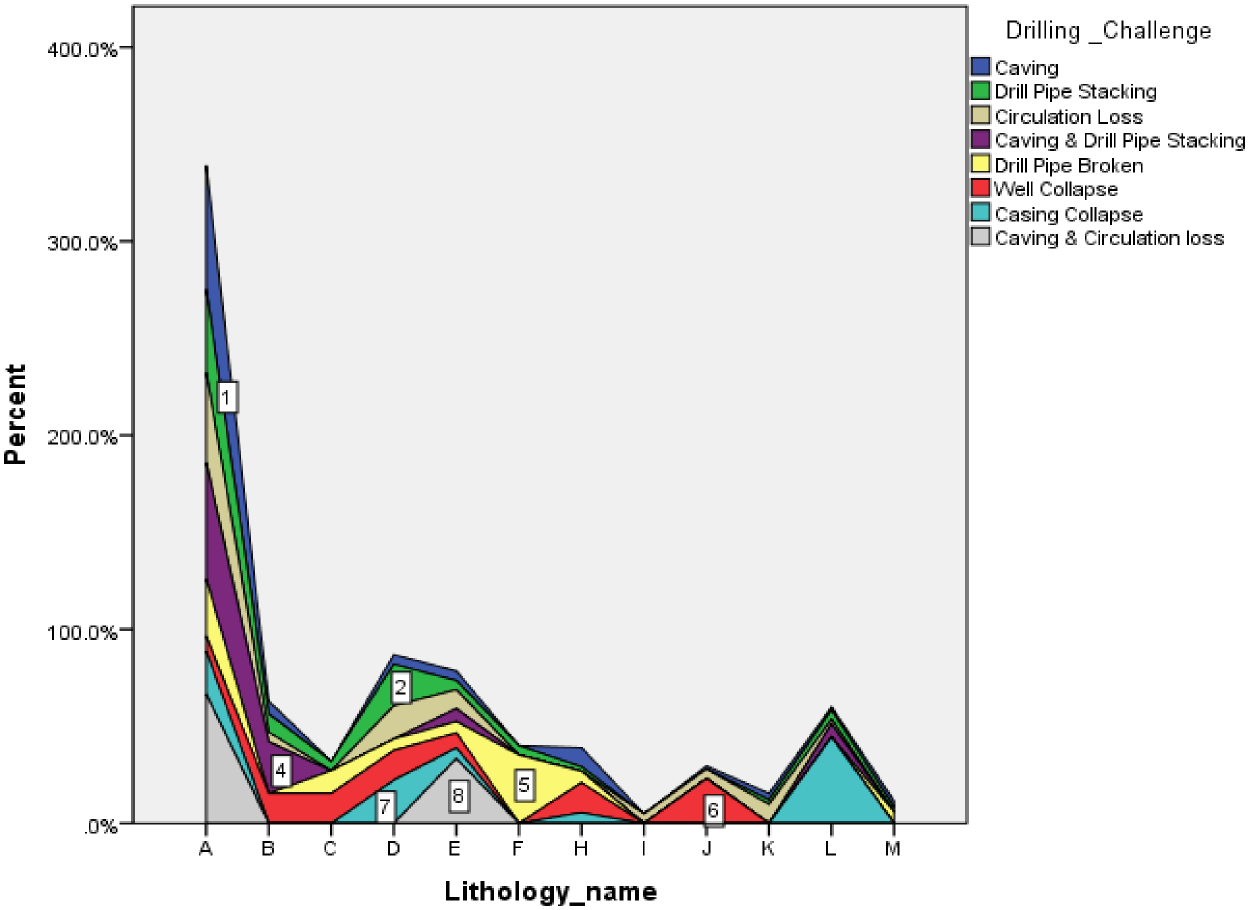


Figure 9.Area chart of shows degree of vulnerability of lithology for drilling challenges. Lithology types were given from A-L. Lithology code symbolize Fractured and weathered Basalt, B symbolize fractured basalt and ignimbrite, C symbolize Rhyolite, Trachyte and fractured basalt, D symbolize, Moderately fractured Scoraceous basalt, E symbolize Alluvial, lacustrine deposits, F symbolize, Quaternary basalts and alluvial lacustrine deposit. G symbolize, Pyroclastic ash. H symbolize Fractured Limestone. I symbolize,Fracturedkaristic formation. J symbolize, Weathered Meta sediment. K symbolize , fractured and weathered granite. L symbolize, fractured and moderately weathered Ignimbrite.

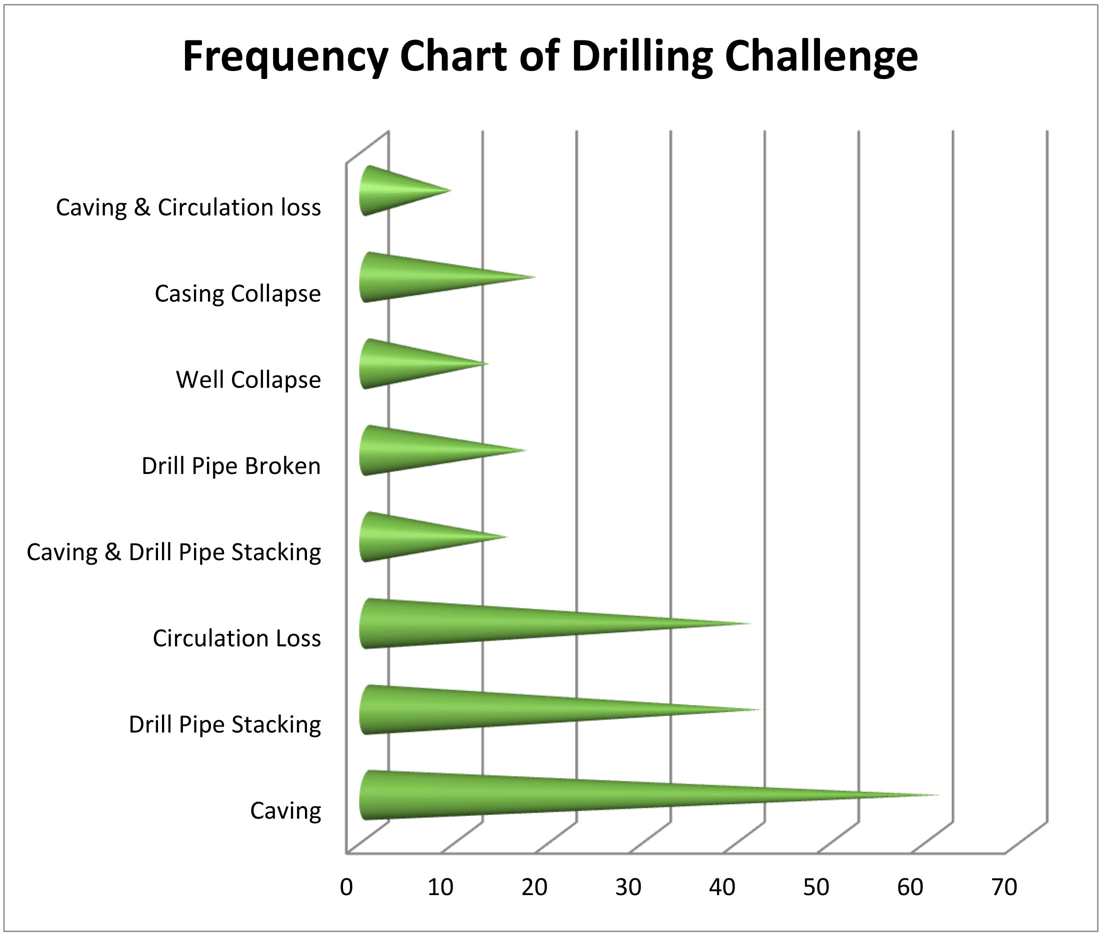


Figure 10.Frequency chart of drilling challenge

According to the analysis shown on fig.8 Fractured and weathered basalt, Ignimbrites, rhyolites, trachytes and moderately fractured and weathered scoraceous basalt are most vulnerable for well caving and drill pipe stacking types of drilling challenges while casing collapse caused by deflection of wells and well collapse are rarely happened. In weathered and fractured rocks, consolidated sedimentary and unconsolidated sediments and pyroclastic deposits, circulation loss, caving and well collapse are dominant source of drilling challenges in Ethiopia.

5.4Exemplary Drilling challenges in Ethiopia

In this section practical drilling problems and cause with drilling type, depth of the wells and possible recommended solution and remark given for selected representative wells which was found through discussions with senior chief drillers and experienced hydro-geologists in the country. Furthermore researcher's personal drilling supervision experience and witnessing also included in this summary table.

S.no	Location/ Owner of the project	Rig type/Drilling Method/Contractor name	Year /Depth(M)	Drilling problem	Cause	Remark
1	Bure/Gojam	Drill Mech/MUD/ Amhara water works Enterprise	2017	After the drilling completed at 176 meter depth, the productive casing were lowered and stacked at 60 meter depth.	The well is deflected due to the heterogeneity of formation	The driller was unaware of the fact. Technical qualification problem
2	Wolaita/Dugunafango/ Wolaita zone Water department	Fraste /DTH/ SNNP water works Enterprise	2016	At 184 meter the drill pipe at the collar joint is broken. The major formation was ash and pyroclastics	The owner of the project with the site engineer made a mistake on choosing the kind of drilling method on the	The drilling contract agreement should allow both DTH and Mud drilling according to the specific site condition. Furthermore proper drilling fluids and

					specification	polymers must be introduced to the water Bureaus in order to minimize the risk of caving and tools stacking
3	Asko/AAWSA	Drill Mech/MUD/ Amhara water works Enterprise	2016	At 312 meter depth the collar broken and the entire drill pipe fallen	Lack of proper experience of drilling deep wells with proper drilling consumables such as polymers	
4	Debrezeit/ EECMY-CES-DASSC	TH 10 Atlas Copco/DTH/ Ethiopian Kalehiwot Church	2016	At the depth of 30 meter the entire well was collapsed and the rig is almost fall	Lack of proper well design which can consider the instability of the actual field situation in the project	For the boreholes which has a loose sediment formation needs surface longer surface casings, construction of cement grouting and clay pad I advance

					area.	
5	Holeta/ AAWSA	Drill MecH/ Ital Drill PLC	2015	Drilling with 10’’ diameter reached up to final 500meter depth. But during rimming of the same borehole with 20’’ diameter at the depth of 220 meter serious circulation loss was happening.	The drilling firm even though has a good exposure on proper application of drilling fluid and polymers, in order to deduct the running cost it avoids purchasing polymers	The drilling of deep wells especially with mud drilling must be reconsidered before the actual challenge is happened
6	BorichaSidama/SNNP water Bureau	Massenza /MUD/ SNNP water works Enterprise	2015	At the depth of 160 meters huge loss of circulation encountered and consumed lots of Bentonite and local clay. Finally the driller and his	Ignorance of application of a proper drilling fluid such as polymers cause them to look for local	Apparently the well is being recovered and become functional however during years of service there might be a case of well discharge decreasing

				supervisor agree and apply plywood(segatura) and the circulation loss is stopped and the drilling continued to the final depth	made solution	. Since the aquifer is blocked with plywood
7	Yirgalem Industrial Zone	Massenza /MUD/ SNNP water works Enterprise	2015	At 217m depth tools stack and eventually drill pipe was broken	The drill might use highest torque to mitigate pipe stacking which leads him on pipe braking at the joint	The drillers were not capable to mitigate such problems. Lack of proper knowledge and experience of drilling trouble shoot
8	Ginchi/Anmol paper	DrillTech/Safe water	2014	Drilling with 10’’ bit reached to	The drilling type was	Basic problem was a drilling method.

	factory	mining P.L.C		target depth 150 meters but the clay swelled and the casing could reach to the target depth	Air/DTH so the clayformation create mud cake and the width of the well decreased by the swelled clay	Since the area is rich with highly fractured volcanic rocks and clay the drilling system must be changed to Mud rotary
9	Modjo/Elmi Olindo	Reichdriller CP 650/DTH/ Safe water Mining PLC	2013	Drilling with 97/8'' DTH Air system drilled, however before the driller reached to the final depth well caving and drill pipe stack happening	The drilling machine didn't have mud drilling system. The drillers took a risk to complete the drilling with the risk of well caving and drill pipe stack	Hydrogeologists and drillers must be aware of the kind of geology they are going to encounter and the most feasible and safe drilling method and be equipped with relevant drilling fluid

10	Wonchi/Woliso/ World vision Ethiopia	DrillTech/DTH/ Safe water Mining PLC	2012	Circulation loss encountered at 78meter depth and continued drilling up to 120meter using blind drilling	Lack of awareness to change a drilling system to Mud and ignorance to use a proper drilling fluids and polymers	The aquifer was highly weathered and fractured basalt and the drillers should stop drilling after the serious circulation loss happening on the well and change drilling method and apply drilling fluids
11	Bahirdar Stadium/	Massenza/ AWWDE	2010	Before it reached to the targeted 120 meter depth both caving and bridging encountered	The drilling system is switched from DTH to Mud	Even though drilling with mud rotary takes more time than DTH drilling for the wells which has loose and unstable formations mud and reverse circulation drilling is highly recommended
12	ChercheraPedagology	Massenza/ AWWDE	2010	Proper drilling method was	The cause of circulation	The drillers should be acquainted and

				applied to reach the target depth	loss might be the lack of awareness of the drillers to apply plymers in addition to bentonite	apply additive polymers in addition to well knownbentonite drilling fluid
13	Kanat BH3	Soil Mec/AWWDE	2009	DTH Air applied for loose unstable pyroclastic formation	Drilling with Air/DTH has a higher risk of collapse on loose formation such as pyroclastic ashes	The drilling systemmust be changed to either mud rotary or Reverse circulation to minimize the risk of collapse
14	Arsi/Robe/ Oromia Water works construction Enterprise	Reichdriller CP 650/DTH/ Safe water Mining PLC	2009	The drill bit is broken with few drill pipes while the driller is operating	The drillers were eager to finish the drilling faster and they apply high torque	The chief drillers must be well trained and tested before they assigned to do the job by themselves

15	Kemerdengay well field	Soil Mec/AWWDE	2008	DTH Air applied for loose unstable unconsolidated sediment	Drilling with Air/DTH has a higher risk of collapse on loose formation such as unconsolidated sediment	The drilling systemmust be changed to either mud rotary or Reverse circulation to minimize the risk of collapse
16	Gassay	Massenza	2005	To reach a targeted depth 170 meter DTH air is applied. However the well was collapsed	Pyroclastic falls are unconsolidated volcanic rocks and are sensitive for Air drilling	The drilling system must be changed with proper drilling fluid to minimize cost, time and future well efficiency
17	Fitche/Kajima Road Corporation	Kneeble/DTH/ Pile foundation & Water well drilling Enterprise	2004	After the driller reached target depth 123 meters and prepare the casing to install, the well was founded being	Ignorance of using a proper drilling method with application of a proper drilling fluid	The well completion work takes more than 6 month just to drill a well having 120 meter depth. This cause huge loss on the drilling

				collapsed up to 80 meters depth and the drillers strive to block the caving up to the given depth using a surface casing	such as polymers	contractor the owner of the project (government) and the beneficiary of the project (community)
18	North Kola diba	Soilmec/AW WDE	2004	To reach a targeted 174 meter depth takes longer time	The drilling method id Mud which is safe to avoid caving and drill pipe stack. However in this specific site the formation is consolidated volcanic rocks	The technical specification of drilling project must be designed based on the actual lithology type of area in order to avoid confusion of drilling methods
19	Bure/Afar/ Ministry of defence	Ingersoll Rand T4W/DTH/	2002	At the depth of 165 meters boulder stacked	The drilling system here must be Mud	Fortunately the rig was very efficient to drill with mud but

		Pile Foundation & Water well drilling Enterprise		the drill pipe with the drilling bit	type with the necessary drilling fluids like bentonite and polymers to avoid the risk of collapsing of the wells	the contractor refuse the technical advice of the drilling super intendants
2 0	Tiya/ Guraghe zone Water department	Worthington High duty/Mud	2002	The target depth was 250 meter using mud rotary	Due to negligence of drillers and low capacity of drilling rig the well could not be completed	The drillers capacity must be built in order to able to drill with different kind of drilling methods and environment

6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Among the drilling problems investigated in this paper, well caving stands out as the major drilling challenge with 26.3% of the total occurrence. Circulation loss with 21.7% and drill pipe stacking with 18.3% of total occurrence are also major challenges with higher frequency encountered in the borehole drilling industry of the country Ethiopia. Drill pipe breakage and well collapse are the least likely occurred recorded 5.5% and 4.1% respectively

The main Ethiopian rift valley and the Tana basin are the areas with highest frequency of drilling challenges are encountered. The geographical locations, the geological settings and tectonic activities had also a vivid significant negative influence of creating multifarious drilling problems on these areas.

Discussions with chief drillers and hydro-geologists in the field revealed that most of the drillers operating in the field lack basic standard training on the drilling of boreholes with various methods of drilling, using appropriate drilling fluids and trouble shooting when the major drilling challenges encountered on the field.

6.2 Recommendation

1. The well drillers must have a proper acquaintance with Air drilling system especially for shallow and deep borehole systems. Air behaves as a fluid and can perform with excellent penetration rate. It allows quick reaction to changes in hole condition and can be an excellent solution for loss of circulation. Typical drilling fluid consumables which are highly recommendable for Air drilling are Soda Ash, EZ-MUD and QUIK –FOAM. Furthermore, proper application of Air drilling reduce hole enlargement due to erosion, fast drilling rate and swift removal of large size drilling cuttings.

2. Water well drilling using Mud system is highly recommended for area which has loose and unstable formation and for drilling of deep wells with larger diameters in general. In addition using bentonite well drillers needs to apply polymers. Polymers have primary and secondary functions for smooth and safe water well drilling process. Primarily, it controls

mud weight, filtrate solid cuttings, stabilize clay and shale by encapsulation, inhibits clay hydration and develop viscosity. Filtration control and lubricity also considered as a secondary function of polymer. From the researcher experience of supervisions of wells and interviewed drilling super intendants, the proper application of drilling fluids on the wells starting from the beginning of drilling activity greatly decrease the risk of circulation loss and caving of wells, furthermore other drilling challenges such as drill pipe stacking, well and casing collapse problems shall be minimized.

3. Properties of the relevant drilling fluids must be tested during drilling of wells in order to avoid complications of drilling challenges. The basic properties to be tested are viscosity, density, rheology, (plastic viscosity, yield point, gel strengths), filtration properties, sand content, PH and calcium content. These fluid properties determine if a drilling fluid can perform its functions such as building and maintaining desirable fluid properties.
4. The technical capability of the drillers must be enhanced. During the researcher’s visit, it was vivid that most of drillers and hydro geologists assigned to supervise water well drilling project, had a little knowledge about the drilling fluids and its application in general and polymers in particular. Therefore it is recommendable for federal and regional water Bureaus and water technology institutes to train and update their professionals in order to minimize risks related to the drilling challenges and boost the success rate of production boreholes.

5. Selection of quality casings and screens are also crucial to minimize drilling challenges such as casing and well collapse. Casings are designed as conduits for protection and support of the wells but can collapse. They are subject to corrosion, water and heat attack depending of the specific geologic area. Furthermore, they can create head loss, develop bacteria slim, incrustation, clogging and can cause gravel bridge. Therefore it is highly recommendable to use high quality casings and screens such as high quality copper bearing, low carbon steel and alloy (corton) casings under normal hydrogeologic condition outside rift and saline areas. High strength low alloy stainless casings should be installed in rift area and high saline underground conditions. Plastic casings (PVC) are also free of corrosion but more susceptible for heat attack poor resistance to collapse and tensile strength, hence they are recommended for shallow wells outside rift and areas where there is no geothermal energy present.

REFERENCE

AbebeG.Hiwot, 1999. Case studies on well drilling problems. IN: Pickford, J. (ed). Integrated development for water supply and sanitation: Proceedings of the 25th WEDC International Conference, Addis Ababa, Ethiopia, 30 August-2 September 1999, pp.173-176.

Carter RC, Danert K (2003) the private sector and water and sanitation services- policy and poverty issues- J Int Dev. 1067-1072

Danert, K. Carter, RC, Adekile, D and MacDonald, A (2008). Cost-Effective Boreholes in sub-Saharan Africa. In: 33rd WEDC International Conference, pp. 3-9 Accra, Ghana, 2008

Geological Survey of Ethiopia(GSE) 1978, Geology and development of Zazreth area, N. Ethiopian rift.(Kazmin V., seife Michael Berhe). Published technical report, GSE, Addis Ababa, Ethiopia.

Larry,W.L.(2006). Petroleum Engineering hand book, Volume II Drilling Engineering: Chapter 10-Drilling [problems and Solutions. Society of Petroleum Engineering, 433-454

Ministry of Water Resource, (MoWR) (2006). Drilling for Water in Ethiopia a Country Case-Study by the Cost-Effective Boreholes Flagship of the Rural Water Supply Network Final Report Volume 1, MoWR, Addis Ababa, Ethiopia,55pp.

SeifuKebede., Addis Hailu., Crane, E., Ó Dochartaigh, B.É and Bellwood-Howard, I. 2018. Africa Groundwater Atlas: Hydrogeology of Ethiopia. British Geological Survey

SeifuKebede, &Travi, Yves &AsfawossenAsrat&Alemayehu, Tamiru&Ayenew, Tenalem& Tessema, Zenaw. (2008). Groundwater origin and flow along selected transects in Ethiopian Rift volcanic aquifers.Hydrogeology Journal. 16. 55-73.

TesfayeCherinet (1982). Hydrogeology of Ethiopia and water resource development. Unpublished technical report, EIGS, Addis Ababa, Ethiopia, 231pp.

TesfayeCherinet (1993). Hydrogeology of Ethiopia and water resource development.Unpublished technical report, EIGS, Addis Ababa, Ethiopia, 227pp.

Tesfayetessema, EleniMulugeta.(2009). Practical Problems in well drilling and pumping test analysis in Ethiopia. Unpublished Msc Thesis, Addis Ababa University, Addis Ababa, Ethiopia, 77pp.

Wegayhu H/Giorgis. (2017). Water well drilling problems and solutions.UnpublishedMsc. Thesis, Mekele University, Mekele, Ethiopia, 166pp.

UNESCO (2006) Groundwater resources of the world: trans-boundary aquifer systems 1:50,000,000 scale, UNESCO, Paris, France

ANNEXES

FIGURES

Tables

Field Collected data