Addis Ababa University

School of Graduate Studies

Faculty of Science

ASSESSMENT ON HYDRAULIC PROPERTIES OF THE ETHIOPIAN ASHANGE FORMATION

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University

In partial fulfillment of the requirements for the Degree of Masters in Hydrogeology

Seid Getahun Molla

May,2011

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By

SEID GETAHUN MOLLA

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENTS

OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

DEPARTMENT OF EARTH SICENCES

FACULITY OF SCIENCE

ADDIS ABABA UNIVERSITY

June2011

Addis Ababa

Addis Ababa University

School of Graduate Studies

Department of Earth Sciences

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By: SEID GETAHUN MOLLA

(Hydrogeology Stream)

Approved by Board of Examiners:

Tigistu Ayalew (PhD) ______________________

(Chairman)

Seifu Kebede (PhD) ______________________

(Advisor)

Dereje Ayalew (PhD) ______________________

(Co-advisor)

Gezahagne Yirgu(Prof.) ______________________

(Internal Examiner)

Wagari Furi (PhD) ______________________

(External Examiner)

Dedication

This work is dedicated to my mother Aminat Muhe (***3x***) and my father Getahun Molla (***1x***).May Almighty Allah bless your souls and grant you paradise (Jenna).

Acknowledgment

The first precious honor goes to Almighty ALLAH, the Merciful and Compassionate, for giving me the passion and strength during my studies and achievement of thesis work.

Next, I would like to express my genuine respect and gratefulness to my advisor and co-advisor, Dr. Seifu Kebede and Dr.Dereje Ayalew respectively, whose kind guidance and constant encouragement had helped me to successfully carry out my work. Really both of you deserve my admiration for you have given me your self-esteemed, constructive and consistent follow ups during my thesis work.

My Special thanks go to Mr.Abreha G/silassie for his excellent assistance and encouragement throughout my study period and especially during the research work. I highly value his continuous constructive criticism and precious suggestions which helped me to locate this research in the right direction.

I would like to thank Prof. Tenalem Ayenew for he had taught me many of the aspects in Hydro-geology including pumping test, which was highly useful for my research accomplishment. I would like also to extend my appreciation to all my lecturers for giving me all the basics of science.

I am great full to Dr.Dessie Nedaw, for sharing me his experience and important data available in his hand without any hesitation and preconditions.

I am also thankful to the Amhara Water Works construction Enterprise, Tigray Water Works construction Enterprise, Ministry of Water Resource, Federal Water works Design and Supervision Enterprise from where I received all kinds of necessary data support during my filed work.

There are no words to express my feelings that I have for those people from all walks of life who had helped me in my times of difficulty during the study period and thesis work. I hope a time will come and a place will be found to write boldly and speak loudly about all the things that you have done for me. Only few among many of you are:-Halewiya S., Mengistu, EMRDA.,Bilalul Habesh, H.Abote Woreda water office staff members,4KMUJ,Seid Y., Asfaw Afera,Mohammed Ali.,IRCC,Ihsan , Melaku A. and others. Thank you very much.

For my beloved family members especially my brother Yimer and my sister Hawa, thank you for encouraging me to pay the price of learning even if you deserve my support.

Last but not least thanks to Ms. Lubaba Adem in treating and bearing me as my mother which lastly brought me near to the point of success.

Abstract:

The Ethiopian Ashange formation is an extensive development of fissural and central type eruptions in Oligocene period (~ 30 mas) that produced a thick succession of the trap serious basalts that forms mainly the north western and southern Ethiopian plateau (see Fig.3). The Ashange basalt is thus considered to be the lower formation in the stratigraphy of Ethiopian volcanic plateau commonly injected by dolerite sills, acidic dykes and other intrusions. It covers an area and volume of about 85,000km^2 and 66,300 m^3 respectively contributing to 37 % of the overall volume of Ethiopian continental flood basalts.

A total of 70 wells raw pumping test data are analyzed and used besides their respective lithological log to determine hydraulic property of Ashange formation. The dominant aquifer types recognized after analysis are consolidated, confined, double porosity and single plane vertical fractured aquifer systems. Ashange formation shows decreasing aquifer productivity with respect to increased drilled boreholes depth and age of formation. The established relationship between T and Sp.Ca data also shows R^2 value 0.957 that shows Sp.Ca can be used as fair estimator of T in areas with only Sp.Ca data.

A relatively less well loss coefficient is observed in the Ashange formation where the existing variation still indicates the existence of improper well site location, improper well design and construction factors and well yield deteriorations with time due to clogging, corrosion and incrustation activities of well screens. Comparison of transmissivity values of the Ethiopian Ashange formation with other continental flood basalts of the world shows a decreasing trend with respect to age which may be related to the gradual closing up of open spaces like fractures by secondary materials hindering free flow as well as storage of water .The productivity of Ashange formation can be generally categorized as moderate to high which is controlled by location and geomorphologic setup of the formation outcrop; hydrothermal processes and nature; extent, frequency and orientation of the associated structural features and nature and degree of weathering. This work can be considered as an effort to characterize the whole aquifer system of Ethiopia for a better understanding of the available ground water reserve and distribution for further use in developmental activities.

Key words:-Ashange, Flood basalts, Aquifers, Pumping test, Theoretical relations, Transmissivity, Specific capacity

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university.

All sources of materials used for the thesis have duly acknowledged.

SEID GETAHUN MOLLA

signature_________________________

Addis Ababa University, May, 2011

ABFBH	Ashange Basalt Formation Borehole
AWWCE	Amhara Water Works Construction Enterprise
DD(S)	Drawdown
EMRDA	Ethiopian Muslims Relief and Development Association
Fig	Figures
HDW	Hand dug well
IRCC	Islamic Research and Cultural Center
K	Hydraulic Conductivity
Km^2	square kilometer
Km	kilometer
L/s	liter per second
M	meter
m^2	square meter
m^3	cubic meter
MER	Main Ethiopian Rift
Min	Minute
Mm	millimeter
Q	discharge (yield)
s(m)	drawdown in meter
S.W.L	Static Water Level
Sci	Specific capacity index
Sp.Ca	Specific Capacity
T	Transmissivity
t	time
TWWCE	Tigray Water Works Construction Enterprise

TABLE OF CONTENT

List of Tables

List of Figures

List of Plates

Appendixes

Appendix-A- Well log, design, description and plots

Appendix-B-Type curves

Appendix-C-Data base

1. Introduction

1.1 Background

Ethiopia, a country of diversity, is situated in the Horn of Africa. In the West the country is bordered by Sudan, In the North by Eritrea, in the South with Kenya and in the east with Somalia & Djibouti .The country is located between latitude 3^{o} and 15^{o} North and longitude 30 ^{o} and 48 ^{o} East. It has a total area of 1.13 million square kilometer. The topography is so varied that elevations range from 125 m below sea level in the Afar Dallol depression to a number of peaks in excess of 4000m, of which the highest is Ras Dejen with 4620 m.a.s.l.

Rainfall varies both in amount and distribution from a few showers in the low lands to thousands of mm per year in the highlands. The temperature variations are also significant in the country with highest mean maximum temperature of about 40 ^{o}C in the low lands and around 0 ^{o}C or lower observed mainly during night in the high land areas. Ethiopia, with its different geological formations and climatic conditions, is endowed with considerable water resources and wetland ecosystems, including twelve river basins, about 14 major lakes, and some manmade reservoirs. About 123 billion cubic meters of water runs off annually from the above sources. The main rift valley acts as a main discharging zone which contains perennial rivers, fresh and salt lakes, cold and thermal springs.

The very high variability exhibited by the climatic components over time and space is the main reason behind the spatial and temporal variability in the availability of water in Ethiopia. Factors like location (latitudinal), altitude, angle of the sun, distance from oceans or other water bodies and terrain contribute for this variability. Despite of this inconsistencies, the country has a huge potential of both surface and groundwater resources. The surface water potential in the country is 199.3 Mm^3 that takes in to consideration the rivers, lakes and the reservoirs and the total groundwater reserve potential of the country, even not assessed in detail, is 183Mm^3.The preliminary estimated amount of yearly groundwater recharge of the country is about 28,000 Mm^3. Ground waters in unconsolidated aquifers are usually of excellent quality; being naturally filtered. The water is normally clear, colorless, and free from microbial contamination and thus requires minimal treatment.

As a consequence of the slow travel times in the flat plains and due to the long contact time with the sediment, the groundwater often contains significant quantities of minerals in solution.

To enhance and promote all national efforts towards the efficient, equitable and optimum utilization of the available Water Resources of Ethiopia, a full-fledged step should be commenced to investigate the potential and amount of the water resources available. The lack of knowledge on resources amount and availability especially of ground water is creating gaps in its current and future utilization. Ground water which can play the lion share for significant socio-economic development on sustainable basis should be studied and designed well. This includes identification and characterization of the aquifer systems of the various geological formations. All the stakeholders including the government have to undertake their maximum efforts to support such objective studies which will subsequently help to reduce poverty and to insure sustainable socio-economic development the government of Ethiopia.

1.2 Statement of the Problem

Very few hydro geological investigations have been done in a regional scale regarding the general Aquifer system Hydraulic parameter characterization of the Ethiopian Volcanic Province rocks. There is no regional hydrogeological investigation report done so far which is very specific to the Ashangi basalt.

Among the few regional previous studies which tried to assess the regional hydraulic parameter behavior of the whole volcanic rocks in the country include:-

- Hydrogeology of Ethiopia, by MoWR and JICA in 2001
- Groundwater occurrence and Movement in Ethiopian Volcanic rocks, Hydrogeology Journal, by Prf. Tenalem Ayalew, 2006
- Groundwater occurrence in Ethiopia. Addis Ababa University, UNESCO press, Tamiru A. (2006).

Those few regional and local hydro geological studies did not specifically assess the Hydraulic parameter of the Ashangi basalt though it has:-

- Extensive outcrop occurrence (~85,000 km^2)
- Regional spatial outcrop distribution pattern in the country that is in North western and central plateau, close to the rift margin escarpments and grabens and in many part highland plateau areas.
- An aquifer of moderate to high groundwater storage potential which shows tholeiitic to transitional type basalts.

So the problems here are:-

- Identifying particularly the aquifer parameter behavior of the Ashange formation and understanding its groundwater potential with respect to the other volcanic province rocks in the country.
- To understand the effect of tectonics and other surface geological processes in the aquifer parameter behavior of the Ashangi formation relative to its regional location relative to the main Ethiopian Rift system.
- Since the Ashangi formation in general has extensive regional occurrence and has potential groundwater source, Its regional aquifer system characteristics will be analyzed in relation to depth of water supply boreholes drilled in the Ashange formation and with respect to age and mode of eruptions and give minimum and maximum range for its transmissivity and storativity value regionally in spite of the previously commonly done local hydrogeological investigations in different part of the country in relation to the whole volcanic rocks in the country.
- To draw conclusions and recommendations specifically to the Ashange formation aquifer system hydraulic characteristics regionally and locally for proper groundwater source usage and future planned management of the groundwater resource in the country.

1.3 Objective

1.3.1 General Objective

The main objective of this thesis is to assess the hydraulic properties of the Ashange formation with respect to depth and age of the formation and to assess the effect of structural features, tectonics, volcanic, hydrothermal and weathering processes.

1.3.2 Specific Objective

The specific objectives of research work are: -

- To identify the aquifer characteristics of the Ashange formation with respect to depth of the boreholes, age and variation of its spatial distribution.
- To investigate geologic and structural controls on the character of the aquifer system of the Ashange formations and on their groundwater potential.
- To compare the Ashange formations aquifer characteristics with other volcanic rocks elsewhere in the world and
- To Evaluate relationship of transmissivity and specific capacity through theoretical and empirical methods

1.4 Description of the Study Area

1.4.1 Location and Accessibility

Ashangi basalt(lower flood basalt formation) consists of a basaltic lava flow inter-bedded pyroclastics ,ignimbrites and rhyolites .The top part of the group is tuffuceous ,contains lacustrine deposits in some places including lignite seams and acidic volcanic .The total thickness varies from 200 to 1,200m.Differently oriented dolerite sills ,acidic dikes and other intrusions are common. In Quorem, there is 1200m thick Ashange group forming the lower part with the top more silicic 300m thick Meqdela group (upper formation).

In central Ethiopia, trap series has the highest thickness in the central part and more numerous than in the northern Ethiopia.

The thickness (in meters) of the lower (Ashange) formation in different parts of the country is as follows (Mohr, 1971):-

Table: - 1.1 thickness of Ashange formation in different parts of Ethiopia

Nº	Locality(area)	Thickness(in meters)
1	Amba Alagi	700
2	Quorem	1200
3	Central Gojam	700
4	Abbay	500
5	S.E Shoa	1000
6	Harar	900

Ashange formation is dominantly outcropped in the in the Amhara and Tigrai regional states. In northwest highland plateau(that covers parts of Tigrai,Gondor,Gojjam,Wollo,Wellega,Illubabor ,kefa and Shewa), it outcropped in areas particularly around Mahbere silase, Wehini,Zarima, Adiarkai,May tsemri ,Jara gedo,Adi remets,Sankaber,Adishoh,Maychew,Sekota, Korem, Weyra Wuha and Alemata areas. It had also outcropped in areas particularly around Woldiya, Sirinka, Mersa, Ayna,Lalibela,Ajibar areas. In the central highland areas around Tulu milki,Biriti, Gebre Guracha,Jemo Lefo ,Bicho,Sheno,and Dejen areas. Sparsely distributed outcrop of Ashange is found in southern Ethiopia mainly in Somali Region including Kere, Bare, yet and Degeh medo areas. (See Fig.1.3 below).

The study area is covered mainly by three soil types , black cotton soil (vertisols) and lateritic soil (leptosols).Lateritic soil is common in the highlands, while the black cotton soil is the dominate soil type in the lowlands of the area. In the highlands, the upper part of the basalt is altered. This alteration that must have occurred during periods when tropical climate prevailed resulted in thick lateritic soils. The soil thickness varies from a few centimeters in the highlands to about 8 m in some parts of the plain. For example, black cotton soil found in the Quara and Metema has a thickness of 5 m at the gully cut (Hydrogeological and Hydrochemical Maps of Gonder ND37-13 and West of Gonder ND 36-16, exploratory notes). It is possible that during the Pleistocene these places were covered by water bodies. Rivers flowing from higher altitudes discharge to these old lakes.

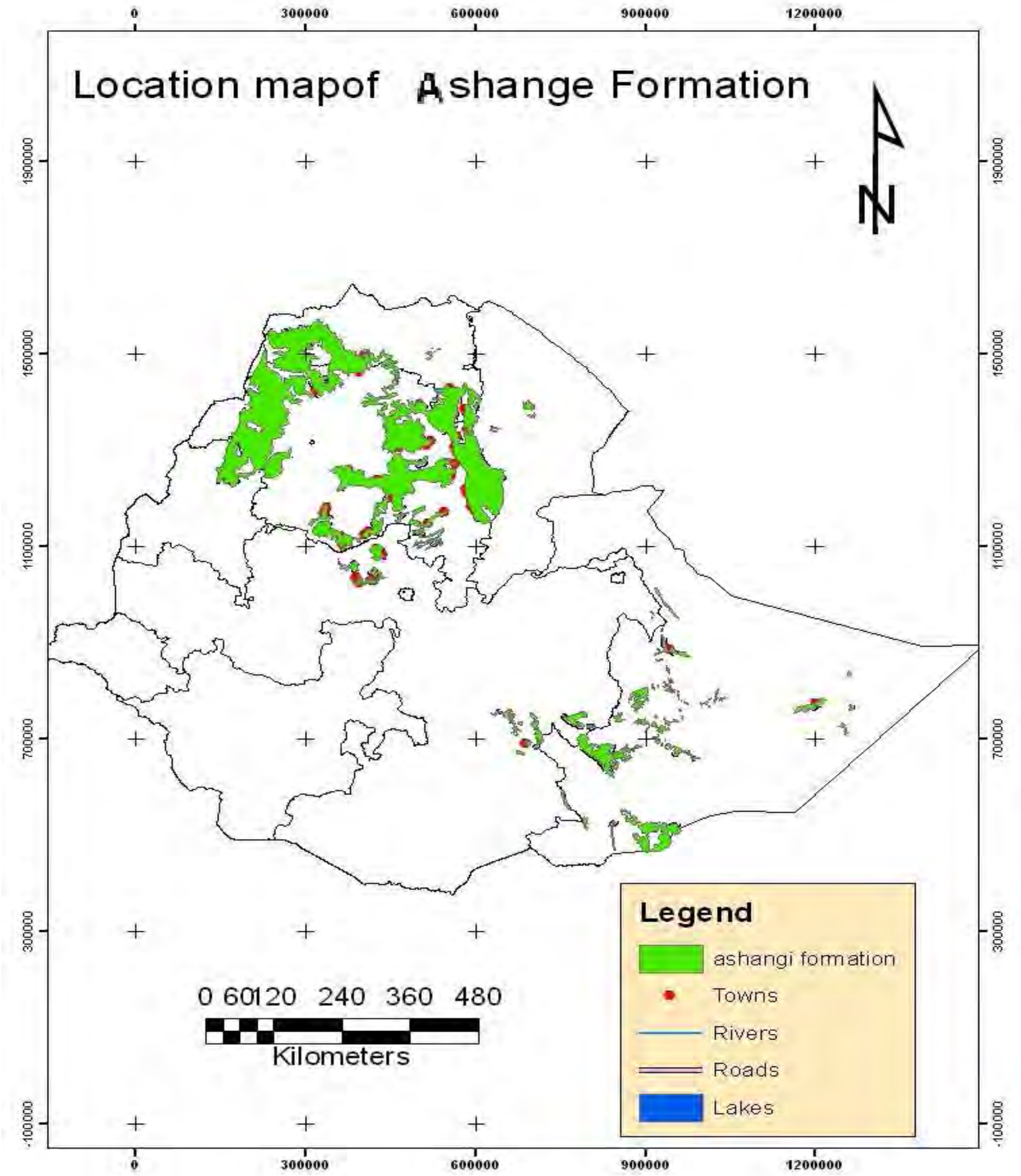


Fig.1.1- Location Map of the Study Area

The name black cotton soil is given due to their physical properties. It is Black because of the color and cotton because of their high moisture (water) absorbing capacity. They are clayey, silty and sandy in composition. These soils have extremely high plasticity and a high degree of swelling when wet compared to other soil types. Thus, they are known to have low infiltration rates and low permeability. This impermeable clay clogs the fractures and prohibits the infiltration of surface water and rainwater. This is a typical problem for infiltration to the Ashange basalts where they are covered by black cotton soil.

Infiltration then occurs through alluvial deposits and seepage of water from different intermittent rivers. Cambisols have a cambic B-horizon or a deep umbric A horizon. Cambisols with a base saturation of less than 50 % are Dystric Cambisols; Chromic Cambisols have a strong brown or red colour and Eutric Cambisols have a base saturation of 50 % or more. Most Cambisols have limited agricultural value as they occur dominantly on slopes, are often shallow or have many stones or rock outcrops. Where Cambisols are deep and not stony they are good for agriculture.

Fluvisols are young soils developed in recent alluvial deposits of river plains, deltas, former lakes and coastal areas. Sediments consist of materials eroded from uplands and mountains. The mineralogical composition of the soil materials is related to type of rocks, their weathering products and alterations during soil formation before transport. Soil conditions are highly variable. In arid regions, many soils are saline. Eutric Fluvisols material is non-calcareous.

Vertisols are heavy clay soils in flat areas that have a pronounced dry season during which they shrink and have large deep cracks in a polygonal pattern. During the wet season the clay swells and causes pressure in the subsoil. Vertisols have fairly good, but limited agricultural potentialities, because the land is rather difficult to prepare. Dry soils are hard and wet soils are sticky. There is only a short period when moisture conditions of the surface layer are favorable to prepare land. Another difficulty is that drainability of the subsoil is very low because of the swelling clay. Very often the soils are flooded or have stagnant water during the wet season. The organic matter content in Vertisols is often not more than 1 %. The soil has high water retention, but a relatively small amount of water is available for plant growth. Rooting might be restricted because of the swelling and shrinking properties of the soil. Chromic Vertisols are brownish and relatively well drained.

Luvisols have an argillic B horizon and a high base saturation (50 % or more). The normal ones are Orthic Luvisols, those with a strong brown or red B-horizon are Chromic Luvisols. Most Luvisols are good for agriculture: base saturation is good and they have weatherable minerals.

In soils with a heavy textured B-horizon or with vertic properties, permeability may be low and a good root distribution can be hindered.

Nitosols are clayey red soils with an argillic B-horizon. They occur on undulating to rolling land. Eutric Nitosols have a pH of 5.5 or greater. Histosols have a very limited agricultural value. Reclamation of Histosols can give problems, because with drainage the organic materials will mineralize and the surface soil will subside.

Lithosols are mineral soils less than 10 cm thick, developed over hard rock. These soils have no agricultural values.

Plate1.1 Black cotton soil of the Metema area (adopted from HYDROGEOLOGICAL AND HYDROCHEMICAL MAPS OF GONDER ND37-13 AND WAST OF GONDER ND 36-16)

1.5 Previous Works & Related Literatures

The Ethiopian volcanic terrain and the associated quaternary deposits represent complex aquifer system where groundwater occurrence and distribution is strongly controlled by the geomorphologic architecture of the plateau, escarpments and the rift valley, the complex spatial and temporal distribution of the volcanic rocks, their different intricate stratigraphic and structural relationship, wide compositional variability, different level of weathering and topographic position complicate the hydrogeological behavior of the volcanic aquifers and hydrochemical signature(JICA, 2001).Therefore, any groundwater exploration and development requires mapping of the important structures and evaluation of their role in the recharge, movement and occurrence of groundwater (Tenalem A, 2009).

- Aquifers were classified in their productivity by Sima et al. (2004) based on their transmissivity ,specific discharge and yielding capacity in Explanatory Notes to the Hydrogeological and Hydrochemical Maps of the Adi Ramets Area (ND 37-5 Adi Ramets and ND 37-9 Gulch sheets) as follows:-
- Extensive and moderately or locally developed and highly productive porous aquifers with T = 100 – 10 m2/d, q = 1 – 0.1 l/s.m, Q = 5 – 1 l/s for alluvial and lacustrine sediments and pyroclastics.
- Extensive and moderately or locally developed and highly productive fissured aquifers T =100 – 10 m2/d, q = 1 – 0.1 l/s.m, Q = 5 – 1 l/s for Adigrat Sandstone and associated siliceous mudstone, Termaber basalt, Alajae basalt and rhyolites, Ashangi basalt.
- Extensive and low productive fissured aquifers with T = 10 – 1 m2/d,q = 0.1 – 0.01l/s .m, Q =1 – 0.5 l /s rocks of Angereb ring complex and Precambrian metamorphic rocks of the Tembien Group.
- Aquitards and/or Minor aquifers with local and limited groundwater resources with T =1 – 0.1 m2/d, q = 0.01 – 0.001 l/s.m, Q = 0.05 – 0.5 l/s for Alkali trachyte, Rhyolite and tuff and Precambrian metamorphosed rocks of Dikama Formation and Tsalie Group: penetrated by granite and diorite).

The Ethiopian volcanics are divided into two main Series: Trap Series (or plateau Series) and Rift volcanics (Mohr, 1971; Mohr, 1983; Zanettin and Justin-Visentin, 1974; Zanettin, 1993)

In the trap series ,an early Cenozoic extrusion of flood lavas occurred from fissures and centers and covered the great part of the Mesozoic sedimentary rocks.

The Ethiopian flood basalts (or traps) cover an area of about 600,000km^2 with a layer of basaltic and felsic volcanic rocks. The thickness of this layer is highly variable but reaches 2km in some regions. The total volume of volcanic and shallow intrusive rocks has been estimated by Mohr (1983*b*) and Mohr & Zanettine (1988) at about 350,000km^3.

The relative volume of flood and shield volcanoes in the northern part of the Ethiopian volcanic plateau was also estimated by Raphael Pik et al, 1998**.** The total area covered by flood basalts is roughly 400km × 600km. The thickness of the pile decreases from about 1·5km at Lima Limo in the north (see plate 1.2 below) to near zero near Alem Ketema in the south. If the average thickness is 0·75km the total volume of flood basalts is then 400 × 600 × 0·75 = 1·8 × 10^5km^3.

Plate 1.2 Lima limo Volcanic Plateau

In the Ethiopian continental flood basalts, the lower formation consists of the Ashange basalt where as the upper formation is built-up by a plateau sequence which contain the Aiba and Alaji fissural volcanisms that was previously known as Meqdela group by Blanford in 1869.

The fissural Alaji volcanism is followed by central volcanism which built up large shield volcanoes called Tarmaber central volcanic (Mohr, 1971b).

The age of Ashange basalts can be traced back to Oligocene age of the Cenozoic period (Hofman et al.1997). The Ashangi group is built predominantly of compact, porphyritic, labradorite basalts often with olivine intercalated with basaltic pyroclastics (Kazmin, 1972).

In summary of volcanic stratigraphy, by (Justin, Visentin et al 1974; Morton et al, 1979; Kazmin et al 1980; Mohr et al 1981; Mohr, 1983) it indicated that, the productivity of the trap series volcanic considerably sometimes varies from place to place.

The yield of the aquifers from the Ashange group rocks varies from 1 to 5.6lt/s on average. In the northwest Ethiopia which is characterized by high rainfall and recharge, it varies from 0.4 to 6.3 lt/s and those for the southeast plateau; it varies from 1.2 to 5 lt/s. For the upper formation flood basalts, it ranges from 1 to 12 lt/s. The yield is extremely high in some localities due to high degree of fracturing and presence of paleo-valleys and buried river gravels in paleo-channel at depth. The major water bearing layers are made of scoracious basalts. (Tamiru, 2006).

Generally, the continental flood basalts of Ethiopia are commonly termed as the trap series to distinguish them from the post rift Aden series. Commonly there are two views concerning the stratigraphy of this thick volcanic pile. The first one is classifying the flow into two distinct chrono stratigraphic units: Ashange basalt; Aiba basalt; Alaji fissural basalts and Rhyolites and Tarmaber basalts (B. Zanettine et.al, 1980, Berhe et.al, 1987) .The second prevailing view is considering this volcanic pile as a continuous lava sequence from the base to the top of the plateau dating around ~30 my back within a span of 1my's(Hofman et al., 1997,R. Pik et.al, 1998).The shield volcanoes ,Overlying these flood basalts, are bimodal and contain sequence of alternating basalts, rhyolitic and trachytic lava flows, tuffs and ignimbrites, particularly near their summits.

This paper considers the second approach as it is recent and most comprehensive study which has got wide acceptance and use. The Ashange (now lower) formation named in its type area at Lake Ashange 50km south of Amba Alaji, applies to strongly weathered and tilted basalts without clear stratification which lie below the upper formation that contains Aiba basalt,Alaji rhyolite and basalt. The unconformity in the two sequence of formations have a thickness of several hundreds of meters (B. Zenetin et.al, 1980).B.Zenetin prefers to apply the low of superposition and interprete the unconformity as an erosional one.

The frequently tectonized nature of ashange formation flows ,which were undeformed show a scoracious and often highly zeolitized lithology ,would then be related to an earle episode of uplift,gravity sliding with associated thin–skin compression ,and block tilting (Marla and Minuci,1938;Mohr and Rogers,1966;Zenettin et .al,1980a).

2. Methodology

2.1 Pump Test Data Collection

Different GIS and other application soft wares including Arc GIS9.2,Aquitest 3.5,Global mapper 11, were used for mapping including geological formations and analysis of data obtained from various sources.

The geological log, well design and construction, depth to water bearing formations is done by using Strater software version 4.00.

The analysis of the pump test data has been made using Theis time-drawdown graphic method by which aquifer properties have been calculated. The pump test data including measured and calculated ones have been organized and processed using the Aquifer test software version 3.5 (Waterloo (Hydrogeologic Inc.)).

The relationship between the computed transmissivity verses specific capacity, transmissivity verses well depth, discharge verses drawdown, transmissivity verses formation age, specific capacity index verses well depth and specific capacity verses formation age have been processed by linear, lognormal, double logarithm and probability plots using Microsoft Excel for windows version 2007 .

Identification, analysis and interpretation of aquifer system hydraulic properties of the geologic formation has been done using the secondary well pump test data, lithological log and data of hydro geological field observations.

The data required for the assessment of hydraulic properties of a formation includes:-

- Well pump test data and well completion reports collected from different sources
- Field measured depth to groundwater data
- Location and geologic map of the formation
- Description and comparison of Aquifer type Master curves
- Softwares to analyze the hydraulic parameter of the formation aquifer system.

Additional information was gathered from different governmental, NGO's and private companies during desk study and the remaining data were gathered during field work.

1. Review of previous works which include: -
    - Geological reports and maps
    - Hydro geological reports and maps
    - Well drilling completion reports
    - Well pump test data's and aquifer type curves
2. Data from field work that includes: -.
    - Boreholes depth to groundwater data
    - Hydro geological field observation data
    - Major structures identification like effect of surface geologic processes and tectonics.

The raw pumping test data collected were evaluated using Aquifer test version 3.5 in order to determine the major aquifer characteristics such as transmissivity, hydraulic conductivity, storage coefficient, specific capacity, and well efficiency.

Finally interpretation was done based on obtained borehole logs, collected and analyzed pump test data results, geological and hydrogeological data from field work.

2.2 Theoretical Background on Interpretation of Pump Test Data's

A pumping test is a controlled pumping of a well so that the response of the production well and the growth of the draw down cone can be measured. The analysis of the pumping test can then be used to evaluate the aquifer characteristics (Clark, 1988:3).The pumping test can be used to determine the probable yield of a well. In the pumping test, the water level in the well is depressed to an amount equal to the safe working head for the subsurface. The water level is kept constant by making the pumping rate equal to the percolation into the well. The quantity of water pumped in a known time suggests a probably yield of the well of a given diameter (Raghunath, 1983: 216-217.).The values of the aquifer characteristics are needed to predict the effect of a particular pumping policy on the groundwater regime, and are obtained by means of pumping tests on test wells.

Pumping tests of wells and boreholes are carried out for three main reasons:

- To measure the well performance;
- To estimate the well efficiency or the variation of well performance with the discharge rate;
- To measure the aquifer characteristics of storativity, hydraulic conductivity and transmissivity.

However one must know that the behavior of aquifer system (aquifer plus well) is not precisely known to calculate the aforementioned characteristics. Interpretation of pump test data in its nature is a matter of identifying an unknown system below the ground surface. This leads to the need for aquifer system identification that on models, the characteristics of which are assumed to represent the characteristics of the real aquifer system of the given formation.

The theoretical models comprise the type of aquifer, initial and boundary conditions. Typical inner boundary conditions are mainly associated with the pumped well i.e. full or partial penetrating, well storage and well loss. The typical outer boundaries are impermeable boundary, permeable boundary, well interference and regional and local water table trends. In a pump test, the type of aquifer and the inner and outer boundary conditions dominate at different times during the test. They affect the drawdown behavior of the system in their own individual ways. So, to identify an aquifer system, one must compare its drawdown behavior with that of the various theoretical models. The model that compares best with the real system is then selected for the calculation of the hydraulic characteristics.

System identification includes the construction of diagnostic plots and specialized plots. Diagnostic plots are log-log plots of drawdown verse time since the pumping started. Specialized plots are semi-log plots of the drawdown verses time or drawdown verses distance to the well, they are specific to a given flow regime. A diagnostic plot allows the dominating flow regimes to be identified; these yield straight line on specialized plots. The characteristic curves help in selecting the appropriate model to identify formation aquifer category, aquifer curve types and proper analysis methods.

In a number of cases, a semi-log plot of drawdown verses time has more diagnostic value than log-log plots. However, it is recommended that both types of the graphs have to be constructed. The choice of the theoretical model is a crucial step in the interpretation of pumping test data. A troublesome fact is that theoretical solutions to well flow problems are usually not unique. Some models develop for different aquifer systems, yield similar response to a given stress exerted to them. This makes system identification and model selection a difficult affair. In many cases, uncertainty as to which model to select will remain. The yield of a well & the shape and the size of the cone of depression are largely determined by the magnitude of the transmissivity and storage coefficient of the aquifer. During the early stages of pumping, most of the water that is abstracted is obtained from the storage of the pumped well. The period of pumping of a well required to achieve equilibrium varies from hours to years according to the nature and type of the aquifer. Consequently, it is important that the type of the aquifer under investigation is identified before a pumping test begins, because the various aquifer types respond to pumping test differently.

Some of the methods available for analyzing pumping test data are based only on the information obtained from the observation holes while others utilize the drawdown observed in the pumped well itself. The pump test data obtained from constant yield tests should be subjected to a preliminary analysis. Perhaps the most important part of this analysis is the rock and aquifer classification. It is a question of whether the pumping test is carried out in an unconsolidated or consolidated: fully confined, unconfined or semi-confined aquifers. Aquifer classification can be made on the bases of data collected during drilling: rock samples, geophysical well logging and groundwater level monitoring give a clue. Nevertheless, the final aquifer classification should be based on the results of the pumping tests.

2.2.1 Time Verses Drawdown Plot

To carry out the preliminary analysis, the drawdown's (s) corrected for natural trends have been plotted against time (t) on semi logarithmic and double logarithmic paper and the resulting curves have been compared with the 'typical curves'. By analyzing the data collected during drilling and by comparing the plotted field data with the typical curves the tested aquifer has been classified. A correct classification of the aquifer type is of vital importance. First, it allows us to select the correct pumping test interpretation method that is for a test carried out in a well test or aquifer test setup.

It also allowed selecting the correct method for the computation of groundwater flow using simple methods or using numerical groundwater models. Most type curves are based on the assumption that, the aquifers are of infinite areal extent and the overlying and underlying confining beds are impermeable and yet no recharge from open water bodies and precipitation. Deviation from these assumptions results in departure from the theoretical time verses drawdown plots. The departures could result due to the effect of an impermeable (or barrier boundaries) or a recharging boundary (See Graph 2.1 A, B, and C, representative Time verses Drawdown plots on double log).

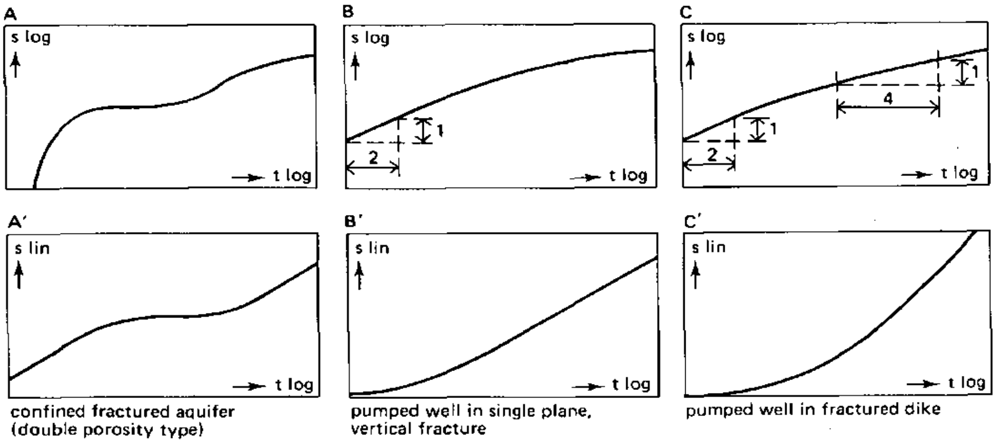


Fig 2.1:- Log-log and semi log plots of the theoretical time-drawdown relationships of consolidated, fractured aquifers:
Parts A and A': Confined fractured aquifer, double porosity type
Parts B and B" : A single plane vertical fracture
Parts C and C': A permeable dike in an otherwise poorly permeable aquifer
(Adopted from G.P Krusman, 1994)

2.2.2 Single Pumping Well Analysis Method

A single-well test is a test in which no piezometers are used. Water-level changes during pumping or recovery are measured only in the well itself. The drawdown in a pumped well, however, is influenced by well losses and well-bore storage. In the hydraulics of well flow, the well is generally regarded as a line source or line sink, i.e. the well is assumed to have an infinitesimal radius so that the well-bore storage can be neglected. In reality, any well has a finite radius and thus a certain storage capacity. Well-bore storage is large when compared with the storage in an equal volume of aquifer material. In a single-well test, well-bore storage must be considered when analyzing the drawdown data.

Papadopulos and Cooper (1967) observed that the influence of well-bore storage on the drawdown in a well decreases with time and becomes negligible at (t > 25 rc^2/KD, where rc is the radius of the unscreened part of the well, where the water level is changing.

To determine whether the early-time drawdown data are dominated by well-bore storage, a log-log plot of drawdown s, versus pumping time t has been made. If the early-time draw downs plot as a unit-slope straight line, we can conclude that wellbore storage effects exist. Most methods are based on the assumption that non-linear well losses can be neglected. Four methods of analysis for single-well constant-discharge tests. The Papadopulos-Cooper curve-fitting method and Rushton- Singh's modified version of it are applicable for confined aquifers.

Jacob's straight-line method, does not require any corrections for nonlinear well losses and can be used for confined or leaky aquifers, and so also can Hurr-Worthington's approximation method. All four methods are applicable if the early-time data are affected by well-bore storage, provided that sufficient late-time data (t > 25 rc^2/KD) are also available. The data obtained from pumping test can be analyzed using two types of formulae, namely, those applicable to equilibrium and non equilibrium conditions. The type of test and analyses employed depend up on the reason for conducting the test. However, the equilibrium equations can be used to predict the response of the aquifer to pumping regardless of which technique is eventually used to analyze the test data.

Generally, certain limiting assumptions have been investigated for the analysis of both equilibrium and non-equilibrium conditions.

- The aquifer contains no boundaries in the area around the well, i.e. it is effectively infinite in aerial extent
- The aquifer has uniform saturated thickness throughout the radius of influence
- The aquifer is homogenous and isotropic
- The slope of the water table, or the piezometric surface is negligible before pumping starts
- The pumped well completely penetrates the saturated aquifer thickness (at least 80%)

Under Theis non equilibrium equation there are two additional limiting assumptions, they are;

- Water storage in the pumped well is negligible
- Water pumped from storage is discharged instantaneously with the fall in head

Theis and Jacob formulated a theory underlying pumping tests carried out in porous confined aquifers whereby groundwater flow to the pumped well is in unsteady state flow. The collection and analyses of unsteady state data in an aquifer or well test set up may be preferred to using steady state flow pumping test data. However, an advantage of using unsteady state pump test data's is the option to compute the storage coefficient of the aquifer. This is not possible in steady state field pump test data's. The other advantage is also it permits measurements from the pumped well and yet transmissivity can be determined at the pumped well and/or at the observation hole and the storage coefficient can be determined at the observation hole only. In steady state flow only a rough estimation of the transmissivity can be obtained. In Theis approach we use the field plot of measured and corrected drawdown data's against time on double logarithmic paper. Also, a type curve is prepared on a double log-paper showing the well function W (u) against (u) or 1/u), because we work on double logarithm paper, the shape of the field curve and the type curve is the same. In Jacob approach, we make a field plot of drawdown verses time in semi-log paper. The plotted points should fall on the straight line. The points corresponding with large u-values (u>.01) may not fall on the straight line. By considering the slope of the straight line shown, we can compute the transmissivity values and yet, the straight line can be extrapolated until it intersects the drawdown is equal to zero axis, and then from the coordinates of the points of intersection we compute the storage coefficients values.

In a single pumping well, there is only one well which used for both pumping and recording drawdown measurement. Single pumping well test data's from confined aquifers can be interpreted by the new derivative analyzing tools of the standard Theis method which assumes well bore storage effect is negligible provided that the recorded drawdown data's are corrected to well lose coefficient values and Papaduplose – Cooper method which accounts effect of well bore storage, and use the diagnostic plots to determine presence of well effect on the drawdown data's during the pumping duration.

The diagnostic plots provide an insight or diagnosis of the aquifer type and conditions. The diagnostic plots are also available for a varity of aquifer types, well effects and boundary conditions.

These plots can be displayed on a log-log or semi-log scales. Each diagnostic plot contains three lines:-

- Theis type curve (dashed black line)
- Theoretical drawdown curve under the expected conditions (solid black line)
- Drawdown derivative curve (solid green line)

The presence of well effect can be confirmed by comparing the observed drawdown data's with the drawdown derivative data's in the well effect diagnostic plot at the early pumping time. If the curve is characteristic of well bore storage conditions, there will be a delay in drawdown as a result of storage in the pumping well and the drawdown deviates from the theoretical Theis curve. However, as pumping duration increase, the drawdown curve becomes more similar to the theoretical Theis curve.

The well effects are more easily identified in semi-log plot of the measured drawdown data's superimposed with the Theis theoretical curve, then, by comparing these plots to the well effect diagnostic plots the presence of the well effects can be confirmed.

Schafer (1978) suggests that in many instances early pumping test data may not fit Jacob's modification of the non equilibrium theory, and that the calculation based on this early drawdown value will be erroneous. These early pump test data reflect the removal of water stored in the casing. When pumping beings, water in the casing is removed first. As water level in the casing falls, water begins to enter the well from the surrounding formation. Gradually, a greater percentage of the wells yield will be from the aquifer. The drawdown value will be higher during the time required to exhaust the casing storage, giving an erroneous low transmissivity value in the early stage of the pumping test.

An interpreter might have mistaken the flattened curve in the early stage of the pumping test which is due to the effect of the casing storage as indication of aquifer recharge. The duration of the casing storage effect varies greatly from well to well depending on the casing diameter and specific capacity. In general, the casing storage effect will last longer for wells with large diameter and low specific capacity.

Papaduplose and Cooper (1967) and Rameyt et al (1973) present equations that modify the early part of the Jacob and Theis curves by taking in to account casing storage. These equations indicate the critical time after which casing storage no longer contributes to the yield of the well.

Most likely, drawdown data collected after this time will represent the true physical conditions within an aquifer.

Unfortunately, these equations can be used only if the transmissivity and well efficiency values are known in advance. Schafer suggests that the critical time (tc) can be calculated by the following equations;

$t_c = 0.6(d_c^2 - d_p^2)/Q/s$ or $t_c = 0.017(d_c^2 – d_p^2)/Q/s$------------------- (1)

Where t_c is time in minutes when casing storage effect becomes negligible, d_c is inside diameter of well casing (in inches), d_p is outside diameter of pump column pipe (in inches) and Q/s is the specific capacity of the well in gallon per meter per feet of drawdown at the critical time.

Determination of true transmissivity value depends on being able to identify whether a casing storage effect has occurred or a recharge boundary has been encountered early in the pumping test.

Analysis of pumping tests in which casing storage is a factor indicate that T1 and T2 can be related by the equation below;

$T_2 = 4T_1/E$--------------------- (2)

Where T1 is the transmissivity value reflecting the true aquifer characteristics and T1 is the apparent transmissivity calculated from the portion of the graph affected by casing storage and E is the well efficiency value. This equation can be used to check calculated transmissivity values and well efficiency values derived from pumping tests, especially, when data from the pumped well are the only data available. The numerical value of 4 on the right side of the equation is based on the value of the exponent of the storage coefficient that is $S = 10^{-4}$, it will change as the exponent varies. Careful collection of early time – drawdown and recover values can be enhance the data base used to evaluate wells and aquifers. The effect, however, of the casing storage on the early measurements cannot be ignored and must be incorporated into the overall data analysis. Estimation of the critical time by equation (1) aids in the interpretation by determining which data are influenced by casing storage and are therefore not subject to conventional analysis. Equation (2) then provides a useful check on obtained values of transmissivity and well efficiency.

2.2.3 Analysis of Step Drawdown Test

A step-drawdown test (or *step test*) is a single-well pumping test designed to investigate the performance of a pumping well under controlled variable discharge conditions. In a step-drawdown test, the discharge rate in the pumping well is increased from an initially low constant rate through a sequence of pumping intervals (steps) of progressively higher constant rates. Each step is typically of equal duration, lasting from approximately 30 minutes to 2 hours (Krusman and de Ridder,1994)).

In addition to estimating hydraulic properties of an aquifer system such as transmissivity and hydraulic conductivity, the goal of a step-drawdown test is to evaluate well performance criteria such as well loss and well efficiency.

All conventional well hydraulic theory is based on the assumption that, laminar flow conditions exist in the aquifer during pumping. If flow is laminar, drawdown is directly proportional to the pumping rate. If turbulent flow occurs, the linear relationship between drawdown and pumping rate no longer holds and part of the drawdown is generally related to the pumping rate raised to some power greater than one.

When turbulent flow occurs, the specific capacity will decline, often dramatically, as the discharge rate is increased. When this happens, it is useful to have a means of computing the turbulent and laminar drawdown components in order to make proper judgments concerning pumping rate and pump –setting depth. For laminar flow condition in a perfectly efficient well, drawdown in confined aquifer can be expressed as :-

$s = 264Q/T \text{ Log } (0.3Tt/r^2S)$ ------------- (1)

The above equation can be shortened as below,

$s = BQ$---------------- (2)

Where,

$B = 264/T \text{ Log } (0.3Tt/r^2S)$ --------------- (3)

For a specific well, the value of B (Aquifer loss factor) is time dependent. However, B changes only slightly after a reasonable pumping duration and can thus be assumed to be a constant. When turbulent flow occurs, Jacob suggests that the total drawdown in a well can be more accurately expressed as the sum of a first order (laminar) drawdown component and a second order (turbulent) drawdown component.

$S = BQ + CQ^2$ --------------- (4)

The first term of the equation (BQ) describes the linear component of the drawdown; i.e., the part in which doubling the pumping rate doubles the drawdown.

The second term (CQ^2) describes what is often called the 'well losses'; the non-linear component of the drawdown. To quantify this it is necessary to pump the well at several different flow rates (commonly called steps). Rorabaugh (1953) added to this analysis by making the exponent an arbitrary power (usually between 1.5 and 3.5).

To analyze this equation, both sides are divided by the discharge rate (Q), leaving s / Q on the left side, which is commonly referred to as specific drawdown. The right hand side of the equation becomes that of a straight line. Plotting the specific drawdown after a set amount of time (Δt) since the beginning of each step of the test (since drawdown will continue to increase with time) versus pumping rate should produce a straight line.

$S/Q = B + CQ$ ----------------- (5)

Fitting a straight line through the observed data, the slope of the best fit line will be C (well losses) and the intercept of this line with Q = 0 will be B (aquifer losses). This process is fitting an idealized model to real world data, and seeing what parameters in the model make it fit reality best. The assumption is then made that these fitted parameters best represent reality (given the assumptions that went into the model are true).

Analysis of real well, however, have show that this correlation is not correct, because, the BQ term almost always includes a major portion of the well losses and CQ^2 term occasionally includes some aquifer losses.

For such reasons, computing well efficiency percentage from a step drawdown test results incorrect values. However, step drawdown test remains helpful, in estimating the magnitude of turbulent head loss for the purpose of determining optimum pumping rates.

Inverting terms in equation five shows how specific capacity declines as discharge increases when only turbulent flow occurs.

$Q/s = 1/CQ + B$ ------------------- (6)

A parameter often computed from a step drawdown test is the ratio of the laminar head loss to the total head loss expressed as a percentage.

$Lp = (BQ/BQ + CQ^2) * 100$ -------------------- (7)

Lp is the percentage of the total head loss that is attributable to laminar flow. If the assumptions made by Jacob were correct, that aquifer loss equals BQ and well los equals CQ^2, the Lp, would equal the well efficiency. However, testing of hundreds of wells has shown that these assumptions are not correct. Depending on the exact nature of the aquifer, the specific capacity may seem to improve with higher discharge rate and longer pumping time, a highly unlikely situation that will occur rarely, if ever, in natural geologic materials.

The efficiency of a pumped well in some cases can be estimated from the distance verses drawdown graph. This can be done by extending the straight line representing the profile of the cone of depression to show the drawdown in the aquifer just outside the well. The intersection of the extended line with the radius of the pumped well shows the theoretical drawdown for a 100% efficient well. The result is valid for a confined aquifer only when the full thickness of the aquifer is screened. The theoretical drawdown of a pumped well can be compared with the actual drawdown by extending the straight line on the distance verses drawdown diagram to a point where the radius of the well (outer face of the well) is indicated on the horizontal line.

The factors contributing to excess drawdown in wells (inefficiency) can be grouped in to two classes. One class comprises those factors related primarily to choice made in the design of wells, the other class includes factors related to well construction.

Design factors include:

- Choice of well screen with insufficient open area that makes entrance velocities too high, resulting in a greater than normal entrance (head) losses.
- Poor distribution of screen openings causes excessive convergence of flow near the individual openings and may produce twice as much drawdown as necessary.
- Insufficient length of well screen, resulting in partial penetration of the aquifer, distorts the flow pattern for some distance around the well.
- Improper sized filter packs or those made from angular or plate like materials can restrict flow in to a well screen, particle shape, size and grain size distribution affect the hydraulic conductivity of the pack.

Construction factors contributing to well inefficiency include:

- Inadequate development of a well reduce original permeability of the formation
- Improper placement of the well screen may put it at a depth that does not cross pond to the best water-bearing formation.

The amount of drawdown required to produce a particular yield is determined by the hydraulic nature of the aquifer and the care with which the well was designed, constructed and developed. Drawdown caused by friction losses in the aquifer as water flows to a well is unavoidable. But, substantial head losses sustained as water passes through the disturbed zone around the well are avoidable. They are caused by drilling fluid left in the formation, damage to the formation caused by drilling, the presence of a poorly design filter pack, or use of a well screen with limited open areas.

Good design practices and enlighten drilling methods can ensure that head losses through the zone near the well hole will be minimal. Well screen with maximum inlet areas, surrounded by a suitable filter pack and in turn surrounded by a formation developed properly to remove drilling fluids and fine materials are necessary for minimizing head losses.

Real aquifers do not conform fully to assumed geologic or hydrologic conditions. Thus, limits for the use of the Jacob equations must be set for those cases in which the differences are significant.

Some major hydro-geological factors that affect the Time verses Drawdown graphs are:-

- Precipitation recharge
- Surface water recharge
- Slow drainage
- Impervious boundaries
- Vertical leakage
- Casing storage

The above equation (7) tells us with increasing the pumping rate the well efficiency decreases. At high pumping rates the well loss may large when the well loss factors B & C take on significant values. Generally when B & C values are small, the wells are efficient. However, if the screen of the well or its gravel pack have not been properly designed or been put in to place (high entry resistance and/or excessive turbulence) the B and C values can be high and the well efficiency will be low.

High values, in particular for B (aquifer loss coefficient) may also be found in a well that have not been properly developed after drilling and during production when the well screen become clogged due to bacterial slim, calcium carbonate precipitate or encrustation of Iron.

The relation of well loss coefficient 'C', to a well condition (after Walton[14]) is given as below.

Well loss Coefficient ('C' (min^2/m^5))	**Well Condition**
< 0.5	properly designed and developed
0.5 to 1	mild deterioration due to clogging
1 to 4	sever deterioration or clogging
>4	difficult to restore well to original capacity

2.3 Estimation of Transmissivity from Specific Capacity

Specific capacity is a quantity that which a water well can produce per unit of drawdown. Specific capacity tests are useful for estimating transmissivity in aquifers that have few good-quality pump tests (Robert E.mace, 1997). Specific capacity is commonly used to estimate transmissivity because specific capacity data are generally much more abundant than aquifer test data. Transmissivity and specific capacity field data's can be related by, Analytical, Empirical, Geo-statistical and hybrid methods. Specific capacity is in part, a function of the hydraulic properties of an aquifer.

Relating specific capacity to transmissivity can increase the value of transmissivity estimating an aquifer by an order of magnitude. Incorporating specific capacity data's in to hydrogeological assessments allows a more rigorous characterization of the hydraulic properties of a regional aquifer and a better understanding of the flow in an aquifer (Hororaka & others, 1998). The appropriate technique for relating specific capacity to transmissivity depends on, well construction, aquifer setting, pumping rates and number of available well tests, and ultimately, the accuracy of the applied technique.

Specific capacity value in semi confined and confined aquifers will tend to have a lower value which is due to less drawdown caused by additional flow in to the well.

2.3.1 Analytical Methods

One approach of estimating transmissivity from specific capacity is to use analytical equations such as those derived by Thomsonet.al (1960),Theis(1963),and Brown (1963).In this method relating transmissivity to specific capacity involves using mathematical equations based on the theory of groundwater flow. These methods are advantageous, because, they are exact. Their application can be limited due to

- Unrealistic assumptions about the aquifer and well hydraulics
- Limited information on the aquifer or the well

However, Razack and Huntly (1991) and Huntly et.al.(1992)showed that the analytical solutions under predict transmissivity in heterogeneous alluvial aquifers and over predict transmissivity in fractured rock aquifers because the analytical solutions assume negligible well loss and a heterogeneous ,isotropic ,granular aquifer.

Thomasson and others (1960), used the Dupuit-Theim equation to show that transmissivity is linearly related to specific capacity by a constant (Cc). This approach assumes that water levels are in steady state and that, storativity, partial penetration and well losses do not influence results. Use of Dupuit-Theim equation requires an assumption on the radius of influence. The steady state radius of influence is dependent on aquifer properties and aquifer setting and is greater for greater transmissivity and comparatively greater for confined aquifers than for unconfined aquifers with similar transmissivity (Driscoll, 1986).

Therefore, the constant (Cc) is partially a function of transmissivity which results in a nonlinear relationship between transmissivity and specific capacity. By this method, Adyalkar and others (1981), calculated the constant (Cc) to be 0.42 for the weathered zone of massive and vesicular basalts of the Deccan trap in India.

2.3.2 Empirical Methods

Instead of using the analytical equations, Razack and Huntly (1991) and Huntly et al. (1992) developed empirical relationships between transmissivity and specific capacity for each aquifer. These methods involve statistically relating transmissivity to specific capacity using paired values of both parameters measured in the same well.

These methods are advantageous, because, the uncertainty in the estimate can be estimated and because, many non ideal conditions, such as, turbulent well loss, are indirectly considered. However, their application can be limited due to too few measurements of transmissivity or too much uncertainty in the relationship compared to actual heterogeneity of the aquifer. As stated by Eagon and Johe, 1972, these methods involve;

- Fitting a line to a cross plot of measured specific capacity
- Determination of well loss constant determined from step-draw down tests
- Compiling all available aquifer test information’s for an aquifer
- Determining the transmissivity and specific capacity data for each of the tests
- Using regression to fit a line to the plotted pairs of log-transmissivity and log-specific capacity
- Calculating the uncertainty in the linear relationship between transmissivity and specific capacity

Uncertainties of estimating well loss are too great, especially when compounded with an uncertain relationship between transmissivity and corrected specific capacity.

For empirical relationship between transmissivity and specific capacity, at least 25 boreholes pumping test of constant discharge rate and step drawdown test data’s is very essential as long as the two pair variables are data’s of a single well.

2.4 Relationship of Specific Capacity Verses Aquifer Thickness

Specific capacity can be normalized to aquifer thickness using the specific capacity index (Si) (Davis & DeWeist, 1966). They normalized specific capacity data to aquifer thickness using specific capacity index by the below equation;

$$Si = Sc/b$$

Where Si, is specific capacity index, Sc, is specific capacity and b, is aquifer thickness.

Poland (1959) and Thomasson and others (1960) calculated specific capacity index using units of gram per meter and feet multiply it by 100ft, and call the result as the “yield factor”, which normalizes specific capacity to a 100ft thick aquifer. Specific capacity index has the same units (L,t-1) and is somewhat analogous to the hydraulic conductivity. Specific capacity index is not commonly used, though it has been used instead of specific capacity to remove the effect of aquifer thickness variation on aquifer productivity (Siddiqui & Parizek, 1971; Lariccia & Rauch 1977; Gelbaum, 1981).

Some wells will be screened in multiple production zones in an aquifer or group of aquifers to achieve the desired yield. For example, a well might be screened from 30 to 40m, 50 to 60m and 65 to 80m. Therefore, the production of the well, and thus the value of the specific capacity are from a combination of the producing zones;

$$Sc = \sum_{i=0}^{n}(Sc)n$$

Where n is the number of the production zones. Back calculating the specific capacity of each zone is not possible unless specific capacity is measured at different well depths as the well was drilled or after the well was drilled by isolating each well section.

Walton (1970) described an approach to qualitatively determine if deeper units are less or more permeable than upper units. This is done by first calculating the specific capacity index for each well, segregating the wells into categories based on formations penetrated or depth of the penetrated formation and comparing the distribution of the specific capacity index for the different categories of the wells. The increase of specific capacity index with depth indicates that the lower units are more productive and vice versa .This relationship can be also evaluated by using the geometric mean of the specific capacity index.

3. Geology and Hydrogeology

3.1 Regional Geology

The eruption of voluminous fissural and central type volcanic during the Cenozoic is the fundamental geological event in the horn of Africa. In Ethiopia the Cenozoic rocks (trap series) cover very wide area overlying the Mesozoic sedimentary rocks forming highlands or plateaus. They are highly weathered and form thick residual soils.

The Ethiopian flood basalts (or traps), covering an area of 600,000Km^2 (Mohr & Zanettine, 1988), are the youngest examples of a major continental volcanic plateaus (see table 3.1, below). Because of their relatively young age and their eruption in a region where plate movements are slow, we can find a complete record from the initial, high-flux, flood volcanic phase through to its shutdown and the onset of continental rifting, and finally the initiation of sea-floor spreading. The region represents an ideal situation to study the nature of the mantle source of continental flood volcanism and the manner in which magmas derived from this source interacted with the continental lithosphere, as has been done by researchers such as Mohr & Zanettine (1988), Baker et.al. (1996a), Hofmann et al. (1997), pik et al (1998, 1999) and Baker et al.(2000,2002).

These flood basalts have a layer of basaltic and felsic volcanic rocks whose thickness is highly variable but reaches up to 2km in some regions. Plateau basalts are overlain by huge shield volcanoes (like Mt.Choke and Guguftu, 22 Ma; Mt.Guna, 10.7 Ma) which are bimodal and mainly composed of alkali lavas (sequences of alternating basalts, rhyolitic and trachytic lava flows, tuffs and ignimbrites) particularly near their summits (Kieffer et al, 2004). The flood volcanic in the northwestern Ethiopia evidenced that most of the Ethiopian flood basalts were erupted some 30Ma ago (Courtillot et al, 1987, Hempton, 1987, Jestin & Huchon, 1992).
These Cenozoic continental flood basalts form part of the larger Afro-Arabian Igneous Province, which is related to the Afar plume and the Red Sea-Gulf of Aden - Ethiopian Rift triple junction.
It is generally accepted that, Ethiopian volcanics were divided into two main Series: Trap Series (or plateau Series or flood basalts) and Rift volcanics (Mohr, 1971 and others).The maximum thickness of Trap Series on the Ethiopian plateau is 3500m and is represented by Semien Mountain while in the NE plateau the maximum thickness is 2500m on Arsi highland.

Table 3.1:- Some prominent Characters of Continental Flood Basalt Volcanics.

(After G.V.S.Poornachandra Rao, 2003)

Flood Basalt Province	**Age Ma**	**Hotspot Source**	**Area ($10^6 km^2$)**	**Geological Boundary**	**Magnetic Polarity**
Columbia River basalts	17.5-6	Yellow stone	0.164	Miocene	Mixed R-N
Ethiopian traps	30	Afar	0.5	Oligocene	R-N-R
Deccan Traps	68-63	Reunion	0.5(1.5)	Cretaceous-tertiary	N-R-N
Parana basalts	130-120	Tristan da Cunha	0.79(1.2)	Jurassic –cretaceous R	Mixed
Karoo /Etendeka	198-204	Crozet/Marion/	1.5(3)	Triassic- Jurassic	Mixed
Siberian traps	250-245	Jan Mayan	1.5(3)	Permian-Triassic	R-N Normal

The Northwestern plateau of Ethiopia is almost entirely covered with extensive continental flood basalts that mask the underlining formations(see fig 3.1 below). Various volcanic episodes and lava flows were followed by short or longer periods of river, lake sediment and soil development that can be found within the volcanic sequence. Traditionally, the Ethiopian flood basalts have been subdivided by Blanford (1869, 1870) in to two groups; the lower Ashange and the unconformably overlying upper Meqdala groups. But a more detailed ,an entirely new stratigraphic scheme of the flood basalt pile was developed by Zenettin and Justin(1973) which has been incorporated into Merla et al' s(1973) comprehensive geological map.

Ashange group:-consists predominantly of thick basalt lava flow. It is injected by dolerite sills, acidic dikes, and gabbro-diabase intrusions. This formation occurs in the north westerly trending rift system now buried under younger volcanic.

The Ashange group with thickness that varies from 200-1200m was occurred in two cycles. The first is, the Ashange cycle and the second is the post Ashange cycle (Zanettin, 1993). Ashange cycle outcropped in Wollega (W. Ethiopia, Seifemichael, et al, 1987), SW Ethiopia (Davidson and Rex, 1980) and SE plateau (Mohr, 1971).

The fissural basalts are represented by transitional basalts with tholeiitic affinity, while the more frequent moderately fissural basalts are still transitional but with alkaline affinity, and are characterized by a lower Na_2O/K_20 ratio and lower content in Al_20_3 (9- 12%). The post Ashange cycle is a plateau sequence which contain Aiba and Alaji fissural volcanisms. The Aiba basalts are typical of transitional basalts with homogeneous composition. They are followed by Alaji volcanics, containing interlayered silicic rocks (perlalkaline rhyolite) and transitional basalts.

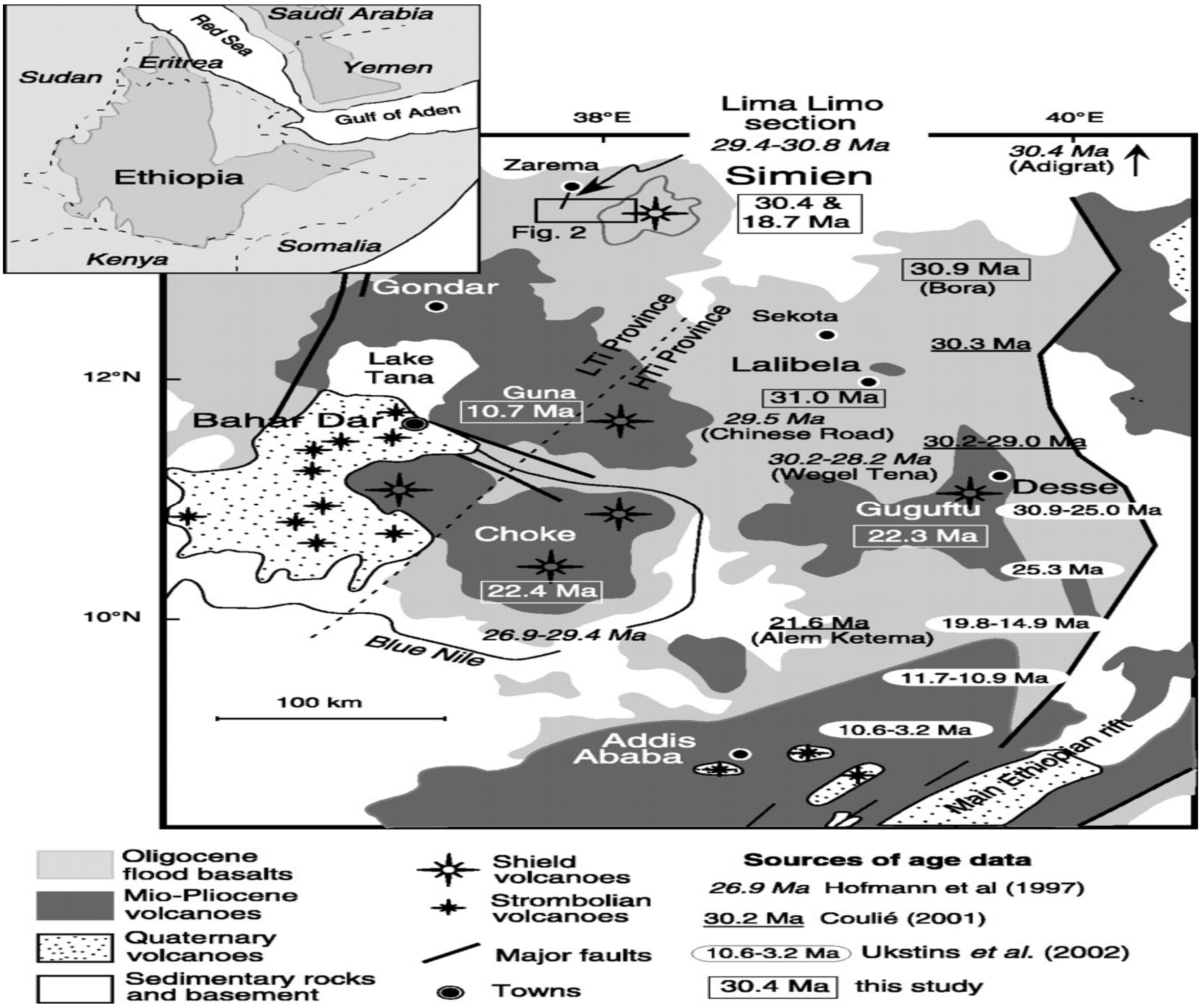


Fig. 3.1. **Map of the northern part of the Ethiopian plateau showing the extent of the flood volcanism and the location and ages of the major shield volcanoes (after Kieffer et al 2004).The dashed line shows the boundary between the LT and HT provinces of** Pik *et al.* (1998)**. The inset shows the location of the Ethiopian volcanic plateau (in grey) in the Horn of Africa**.

The fissural Alaji volcanism is followed by central volcanism, which built up large shield volcanoes called Tarmaber central volcanics (Mohr, 1971b).Magdala group (currently named as Upper basalt formation) Outcropped within the Ethiopian rift, on the escarpment and nearby plateaus. The thickness of the unit increases away from the rift (Morton et al 1980). Acidic rocks dominate including acid tuffs, mostly ignimbrites, pantelleritic rhyolites and trachytes. They are inter-bedded with lavas and agglomerates of basaltic composition. In Quoram, there is 1200m thick Ashangi group forming the lower part with the top more silicic 300m Maqdala group(Tamiru,2006).

The Ashange formation named in its type area at Lake Ashange, 50km south of Amba Alaji, applies to strongly weathered and tilted (?)basalts without clear stratification having a thickness of several hundreds of meters(B. Zenetin et.al, 1980). Unliken the Aiba formation which is characterized by a huge tholeiitic basalt pile and alkaline Tarmaber basalt ,the Ashangi basalts are transitional basalt flows with rare tuff intercalations(Justin-Visentin 1974, Zanettine and Piccirillo, 1978). These earlier classifications of flood basalts put the age of Ashange as Eocene. The geological map of Ethiopia, published in 1996, depicts the Ashange basalt to be pre-Oligocene age of the tertiary period. However a more comprehensive and recent study by the French researchers in the 1990's rather shows a continuous succession of the Ethiopian flood basalts all dating back to ~30my erupted in a span of 1ma(see fig 3.1 above).The whole volcanic sequence has been emplaced with no apparent development of paleosoils and erosional surfaces (Rochette et al., 1998).

Bedding is a primary structure noted in Ashangi basalt. The bedding in the Ashangi formation is formed as the alternation of aphanitic (see plate 3.3 below), phenocrystic and amygdale basalts, and dips between 10-20 degree to NE, SE and E.

Ashange is a basaltic formation marked by its deep weathering, thin layering (<10 meters), smooth topography and cross cutting sets of dykes. There are minor acid products (such as volcanic ash, rhyolites, and ignimbrites) in the Ashange formation. Individual flows are discontinuous laterally and have irregular thicknesses.

Plate 3.1, Ashange basalt cliff near Ashange Lake (12^{o}32’-12^{o}39’ N latitude, 39^{o}27’-39^{o}32’ E longitude and 2440 masl).

Plate 3.2:- outcrop of Ashange basalt (after explanatory notes of Adi Ramets are by GSIE)

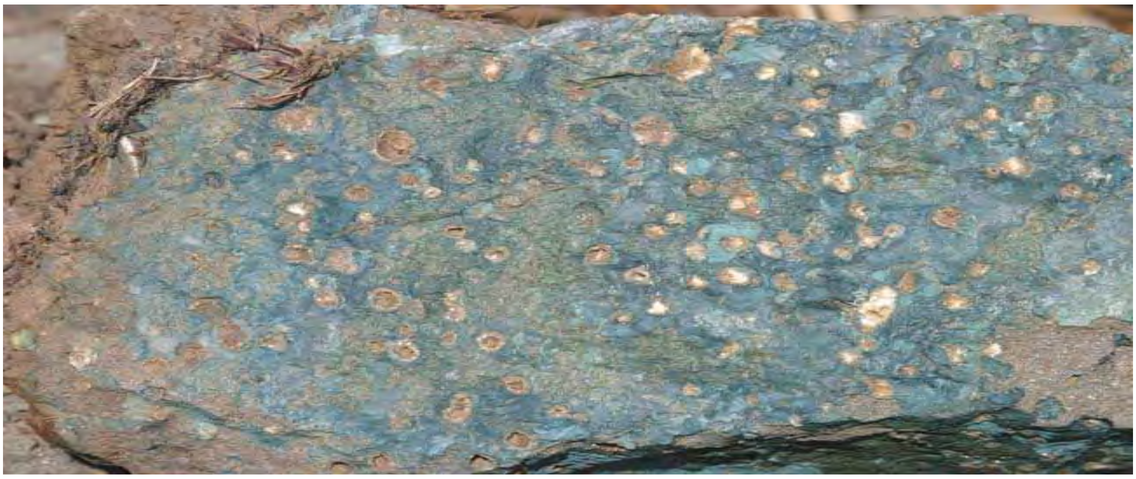


Plate 3.3:- Alteration in the Ashange basalts

Intrusions of diabase and dykes are common in the Ashange formation (see fig 3.1 below). In the north central sector extensive quartz and opal mineralization owing to paleo thermal groundwater circulation has been noted. In most parts brecciated materials has been noted in the Ashange formation. The most extensive breccia is being observed in the Weleh valley south of Sekota area at the foot hill of the Amdework ridge. Evolved acidic product is minor in the Ashange formation.

By contrast, the Aiba formation is a succession of massive cliffs corresponding to thick (10 to 50m) basaltic flows (Rochette, et al. 1998). The Aiba and Alaji formations are marked by their relative freshness, thick layering, and cliff forming topography. Frequent lacustrine deposits have been marked in the Aiba formation as evidenced by lenses of diatomites and porcelain lithologies particularly surrounding the Sekota complex. Tarmaber formation is marked by its jointing, thick layering, cliff forming topography with flat tops.

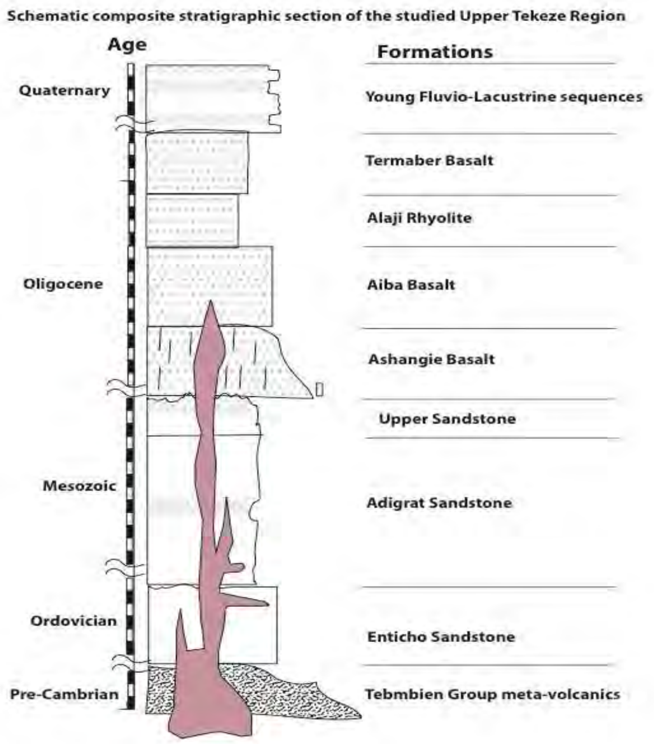


Fig. 3.2 ***Stratigraphy of the Upper Tekeze River Basin. The red intrusion is Dolerite formation (Adopted from first draft report of upper tekeze Basin).***

Ashange formation is an extensive development of fissural eruptions in Oligocene period that produced a thick succession of the trap serious basalts formings the north western and southern Ethiopian plateau. The Ashange basalt is thus considered to be the lower formation in the stratigraphy of Ethiopian volcanic plateau commonly injected by dolerite sills, acidic dykes and other intrusions. The top most part of the group is tuffacious, contains lacustrine deposits in some places including lignite seams and acidic volcanic.

The Ashangi formation is divided into aphanitic and amygdaloidal basalts according to its textural property. Aphanitic basalt again is divided into olivine, pyroxene, olivine-pyroxene and anorthoclase basalts in terms of phenocrystic. The Aphyritic vesicular basalt is dark to dark-gray in color. It shows flow layers in places and in others boulder type basalts are seen.

Chonchoidally fractured portions with less vesicles are also seen in some places. In other layers within this unit, highly altered secondary green minerals are common. The distribution of secondary minerals is also variable and shows a higher alternation of the rocks at depth. Vertical, columnar and inter-bedding jointing also occurs in the aphanitic basalt of the Ashangi formation (See plate 3.4). Faults running in a EW, SE, or SSE direction can be locally found crossing this unit.In amygdaloidal basalt, there may be a case that amygdale is included in both aphanatic and anorthoclase basalts. In the aphanatic basalt amygdale is 1mm-15mm in size, it's surrounding composed of aphanitic quartz and central quartz crystal. In the anorthoclase basalt amygdales consist of basic feldspar or rarely olivine, quartz and calcite. Less developed vertical, polygonal and inter-bedding fissures also occur in the amygdale basalts.

Plate 3.4 columnar Jointing and inter-bedding in the Ashange basalts

Intercalation of aphanitic and amygdale basalts are common in Ashangi formation with thickness of every bed being between 2m to 5m as shown in plate 3.5 below. Lithological log data information shows a variable degree of weathering, fracturing and even different color staining and a variable extent of vesiculation and vesicle fillers are reported.

Plate 3.5 Aphanitic and amygdale basalts in Ashange formation beds (adopted from Preliminary geological investigation on the Raya basin)

Ashangi basalts in general are well-fractured and weathered basaltic rock. They are mountain or cliff forming with several flows layered like slices of bread. The flows are sometimes tilted and are highly fractured and faulted with respect to the overlying Aiba basalts (Merla et al., 1979). Like the Alaji basalt rocks, the rocks in this group also have different layers that show the differences in eruption times of the layers. The surface geology of Ethiopian Ashange formation is shown in fig 3.2 A and B below.

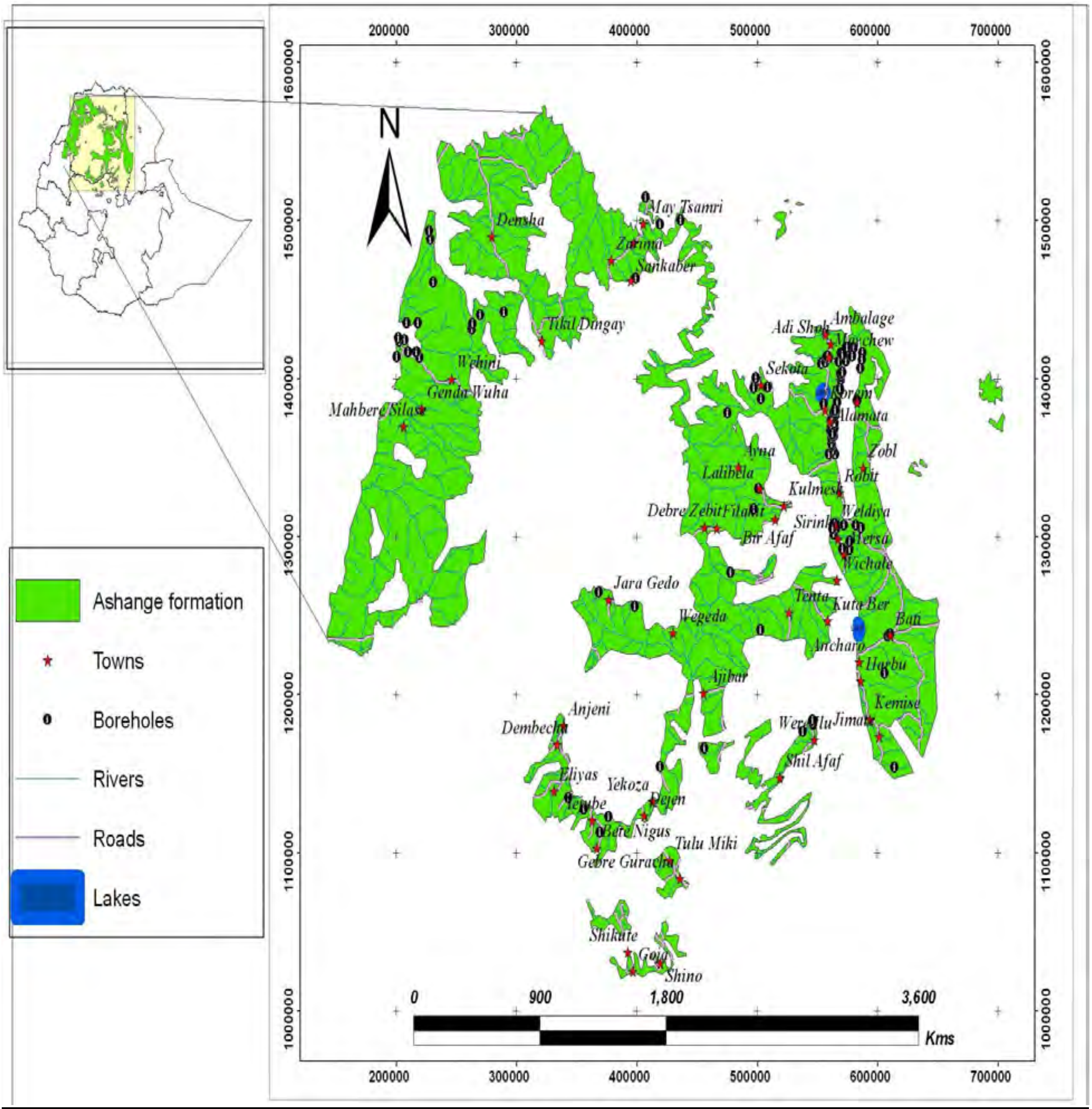


Fig.3.3a , Geological map of ASHANGE formation in Northwestern, South Eastern and Central highlands

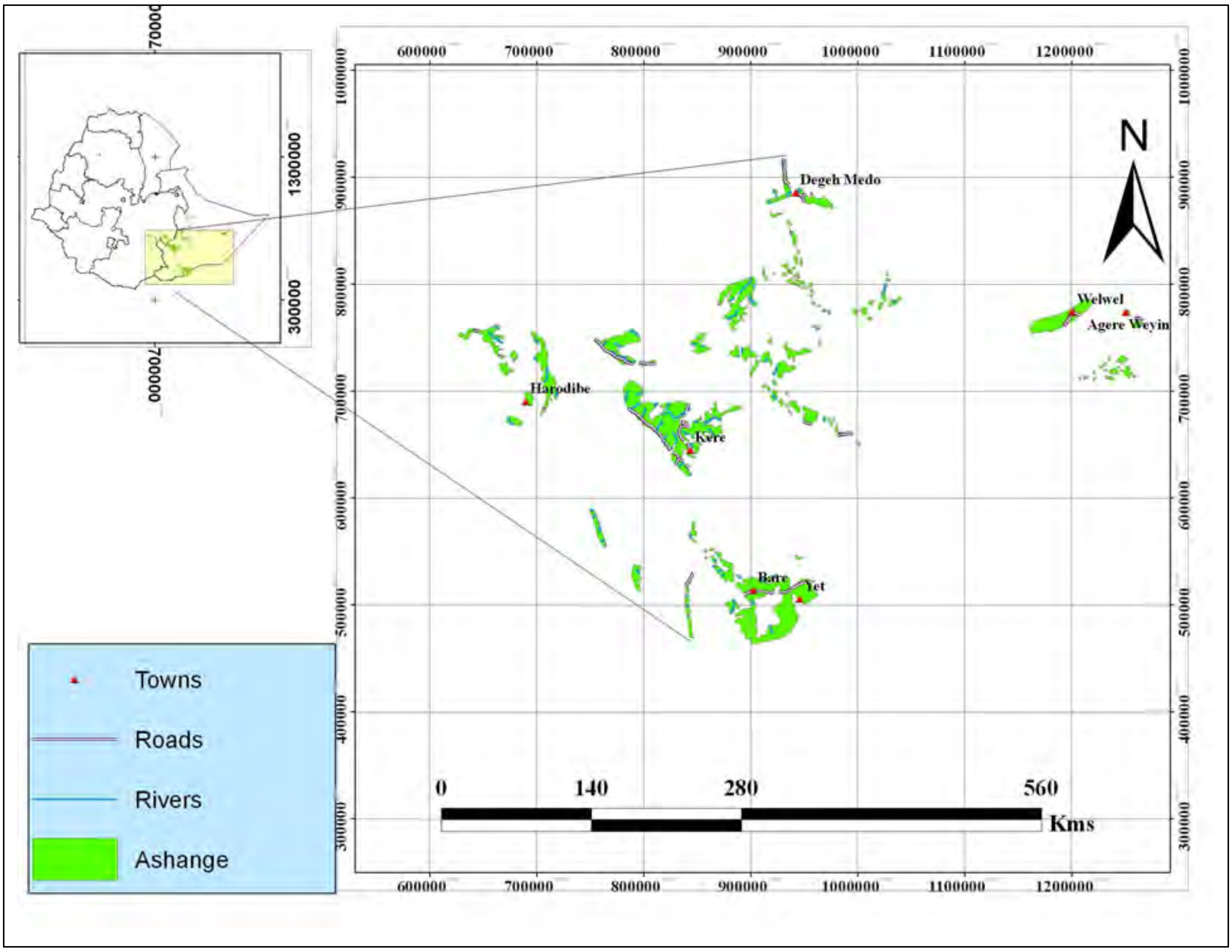


Fig.3.3b, Geological map of ASHANGE formation in the Southern part of Ethiopia

The total surface area covered by Ashange is estimated here to cover 85,000km^2 .According to Raphael pik et.al 1998 the average thickness of Ethiopian flood is taken as 0.75.This gives a total volume of 63,700 m^3. When compared to the total volume of Ethiopian flood basalts (180,000 km^3), the Ashange formation covers about 35 % which is a huge amount as compared to upper formation flood basalts.

Well data are not found from Ashange formation in the southern part of Ethiopia. Thus, only well data collected from the Northwestern and central part of Ethiopia will be used for description and analysis.

1.2 Regional Hydrogeology

Ethiopia is characterized by high-altitude volcanic plateaux tapering into Rift valley and peripheral lowlands. The country has huge groundwater potential, mostly localized in the volcanic terrain covered with Quaternary deposits.(Tenalem,A.2009). These volcanic terrain and associated Quaternary deposits represent complex aquifer systems where groundwater occurrence and distribution is strongly controlled by the geo-morphological architecture of the plateaux, escarpments and the rift valley. The complex spatial and temporal distribution of the volcanic rocks, their different intricate stratigraphic and structural relationships, wide compositional variability, different level of weathering and topographic position complicate the hydrogeological behavior of the volcanic aquifers and the hydrochemical signature,(Tenalem A.2009). The main source of groundwater recharge is rainfall and river channel losses. The average yearly groundwater recharge for the entire country is around 2.8 billion cubic meters (Tadesse, 2004).The major recharge occurs in the highlands where annual rainfall is more than 1000 mm.

The hydrogeological map of Ethiopia at a scale of 1:2,000,000 was published by Tesfaye Chernet (1993). He classified the geological units of Ethiopia into four major groups depending on the type of permeability and the extent of the aquifer. This hydrogeological map was the basic document for preparation of the field work. Tesfaye (1993) identified the following units:

- Mesozoic sediments (south of the mapped area) and volcanic rocks with fissured permeability, and lacustrine sediments nearby Lake Tana, alluvial sediments and eluvia along rivers and plain areas with inter-granular permeability. Aquifers were classified as moderately productive. The specific yield of wells was estimated to be in interval 0.05 – 1.1 l/s/m of drawdown and total yield of wells with 20 m of drawdown varies in interval 0.45 – 9.9 l/s. These moderately productive aquifers include most of the Tertiary volcanic rocks in the highlands, as well as Quaternary sediments in the lowlands. Recharge and discharge characteristics were derived for 50 – 150 mm/year for the lowlands and 150 – 250 mm for the highlands.
- The highlands were classified as an area with major water resources. These were assessed to be widespread and moderate to large in quantity. Groundwater and surface water are of good chemical quality (TDS less than 500 mg/l).

Most of the streams are perennial; there are many cold springs, and the groundwater level is between 0 and 100 m and can be exploited in low relief areas (valleys).

- The lowlands were classified as an area with major water resources. These were assessed to be widespread and moderate to large in quantity. Groundwater and surface water are of variable chemical quality (TDS 500 – 1,500 mg/l), with most of the perennial streams, and with a groundwater level of below 150 m.

The hydrogeological map shows aquifers and aquitards defined based on the character of the groundwater flow (pores, fissures), the yield of springs and the hydraulic characteristics of boreholes. The following aquifers and aquitards were defined:

1. Extensive (larger than 100 km^2 – 2,579 km^2) and moderately productive or locally developed and highly productive porous aquifers (T = 1.1 – 10 m^2/d, q = 0.011 – 0.1 l/s.m, with spring and well yield Q = 0.51 – 5 l/s. Aquifers consist of Quaternary unconsolidated deposits and slightly consolidated Tertiary sediments.
2. Extensive (larger than 100 km^2 – 16,939 km^2) and moderately productive or locally developed and highly productive fissured aquifer (T = 1.1 – 10 m^2/d, q = 0.011 – 0.1 l/s.m, with spring and well yield Q = 0.51 – 5 l/s). The aquifer is shown in light green. The aquifer consists of basalts, associated pyroclastics and sandstone.
3. Extensive (larger than 100 km^2 – 562 km^2) low productive fissured aquifers y (T = 0.11 – 1 m2/d, q = 0.0011 – 0.01 l/s.m, with spring and well yield Q = 0.051 – 0.5 l/s). The aquifer is shown in a brown red color. The aquifer consists of basement rocks (no data on sheet but analogy from the adjacent Adi Ramets and Abu Ramla sheets).
4. Aquitards and/or Minor aquifers – 140 km^2 with local and limited groundwater resources (T = 0.01 – 0.1 m^2/d, q = 0.0001 – 0.001 l/s.m, with spring and well yield Q = 0.005 – 0.05 l/s).

The aquifers consist of Tertiary volcanic rocks (dominating trachyte) of a limited extent. The aquifers are shown in light brown. Ashange basalt is thus classified under extensive and moderately productive fissured aquifers.

The flood basalts of Ethiopia are highly productive commonly in their scoracious basaltic layers; the productivity of these formations considerably varies from place to place. The yield of aquifers from lower formation (Ashange group rocks) varies from 1lt/s to 5.6 lt/s on average. In the northwestern plateau areas, it varies from 0.4lt/s to 6.3lt/s and that for southeastern plateau varies from 1.2lt/s to 5lt/s.

For the upper formations (Maqdala group rocks) it ranges from 1lt/s to 12lt/s. The yield is extremely high in some localities due high degree of fracturing and the presence of paleo-valleys and buried river gravels in paleo-channel at depth. The major water bearing layers are made of scoracious basalts (Tamiru Alemayehu, 2006).Another classification of aquifer productivity is also done by Sima et al. (2004) in Explanatory Notes to the Hydrogeological and Hydrochemical Maps of the Adi- Ramets Area (ND 37-5 Adi Ramets and ND 37-9 Gulch sheets) described the following:-

- Extensive and moderately or locally developed and highly productive porous aquifers with T = 100 – 10 m^2/d, q = 1 – 0.1 l/s.m, Q = 5 – 1 l/s for alluvial and lacustrine sediments and pyroclastics.
- Extensive and moderately or locally developed and highly productive fissured aquifers T =100 – 10 m^2/d, q = 1 – 0.1 l/s.m, Q = 5 – 1 l/s for Adigrat Sandstone and associated siliceous mudstone, Termaber basalt, Alajae basalt and rhyolites, Ashangi basalt.
- Extensive and low productive fissured aquifers with T = 10 – 1 m^2/d, q = 0.1 – 0.01 l/s .m, Q =1 – 0.5 l /s rocks of Angereb ring complex and Precambrian metamorphic rocks of the Tembien Group.
- Aquitards and/or Minor aquifers with local and limited groundwater resources with T =1 – 0.1 m^2/d, q = 0.01 – 0.001 l/s.m, Q = 0.05 – 0.5 l/s for Alkali trachyte, Rhyolite and tuff and Precambrian metamorphosed rocks of Dikama Formation and Tsalie Group: penetrated by granite and diorite).

Volcanic rocks of the plateau represent large and moderately productive fissured aquifers which are the principal aquifers on the map sheet. The nature and distribution of aquifers and aquitards in a geologic system can be identified by having a clear knowledge on:-

- Lithology including mineral composition, grain size, grain package of sediments and rocks.
- Stratigraphy which describes the geometrical and age relationships of geological systems
- Structural features including bedding, jointing, fracturing, weathering, folding and faulting.

Groundwater is mostly under water table conditions, however semi-confined conditions can be found in a large number of the wells. These semi-confined conditions are a result of vertical as well as lateral heterogeneity of volcanic rocks partly intercalated by various permeable and impermeable sediments.

Recharge rate estimation assumes that recharge takes place via soils depending upon the soil moisture capacity, monthly soil moisture surplus or deficit and amount of rainfall.

Different aquifer systems in various parts of Ethiopia have variable discharge rate depending upon the aquifer system (see table 3.2 below).

Aquifer size, transmissivity, storage, yield, aquifer layers, groundwater water occurrence, structural and morphologic control on flow, aquifer geometry, water level maps, surface water groundwater interaction, recharge discharge relations, water quality and groundwater geochemistry, overlay analyses, groundwater balance etc all appear to be important components of hydrogeological investigations

Table 3. 2 Regional groundwater recharge (adopted from Tenalem A., 2009)

Aquifer systems	Common depth to water(m)	Specific yield range(lps)	Location
Cenozoic volcanic rocks	30-250	2-6	Central, Eastern and Western highlands
Quaternary volcanic rocks	50-250	2-5	Rift valley floor
Unconsolidated sediments	20-80	1-5	Mostly in the rift and intermountain valleys
Insitu developed soils and river gravel	5-20	0.1-1	Highland and escarpment

Ashange basalts are fissured flood basalts covering a large part of the northwestern lowlands and highlands. It consists of several kinds of basalt and generally dips to the Raya basin. This lower flood basalt formation is often slightly to moderately jointed and highly weathered toward top, strongly dissected along the faults structures, which results in valleys with steep slopping sides and surfacial water flow.

It is a regional aquifer containing groundwater in fissures and fractures. The discharge of springs in this unit varies from place to place and ranges between 0.5 to 10 l/s, with most being greater than 2 l/s with a mean of 5.72 l/s.

This formation is fissural basalts, generally aphyric, compact rocks showing stratification at the top and its vertical permeability is low. It contains rare interbeds of tuffs. N-S and NW-SE trending faults are common but they are filled with clay which reduces infiltration. These units are jointed and highly weathered. Yields of dug wells vary from 1.5 to 0.18 l/s with a mean value of 0.85 l/s.

Discharge of springs varies from 0.2 to 1 l/s with a mean value of 0.6 l/s. The fractured and thick alluvial soil covered area might be the productive aquifer as groundwater storage is high. The topography is steep with deep river incisions which encourages run-off rather than infiltration.
From the collected and analyzed borehole's constant test data, the Ashange formation has a borehole yield that ranges from $51m^3$/day to $2074m^3$/day and a mean yield of 500 m^3/d, transmissivity value that ranges from $0.343m^2$/day to $594m^2$/day and a mean of 52 m^2/day and a specific capacity range from 0.63 m^3/m/day to 399 m^3/m/day and a mean of $44m^3$/m/day.

As can be seen from the collected boreholes secondary pump test data's time verses drawdown plot on double logarithm, these formations have an aquifer type which is dominantly confined consolidated with double porosity fracture systems and single plane vertical fracture aquifer systems. This confined groundwater condition is due to the overlying weathering product thick soil horizons, tuff, slightly weathered & fractured rhyolite & ignimbrites.

The degree of weathering is related to the kind of basalt in the Ashangi formation. The weathering in the aphanatic basalt penetrates along the verticular, polygonal and columnar jointing. Calcareous materials or rarely siliceous materials fill the fissures in the aphanatic basalt. Aphanatic basalt consists of very steep relief and cliff in the surface. Under cliffs are developed talus and colluviums. The basalt forms isolated hills and peaks. Various fissures developed in the aphanatic basalt, support groundwater flow into neighboring feldspar basalt. Calcareous and ferrous materials jointing, through which fill feldspar basalts are well weathered along the pillow, inter-bedding and globular. Feldspar basalt has a gentle relief in the surface and consists of very thick weathered crust, which means favorable condition for the infiltration of surface-water. The feldspar basalts that occur between aphanatic basalts are affected by weathering and erosion hence the beds are favorable for underground water flow. Groundwater in Ashange basalts mainly occurs in contact zones, along dyke swarms and in weathered volcanic materials.
The volcanic rocks of the Ashange basalts which form the western and eastern highlands bear considerable amount of secondary porosities and permeability resulting from the effects of extensive weathering, jointing, faulting and fracturing. Emergence of springs of significant discharge at the rift escarpment from the Ashange basalts suggests the productivity of the Aquifer systems. The flows in these basalts are sometimes tilted and are highly fractured and faulted with respect to the overlying Aiba basalts (Merla et al., 1979).

Ethiopia has huge groundwater potential, mostly localized in the volcanic terrain covered with Quaternary deposits, (Tenalem Ayenew, 2009).Finally, mapping of the important structures and evaluating their role in the recharge, movement and occurrence of this resource (groundwater) will subsequently help in groundwater exploration and development.

4. Results

4.1 Characteristics of the Data

4.1.1 Data Type

Secondary boreholes pumping test data of the Ashange formation system were collected so as to interpret and investigate different hydraulic properties. The methods applied in thesis are described in various literatures and works including Robert E.macea(1987), Castany (1982), Kruseman and De Ridder (1991), Fetter (1994). For this work, A pump test data base of about 70 secondary boreholes pump test row data has been collected from governmental offices ,private companies, NGO's and different several research programs carried out in different parts of the country. Even though different in number step drawdown test, constant rate test and recovery test data have been gathered and used for analysis. Additional finalized report from 13 boreholes was also used giving a total of 83 boreholes which are representatives to the Ashange formation (see Appendix i). The wells are of various depths and penetrate a variety of thicknesses of the saturated Ashange formation. Out of the 70 wells, 36 wells have recovery test, 26 wells have constant test and all wells have constant yield pumping tests (See Table 4.1). The entire collected secondary well pumping test data use single well for both pumping and measuring the water level data i.e no observation wells are used. Constant rate pumping tests and recovery tests were analyzed to determine the transmissivity, hydraulic conductivity and storativity of Ashange formation aquifer systems. While step drawdown or variable discharge test was used to determine both aquifer and well losses, well efficiency and also specific capacity index which is a measure of aquifer productivity. Transmissivity value is also calculated from specific capacity using its theoretical relationship, for all collected wells which were subjected to a variety of types of pumping test analysis.

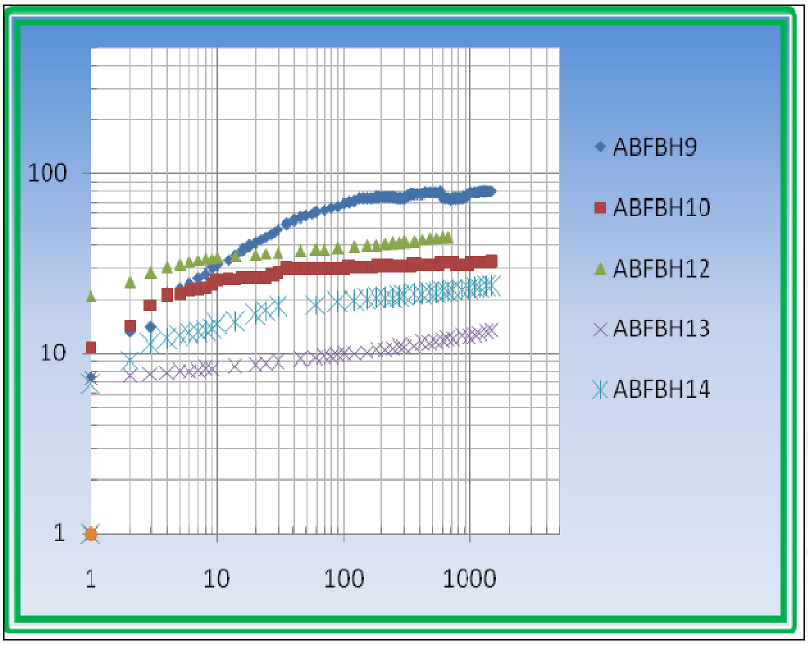
Table-4.1 –Age, pumping test types and number of wells subjected to analysis

Aquifer	Age (My)	Total Nº of BH's	Nº of BH's subjected to C.R.T	Nº of Bh's subjected to R.M.T	Nº of BH's subjected to S.DD.T
Ashange formation	30my	83	70	36	26

Note:- **C.R.T – Constant Rate Test ,R.M.T – Recovery Monitoring Test, S.DD.T- Step Drawdown Test**

4.2 Time Verses Drawdown plots

Semi-log and double log plots of Time versus drawdown data collected borehole pump test data are compared with diagnostic type (master) curves this has helped in the identification the formation aquifer category, classification of aquifer type whether confined ,unconfined or leaky etc and choice of proper pump test data analysis methods to be employed. The final result ,as can be seen from the graphs below, confirms that, the Ashange formation in general can be categorized as consolidated and highly fractured aquifer which is dominantly confined aquifer type with double porosity and single plane vertical fracture aquifer systems(See fig4.1:-A -F below).



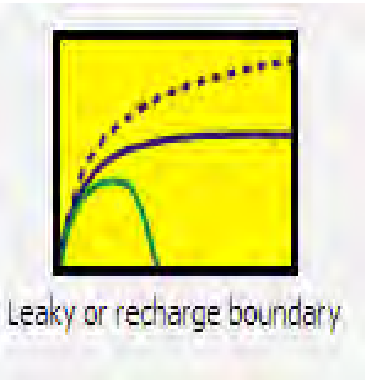


Fig-4.1A- Double log plot of Time Verses Drawdown data of Ashange Formations indicating Leaky (recharge) boundary aquifer type curves

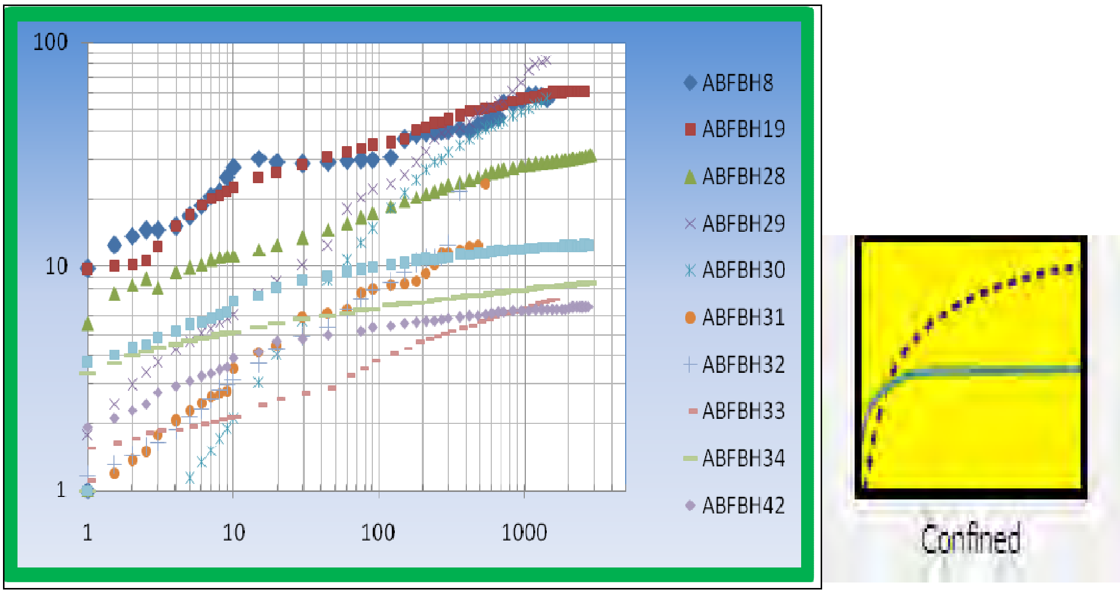
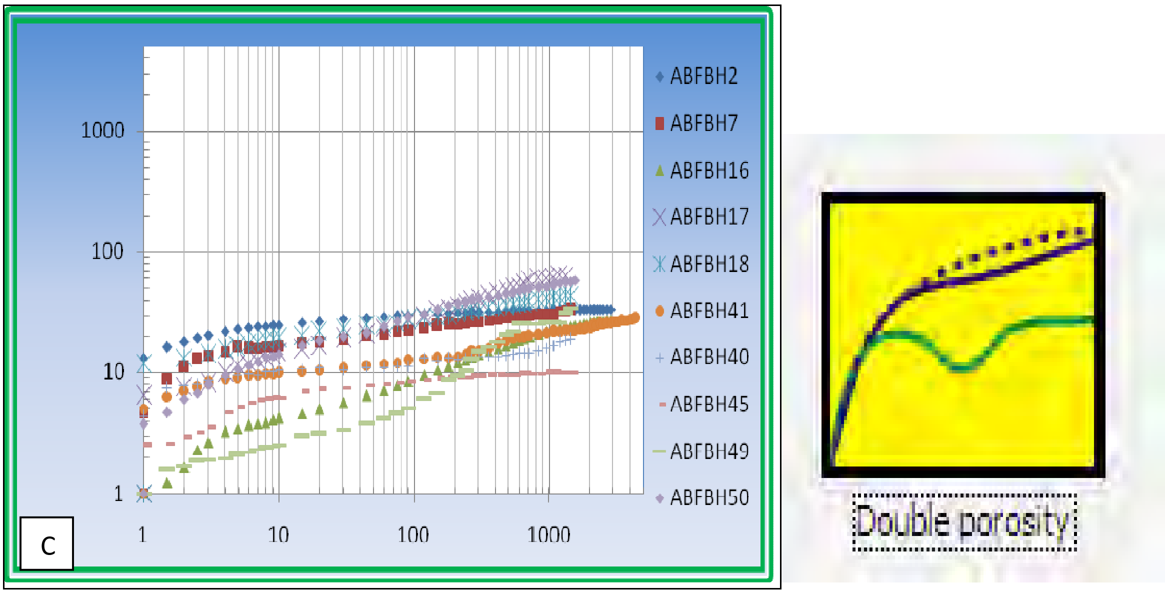


Fig 4.1B- Double log plot of Time Verses Drawdown data's of Ashange Formations indicating Confined aquifer type curves



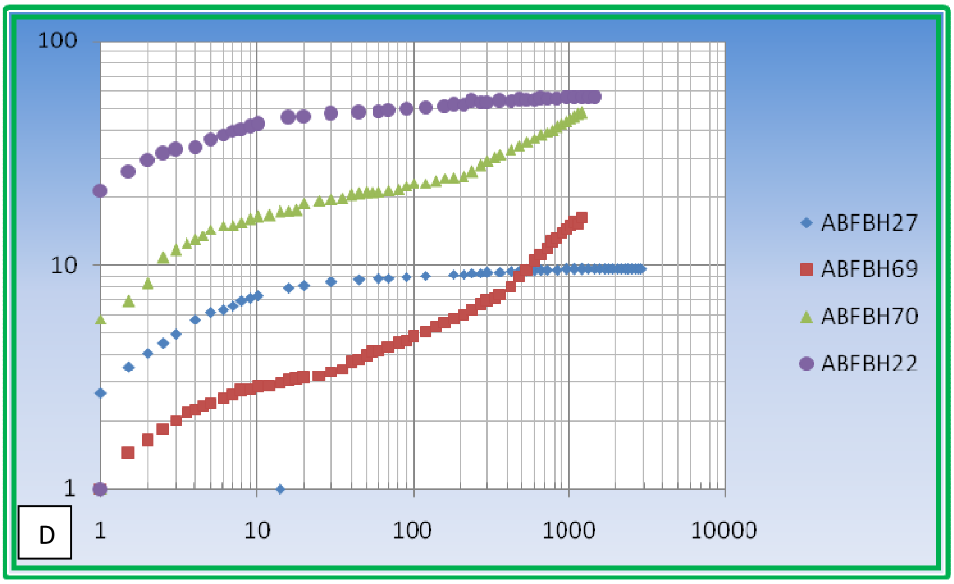
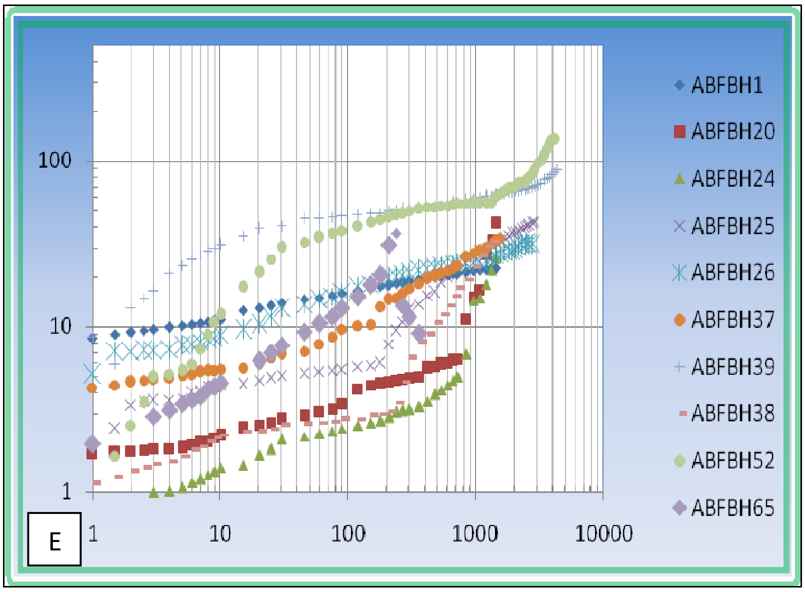


Fig 4.1 C and D - Double log plot of Time Vs Draw Down data's of Ashange Formation indicating confined Double porosity fracture aquifer type curves



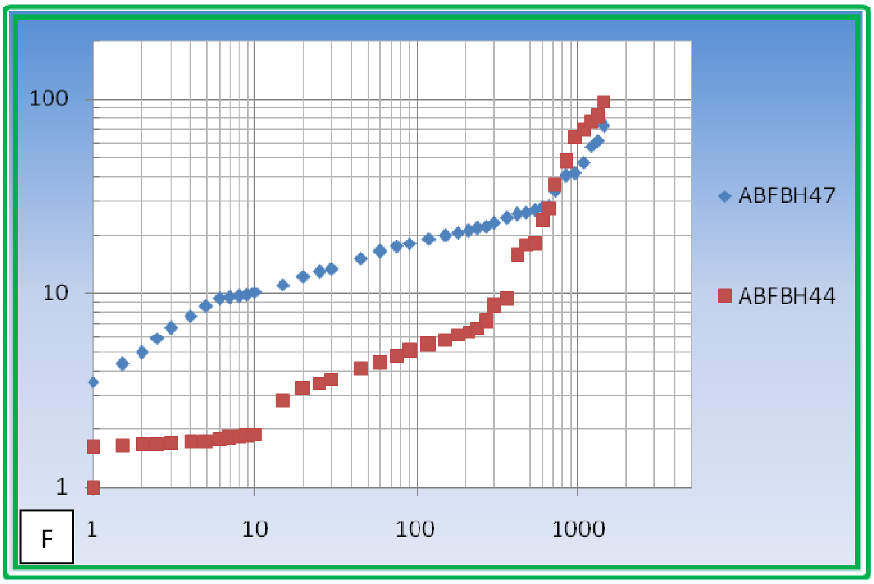


Fig 4.1 E and F-Double log plot of Time Verses Drawdown data's of Ashange Formations indicating Barrier boundary aquifer type curves

4.3 Determination of Transmissivity of the Ashange Basalts from Constant & Recovery tests

Among the different stages of pumping tests, constant rate pumping tests and recovery tests are used to determine transmissivity, hydraulic conductivity, and storativity values. Therefore besides using these tests to determine the hydraulic property of Ashange formation, they are also applied to recognize boundary conditions of the aquifer system of the study area. Although erratic from formation to formation, pumping test times vary between 5 and 72 hours. Single pumping well test data can be analyzed using standard Theis analysis method, Papadopulos – Cooper analyses method, Theis with Jacob correction analyses method and Double porosity analyzing methods are used to analyze the constant yield test data.

The Theis equation (Thiess 1935) was applied to determine transmissivity and storage coefficient for both the steady state and unsteady state flow data. Recovery data were interpreted using the Theis recovery method. The layout of drawdown curves shows well-bore storage effects at the beginning of pumping followed by a straight-line evolution in semi log graphs.

This linear evolution is then affected by changes in slope as a result of boundary effects, in some cases when the pumping time is increased, the curves become similar to the theoretical Theis curve in the log-log plot.

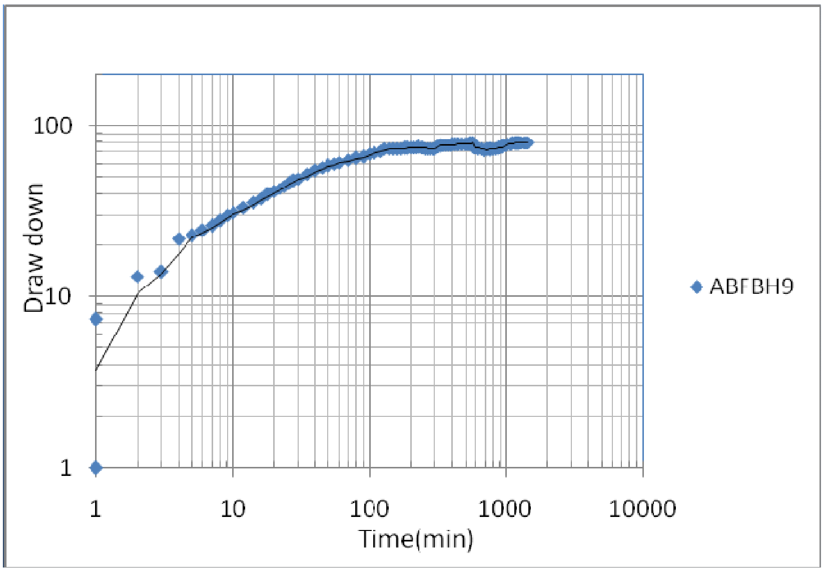
According to whether the aquifer exhibits recharge boundaries (or high transmissivity) or barrier boundaries (or low transmissivity), drawdown evolves towards a Stabilized or an increased slope, respectively.

Whenever possible, recovery data should be taken to verify the accuracy of pumping test data, often, the recovery data will be more reliable because no pumping is required. Any previously inexperienced personnel will have learned proper measurement techniques by the time recovery data can be taken. From recovery data analyses, we can determine the aquifer transmissivity which gives us a check on the results obtained from the data collected during the pumping period. Moreover, analyses of recovery data's have the advantage that the pumping discharge rate is constant and it can be considered equal to the mean rate of pumping discharge during pumping. This means that drawdown variations resulting from slight differences in the rate of pumping are eliminated. Also, the recording of recovery data helps in assessing the response and extent of the aquifer concerned, that is, for an aquifer system which is to be exploited for groundwater, the recovery levels must be adequate and yet recovery measurements should be recorded with the same frequency as those taken during the constant yield test portion of the aquifer and/or well test.

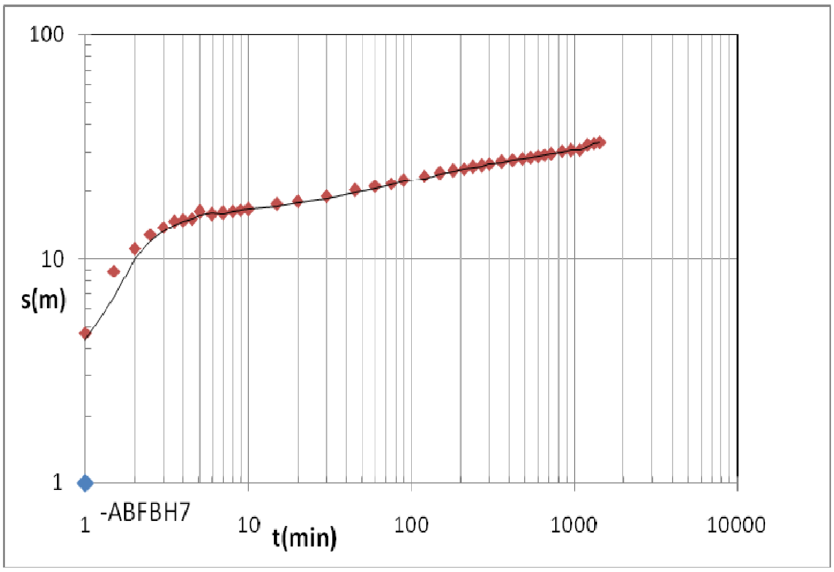
The analysis of a recovery test is based on the principle of superimposition. Applying this principle, we assume that, after the pump has been shut down, the well continues to be pumped at the same discharge as before and an imaginary recharge, equal to the discharge, is injected in to the well. The recharge and the discharge thus cancel each other, resulting in an idle well as is required for the recovery period. The Theis recovery method is widely used for the analysis of recovery tests. Strictly speaking, this method is only valid for confined aquifers which are fully penetrated by a well that is pumped at a constant rate. Nevertheless, if additional limiting conditions are satisfied, the Theis method can also be used for leaky aquifers and unconfined aquifers.

Transmissivity values collected and summarized from these tests are provided in Table5 below. The transmissivity values of the Tarmaber basaltic aquifers, as indicated in Abraham's unpublished thesis, range between 3.1m^2/day to 1940 m^2/day with a mean of value 105m^2/d. The transmissivity values of the Ashange basaltic aquifers range between 0.343 m^2/day to 594m^2/day and a mean transmissivity value of 52m^2/d for constant test and between 9.49 m^2/day to 380 m^2/day and an average value of 118m^2/d for recovery pumping test.

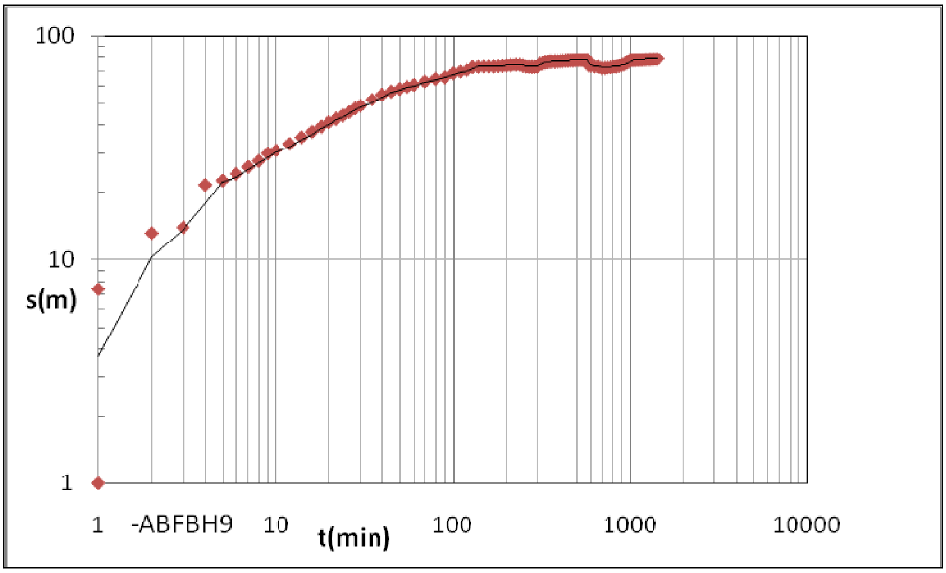
The type curves which represent confined aquifer with recharge boundary and barrier boundary, confined double porosity and single plane, vertical fractured aquifer systems of the Ashange formations are presented below in fig 4.2-A, B, C & D below.



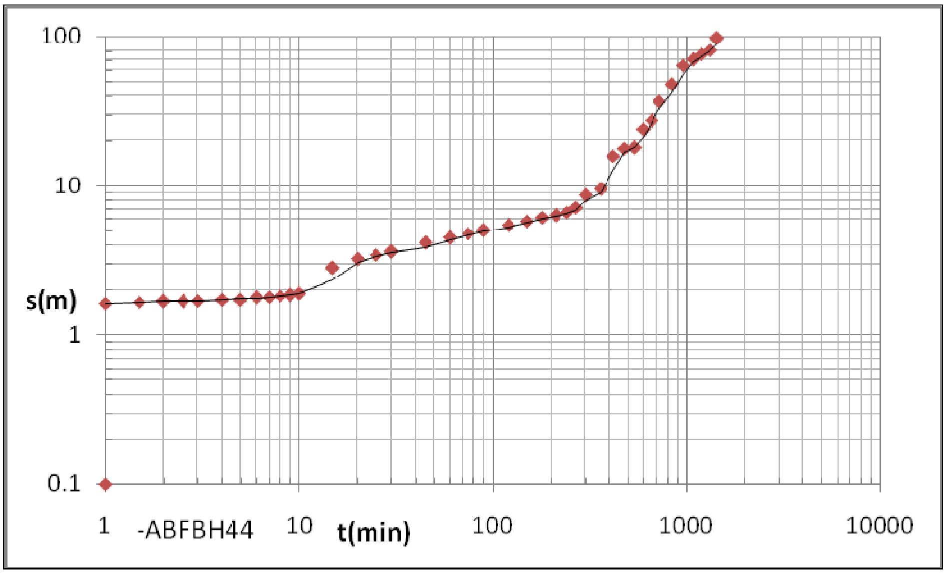
A-Confined Aquifer system with recharging boundary



B-Confined Double Porosity Aquifer System



C-Single plane vertical fracture aquifer system



D- Confined aquifer with barrier boundary

Fig 4.2 A, B, C and D:-Aquifer typical curves of the Boreholes Drawdown vs. Time data representing infinite extension and boundary effects

Table4.2 - Summary Statistics of T (m^2/day) of Ashange formation calculated from constant rate & recover monitoring tests

Description	T(m2/day) from constant rate Pumping test	T(m2/day) from Recovery test
Minimum	0.343	9.49
Maximum	594	380
Mean	52	118

Table 4.3- Summary Statistics of Hydraulic conductivity (K (m/day)) of Ashange formation calculated from constant rate & recover monitoring tests

Description	K (m/day) from constant rate Pumping test	K (m/day) from Recovery test
Minimum	0.012	0.237
Maximum	12.7	10.7
Mean	1.32	3.30

Table 4.4- Summary Statistics of Storativity(S) of Ashange formation calculated from constant rate & recover monitoring tests

Description	S from constant rate Pumping test
Minimum	5.88E-09
Maximum	4.00E-02
Mean	0.007286

4.4 Estimation of Transmissivity from Specific Capacity Data's

The specific capacity of a well (Q/s, m3 /day/m) is defined as the ratio of discharge (Q, m3 /day/m) to drawdown (s, m) at the pumping well for a given time. Many authors were interested in the theoretical and empirical relationships between aquifer transmissivity and well specific capacity. Note that specific capacity is readily calculable using a single pair of pumping rate and drawdown values for a given time. Some of the Theoretical relations developed by different scholars in the field are discussed below.

4.4.1Theoretical Development

The Dupuit-Thiem equation (Dupuit 1863; Kruse man and de Ridder 1991), which gives the drawdown (Sw) in a well with 100% efficiency, for steady state conditions, is:

$S = Q/2\prod T \ln (R/r)$ -------------------1

Where s is drawdown in the well (m); Q is constant discharge rate (m3 /day); T is aquifer transmissivity (m2 /day); R is radius of influence of the well (m); and r is radius of the well (m). Thomason et al. (1960) solved Equation (1) for transmissivity (T) for steady state conditions and showed that it should be linearly related to specific capacity (Q/s):

$T = (Q/s)\ 1/2\prod \ln (R/r)$ --------------------2

Or $T = C\ (Q/s)$ ------------------2a

They noted that the constant C varies from 0.9 to 1.5 and averaged 1.2 for self consistent units of specific capacity and transmissivity. Theis (1963) and Brown (1963) arrived at a similar range of values for the constant C.

Equation (1) shows also that, in a well with 100% efficiency, the drawdown s is linearly proportional to the discharge rate Q and can be written:

$S = BQ$-------------------3

Where B (m /day) is the laminar head-loss coefficient.

However, Eq. (1) does not take into account the effect of turbulent head loss in the well bore and gravel pack. The gravel pack and well screen can increase flow velocities, which often produces turbulent flow. Jacob (1950) suggested that in most cases, the total drawdown in a well may be expressed by:

$S = BQ + C_tQ^2$-------------------------4

Where B (m/day) is laminar head-loss coefficient given by the Dupuit-Thiem equation; and C_t [m2/day)] is turbulent head-loss coefficient.

Under these conditions, the linear analytical relationship of equation (2) T vs. (Q/s) is not valid anymore and transmissivity cannot be evaluated in a simple way. When drawdown in the well is aggravated by turbulent head losses and using again the Jacob Eq. (4), the expression of T becomes: $T=1/2\prod ((Q/s)-C_tQ) \ln (R/r)$ ------------------5

The simple linear analytical expression of equation (2) of T vs. Q/s is considerably altered. In addition to this, using relationship (2a) tends to under predict transmissivity each time turbulent head loss (coefficient C_t, above) cannot be neglected, Razack and Huntley (1991), Huntley et al. (1992) and Fetter (1994) .This makes the consideration of head loss analysis reasonable before applying the above mentioned empirical relationships.

4.4.1.1 Head Loss Analysis

Laminar head loss coefficient B and turbulent head loss coefficient C_t were evaluated for all available step-drawdown tests in the volcanic aquifers. Principles of step-drawdown tests are described in Rorabaugh (1953), Mogg (1969), Clark (1977) and Forkasiewicz (1978). The minimum, maximum and average values of laminar head loss coefficient B are reported in Table (4.5).Laminar head loss coefficients B in Ashange basalts aquifer system are lower than those in the Tarmaber formation indicating better aquifer productivity for former basalts.

Higher degree of well loss due to human factor is observed in the Tarmaber basalts giving rise to larger well loss coefficient c.

Table-4.5-Turbulent well loss coefficient (C) (day^2/m^5) determined by step drawdown tests

Aquifer	Min.	Max.	Average
Ashange formation	1.61E-07	0.003	5.7E-05
Tarmaber formation	1E-05	914	206

Table4.6:- Laminar Head Loss Coefficient B (day/m) determined by Step Draw Down tests

Aquifer	Min.	Max.	Average
Ashange formation	0.0004	0.11	0.019515
Tarmaber formation	0.002	0.324	0.118

Well efficiency on Ashange basalts varies from 6.77 % to 99.9 % having an average efficiency of 54.8%.This variation mainly comes from the human factor during pre and post construction activities of wells besides the lateral and vertical aquifer system heterogeneity.

4.4.1.2 Estimation of Transmissivity from Specific Capacity Using Theoretical Methods

An arithmetic plot of Transmissivity versus Specific Capacity (Fig 4.3A) shows a good correlation of transmissivity and specific capacity data giving rise to a determination coefficient of R^2 = 0.957.But still there is a dispersion of the data as can be seen from the graph. Theoretical relations proposed by Thomasson et al (1960) have been plotted on this diagram. It is found out in a variety of studies that theoretical relations tend in most cases to under predict transmissivity. Such significant deviation between observed and theoretical data of transmissivity can be explained by the importance of the turbulent head loss calculated in the analysis of the present study. The turbulent head loss increase drawdown in the production well, thereby decreasing the specific capacity at the well. The use of these low values of (Q/S) would accordingly underestimate transmissivity values.

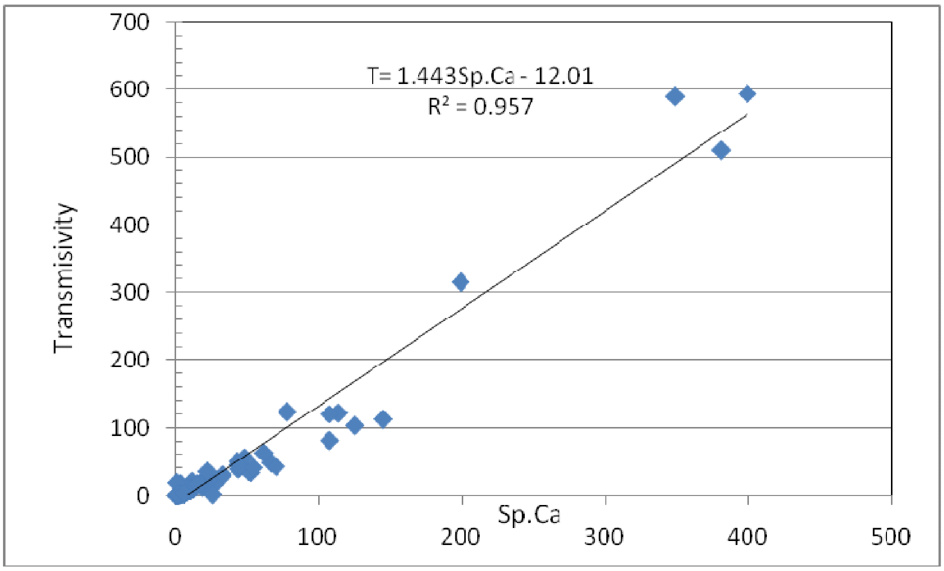
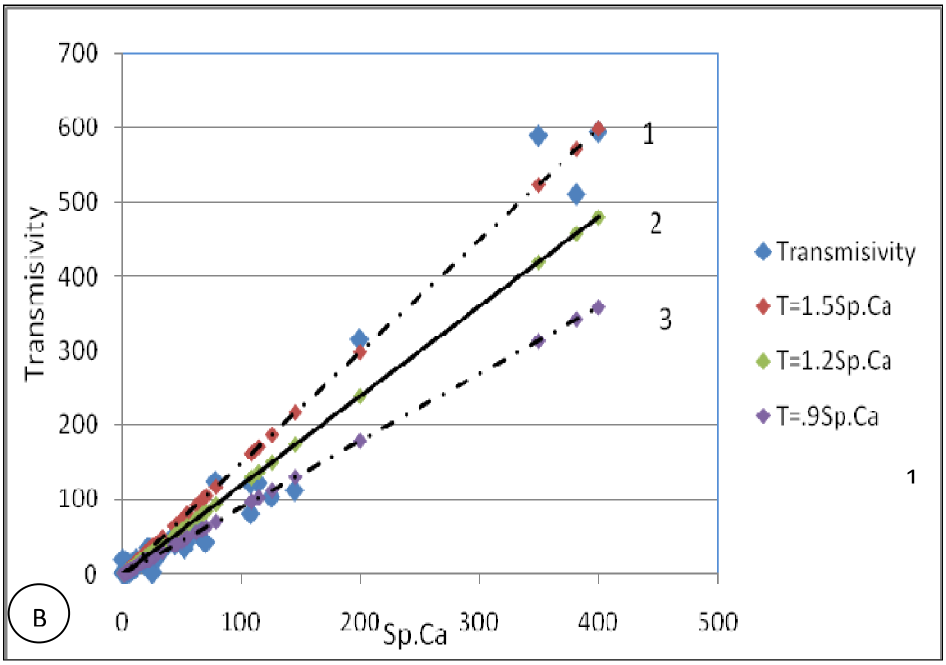


Fig 4.3A: Uncorrected Transmisivity Versus specific capacity values from constant test



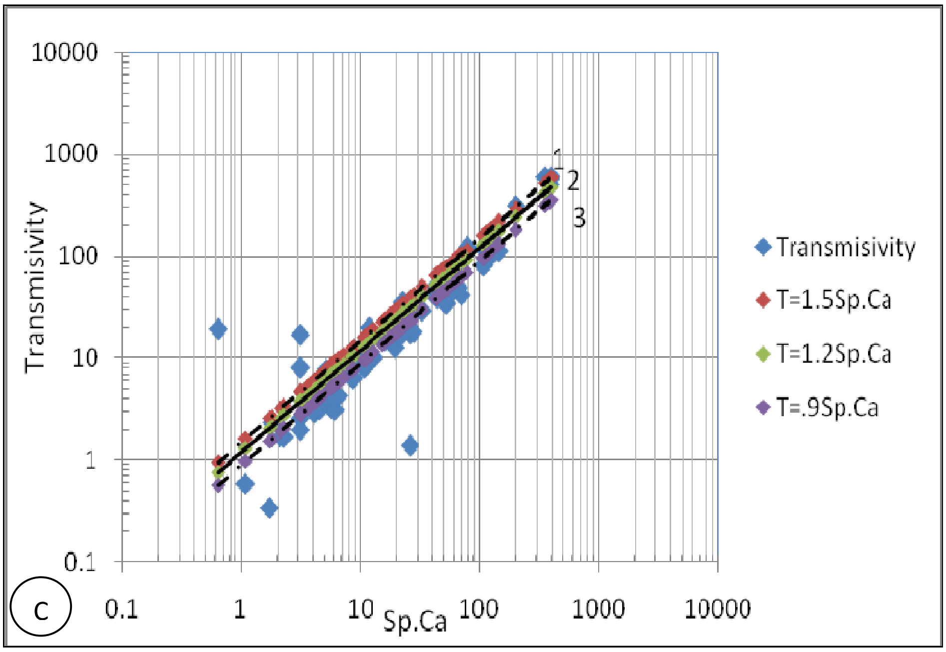


Fig 4.3 -B,C Plot of Transmissivity (m^2/day) versus Specific Capacity (Q/S, m^2/day) with theoretical relations superimposed

B.Arithmetic plot, C- Log-Log plot

1: T = 1.5Q/S

2: T = 1.2Q/S

3: T = .9Q/S

4.4.2 Estimation of Transmissivity from Specific Capacity using Empirical Methods

Many regional aquifer studies are hampered by sparse measurements of transmissivity. Therefore, specific capacity is commonly used to estimate transmissivity because specific capacity data are much more abundant than aquifer test data. Because of such a contradiction between theoretical predictions and observed data, the search of transmissivity estimates was directed towards empirical relationships. Numerous empirical relations are studied and used by experts in the field with and without correcting specific capacity for turbulent flow.

Some of these are indicated in table -4.7-below. Authors like Razack and Huntley 1991; Huntley et al. 1992 and Mace, 1997 proposed relationships of T vs. Q/s without correcting Q/s for turbulent head loss. Eagon and Johe (1972) proposed first to correct Q/s for turbulent head loss using an empirical relationships between Q/s and well loss coefficient C_t and then to estimate T from an empirical relationship between T and corrected Q/s.

Table -4.7- previously studied Empirical relations by different authors.

Authors	Formula	Limitations	
Driscoll, 1986 And BATU 1999	$T = 1.385(Q/s_w)$	confined aquifer	Errors of less than 7% are reported by Driscoll
	$T = 1.042(Q/s_w)$	unconfined aquifer	
EL-NAQA,1994	$T = 1.81(Q/s_w)^{0.917}$	Fractured carbonate aquifer	
Mace,1997	$T = 1.23(Q/s_w)^{1.05}$	Carbonate aquifer	
Fabbri(1997)	$T = 0.785(Q/s_w)^{1.07}$	Fractured carbonate aquifer	
Edwards-Trinity	$T = 0.78(Q/s_w)^{0.98}$	Limestone aquifer	
Razack and Huntly,1991	$T = 15.3(Q/s_w)^{0.67}$	Alluvial deposits	
Robert E. mace,1997	$T = 0.76(Q/s_w)^{1.08}$	Karst aquifers	

After correction of Transmissivity and specific capacity for well losses, least-squares regression can be used to fit a line to the log transformed values of transmissivity and specific capacity variables. This is done by defining

∏ = B0 + B1Xi----------------- (1), where∏, is log transformed transmissivity, where in the present case, ∏i = log (Ti) and Xi = log (Sc), where Sc, is log transformed specific capacity.

B1 = SSxy/ SSx, ------------------------------------- (1a)

SSxy = $\sum_{n=0}^{n}(xiyi) - \frac{1}{n}(\sum xi \sum yi)$------------------- (1b)

SSx =$\sum(xi)^2$ -1/n$(\sum xi)^2$--------------------------------(1c)

B0 = Y(mean) – B1x(mean) ------------------------ (1d)

By solving for B0 and B1 using equation (1a) and (1d), respectively, log transmissivity can be directly estimated using equation one above. And yet equation (1) can be rearranged into,

T = $10^{B0}(Sc)^{B1}$-- (1e)

From this the, an untransformed transmissivity can be directly calculated. Once the best fit line is found, how well the line fits the data can be estimated. The coefficient of determination (also called the goodness of fit) R^2, describes how much of the observed variability of a parameter can be explained by the regression model. The coefficient of determination can be found

R^2 = 1 – (SSe/SSy)

SSe = $\sum(yi\text{-}Ymean)^2$, and SSy = $\sum(\prod\text{-}yi)^2$

For this study, constant yield and step drawdown test data's from 26bhs formation were collected which conducted constant rate and step drawdown tests tapping the Ashange Basaltic formation in general. Consequently, a search was made for an empirical Relationship between T and uncorrected Q/s for turbulent head loss on the one hand, and between T and corrected Q/s for turbulent head loss on the other hand. This approach also enabled the investigation of whether correcting Q/s for turbulent head loss makes it possible to considerably reduce the uncertainty on the estimates of transmissivity. Specific capacity, which is a measure of aquifer productivity, of Ashange basalt formation is generally higher as compared to that of the upper Tarmaber formation.

Table-4.8-specific capacity not corrected for turbulence head loss

Aquifer	Minimum	Maximum	Mean
Ashange formation	0.63	399	44
Tarmaber formation	1.24	173	32

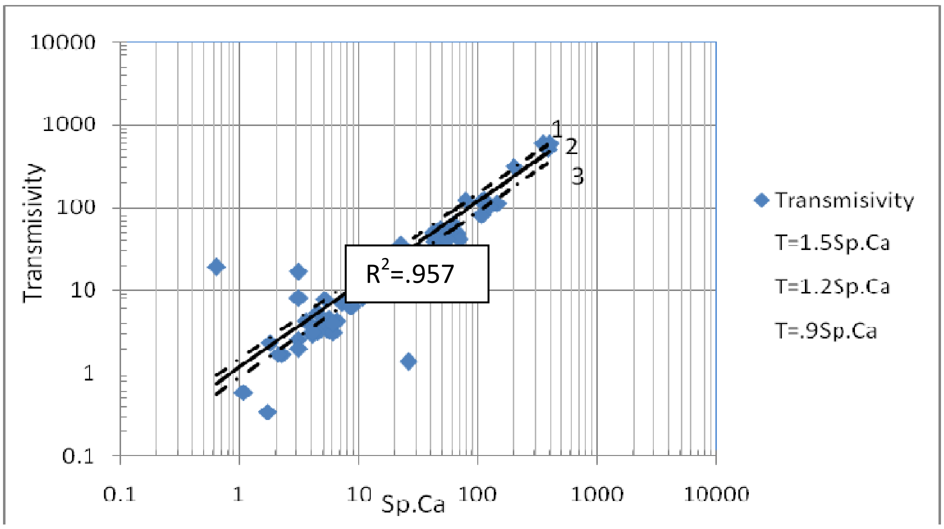
Table – 4.9- Specific capacity (Q/s) corrected for turbulent head loss

Aquifer	Min.	Max.	Mean
Ashange formation	0.21	2016	148
Tarmaber formation	17.28	71	29

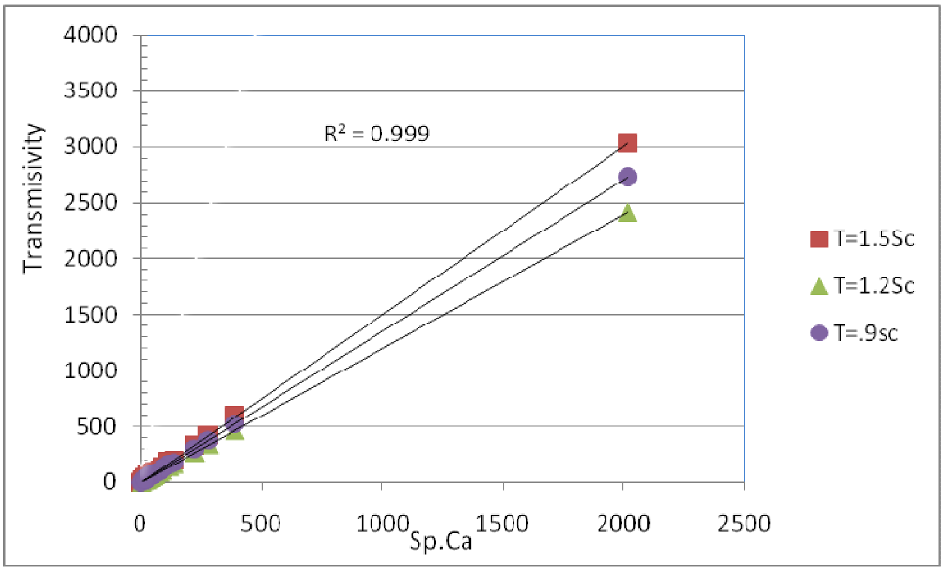
The search for empirical relationships between transmissivity and specific capacity focused on using directly a log-log plot which conforms to the lognormal character of both variables, widely accepted in the literature (Aboufirassi and Marino 1984). The best-fit line is reported together with the 95% prediction interval, in order to assess the uncertainty associated with the estimates of transmissivity. The prediction interval is calculated as follows:

Interval = Yi≠ tα/2 Syz√ (1+1/n+ (xi – (xmean)) ^{2}/∑ (xi-(xmean)) ^{2}------- (1)

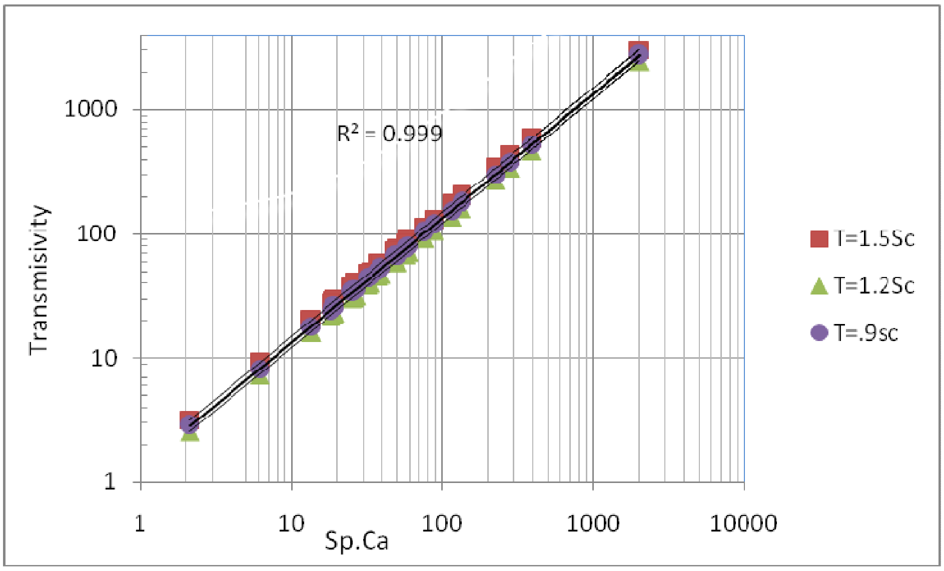
Where yi is the predicted value of the dependent variable (here transmissivity) using the regression equation; tα is the critical value of the student t distribution; Syz is the standard error of estimates; n is sample size; xi is the nth value of the independent variable (here Q/S) and x (mean) is the arithmetic mean of the independent variable. Log-log regression plot between transmissivity and uncorrected specific capacity is shown in Fig 4.3A below. The plot displays strong correlation and the determination coefficient remains high (R^2 =.957).



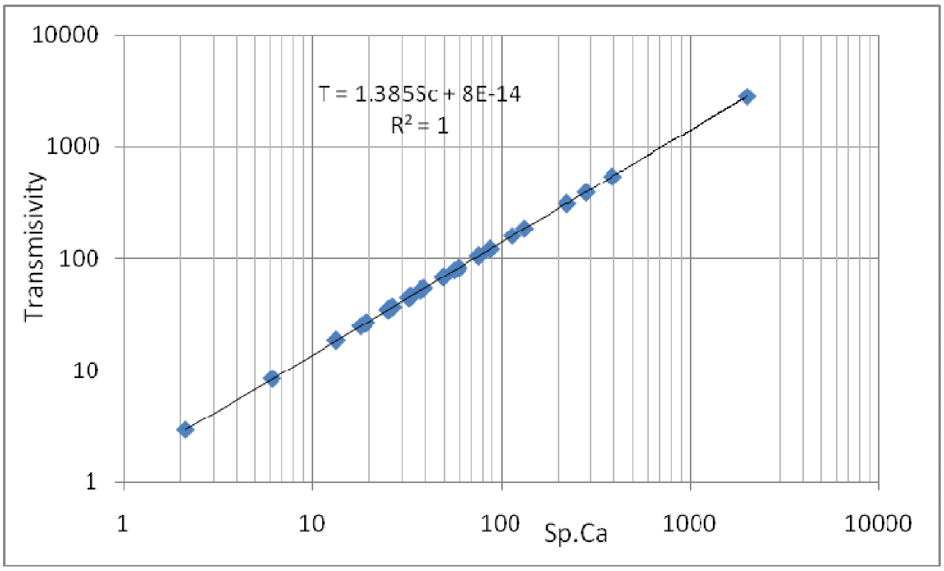
A


Transmisivity
4000
3500
3000
2500
2000
1500
1000
500
0
R² = 0.999
0
500
1000
1500
2000
2500
Sp.Ca
T=1.5Sc
T=1.2Sc
T=.9sc

B.


Transmisivity
1000
100
10
1
R² = 0.999
1
10
100
1000
10000
Sp.Ca
T=1.5Sc
T=1.2Sc
T=.9sc

C.



D.

Fig 4.4A, B & C –Ashange Aquifer Specific Capacity (m^2/day) vs T (m^2/day)

A- T vs uncorrected Q/s in log log

B- T vs Q/S corrected for turbulent head loss in linear plot (T (m^2/day from Constant Test)

C- T vs Q/S corrected for turbulent head loss in log log plot (T(m^2/day from constant Test)

D- T vs Q/S from Driscoll's empirical relationship between T and sp.Ca for confined aquifers.

E- Solid Lines- are best fit lines

Correcting specific capacity for turbulent head loss markedly improves the relationship between transmissivity and specific capacity (Fig. 4.4B & C above).The determination coefficient is a much higher (R^2 =0.999).The 95% prediction interval span doesn't show an observable change in the log cycle confirming the original transmissivity and specific capacity had good correlation.

However this by itself has reduced the available uncertainty on the estimates of transmissivity. The best-fit line to these data is:

$T = 11(Q/S)^{0.93}$--------------- (7)

This relationship extends the lower limits of transmissivity values over four to five orders of magnitude and three to four orders of magnitude of specific capacity values' by upgrading the underestimated and minimizing the overestimated transmissivity and specific capacity values. Therefore, it allows the transmissivity values to be estimated from specific capacity with acceptable accuracy.

consequently, the relationship of equation (7) above , where transmissivity values is used from constant yield test results, is used to supplement the database concerning the transmissivity of the Ashange formation in wells where transmissivity had not been evaluated but where corrected specific capacity was available. Table 14 below shows the summary statistics of the whole transmissivity database.

Table 4.10a- Variation of Transmissivity (m^2/d) values from constant pumping test in the Ashange and Tarmaber basaltic formations.

Aquifer	Minimum	Maximum	Mean
Ashange formation	0.343	594	52
Tarmaber formation	3.1	1940	101

Table 4.10b- Variation of Transmissivity (m^2/d) values from corrected Sp.Ca in the Ashange and Tarmaber basaltic formations.

Aquifer	Minimum	Maximum	Mean
Ashange formation	22	13019	1055
Tarmaber formation	27.8	718	301

4.5 Specific Capacity Verses Aquifer Thickness

From Walton (1970) description, by calculating the specific capacity index (Si) for each wells, segregating the wells into categories based on the formation penetrated depth, and comparing the distribution of the specific capacity index for the wells which are categorized depth wise into, shallow (less than 90m depth), intermediate depth (90m to 150m) and deeper depth (greater than 150m). Based on these categories, the Ashange basalts have mean specific capacity index that varies from 1.01m/day for the shallow wells, 1.5m/day for the intermediate depth wells and 0.72m/day for the deeper drilled wells. This implies the decrease of aquifer productivity of the Ashange basalts with increasing depth of formation. The specific capacity index value also shows a decreasing trend with increasing boreholes depth which indirectly implies that, shallow to intermediate depth Ashange basalts have better aquifer productivity than the deeply buried basalts. Therefore, the specific capacity index verses Boreholes depth relationship of the Ashange basalts directly agrees with the decrease of the Ashange basalts transmissivity as boreholes depth increases.

4.6 .Well Yield and specific capacity

Collected and analyzed yield and specific capacity of 70 wells on Ashange formation shows that it has moderate aquifer productivity .A comparison of the national classification of yield and aquifer productivity developed by Cherenet 1988 and gathered Ashange well data is applied here for characterization (see table 14 below).

Table 4.11: productivity of Ashange formation as compared to National Aquifer productivity

Aquifer	Specific capacity(L/sec/m)			Estimated optimum yield(L/sec)			Productivity Ranking
	Range	mean	median	Range	mean	Median	
National Aquifer productivity	0.2-7.6	3.3	2	1.8-68.4	29.7	18	High
	0.05-1.1	0.53	0.13	0.45-9.9	4.8	1.2	Moderate
	0.006-0.5	0.1	0.04	0.05-4.5	0.9	0.4	Low
Ashange basalt	0.01-4.62	0.51	0.15	0.6-24	5.8	3.6	Moderate to High

In this study, the Ashange basalts have shown an average discharge of 5.8 l/s and average specific capacity of 0.51 m^2/d, which shows greater value as compared to the results indicated in the yield and specific capacity values of major aquifers by SMEC2007 around Lake Tana region (see table 4.12 below).

Explanatory notes of the hydrogeological and geological maps of Gondor and west of Gondor area indicated less value average yield which is 2 l/sec for wells and 5.72 l/sec for springs on Ashange basalts found in the area. This document also indicated the specific capacity distribution as shown in Fig. 12 below. The frequency distribution shows a relatively larger percentage of wells have moderate to high productivity based on the national aquifer productivity classification shown in table 4.12 above. However the specific capacity as well as discharge varies from place to place due to lateral as well as vertical in-homogeneity.

Table 4.12: yield and specific capacity values of major aquifers by (SMEC2007)

Aquifer	**Specific capacity(L/sec/m)**			**Estimated optimum yield(L/sec)**		
	Range	Mean	Median	Range	Mean	Median
Quaternary alluvials	0.02-0.53	0.28	0.33	1.3-6.5	4.14	4.06
Quaternary basalts	0.034-6.43	0.65	0.11	1-10	3.85	3.1
Tarmaber basalts	0.018-3.31	0.25	0.14	0.7-16.8	3.63	2.78
Ashange and Aiba basalts	0.008-1.49	0.27	0.11	0.67-17	4.2	2.68

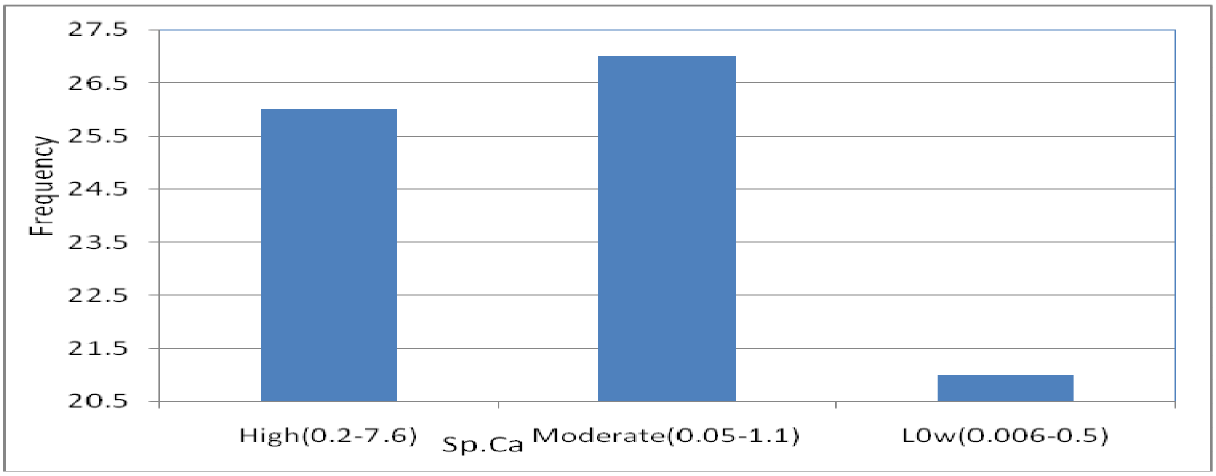


Fig.4.5 Specific capacity value versus frequency of wells in the Ashange formation

5. Discussion

5.1 Aquifer Characterization

Well log data and the single pumping well test, time verses drawdown plot clearly shows that, the shapes of the curves of Ashange basalts refers to consolidated fracture aquifer category which is dominantly confined aquifer types with double porosity and single plane vertical fracture aquifer systems. On a double logarithmic paper plots , the shape of the double porosity aquifers resemble those of the unconfined and/or semi-unconfined unconsolidated aquifers with delayed yield response having an ‘S’ shape type curve . The consolidated fractured aquifer category refers to confined, densely fractured, consolidated aquifers of the double porosity type which is dominantly: Confined, Double porosity fractured aquifer system and single plane, vertical fractured aquifer system. The double porosity aquifer type is mainly related to the deeply drilled wells of Ashange basalts which refer to presence of many large and narrow fracture systems which have high permeability but lower storage capacity. In a double porosity fractured aquifer systems, we can recognize two systems: the fracture of high permeability and low storage capacity, and the matrix blocks of low permeability and high storage capacity. The flow towards the well in such a system is entirely through the fractures and is in an unsteady state. The flow from the matrix blocks in to the fractures is assumed to be in a pseudo-steady state.

A characteristic' of the flow in the double porosity fractured aquifer system is that three time segments' can be recognized.

- Early pumping time; when all the flow comes from a storage in the fractures
- Medium pumping time; a transition period during which the matrix blocks feed their water at an increasing rate to the fractures, resulting in a (partly) stabilizing drawdown
- Late pumping time; when the pumped water comes from storage in both the fractures and the matrix blocks

The concept of double porosity is applied to this consolidated (hard rock) aquifer categories. This means that two fractures or joint systems can be distinguished : one system with (a few) large and wide joints and fractures with a high permeability and another system with many small pores, fractures or joints with a low permeability but appreciable amount of storage.

The flattening of the curve reflects water contribution of the second system that begins to take effect. As indicated in (graph-3A) above, the purely confined aquifers curve shows that, during the early time pumping periods there is recharging boundaries that take an effect which later be eliminated during the medium and late time pumping periods, while the curve indicated in (Graph-3D) above, the purely confined aquifer curve shows that, there is a barrier boundaries which takes an effect throughout the pumping period. In the double porosity fractured aquifer system curves (Graph-3B) above, there is a recharging boundary which take an effect throughout the pumping duration.

The curves for the single plane vertical fracture aquifer system (Graph3-c), refer the fracture has a finite length and a high hydraulic conductivity. Characteristic of this system is that a log-log plot of early pumping time shows a straight line segment of slope 0.5 (See Graph-3C). This segment reflects the dominant flow regime in that period is horizontal, parallel and perpendicular to the fracture. This flow regime gradually changes, until, at late time, it becomes pseudo-radial. The shapes of the curves at late time resemble those of the double porosity fractured aquifer systems. The first part of this curve is generally flatter than the curves for confined unconsolidated rock aquifers.

This curve is based on pumping tests carried out in a pumped well located in a vertical highly permeable fracture (e.g. fault zone). The coefficient of permeability of the surrounding country rock is much lower.

During pumping test, when recharging boundary is encountered, on the time verses drawdown graph, slope of the curve becomes flatter. Transmissivity calculated from the flatter slope will be higher than the true value. Extending of the flatter slope gives a value for t_o that is too low. Storage coefficient calculated from this figure will be lower than the correct value. And yet, when barrier boundary is encountered, on the time verses drawdown graph, the slope of the curve becomes steeper. Transmissivity calculated from the steeper slope will be lower than the true value. Extending line of the steeper slope gives a value for t_o that is too high. Storage coefficient calculated from this figure will be higher than the correct value.

During the analyses of the constant yield test data's, standard Theis analyses method assumes that well bore storage effect is negligible while Papaduplose – Cooper analyses method take in to account the well bore storage effects, however, ignoring the well bore storage effect which occurred on the pumping well during the test duration will result in low computed aquifer parameter values which again could result in high aquifer and well loss coefficient values.

The analysis of the Ashange basalts step drawdown tests clearly shows that, the wells have highly variable efficiency and well loss coefficient values which directly reflect the effect of:

- Improper well design and construction factors
- Functional wells yield deterioration due to clogging, corrosion and incrustation of the well screens
- Improper location of well site with respect to the effect of the Palo- morphological set up of the formation outcrop

5.2 Transmissivity of Ashange Formations

Summary statistics of transmissivity values for Ashange basalts is provided in Tables 4.2. In addition, the frequency distributions of transmissivity data in a log-probability diagram are plotted for aquifers (fig 5.1). A relatively larger percentage of wells have moderate yield based on the national aquifer productivity classification shown in table 2 above. Even though high degree of fracturing and faulting enhance the productivity of Ashange basalts, weathering and other volcanic activities still play a negative role of reducing productivity and permeability. Dikes and sills which are found in the Ashange basalts have also a role of minimizing transmissivity and aquifer storage by increasing aquifer heterogeneity within the aquifer.

Various fissures developed in the aphanitic basalt, support groundwater flow into neighboring feldspar basalt. Calcareous and ferrous materials jointing, through which fill feldspar basalts are well weathered along the pillow, inter-bedding and globular also create a suitable situation for ground water availability.

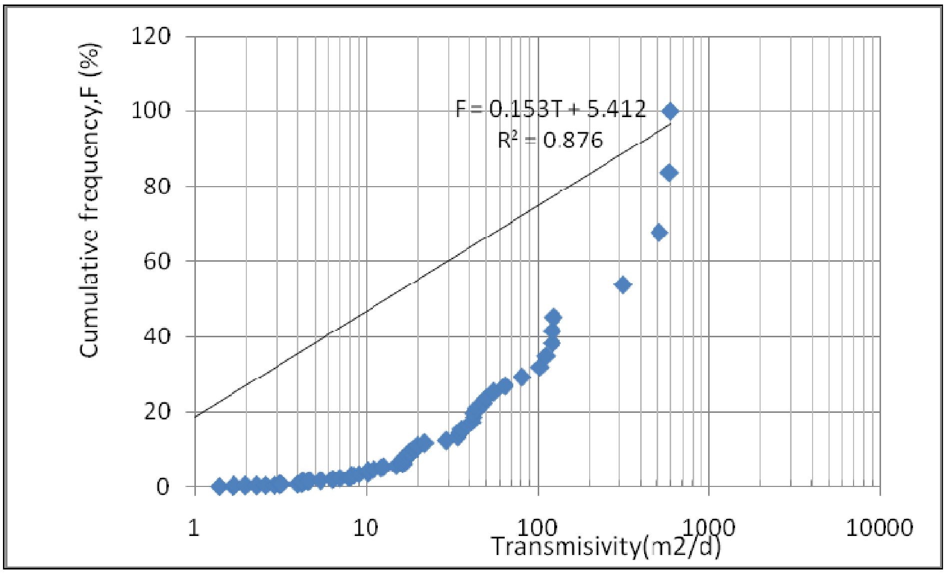


Fig 5.1- Transmissivity Verses Cumulative Frequency %

5.3 Transmissivity Variation within the Ashange Formations

The plot of the representative step drawdown tests, Drawdown verses Discharge rate, clearly shows that there is an increase of well drawdown with increasing variable pumping discharge rate which directly correlates with the decrease of Ashange basalts aquifer productivity with drilled boreholes depth and age of the formation. And yet the boreholes yield from the central massive highland plateau areas have low yield as compared to the boreholes yield located elsewhere away from those areas.

The older the basaltic formation, the lower will be its transmissivity. These positive or negative changes in transmissivity are due to weathering and other surface & subsurface effects, volcanic and tectonic activities and the location of geological units in relation to active tectonic zones. Some of these activities like weathering and volcanic activity play the role of decreasing transmissivity while fracturing, faulting and other tectonic activities increase transmissivity value.

It seems that when rifting occurred, the opening of fractures under tectonic stresses was the major factor, and as volcanic units moved progressively away from the rifting area, weathering effects became dominant and disappeared progressively when the area reached stable tectonic conditions. These changes are believed to have taken place relatively quickly in time.

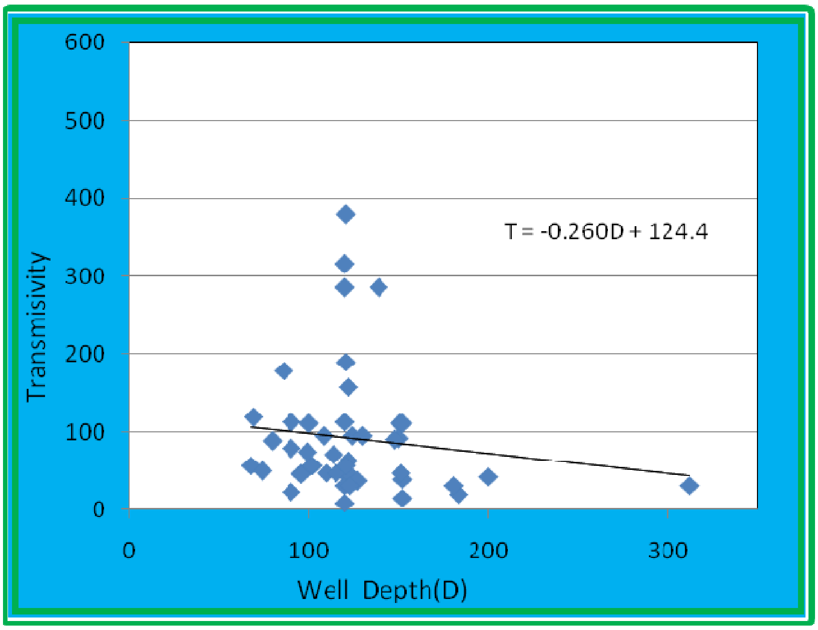
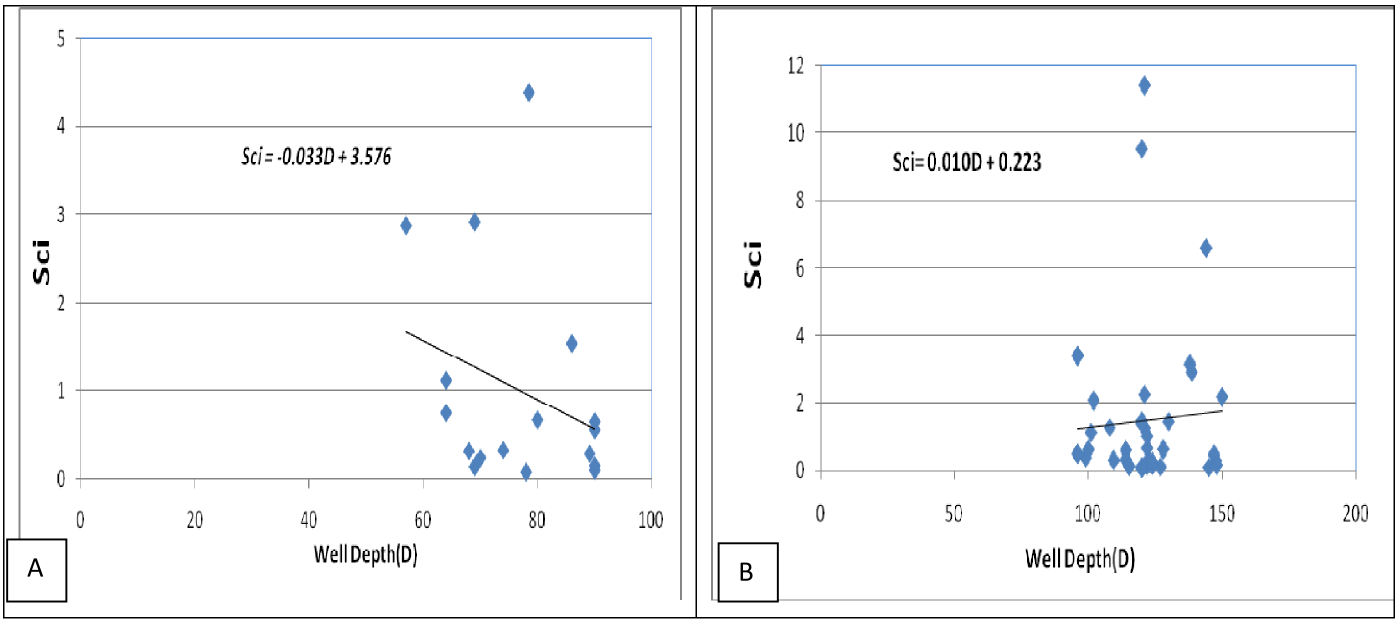


Fig 5.2- Transmissivity Verses Well Depth



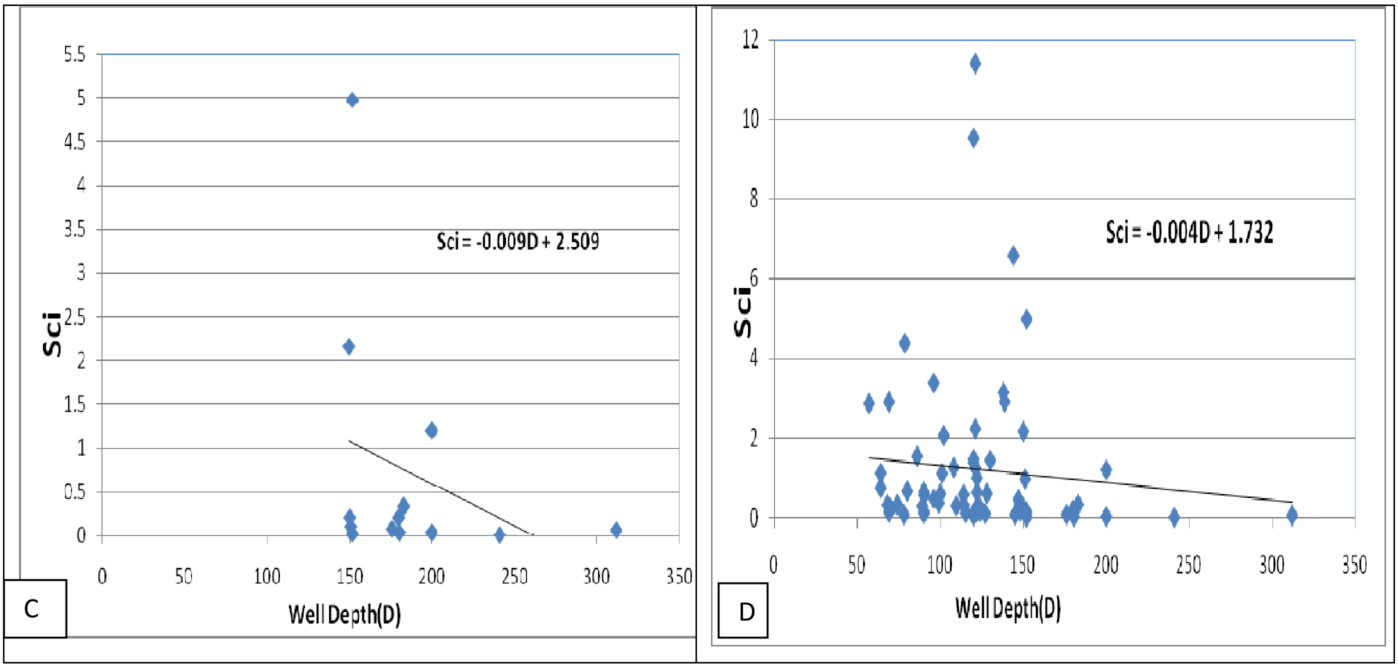


Fig 5.3 –Specific Capacity index (Si) verses Boreholes depth

A: Shallow wells (≤90m)

B: Intermediate depth wells (90<x≤150m)

C: Deeper wells (>150m)

D: General trend

The Ashange formation have mean specific capacity index (Si) that varies from 0.72m/day for the shallow depth wells (≤90m depth), 1.5m/day for the intermediate depth wells (90m-150m) and 1.01 m/day for the deeper wells (>150m). When shallow and deeper wells show a decreasing trend of Sci, intermediate depth wells relatively show an increasing value .This confirms higher aquifer productivity for wells having moderate depth. At the same time, the mean specific capacity index for the Ashange formation in general is 1.2m/day and, so this relation justifies the decrease of Ashange formation aquifer productivity with increased well depth and age of the formations. The mean specific capacity index for the whole Tarmaber formation is 0.305 which is less than the value for Ashange formation, which again depicts the relatively high yield of Ashange basalts.

5.4 Spatial Variations in Aquifer Characteristics of the Ashange Formations

The Ashange Basalts in Ethiopia have an extensive surface outcrop aerial extent with spatial distribution pattern throughout the country. Groundwater in Ashange basalts mainly occurs in contact zones, along dyke swarms and in weathered volcanic materials. The volcanic rocks of the Ashange basalts which form the western and eastern highlands bear considerable amount of secondary porosities and permeability resulting from the effects of extensive weathering, jointing, faulting and fracturing.

The yield of the aquifers from the Ashange group rocks varies from o.6 to24lt/s. Ashange basalts outcrop as cliff and ridge forming highland plateaus, flat lying plain, rugged terrain with peaks and deep gorges and intermountain basins. At places, their paleo morphological set up make difficult to explore and further develop the groundwater resource associated within the formation. The degree of weathering is related to the kind of basalt in the Ashangi formation. The weathering in the aphanatic basalt penetrates along the verticular, polygonal and columnar jointing. Calcareous materials or rarely siliceous materials fill the fissures in the aphanatic basalt. Aphanatic basalt consists of very steep relief and cliff in the surface. Under cliffs are developed talus and colluviums.

The basalt forms isolated hills and peaks. Various fissures developed in the aphanatic basalt, support groundwater flow into neighboring feldspar basalt. Calcareous and ferrous materials jointing, through which fill feldspar basalts are well weathered along the pillow, inter-bedding and globular. Feldspar basalt has a gentle relief in the surface and consists of very thick weathered crust, which means favorable condition for the infiltration of surface-water.

The feldspar basalts that occur between aphanatic basalts are affected by weathering and erosion hence the beds are favorable for underground water flow. Emergence of springs of significant discharge at the rift escarpment from the Ashange basalts suggests the productivity of the Aquifer systems. The flows in these basalts are sometimes tilted and are highly fractured and faulted giving appropriate condition for ground water infiltration and movement with respect to the overlying Aiba basalts (Merla et al., 1979).

The massive plateau forming Ashange basalts have generally low productivity.

Their groundwater occurrence, localizations and movement is highly controlled by:

- The degree of fracturing , weathering
- The paleo morphological set up of the formation outcrop
- The nature, extent and orientation of the associated main structural features
- The architectural stratigraphic inter relationships of the overlying and underlying other formation

5.5 Comparison of Ashange Formations Aquifer Characteristics with other Large Volcanic Province Rocks

The trend of transmissivity values with age is compared in fig 5.4 below for different continental flood basalts of the world. Younger volcanic rock in Djibouti known as Dalha (3.4-9Ma) has a transmissivity value of (1570m^2/day, Moumtaz Razack,2004).Colombian river basalt group(CRBG) is another recent basalt when its eruption occurred from about 16 to 6Ma,mostly over a short time period centered around 15Ma(Randall E.brown 1983 and references there in).As estimated by J.J.Vaccaro on the basis of work by Drost and Whiteman (1985),transmissivity of CRBG commonly ranges from about 2,000 to 100,000 m^2/d with the extreme values of o.15 and 200,000m^2/d and an average of about 7,600m^2/d . In this study, average transmissivity values of the Ethiopia Ashange basalts, having an age of ~ 30Ma, is calculated as 1054 m^2/day. The Deccan volcanic rock of India(64Ma) have an average transmissivity value of 234 m^2/d (Robert E.Mace,2000).Jiri Krasny and John Maccolm Sharp(2007) in their work on ground water in fractured rocks had estimated the range of transmissivity values of Parana flood basalts in southern brazil (120-130 Ma) from 200 to 800 m^2/d with an average value of 300 m^2/d. Transmissivity varies from 5 to 150 m^2/d for the relatively older karo volcanic rocks(198-204ma) in the southern part of Africa(Reynders et al 1985).

Generally the above condition proves that as volcanic rock formation gets older and older, its hydraulic properties including transmissivity, permeability and hydraulic conductivity value goes decreasing(see fig 5.4 below) .This may be related to the gradual closing up of open spaces like fractures by secondary materials hindering free flow as well as storage of water.

Hydraulic conductivity of major basalt units in the Colombian river basalt group was estimated (Randall E.brown 1983 and references there in).It ranges from 0.002 to 1,600 m/d and average about 18m/d. However for the older Ethiopian Ashange formation, conductivity varies from 0.237 to 10.7 m/d with mean value of 3.3 m/d.

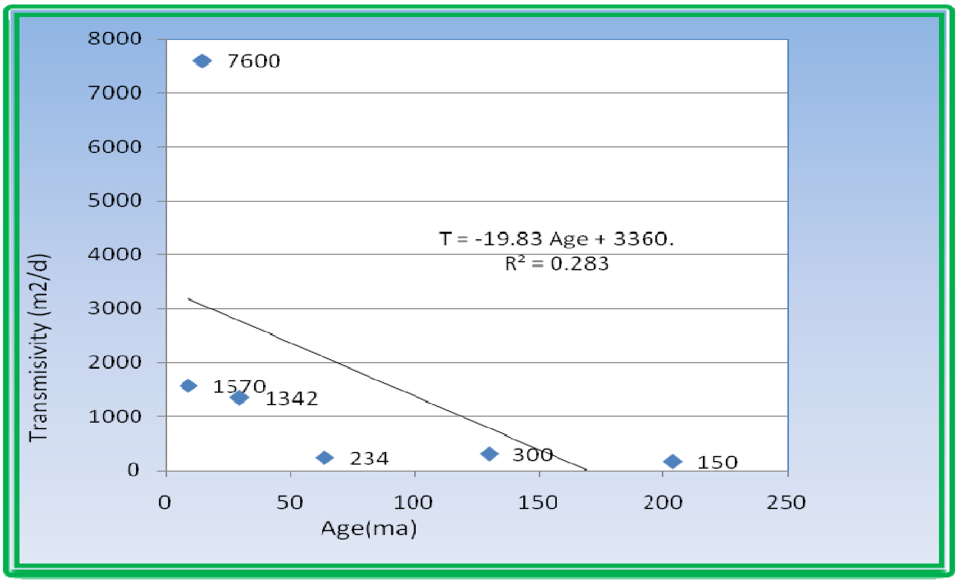


Fig 5.4- Transmissivity of Ashange formation as compared to transmissivity value of other continental flood basalts of the world.

5.6 Cost Implication for Groundwater Resource Developments

It is reported is many works of ground water investigation and development projects in different parts of Ethiopia that the available amount of groundwater reserve is not appropriately known exploited. This study also has found out significant amount of well loss coefficients .This loss is due to poor well design and construction factors in addition to the improper well site location and time factor, deterioration of functional wells due to corrosion, incrustation and clogging of the well screens. The above shortcomings create a problem in the sustainability of the wells drilled which will again result in wastage of money and resources for well rehabilitation and maintenance works. There is also a situation where boreholes will be abandoned after a huge amount of money is invested because high well and aquifer loss values make it difficult to understand the true potential productivity behaviors of aquifers.

Figs 5.2 and 5.3A-D above plotted for transmissivity and specific capacity index versus borehole depth reveals that wells with intermediate depth have higher aquifer productivity than shallow and deeper wells .This shows that from sustainability and economical point of view intermediate depth wells are preferable. Shallow wells have a problem of partial aquifer penetration giving rise to reduced productivity and relatively prone to pollution problem. Dipper wells need have low aquifer productivity requiring high construction cost and complex drilling technical knowledge.

6 Conclusions & Recommendations

6.1 Conclusions

Due to the rapidly growing demand and decreasing availability of water, ground water is becoming the dependable source to be explored and developed to improve the socio-economic and cultural well being of the Ethiopian society especially in areas where there is limited access to surface water. Identification and characterization of the main different types of Groundwater Aquifer systems will thus help greatly to develop the existing groundwater potential of the country. This study has quantified the hydraulic properties of Ashange formation including specific capacity, hydraulic conductivity, well efficiency, transmissivity etc.

The main conclusions of the analysis results of this study are:-

- In the various formations in ground water storage, transmission and yield are the basis for the classification of the aquifer. Lithology, topography, area coverage, fracture, weathering etc are considered for the qualitative classification of the aquifers. Quantitative data including pumping test data are collected, re-interpreted and used in the classification of aquifers. The occurrence of ground water depends not only on the nature of rocks but also in their geologic history.
- The Ashange basalt represents the lower fissural flood basalt volcanism on the north-west plateau. The basalts are several hundred of meters to kilometers thick of strongly weathered, crushed, tilted basalts of Oligocene age.

- It covers a total area of 85,000km^2 .According to Raphael Pik et.al 1998 the average thickness of Ethiopian flood is taken as 0.78.This gives a total volume of 66,300 m^3.

When compared to 180,000km3 of total volume of Ethiopian continental flood basalts, the Ashange formation covers about 37 % which is a huge amount as compared to upper formation flood basalts. Tarmaber formation covers, about 47,194Km^2, which is 8% of the total flood basalts aerial coverage in the country.

- Ashange fissural flood basalts are commonly injected by dolerites dykes and sills. They cover a large part of northern Ethiopia. Regional aquifer ground water in fracture and fissures has high water yield formation and often big springs are found in the formation. Springs with discharge ranging from 0.5 to 10 L/s mostly greater than 2L/s with a mean of 2.72 L/s are found. Yield of boreholes range from very low (51 m^3/d) to very high (2074m^3/d).Therefore, this unit is considered as a moderate to highly productiv aquifer.
- Total depth of boreholes in the Ashange basalts ranges from 57 to 312m.Mean discharge is 500m^3/d while mean drawdown is 34 meters.
- Analysis results of raw pumping test data from a data set of 70 boreholes show that the maximum and minimum transmissivity obtained is 594 m^2/day and 0.343m^2 /day respectively and a mean value of 52m^2/day this indicates the heterogeneity of the aquifer materials as indicated by their variation in the values of transmissivity.
- Measured and analyzed transmissivity values indicate that transmissivity decreases with increasing borehole depth and age of formation resulting from differential weathering and Hydrothermal activities. This shows that intermediate depth wells are advisable and economical to drill for domestic as well as other social purposes.
- The discharge of wells collected from Ashange formation range from 0.6 to 24 L/s with an average value of 5.8 L/s .
- Empirical relations between transmissivity and specific capacity was calculated for Ashange formation rather than using other theoretical relations like analytical methods which do not account for turbulent well loss .The turbulent head loss in wells collected and analyzed found from step drawdown test data ranges from 1.61E-07 to 0.003. Log-log plot of transmissivity and uncorrected specific capacity for turbulent head loss has a determination coefficient R^2 of 0.957 which shows a good correlation. Nevertheless the relation still is not best suggesting that a search for an empirical formula is helpful.

Besides to this, various studies have shown that the uncertainties of the transmissivity estimates using uncorrected specific capacity values are large.

- The obtained transmissivity versus specific capacity values after correction for turbulent flow has a determination coefficient of R^2 = 0.999 .This shows improvement in the empirical relationships between transmissivity and specific capacity. The 95% prediction interval still spans three log cycles.
- The best fit regression equation for the Ashange basalts aquifer is $T=11(Q/s)^{0.93}$ where T (m^2/day) is estimated transmissivity and (Q/S) is corrected specific capacity in (m^2/day).The comparison the Ethiopian Ashange formation having an age of 30ma with other younger and older continental flood basalts proved that younger flood basalts have higher aquifer productivity than their older counterparts. The decrease of aquifer productivity through age is due to factors such as long term hydrothermal processes, weathering effects, and other volcanic activities.

6.2 Recommendations

An understanding of the regional and local hydrogeological condition is necessary for the future development of ground water resources of an area. Geologic structures like faulting and fracturing most likely control the ground water movement in the study area. Sufficient knowledge of the ground water systems is also important for safe, adequate and sustainable ground water supply for various uses as well as to the desired purposes. Further works recommended here are:- An integrated data management system should be strengthened up to regional levels and below to minimize the wastage of time and energy for collecting secondary data. This will also minimize incompleteness of data which will hinder further studies.

- For better understanding of the hydrogeological system of Ashange formation as a whole ground water modeling will be essential.
- Mapping and identification of the overlying flood basalts and the underlying basement formation is significant for a better understanding of Ethiopian aquifer systems.
- Water quality assessment will be helpful if done focusing mainly on the study area to have a wider knowledge and perspective.

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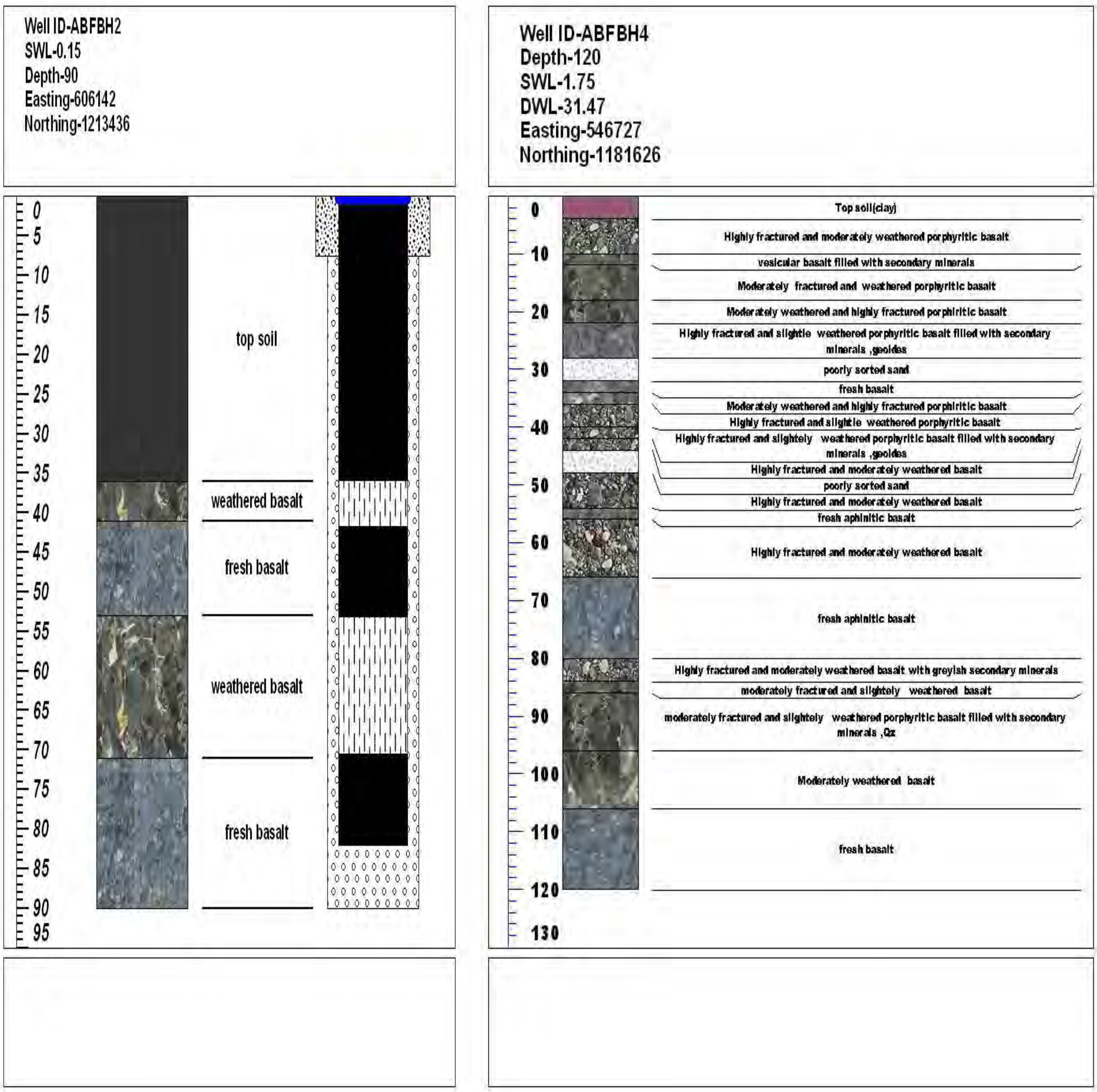
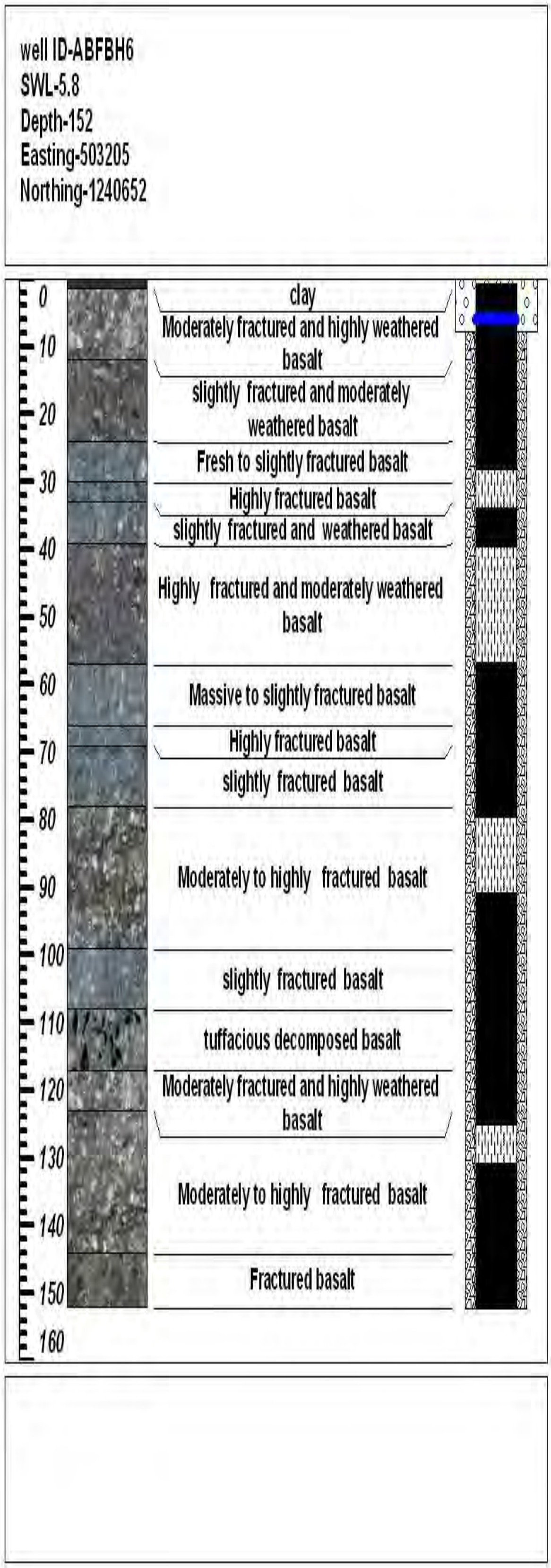
APPENDIXES

AI. Lithological log, well design and construction of representative wells

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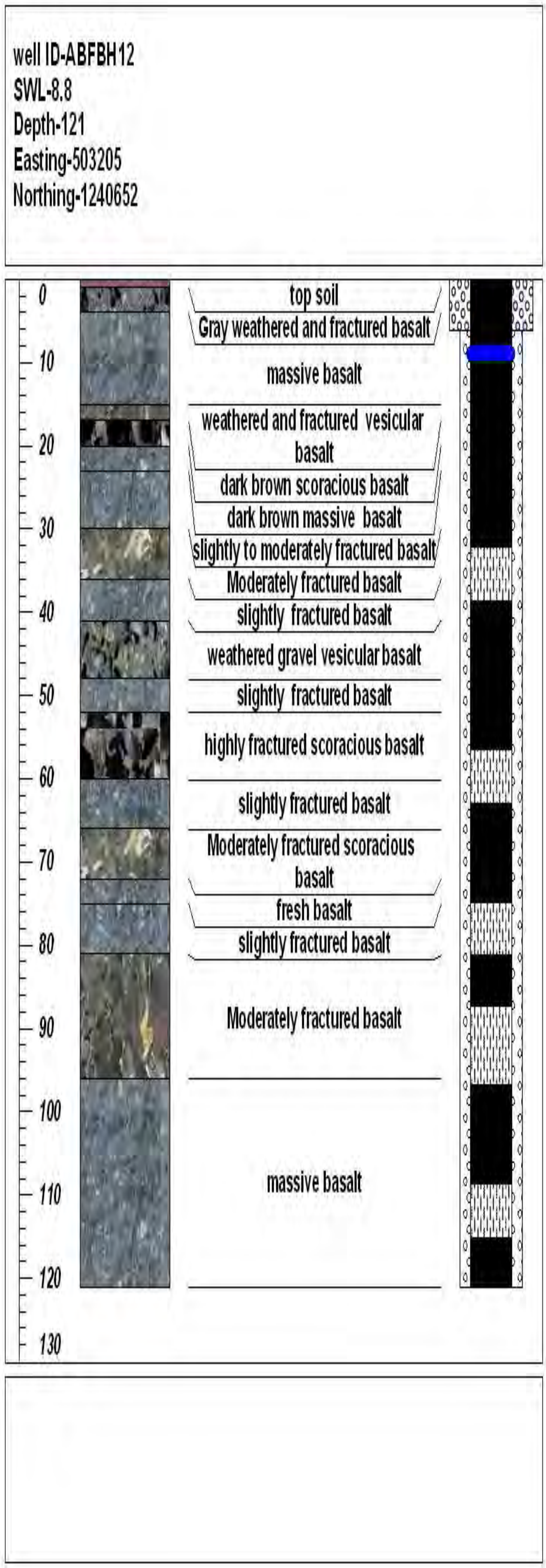
SWL-5.8
Depth-152
Easting-503205
Northing-1240652
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
clay
Moderately fractured and highly weathered basalt
slightly fractured and moderately weathered basalt
Fresh to slightly fractured basalt
Highly fractured basalt
slightly fractured and weathered basalt
Highly fractured and moderately weathered basalt
Massive to slightly fractured basalt
Highly fractured basalt
slightly fractured basalt
Moderately to highly fractured basalt
slightly fractured basalt
tuffacious decomposed basalt
Moderately fractured and highly weathered basalt
Moderately to highly fractured basalt
Fractured basalt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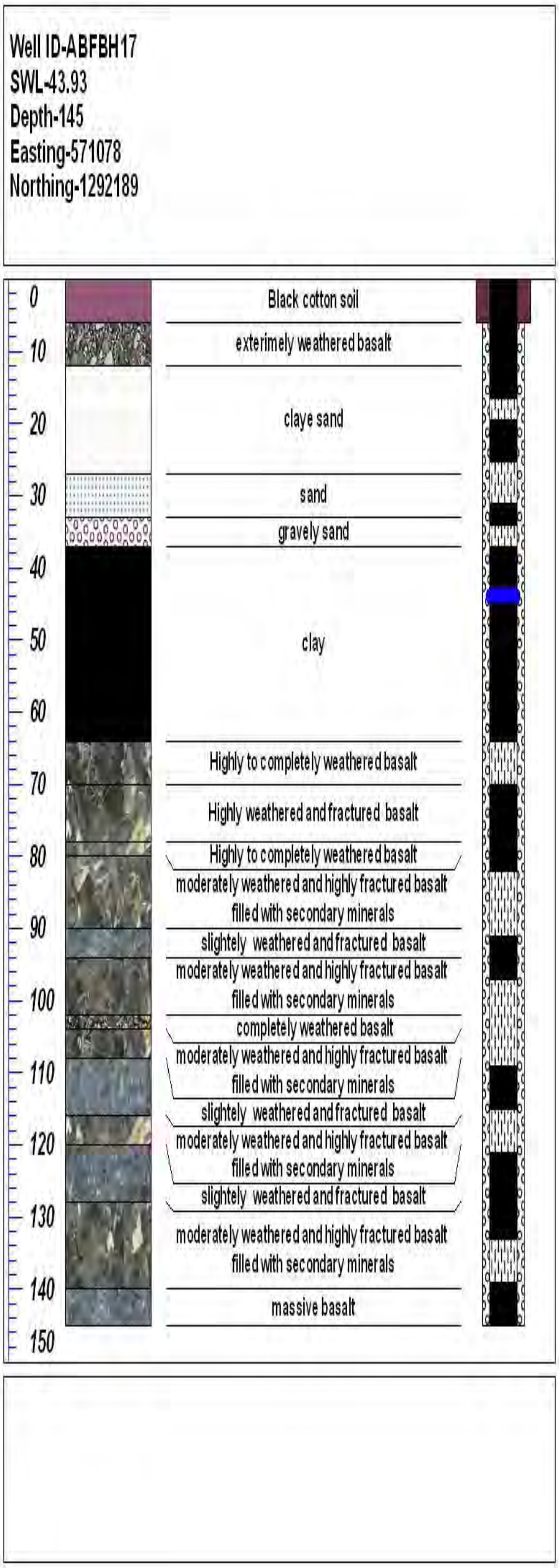
SWL-8.8
Depth-121
Easting-503205
Northing-1240652
0
10
20
30
40
50
60
70
80
90
100
110
120
130
top soil
Gray weathered and fractured basalt
massive basalt
weathered and fractured vesicular basalt
dark brown scoracious basalt
dark brown massive basalt
slightly to moderately fractured basalt
Moderately fractured basalt
slightly fractured basalt
weathered gravel vesicular basalt
slightly fractured basalt
highly fractured scoracious basalt
slightly fractured basalt
Moderately fractured scoracious basalt
fresh basalt
slightly fractured basalt
Moderately fractured basalt
massive basalt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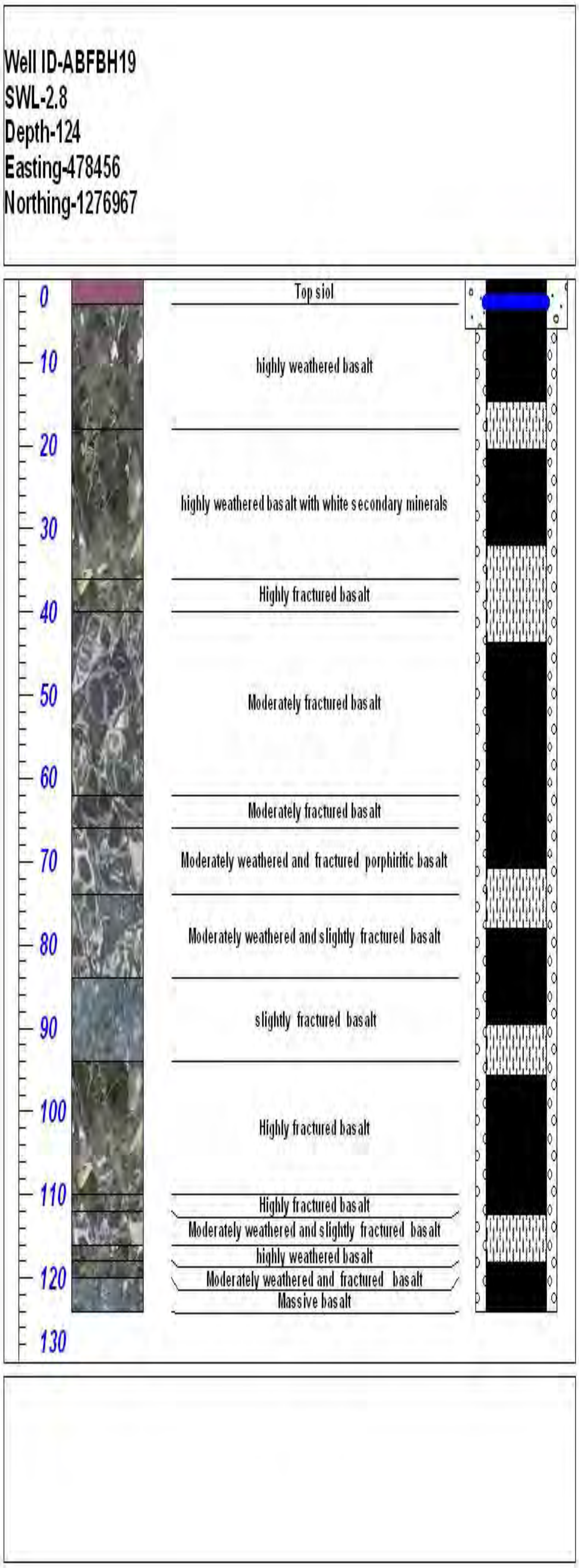
Depth-145
Easting-571078
Northing-1292189
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Black cotton soil
exterimely weathered basalt
claye sand
sand
gravely sand
clay
Highly to completely weathered basalt
Highly weathered and fractured basalt
Highly to completely weathered basalt
moderately weathered and highly fractured basalt filled with secondary minerals
slightely weathered and fractured basalt
moderately weathered and highly fractured basalt filled with secondary minerals
completely weathered basalt
moderately weathered and highly fractured basalt filled with secondary minerals
slightely weathered and fractured basalt
moderately weathered and highly fractured basalt filled with secondary minerals
slightely weathered and fractured basalt
moderately weathered and highly fractured basalt filled with secondary minerals
massive basalt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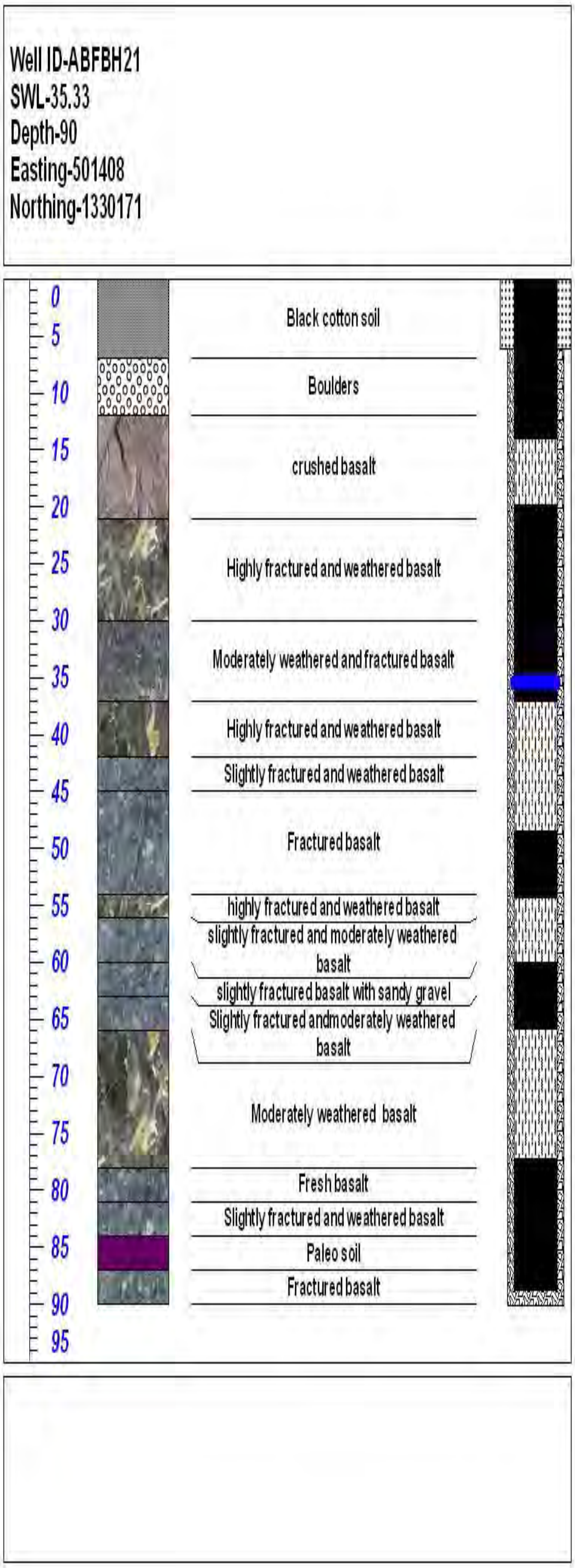
Depth-124
Easting-478456
Northing-1276967
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Top siol
highly weathered basalt
highly weathered basalt with white secondary minerals
Highly fractured basalt
Moderately fractured basalt
Moderately fractured basalt
Moderately weathered and fractured porphiritic basalt
Moderately weathered and slightly fractured basalt
slightly fractured basalt
Highly fractured basalt
Highly fractured basalt
Moderately weathered and slightly fractured basalt
highly weathered basalt
Moderately weathered and fractured basalt
Massive basalt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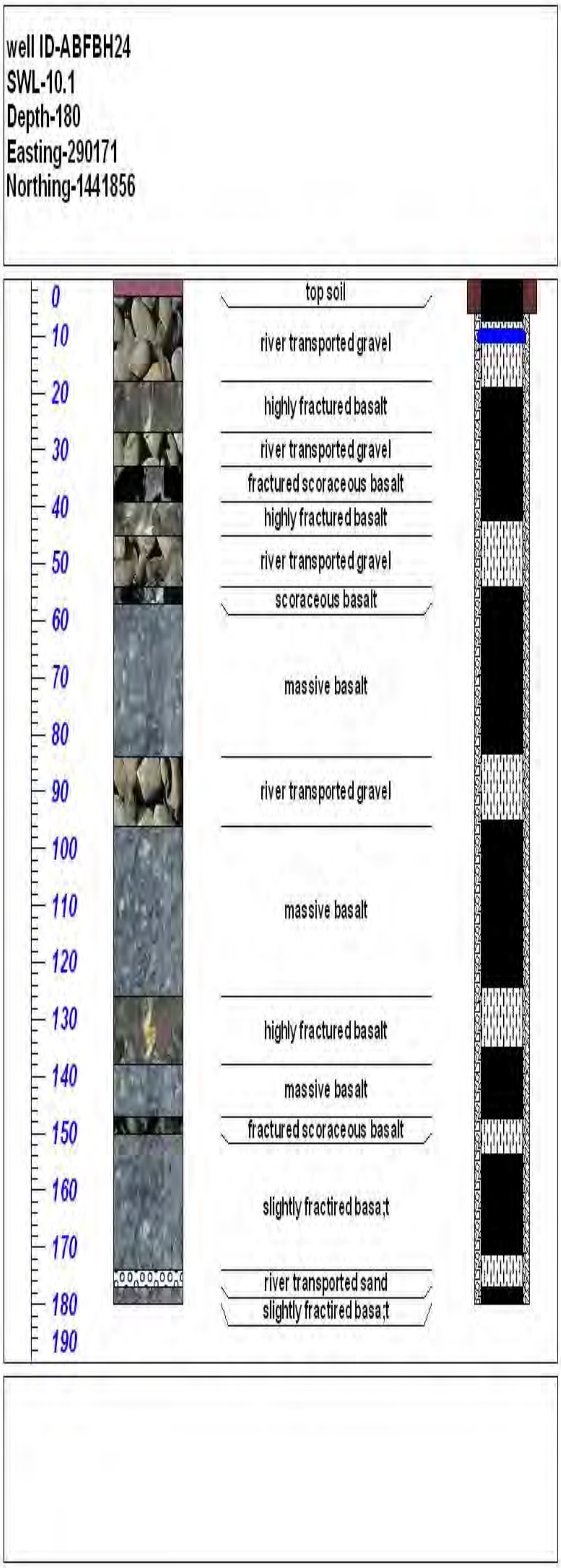
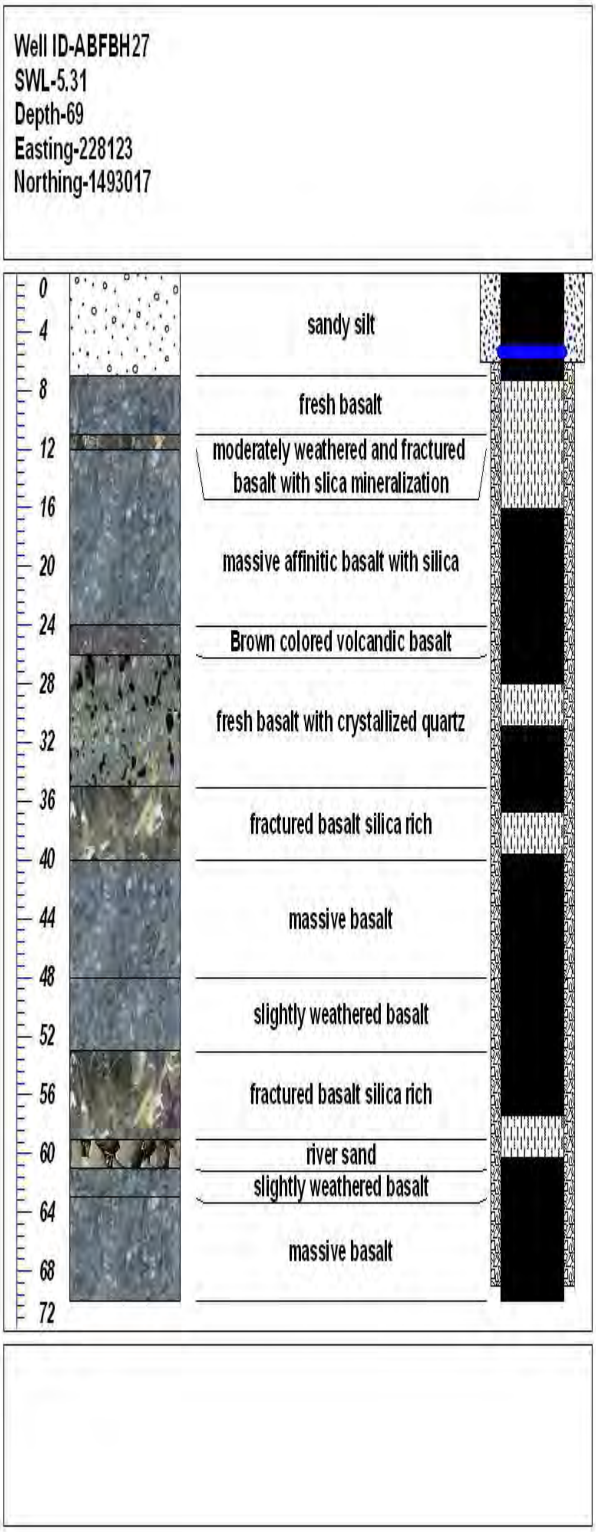
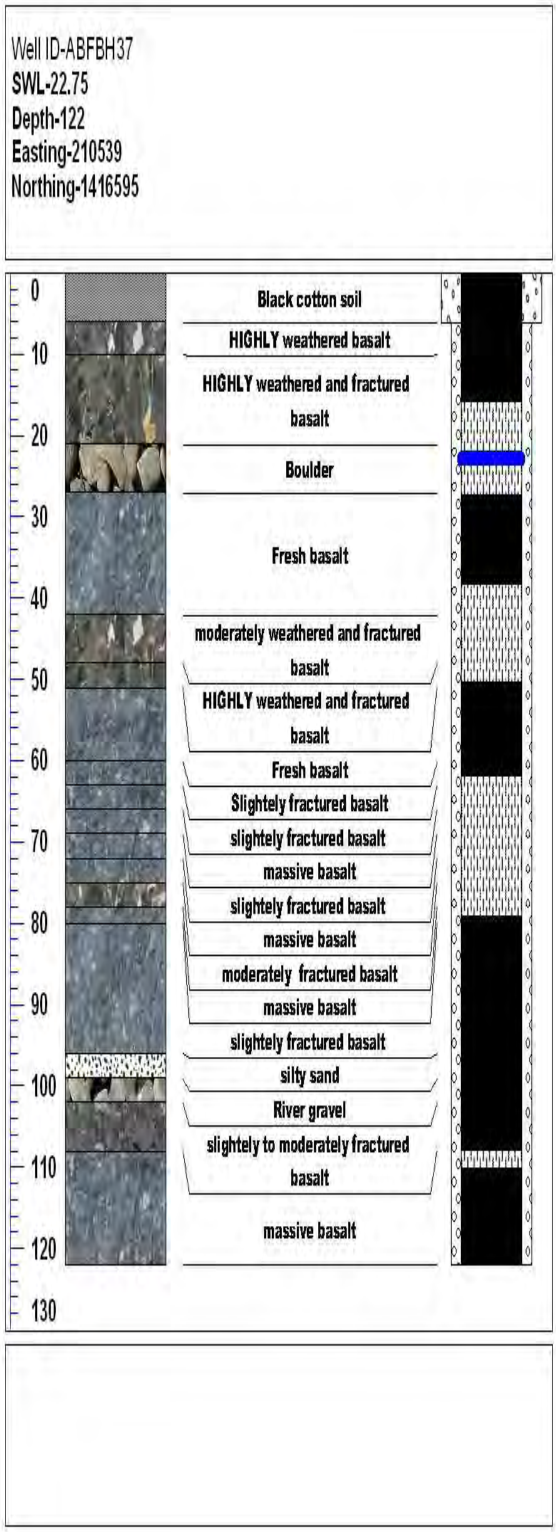
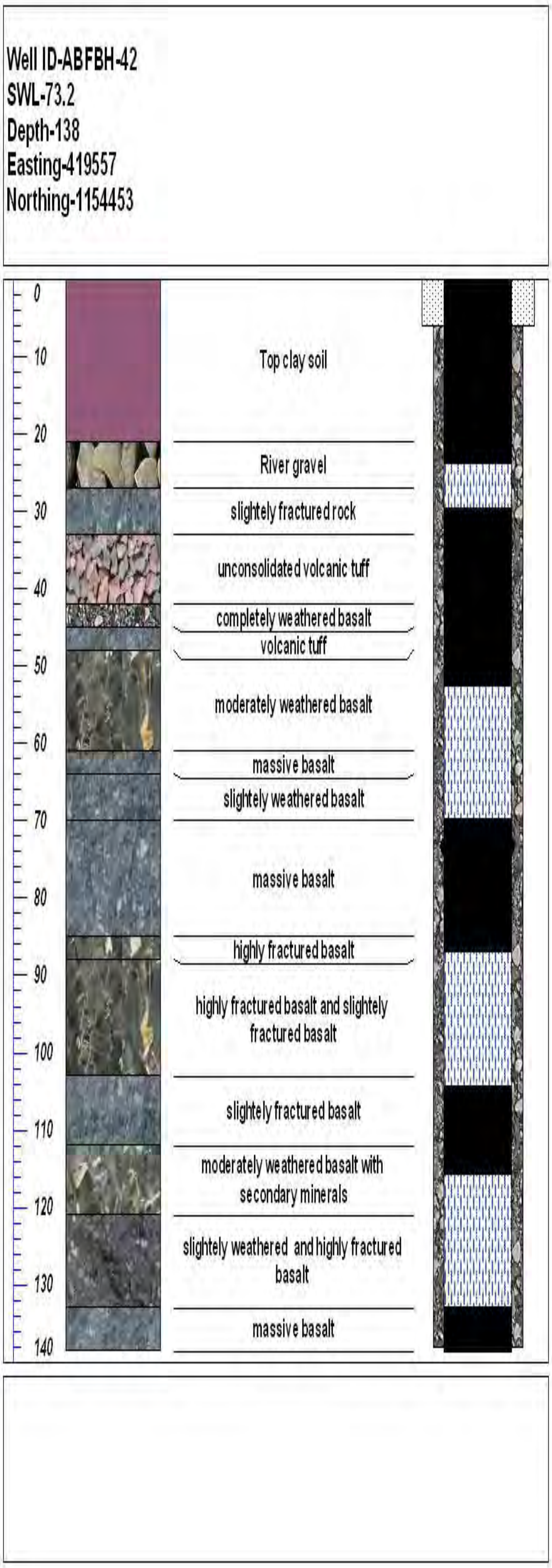
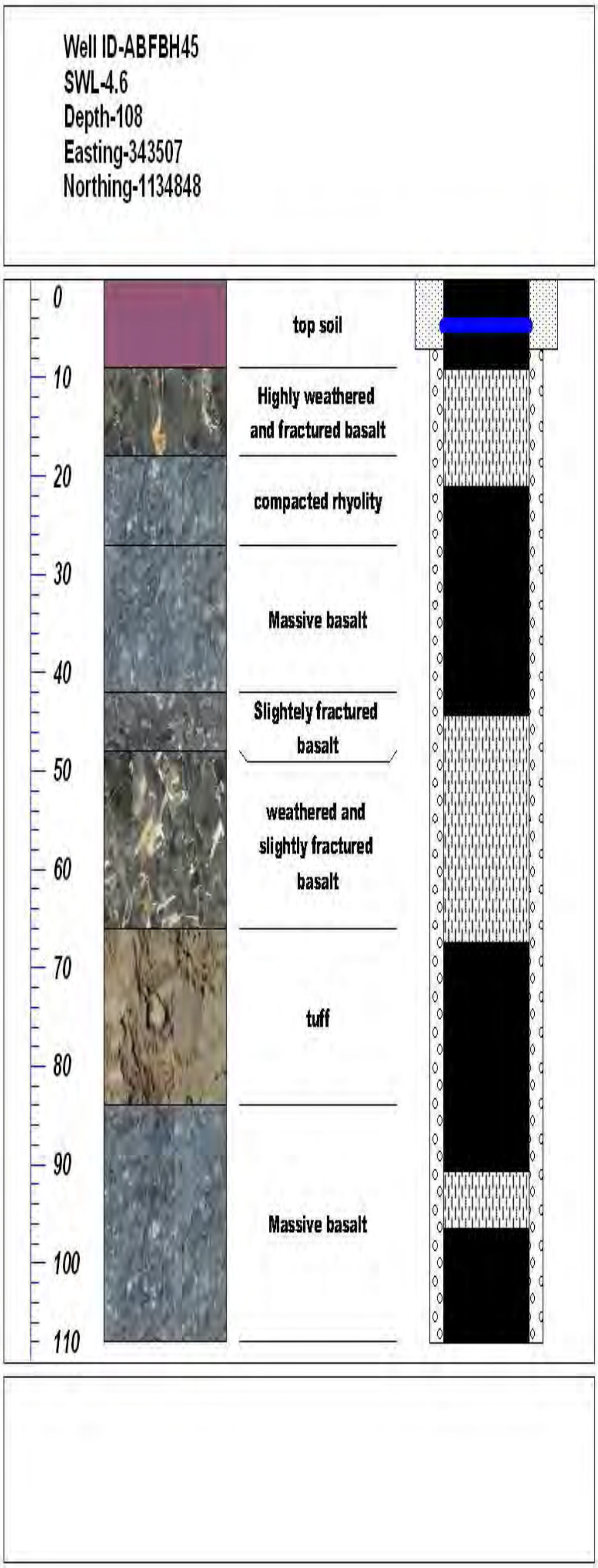
SWL-35.33
Depth-90
Easting-501408
Northing-1330171
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
Black cotton soil
Boulders
crushed basalt
Highly fractured and weathered basalt
Moderately weathered and fractured basalt
Highly fractured and weathered basalt
Slightly fractured and weathered basalt
Fractured basalt
highly fractured and weathered basalt
slightly fractured and moderately weathered basalt
slightly fractured basalt with sandy gravel
Slightly fractured andmoderately weathered basalt
Moderately weathered basalt
Fresh basalt
Slightly fractured and weathered basalt
Paleo soil
Fractured basalt

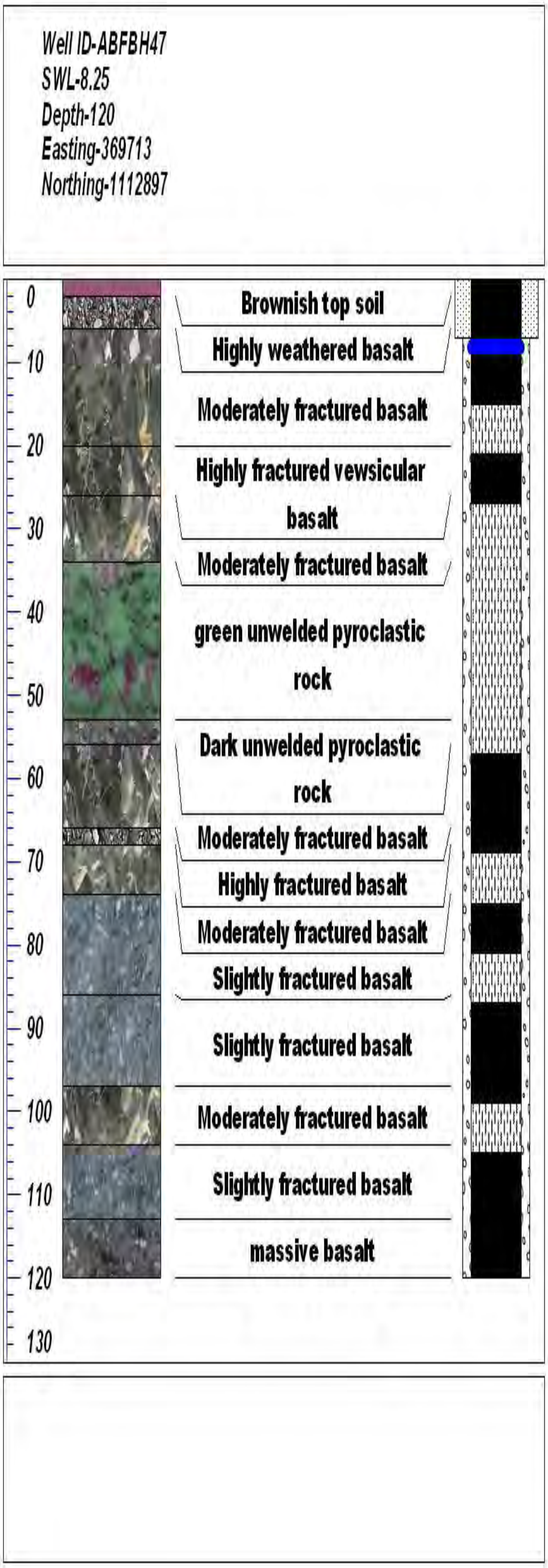

well ID-ABFBH24
SWL-10.1
Depth-180
Easting-290171
Northing-1441856
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
top soil
river transported gravel
highly fractured basalt
river transported gravel
fractured scoraceous basalt
highly fractured basalt
river transported gravel
scoraceous basalt
massive basalt
river transported gravel
massive basalt
highly fractured basalt
massive basalt
fractured scoraceous basalt
slightly fractired basa;t
river transported sand
slightly fractired basa;t

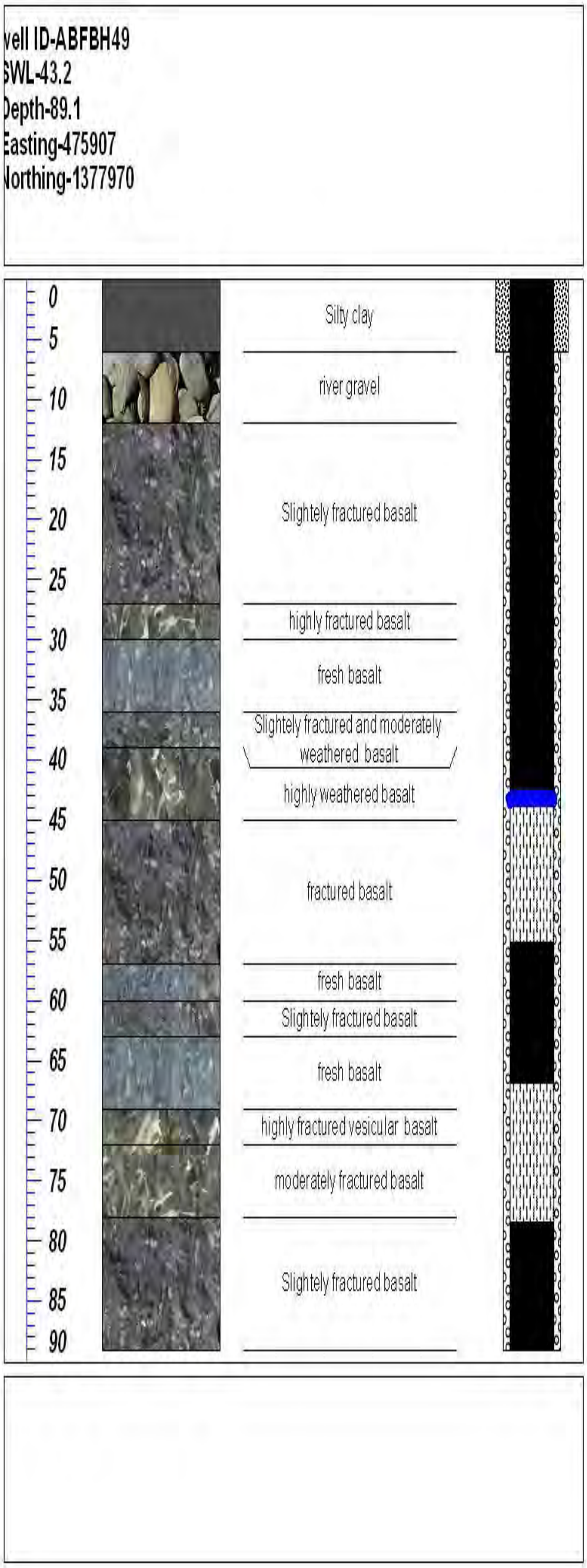

Well ID-ABFBH27
SWL-5.31
Depth-69
Easting-228123
Northing-1493017
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
sandy silt
fresh basalt
moderately weathered and fractured basalt with slica mineralization
massive affinitic basalt with silica
Brown colored volcandic basalt
fresh basalt with crystallized quartz
fractured basalt silica rich
massive basalt
slightly weathered basalt
fractured basalt silica rich
river sand
slightly weathered basalt
massive basalt

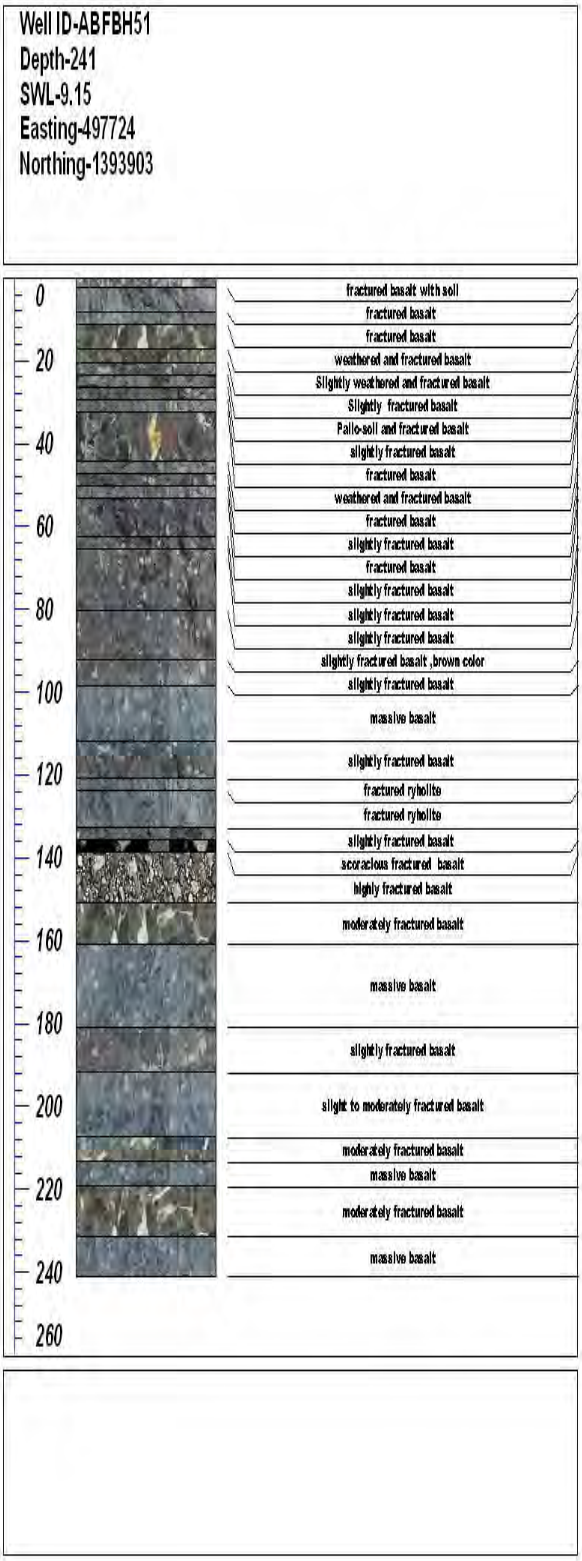

Well ID-ABFBH37
SWL-22.75
Depth-122
Easting-210539
Northing-1416595
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Black cotton soil
HIGHLY weathered basalt
HIGHLY weathered and fractured basalt
Boulder
Fresh basalt
moderately weathered and fractured basalt
HIGHLY weathered and fractured basalt
Fresh basalt
Slightely fractured basalt
slightely fractured basalt
massive basalt
slightely fractured basalt
massive basalt
moderately fractured basalt
massive basalt
slightely fractured basalt
silty sand
River gravel
slightely to moderately fractured basalt
massive basalt

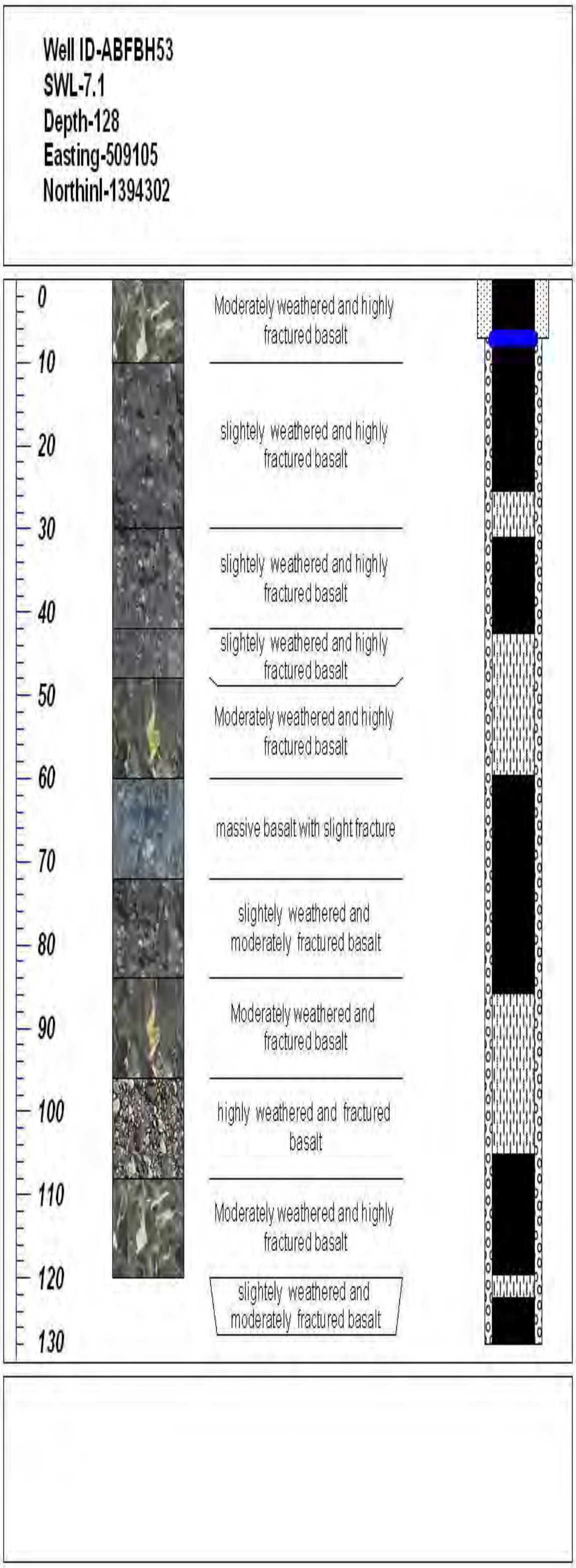

Well ID-ABFBH-42
SWL-73.2
Depth-138
Easting-419557
Northing-1154453
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Top clay soil
River gravel
slightly fractured rock
unconsolidated volcanic tuff
completely weathered basalt
volcanic tuff
moderately weathered basalt
massive basalt
slightely weathered basalt
massive basalt
highly fractured basalt
highly fractured basalt and slightely fractured basalt
slightely fractured basalt
moderately weathered basalt with secondary minerals
slightely weathered and highly fractured basalt
massive basalt

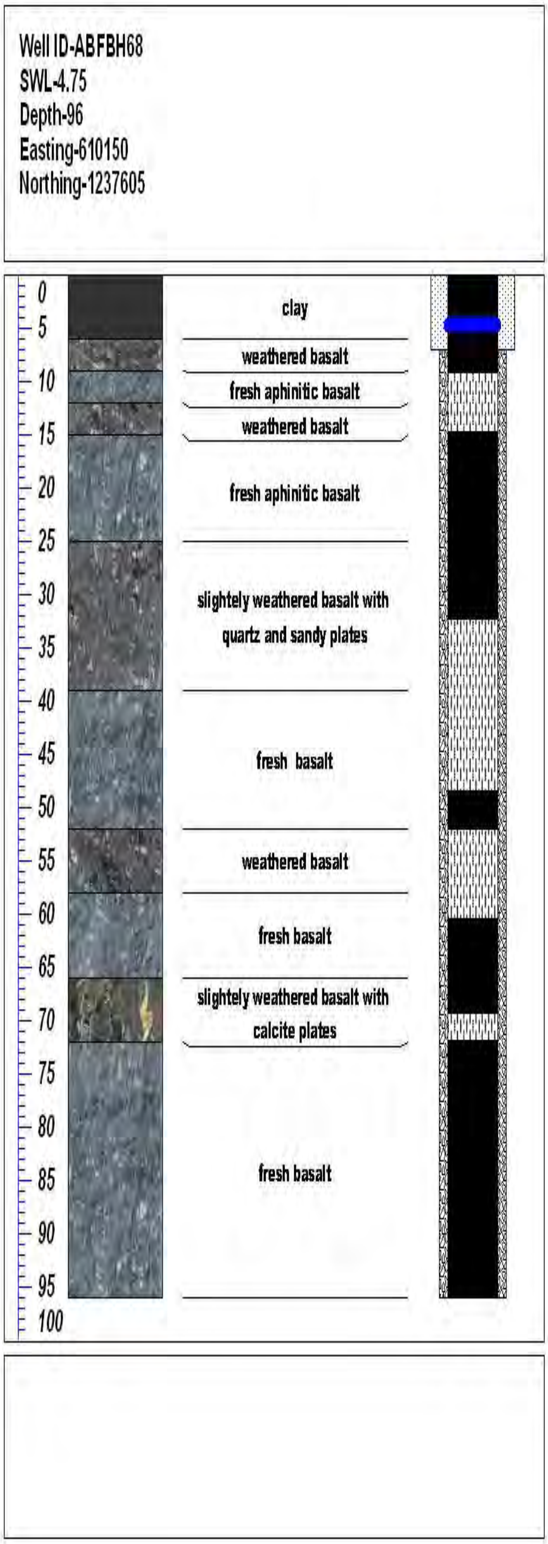

Well ID-ABFBH45
SWL-4.6
Depth-108
Easting-343507
Northing-1134848
0
10
20
30
40
50
60
70
80
90
100
110
top soil
Highly weathered and fractured basalt
compacted rhyolity
Massive basalt
Slightely fractured basalt
weathered and slightly fractured basalt
tuff
Massive basalt

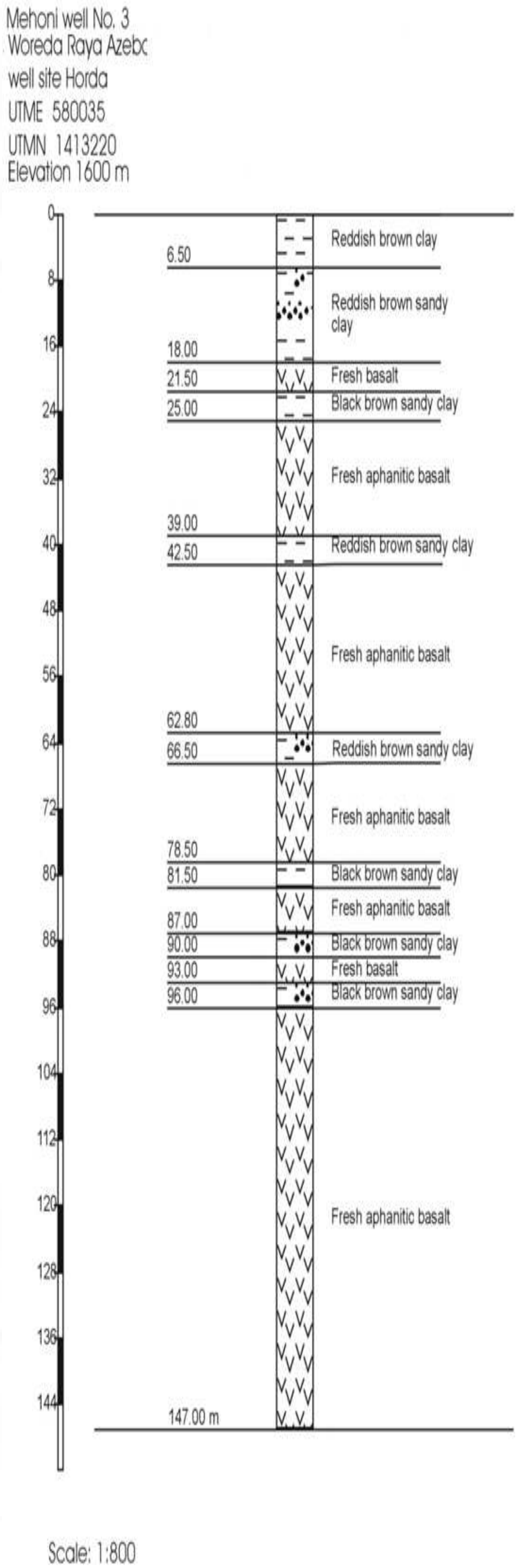

Well ID-ABFBH47
SWL-8.25
Depth-120
Easting-369713
Northing-1112897
Brownish top soil
Highly weathered basalt
Moderately fractured basalt
Highly fractured vewsicular basalt
Moderately fractured basalt
green unwelded pyroclastic rock
Dark unwelded pyroclastic rock
Moderately fractured basalt
Highly fractured basalt
Moderately fractured basalt
Slightly fractured basalt
Slightly fractured basalt
Moderately fractured basalt
Slightly fractured basalt
massive basalt

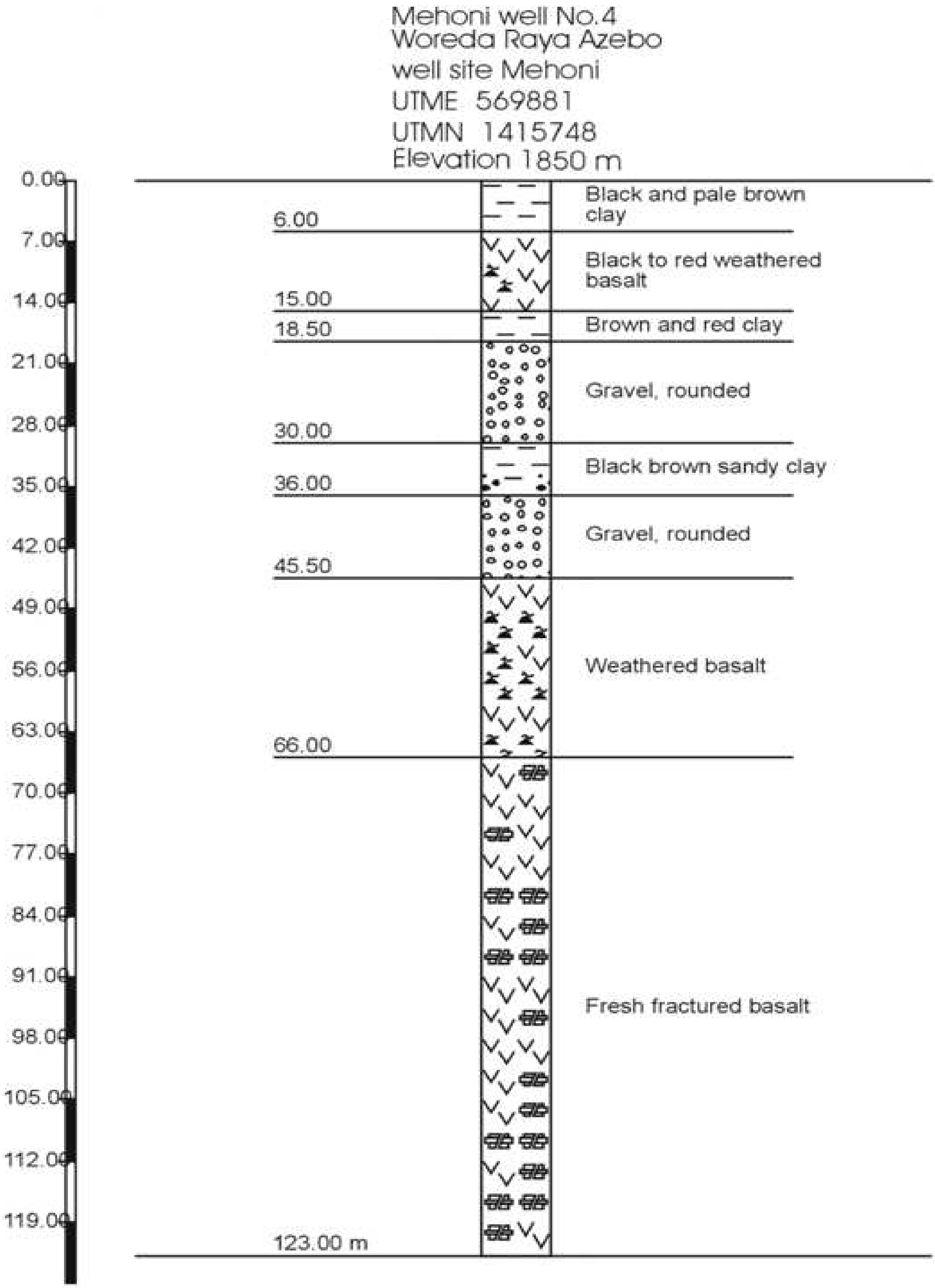

vell ID-ABFBH49
WL-43.2
epth-89.1
asting-475907
lorthing-1377970
Silty clay
river gravel
Slightely fractured basalt
highly fractured basalt
fresh basalt
Slightely fractured and moderately weathered basalt
highly weathered basalt
fractured basalt
fresh basalt
Slightely fractured basalt
fresh basalt
highly fractured vesicular basalt
moderately fractured basalt
Slightely fractured basalt


Well ID-ABFBH51
Depth-241
SWL-9.15
Easting-497724
Northing-1393903
0
20
40
60
80
100
120
140
160
180
200
220
240
260
fractured basalt with soil
fractured basalt
fractured basalt
weathered and fractured basalt
Slightly weathered and fractured basalt
Slightly fractured basalt
Pallo-soil and fractured basalt
slightly fractured basalt
fractured basalt
weathered and fractured basalt
fractured basalt
slightly fractured basalt
fractured basalt
slightly fractured basalt
slightly fractured basalt
slightly fractured basalt
slightly fractured basalt ,brown color
slightly fractured basalt
massive basalt
slightly fractured basalt
fractured ryholite
fractured ryholite
slightly fractured basalt
scoracious fractured basalt
highly fractured basalt
moderately fractured basalt
massive basalt
slightly fractured basalt
slight to moderately fractured basalt
moderately fractured basalt
massive basalt
moderately fractured basalt
massive basalt


Well ID-ABFBH53
SWL-7.1
Depth-128
Easting-509105
Northinl-1394302
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Moderately weathered and highly fractured basalt
slightely weathered and highly fractured basalt
slightely weathered and highly fractured basalt
slightely weathered and highly fractured basalt
Moderately weathered and highly fractured basalt
massive basalt with slight fracture
slightely weathered and moderately fractured basalt
Moderately weathered and fractured basalt
highly weathered and fractured basalt
Moderately weathered and highly fractured basalt
slightely weathered and moderately fractured basalt

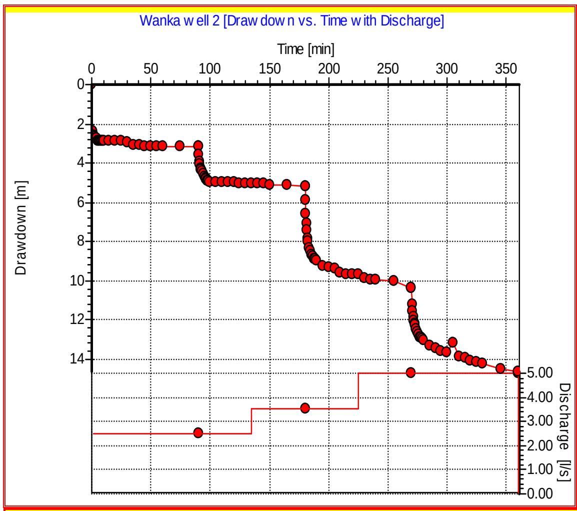

Well ID-ABFBH68
SWL-4.75
Depth-96
Easting-610150
Northing-1237605
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
clay
weathered basalt
fresh aphinitic basalt
weathered basalt
fresh aphinitic basalt
slightely weathered basalt with quartz and sandy plates
fresh basalt
weathered basalt
fresh basalt
slightely weathered basalt with calcite plates
fresh basalt

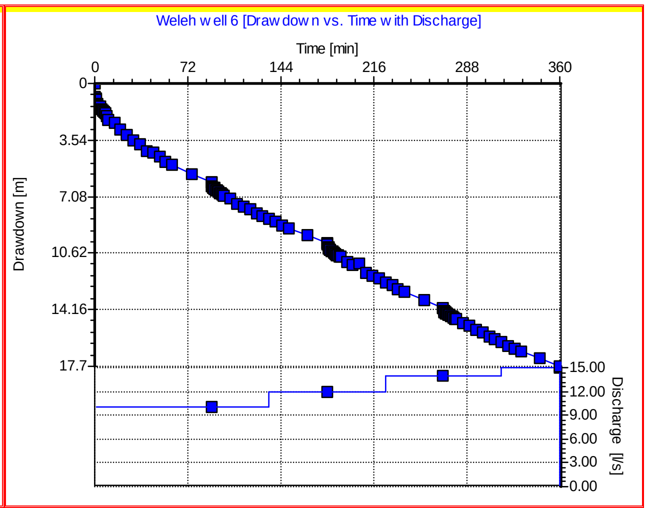

Mehoni well No. 3
Woreda Raya Azebc
well site Horda
UTME 580035
UTMN 1413220
Elevation 1600 m
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
6.50
18.00
21.50
25.00
39.00
42.50
62.80
66.50
78.50
81.50
87.00
90.00
93.00
96.00
147.00 m
Reddish brown clay
Reddish brown sandy clay
Fresh basalt
Black brown sandy clay
Fresh aphanitic basalt
Reddish brown sandy clay
Fresh aphanitic basalt
Reddish brown sandy clay
Fresh aphanitic basalt
Black brown sandy clay
Fresh aphanitic basalt
Black brown sandy clay
Fresh basalt
Black brown sandy clay
Fresh aphanitic basalt
Scale: 1:800

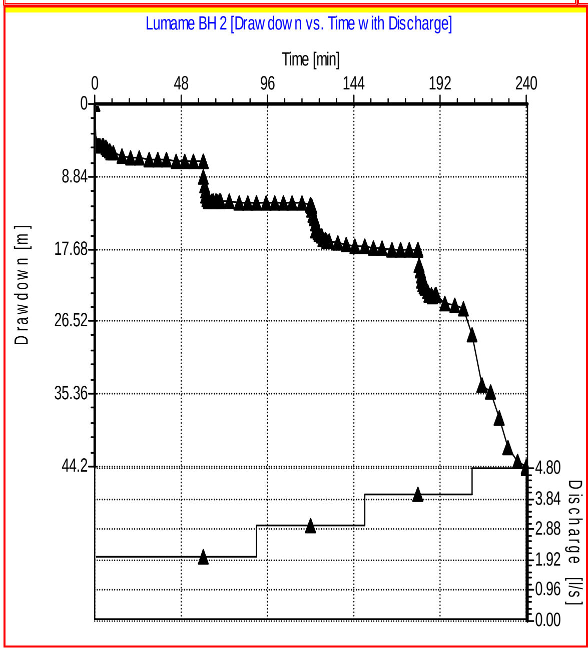

Mehoni well No.4
Woreda Raya Azebo
well site Mehoni
UTME 569881
UTMN 1415748
Elevation 1850 m
0.00
7.00
14.00
21.00
28.00
35.00
42.00
49.00
56.00
63.00
70.00
77.00
84.00
91.00
98.00
105.00
112.00
119.00
6.00
Black and pale brown clay
15.00
Black to red weathered basalt
18.50
Brown and red clay
30.00
Gravel, rounded
36.00
Black brown sandy clay
45.50
Gravel, rounded
66.00
Weathered basalt
123.00 m
Fresh fractured basalt

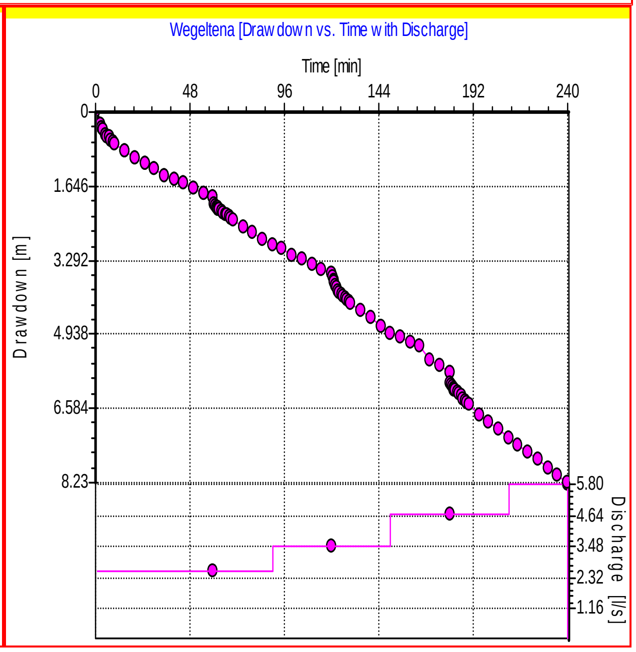
Scale: 1:700

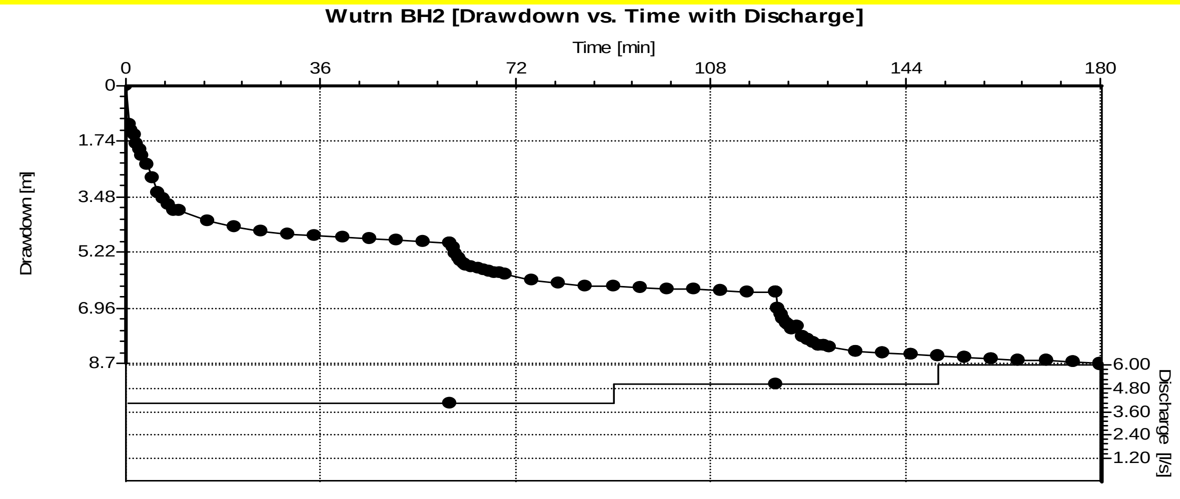
AII. Drawdown and Time versus Discharge after step (variable) test

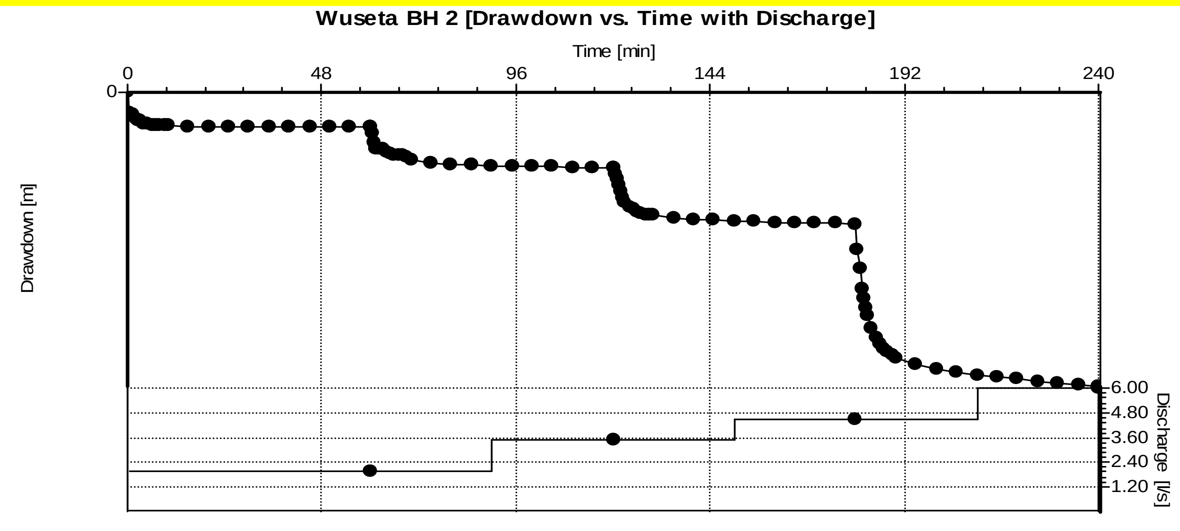


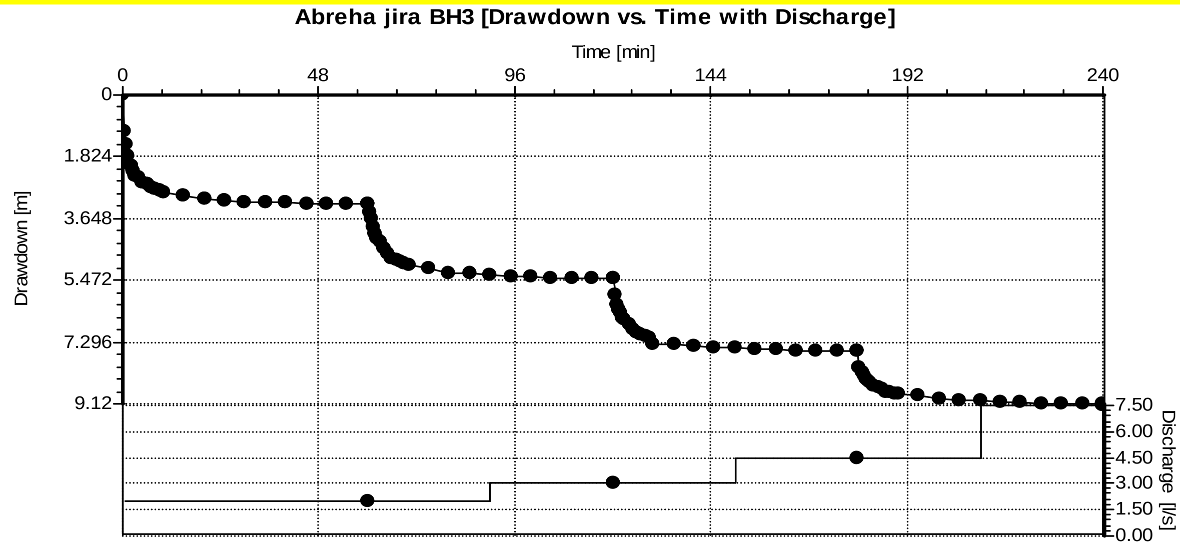


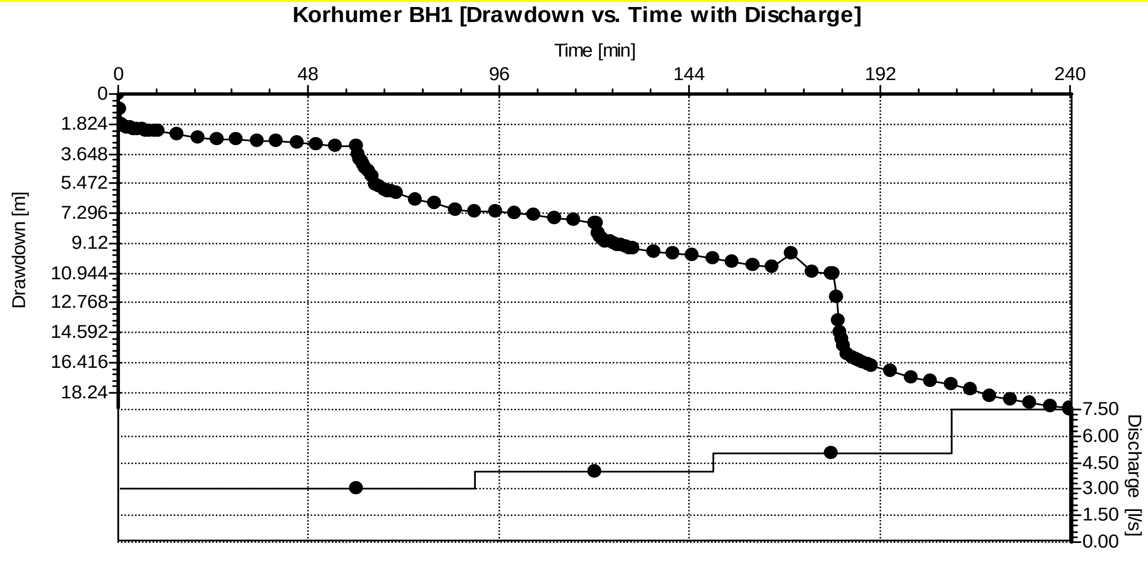


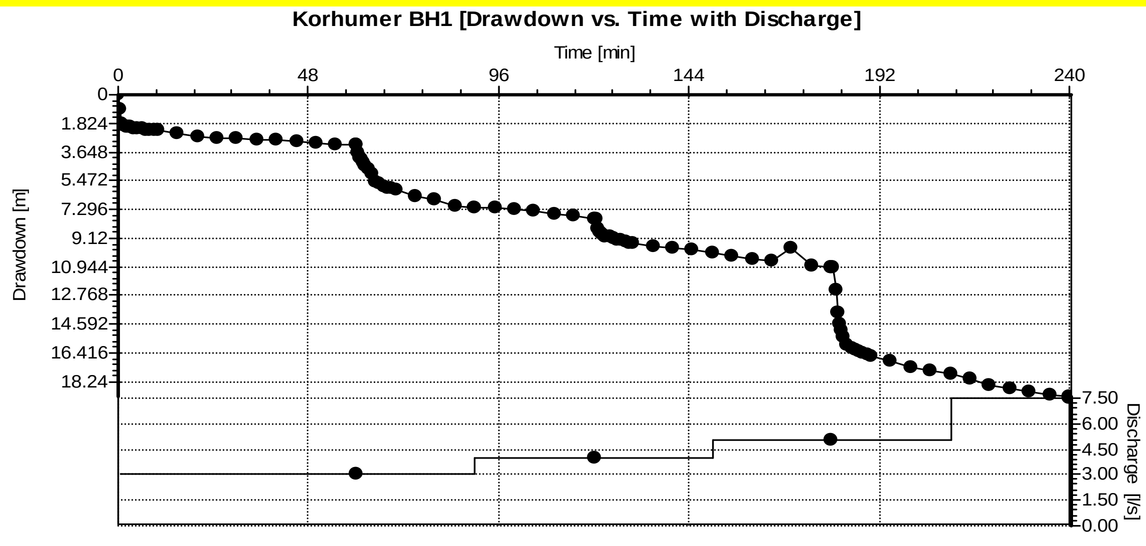


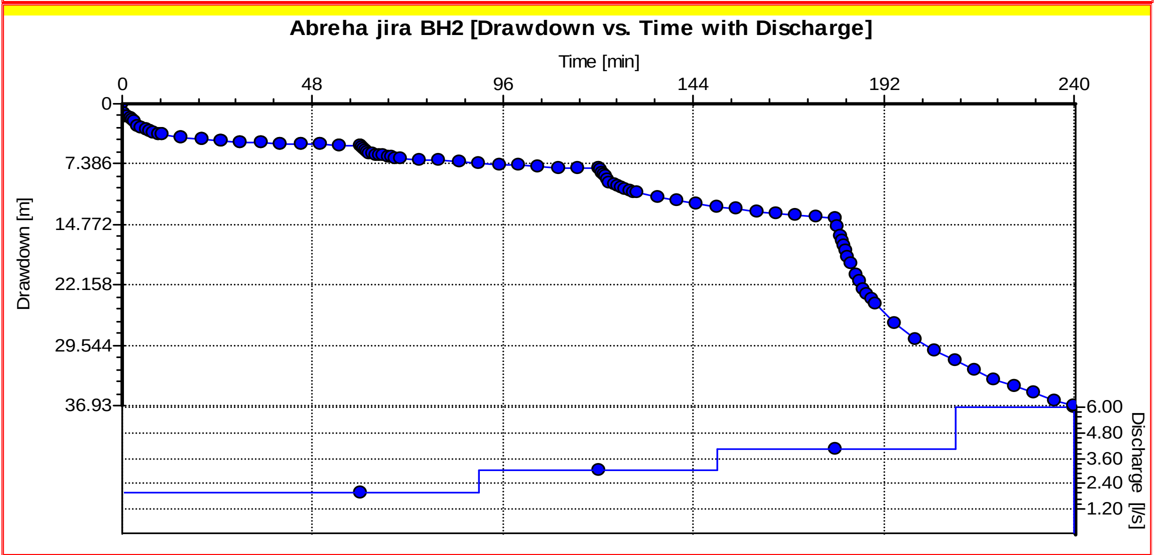

Wutrn BH2 [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
144
180
Drawdown [m]
0
1.74
3.48
5.22
6.96
8.7
Discharge [l/s]
6.00
4.80
3.60
2.40
1.20

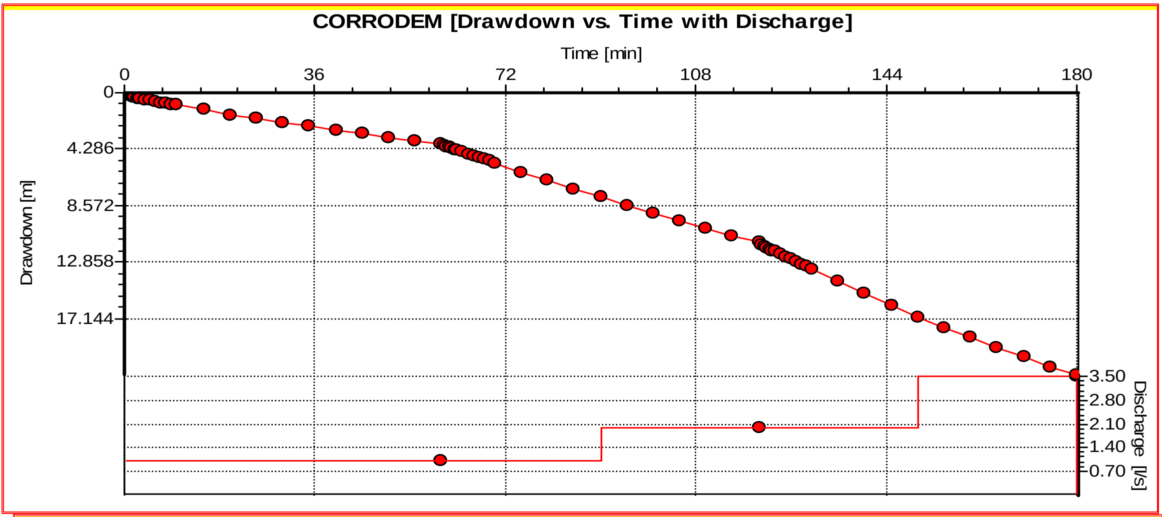

Wuseta BH 2 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
Discharge [l/s]
6.00
4.80
3.60
2.40
1.20

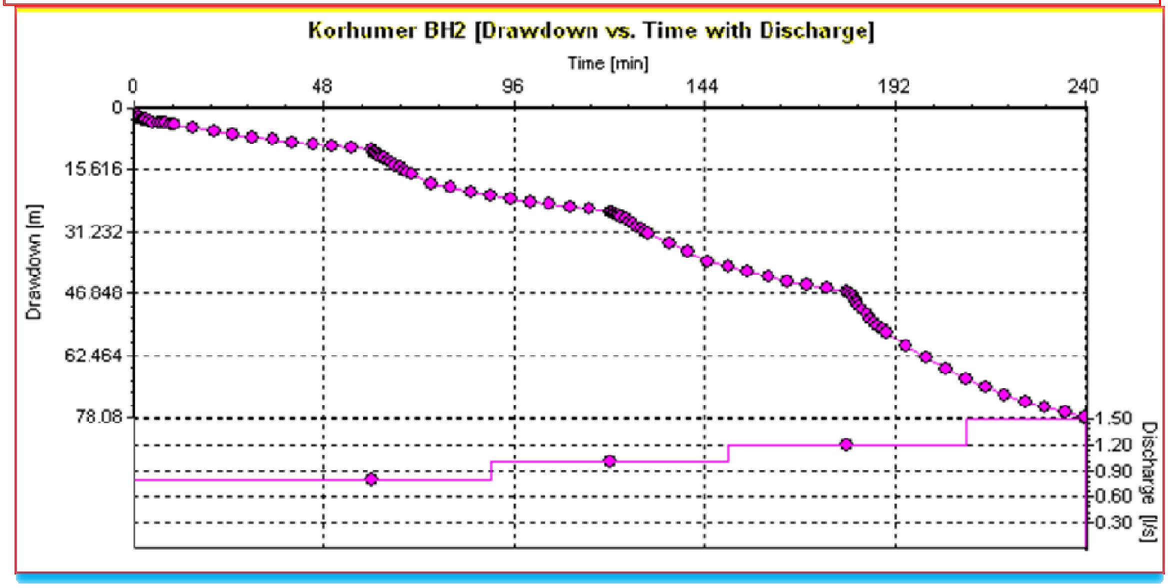

Abreha jira BH3 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
1.824
3.648
5.472
7.296
9.12
Discharge [l/s]
7.50
6.00
4.50
3.00
1.50
0.00

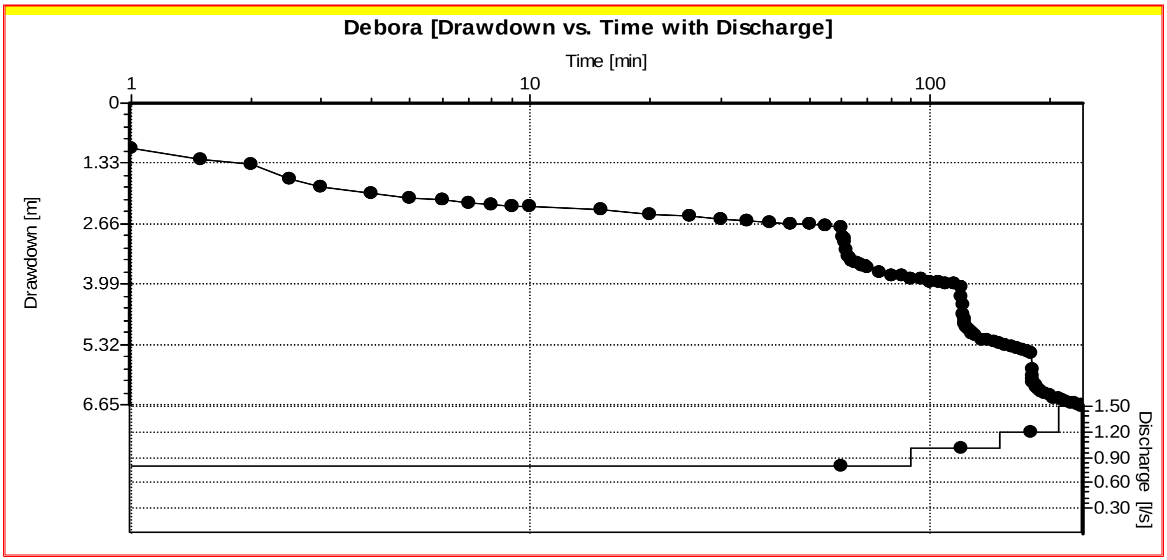

Korhumer BH1 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
1.824
3.648
5.472
7.296
9.12
10.944
12.768
14.592
16.416
18.24
Discharge [l/s]
7.50
6.00
4.50
3.00
1.50
0.00

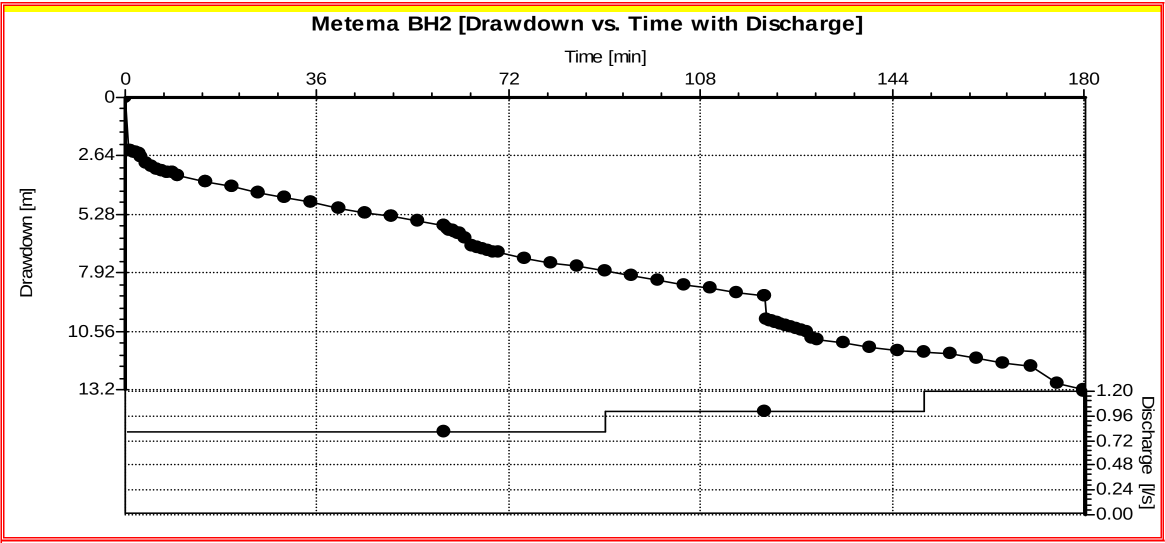

Korhumer BH1 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
1.824
3.648
5.472
7.296
9.12
10.944
12.768
14.592
16.416
18.24
Discharge [l/s]
7.50
6.00
4.50
3.00
1.50
0.00

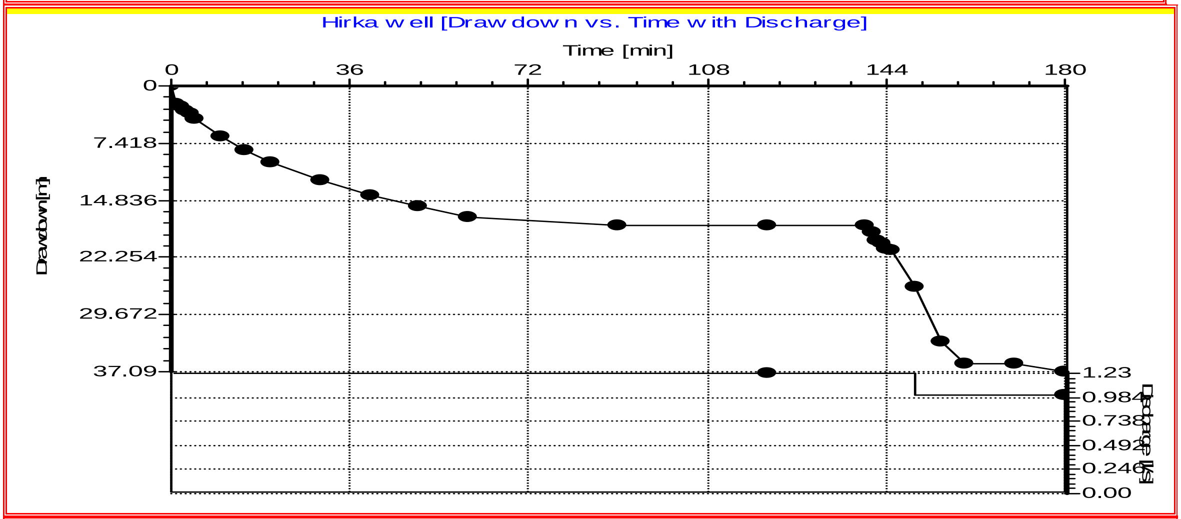

Abreha jira BH2 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
7.386
14.772
22.158
29.544
36.93
Discharge [l/s]
6.00
4.80
3.60
2.40
1.20

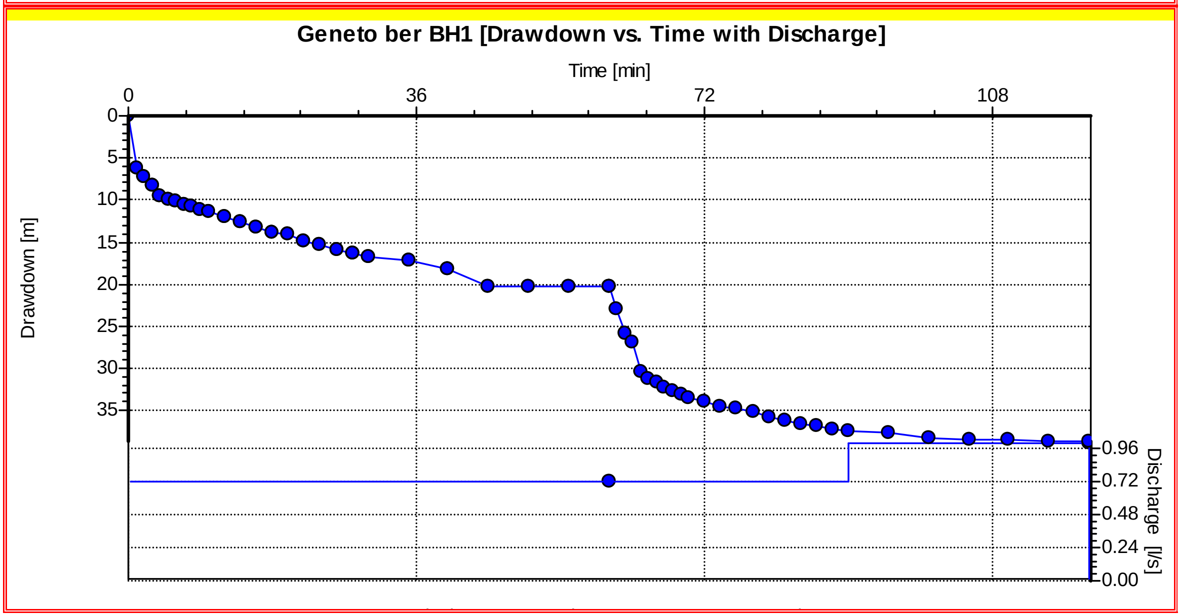

CORRODEM [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
144
180
Drawdown [m]
0
4.286
8.572
12.858
17.144
Discharge [l/s]
3.50
2.80
2.10
1.40
0.70

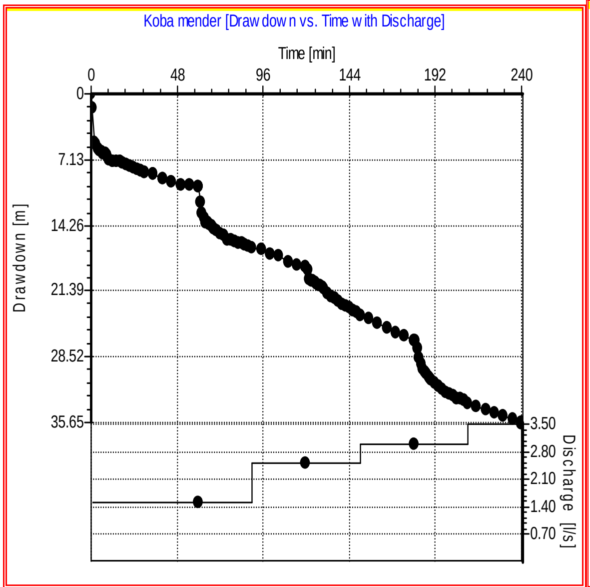

Korhumer BH2 [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
192
240
Drawdown [m]
0
15.616
31.232
46.848
62.464
78.08
Discharge [l/s]
1.50
1.20
0.90
0.60
0.30

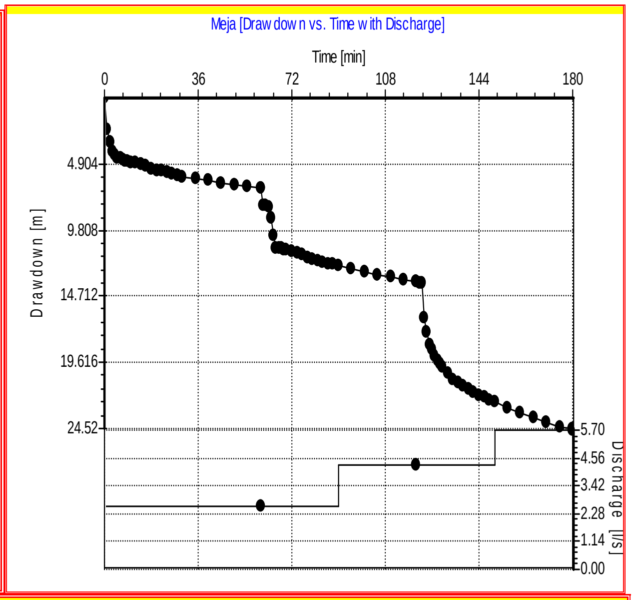

Debora [Drawdown vs. Time with Discharge]
Time [min]
1
10
100
Drawdown [m]
0
1.33
2.66
3.99
5.32
6.65
Discharge [l/s]
1.50
1.20
0.90
0.60
0.30

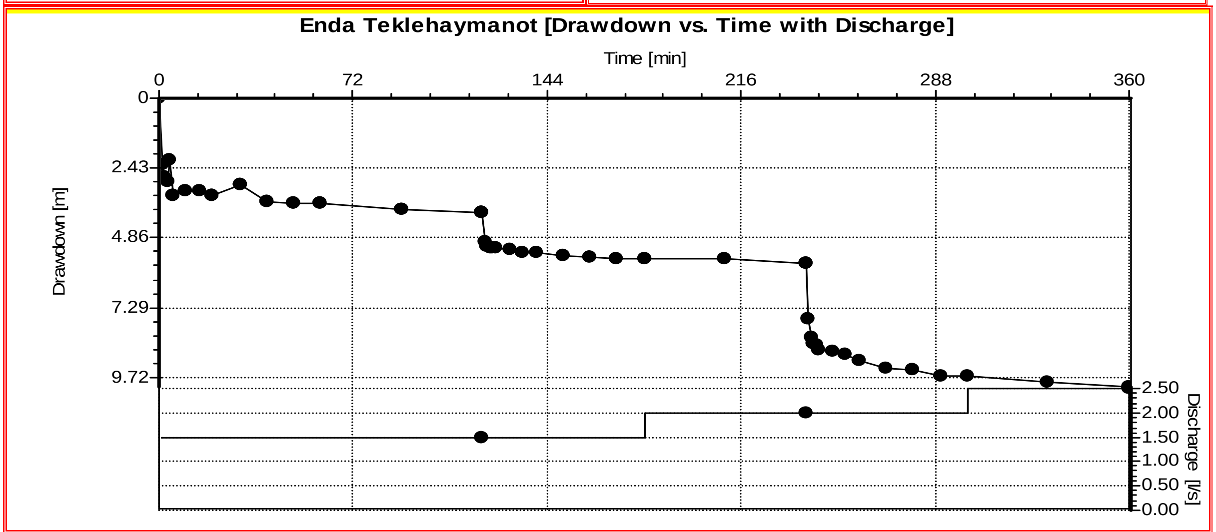

Metema BH2 [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
144
180
Drawdown [m]
0
2.64
5.28
7.92
10.56
13.2
Discharge [l/s]
1.20
0.96
0.72
0.48
0.24
0.00

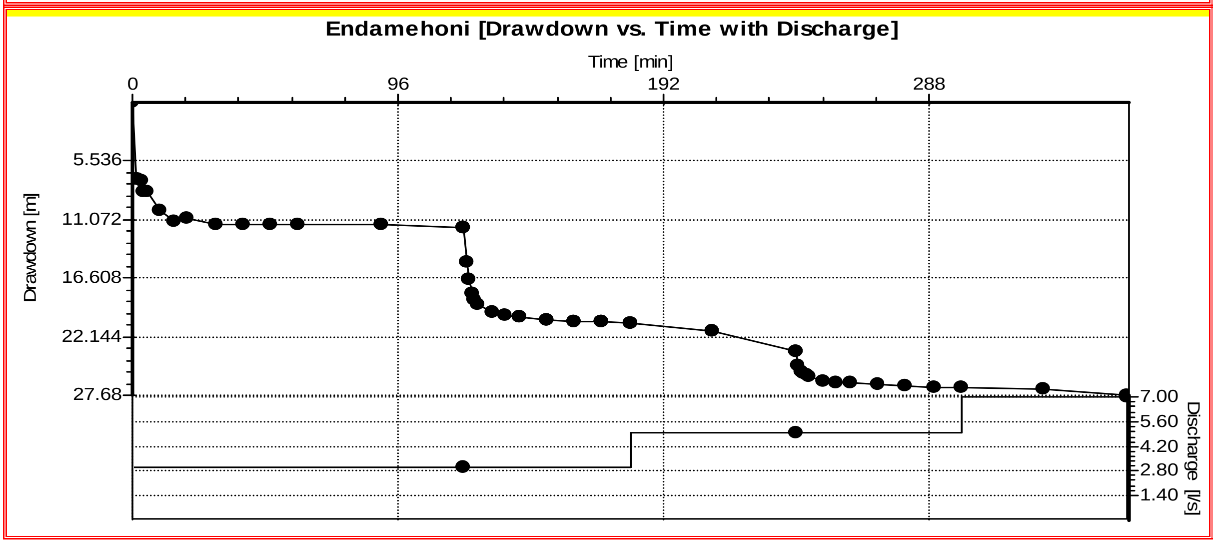

Hirka w ell [Draw dow n vs. Time w ith Discharge]
Time [min]
0
36
72
108
144
180
0
7.418
14.836
22.254
29.672
37.09
1.23
0.984
0.738
0.492
0.246
0.00

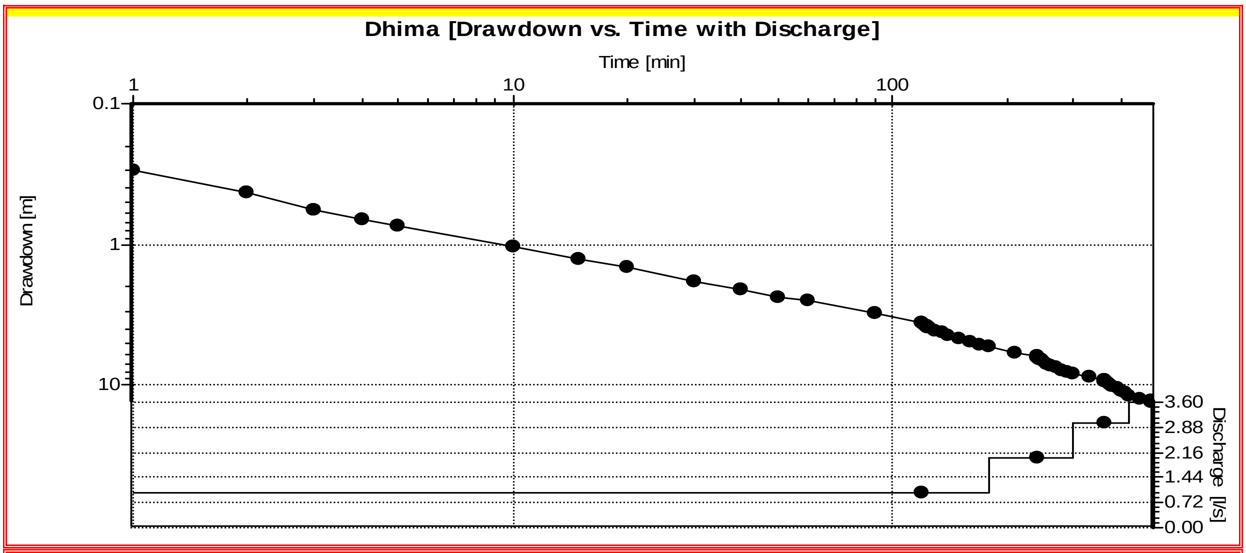

Geneto ber BH1 [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
Drawdown [m]
0
5
10
15
20
25
30
35
Discharge [l/s]
0.96
0.72
0.48
0.24
0.00

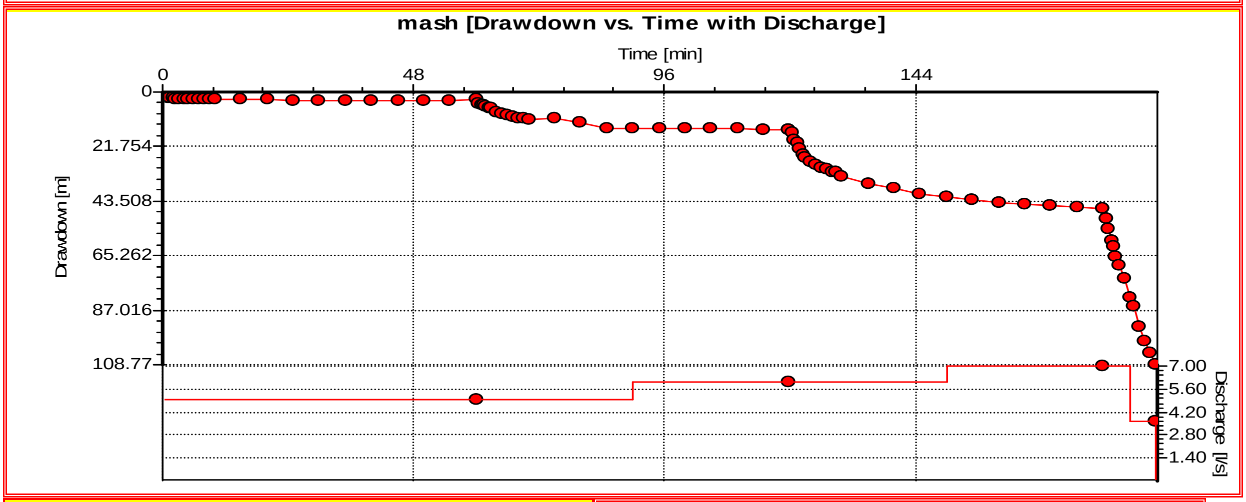

Koba mender [Draw dow n vs. Time w ith Discharge]
Time [min]
0 48 96 144 192 240
Drawdown [m]
0 7.13 14.26 21.39 28.52 35.65
Discharge [l/s]
3.50 2.80 2.10 1.40 0.70

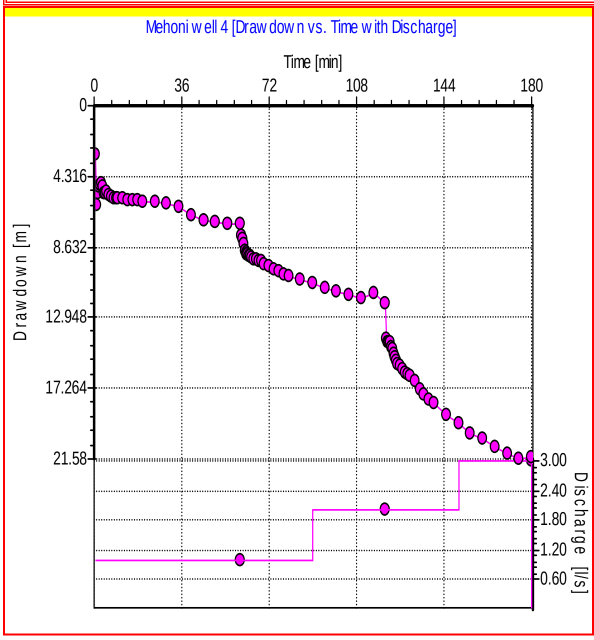

Meja [Draw dow n vs. Time w ith Discharge]
Time [min]
0 36 72 108 144 180
Drawdown [m]
4.904 9.808 14.712 19.616 24.52
Discharge [l/s]
5.70 4.56 3.42 2.28 1.14 0.00

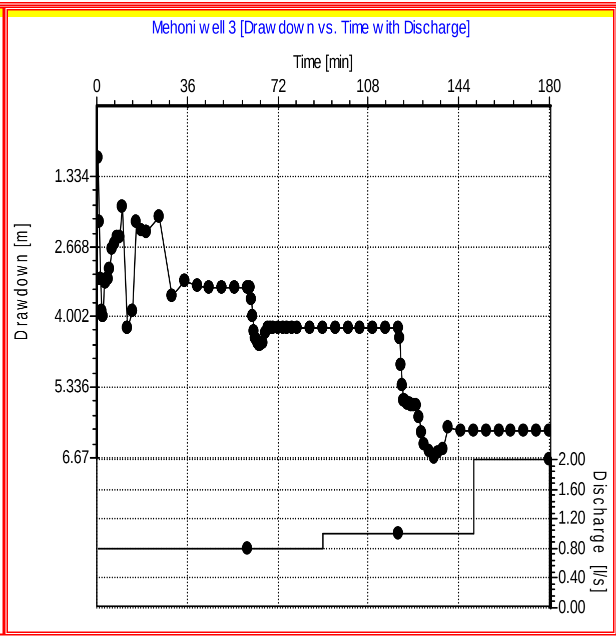

Enda Teklehaymanot [Drawdown vs. Time with Discharge]
Time [min]
0 72 144 216 288 360
Drawdown [m]
0 2.43 4.86 7.29 9.72
Discharge [l/s]
2.50 2.00 1.50 1.00 0.50 0.00

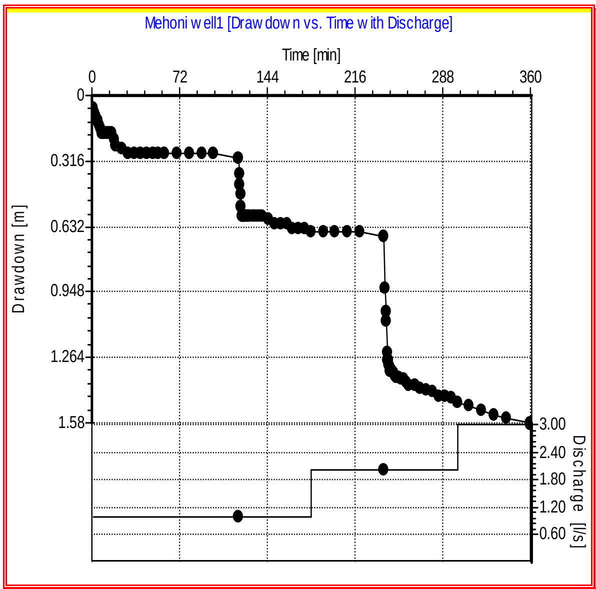

Endamehoni [Drawdown vs. Time with Discharge]
Time [min]
0 96 192 288
Drawdown [m]
5.536 11.072 16.608 22.144 27.68
Discharge [l/s]
7.00 5.60 4.20 2.80 1.40

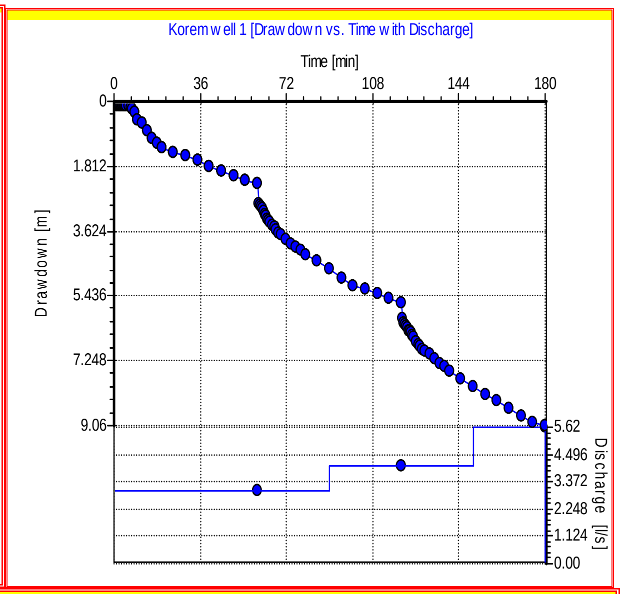

Dhima [Drawdown vs. Time with Discharge]
Time [min]
1
10
100
Drawdown [m]
0.1
1
10
3.60
2.88
2.16
1.44
0.72
0.00
Discharge [l/s]

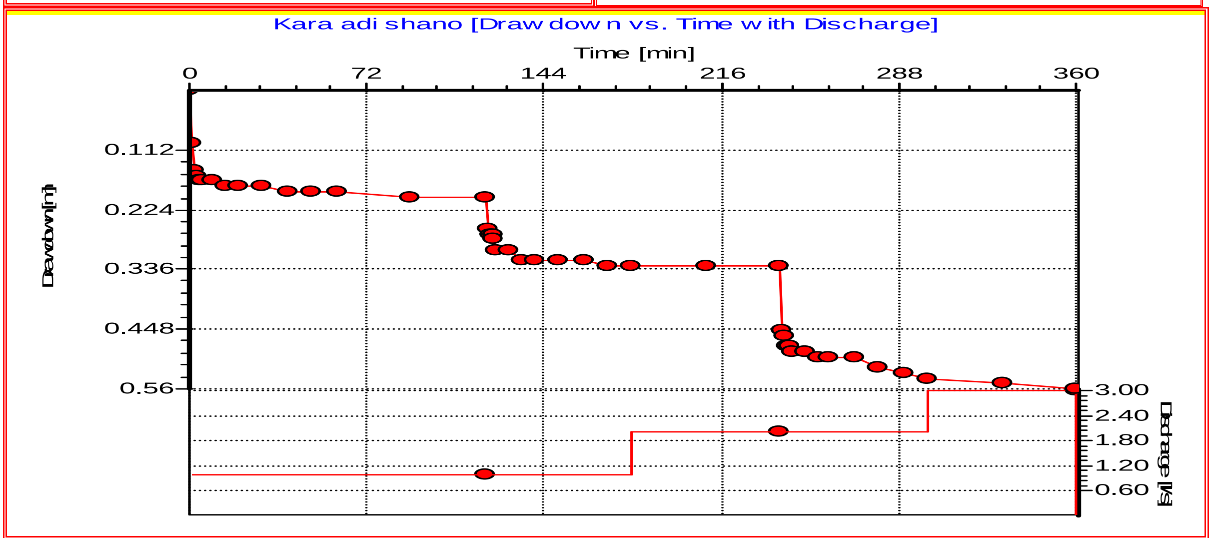

mash [Drawdown vs. Time with Discharge]
Time [min]
0
48
96
144
Drawdown [m]
0
21.754
43.508
65.262
87.016
108.77
7.00
5.60
4.20
2.80
1.40
Discharge [l/s]

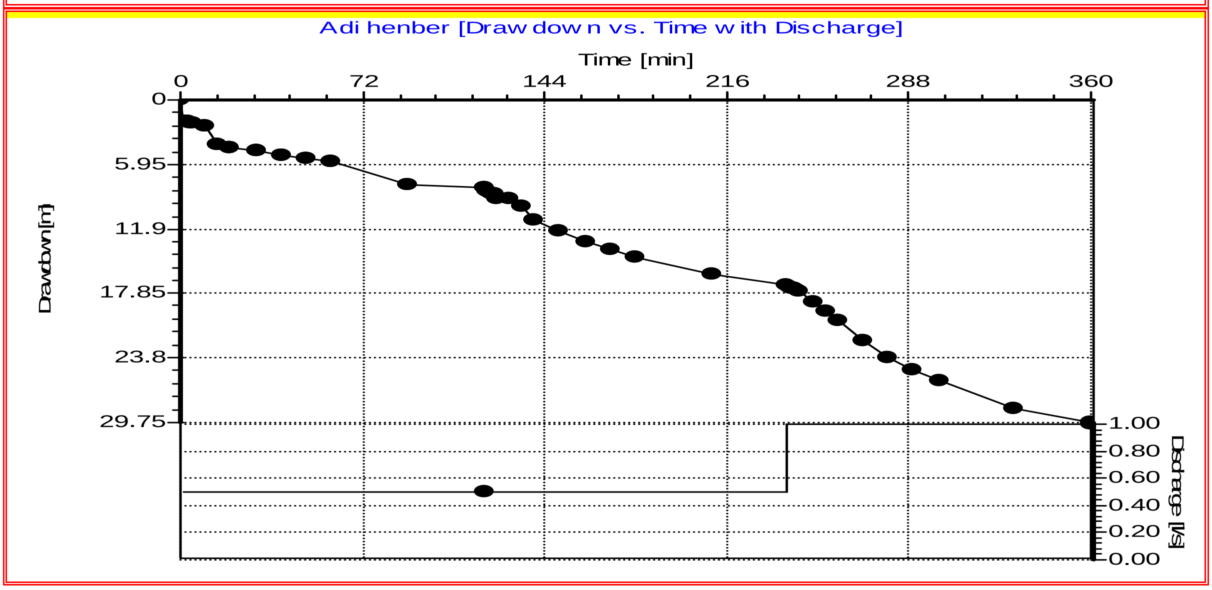

Mehoni well 4 [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
144
180
Drawdown [m]
0
4.316
8.632
12.948
17.264
21.58
3.00
2.40
1.80
1.20
0.60
Discharge [l/s]


Mehoni well 3 [Drawdown vs. Time with Discharge]
Time [min]
0
36
72
108
144
180
Drawdown [m]
1.334
2.668
4.002
5.336
6.67
2.00
1.60
1.20
0.80
0.40
0.00
Discharge [l/s]

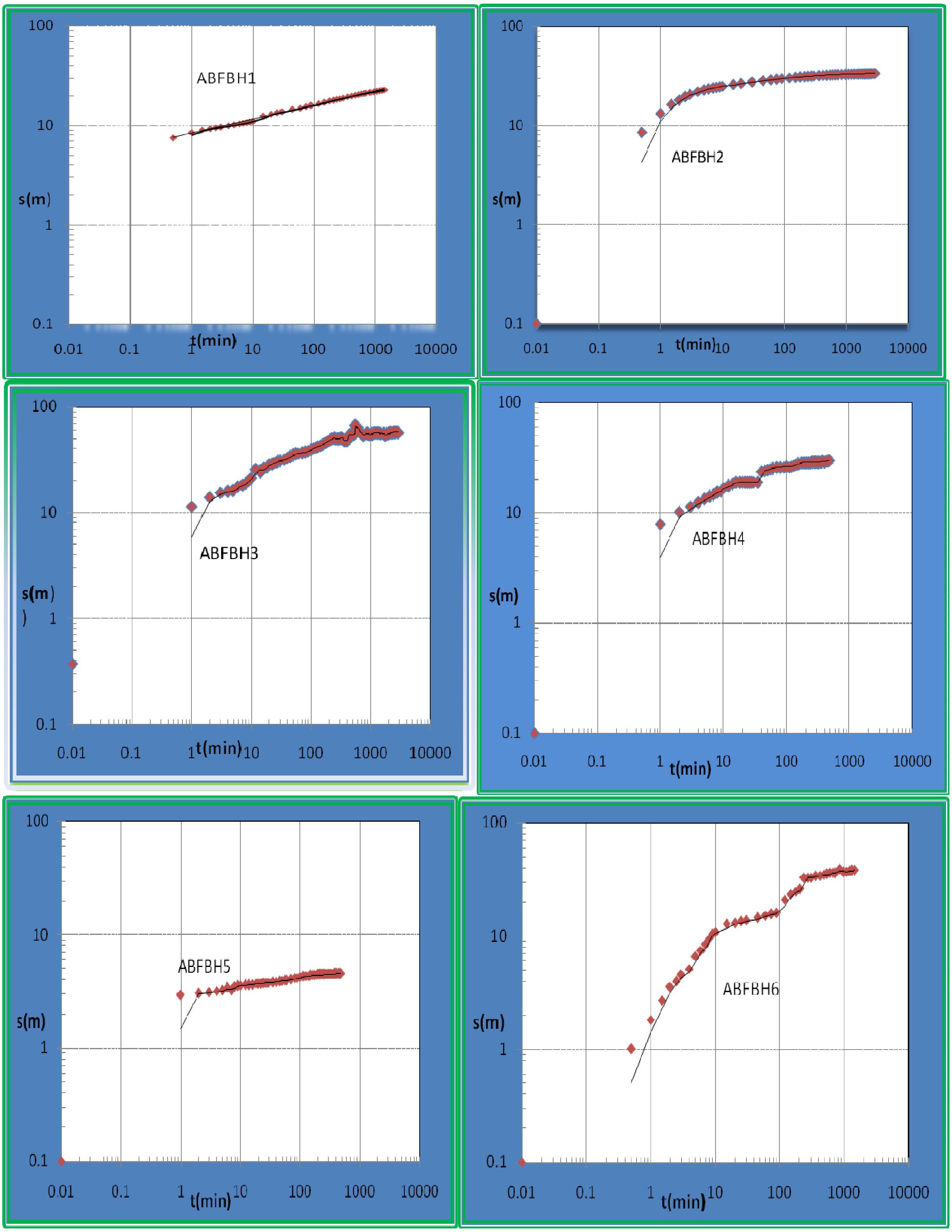

Mehoni well1 [Drawdown vs. Time with Discharge]
Time [min]
0 72 144 216 288 360
Drawdown [m]
0 0.316 0.632 0.948 1.264 1.58
Discharge [l/s]
3.00 2.40 1.80 1.20 0.60

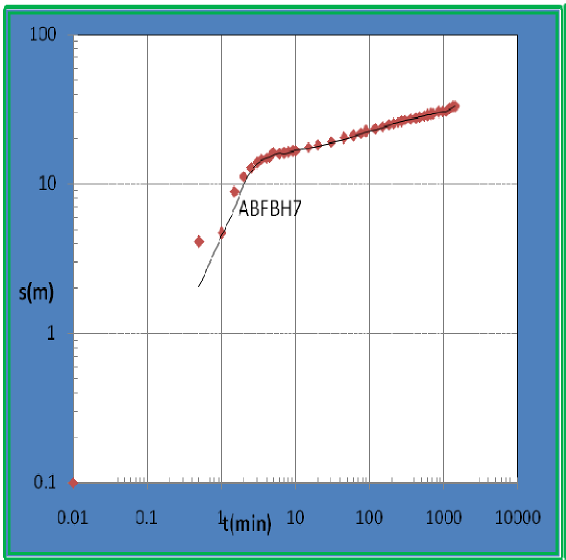

Korem well 1 [Drawdown vs. Time with Discharge]
Time [min]
0 36 72 108 144 180
Drawdown [m]
0 1.812 3.624 5.436 7.248 9.06
Discharge [l/s]
5.62 4.496 3.372 2.248 1.124 0.00

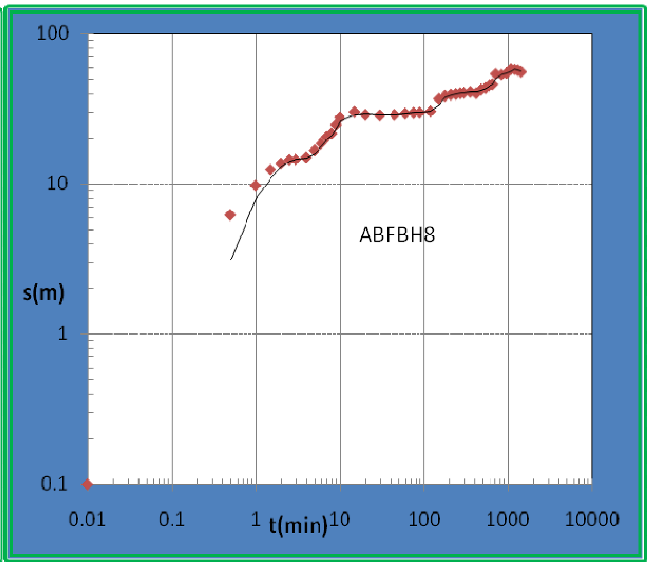

Kara adi shano [Drawdown vs. Time with Discharge]
Time [min]
0 72 144 216 288 360
Drawdown[m]
0.112 0.224 0.336 0.448 0.56
Discharge [l/s]
3.00 2.40 1.80 1.20 0.60

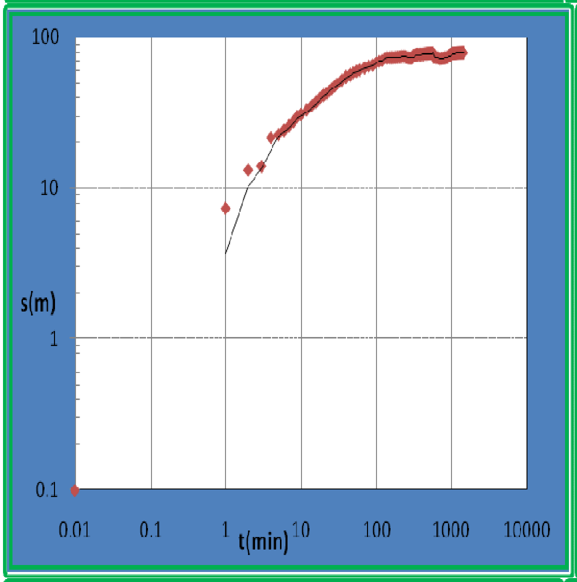

Adi henber [Drawdown vs. Time with Discharge]
Time [min]
0 72 144 216 288 360
Drawdown[m]
0 5.95 11.9 17.85 23.8 29.75
Discharge [l/s]
1.00 0.80 0.60 0.40 0.20 0.00

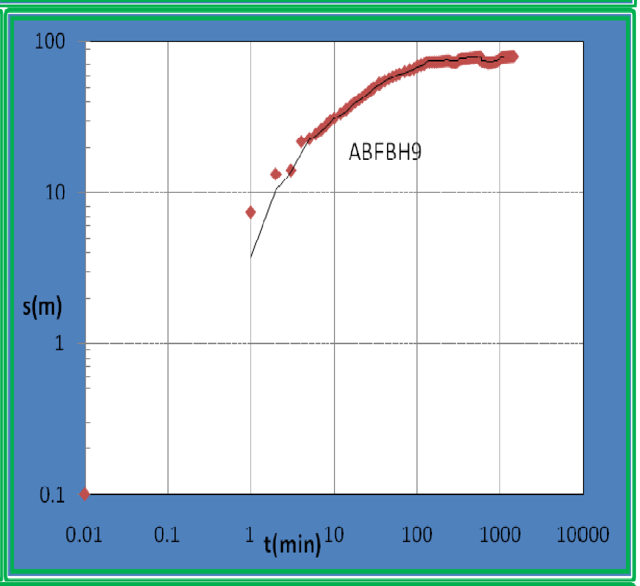
B.Log-log curves of drawdown Vs Time of observd wells in Ashange formation

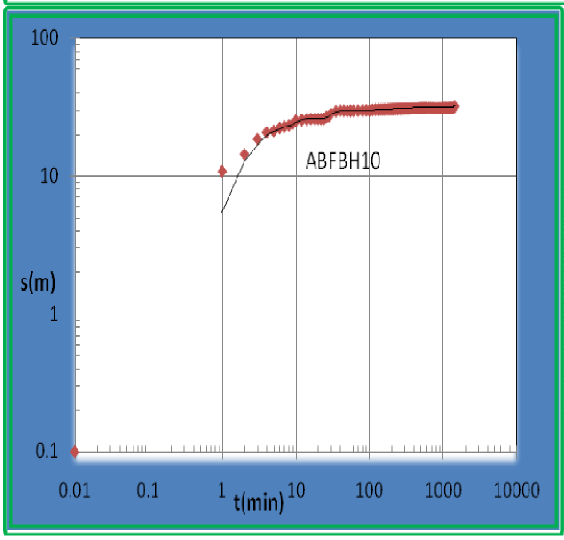


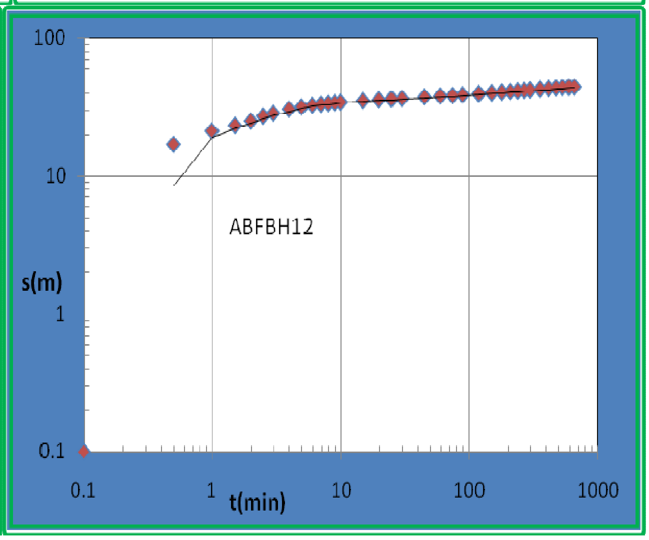

100
10
1
0.1
s(m)
ABFBH7
0.01
0.1
1
t(min)
10
100
1000
10000

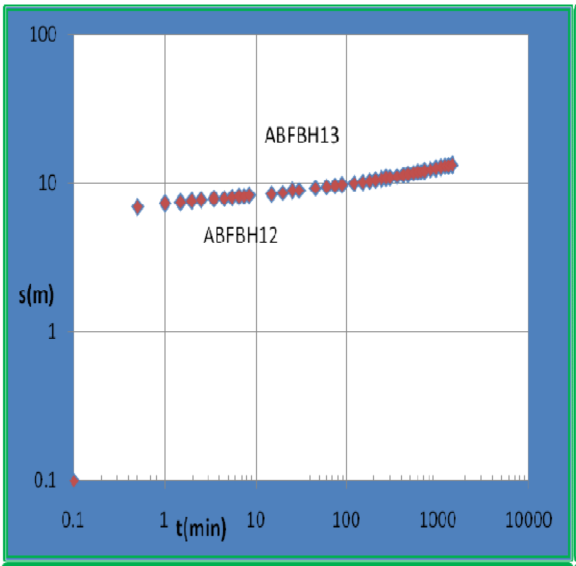

100
10
1
0.1
s(m)
ABFBH8
0.01
0.1
1
t(min)
10
100
1000
10000

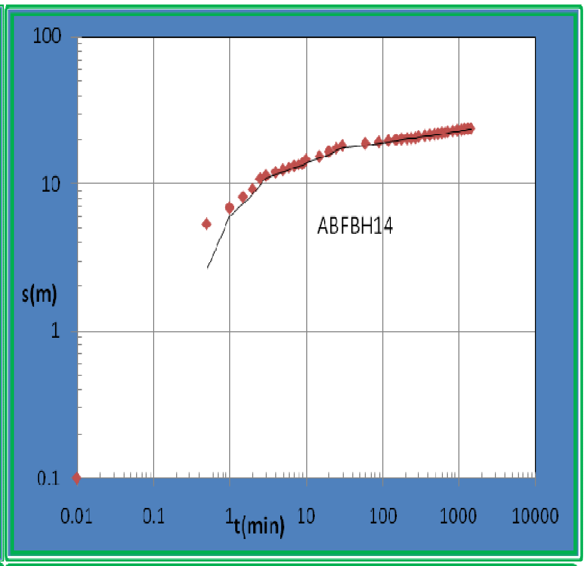

100
10
1
0.1
s(m)
0.01
0.1
1
t(min)
10
100
1000
10000

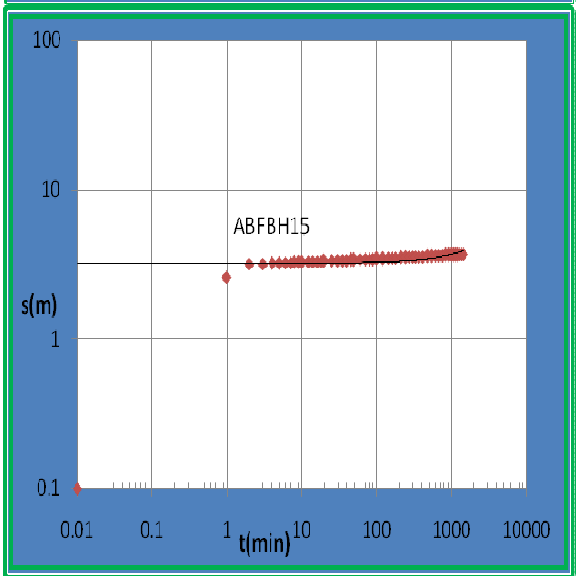

100
10
1
0.1
s(m)
ABFBH9
0.01
0.1
1
t(min)
10
100
1000
10000

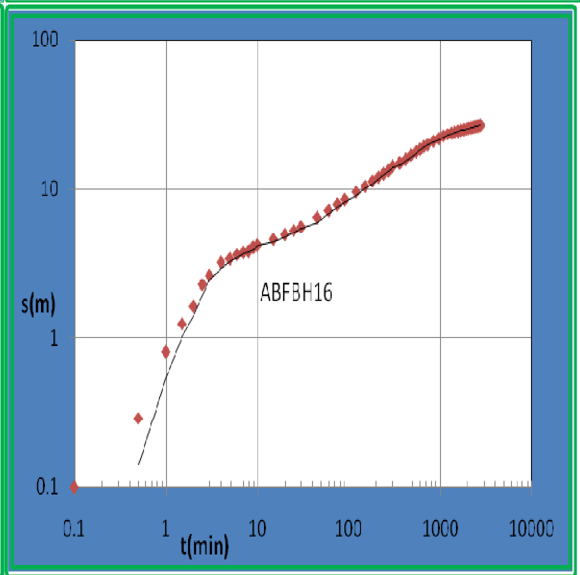

100
10
1
0.1
s(m)
ABFBH10
0.01
0.1
1
t(min)
10
100
1000
10000

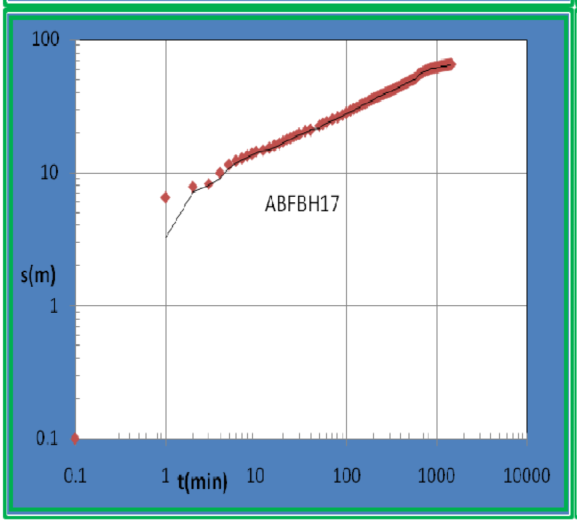

100
10
1
0.1
s(m)
ABFBH12
0.1
1
t(min)
10
100
1000

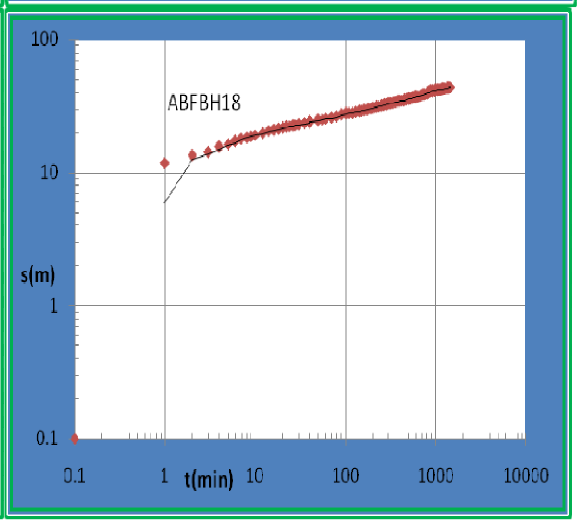

ABFBH13
ABFBH12
s(m)
100
10
1
0.1
0.1
1
t(min)
10
100
1000
10000

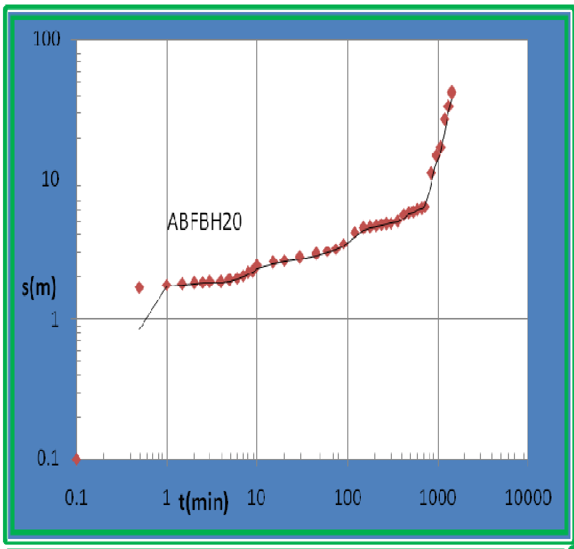

ABFBH14
s(m)
100
10
1
0.1
0.01
0.1
1
t(min)
10
100
1000
10000

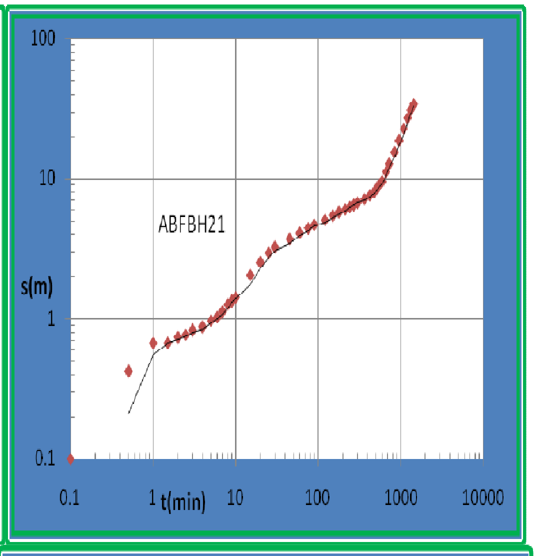

ABFBH15
s(m)
100
10
1
0.1
0.01
0.1
1
t(min)
10
100
1000
10000

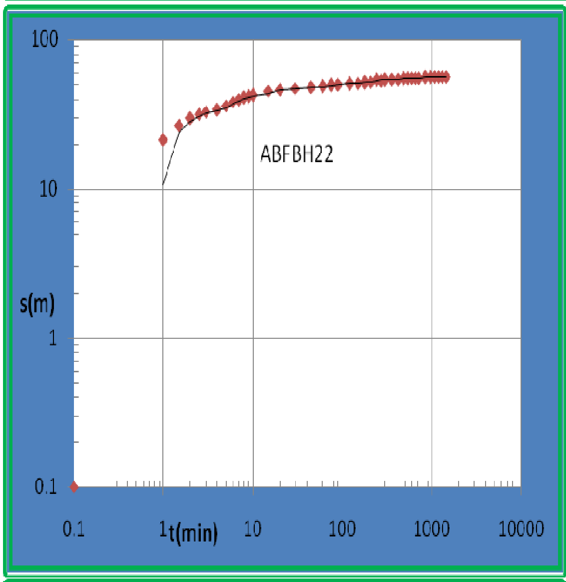

ABFBH16
s(m)
100
10
1
0.1
0.1
1
t(min)
10
100
1000
10000

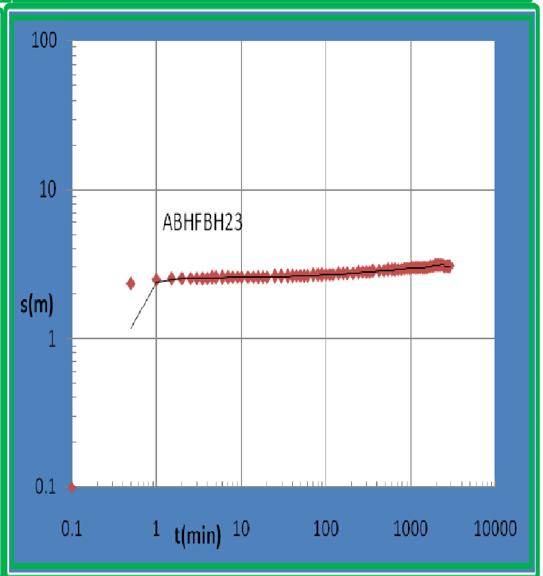

ABFBH17
s(m)
100
10
1
0.1
0.1
1
t(min)
10
100
1000
10000

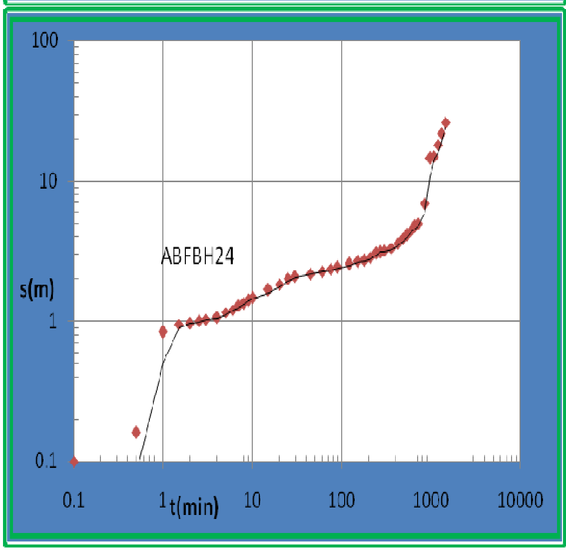

ABFBH18
s(m)
100
10
1
0.1
0.1
1
t(min)
10
100
1000
10000

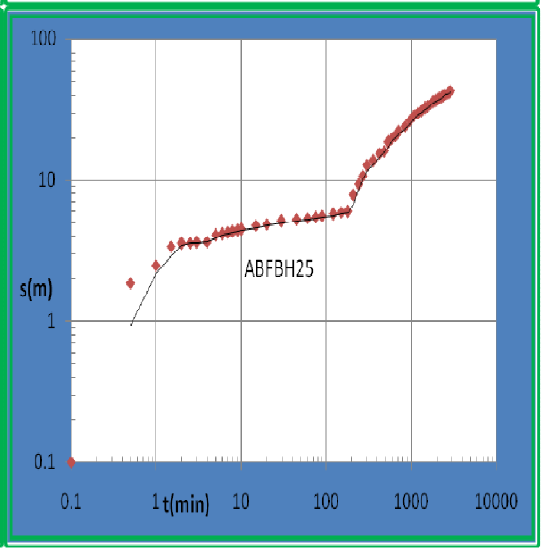

100
10
1
0.1
s(m)
ABFBH20
0.1
1
t(min)
10
100
1000
10000

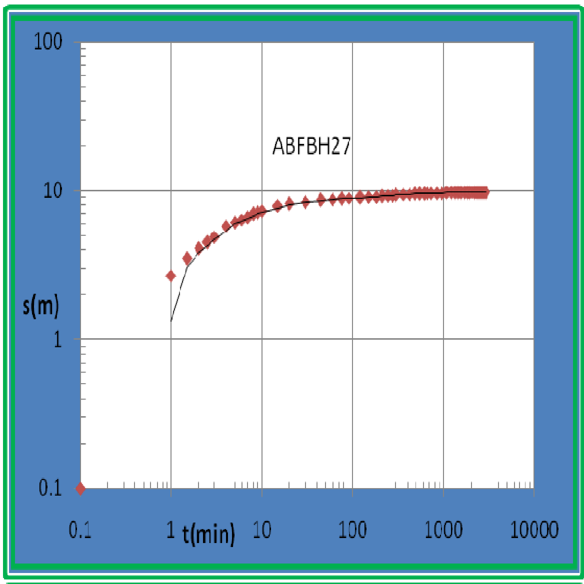

100
10
1
0.1
s(m)
ABFBH21
0.1
1
t(min)
10
100
1000
10000


100
10
1
0.1
s(m)
ABFBH22
0.1
1
t(min)
10
100
1000
10000


100
10
1
0.1
s(m)
ABHFBH23
0.1
1
t(min)
10
100
1000
10000


100
10
1
0.1
s(m)
ABFBH24
0.1
1
t(min)
10
100
1000
10000


100
10
1
0.1
s(m)
ABFBH25
0.1
1
t(min)
10
100
1000
10000


ABFBH27
s(m)
t(min)
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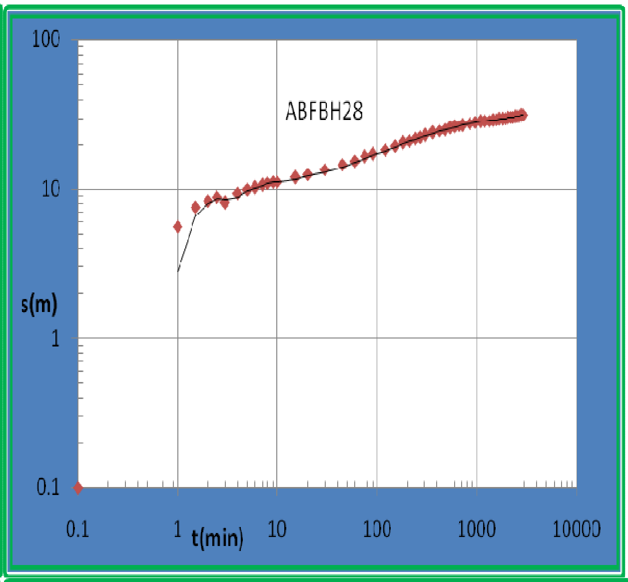
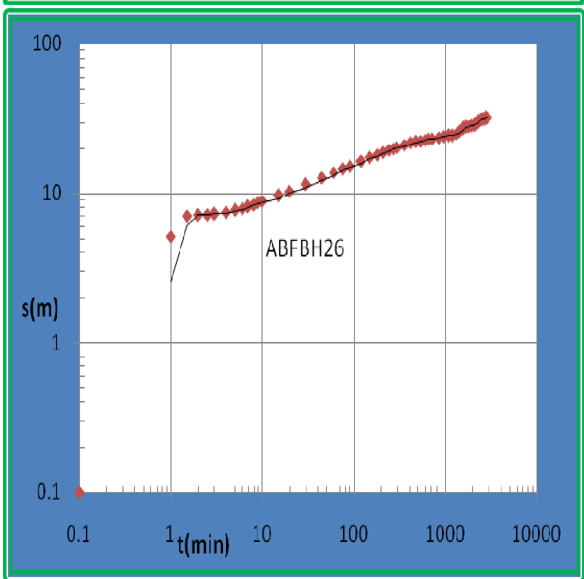
10
1
0.1
0.1 1 10 100 1000 10000


ABFBH28
s(m)
t(min)
100
10
1
0.1
0.1 1 10 100 1000 10000


ABFBH26
s(m)
t(min)
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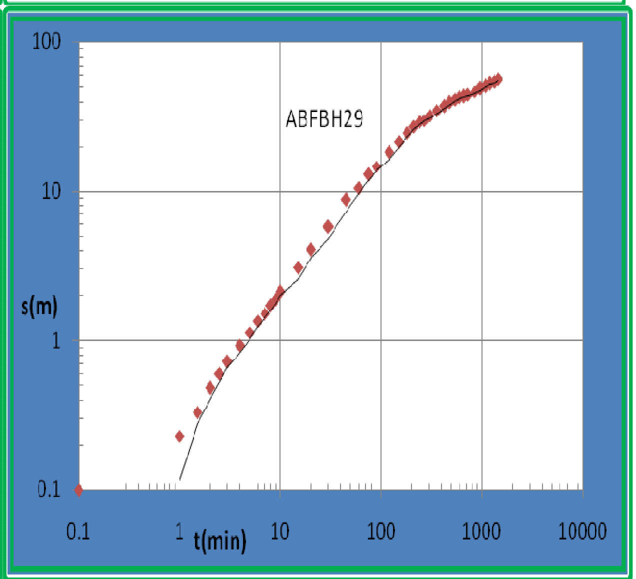
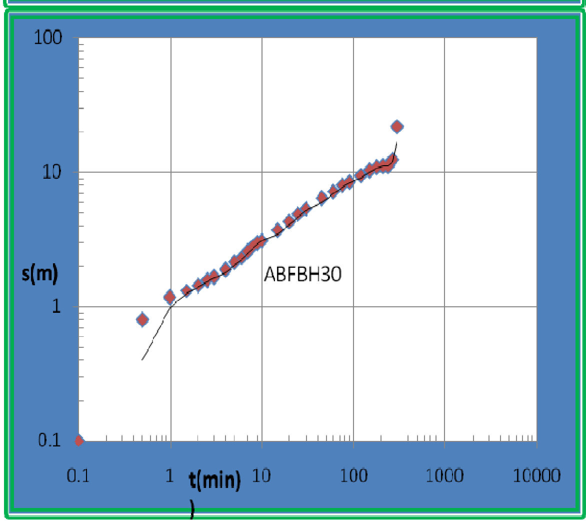
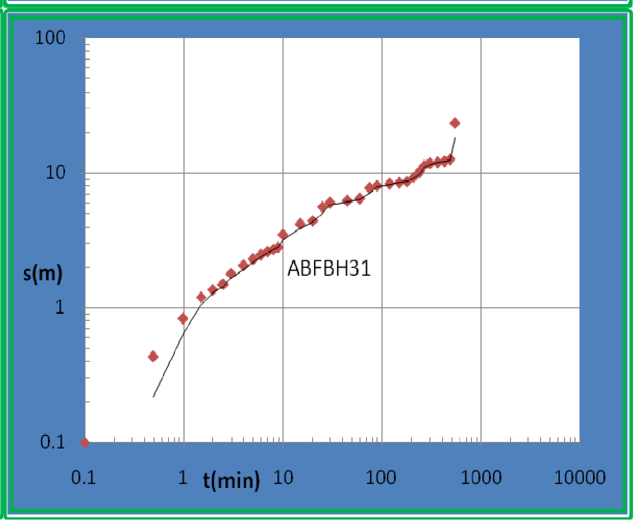
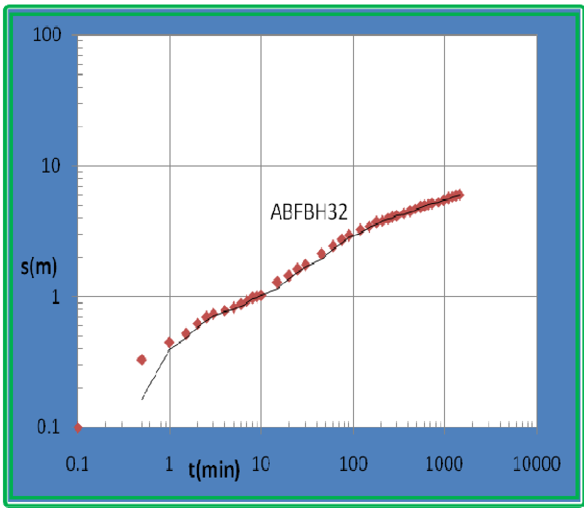
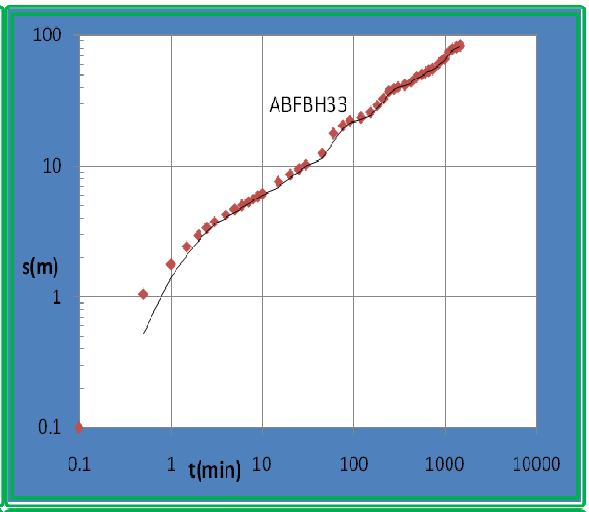
1
0.1
0.1 1 10 100 1000 10000

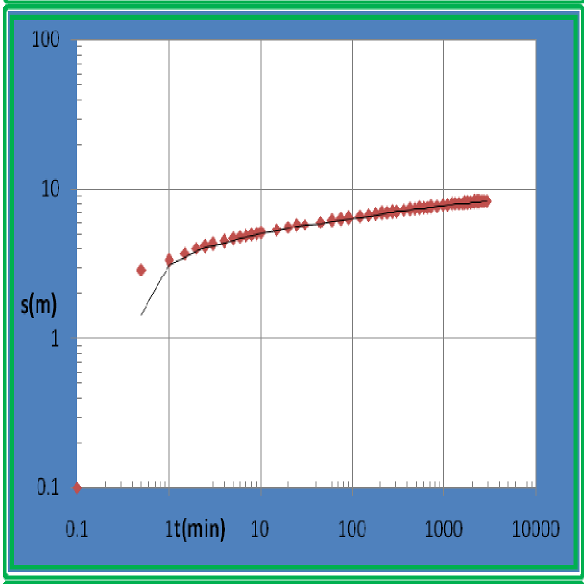

ABFBH29
s(m)
t(min)
100
10
1
0.1
0.1 1 10 100 1000 10000

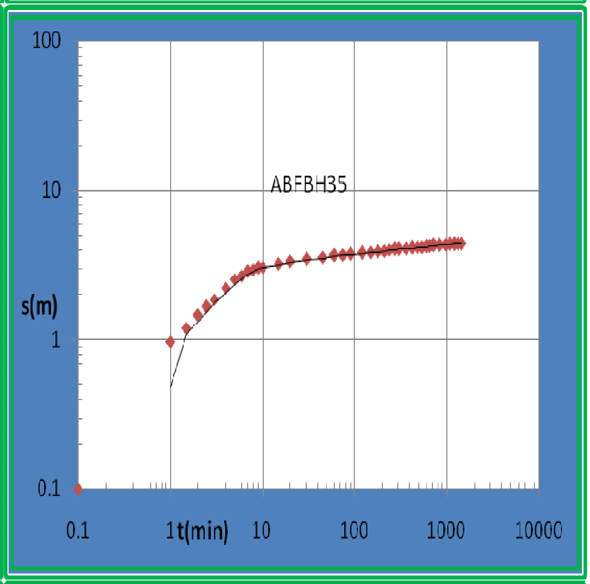

ABFBH30
s(m)
t(min)
100
10
1
0.1
0.1 1 10 100 1000 10000

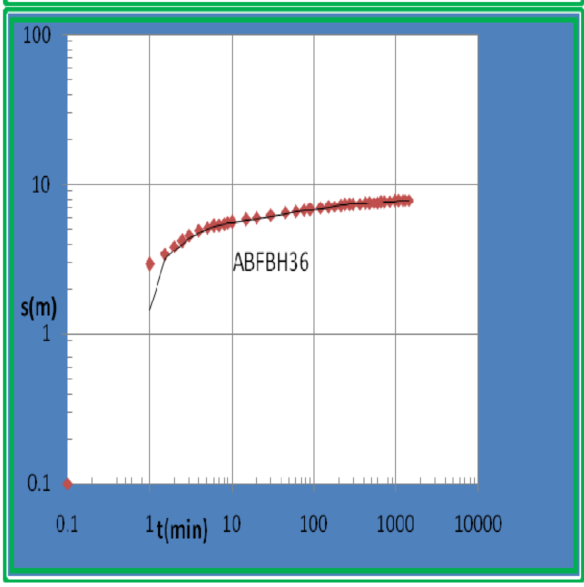

ABFBH31
s(m)
t(min)
100
10
1
0.1
0.1 1 10 100 1000 10000

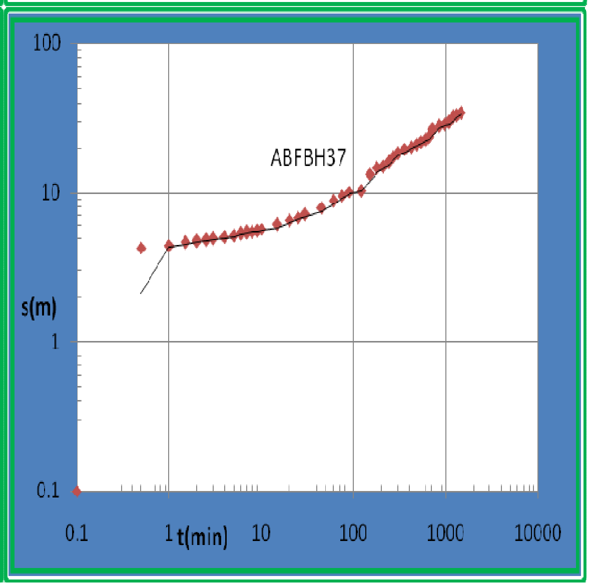

ABFBH32
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

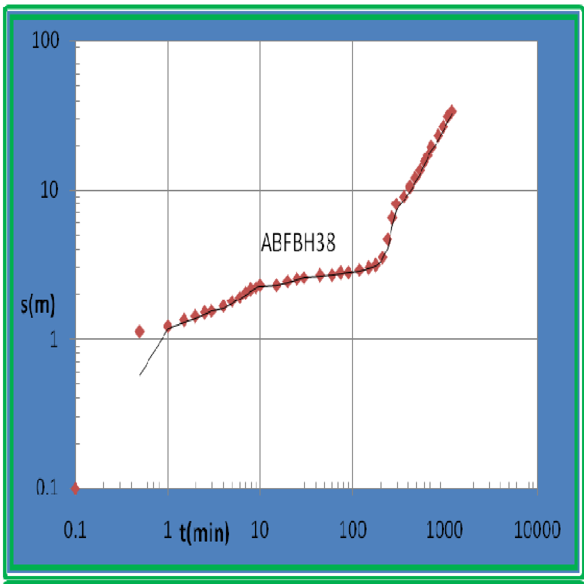

ABFBH33
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

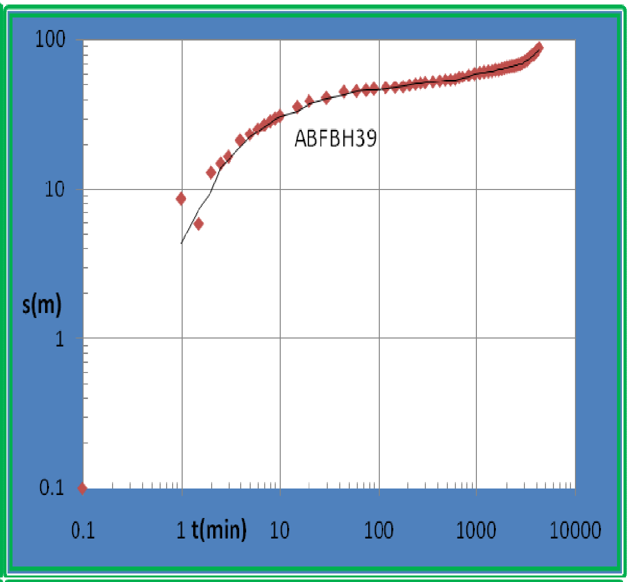

s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

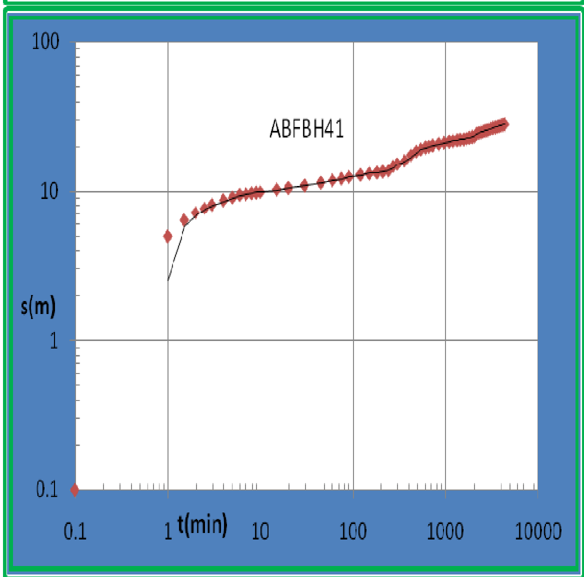

ABFBH35
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH36
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH37
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH38
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH39
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH41
s(m)
t(min)
100
10
1
0.1
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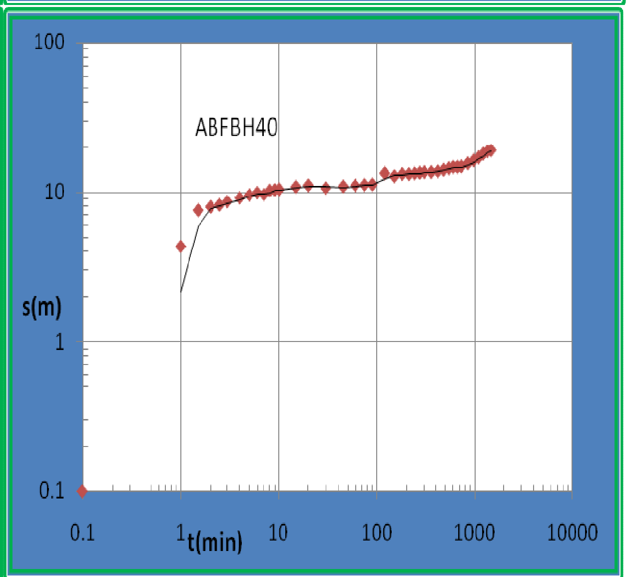
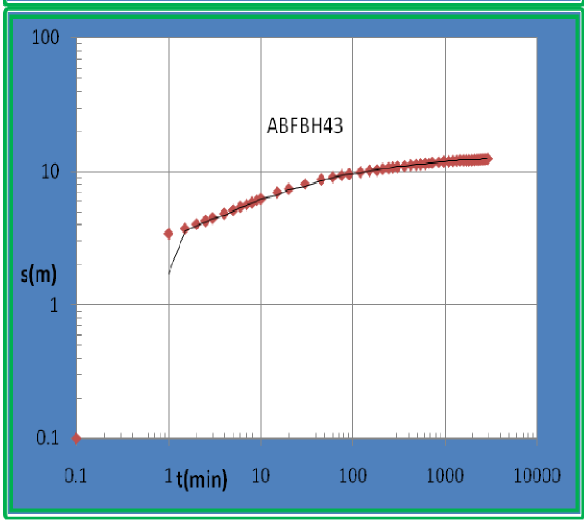
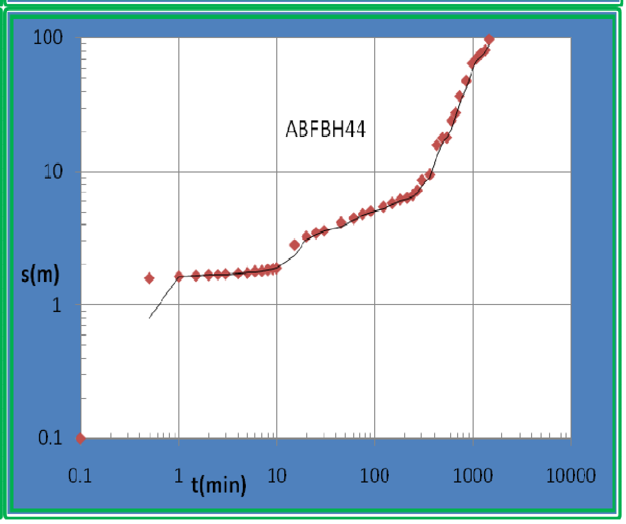
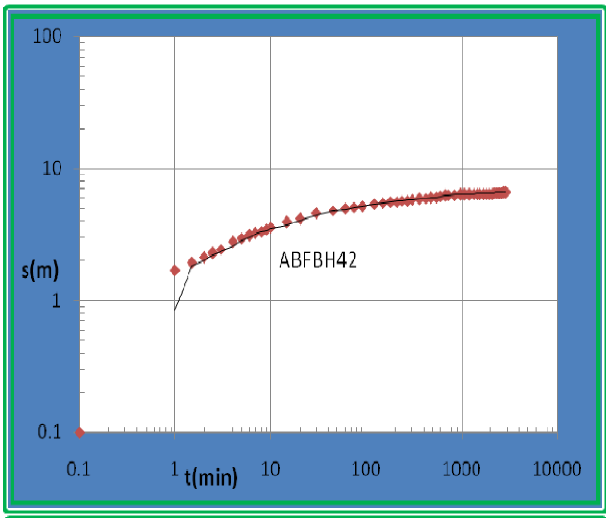
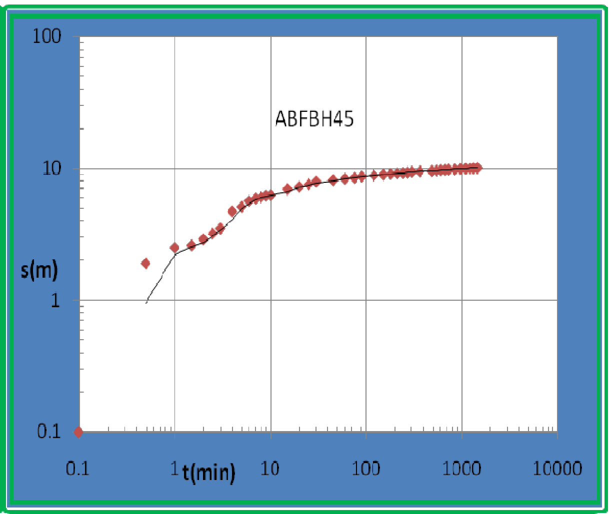
1
10
100
1000
10000

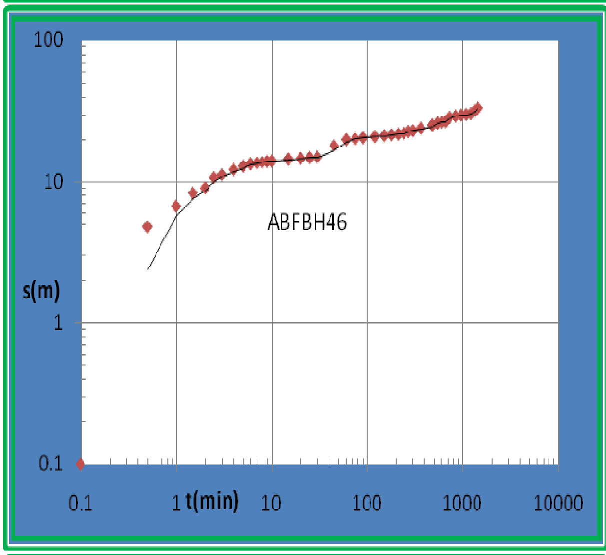

ABFBH40
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

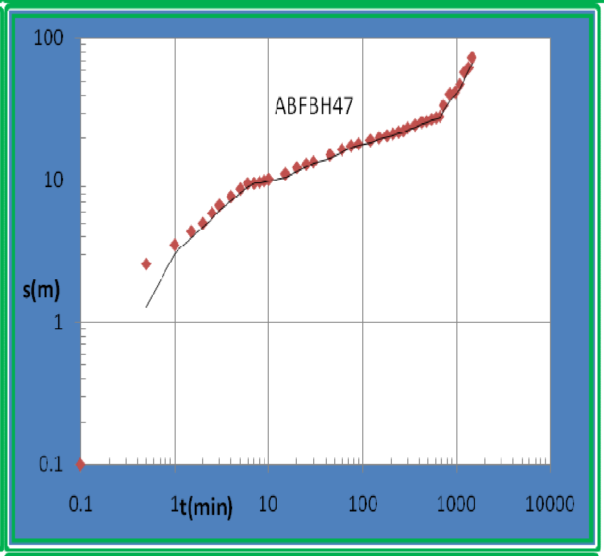

ABFBH43
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

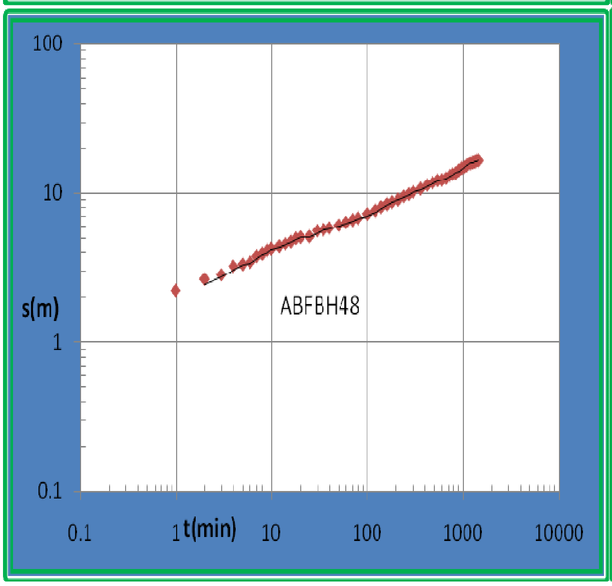

ABFBH44
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000

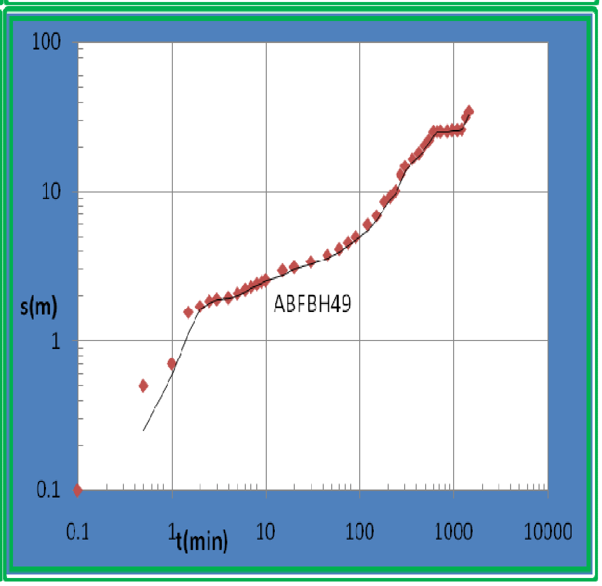

100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH42

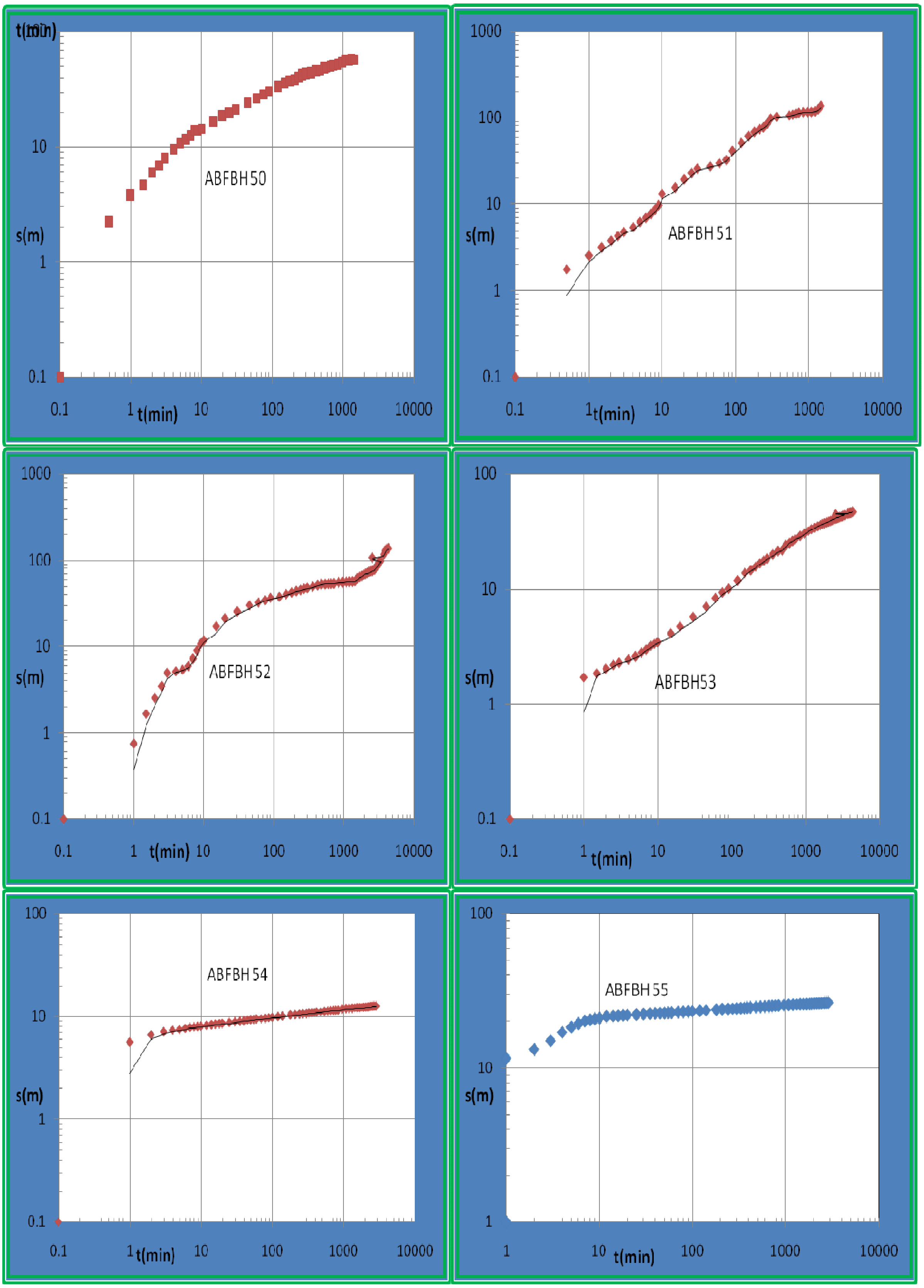

100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH45

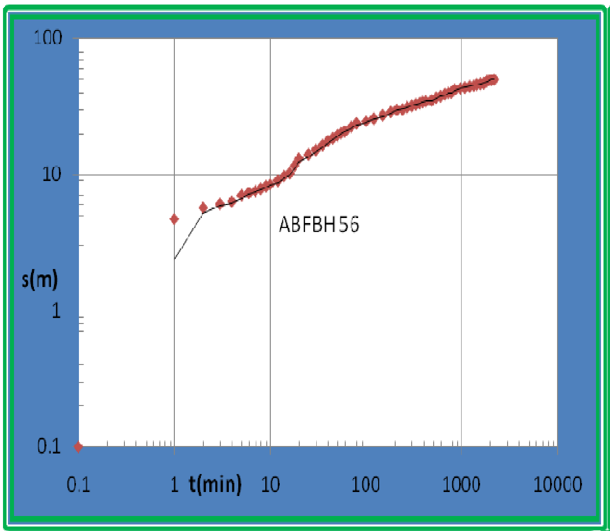

100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH46

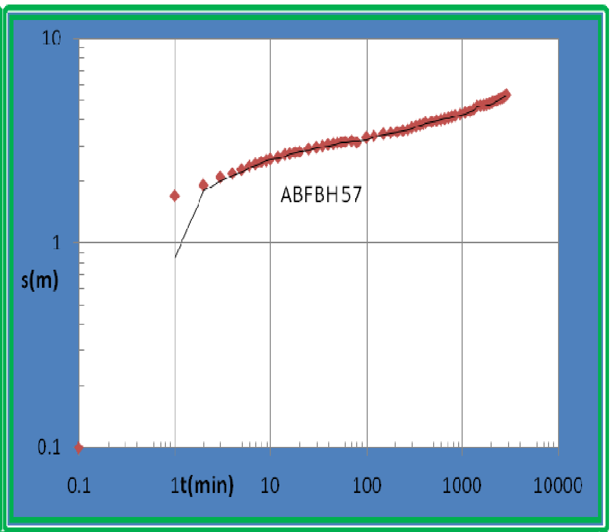

100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH47

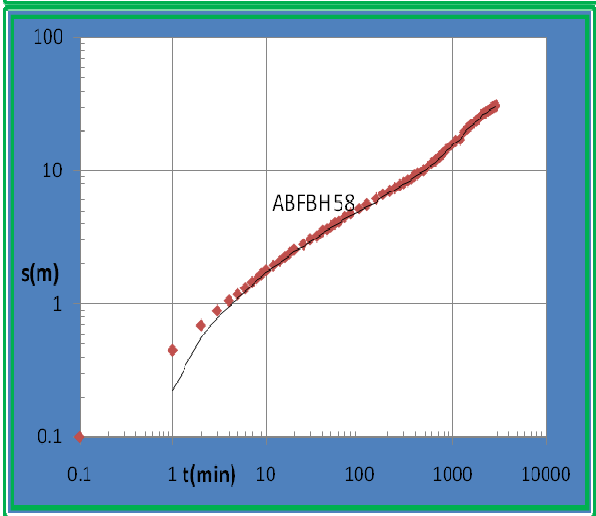

100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH48


100
10
s(m)
1
0.1
0.1
1 t(min)
10
100
1000
10000
ABFBH49


ABFBH50
ABFBH51
ABFBH52
ABFBH53
ABFBH54
ABFBH55
s(m)
t(min)


ABFBH56
s(m)
t(min)
100
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH57
s(m)
t(min)
10
1
0.1
0.1
1
10
100
1000
10000


ABFBH58
s(m)
t(min)
100
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1
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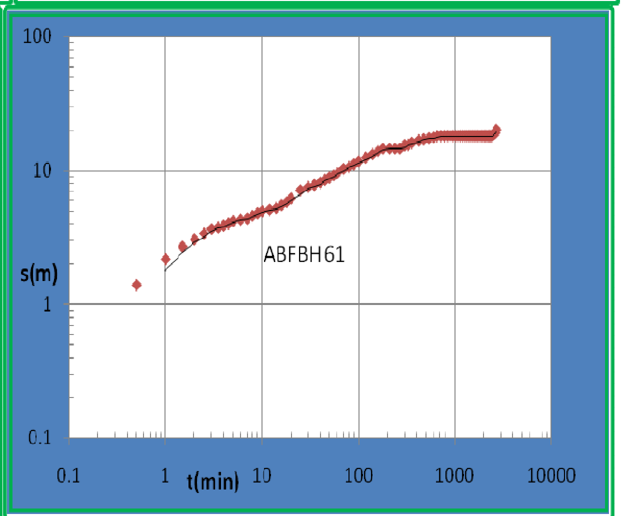
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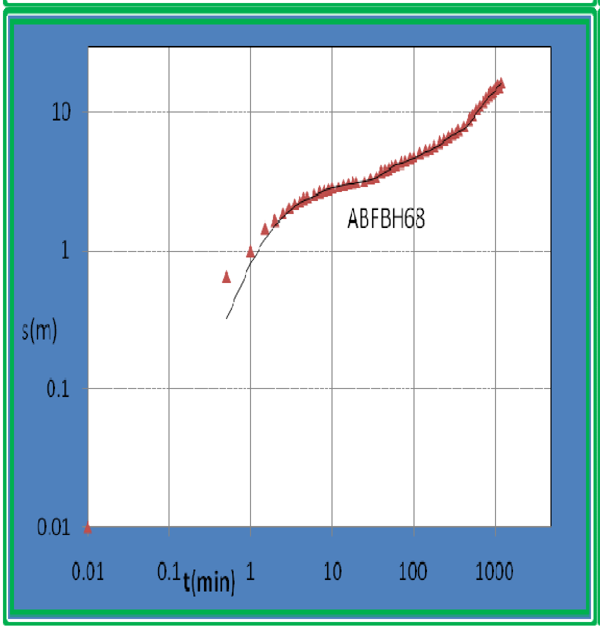
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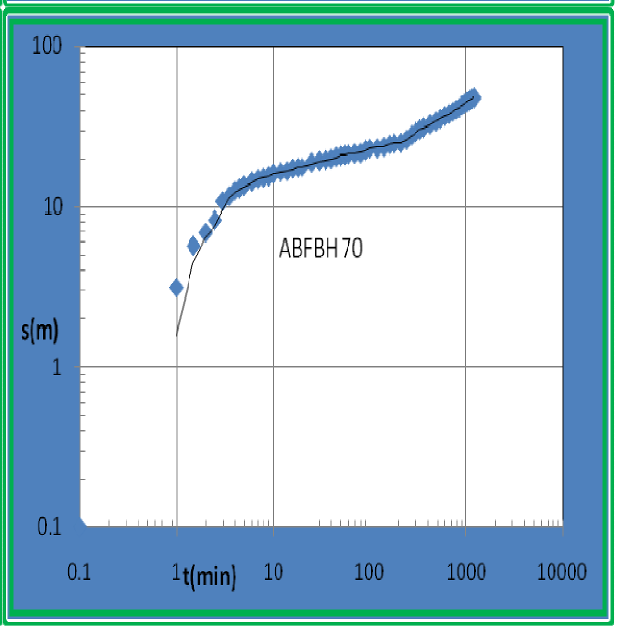
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t(min)
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CI. Constant Rate Pump Test Data Analysis Results Of Boreholes in Ashange (Lower) formation

ID NO	Well name	x	Y	Code	Depth	Source	SWL	Hrs	m3/day	DD	DWL	T	K	S	TYPE	Analysis Method(Theis,Thime,Huntush etc)
1	Lege chaketa	456529	1165863	ABFBH1	86	AWWCE	18.3	24	976.32	22.6		44.8	1.6	4.72E-04	Confined unsteady	Thies and cooper -Jacob
2	Tekaki	606142	1213436	ABFBH2	90	AWWCE	0.15	48	432	33.6	33.75	10.1	0.44	6.75E-04	Confined unsteady	Thies and cooper -Jacob
3	Wereilu BH1	546535	1183793	ABFBH3	150.5	AWWCE	1.77	48	604.8	56.33	58.1	8.01	0.157	2.23E-03	Confined unsteady	Thies and cooper -Jacob
4	Wereilu BH2	546727	1181626	ABFBH4	120	AWWCE	1.77	8	1555.2	29.59	31.47	33.9	0.848	6.52E-03	Confined unsteady	Thies and cooper -Jacob
5	Wereilu BH3	546727	1181025	ABFBH5	120	AWWCE	2.15	8	1728	4.53	6.71	510	12.7	1.70E-05	Confined unsteady	Thies and cooper -Jacob
6	Yirga/Masha/	503205	1240652	ABFBH6	152	AWWCE	5.8	24	216	38.35		3.22	0.081	4.90E-03	Confined unsteady	Thies and cooper -Jacob
7	Weinamba	525024	1182427	ABFBH7	122	AWWCE	18.62	24	864	33.14	90.47	17.5	0.427	6.10E-03	Confined unsteady	Thies and cooper -Jacob
8	SHEKEFA	538268	1176691	ABFBH8	122	AWWCE	6.5	24	345.6	55.9	76.73	3.07	0.118	1.62E-02	Confined unsteady	Thies and cooper -Jacob
9	genetober bh1	566177	1304989	ABFBH9	152	AWWCE	10.9	24	86.4	79.27		0.594	0.012	7.27E-04	Confined unsteady	Thies and cooper -Jacob
10	genetober bh2	563729	1301682	ABFBH10	151	AWWCE	44.66	24	181.44	32.13		4.27	0.085	2.72E-04	Confined unsteady	Thies and cooper -Jacob
11	genetober bh3	581712	130901	ABFBH11	150	AWWCE	47	24	501.12	4.66	51.66	80.7	1.61	2.46E-03	Confined unsteady	Thies and cooper -Jacob
12	lengesa	503205	1240652	ABFBH12	121	AWWCE	8.8	11	2073.6	46.83		38.9	1.1	2.84E-04	Confined unsteady	Thies and cooper -Jacob
13	gola mechare	572555	1307073	ABFBH13	121	AWWCE	14.75	24	1036.8	13.25		124	3.52	2.98E-06	Confined unsteady	Thies and cooper -Jacob
14	girar kebele	564748	1307974	ABFBH14	109.5	AWWCE	17.75	24	259.2	23.61		8.41	0.23	8.08E-04	Confined unsteady	Thies and cooper -Jacob
15	dana bh2	582325	1307161	ABFBH15	144	AWWCE	73.1	24	1296	3.71		589	11.1	3.42E-07	Confined unsteady	Thies and cooper -Jacob
16	wegel tena	532275	1273871	ABFBH16	114	AWWCE	4.51	46	518.4	26.8		12.6	0.38	2.76E-02	Confined unsteady	Thies and cooper -Jacob
17	kobamender	571078	1292189	ABFBH17	145	AWWCE	43.93	24	259.2	64.17		2.89	0.057	2.42E-03	Confined unsteady	Thies and cooper -Jacob
18	meja	576989	1296992	ABFBH18	147.68	AWWCE	38.85	24	492.48	43.65		10.1	0.26	7.76E-04	Confined unsteady	Thies and cooper -Jacob
19	gashena bh1	478456	1276967	ABFBH19	124	AWWCE	2.8	44	518.4	60.62		6.43	0.175	2.58E-03	Confined unsteady	Thies and cooper -Jacob
20	lalibela tourism bh1	500440	1329326	ABFBH20	90	AWWCE	19.8	24	129.6	41.5		8.12	0.271	1.96E-03	Confined unsteady	Thies and cooper -Jacob
21	lalibela tourism bh2	501408	1330171	ABFBH21	90	AWWCE	35.33	24	151.2	33.87		5.36	0.179	8.16E-03	Confined unsteady	Thies and cooper -Jacob
22	lalibela bh2	505180	1328438	ABFBH22	183	AWWCE	88.3	24	1123.2	55.65		16.4	0.269	5.00E-04	Confined unsteady	Thies and cooper -Jacob
23	giragne Meda bh	497752	1317239	ABFBH23	152	AWWCE	30	48	604.8	3.04		315	7.86	5.25E-08	Confined unsteady	Thies and cooper -Jacob
24	taymen	290171	1441856	ABFBH24	180	AWWCE	10.1	24	302.4	25.93		19.8	0.344	3.63E-02	Confined unsteady	Thies and cooper -Jacob
25	abdurafi bh2	231695	1460518	ABFBH25	68	AWWCE	5.33	48	311.04	42.57		7.03	0.305	5.12E-03	Confined unsteady	Thies and cooper -Jacob
26	abrehajira bh 2	228798	1487980	ABFBH26	114	AWWCE	8.7	48	388.8	31.9	40.6	11	0.289	3.05E-03	Confined unsteady	Thies and cooper -Jacob
27	abreha jira bh3	228123	1493017	ABFBH27	69	AWWCE	5.31	48	648	9.67		48.1	2.09	6.40E-03	Confined unsteady	Thies and cooper -Jacob
28	korhumer bh1	263628	1431073	ABFBH28	69	AWWCE	4.41	48	648	31.28	35.69	16.9	0.736	4.70E-03	Confined unsteady	Thies and cooper -Jacob
29	korhumer bh2	263215	1431010	ABFBH29	120	AWWCE	4.55	48	259.2	83.35		2.59	0.065	4.74E-03	Confined unsteady	Thies and cooper -Jacob
30	corrodem	209368	1475651	ABFBH30	120	AWWCE	24.92	24	172.8	55.68		1.97	0.05	1.25E-02	Confined unsteady	Thies and cooper -Jacob

ID NO	Name	x	Y	Code	Depth	Source	SWL	Hrs	m3/day	DD	DWL	T	K	S	TYPE	Analysis Method(Theis,Thime,Huntush etc)
31	zemen merek bh1	264043	1434390	ABFBH31	122	AWWCE	17.6	9	259.2	23.4		12.2	0.298	1.55E-02	Confined unsteady	Thies and cooper -Jacob
32	zemen merek bh2	283579	1436219	ABFBH32	64	AWWCE	18.7	24	129.6	6.02		16.6	0.864	1.21E-02	Confined unsteady	Thies and cooper -Jacob
33	zemen merek bh3	270264	1440197	ABFBH33	64	AWWCE	18.44	5	345.6	21.65		14.9	0.698	1.30E-02	Confined unsteady	Thies and cooper -Jacob
34	Debora	282542	1401844	ABFBH34	130	AWWCE	7.4	48	518.4	8.38	15.78	63.9	1.49	5.60E-02	Confined unsteady	Thies and cooper -Jacob
35	Abuthir bh2	224031	1428636	ABFBH35	102	AWWCE	49.2	24	311.04	4.43		42.16	1.24	LEAKY	Confined unsteady	Walton method
36	abuthir bh3	226683	1420150	ABFBH36	101	AWWCE	44.8	24	259.2	7.81		29.02	0.854	LEAKY	Confined unsteady	Walton method
37	metema bh2	210539	1416595	ABFBH37	122	AWWCE	22.75	20	1468.8	34.07		49.7	1.14	6.90E-03	Confined unsteady	Thies and cooper -Jacob
38	metema shinfa	329903	1391493	ABFBH38	312	AWWCE	6.93	20	172.8	33.12	40.05	7.92	0.086	4.80E-03	Confined unsteady	Thies and cooper -Jacob
39	chena	368646	1264886	ABFBH39	176	AWWCE	8.2	72	432	87.8		4.16	0.071	2.90E-03	Confined unsteady	Thies and cooper -Jacob
40	lumame bh2	377073	1122534	ABFBH40	74	AWWCE	12.95	24	518.4	28	31.71	17.9	0.779	9.89E-05	Confined unsteady	Thies and cooper -Jacob
41	wanka bh2	398701	1255600	ABFBH41	200	AWWCE	14	72	518.4	18.76		17.8	0.315	1.48E-02	Confined unsteady	Thies and cooper -Jacob
42	bichena/suha/ bh1	419557	1154453	ABFBH42	138	AWWCE	73.2	48	950.4	6.56		112	2.42	1.48E-02	Confined unsteady	Thies and cooper -Jacob
43	bichena/suha/ bh2	421367	1156064	ABFBH43	138.7	AWWCE	73.16	48	1555.2	12.47	85.63	103	2.23	9.50E-03	Confined unsteady	Thies and cooper -Jacob
44	segnogebeya	732384	1197882	ABFBH44	180.5	AWWCE	1.12	24	172.8	96.88	98	2.29	0.049	3.07E-03	Confined unsteady	Thies and cooper -Jacob
45	wutrn bh2	343507	1134848	ABFBH45	108	AWWCE	4.6	24	518.4	10.07	14.67	36	0.878	6.01E-03	Confined unsteady	Thies and cooper -Jacob
46	wuseta bh2	356469	1127490	ABFBH46	99	AWWCE	16.8	24	406.08	33.05	49	10.1	0.305	2.02E-03	Confined unsteady	Thies and cooper -Jacob
47	muqechit bh1	369713	1112897	ABFBH47	120	AWWCE	8.25	24	259.2	72.45		4.26	0.079	3.10E-03	Confined unsteady	Thies and cooper -Jacob
48	sekota bh8	506333	1396244	ABFBH48	70	AWWCE	16.3	24	94.176	16.52		4.52	0.194	2.18E-03	Confined unsteady	Thies and cooper -Jacob
49	dehana bh2	475907	1377970	ABFBH49	89.1	AWWCE	43.2	24	302.4	34.48	76.73	9	0.3	1.37E-02	Confined unsteady	Thies and cooper -Jacob
50	weleh bh2	499308	1400359	ABFBH50	115.25	AWWCE	10.5	24	260.06	57.38		3.15	0.083	3.32E-03	Confined unsteady	Thies and cooper -Jacob
51	weleh bh3	497724	1393903	ABFBH51	241	AWWCE	9.15	24	86.4	137.15		19	0.05	2.09E-03	Confined unsteady	Thies and cooper -Jacob
52	weleh bh5	503716	1387088	ABFBH52	200	AWWCE	9.35	72	233.28	136.85		0.343	0.02	7.31E-03	Confined unsteady	Thies and cooper -Jacob
53	weleh bh6	509105	1394302	ABFBH53	128	AWWCE	7.1	72	1209.6	46.9		1.38	0.045	4.00E-02	Confined unsteady	Thies and cooper -Jacob
54	enda t/haymanot	557049	1410189	ABFBH54	120	TWWCE	7.4	48	616.03	12.54		55.4	1.56	1.54E-04	Confined unsteady	Thies and cooper -Jacob
55	endamehoni bh1	553612	1409537	ABFBH55	90	TWWCE	10	48	613.44	26.5	10.57	22.1	0.624	1.86E-04	Confined unsteady	Thies and cooper -Jacob
56	mytsemri	419555	1497409	ABFBH56	127	TWWCE	3.6	36	203.04	49.6	53.2	3.1	0.074	2.60E-03	Confined unsteady	Thies and cooper -Jacob
57	sekota silase	407835	1514390	ABFBH57	78.5	TWWCE	10	48	604.8	5.3	15.3	122	4.7	2.57E-03	Confined unsteady	Thies and cooper -Jacob
58	dhima	436698	1499984	ABFBH58	100	TWWCE	11.93	48	604.8	30.67	42.6	20	0.606	6.09E-02	Confined unsteady	Thies and cooper -Jacob
59	mehoni well1	569881	1415248	ABFBH59	96	TWWCE	58.42	42	259.2	2.41		121	3.78	6.40E-03	Confined unsteady	Thies and cooper -Jacob
60	mehoni well3	580035	1413220	ABFBH60	147	TWWCE	97	45	172.8	7.65		35.2	0.072	5.88E-09	Confined unsteady	Thies and cooper -Jacob

ID NO	Name	x	Y	Code	Depth	Source	SWL	Hrs	m3/day	DD	DWL	T	K	S	TYPE	Analysis Method(Theis,Thime,Huntush etc)
61	mehoni well4	569881	1415748	ABFBH61	123	TWWCE	39.12	45	172.8	20.08		6.33	0.154	3.84E-03	Confined unsteady	Thies and cooper -Jacob
62	korem well 1	555834	1383618	ABFBH62	80	TWWCE	artesian	45	485.57	27.82		16.3	0.628	8.23E-03	Confined unsteady	Thies and cooper -Jacob
63	kara adi sheno	570637	1403161	ABFBH63	121	TWWCE	40.48	24	311.04	0.78		594	14.9	2.39E-05	Confined unsteady	Thies and cooper -Jacob
64	adi henber	563336	1363248	ABFBH64	120	TWWCE	74.66	24	51.84	22.55		1.68	0.042	2.04E-03	Confined unsteady	Thies and cooper -Jacob
65	hirka well	574336	1419297	ABFBH65	78	TWWCE	40.35	6:45	78.624	37		1.7	0.066	2.48E-03	Confined unsteady	Thies and cooper -Jacob
66	fecha	614307	1153867	ABFBH66	151	AWWCE	25.5	24	302.4	6.75		42.5	0.925	5.16E-04	Confined unsteady	Thies and cooper -Jacob
67	bati well 1	610372	1237716	ABFBH67	57	AWWCE	8.55	20	190.08	3.49		41.8	2.2	6.98E-03	Confined unsteady	Thies and cooper -Jacob
68	bati well 2	610150	1237605	ABFBH68	96	AWWCE	4.75	20	250.56	16.4		16.3	0.509	1.19E-02	Confined unsteady	Thies and cooper -Jacob
69	bati well 3	610893	1238170	ABFBH69	124	AWWCE	0.93	20	190.08	29.15		4.28	0.104	3.75E-03	Confined unsteady	Thies and cooper -Jacob
70	bati well 5	608710	1236810	ABFBH70	148	AWWCE	27.24	20	293.76	47.76		3.98	0.0904	5.80E-03	Confined unsteady	Thies and cooper -Jacob
71	Bagile Dolo	569309	1392764	ABFBH71	75				200			11.4				
72	Alamata	561803	1373125	ABFBH72	68				550			1450				
73	Alamata	561713	1373200	ABFBH73	72							415				
74	Jahan	562000	1374000	ABFBH74	63				450			69.3				
75	Ware Abaye	569675	1401249	ABFBH75	66				440			71				
76	*Mahoni*	569881	1415748	ABFBH76	123							10.5				
77	Wargiba	574204	1410936	ABFBH77	95				570			1283				
78	Muka Lench	562048	1362061	ABFBH78	99				450			435.2				
79	Chilakot	562783	1357379	ABFBH79	51				420			702.7				
80	Adi Koba	563336	1363248	ABFBH80	69				450			527				
81	*Hirka*	574336	1419297	ABFBH81	78				90			3				
82	Rarhe	561800	1370100	ABFBH82	59				730			554				
83	Shehedin	219938	1413002	ABFBH83	80				670			9.23				

CII. Step draw down test results and related data of Ashange (lower) formation---

		Q(l/s)	Transmissivity(m2/d)			Hydraulic conductivity(m/d)			Storativity	Sp. ca(m2/d)	Sp.ca (m2/d)		Corrected	Efficiency,%	uncorrected	corrected
No	well name		Theis	Cooper -Jacob	Recovery	Theis	Cooper -Jacob	Recovery	Theis	uncorrected	corrected	Depth(m)	Sw=BQ+CQ2	Ew=BQ/Sw*100	Si=Sc/b(m/d)	Si*=Sc/b(m/d)
1	Lege chaketa	11.3	44.8	37.8	179	1.6	1.35	6.38	4.72E-04	43.2		86			1.542857	
2	Tekaki	5	10.1	15.5	79.1	0.44	0.672	3.43	6.75E-04	12.9		90			0.559653	
3	Wereilu BH1	7	8.01	7.41	111	0.157	0.145	2.17	2.23E-03	10.7		150.5			0.209804	
4	Wereily BH2	18	33.9	33	285	0.848	0.825	7.12	6.52E-03	52.6		120			1.461111	
5	Wereilu BH3	20	510	478	316	12.7	11.9	7.91	1.70E-05	381		120			9.525	
6	Yirga/Masha/	2.5	3.22	3.02	39.5	0.081	0.076	0.994	4.90E-03	5.63		152			0.141528	
7	Weinamba	10	17.5	21.5	158	0.427	0.523	3.86	6.10E-03	26.1		122			0.636585	
8	SHEKEFA	4	3.07	3.19	63.3	0.118	0.123	1.54	1.62E-02	6.18		122			0.150732	
9	genetober bh1	1	0.594	0.654	15.8	0.012	0.013	0.316	7.27E-04	1.09		152			0.0218	
10	genetober bh2	2.1	4.27	6.96	47.4	0.085	0.138	0.946	2.72E-04	5.65	15.2173913	151	29.8	66.9745	0.112259	0.120973
11	genetober bh3	5.8	80.7	54.4	91.7	1.61	1.09	1.83	2.46E-03	108	5.321100917	150	3.76	79.96596	2.16	2.665532
12	lengesa	24	38.9	50.6	380	1.1	1.42	10.7	2.84E-04	44.3		121			1.247887	
13	gola mechare	12	124	99.6	190	3.52	2.84	5.41	2.98E-06	78.2		121			2.228555	
14	girar kebele	3	8.41	9.49	47.4	0.23	0.26	1.3	8.08E-04	11		109.5			0.30137	
15	dana bh2	15	589	1020	_	11.1	19.3	_	3.42E-07	349		144			6.584906	
16	wegel tena	6	12.6	11.4	_	0.38	0.345	_	2.76E-02	19.3	17.39130435	114	2.32	44.68966	0.584848	6.77116
17	kobamender	3	2.89	2.06	_	0.057	0.041	_	2.42E-03	4.04	73.17073171	145	13.7	70.00292	0.079637	0.372949
18	meja	5.7	10.1	8.29	90.1	0.26	0.213	2.31	7.76E-04	11.3	26.76056338	147.68	13.1	67.66901	0.289744	0.963946
19	gashena bh1	6	6.43	5.73	94.9	0.175	0.156	2.58	2.58E-03	8.55		124			0.232653	
20	lalibela tourism bh1	1.5	8.12	2.8	23.7	0.271	0.093	0.791	1.96E-03	3.12		90			0.104	
21	lalibela tourism bh2	1.75	5.36	3.36	_	0.179	0.112	_	8.16E-03	4.46		90			0.148667	
22	lalibela bh2	13	16.4	21.3	20.6	0.269	0.35	3.37	5.00E-04	20.2		183			0.331148	
23	giragne Meda bh	7	315	546	111	7.86	13.7	2.77	5.25E-08	199	0.510948905	152	0.3	80.64	4.975	50.4
24	taymen	3.5	19.8	9.58	_	0.344	0.167	_	3.63E-02	11.7		180			0.203478	
25	abdurafi bh2	3.6	7.03	4.46	56.9	0.305	0.194	2.48	5.12E-03	7.31		68			0.317826	
26	abrehajira bh 2	4.5	11	8.98	71.2	0.289	0.236	1.87	3.05E-03	12.2	19.06779661	114	10	50.544	0.321053	1.023158
27	abreha jira bh3	7.5	48.1	69.2	119	2.09	3.01	5.16	6.40E-03	67	2.491694352	69	13.1	34.62595	2.913043	2.15068
28	korhumer bh1	7.5	16.9	15.2	_	0.736	0.659	_	4.70E-03	3.11	11.38088012	69	10.9	29.72477	0.135217	2.584763
29	korhumer bh2	3	2.59	1.88	47.4	0.065	0.047	1.19	4.74E-03	3.1		120			0.0775	
30	corrodem	2	1.97	1.59	31.6	0.05	0.04	0.791	1.25E-02	3.1	50	120	2.27	76.12335	0.091176	2.238922

		Q(l/s)	Transmissivity(m2/d)			Hydraulic conductivity(m/d)			Storativity	Sp. ca(m2/d)	Sp.ca (m2/d)		Corrected	Efficiency,%	uncorrected	corrected
No	well name		Theis	Cooper -Jacob	Recovery	Theis	Cooper -Jacob	Recovery	Theis	uncorrected	corrected	Depth(m)	Sw=BQ+CQ2	Ew=BQ/Sw*10	Si=Sc/b(m/d)	Si*=Sc/b(m/d)
31	zemen merek bh1	3	12.2	8.58	47.4	0.298	0.209	1.16	1.55E-02	11.1		122			0.270732	
32	zemen merek bh2	1.5	16.6	12.5	_	0.864	0.653	_	1.21E-02	21.5		64			1.119792	
33	zemen merek bh3	4	14.9	10.7	_	0.698	0.504	_	1.30E-02	16	7.9365079	64	3.02	80.10596	0.751174	5.372633
34	Debora	6	63.9	67.3	94.9	1.49	1.57	2.21	5.60E-02	61.9	3.8216561	130	38.8	30.7299	1.439535	0.310717
35	Abuthir bh2	3.6	42.16	57.7	56.9	1.24	1.7	1.67	LEAKY	70.2		102			2.064706	
36	abuthir bh3	3	29.02	41.2	56.9	0.854	1.21	1.9	LEAKY	33.2		101			1.106667	
37	metema bh2	17	49.7	28.8	_	1.14	0.662	_	6.90E-03	43.1	25.679758	122	694	6.772565	1.002326	0.049219
38	metema shinfa	2	7.92	3.61	31.6	0.086	0.04	0.344	4.80E-03	5.22		312			0.056739	
39	chena	5	4.16	4.4	_	0.071	0.075	_	2.90E-03	4.92		176			0.083959	
40	lumame bh2	6	17.9	15.4	49.8	0.779	0.669	2.17	9.89E-05	18.5	8.9686099	74	20.6	78.01165	0.326855	0.444612
41	wanka bh2	6	17.8	15	_	0.315	0.265	_	1.48E-02	27.6	22.641509	200	9.19	56.40914	1.2	2.452571
42	bichena/suha/ bh1	11	112	123	_	2.42	2.67	_	1.48E-02	145		138			3.138528	
43	bichena/suha/ bh2	18	103	104	285	2.23	2.24	6.16	9.50E-03	125		138.7			2.906977	
44	segnogebeya	2	2.29	1.27	31.6	0.049	0.021	0.527	3.07E-03	1.78		180.5			0.029667	
45	wutrn bh2	6	36	38.5	94.9	0.878	0.938	2.31	6.01E-03	51.5	6.3965885	108	5.93	61.19393	1.256098	2.132193
46	wuseta bh2	4.7	10.1	10.1	74.3	0.305	0.307	2.25	2.02E-03	12.3	15.309446	99	15.3	15.92471	0.372727	0.804278
47	muqechit bh1	3	4.26	2.99	_	0.079	0.056	_	3.10E-03	3.58		120			0.066296	
48	sekota bh8	1.09	4.52	34.2	_	0.194	0.147	_	2.18E-03	5.7		70			0.244635	
49	dehana bh2	3.5	9	54.6	_	0.3	0.182	_	1.37E-02	8.77		89.1			0.292333	
50	weleh bh2	3.01	3.15	2.64	47.6	0.083	0.069	1.25	3.32E-03	4.53		115.25			0.119211	
51	weleh bh3	1	19	0.345	_	0.05	0.005	_	2.09E-03	0.63		241			0.009103	
52	weleh bh5	2.7	0.343	1.37	42.7	0.02	0.02	0.637	7.31E-03	1.7		200			0.025373	
53	weleh bh6	14	1.38	15.1	_	0.045	0.359	_	4.00E-02	25.8		128			0.612827	5.655825
54	enda t/haymanot	7.13	55.4	60.5	113	1.56	1.7	3.17	1.54E-04	49.1	4.1941176	120	32	34.6518	1.381153	0.541519
55	endamehoni bh1	7.1	22.1	34.3	112	0.624	0.968	3.17	1.86E-04	23.1	7.3347107	90	24	69.012	0.651622	0.721016
56	mytsemri	2.35	3.1	235	37.2	0.074	0.056	0.885	2.60E-03	4.09		127			0.097381	0.389862
57	sekota silase	7	122	113	_	4.7	4.33	_	2.57E-03	114		78.5			4.384615	
58	dhima	7	20	11.3	111	0.606	0.342	3.35	6.09E-02	19.7	20.467836	100	12.3	14.75122	0.59697	1.490022
59	mehoni well1	3	121	103	47.4	3.78	3.21	1.48	6.40E-03	108	0.9345794	96	0.92	28.17391	3.375	8.804348
60	mehoni well3	2	35.2	46.6	_	0.072	0.95	_	5.88E-09	22.6	2.1052632	147	5.23	42.9522	0.461224	0.674289

		Q(l/s)	transmissivity(m2/d)			Hydraulic conductivity(m/d)			Storativity	Sp. ca(m2/d)	Sp.ca (m2/d)		Corrected	Efficiency	uncorrected	corrected
No	Well name		Theis	Cooper -Jacob	Recovery	Theis	Cooper -Jacob	Recovery	Theis	uncorrected	corrected	Depth(m)	Sw=BQ+CQ2	Ew=BQ/Sw*100	Si=Sc/b(m/d)	Si*=Sc/b(m/d)
61	Mehoni well4	2	6.33	5.57	31.6	0.154	0.136	0.77	3.84E-03	8.61	14.70588235	123	5.36	99.9403	0.21	0.786312
62	Korem well 1	5.62	16.3	10.8	88.9	0.628	0.414	3.42	8.23E-03	17.5		80			0.673077	
63	Kara adi sheno	3.6	594	469	56.9	14.9	11.7	1.42	2.39E-05	399	0.307692308	121	0.8	38.88	11.4	11.10857
64	Adi henber	0.6	1.68	1.37	9.49	0.042	0.034	0.237	2.04E-03	2.3	17.64705882	120	2.71	93.73284	0.0575	0.478229
65	Hirka well	0.91	1.7	0.972	_	0.066	0.037	_	2.48E-03	2.12	24.59459459	78	4.38	71.80274	0.081538	0.690411
66	Fecha	3.5	42.5	39.3	_	0.925	0.855	_	5.16E-04	44.8		151			0.973913	
67	Bati well 1	2.2	41.8	46.4	_	2.2	2.44	_	6.98E-03	54.5		57			2.868421	
68	Bati well 2	2.9	16.3	9.92	45.9	0.509	0.31	1.43	1.19E-02	15.3		96			0.478125	
69	Bati well 3	2.2	4.28	4.68	_	0.104	0.114	_	3.75E-03	6.52		124			0.159024	
70	Bati well 5	3.4	3.98	4.22	-	0.0904	0.0958	-	5.80E-03	6.15		148			0.15375	
	Total	405.86	3649.737	4402.191	4236.59	92.8804	102.3008	119.138	0.51004318	3109.96	404.3582233	8647.73	973.79	1424.004985	84.18861	112.198709
	Mean	5.798	52.1391	62.88844286	117.6830556	1.326862857	1.46144	3.309388889	0.007286331	44.428	15.55223936	123.539	37.45346154	54.7694225	1.202694	4.315334962
	Minimum	0.6	0.343	0.345	9.49	0.012	0.005	0.237	5.88E-09	0.63	0.21	57	0.3	6.7	0.009103	0.004984
	Maximum	24	594	1020	380	12.7	19.3	10.7	4.00E-02	399	2016	312	38.8	99.9	11.4	50.4