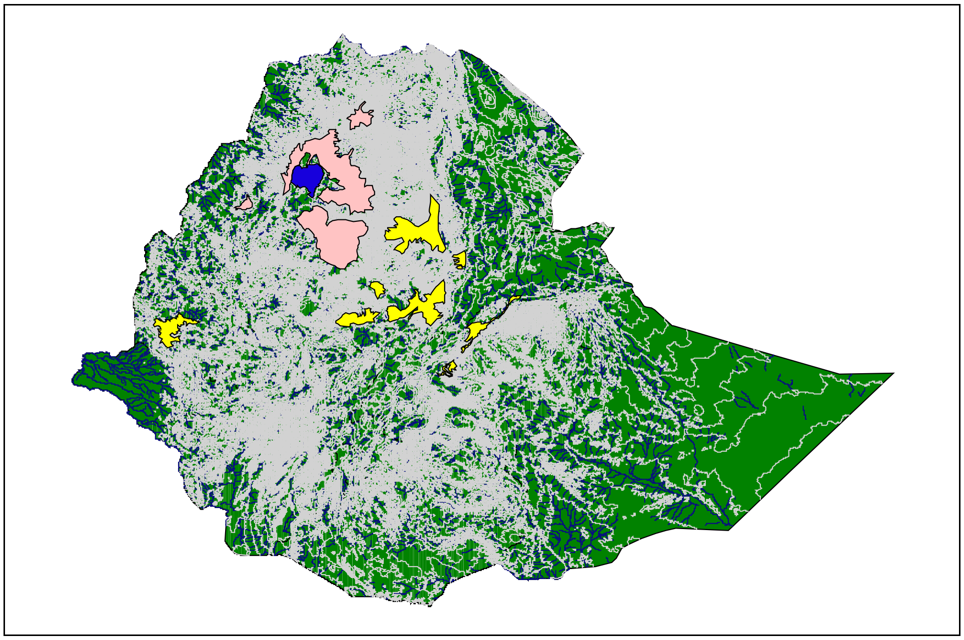
ASSESSMENT ON HYDRAULIC PROPERTIES OF THE ETHIOPIAN TARMABER FORMATIONS



A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENTS OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

BY

ABREHA G/SLASSIE

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ASSESMENT ON THE HYDRAULIC PROPERTIES OF THE ETHIOPIAN TARMABER FORMATIONS

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Abstract:

The Ethiopian Tarmaber formation represents, Oligocene – Miocene basaltic shield volcanism on the northwestern and southeastern plateaus covering an area of about 47,194Km^2 (which is 8% of the total flood basalts aerial coverage in the country). Two types of Tarmaber formations have been mapped. The Tarmaber Megezez formation (Ntb) with an absolute age of (16 – 13 Ma, Kazmine, 1979) is transitional to alkali basalt which covers an area of about 22,058Km^2 (which is 3.4% of the flood basalts (or traps) aerial coverage in the country). This formation commonly outcrops in the central highland plateau, the escarpments and the rift floor and at some localities in the south western highland plateau part of the country (sees Fig.-2.1 & 2.3). The Tarmaber Guessa formation (PNtb), with an absolute age of (26 – 16Ma, Kazmine, 1979) is alkaline to transitional basalt, often ridge and cliff forming shield volcanoes with minor trachytic and phonolite flows. It covers a total area of about 25,136Km^2 (which is 4.5% of the flood basalts aerial coverage in the country). This formation dominantly outcrops in northwestern highland plateau part of the country (see fig.-2.1). The Tarmaber shield volcanoes become progressively younger to southeastern and south western part of the northwestern Ethiopian plateaus. Well-log data and pump test data's analyses show that, the Tarmaber formations aquifer system can be categorized as consolidated fractured aquifer category where the dominant aquifer types are, confined, double porosity fractured aquifer system and single plane vertical aquifer systems. The double porosity aquifers are related to deeply drilled wells reflecting presence of large and narrow fracture systems with high permeability but lower storage capacity. It also shows that, Tarmaber Megezez formation (Ntb) has better aquifer productivity than the Tarmaber Guessa formation (PNtb) and yet, both formations show decrease aquifer productivity with respect to increased drilled boreholes depth and increased age of the formation. Besides, boreholes drilled within the Tarmaber formations shows that, the wells have high well loss coefficient values, indicating improper well site location, improper well design and construction factors and well yield deteriorations with time due to clogging, corrosion and incrustation activities of the well screens. Spatially, the Ethiopian Tarmaber formations show an increasing aquifer productivity trend from the highland plateau areas towards the escarpment and the rift floor areas, and yet, from the north, south, northwest, southwest, northeast, southeast and east- west directions of the highland plateau areas toward the Lake Tana basin areas. Generally, the Tarmaber basalts aquifer productivity is highly controlled by the location and geomorphologic setup of the formation outcrop, nature and degree of weathering, hydrothermal processes and nature, extent, frequency and orientation of the associated structural features and yet, weathering, hydrothermal processes and other volcanic activities tend to decrease aquifer permeability while, fracturing, faulting and other tectonic activities tend to increase aquifer productivity of the Tarmaber formations.

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1. Introduction

1.1 Background

Ethiopia is a landlocked country with surface area of 1,127,000km^2 with peculiar three physiographic regions of the northwestern, southeastern and the rift valley that separates them. The surface elevation of the country varies between 120m below sea level in the Afar area and to 4620m above sea level in the northwestern plateau and yet greater than 80 million people are living within the three physiographic regions of the country.

Due to the great extent in territory, the country is characterized by sporadic rainfall pattern which has uneven distribution pattern both in space and time. Though the distribution is uneven, Ethiopia has a potential 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 is 183Mm^3.

The recharge to the groundwater system of the country is variable as the rainfall distribution in the country is variable both in space and time. The main source of recharge for the vast groundwater system in the country is the rainfall on the northeastern and the southwestern highland plateau where annual rainfall is very high. The Ethiopian main rift valley acts as a main discharging zone which contains perennial rivers, fresh and salt lakes, cold and thermal springs. The mean groundwater recharge for the entire country is 200mm.

The total groundwater reserve of the country which is 183 Mm^3 is distributed in area of 924,140km^2 which is made up of; 25%-Sedimentary formation, 40%- Tertiary volcanic rocks and 17%- Quaternary sedimentary and volcanic formations excluding the unproductive basement formation which covers an area of 202,860km^2 which is 18% of the total surface area of the country.

One of the fundamental conditions for the growth and development of a nation like Ethiopia is certainly the progressive fulfillment of its most urgent water needs. Hence, along with this, the fast growing population and recurrent drought in Ethiopia has demanded good scientific and technical capabilities for the assessment, judicious and substantial development of the country water resource potential (particularly the groundwater) with a very limited expense in irrigation, hydropower and water supply for communities.

So far, little had been done in the field of development of water resources particularly in area of groundwater resource. To develop the existing groundwater potential in the country, the first attempt is to identify the main different types of Groundwater Aquifer systems in various part of the country which are located within the different geo-petro graphical environments and climates and yet to characterize the aquifer systems of the different geological formations which covered the whole country.

1.2 Statement of the Problem

Groundwater is considered as a very precious resource for the growth and development of a nation like Ethiopia. Reliance on groundwater has increased greatly. Similarly, substantial increases in groundwater withdrawals have occurred in almost every part of the country. The Vulnerability of groundwater to overuse and water quality degradation was not widely understood until recently. Nowadays, as much attention is paid to water quality preservation and resource conservation as to resource development by providing the necessary technical knowledge to locate, extract, treat and protect groundwater so that current and future generation can depend on this resource to enhance their quality of life.

When considering a ground development project, one of the highest problems to be encountered is often the lack of data up on which to base an assessment of the viability of the aquifer. A common problem is the scarcity of data relating to the variations in the value of the coefficient of transmissivity and storage. Knowledge relating to the position and nature of the boundaries and recharge – discharge mechanisms of the aquifer may also be inadequate.

In order to carry out successful test it is necessary to have some knowledge of the aquifer and well hydraulics and in particular how the drawdown varies with the duration of pumping and distance from the pumped well. Without an appreciation of these relationships and the factors which affect them, it may prove difficult or impossible to design a suitable observation hole network and to produce a meaningful test and reliable aquifer parameter behavior of a given formation.

Although it is possible to obtain some approximate idea of the perennial yield of an aquifer from a desk study, detailed information can be obtained only from proper interpretation and evaluation of a field pump test data’s and yet it demands a scientific and technical capabilities for its assessment, exploration and development for use in domestic water supply, irrigation and hydropower. To successfully achieve this objective, the first attempt must be to identify the different aquifer systems within different geological formations and to accurately characterize the existing aquifer systems within a region for proper, planned and manageable future uses of the groundwater resource.

Regarding the hydrogeology of Ethiopia, so far, very few investigations have been done but, many local hydrogeological investigations had been done previously and currently are under progress. However, regional hydroegeological investigations which are very specific to a given existing rock type is not yet done so far. The few regional and the many local hydrogeological investigations indicate that the volcanic rocks of the country have huge groundwater resource potential and high aquifer productivity.

Therefore, this Thesis mainly focuses on the assessment of the hydraulic properties of the Tarmaber basalts (i.e. Tarmaber Guessa and Tarmaber Megezez formations) which have an extensive areal coverage of about (47,194km2) or 7.9% of the total surface aerial coverage of the Continental Flood Basalts in the country using interpretation and analysis of the collected secondary borehole pump test data’s. Attempt has also be made to compare the hydraulic properties of the Tarmaber formations with other volcanic aquifers elsewhere in the world.

1.3 Objective

1.3.1 General Objective

The main objective of this thesis is to assess the hydraulic properties of the Tarmaber formations (variation of transmissivity, hydraulic conductivity and storativity of the aquifer systems) in Ethiopia in relation to depth and age of the formation and yet to assessing effect of structural features, tectonics, volcanic, hydrothermal and weathering processes. Geological and hydro geological data's, interpretation and analysis of collected secondary well pump test data's will be applied to identify aquifer type and behavior and to see the variation of the formation hydraulic properties with respect to depth and age.

1.3.2 Specific Objective

The specific objectives of research work are expected to address the following ideas: -

- Mapping the surface outcrop location and aerial coverage of the Tarmaber formations in Ethiopia,
- Identifying the aquifer characteristics of the Tarmaber 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 Tarmaber formations and on their groundwater potential.
- To compare the Tarmaber formations aquifer characteristics with other volcanic rocks elsewhere in the world.
- Evaluation relationship of transmissivity and specific capacity through theoretical and empirical methods

1.4 Description of the Study Area

1.4.1 Location and Accessibility

The Ethiopian Tarmaber formations dominantly outcropped in the northwestern highland plateau and southeast and southwest part of the northwestern highland plateau. In northwest highland plateau, they outcropped in areas particularly around Gondor, Azezo, Addis Zemen, Debretawor, Nefas mewcha and in central Gojjam areas. In southeast highland plateaus, they outcropped in areas particularly around Wurgessa, Wuchale, Haike, Dessie, Akista, Kurkur, Debresina, Tarmaber, Ankober, Debrebrhan and sheno areas and in the central highland areas around Legedadi, Sululta, Chancho, Muketure and Gohatsion areas. In the southwestern highland, they particularly outcropped around Tebi town areas (see Fig. 1 below).

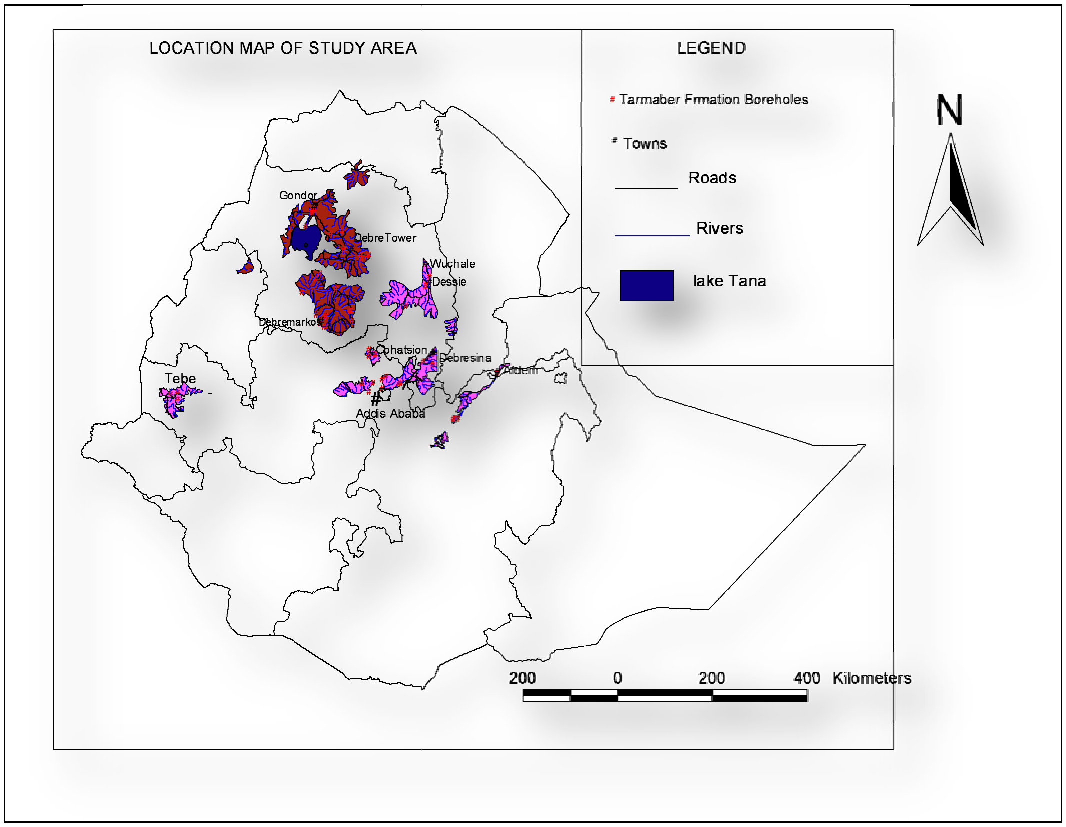


Fig.1- Location Map of the Study Area

Most of the country is characterized by grasslands with scarce woodlands and thorn bushes. This includes, the mountain grasslands, which is largely used for plough cultivations and the lowland grasslands, which is mostly used as grassland for the Nomads' cattle. Only limited areas of the highland forests remain and they occur as islands within the extensive grasslands.

The Ethiopian western volcanic highlands have shallow to deep brown & black clay soils while the eastern volcanic highlands have shallow red clays. The crystalline basement areas of northern Ethiopia have shallow silty, sandy & rocky soils while in the southern and western Ethiopia they have deep red lateritic soils. The granite and gneiss areas in the semiarid and arid zones have in general thin sandy soils. Alluvial plains in the rift valley have silty – sandy alluvial soils.

1.5 Previous Works & Related Literatures

Among the few regional and/or local previous studies which tried to assess the regional hydraulic parameter behaviors of the whole volcanic rocks in the country are,

Tarmaber basalts (Tv) (about, 100m in thickness) erupted from shield volcanoes, are lenticular basalts with tuffs and scoracious lava flow and plaeosoils. They have dyke swarms and have heterogeneous basalts with alkaline. Next to the Ashangi basalts, the Tarmaber basalts occupy extensive areas in the

northern part of the western highlands and rift escarpment areas. The Tarmaber basalts have moderate permeability and productivity (JICA, 2001).
It concluded that: 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. 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)
Tarmaber basalt has potential groundwater among the volcanic rocks in the upper Awash Basin (WWDSE, 2008).

Tarmaber Basalts of Ethiopia as two formations; namely, the first, Tarmaber Megezez formation, which is middle Miocene in age and transitional to alkali basalts, and the second, Tarmaber Guessa, which is Oligecen – Miocene in age and Alkali to transitional basalt often ridge and cliff forming shield volcanoes with minor trachytic and phonolite flows (EIGS,1996).

The flood lavas extruded from fissures and centers and covered the great part of the Mesozoic sedimentary rocks, with a total aerial coverage of 600, 000km2 (Mohr & zanettine, 1988). These flood basalts have two groups, Ashangi and Maqdala, The Ashangi group occure in two cycle, the Ashangi cycle and the post Ashangi cycle. The post Ashangi cycle is a plateau sequence which contain the Aiba and Alaji fissural volcanisms. The fussural Alaji volcanism is followed by central volcanism which built up large shield volcanoes called Tarmaber central volcanic (Mohr, 1971b). In summary of volcanic stratigraphy, by (Justin, Visentin et al 1974; Morton et al, 1979; Kazmin et al 1980; Mohr et al 198, Mohr, 1983), it stated that the Tarmaber basalts of Ethiopia have an age that ranges from (22- 26 Ma). And yet, it says that, the productivity of the trap series volcanic considerably 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, it varies from 0.4 to 6.3lt/s and those for the southeast plateau; it varies from 1.2 to 5lt/s. For the Maqdala group rocks, it ranges from 1 to 12lt/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 scoracoius basalts. (Dr. Tamiru Alemayhu, 2006).

This paper concluded that**,** the Ethiopian flood basalts (or traps) cover an area of about 600,000km2 (Mohr & Zanettin, 1988) with a layer of basaltic and felsic volcanic rocks whose thickness varies from place to place but reach 2km in some regions. Overlying these flood basalts are, the shield volcanoes which are bimodal and contain sequence of alternating basalts, rhyolitic and trachytic lava flows, tuffs and ignimbrites, particularly near their summits. The flood basalts in Ethiopia was erupted some 30Ma ago (Courtillot et al, 1987, Hempton, 1987, Jestine & Huchon, 1992).

2. Methodology

2.1 Pump Test Data Collection

The geological data of the boreholes including the water bearing formations and the record on the well design and construction has been presented in plots processed by computer using Strater software version 4.00.

The analysis of the pump test data has been made using Theis time-drawdwon 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 for windows software version 4.00 (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 and No.48, SATEM: Selected Aquifer Test evaluation methods by J. Boonstra.

Geological formations of the Tarmaber formations have been mapped using Arcview GIS and Surfur computer software's.

With the secondary well pump test data and data of hydro geological field observations, it is possible to identify the type of the aquifer system, interpret and analyzed the aquifer system hydraulic properties of a given geologic formation.

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 on Aquifer type Master curves
- Software's to analyze the hydraulic parameter of the formation aquifer system.

In addition to the above mentioned data's, the following information's are also gathered during desk study from different governmental, NGO's and private companies and the remaining data's are gathered during field work arranged for this study.

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 curve types
2. Field work to fill data gap which includes: -.

- Boreholes depth to groundwater data
- Hydro geological field observation data records
- Major structure identification like effect of surface geologic processes and tectonics, and rifting.

Finally organizing a comprehensive well pumps test data's and yet interpreting and analyzing pump test data's and classify the borehole technical data's based on aquifer productivity with respect to boreholes depth and age of the formations using Aquifer test version 4.00 computer software's has been done.

2.2 Theoretical Background on Interpretation of Pump Test Data's

Calculating the hydraulic characteristics of an aquifer would be relatively easy if the aquifer system (i.e. the aquifer plus well) were precisely known. But this is not generally the case, so interpreting a pump test data is primarily a matter of identifying an unknown system. System identification relies 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.

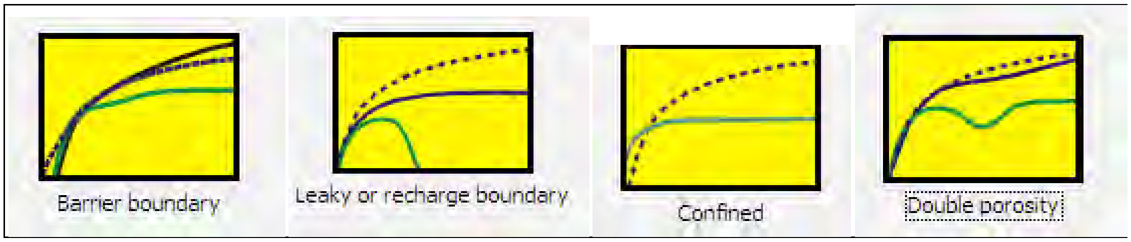
System identification includes the construction of diagnostic plots and specialized plots. Diagnostic plots are log-log plots of drawdown verse time since the pumping started. Specialized plots are semi-log plots of the drawdown verses time or drawdown verses distance to the well, they are specific to 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's 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's 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. Are we carrying out the pump test 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 has 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 1A & 1B, representative Time verses Drawdown plots on double log).



Graph-1- Diagnostic type curves for pump test data

2.2.2 Single Pumping Well Analysis Method

The data's 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's.

To analyze the pump test data's in a correct manner, for both equations i.e. the equilibrium and non equilibrium equations, the following five limiting assumptions have been investigated and conditions allow these are valid assumptions for the studied case.

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 pieozometric surface is negligible before pumping starts
- The pumped well completely penetrates the saturated aquifer thickness (at least 80% of it)

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's in an aquifer or well test set up may be preferred to using steady state flow pumping test data's. 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 dounle logarithm 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 shap 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. Presumably, 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;

$$t_c = 0.6(d_c^2-d_p^2)/Q/s \text{ or } t_c = 0.017(d_c^2 - d_p^2)/Q/s\text{-------------------} (1)$$

Where t_c is time in minutes when casing stotage effect becomes negligible, d_c is inside diameter of well casin (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 tarnsmissivity 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;

$$T_2 = 4T_1/E\text{---------------------} (2)$$

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

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)

BQ – the laminar term, is the aquifer loss factor
CQ^2- the turbulent term is the well loss factor (or head loss attributable to inefficiency)

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 this reason, computing well efficiency percentage from a step drawdown test results erroneous values. The step drawdown test is still useful, however, in evaluating the magnitude of turbulent head loss for the purpose of determining optimum pumping rates. If we divided the above equation (4) by pumping rate in both sides of the equation and yet if we plot s/Q verses pumping rates, the resulting graph is a straight line with slop C (well loss) and intercept B (aquifer loss).

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

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 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. The main hydro geologic conditions that affect the Time verses Drawdown graphs are:

- Precipitation recharge
- Surface water recharge
- Slow drainage
- Vertical leakage
- Impervious boundaries
- 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 design 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' (min2/m5)	**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 Capcity through Theoretical & Empirical Methods

Transmissivity and specific capacity field data's can be related by, Analytical, Emperical, Geostatistical and hybrid methods. Specific capacity is in part, a function of the hydraulic properties of an aquifer. Specific capacity data's are typically much more abundant and readily available than the time – drawdown data's. 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

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. However, their application can be limited due to

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

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

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. These methods involve;

- 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

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;

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

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. If lower specific capacity indexes are found for wells that intersect more of the formation or deeper depths, then, the lower units are less productive. If specific capacity index increases, then the lower units are more productive. If specific capacity index remains the same, then the formations have similar productivity. A similar comparison can be done with the geometric mean of the specific capacity index.

3. Geology and Hydrogeology

3.1 Regional Geology

The Ethiopian flood basalts (or traps) cover an area of about 600,000Km2 (Mohr & Zanettine, 1988) with a layer of basaltic and felsic volcanic rocks whose thickness is highly variable but reaches up to 2km in some regions. Overlying these flood basalts, are the shield volcanoes which are bimodal and contain sequences of alternating basalts, rhyolitic and trachytic lava flows, tuffs and ignimbrites, particularly near their summits. 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). Traditionally, these flood basalts have been divided in to two groups; The Ashange and Mequdala groups. 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. The post Ashange cycle is a plateau sequence which contain Aiba and Alaji fissural volcanisms. The Alaji fissural volcanism was followed by central volcanism which built up large shield volcanoes called Tarmaber central volcanic (Mohr, 1971b).

The Tarmber formation in Ethiopia represents, Oligocene – Miocene basaltic shield volcanism on the northwestern and southeastern plateaus. The central type Tarmaber formation basaltic volcanism was followed by fissural eruption particularly along the escarpment of northwestern and southeastern plateaus. The Tarmaber basalts, in contrast to the thieollitic and mildly alkaline nature of the flood basalts, are typically alkaline in nature. On the northwestern plateau, the Tarmaber shield volcanoes become progressively younger from north to south. Thus, the classification Tarmaber Guessa formation (PNtb) for the shield volcanoes of the northern Ethiopia plateau with an absolute age range of (26 – 16 Ma) and the name Tarmaber Megezez formation (Ntb) for the younger shield volcanoes with an absolute age range from (16 – 13 Ma) in the southern part of the northwestern plateau and the southeastern plateau become essential (Kazmin, 1979 and references therein). The upper age limits of the Tarmaber Megezez formation (Ntb) is lowered to (7 – 8 Ma), when the large basaltic center of Arba Gugu with the same alkaline nature is considered as the youngest episode of the Tarmber type volcanism. Other dominant basaltic units erupted within the age intervals from 14 – 10 Ma ago (Anchar basalts of Kazmine & Berhe, 1987) mapped on the eastern escarpment of the MER and southern Afar, and Miocene basaltic volcanism in the western Ethiopia with an age range of 9 to 10Ma (upper aphiric basalt of Berhe et al, 1987) are also considered with the Tarmaber Megezez formation (Ntb) on chronological ground. The geological map of the Ethiopian Tarmaber formations is presented as below separately for each of the two Tarmaber formations. Figure-2.1, represents surface outcrop geological map of Tarmaber Guessa formation which outcrop in northwestern highland plateau part of the country, Figure-2.2, represents surface outcrop geological map of Tarmaber Megezez formation which outcrop in central highland, escarpment and rift floor part of the country and Figure-2.3, represents surface outcrop geological map of Tarmaber Megezez formation which out crop in southwestern highland plateau part of the country.

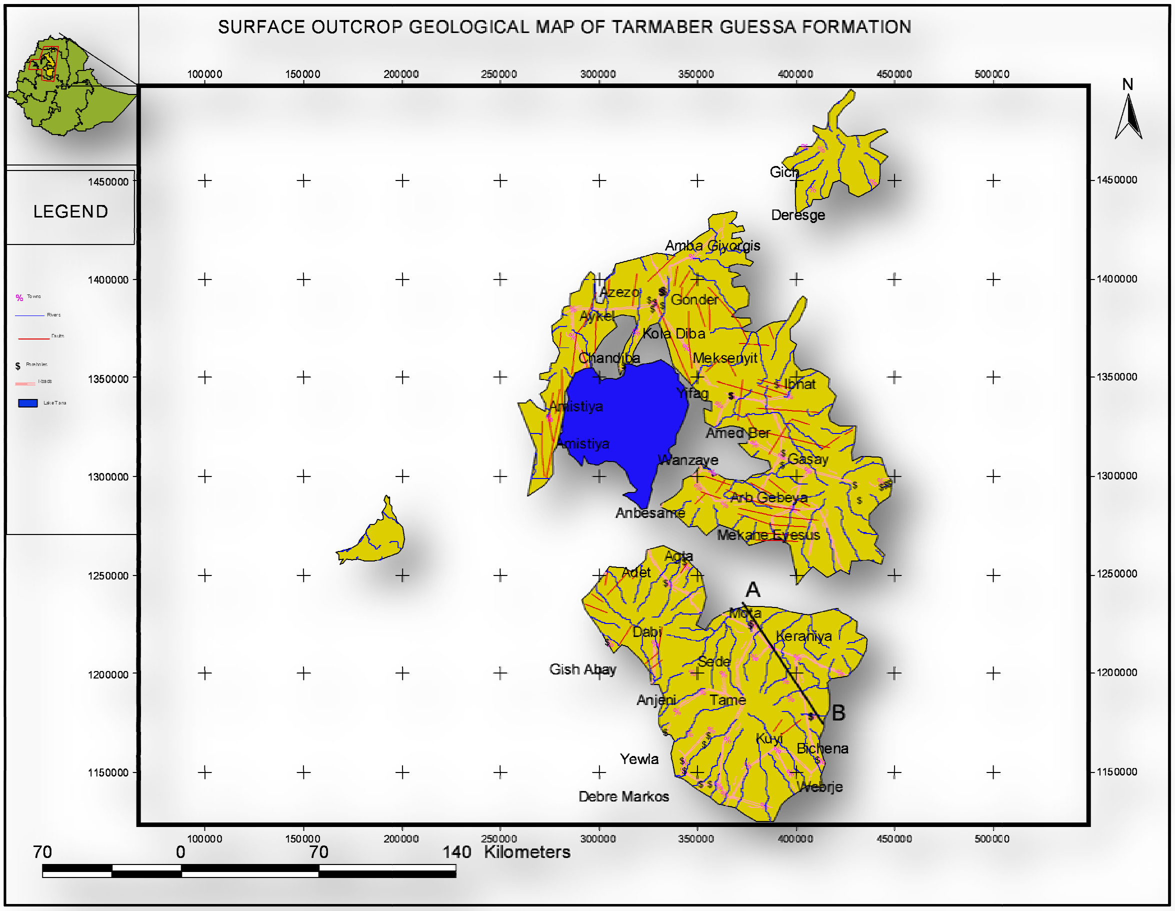


Fig.2.1 Geological map of Tarmaber Guessa formation in Northwestern highlands

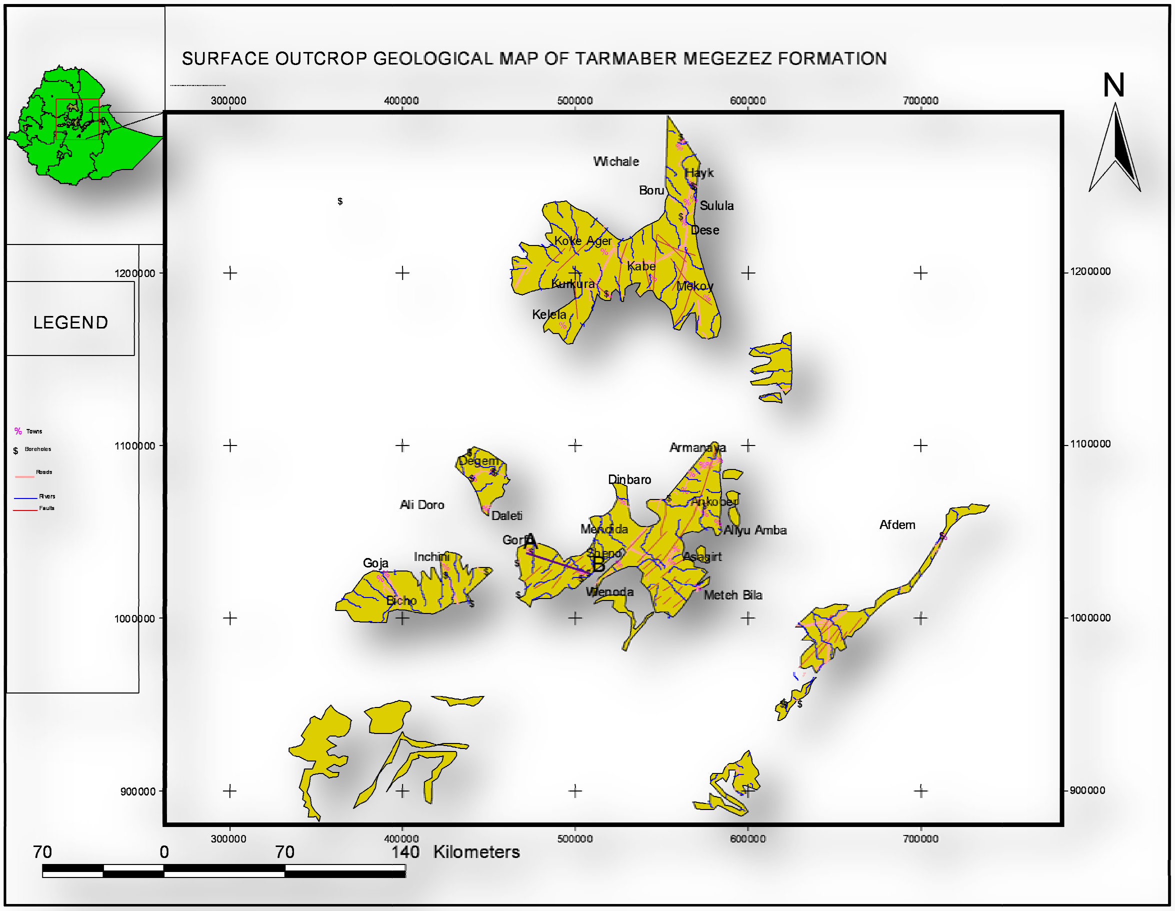


Fig.2.2 Geological of Tarmaber Megezez formation in central highland and rift valley

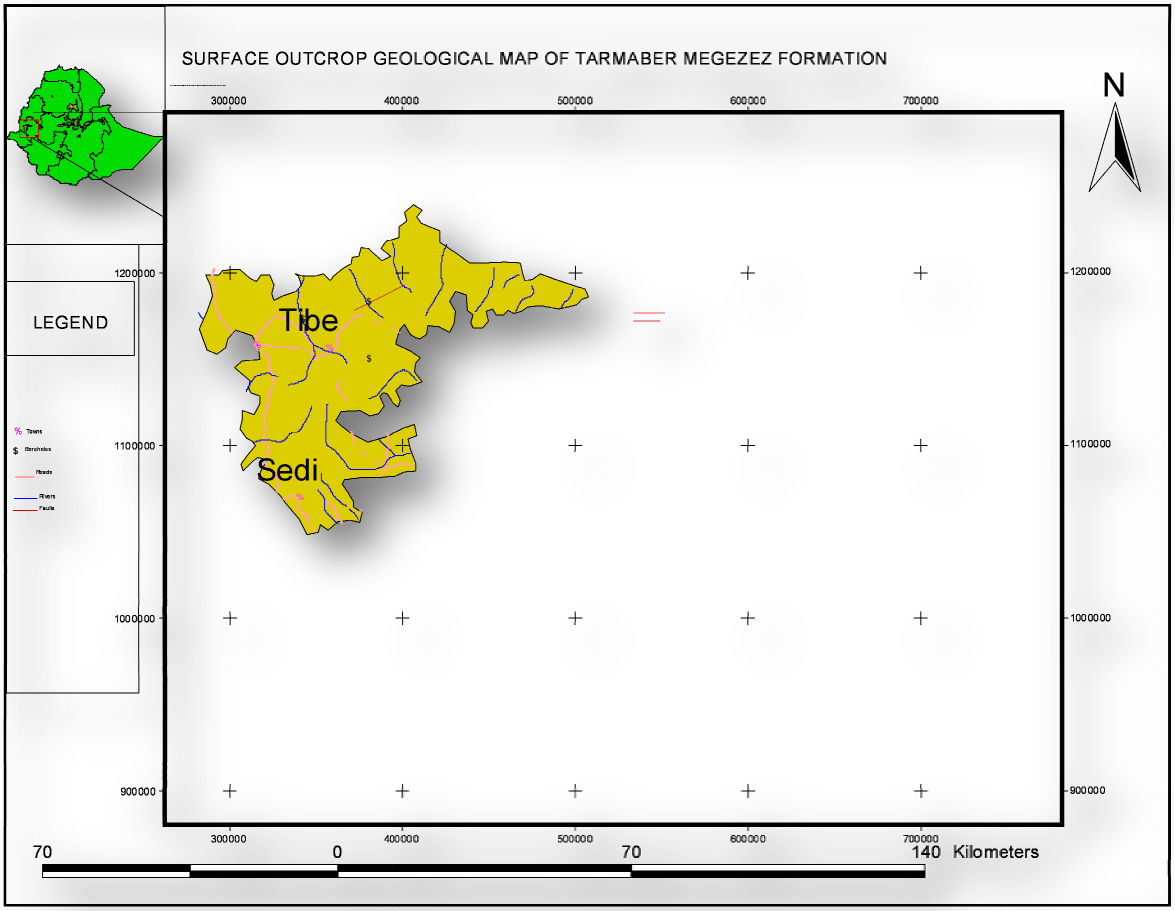


Fig.2.3 Geological map of Tarmaber Megezez formation in southwestern highlands

3.2 Regional Hydrogeology

Ethiopian flood basalts 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 Ashange group rocks varies from 1lt/s to 5.6lt/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 Maqudala 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).

In addition to the quaternary volcanic, alluvial sediment & lacustrine deposit aquifers, the main aquifer system for the Tarmaber formations are mainly their fractured and faulted scoracious layers. Presence of overlying volcanic trachyte, tuff, ash and pale soil make the groundwater condition of the Tarmaber formations to be under semi-confined and artesian condition.

From the collected and analyzed borehole's constant yield and recovery tests result, the Tarmaber Megezez formation has a borehole yield that ranges from 63m^3/day to 1728m^3/day, it's transmissivity ranges from 3.1m^2/day to 1940m^2/day and a mean of 105m^2/day. The specific capacity ranges from 2m^3/m/day to 173m^3/m/day and a mean of 48m^3/m/day.

Tarmaber Guessa Formation (PNtb) has a boreholes yield that range from a minimum of 47m^3/day to a maximum of 1995m^3/day. The transmissivity these formation ranges from a minimum of .413m^2/day to a maximum of 1320m^2/day and mean of 97m^2/day. The Specific capacity ranges from a minimum of 1m^3/day/m up to a maximum of 153m^3/d and with a mean of 32m^3/day/m. 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.

Boreholes from the massive highland plateau of the Tarmaber formations have low aquifer productivity as compared to boreholes located elsewhere from these areas. The Tarmaber Megezez formation has better aquifer productivity than the Tarmaber Guessa formation and yet both formations show decrease aquifer productivity with increased boreholes depth and age of the formations. Boreholes from massive highland plateau of the Tarmaber formation have low yield than as compared with boreholes located elsewhere from these areas. The Tarmaber formations aquifer productivity is highly controlled by:

- Spatial distribution and geomorphologic set up of the formation outcrop
- Nature and degree of weathering and hydrothermal processes
- Nature, extent, frequency and orientation of the associated structural features

Hence, weathering, hydrothermal processes and other volcanic activities tends to decrease aquifer permeability while, fracturing, faulting and other tectonic activities tends to increases aquifer productivities. The lake Tana basin and pre-& post MER forming faulting and other tectonic activities play an important role in the Tarmaber formations groundwater occurrence, localization and movements and yet in the permeability and productivity of the Tarmaber formations.

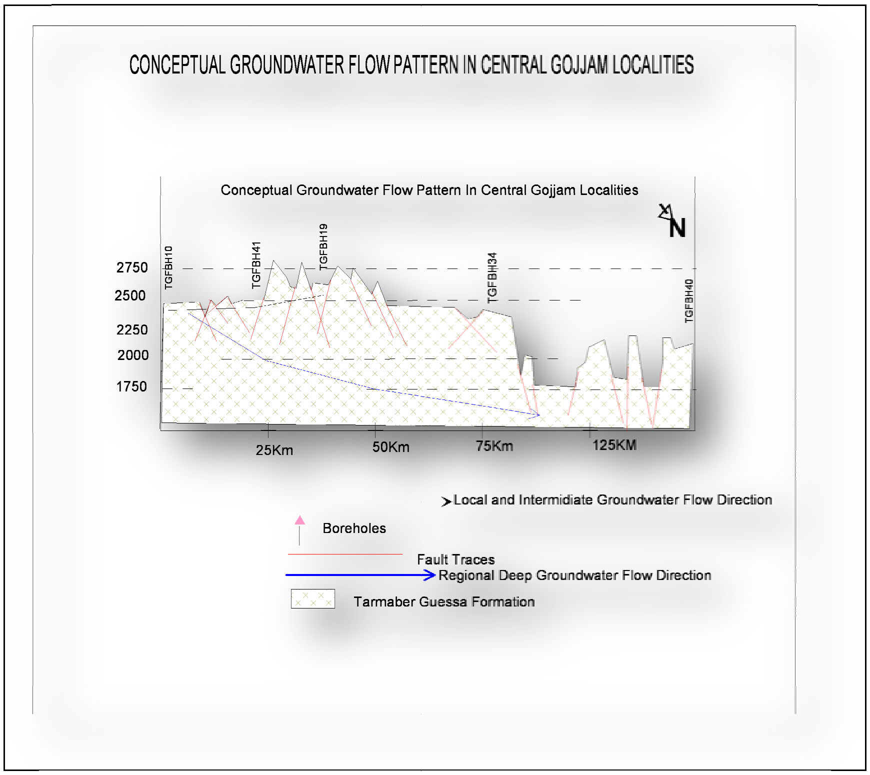


Figure-3- Conceptual Groundwater flow pattern in central Gojjam areas

As indicated in figure 3 above, the groundwater flow in the central Gojjam area is highly controlled by major, north-south, northwest-southeast, and east – west regional faults and geomorphological set up of the area. The regional faults develop north-south aligned parallel local grabns and yet caused the groundwater of the area to flow partly to northwest and partly to southeast; however, the regional deep groundwater flow direction is generally towards northwest direction.

Finally, the Ethiopian volcanic terrain and associated quaternary deposits represent complex aquifer systems where groundwater occurrence, and its spatial distribution is highly controlled by the geomorphic architectures of the plateau, escarpments and the rift floor, the complex spatial and temporal distribution of the volcanic rocks, their different intricate stratigraphic relationships, wide compositional variability, different level of weathering and topographic positions complicate the hydro geological behaviors of the volcanic aquifers and their hydrochemical signatures. Therefore, any groundwater exploration and development requires mapping of the important structures and evaluating their role in the recharge, movement and occurrence of the groundwater (Tenalem Ayenew, 2009).

4. Results

4.1 Characteristics of the Data

4.1.1 Data Type

Assessment of the hydraulic properties of the Tarameber formation aquifer systems outcropped in the Ethiopia has been conducted through the interpretation and analysis of collected secondary boreholes pumping test data. Methods used in this study are described in Castany (1982), Kruseman and De Ridder (1991), Fetter (1994). For this work, step drawdown test, constant rate test and recovery test data have been gathered from governmental offices ,private companies, NGO's and different several research programs carried out in different parts of the country. A pump test data base of about 81 secondary boreholes pump test data's which are assumed to be representatives to the Tarmaber formation were assembled (see Appendix A). About 34 wells tap the Tarmaber Megezez basalts and the remaining 47 wells tap the Tarmaber Guessa basalt. The wells are of various depths and penetrate various thicknesses of the saturated Tarmaber formation. Out of the 34 wells of the Tarmaber Megezez formation, 26 wells are only with constant yield tests and out of which only 5wells have recovery test data's and the remaining 8 wells are with constant yield test and step drawdown test data's and yet, 33 wells of the Tarmaber Guessa formations are with constant rate tests & out of which 9 wells are with recovery test data's and the remaining 19 wells are also with constant and step drawdown test data's (See Table 1). All the collected secondary well pumping test data's were used one well for pumping and measuring the water level data's. Constant rate pumping tests and recovery tests were analyzed to determine the transmissivity of both tarmaber formation aquifer systems. Concerning the wells in the Tarmaber aquifer systems, where neither constant rate nor recovery tests were run, an attempt was made to estimate transmissivity with the use of specific capacity. To this end, a task was undertaken to find the best relationship between transmissivity and specific capacity, for the 81 wells which were subjected to both constant rate and/or recovery tests and step drawdown tests.

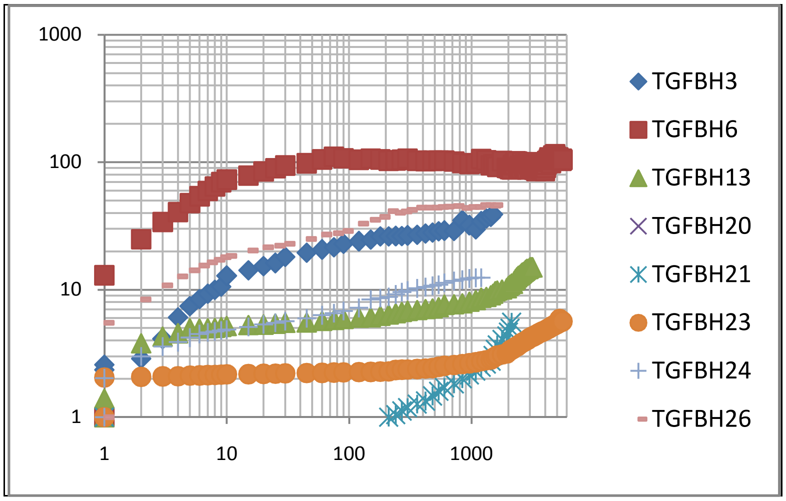
Table-1 -Number of wells and types of pumping tests in each the two Tarmaber formations

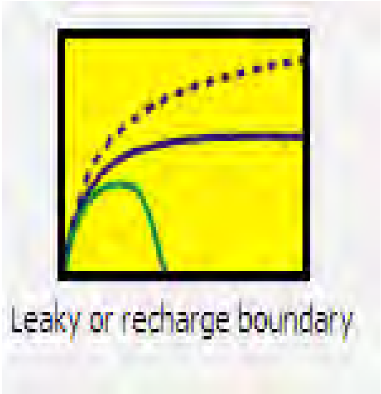
Aquifer	Age (My)	Total No. of BH's	No. of BH's subjected to C.R.T	No. of Bh's subjected to R.M.T	No. of BH's subjected to S.DD.T
Tarmaber Megezez	16-13	34	26	5	8
Tarmaber Guessa	26-16	47	33	9	19
Tota No. of Bhs		**81**	**59**	**14**	**27**

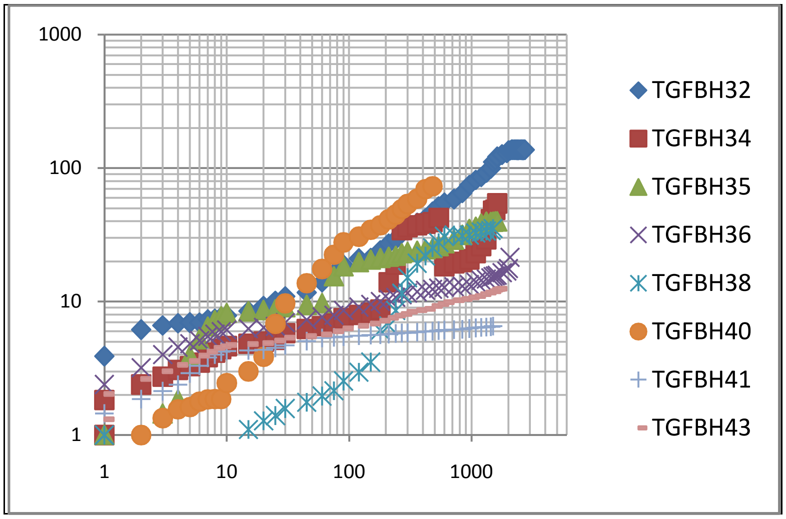
Not:- **C.R.T – Constant Rate Test**
R.M.T – Recovery Monitoring Test, S.DD.T- Step Drawdown Test

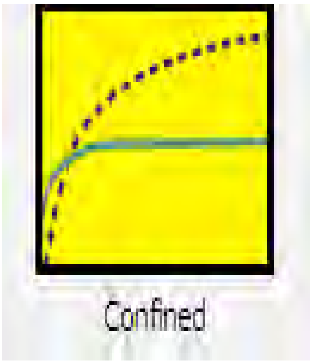
4.2 Time Verses Drawdown plots

The collected boreholes pump test data's with Time and drawdown data's are plotted in semi-log and double log plots and compared with the diagnostic type curves to identify the formation aquifer category, to classify the aquifer types and to select proper pump test data analysis methods. Thus, the result shows that, the Tarmaber formation in general can be categorized as consolidated fractured aquifer which is dominantly confined aquifer type with double porosity fracture and single plane vertical fracture aquifer systems. (See Graph-1-A & B & Graph – 2-A, B & C below).

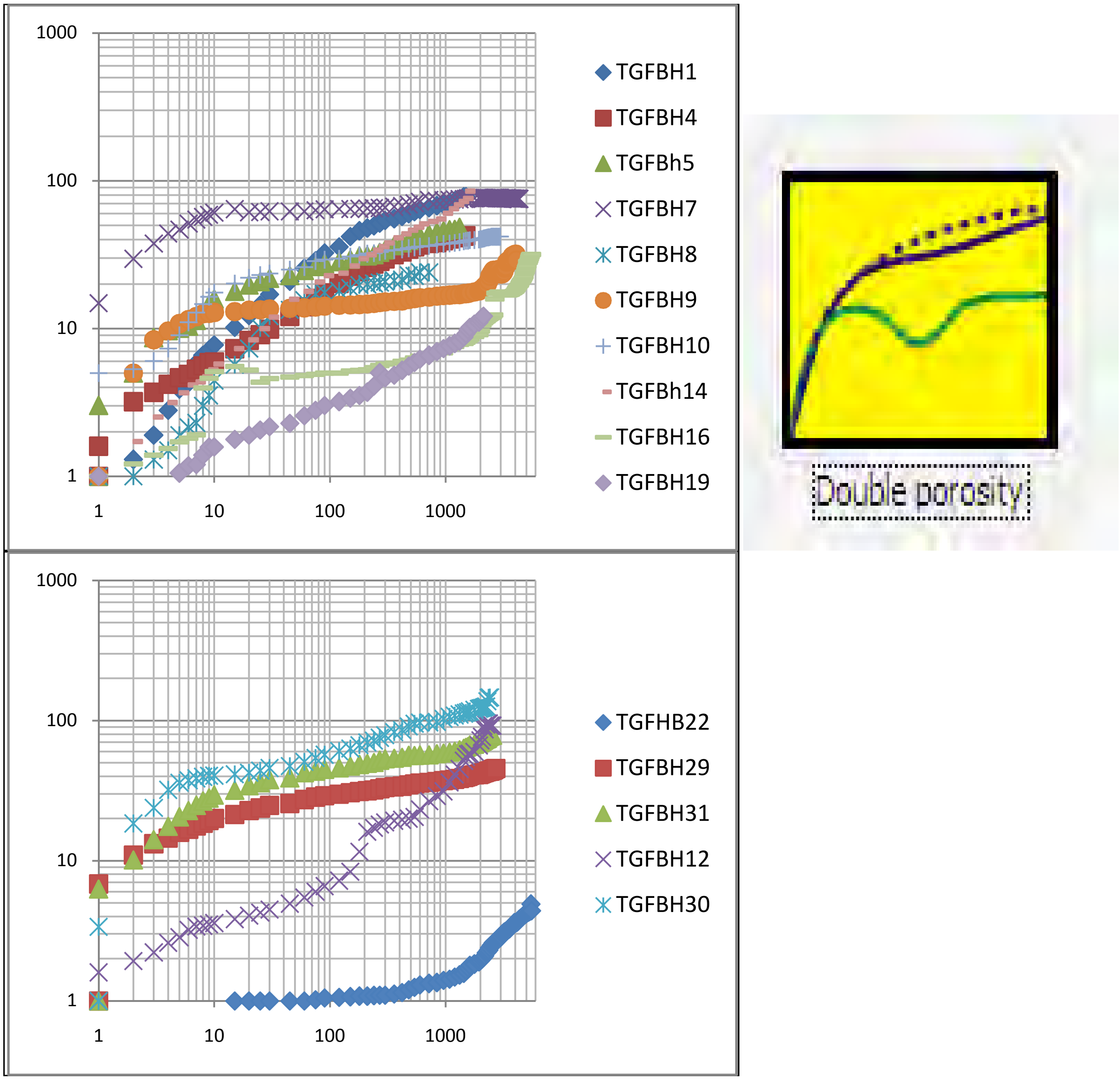




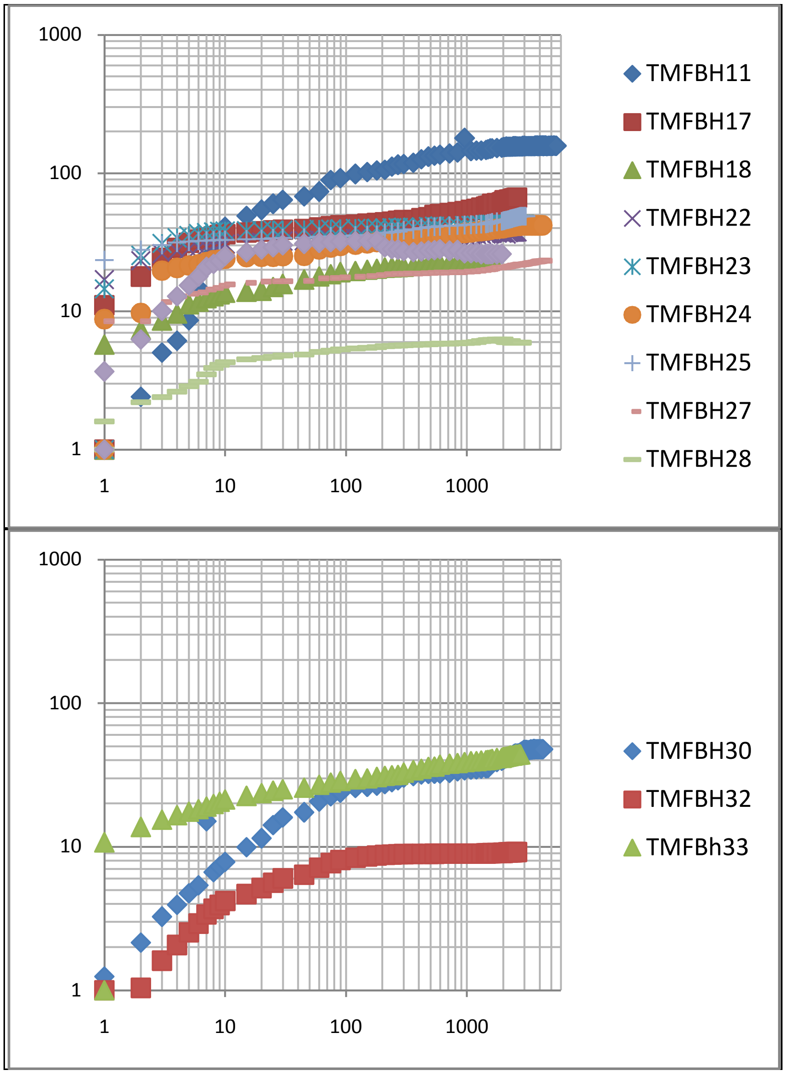


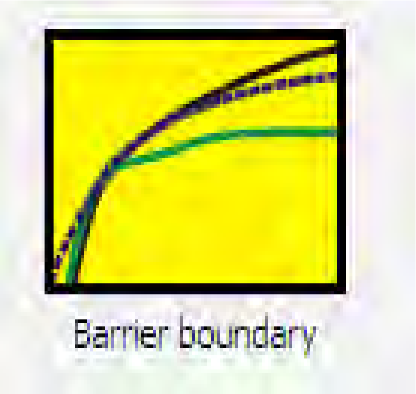


Graph-2-A- Double log plot of Time Verses Drawdown data's of Tarmaber Guessa Formations indicating Confined aquifer type curves

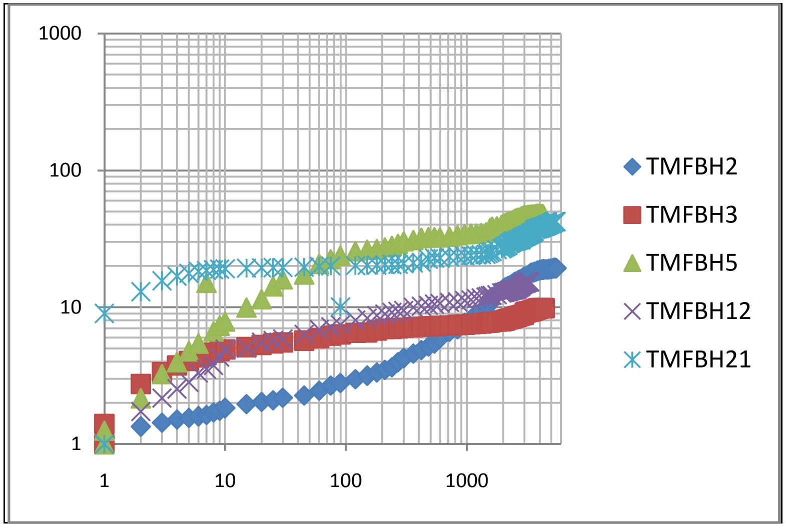


Graph 2 B - Double log plot of Time Vs Draw Down data's of Tarmaber Guessa Formation indicating confined Double porosity fracture aquifer type curves

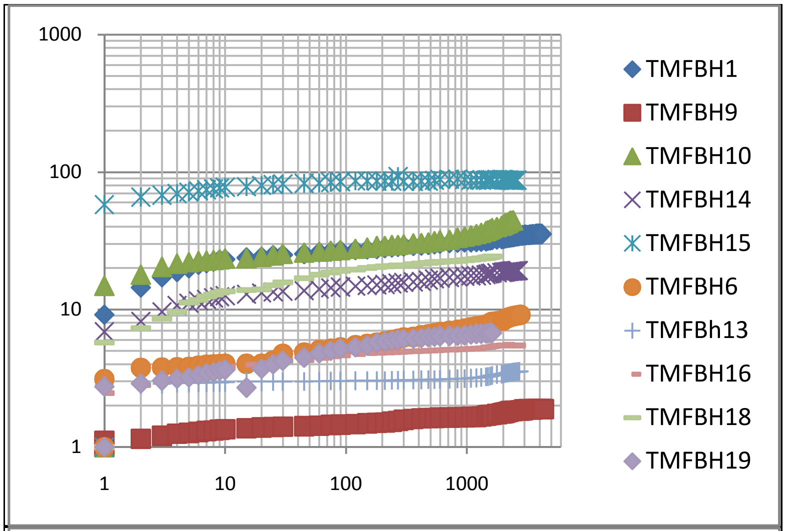


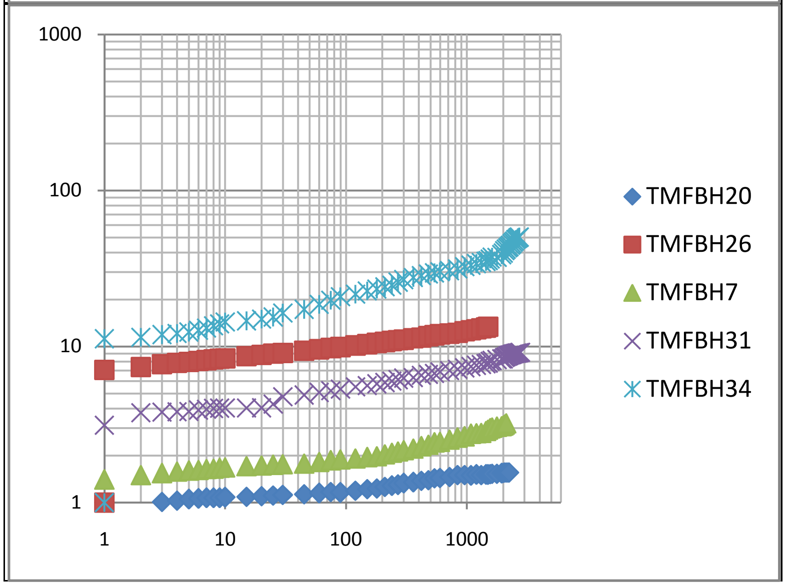


Graph-3- A- Double log plot of Time Vs Draw Down data's of Tarmaber Megezez Formation indicating Confined aquifer type curves



Graph-3-B- Double log plot of Time Vs Draw Down data's of Tarmaber Megezez Formation indicating Confined Double porosity fracture aquifer type curves





Graph-3-C- Double log plot of Time Vs Draw Down data's of Tarmaber Megezez Formation indicating Confined Single plane Vertical fracture aquifer type curves

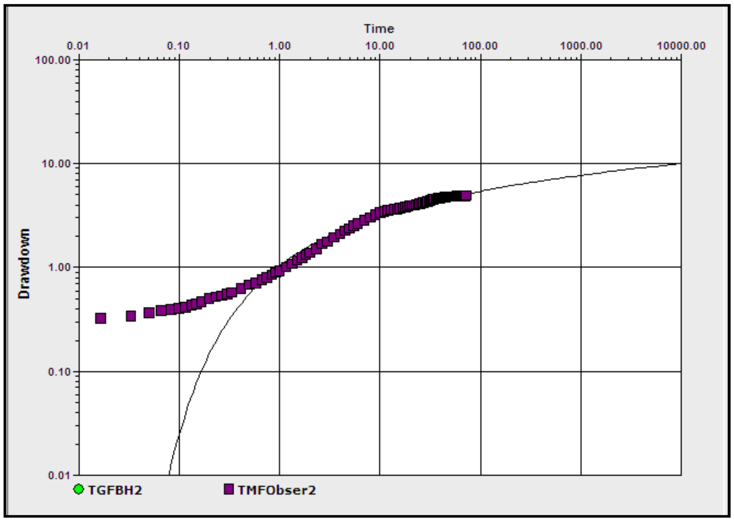
4.3 Determination of Transmissivity of the Tarmaber Basalts from Constant & Recover

Constant rate pumping tests and recovery tests were used primarily to determine transmissivity of the two different Tarmaber formation aquifer systems. Whenever feasible, the storage coefficient was also determined. These tests were also interpreted to recognize the boundary effects of the aquifers. The pumping times are rather different for each formation and vary between 10 and 72 hours. Single pumping well test data's 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's. The Theis equation (Thiess 1935) was applied to determine transmissivity and storage coefficient for both the steady state and unsteady state flow data's. 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 lo-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. (Graph –(1-A& B) & (2A, B & C).

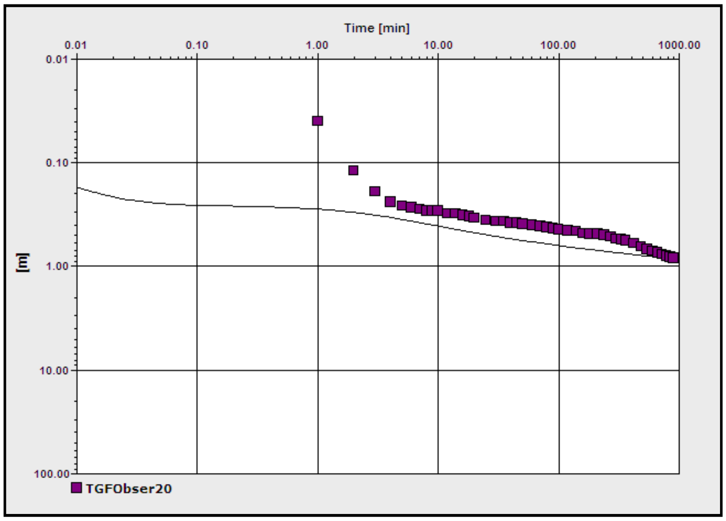
Whenever possible, recovery data should be taken to verify the accuracy of pumping test data's, often, the recovery data's will be more reliable because no pumping is required. Any previously inexperienced personnel will have learned proper measurement techniques by the time recovery data can be taken. 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.

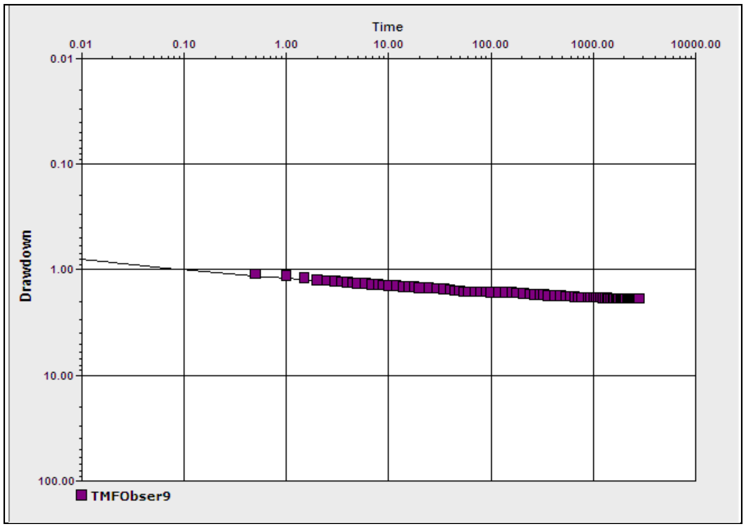
The summary statistics of transmissivity values deduced from these tests are provided in Tables 2 and 3. The transmissivity values of the Tarmaber Megezez basaltic aquifers range between 3.1m^2/day to 1940 m ^{2}/day. The transmissivity values of the Tarmaber Guessa basaltic aquifers are lower than those of the younger Tarmaber Megezez basaltic aquifers, and range between .413 m^2/day to 1320m^2/day. 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 Tarmaber formations are presented below in graph-3-A, B, C & D.



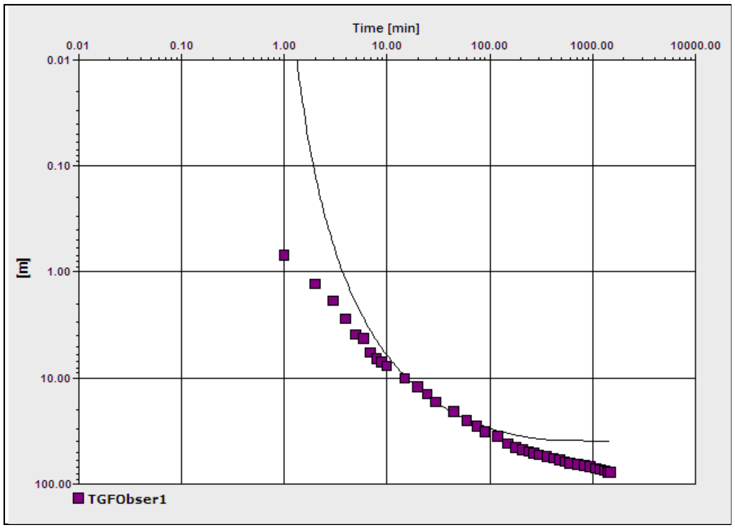
A-Confined Aquifer system with recharging boundary



B-Confined Double Porosity Aquifer System



C-Single plane vertical fracture aquifer system



D- Confined aquifer with barrier boundray

Graph:-4A, B & C– Aquifer typical curves of the Boreholes Drawdown vs. Time data representing infinite extension and boundary effects

Table 2- Summary Statistics of T (m2/day) deduced from constant rate & recover monitoring tests

Description	T(m2/day) from constant rate Pumping test	T(m2/day) from Recovery test
A-Tarmaber Guessa formation		
Minimum	.413	10.74
Maximum	132	410
Mean	97	84.2
B-Tarmaber Megezez formation		
Minimum	1.51	84.2
Maximum	194	704
Mean	105	196

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. Theoretical relations are briefly reviewed.

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∏ In (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.

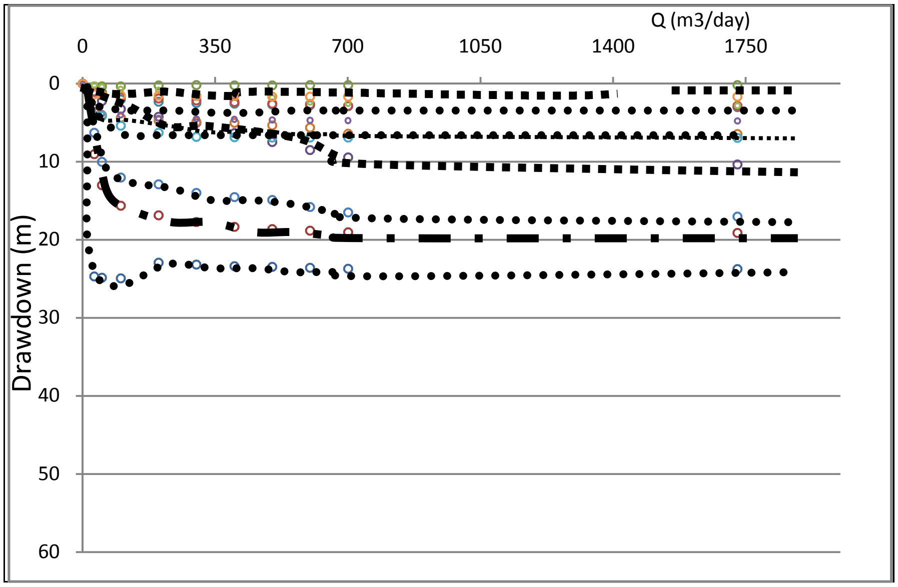
Under these conditions, the linear analytical relationship of equation (2) T vs. (Q/s) is not valid anymore and transmissivity cannot be evaluated in a simple way. When drawdown in the well is aggravated by turbulent head losses and using again the Jacob Eq. (4), the expression of T becomes:

T=1/2∏ ((Q/s)-C_tQ) In (R/r) ------------------5

The simple linear analytical expression of equation (2) of T vs. Q/s is considerably altered. In addition, Razack and Huntley (1991), Huntley et al. (1992) and Fetter (1994) have shown that using relationship (2a) tends to under predict transmissivity each time turbulent head loss (coefficient C_t, above) cannot be neglected. Accordingly, before using these relations, it is recommended to proceed to the head loss analysis.

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). Generally, laminar head loss coefficients B in Tarmaber Guessa basalts aquifer system are higher than those in the Tarmaber Megezez basalt aquifers. These aquifers provide better yields.



Graph-5 Discharge Verses Draw Down -Typical Step Draw Down test curve for the Tarmaber Basalts

Table-3-Turbulent well loss coefficient (C) (m5/day2) determined by step drawdown tests

Aquifer	Min.	Max.	Average
Tarmaber Guessa	9E-04	914	407
Tarmaber Megeze	1E-05	9	4.5

Table 4:- Laminar Head Loss Coefficient B (m3/day) determined by Step Draw Down tests

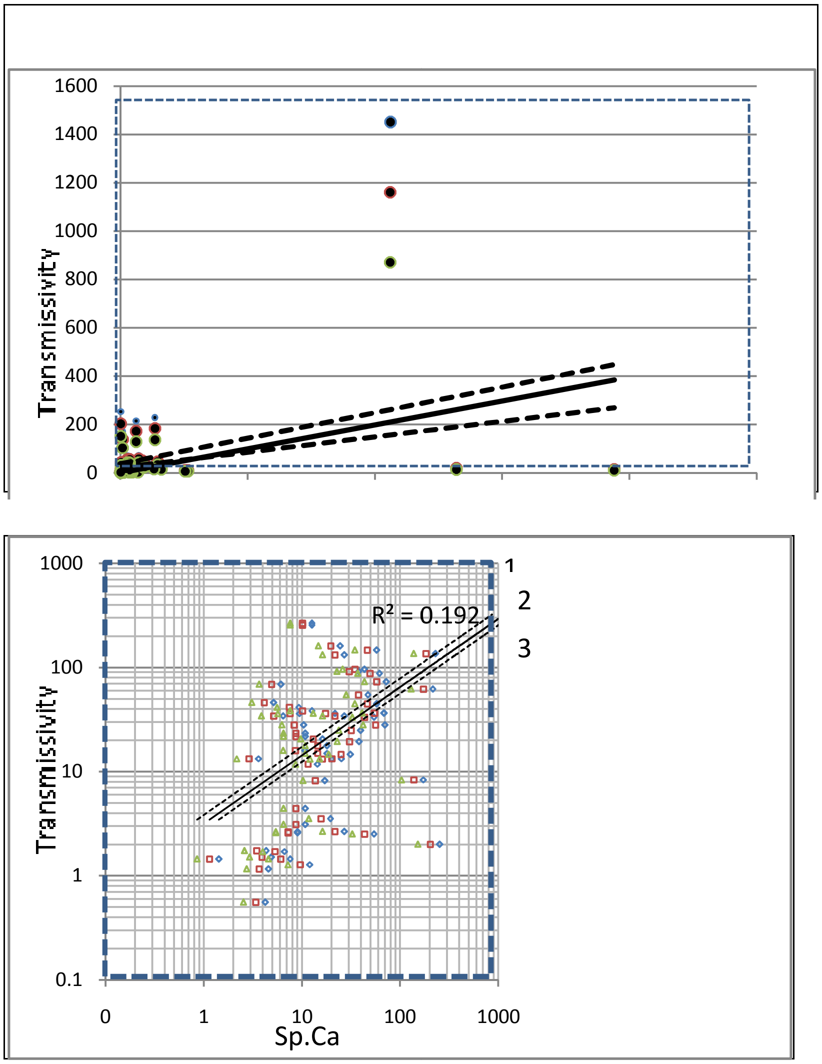
Aquifer L	Min.	Max.	Average
Tarmaber Guessa	.002	0.324	.163
Tarmaber Megezez	.012	.133	.073

Tabel-5-shows the turbulent head losses expressed in percentages as compared to total drawdown in the boreholes, the turbulent losses (C_tQ^2) are quite significant and can thus deteriorate considerably the simple analytical relationship between T & Q/S.

Aquifer	Min. CQ2/s*100	Max. CQ2/s*100	Average CQ2/s*100
Tarmaber Guessa	0	58	10.70
Tarmaber Megezez	0	82.92	41.46

4.4.1.2 Estimation of Transmissivity from Specific Capacity Using Theoretical Methods

An arithmetic plot of Transmissivity versus Specific Capacity (Graph5—A) shows a substantial dispersion of the data and a very poor determination coefficient ($R^2 = 0.192$). Theoretical relations proposed by Thomasson et al (1960) have been plotted on this diagram. It is seen very clearly on this plot, that these theoretical relations tend in most cases to under predict transmissivity. The log-log plot (Graph.5A & B) shows that in most cases the theoretical values are under predicted by more than one order of magnitude (i.e. by more than 1.2 log cycle). Such significant deviation between observed and theoretical data of transmissivity can be explained by the importance of the turbulent head loss highlighted 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.



Graph 6-A, B Plot of Transmissivity (m2/day) versus Specific Capacity (Q/S, m2/day) with theoretical relations superimposed

A- Arithmetic plot, B- 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

Because of such a contradiction between theoretical predictions and observed data, the search of transmissivity estimates was directed towards empirical relationships. The studies on empirical relationships between T and Q/s are rather numerous in the literature (Hurr 1966, Eagon and Johe 1972; Razack and Huntley 1991; Huntley et al. 1992; Fetter 1994; El Naqa 1994; Fabbri 1997). Some authors (Razack and Huntley 1991; Huntley et al. 1992; 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. However, as stated by Mace (1997), indirect estimates of well loss can be very uncertain and can greatly affect transmissivity estimates.

Once the Transmissivity and specific capacity corrected for well loss pairs are compiled, 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

$\hat{Y} = B0 + B1Xi$----------------- (1), where$\hat{Y}$, is log transformed transmissivity, where in the present case, $\hat{Y}i$ = log (Ti) and Xi = log (Sc), where Sc, is log transformed specific capacity.

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

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

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

B0 = Y(mean) – x(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)

So that, 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 = $\sum(\hat{Y}\text{-}yi)^2$

For this study, constant yield and step drawdown test data's from 27bhs (19bhs from Tarmaber Guessa and the other 8 bhs from Tarmaber Megezez) formation were collected which conducted constant rate and step drawdown tests tapping the Tarmaber 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 substantially reduce the uncertainty on the estimates of transmissivity.

Table-6-specific capacity not corrected for turbulence head loss

Aquifer	Minimum	Maximum	Mean
Tarmaber Guessa	1.24	152	19
Tarmaber Megezez	2	173	46.5

Table – 7- Specific capacity (Q/s) corrected for turbulent head loss

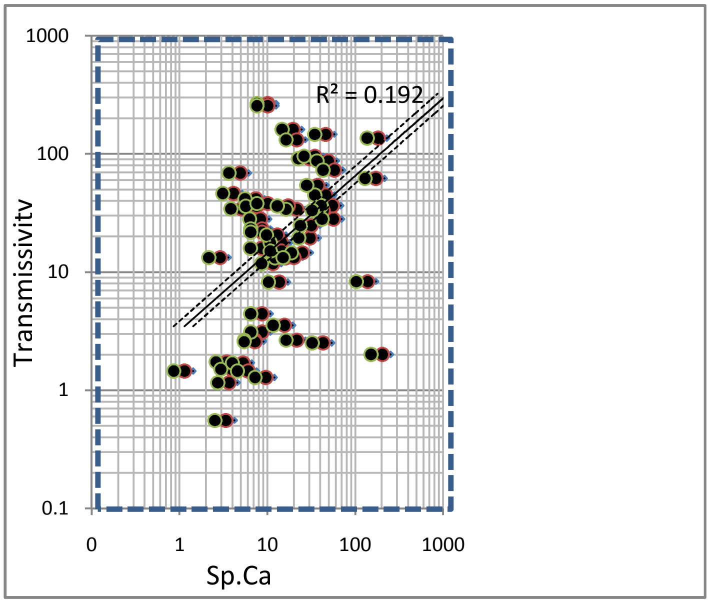
Aquifer	Min.	Max.	Mean
Tarmaber Guessa formation	24	28	16
Tarmaber Megezez formation	17.28	71	42

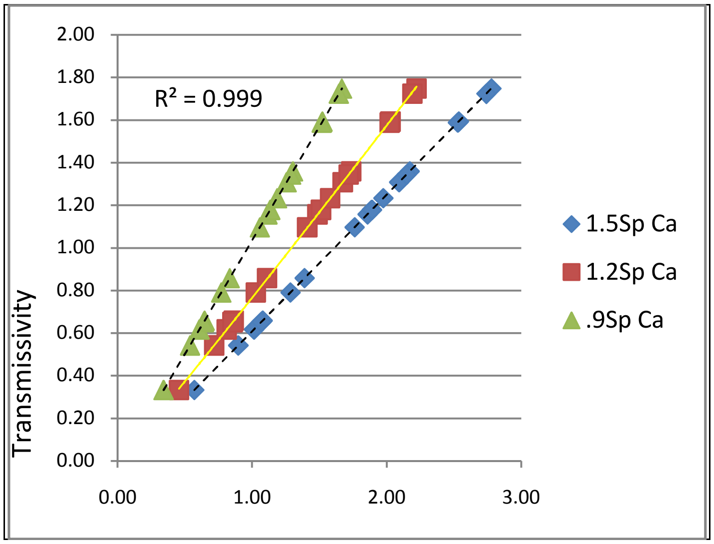
The search for empirical relationships between transmissivity and specific capacity focused on using directly a log-log plot which conforms to the lognormal character of both variables, widely accepted in the literature (Aboufirassi and Marino 1984). The best-fit line is reported together with the 95%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

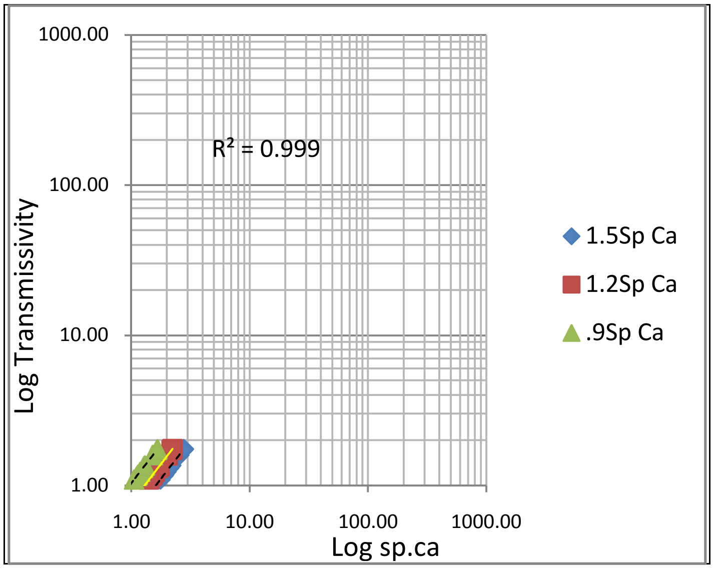
$Interval = Y_i \neq t_{\alpha/2} S_{yz} \sqrt{} (1+1/n+ (x_i - (x_{mean}))^2/\sum (x_i-(x_{mean}))^2$ ------- (1)

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 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. 6A. The plot displays significant scatter and the determination coefficient remains rather low (R^2 =.192). The 95% prediction interval spans 1.2 log cycles indicating that, for a given value of uncorrected specific capacity, the range of predicted values of transmissivity is quite large and of 1.2 order of magnitude. This leads to a similarly large uncertainty for the estimates of transmissivity.







Graph-7A, B & C – Tarmaber Aquifer Specific Capacity (m2/day) vs T (m2/day)

- A- T vs uncorrected Q/s in log log
- B- T vs Q/S corrected for turbulent head loss in linear plot (T (m2/day from Constant Test)
- C- T vs Q/S corrected for turbulent head loss in log log plot (T(m2/day from constant Test)
- D- Solid yellow Lines- are best fit lines
- E- Dashed lines – are 95% prediction interval

Correcting specific capacity for turbulent head loss markedly improves the relationship between transmissivity and specific capacity (Fig. 6B & C). The determination coefficient is a much higher (R^2 =.999)and the 95% prediction interval spans much less than 1 log cycle, thus significantly reducing the uncertainty on the estimates of transmissivity. The best-fit line to these data is:

T = 12Q/S) $^{.96}$--------------- (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. Subsequently, the relationship of equation (7), where transmissiviy values is used from constant yield test results are used to supplement the database concerning the transmissivity of the Ethiopian Tarmaber basalt aquifers in wells where transmissivity had not been evaluated but where corrected specific capacity was available. Summary statistics of the whole transmissivity database are given in Table 7 below.

Table 8- Variation of Transmissivity values in the two basaltic formations

Description	T(m2/day) from constant rate Pumping test	T(m2/day) from corrected Sp.Ca
A-Tarmaber Guessa formation		
Minimum	0.413	27.8
Maximum	1320	679
Mean	97	167
B-Tarmaber Megezez formation		
Minimum	3.1	185
Maximum	1940	718

Mean	**105**	**434**

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 100m depth), intermediate depth (100m to 200m) and deeper depth (greater than 200m). Based on these categories, the Tarmaber basalts have mean specific capacity index that varies from 1.5m/day for the shallow wells, 1.1m/day for the intermediate depth wells and 0.29m/day for the deeper drilled wells. The mean specific capacity of the Younger Tarmaber Megezez basalt is 0.55m/day and the mean specific capcity of the relatively older Tarmaber Guessa basalt is 0.06m/day which implies the decrease of aquifer productivity of the Tarmaber formations with increasing age of the formation. The specific capacity index value also shows a decreasing trend with increasing boreholes drilled depth which indirectly implies that, shallow to intermediate depth Tarmaber basalts have a better aquifer productivity than the deeply buried Tarmaber basalts. Therefore, the specific capacity index verses Boreholes depth relationship of the Tarmaber basalts directly agrees with the decrease of the Tarmaber basalts transmissivity as boreholes depth increases.

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 Tarmaber 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 (See Graph-3B). 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 Tarmaber 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 radial and 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 assume 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.

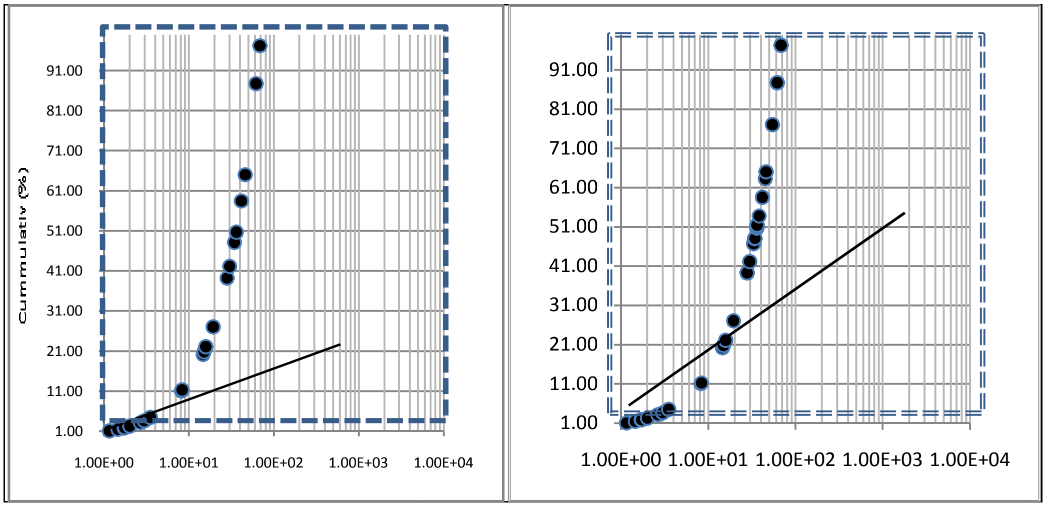
The analysis of the Tarmaber basalts step drawdown tests clearly show that, the wells have lower well efficiency and higher well loss coefficient values which directly reflect the effect of:

- 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

5.3 Transmissivity of Tarmaber Formations

Summary statistics of transmissivity values for each aquifer are provided in Tables 2 & 8. In addition, the frequency distributions of transmissivity data in a log-probability diagram are plotted for aquifers where data are sufficient (Graph. 10A & B). Minimum and maximum values indicate that transmissivity spans around two orders of magnitude. The variation coefficient is quite large and exceeds 100%. This important scatter in the transmissivity data is related to the strong Heterogeneity characterizing the two Tarmaber basalt aquifers.

A comparison of the statistics (Table 2 & 8) reveals that Tarmaber Megezez basalt (16-13Ma) shows better aquifer productivity than that of the Tarmaber Guessa basalt (26-16Ma). The effects of weathering and hydrothermal processes and other volcanic activities decrease aquifer transmissivity, whereas effects of fracturing, faulting and other tectonic activities increase aquifer permeability and productivity. The simultaneous occurrence of these effects in geological time explains to some extent the differences in hydrodynamic characteristics between more recent basalts and older basalts. These deductions are consistent with well cuttings and field observations. Hydrothermal activity, which results in calcite and silica partly or completely clogging fissures and pores, is to be linked to the presence of volcanic and tectonic activities within the main deformational zones. Therefore, the same geological unit may undergo different hydrothermal effects, considering its outcrop location with respect to the main deformational area. Moreover, intrusive dykes linked to the major tectonic trends are frequently observed through the alignments of volcanic cones on recent volcanic series or as eroded dyke structures in old volcanic formations. The exploration wells located on dykes or within the dyke system area have found that they are characterized by low to very low transmissivity, and therefore increase the heterogeneity of aquifers.

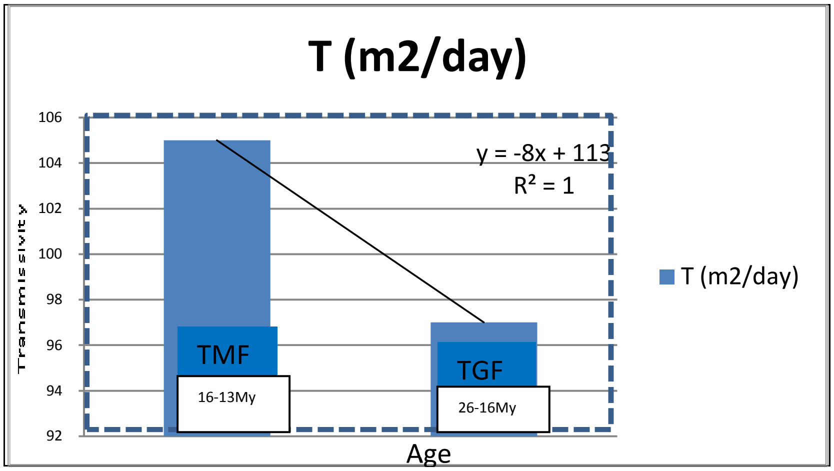


Graph-8- Transmissivity Verses Cumulative Frequency %

5.4 Transmissivity Variation within the Tarmaber Formations

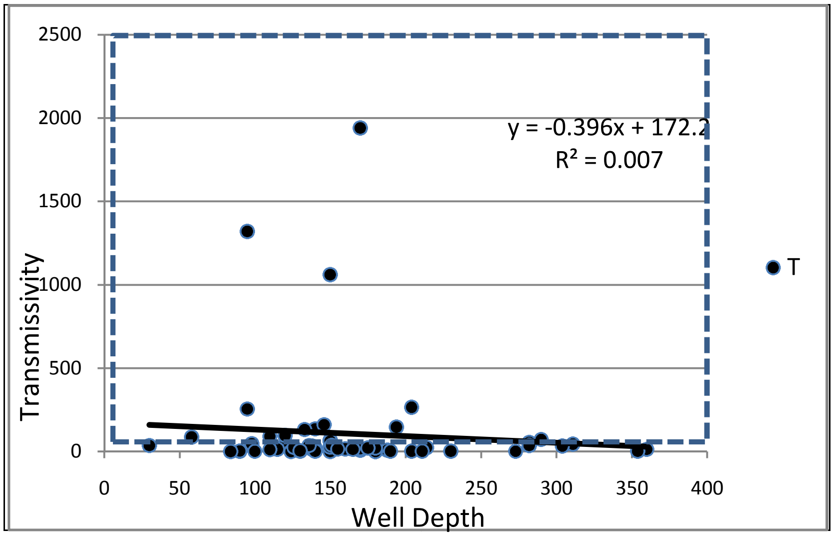
The plot of the representative step drawdown tests, Drawdown verses Discharge rate, clearly shows that there is an increase of well drawdown with increasing variable pumping discharge rate which directly correlates with the decrease of Tarmaber basalts aquifer productivity with drilled boreholes depth and yet 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 mean transmissivity value of each aquifer has been plotted against its outcropping duration (Fig. 9). Analysis of this diagram describes fairly well the decrease in transmissivity during the geological time. The older the basaltic formation, the lower its transmissivity. As described previously, weathering and other surface & subsurface effects, volcanic and tectonic activities and the location of geological units in relation to active tectonic zones might explain these changes in transmissivity. Weathering and volcanic activity decreases transmissivity while fracturing, faulting and other tectonic activitiy increases transmissivity. 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.

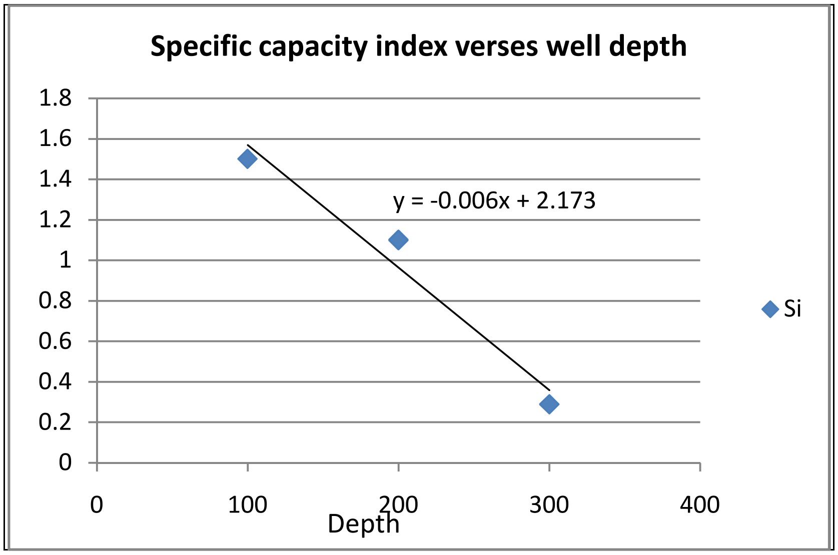


Graph-9- Transmissivity (m2/Day) verses outcropping time in Million years (Myrs)

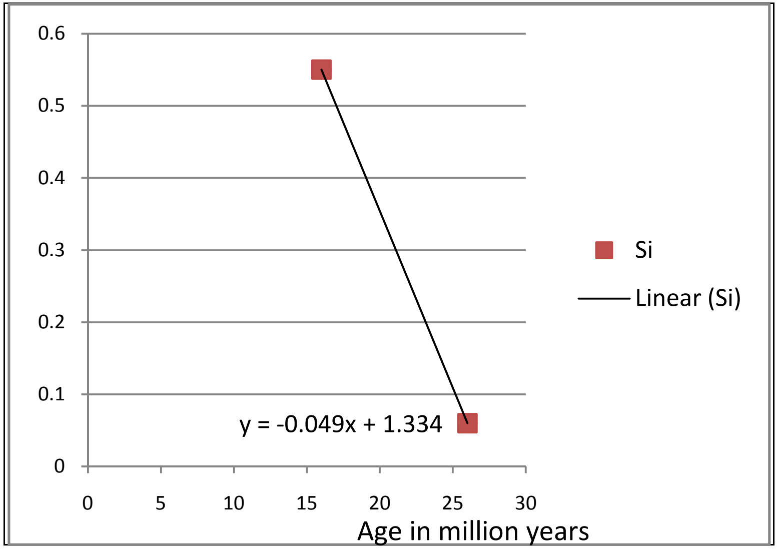
Note- **TMF** – Tarmaber Megezez Formation
TGF – Tarmaber Guessa Formation
Ma – Million Years



Graph-10- Transmissivity Verses Well Depth’s



Graph-11 –Specific Capacity index (**Si**) verses Boreholes depth



Graph-12- Specific capacity index (Si) verses Formation age

Yet again, the Tarmaber formations have mean specific capacity index (Si) that varies from 1.5m/day for the shallow depth wells (<100m depth), 1.1m/day for the intermediate depth wells (100m-200m) and .029 m/day for the deeper wells (>200m). At the same time, the mean specific capacity index for the Tarmaber Megezez is .55m/day and for that of the relatively older Tarmaber Guessa is .06m/day, so both relations justify the decrease of Tarmaber formations aquifer productivity with increased well depth and age of the formations.

5.2 Spatial Variations in Aquifer Characteristics of the Tarmaber Formations

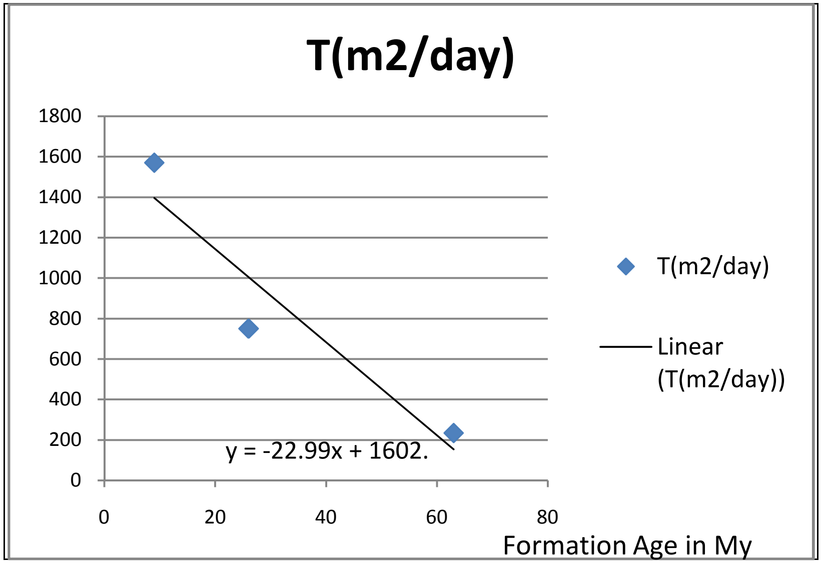
The Tarmaber Basalts in Ethiopia have an extensive surface outcrop aerial extent with spatial distribution pattern throughout the country. They outcrop as cliff and ridge forming highland plateaus, flat lying plain, rugged terrain with peaks and deep gorges and intermountain basins. At places, their paleo morphological set up make difficult to explore and further develop the groundwater resource associated within the formation. The Tarmaber shield volcanoes become progressively younger to southeast and western direction of the northwestern Ethiopian plateau. Hence, the Tarmber formations aquifer productivity tends to increase towards the younging direction of the formations. The rift ward increased aquifer productivity of the Tarmaber formations could be justified by the fact that effect of intense weathering and hydrothermal processes, and other volcanic activities results in a decrease aquifer productivity, on the other hand, intense effect of fracturing and faulting, and other tectonic activities results in increased aquifer permeability and productivity. Along with their extensive surface aerial extent, they are considered as potential water bearing formations and when they form ridges and mountains, they act as main recharging zones, and when they form plains and valleys, they act as main discharging zones. Their groundwater occurrence, localizations and movement is highly controlled by:

- 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

The massive plateau forming Tarmaber basalts have generally low productivity; however, their aquifer productivity shows an increasing regional trend from the central massive plateau to west, northwest direction towards the Lake Tana basin and southeast and southwest direction towards the rift margin.

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

Recent fractured volcanic series basalts have a higher transmissivity than older series. These idea is proved by comparing the Transmissivity values of the Tarmaber basalts of Ethiopia which have an age of about (13-26Ma) with that of the Younger Dalha (3.4-9Ma),(), volcanic rock of Djibouti and with that of the older Deccan (64Ma) volcanic rock of India, where the transmissivity values show a decreasing trend from the younger Dalha volcanic rock (1570m^2/day, Moumtaz Razack,2004), the Tarmaber basalts (750m^2/day and to that of the Deccan volcanic rock (234m^2/day, Robert E.Mace,2000)



Graph-13- Tarmaber formation Transmissivity as compared to Dalha and Deccan formations transmissivity

5.6 Cost Implication for Groundwater Resource Developments

Results of the step drawdown data analysis shows that the collected wells have high aquifer and well loss coefficients, which suggesting 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. Sustainable well function is highly shortened due to the effect of the above factors and caused abandonment of potential well sites and at the same time incurs additional cost investment to rehabilitate the wells because high well and aquifer loss values obscure the true potential productivity behaviors of aquifers.

Evaluation of the relationship of computed transmissivity verse specific capacity and specific capacity verses aquifer thickness (i.e. specific capacity index verses wells depth) values reveals that, within the Tarmaber formations, shallow to intermediate depth productive wells which are drilled within the younger Tarmaber Megezez formation has higher aquifer productivity than the deeply drilled wells which occur under similar geologic environments. Therefore, under similar geologic environment of the Tarmaber formations, drilling of multiple shallow to intermediate depth wells within the Tarmaber formations has more aquifer productive, economical cost and require applicable drilling skills than deep wells which have low aquifer productivity and require high cost and complex drilling technical skills.

6. Conclusions & Recommandations

The analyses of the data from pumping tests conducted in the Tarmaber basalts have shown the following:

- Measured transmissivity data collected on the formation aquifers range between low (T=.413m2 /day) and high (T=1320 m2/day) and mean of (T=97m2/day) in Tramber Guessa and low (T=3.1m2/day and high (T=1940m2/day) and mean of (T= 105m2/day), showing that these formations are quite heterogeneous.

- Measured transmissivity values of the Tarmaber volcanic aquifers have been supplemented using an empirical relationship between transmissivity (T, m /day) and specific capacity (Q/s, m /day). Noteworthy results of the analysis of transmissivity and specific capacity in the volcanic aquifers are listed below:

    - The theoretical relationships between T and Q/s (Thomasson et al. 1960) do not agree with the measured values of T. These theoretical relationships tend to underestimate the transmissivity of the volcanic aquifers by more than one order of magnitude.
    - Analytical solutions assume 100% efficient wells and do not take into account turbulent well loss. The turbulent head loss in wells completed in volcanic rocks was calculated using step drawdown tests. These abnormal head losses are quite important. They represent in fact 21.39–82.92% of the total head decline in the wells are the cause of the inadequacy of the analytical solutions. Accordingly, it is better to search for empirical relationships between transmissivity and specific capacity.
    - The lognormal character of transmissivity and specific capacity (Aboufirassi and Marino 1984) suggests that a linear regression model is more appropriate to the logs of both variable values rather than the original values. Log-log regression between transmissivity and uncorrected specific capacity for turbulent head loss has a determination coefficient R^2 of 0.192. The 95% prediction interval spans 1.2 log cycles. These results indicate that the uncertainties of the transmissivity estimates using uncorrected specific capacity values are quite large.
    - The values of specific capacity have been corrected for turbulent head loss. The logarithm regression between transmissivity and corrected specific capacity values has a determination coefficient of $R^2 = 0.999$. The 95% prediction interval now spans much less than one log cycles. These results indicate that correcting specific capacity for turbulent head loss markedly improves the empirical relationships between transmissivity and specific capacity. The potential error in the predicted transmissivity is however not negligible. As the entire range of transmissivity spans three log cycles, the estimation of transmissivity provided by specific capacity remains nevertheless quite useful.

  - The best fit regression equation for the Tramaber basalts aquifer is $T=12(Q/s)^{.96}$ where T (m^2/day) is estimated transmissivity and (Q/S) is corrected specific capacity in (m^3/m/day).

- The plot of the average transmissivity values of the Tarmaber volcanic aquifers according to their respective ages of outcropping points out the following:
  - All the Tarmaber basalts aquifer transmissivity decreases with increase depth of the drilled boreholes and age of the formation, and yet the drawdown of the bore holes increase with increased variable pumping discharge rates. In agreement with this, results of the relationship of specific capacity index verses well's depth justify the decrease of Tarmaber formations aquifer productivity with increased well depth and increased formation ages.
  - Recent fractured volcanic series basalts have a higher transmissivity than older series. These idea is proved by comparing the Transmissivity values of the Tarmaber basalts of Ethiopia which have an age that ranges from 13-26My with that of the Younger Dalha (3.4-9Ma) volcanic rock of Djibouti and with that of the older Deccan (64Ma) volcanic rock of India, where the transmissivity values show a decreasing trend from the younger Dalha volcanic rock (1570m2/day), the Tarmaber basalts (750m2/day and to that of the Deccan volcanic rock (<234m2/day).
  - The transmissivity of older series has decreased during geological time, due to weathering effects, hydrothermal processes and other volcanic activities.
  - The decrease in transmissivity is believed to have taken place in a short geological time period.
  - The appearance of new faults and the reactivation of existing fault systems have maintained a certain degree of permeability in the old volcanic series but did not completely compensate for the effects of the first factors (weathering and volcanic activities).
  - At present, a fair amount of knowledge regarding these aquifers is available. Their Hydraulic properties can be assessed with acceptable accuracy. Further tasks are in progress, focusing on the development of numerical models for the groundwater resources management of these aquifers.

Finally this study highlights the regional hydro geological behavior of the Tarmaber basalts in Ethiopia and the data analysis results can be considered only as first hand information's about the formation about the formation hydro geological behaviors', however,

- For proper interpretation and analyses of well pump test data's and to accurately evaluate and understand the true physical conditions and hydraulic properties of an aquifer system, in addition to constant rate pumping test data's, a step drawdown test data's is a must.
- One cannot discuss issues of regional scale aquifer development and management without taking about simulation models that are now the core of most basin-wide assessments. What has made aquifer simulation model indispensible for groundwater studies is the power to integrate the complexity of hydrogeological settings, hydrogeology processes and water utilization.
- Long term regional hydro geological investigation using primary data of mapping wells which have spatial distribution pattern with respect to the surface outcrop pattern of the formation has to be done.

The numer, spac and location of mapping wells should target to identify: surface paleo morphological set up of the formation, degree of surface geological processes the formation had undergone and effect of associated structural features, boundary conditions and recharge and discharge mechanisms of the formation. Besides, in order to properly characterize the aquifer behaviors' of the Tarmaber formations, the following tasks has to be done in advance;

- Nature, orientation, extent and inter relationship of the associated structural features has to be identified and mapped.
- Architectural stratigraphic relationship of the Tarmaber basalts with the overlying and underlying other formations has to be identified and mapped.
- Based on the out puts of the regional investigation, local scale very detailed hydro geological investigations on selected highland plateaus and basins has be launched.

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APPENDIXES

APPENDIXE – A LIST OF TABLES
APPENDIX E –B LIST OF GRAPHS
APPENDIXE – C LIST OF CURVES

TGF Boreholes’ Constant Rate Pump Test Data Analysis Results

	Borehole							Test	Discharge	Draw		Analysis Results			Aquifer	Analysis
No.	Name	x	y	Depth	Source	Code	SWL	Hrs	M3/day	Down	DWL	T	K	S	Type	Method
1	Addis Zemenbh3	367561	1340932	_	M0W	TGFBH1	5	32.6	345.6	78.2	83.2	1.71	0.057	1.28E-03	confined unsteady	Hantush
2	Adet bh2	334033	1245738	_	M0W	TGFBH2	0.4	Step drawdown test								
3	Amanuealbh4	342715	1155332	100	M0W	TGFBH3	34.63	24	199	39.12	73.15	3	0.1	3.10E-04	Confined unsteady	Thiess
4	Amed berbh1	367262	1340932	58	M0W	TGFBH4	1.3	16	950	23.15	25.15	87.5	0.292	5.33E-03	confined unsteady	Thiesis
5	Azezo bh1	332421	1386604	150	M0W	TGFBH5	3.24	6	337	48.51	51.75	28	0.048	3.52E-04	leaky unsteady	Thiesis
6	Azezobh2	327398	1385123	150	M0W	TGFBH6	4.85	72	425	104.15	109	68.7	0.114	1.11E-09	confined unsteady	Thiesis
7	Azezobh3	326028	1389119	98	M0W	TGFBH7	12.2	52	259.2	75.5	87.7	46.1	0.154	1.40E-08	confined unsteady	Thiesis
8	Azezo mest bh1	328645	1387931	110	M0W	TGFBH8	13	16	605	24	37	91.2	0.154	3.11E-03	confined steady	Thiesis
9	Bechenabh2	411267	1156231	120	M0W	TGFBH9	2.73	48	121	28.28	31.01	34.2	0.0572	5.55E-05	confined unsteady	Thiesis
10	Bechenabh4	411250	1156221	120	M0W	TGFBH10	11.98	24	259.2	41.88	53.86	41.5	0.0692	3.30E-05	confined unsteady	Thiesis
11	Gorgorabh2	313079	1355600	110	M0W	TGFBH11	0.75	Step drawdown test								
12	Debretaworbh1	393329	1305500	150	M0W	TGFBH12	8.4	14.3	259.2	92.04	100.4	0.556	0.0093	2.22E-03	confined unsteady	Thiesis
13	Debretaworbh7	393665	1311708	140	M0W	TGFBH13	63.7	24.3	380	14.93	78.63	19.4	0.324	3.61E-04	confined unsteady	Thiesis
14	Gassay bh1	407974	1178083	124	M0W	TGFBH14	3.6	24	106	85.16	88.76	0.413	0.0069	1.10E-03	confined unsteady	Thiesis
15	Debreworkbh2	407674	1178383	100	M0W	TGFBH15	8.56	Step drawdown test								
16	DM bh 7	407670	1178383	140	M0W	TGFBH16	1.5	35	345.6	43.16	44.66	30	0.043	0.098	confined unsteady	Thiesis
17	DM Bh8	407665	1178380	90	M0W	TGFBH17	1	Step drawdown test				28				
18	Dembechabh1	334333	1170001	95	M0W	TGFBH18	12.95	24	1296	0.08	13.03	132	440	0.259	confined unsteady	Thiesis
19	Debremarkosbh1	356378	1143709	150	M0W	TGFBH19	2.5	72	916	19.53	22.33	28	0.47	0.0163	confined unsteady	Thiesis
20	Debremarkosbh2	352113	1143960	150	AWWCE	TGFBH20	3	44	1296	1.34	4.34	106	18	1.00E-04	confined unsteady	Thiesis
21	Debremarkosbh3	353830	1163944	170	AWWCE	TGFBH21	9	108	1754	15.25	24.25	8.33	1.39	0.341	Leaky steady	Thiesis
22	Debremarkosbh4	356109	1168503	150	AWWCE	TGFBH22	12.2	72	605	4.21	16.41	62	1	0.111	confined unsteady	Thiesis
23	Debremarkosbh5	343838	1150482	140	AWWCE	TGFBH23	8.85	72	864	5.65	14.5	136	2.27	0.0025	confined unsteady	Thiesis
24	Gonderbh1	333444	1393528	115	AWWCE	TGFBH24	3.72	24	259.2	12.45	16.17	14.6	0.244	3.38E-04	confined unsteady	Thiesis
25	Gonderbh2	407665	1178380	120	AWWCE	TGFBH25	1	Step drawdown test								
26	Gonderbh3	333252	1394388	130	AWWCE	TGFBH26	8.6	24	138.24	48.05	56.65	1.74	0.029	6.49E-05	Confined unsteady	Thiesis

27	Gonderbh4	333240	1394288	190	AWWCE	TGFBH27	2	35	302	146.8	148.8	2				
28	Gonderbh5	333235	1394288	70	AWWCE	TGFBH28	1	46	570	3.37	4.37	3				
29	Gonder DB bh5	332105	1393241	188	EAD PLC	TGFBH29	33.52	24	518	45.48	79	8.64E-08	1.44E-09	1.59E-04	confined unsteady	Thiesis with Ja
30	Gonder DB bh6	332296	1392954	230	EAD PLC	TGFBH30	32.52	24	518	146.48	180	2	0.034	1.96E-04	confined unsteady	Thiesis
31	Gonder DB bh7	332009	1393336	188	EAD PLC	TGFBH31	31.45	21	1020	78.48	109.9	8.2	0.137	2.60E-04	confined unsteady	Thiesis
32	Gonder DB bh8	331850	1393799	180	EAD PLC	TGFBH32	13.16	24	130	136.73	149.9	0.246	0.008	6.27E-04	confined unsteady	Thiesis
33	Motabh1	377739	1225382	100	MoW	TGFBH33	2.7	Step drawdown test								
34	Motabh4	377141	1224184	90	MoW	TGFBH34	3.39	24	388.8	54.31	57.7	3.53	0.118	3.05E-03	confined unsteady	Thiesis
35	Nefas Mewchabh1	432633	1287908	180	MoW	TGFBH35	2.39	18	121	39.7	42.7	1.45	0.0241	3.19E-04	confined unsteady	Thiesis
36	Nefas Mewchabh2	430203	1295687	160	MoW	TGFBH36	4.21	24	388	21.47	25.68	15.9	0.266	3.34E-04	confined unsteady	Thiesis
37	Nefas Mewchabh3	445952	1295491	175	MoW	TGFBH37	2.75	Step drawdown test								
38	Nefas Mewchabh4	447563	1296243	180	MoW	TGFBH38	2	24	259	35.29	37.29	1.16	0.0193	0.0139	confined unsteady	Thiesis
39	Nefas Mewchabh5	443590	1294632	190	MoW	TGFBH39	19	64	259	41.2	60.2	2.66	0.0443	5.60E-03	confined unsteady	Thiesis
40	Agtabh1(Tsedabh1)	343912	1256514	84	MoW	TGFBH40	3.65	15.2	237.6	74.35	78	0.516	0.0172	3.27E-03	confined unsteady	Thiesis
41	Felege Birhan	396765	1188313	30	MoW	TGFBH41	3.4	24	294	6.85	8.55	36	2.4	8.00E-05	confined unsteady	Thiesis
42	Gish Abay	304397	1215503	100	MoW	TGFBH42	1.5	Step drawdown test								
43	Chuihait bh2	290464	1354833	100	MoW	TGFBH43	3.72	24	259	12.45	16.17	15	0.5	3.07E-04	confined unsteady	Thiess
44	Debremarkos bh6	356370	1143709	106	Saba Eng.	TGFBH44	16.58	72	1720	3.44		0.008	0.0004	1.88E+00	confined unsteady	Thiess
45	Debremarkos bh9	356372	1143709	150	Saba Eng.	TGFBH45	18.2	72	1724	13.95		0.02	0.0005	9.00E-06	confined unsteady	Thiess
46	Debremarkos bh10	356374	1143709	100	Saba Eng.	TGFBH46	12.45	72	1720	30.28		0.003	4E-06	6.00E-04	confined unsteady	Thiess
47	Debremarkos bh11	356376	1143709	100	Saba Eng.	TGFBH47	19.67	72	1726	3.27		0.02	0.0005	2.00E-02	confined unsteady	Thiess

TMF Boreholes' Constant Rate Pump Test Data Analysis Results

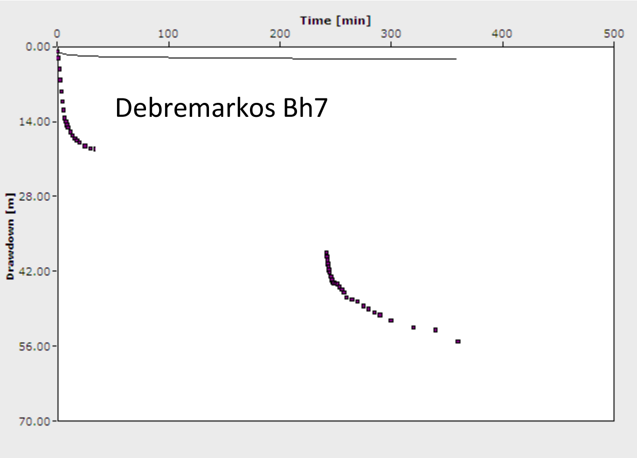
	Borehole	Well Data's						Test	Discharge	Draw		Analysis Results			Aquifer	Analysis
No.	Name	x	y	Depth	Source	Code	SWL	Hrs	M3/day	Down	DWL	T	K	Ss	Type	Method
1	ADBh0272	461185	1084147	311	WWDSE	TMFBH1	8	48	1382	35.88	43.88	44.8	0.498	0.000003	Confined	Theis
2	ADBH0279	482263	1038145	282	WWDSE	TMFBH2	91	72	1123	19.19	110.2	54.5	0.61	0.0188	confined steady	Theis
3	ADBH0362	432432	1024464	194	WWDSE	TMFBH3	7	51	1382	9.87	16.87	147	2.48	0.000181	confined steady	Theis
4	ADBH1153	447549	1007893	282	WWDSE	TMFBH4	11	48	1641	42	53	36.5	0.41	0.00003	confined steady	Theis

5	Alidorobh1	447678	1081008	204	EAD PLC	TMFBH5	56	57	259	59.25	115.3	3.1	0.0344	0.0003	confined steady	Theis
6	Alidorobh2	447936	1080594	214	EAD PLC	TMFBH6	39	24	259	99	138	23.3	0.258	0.00012	confined steady	Theis
7	Inchinibh1	561897	1069503	146	EWWDSE	TMFBH7	81	24	588	3.39	21.49	161	2.7	0.0003	confined steady	Theis
8	AMW6	455620	1026514	273	EWWDSE	TMFBH8	69	37	181	100	169	1.45	0.016	0.000005	confined steady	Theis
9	Ankoberbh1	582208	1064886	204	WWDE	TMFBH9	8	48	302	2.14	92.14	266	2.59	3.00E-09	confined	Theis
10	Borumedabh3	371122	1240948	126	AWWCE	TMFBH10	2.85	48	950	44.65	47.5	24.8	0.413	0.00000957	confined	Theis
11	Chanchobh7	473911	1031930	324	WWDSE	TMFBH11	83	72	518	158.55	241.6	8.64E-08	9.60E-10	1.72E-04	Cnfined steady	Theis
12	Degembh1	459422	1084526	170	EAD PLC	TMFBH12	34	33	432	23	56	17.7	0.295	0.00091	Cnfined steady	Theis
13	DessieMohabh1	568838	1232292	170	WWDE	TMFBH13	13.51	24	432	3.49	17	194	32.4	1.51E-13	Cnfined unsteady	Theis
14	Ejerebh1	446178	1095804	138	EAD PLC	TMFBH14	6.54	24	648	19.24	25.78	34.1	0.568	5.00E-06	Cnfined unsteady	Theis
15	Ejerebh2	446333	1095959	138	EAD PLC	TMFBH15	75	24	483	29.38	104.5	13.2	0.221	2.32E-14	Cnfined unsteady	Theis
16	Ejerebh3	446229	1095649	133	EAD PLC	TMFBH16	13.37	24	648	5.48	18.85	132	2.21	4.00E-06	Cnfined unsteady	Theis
17	Ejerebh4	446643	1095649	211	EAD PLC	TMFBH17	64	24	216	67	131	2.64	0.029	9.00E-06	Cnfined unsteady	Theis
18	Haikbh1	574835	1250432	110	AWWCE	TMFBH18	17.25	24	345	24.31	41.56	11.8	0.197	2.00E-05	confined unsteady	Theis
19	Haikebh2	576064	1249203	151	AWWCE	TMFBH19	25.5	24	302	6.77	32.27	38.2	0.64	5.00E-05	confined unsteady	Theis
20	Kurkurbh1	525021	1187962	95	AWWCE	TMFBH20	34	24	302	1.96	35.96	255	8.49	1.55E-06	confined unsteady	Theis
21	Legedadibh1	510520	1023108	360	AAWSA	TMFBH21	15.1	72	604	42	57.37	13.3	0.2	1.09E-04	confined unsteady	Theis
22	Legedadibh2	515025	1025975	290	AAWSA	TMFBH22	12.1	72	1728	34.55	46.65	72.7	1.1	6.84E-09	confined unsteady	Theis
23	Legedadibh8	510529	1023108	354	WWDSE	TMFBH23	27.75	30	1296	42.68	70.43	2.51	0.03	4.00E-11	confined unsteady	Theis
24	Legedadibh14	515035	1025975	282	WWDSE	TMFBH24	11	48	1641	42	53	36.5	0.41	3.00E-05	confined steady	Theis
25	Sulultabh13	474421	1013070	304	WWDSE	TMFBH25	18	29	1296	49.51	67.11	33.2	0.37	9.00E-07	confined steady	Theis
26	Wurgessabh1	568282	1277875	120	AWWCE	TMFBH26	14.6	24	1036	13.4	28	96	1.59	4.00E-06	confined steady	Theis
27	Chelokobh1	637360	950487	180	WWDE	TMFBH27	36.1	48	389	23.25	59.35	20.5	0.34	7.00E-07	confined steady	Theis
28	Chelokobh2	627360	950487	165	WWDE	TMFBH28	39.45	48	86.4	47.87	87.32	13.3	0.222	3.00E-06	confined unsteady	Theis
29	Chelokobh3	628937	949698	155	WWDE	TMFBH29	50	24	432	5.95	55.95	15	0.245	9.00E-07	confined unsteady	Theis
30	Afdembh1	719366	1047475	140	WWDE	TMFBH30	63.85	10	216	33	96.3	2.58	0.043	2.52E-04	confined unsteady	Theis
31	Afdembh2	719355	1047475	175	WWDE	TMFBH31	56.67	24	259	9.17	65.84	21.7	0.4	1.40E-04	confined unsteady	Theis
32	Tebibh1	43680	1006047	136	WWDE	TMFBH32	2.6	24	518	9	11.8	36.2	0.6	3.14E-04	confined unsteady	Theis
33	Tebibh2	43682	992327	130	WWDE	TMFBH33	4.3	24	259	44	48.33	4.42	0.074	2.36E-05	confined unsteady	Theis
34	Tebibh3	28000	1001735	100	WWDE	TMFBH34	8.77	24	117	50.33	59.1	1.51	0.025	9.25E-05	confined unsteady	Theis

Tarmaber formations Step
Drawdown test Analyses Results

	BH							No. of Steps & Hrs				Step Discharges(m3/day)				Analysis Results			
No.	Name	x	y	Depth	Source	Code	SWL	1	2	3	4	1	2	3	4	B	C	BQ	CQ2
1	Bichena bh4	411250	1156221	120m	MoW	TGFBH10	0.4	3	3	_		95		130	_	0.31	0	107	0
2	Addis Zemen Bh3	367561	1340932		MoW	TGFBH1	5	2.5	2.5	2.5		345	432	518		0.074	9.00E-04	38	-24
3	Azezo Meat Plant	328645	1387931	110m	MoW	TGFBH8	3.18	0.67	0.67	0.67		259	345	432		0.009	3.00E-04	3.9	6
4	Debremarkos Bh7	407670	1178383	140m	MoW	TGFBH16	1.5	12	12	12		47	129	216		0.324	70	-0.001	-47
5	Debremarkos Bh8	407665	1178380	90m	MoW	TGFBH17	1	18	18	18		259	432	604		0.002	1	1.00E-04	3
6	Debrework Bh2	407674	1178383	100m	EAD PLC	TGFBH15	8.56	0.5	0.5	_		345	509		_	0.118	0	60	0
7	Gondor Bh2	407665	1178380	120m	MoW	TGFBH25	1	14	14	_		86	173		_	0.165	4.00E-04	29	1.2
8	Gondor Bh4	333240	1394288	190m	MoW	TGFBH27	2	11	11	11		129	181	302		0.09	0.001	27	91
9	Gondor Bh5	333235	1394288	70m	MoW	TGFBH28	1	15	15	15		172	345	570		0.002	5.00E-05	1	2
10	Chuhait Bh2			100m	MoW	TGFBH43	3.72	0.5	0.5	0.5		129	172	259		0.035	0	9	0
11	Nefas Mewcha Bh2	430203	1295687	160m	MoW	TGFBH37	4.21	0.5	1	1		631	648	691		0.03	1.00E-04	21	-5
12	Felege Birhan Bh1	396765	1188313	30m	MoW	TGFBH41	3.4	2.5	2.5	2.5		86	172	259		0.07	-5.00E-05	50	-26
13	Mota Bh1	377739	1225382	90m	MoW	TGFBH33	3.39	0.5	1	1		146	224	276		0.19	0	52	0
14	Amanuel Bh4	342715	1155332	100m	MoW	TGFBH3	34.63	1	2	2		63	190	259		0.114	0	30	0
15	D/markos bh10	356374	1143709	102	Saba Eng.	TGFBH46	12.65	1	1	1		1720	1722	1725		403	914	13	14
16	Haikbh1	574835	1250432	110	AWWCE	TMFBH18	17.25	1	1	1		172	259	302		0.133	0	40	0
17	Haikbh2	576064	1249203	151	AWWCE	TMFBH19	25.5	1	1	1		172	216	259		0.031	0	8	0
18	Wurgessabh1	568282	1277875	120	AWWCE	TMFBH26	14.6	1	1	1		691	864	1036		0.016	-0.00001	17	-11
19	Legedadi Bh2	515025	1025975	290	AWSA	TMFBH22	8.25	2	2	2	2	1036	1296	1555	1728	0.012	0.000005		
20	Debremarkos Bh3	356370	1025970	150	MoW	TGFBH20	9	2	2	2		250	500	950		0.102	0.00001	96.6	9.6
21	Debremarkos Bh6	356371	1025971	106	MoW	TGFBH21	16.58	2	2	2		200	425	850		0.002	0.00004	1.7	28.9

22	Debremarkos Bh9	356373	1025972	150	MoW	TGFBH22	18.2	1	1	1		516	750	1036		..0003	0.000001	0.311	1.1
23	D/markos bh10	356374	1143709	102	Saba Eng.	TGFBH46	12.65	1	1	1		1720	1722	1725		0.403	0.914	0.13	14
24	Debremarkos Bh11	356376	1143709	106	MoW	TGFBH24	19.67	1	1	1		250	400	750		0.017	0.0000034	12.5	1.9
25	Tebi Bh1	43680	1006047	136	WWDE	TMFBH31	2.6	2	2	2		173	345	518		0.001	0.00001	0.52	2.7
26	Tebi Bh2	43682	992327	130	WWDE	TMFBH32	4.3	2	2	2		86	173	259		0.0001	0.0001	0.026	6.7
27	Tebi Bh3	28000	1001735	100	WWDE	TMFBH33	8.77	2	2	2		43	86	216		0.008	0.00001	1.7	0.47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Drawdown [m]
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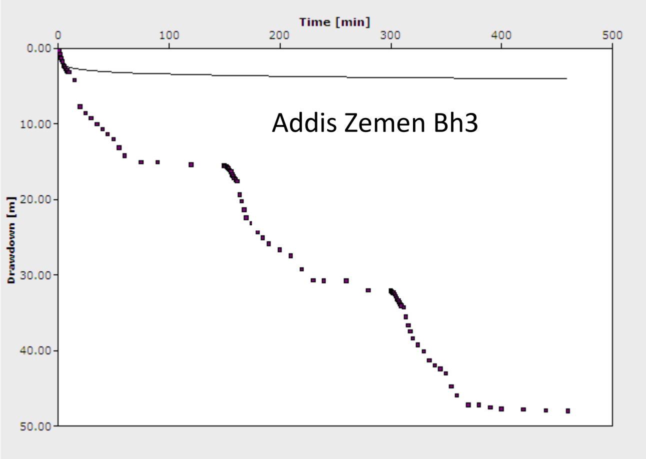
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Drawdown [m]
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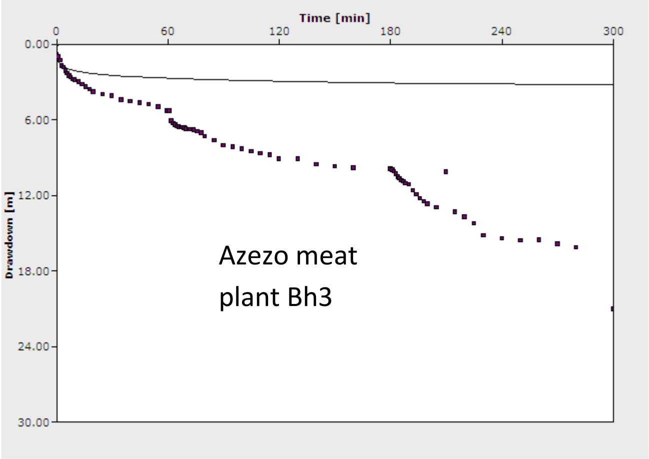
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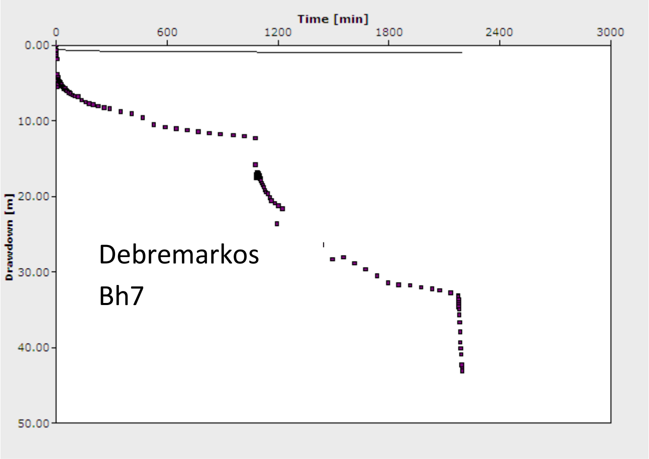
Drawdown [m]
Azezo meat
plant Bh3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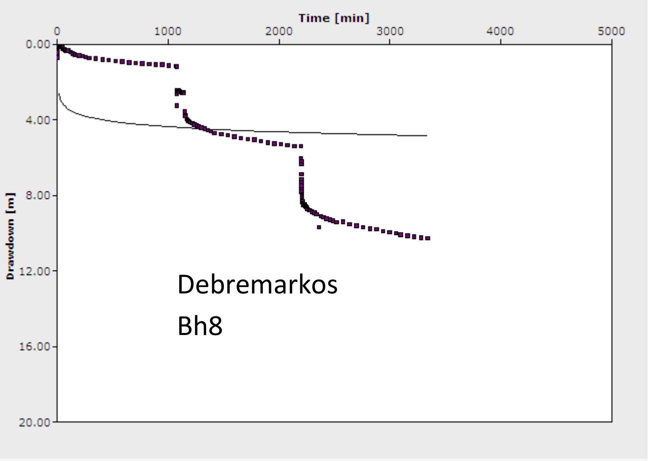
Debremarkos
Bh7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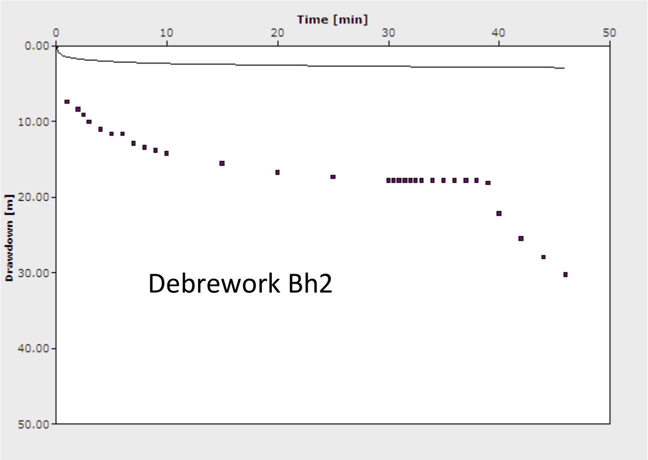
Bh8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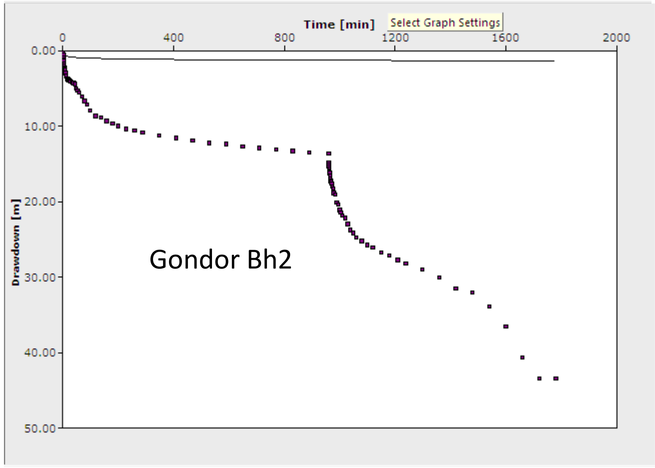
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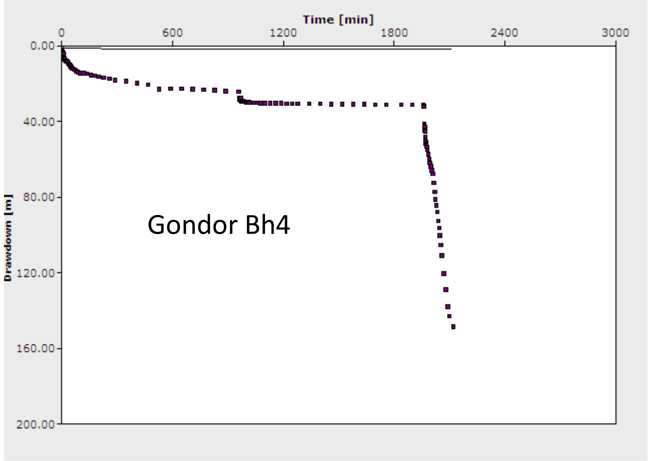
Gondor Bh2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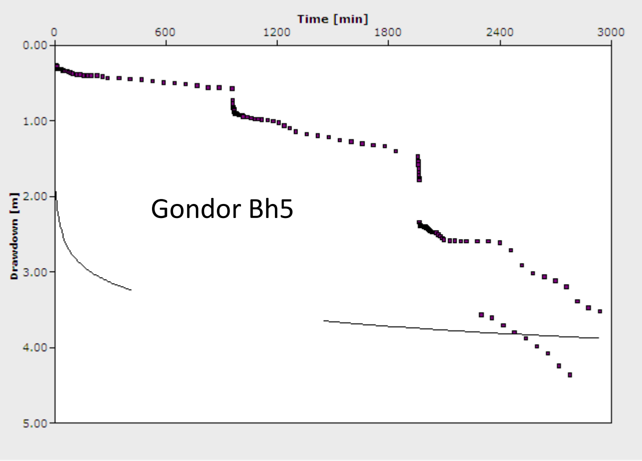
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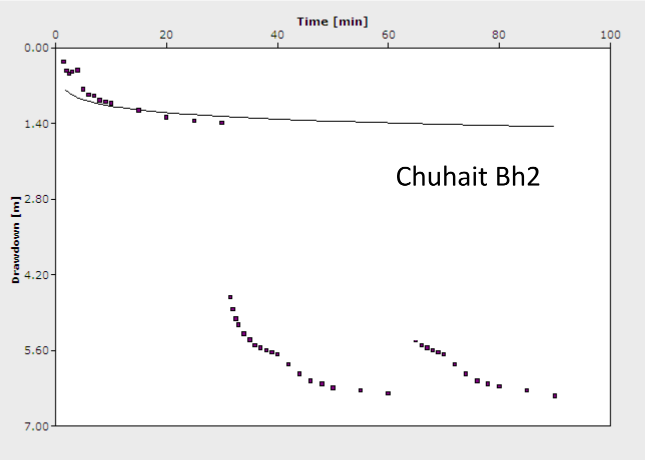
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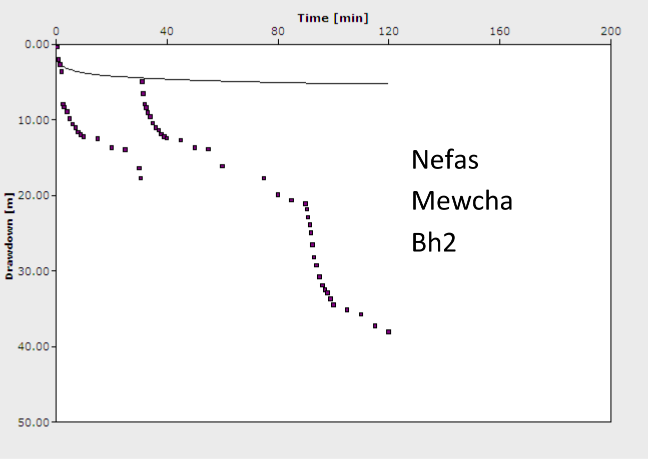
Chuhait Bh2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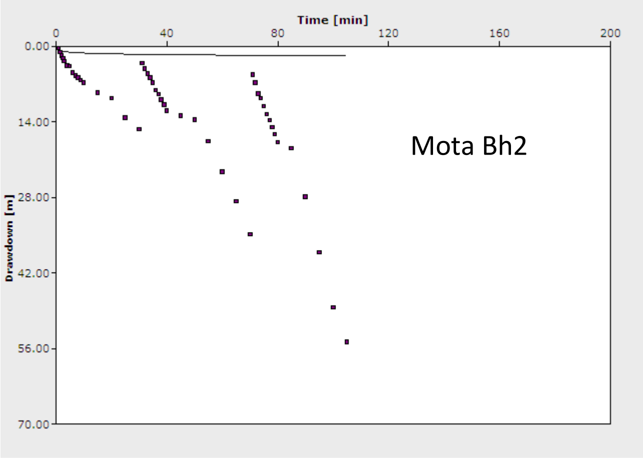
Nefas
Mewcha
Bh2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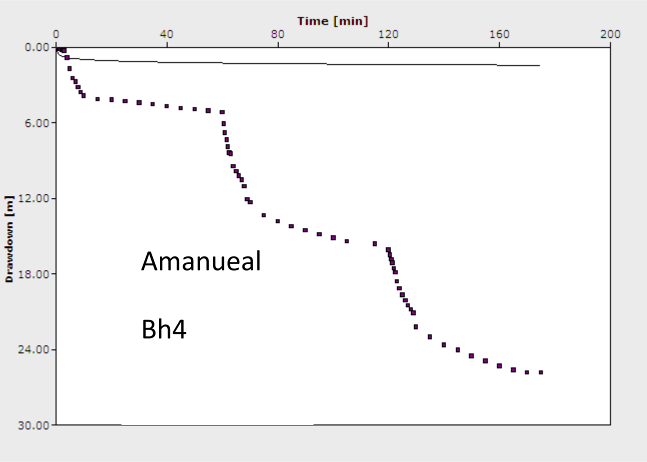
Mota Bh2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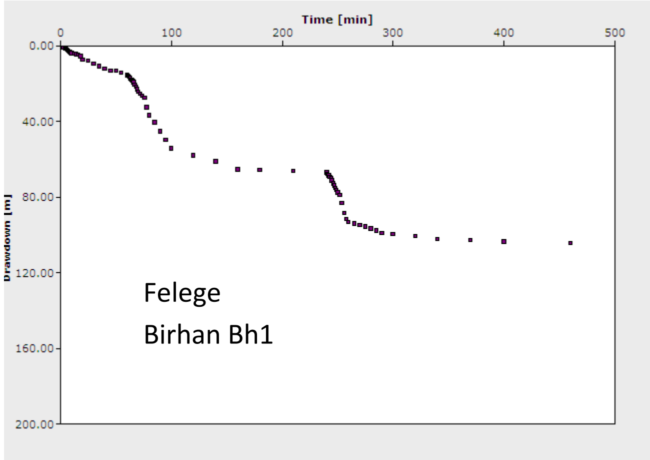
Amanueal
Bh4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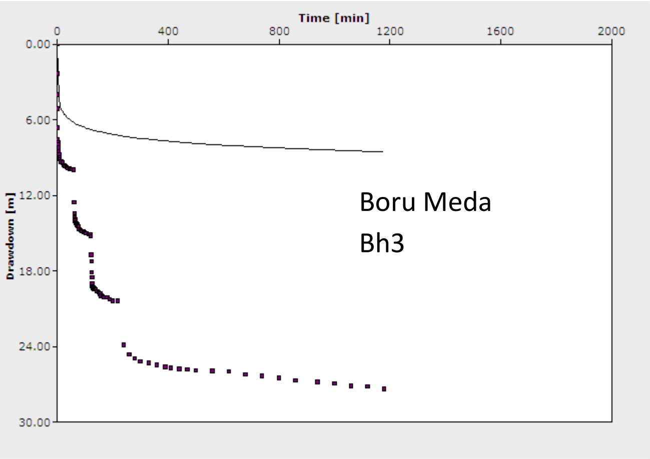
Felege
Birhan Bh1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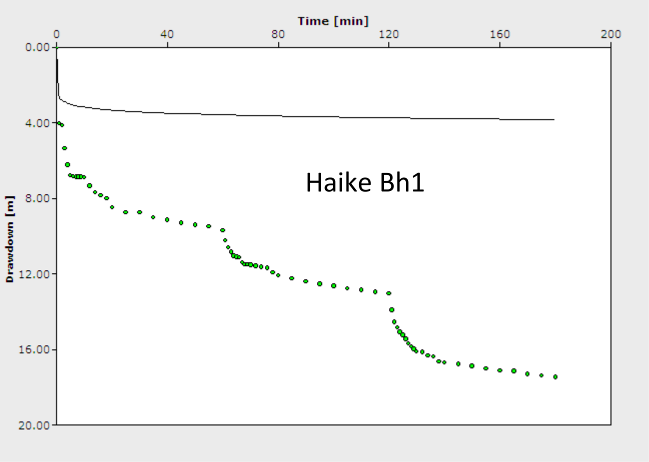
Boru Meda
Bh3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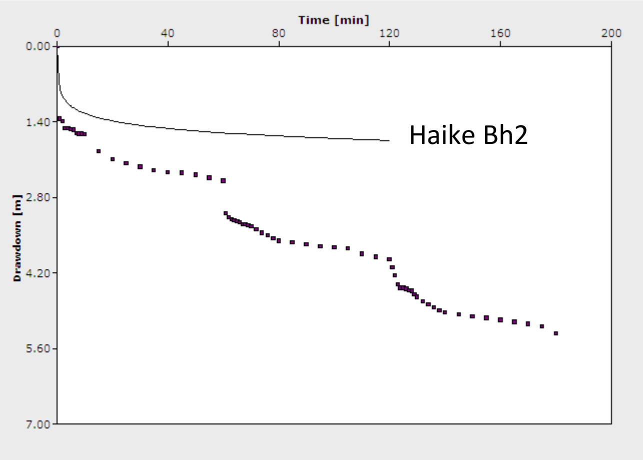
Haike Bh1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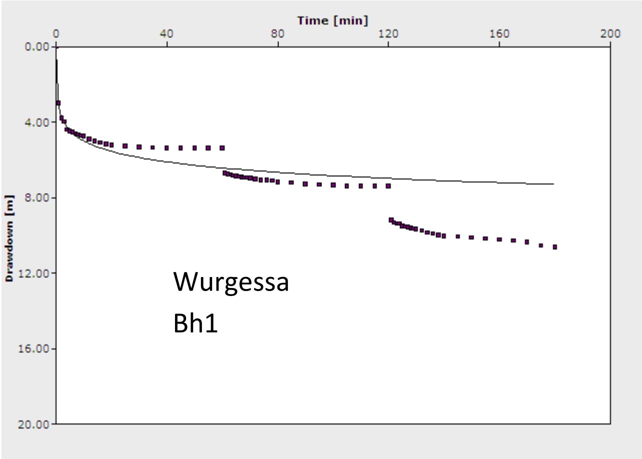
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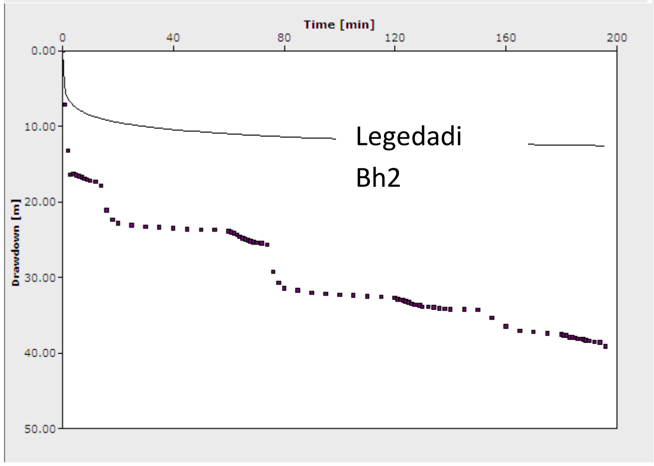
Drawdown [m]
Wurgessa
Bh1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40.00
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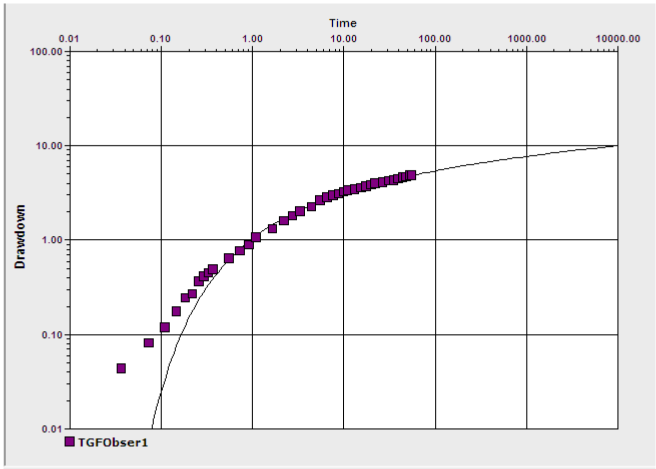
Drawdown [m]
Legedadi
Bh2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Drawdown
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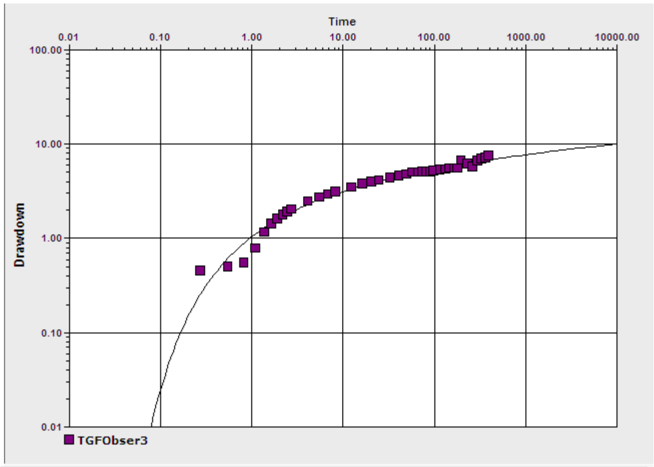
0.01
TGFObser1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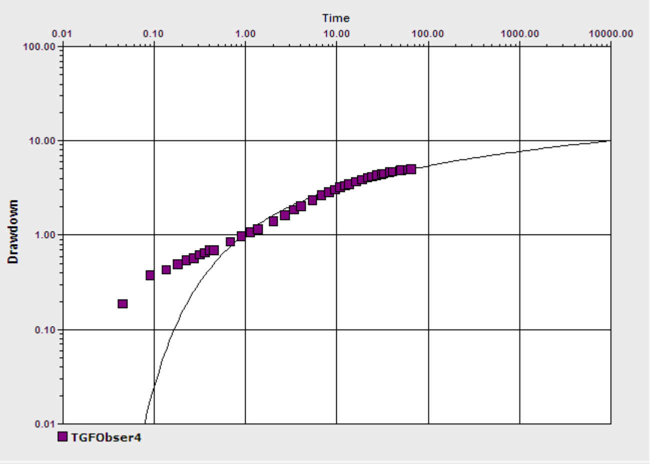
0.01
TGFObser3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Drawdown
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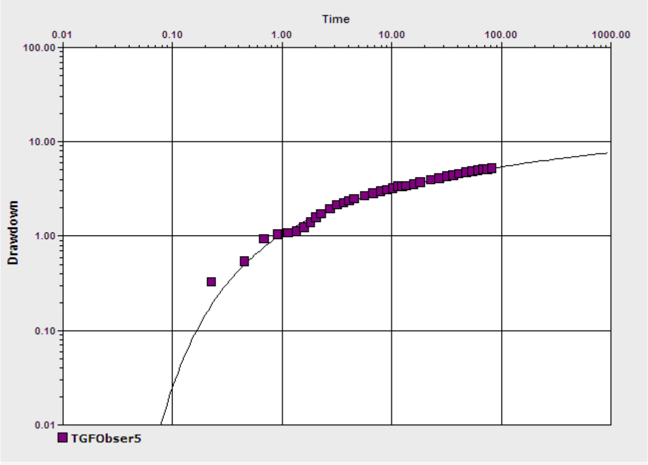
0.01
TGFObser4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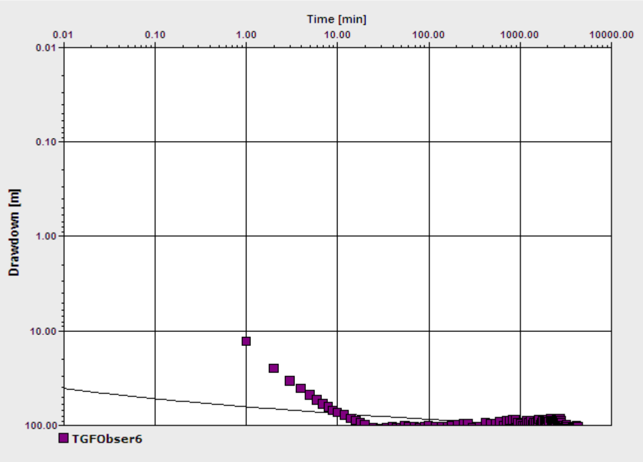
0.01
TGFObser5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1000.00
10000.00
Drawdown [m]
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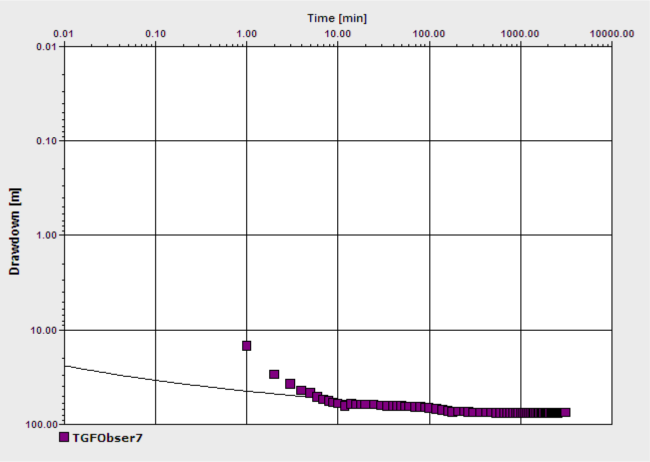
1.00
10.00
100.00
TGFObser6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1000.00
10000.00
Drawdown [m]
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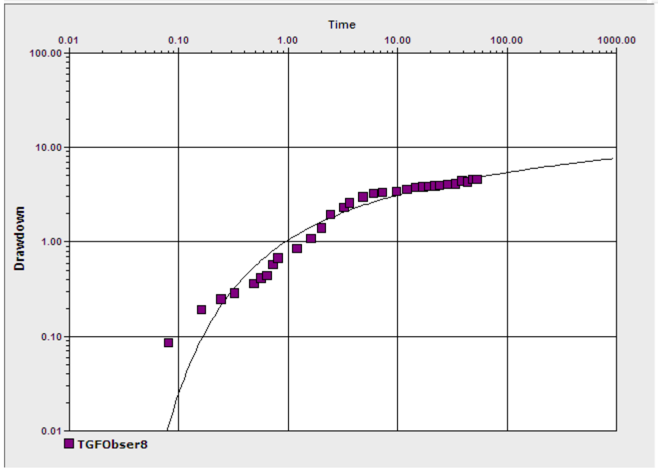
0.10
1.00
10.00
100.00
TGFObser7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1000.00
Drawdown
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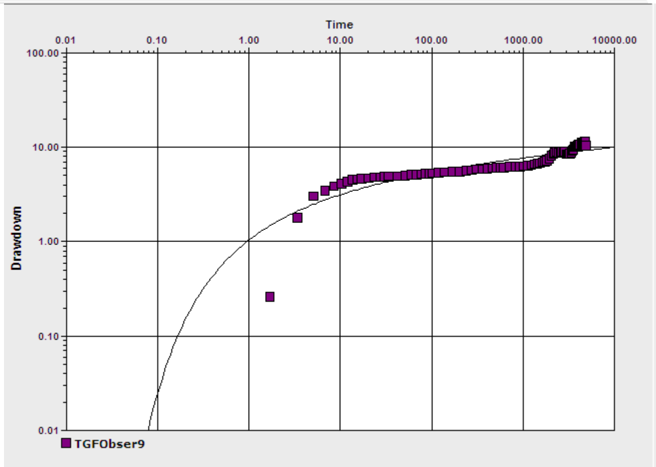
0.01
TGFObser8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Drawdown
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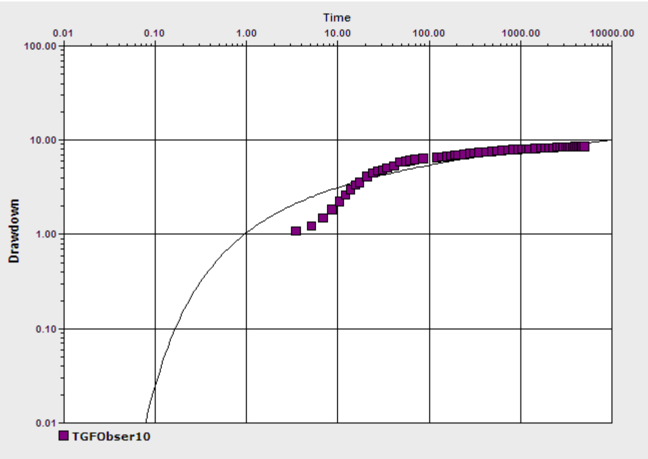
0.01
TGFObser9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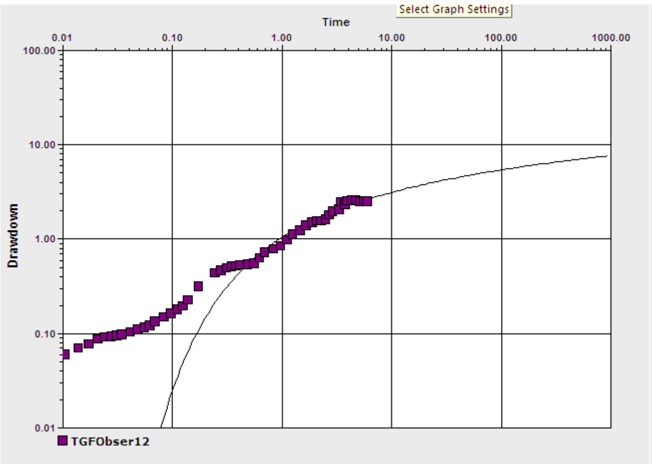
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Drawdown
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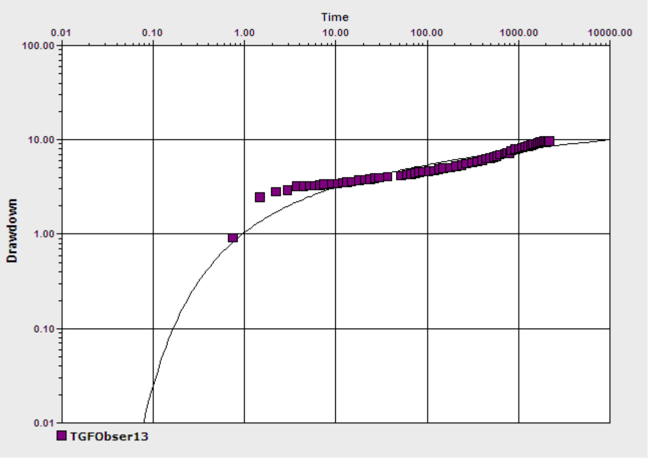
TGFObser12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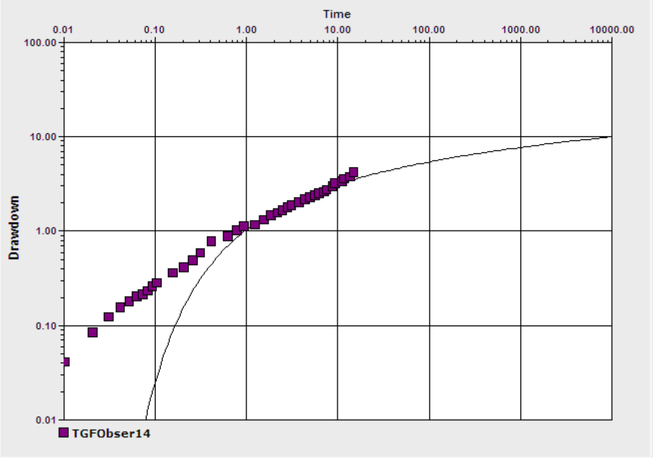
TGFObser13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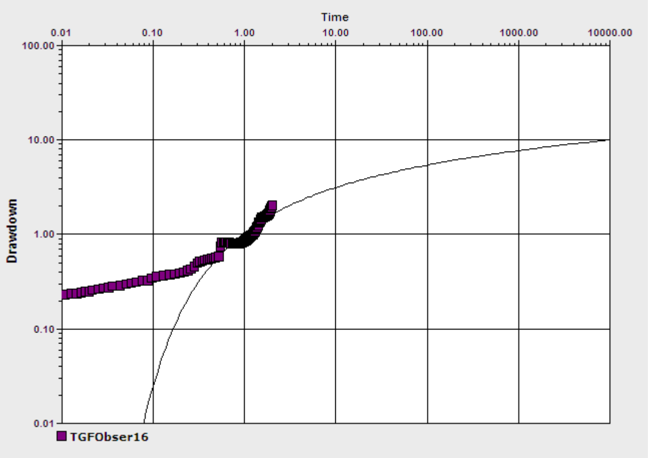
TGFObser14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Drawdown
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1.00
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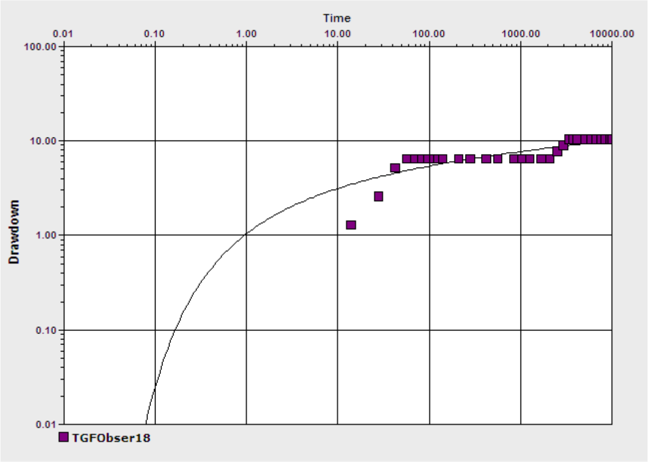
0.01
TGFObser16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1000.00
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Drawdown
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10.00
1.00
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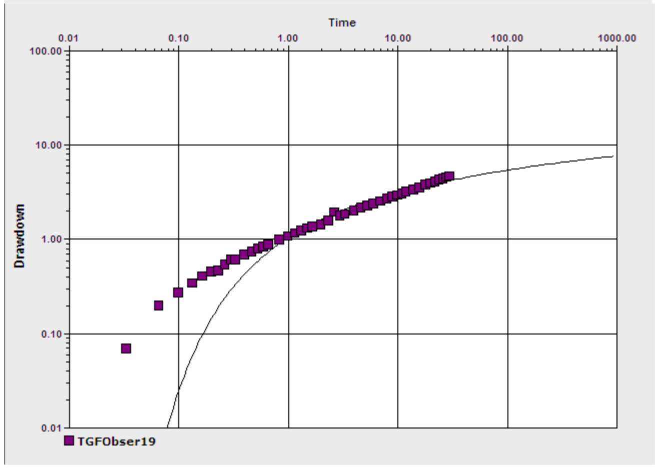
0.01
TGFObser18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Drawdown
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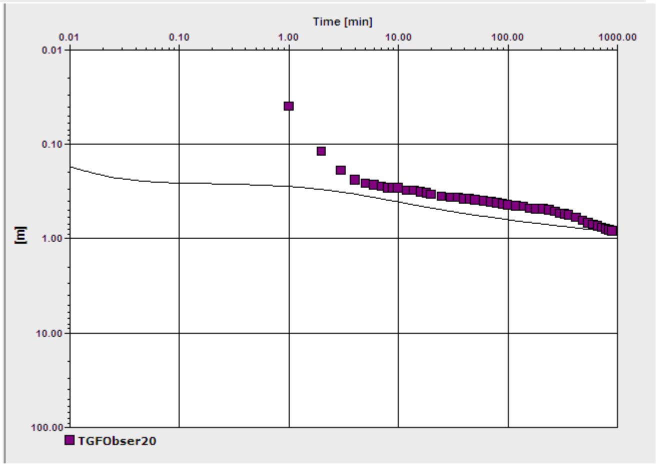
TGFObser19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100.00
1000.00
[m]
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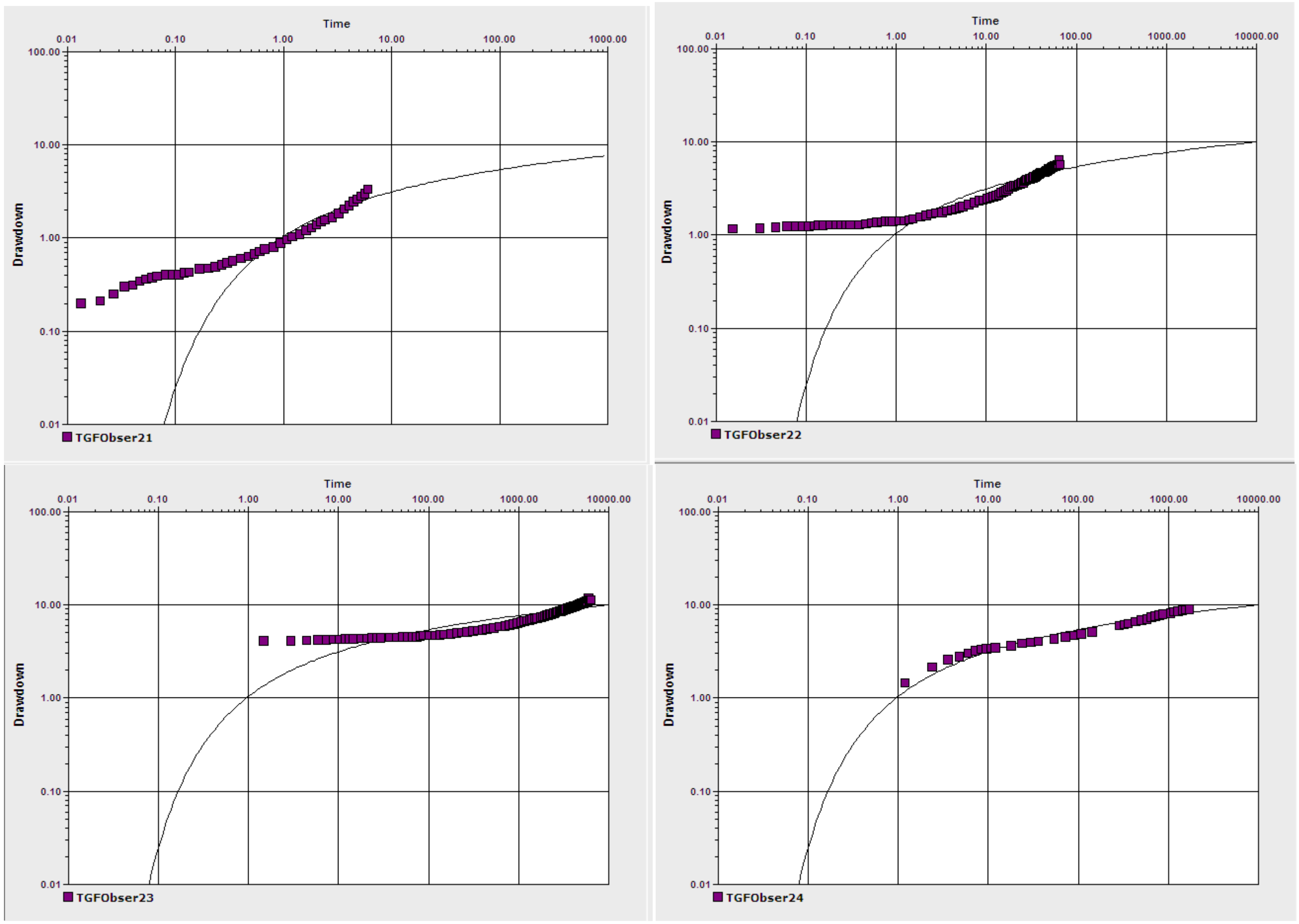
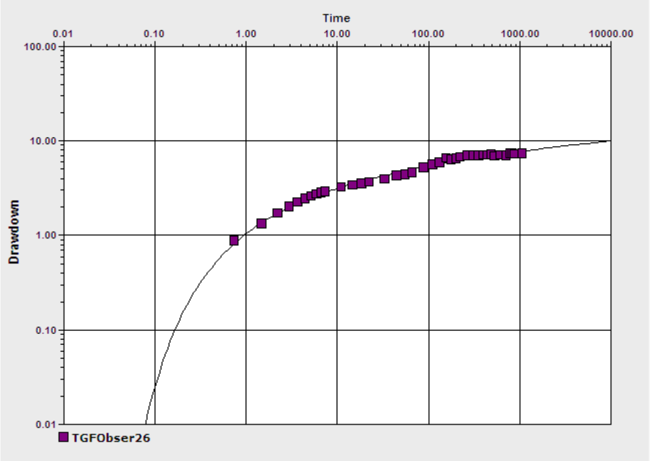
0.10
1.00
10.00
100.00
TGFObser20


Time
0.01
0.10
1.00
10.00
100.00
1000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFObser21
Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFObser22
Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFObser23
Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFObser24


Time
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1000.00
10000.00
Drawdown
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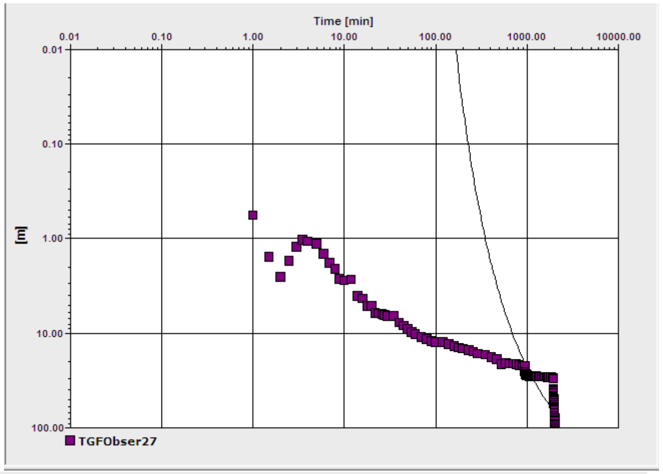
10.00
1.00
0.10
0.01
TGFObser26


Time [min]
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0.10
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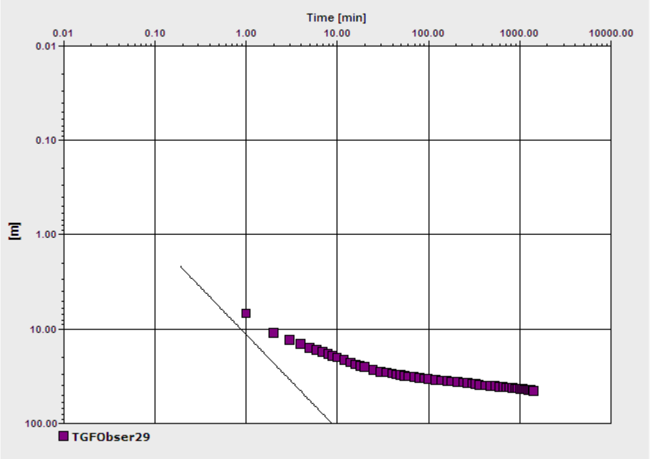
1000.00
10000.00
[m]
0.01
0.10
1.00
10.00
100.00
TGFObser27


Time [min]
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100.00
1000.00
10000.00
[m]
0.01
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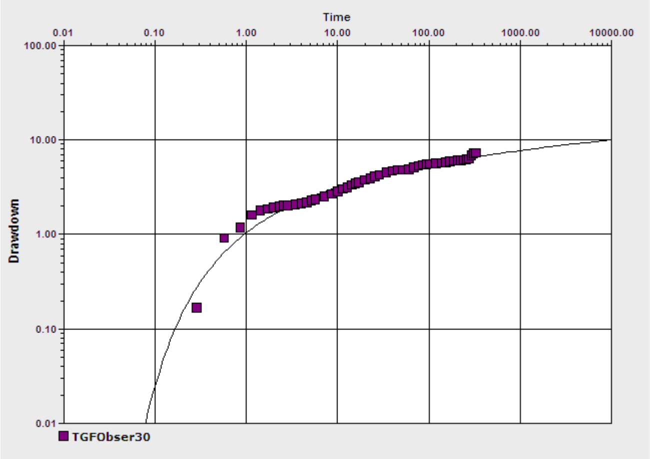
1.00
10.00
100.00
TGFObser29


Time
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1000.00
10000.00
Drawdown
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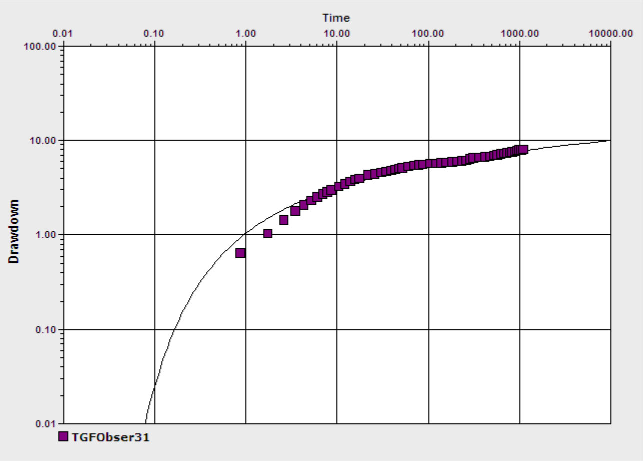
10.00
1.00
0.10
0.01
TGFObser30


Time
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1000.00
10000.00
Drawdown
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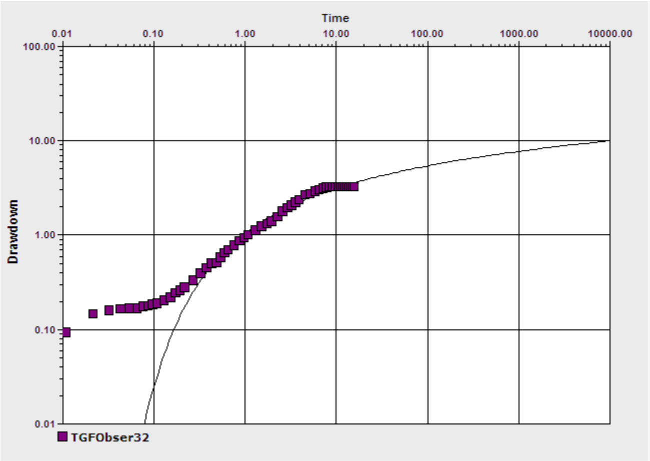
10.00
1.00
0.10
0.01
TGFObser31


Time
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0.10
1.00
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100.00
1000.00
10000.00
Drawdown
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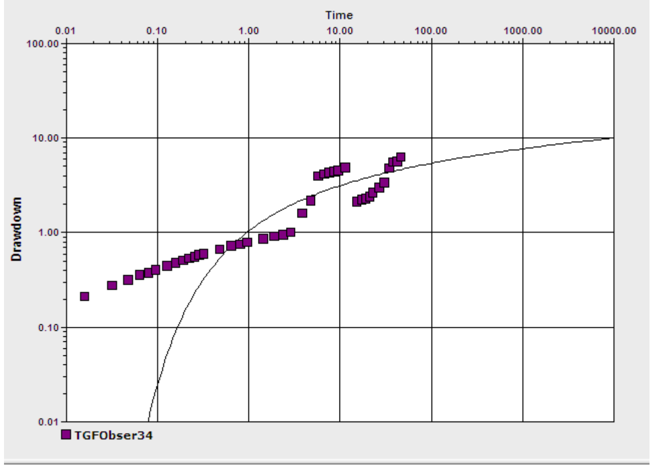
10.00
1.00
0.10
0.01
TGFObser32


Time
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1000.00
10000.00
Drawdown
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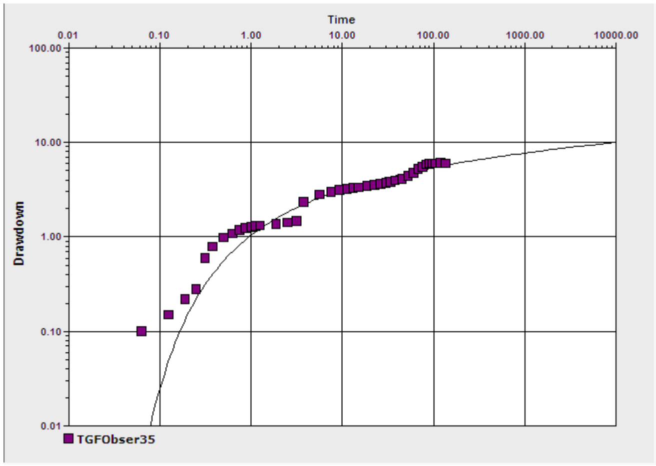
10.00
1.00
0.10
0.01
TGFObser34


Time
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100.00
1000.00
10000.00
Drawdown
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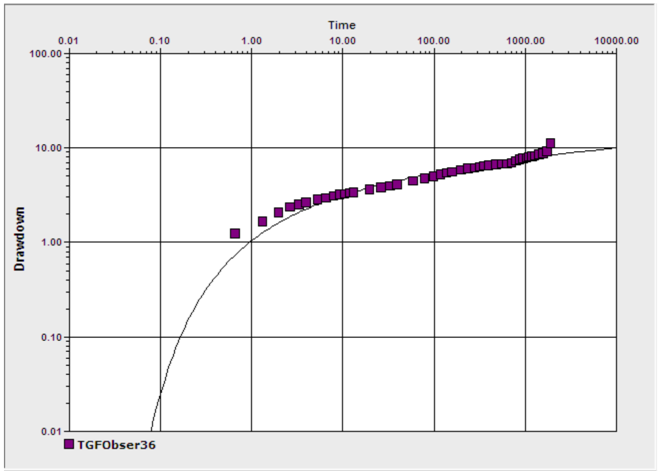
10.00
1.00
0.10
0.01
TGFObser35


Time
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1.00
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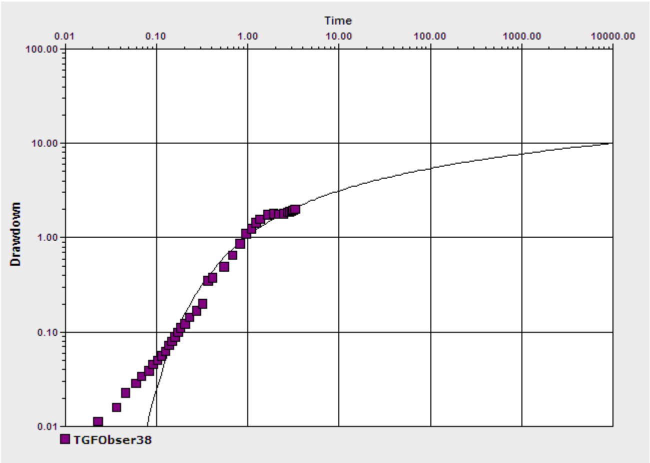
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TGFObser36


Time
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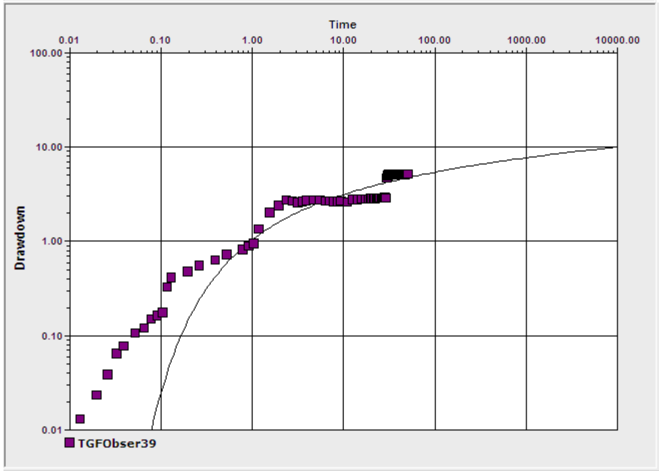
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TGFObser38


Time
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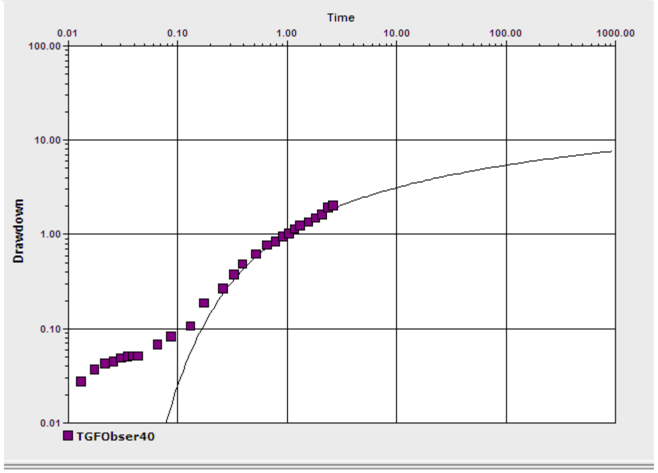
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TGFObser39


Time
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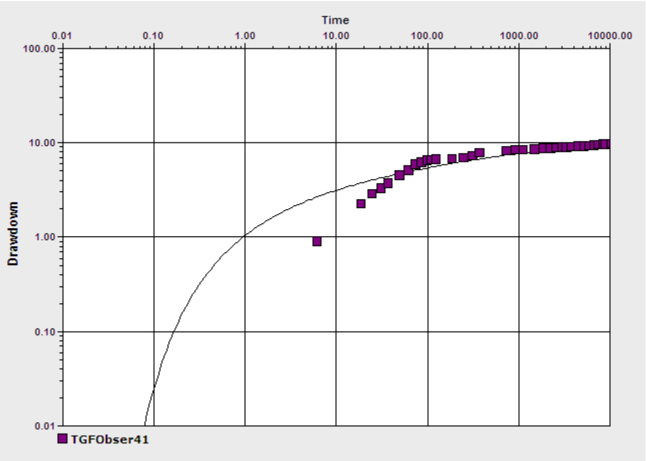
1.00
10.00
100.00
1000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TGFObser40


Time
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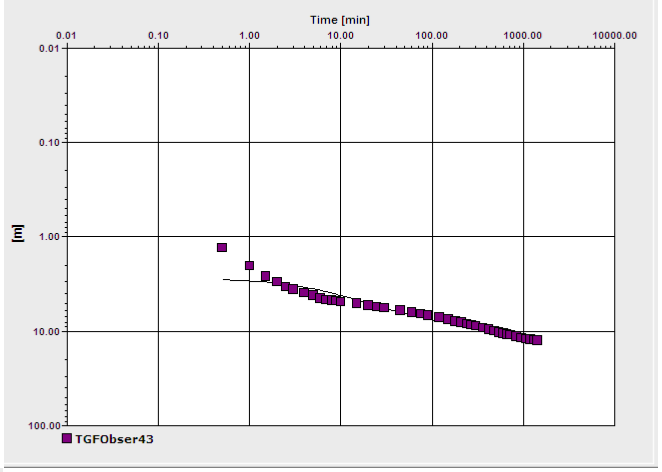
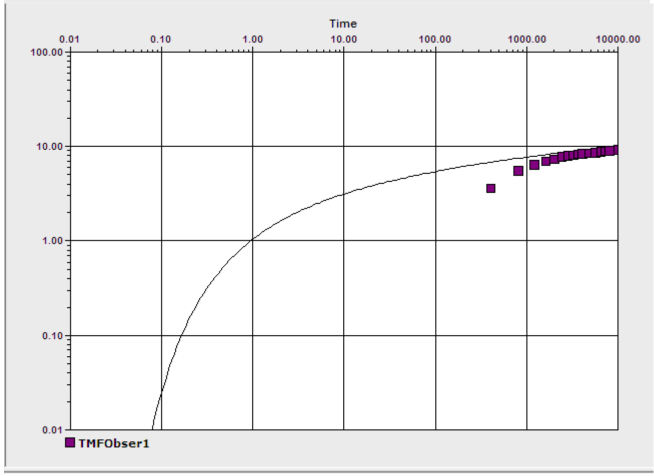
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFObser41


Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
[m]
0.01
0.10
1.00
10.00
100.00
TGFObser43


Time
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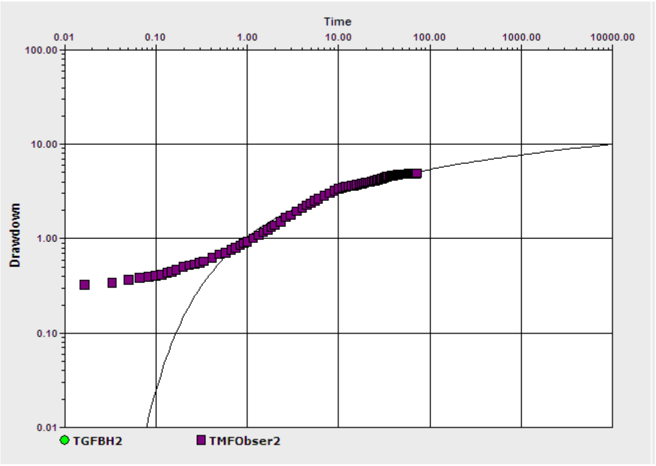
0.10
1.00
10.00
100.00
1000.00
10000.00
100.00
10.00
1.00
0.10
0.01
TMFObser1


Time
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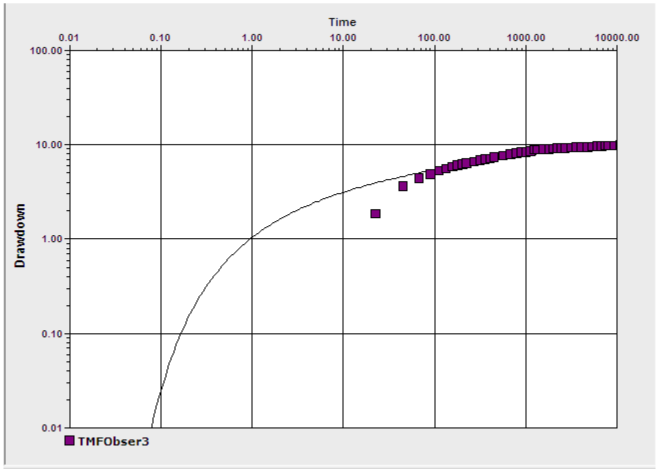
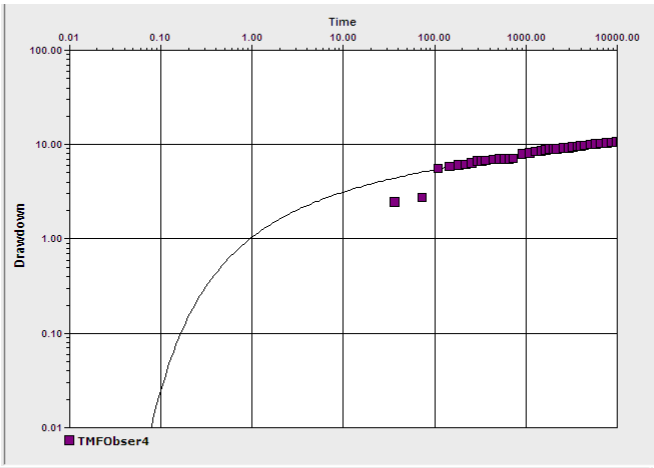
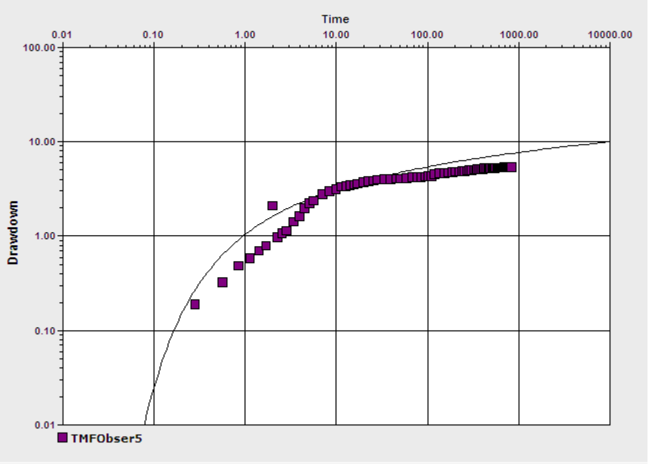
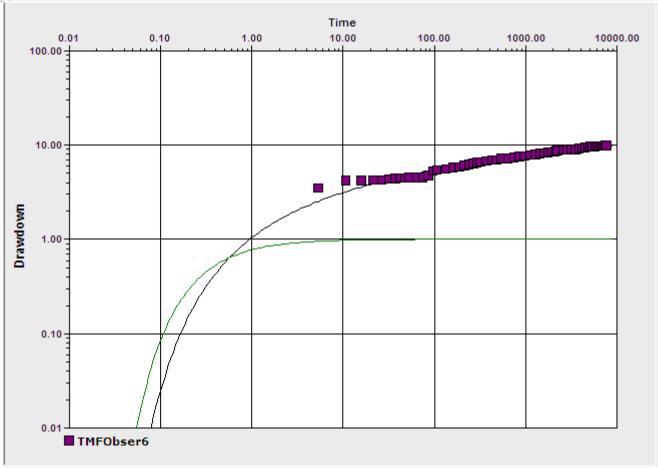
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TGFBH2
TMFObser2


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser3


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser4


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser5


Time
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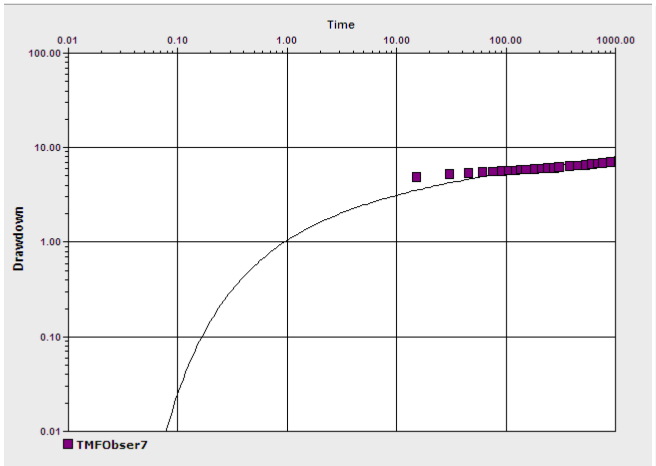
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser6


Time
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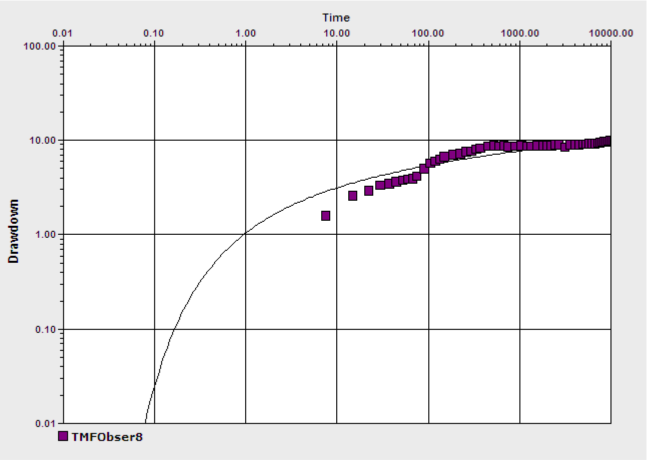
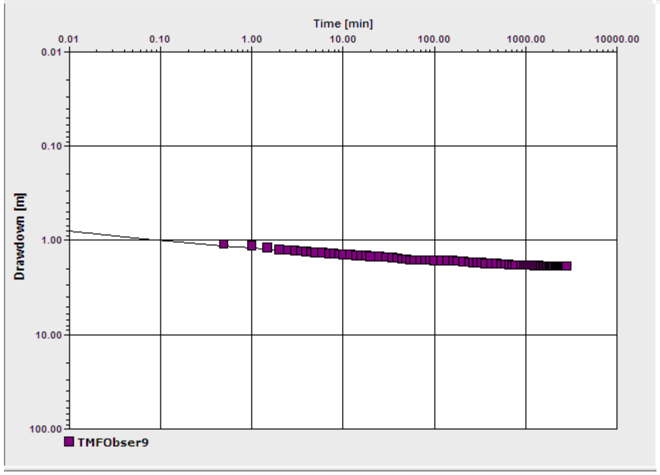
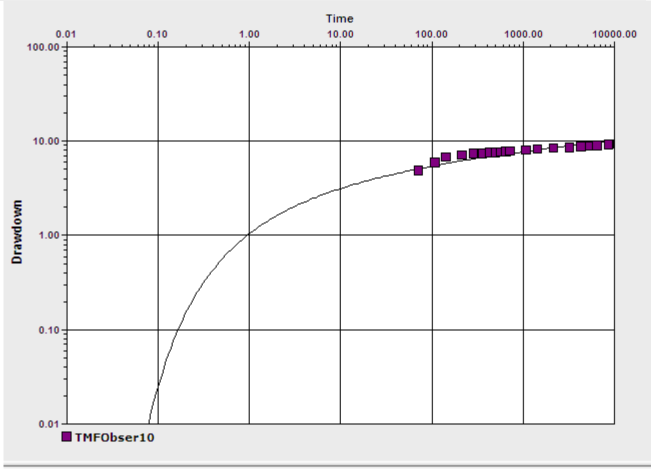
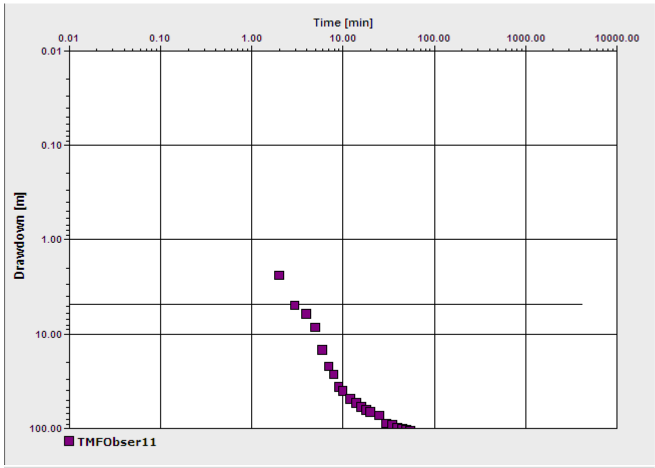
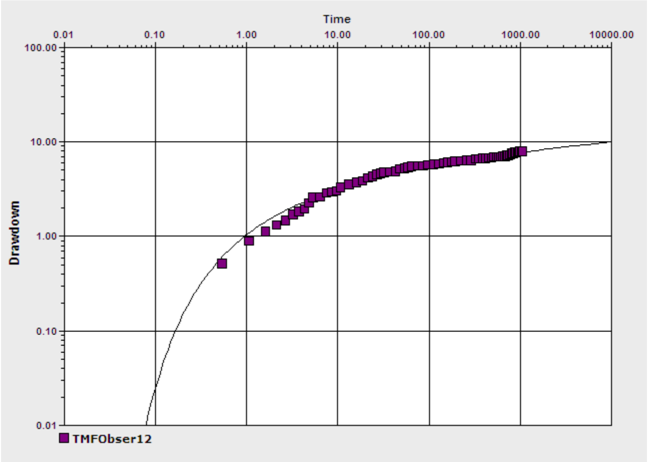
0.10
1.00
10.00
100.00
1000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser7

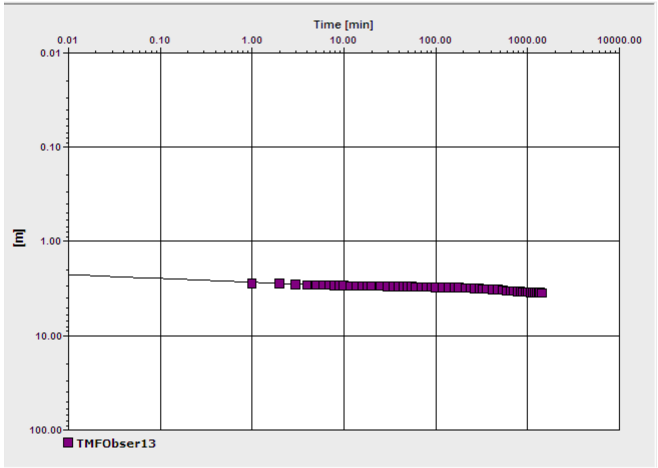

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser8

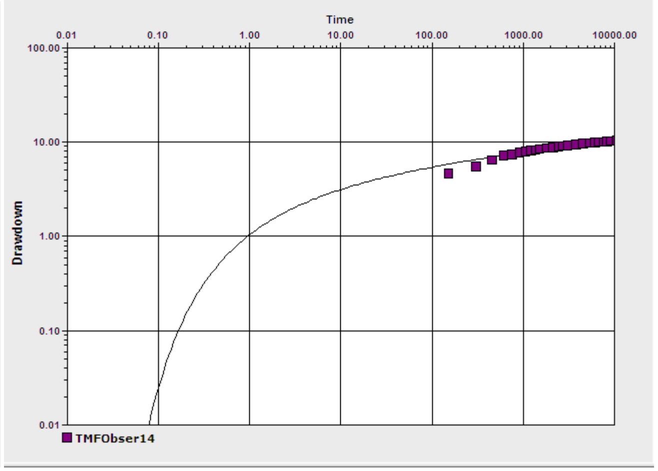

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser9

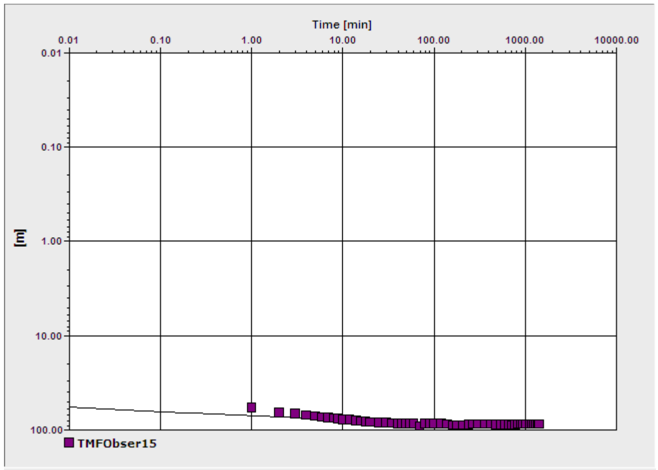

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser10

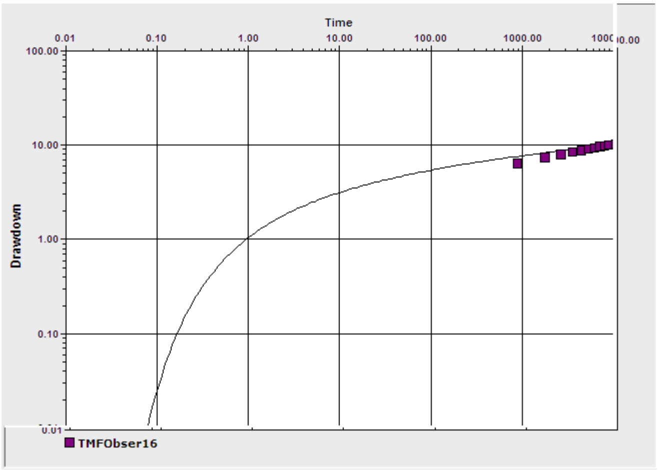

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
■ TMFObser11

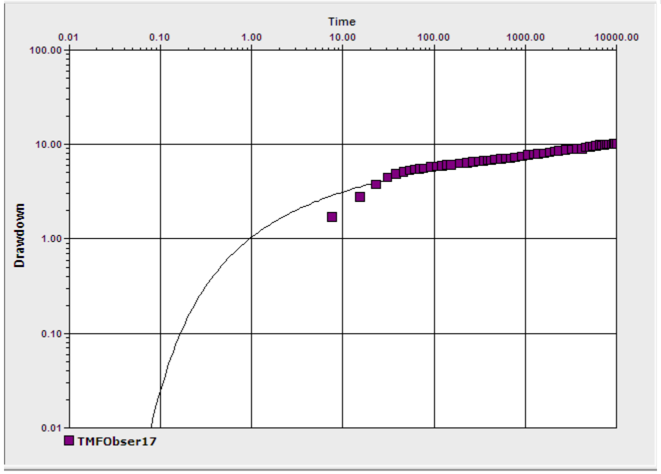

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TMFObser12

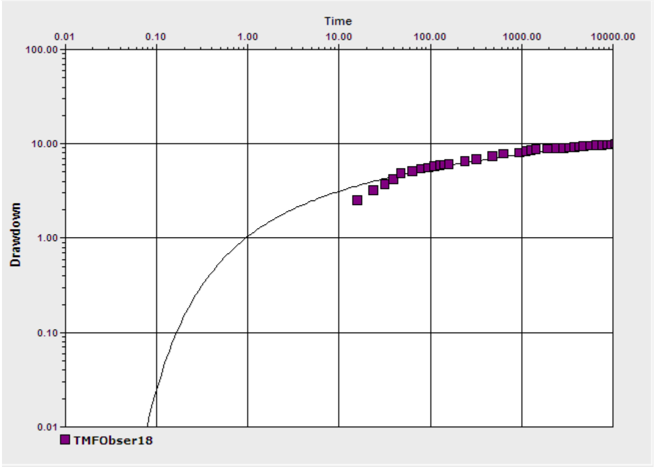

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
[m]
0.01
0.10
1.00
10.00
100.00
■ TMFObser13

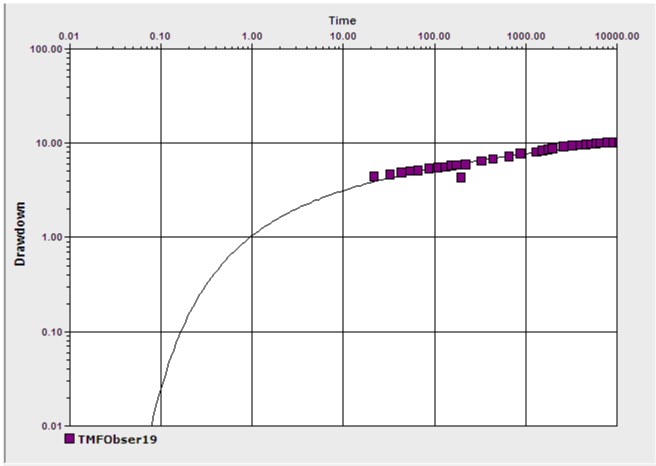

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
■ TMFObser14

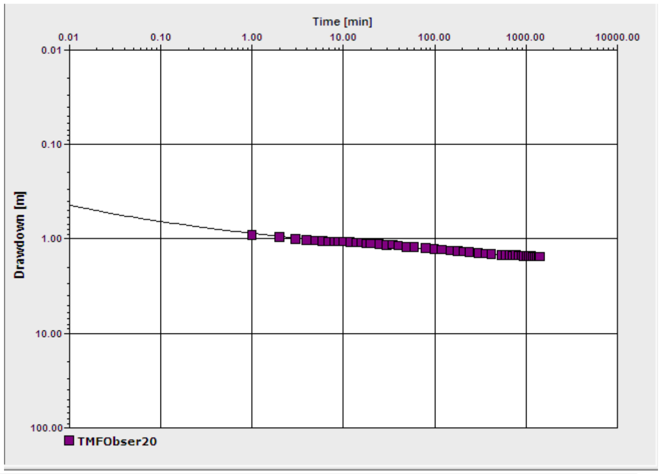

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
[m]
0.01
0.10
1.00
10.00
100.00
TMFObser15

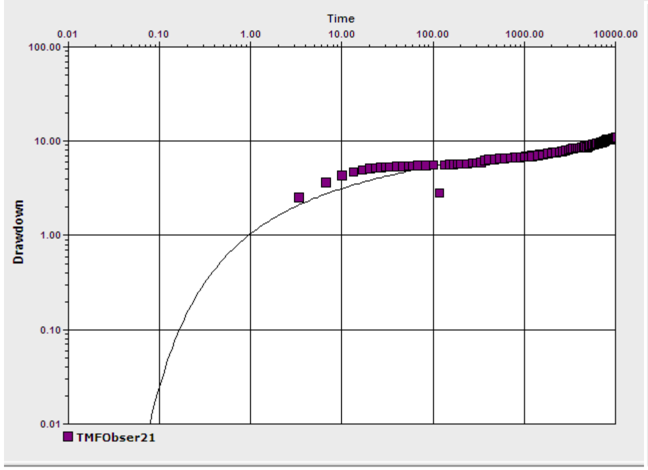

Time
0.01
0.10
1.00
10.00
100.00
1000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser16

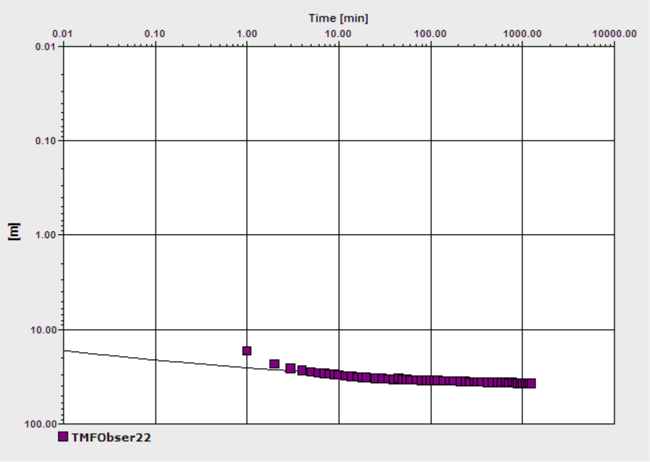

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser17

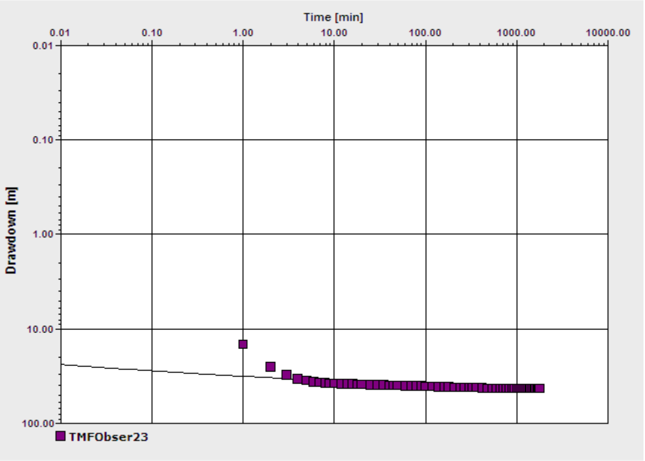

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser18

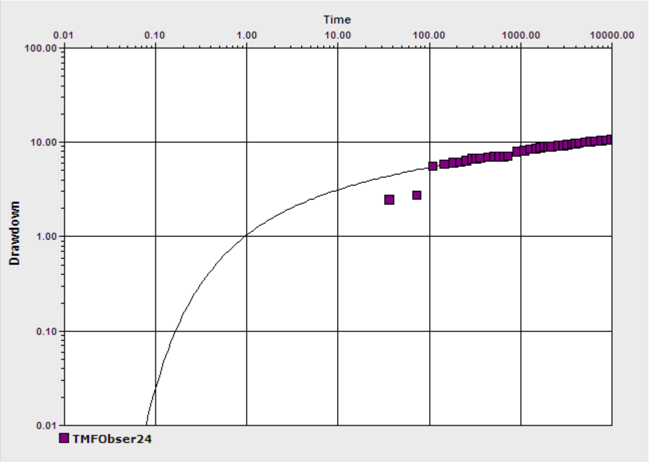

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser19

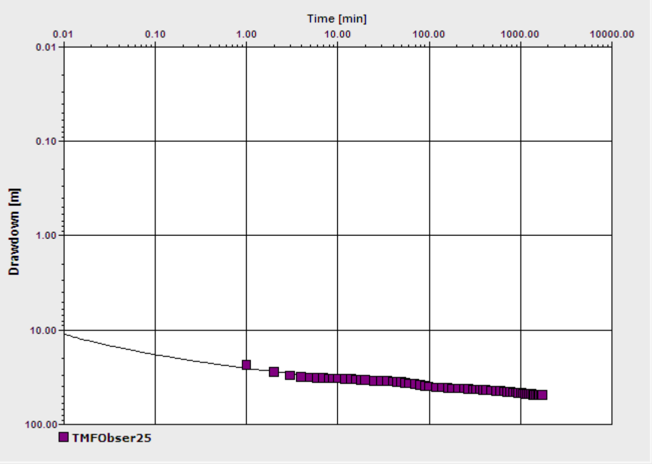

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser20

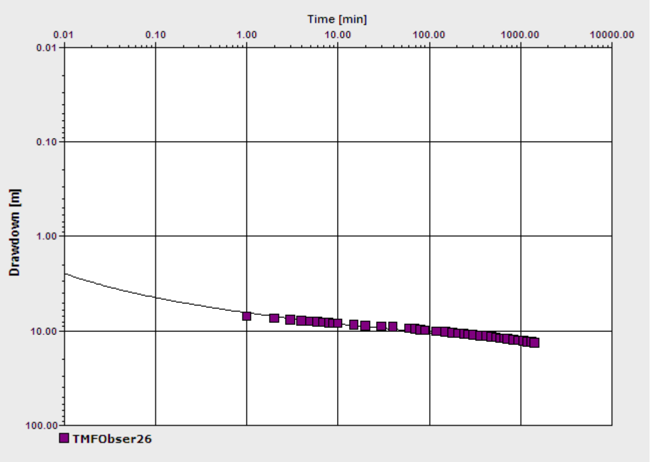

Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser21

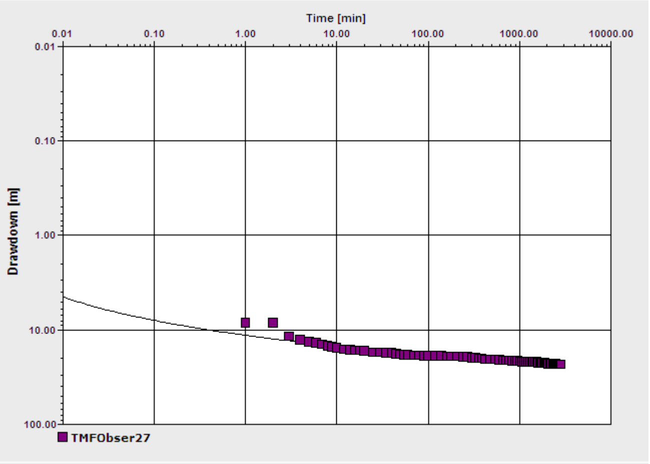

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
[m]
0.01
0.10
1.00
10.00
100.00
TMFObser22

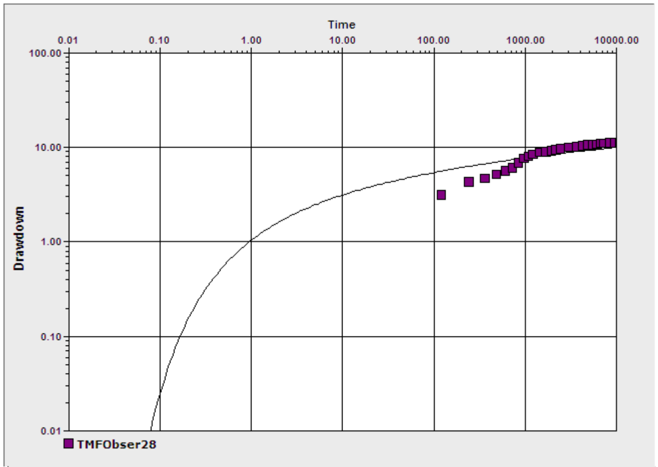

Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser23


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser24


Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser25


Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser26


Time [min]
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser27


Time
0.01
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1.00
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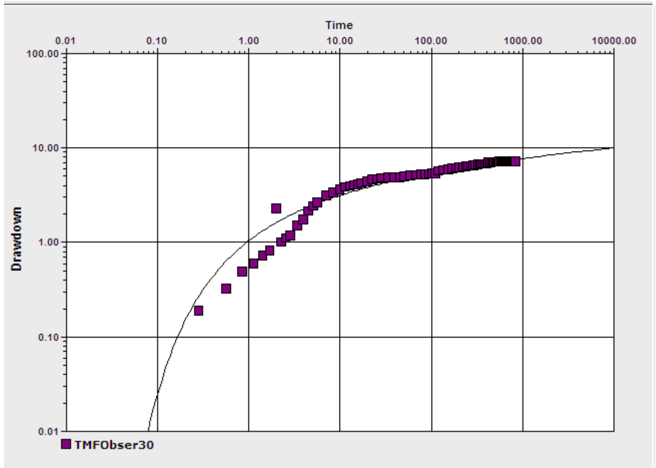
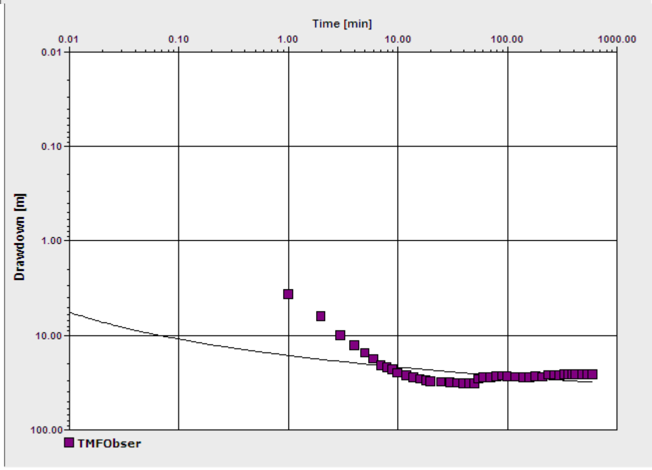
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser28


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser30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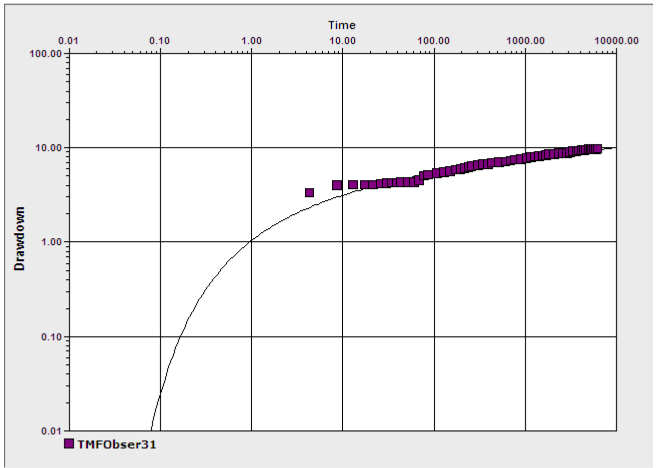
1000.00
Drawdown [m]
0.01
0.10
1.00
10.00
100.00
TMFObser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1000.00
10000.00
Drawdown
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10.00
1.00
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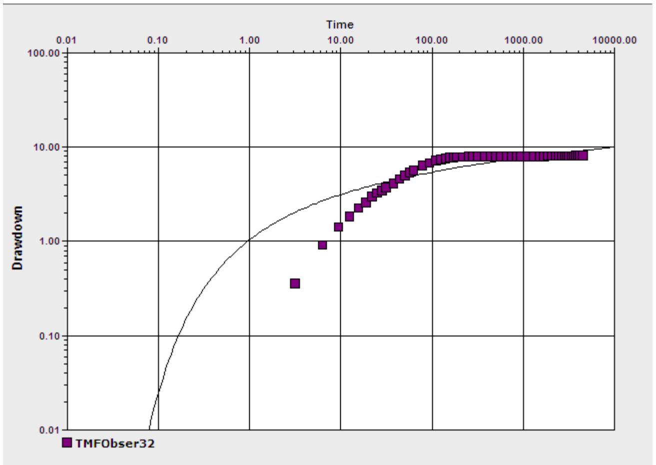
0.01
TMFObser31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Drawdown
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10.00
1.00
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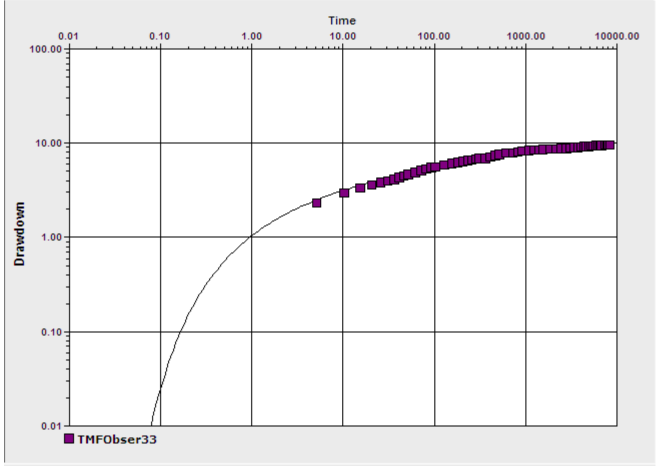
0.01
TMFObser32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1.00
10.00
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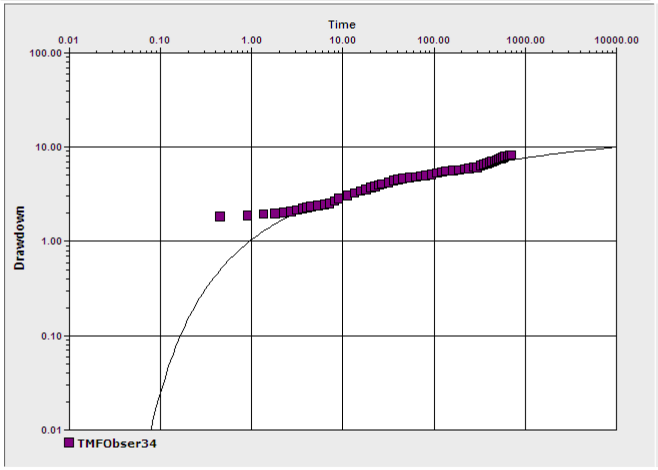
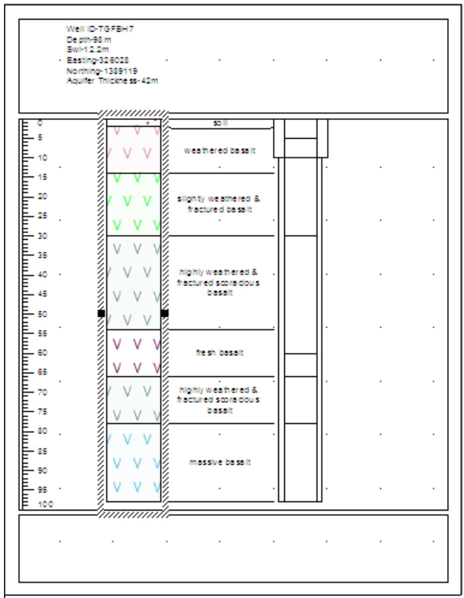
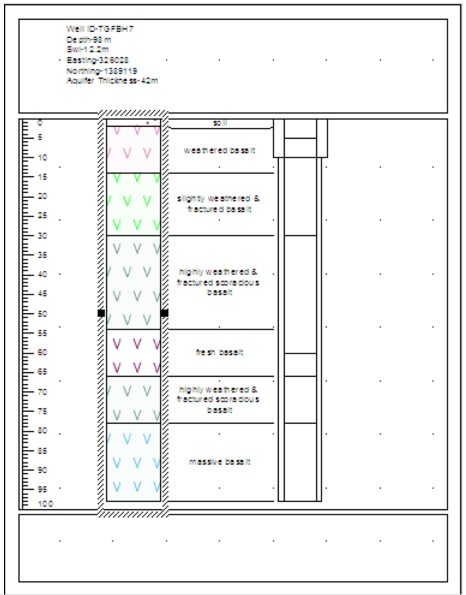
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser33


Time
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Drawdown
100.00
10.00
1.00
0.10
0.01
TMFObser34


Well ID-TGFBH7
Depth-98 m
Swl-12.2m
Easting-326028
Northing-1389119
Aquifer Thickness-42m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
soil
weathered basalt
slightly weathered & fractured basalt
highly weathered & fractured scoracious basalt
fresh basalt
highly weathered & fractured scoracious basalt
massive basalt


Well ID-TGFBH7
Depth-98 m
Swl-12.2m
Easting-326028
Northing-1389119
Aquifer Thickness-42m
0
5
10
15
20
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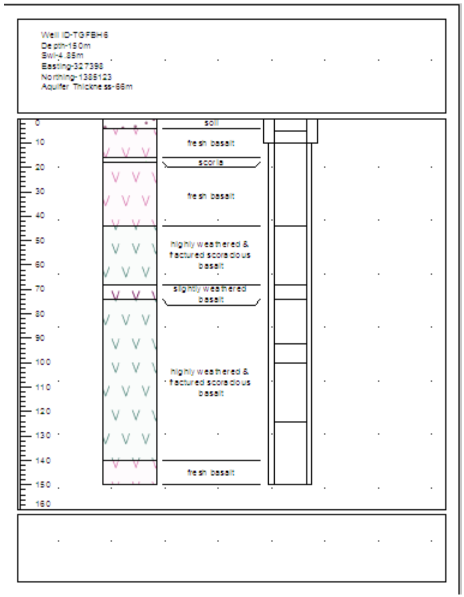
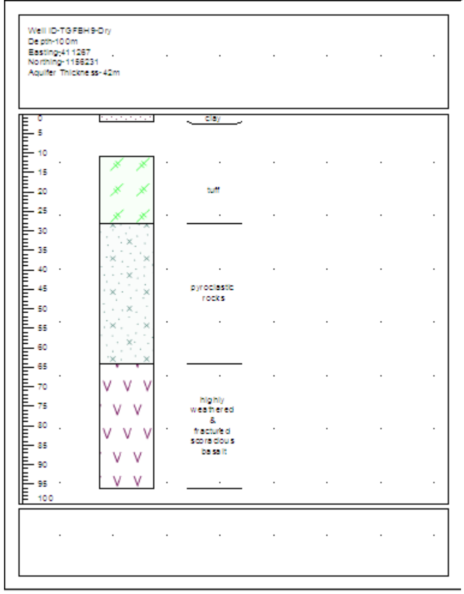
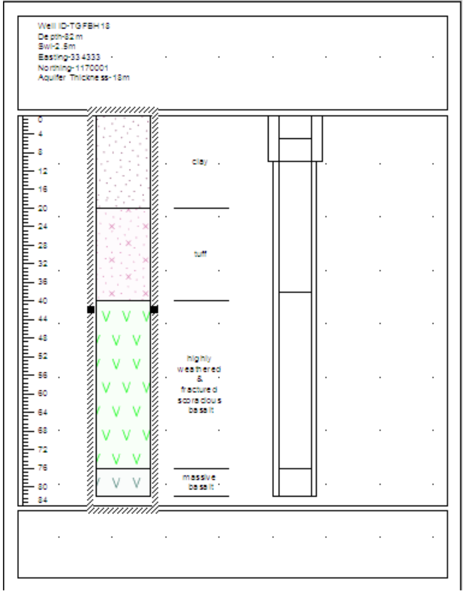
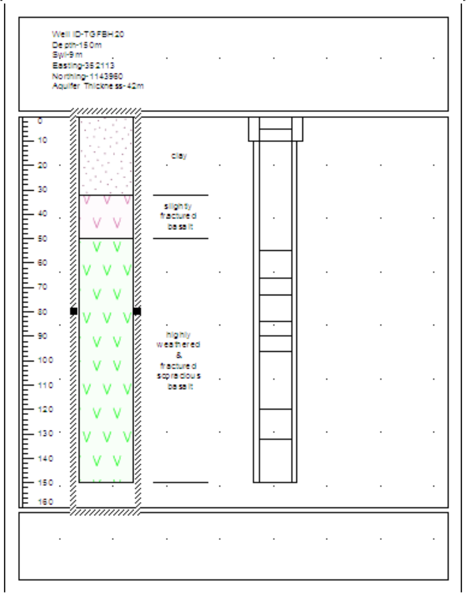
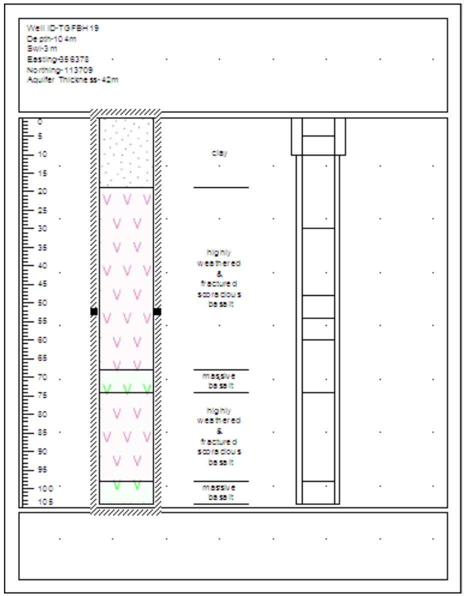
45
50
55
60
65
70
75
80
85
90
95
100
soil
weathered basalt
slightly weathered & fractured basalt
highly weathered & fractured scoracious basalt
fresh basalt
highly weathered & fractured scoracious basalt
massive basalt

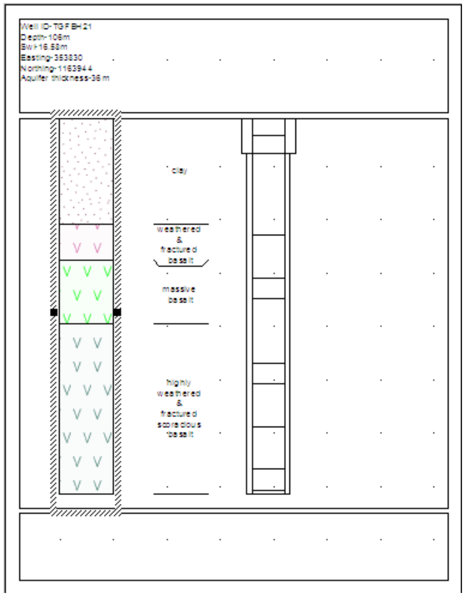

Well ID-TGFBH6
Depth-150m
Swl-4.85m
Easting-327398
Northing-1385123
Aquifer Thickness-66m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
soil
fresh basalt
scoria
fresh basalt
highly weathered & factured scoracious basalt
slightly weathered basalt
highly weathered & factured scoracious basalt
fresh basalt

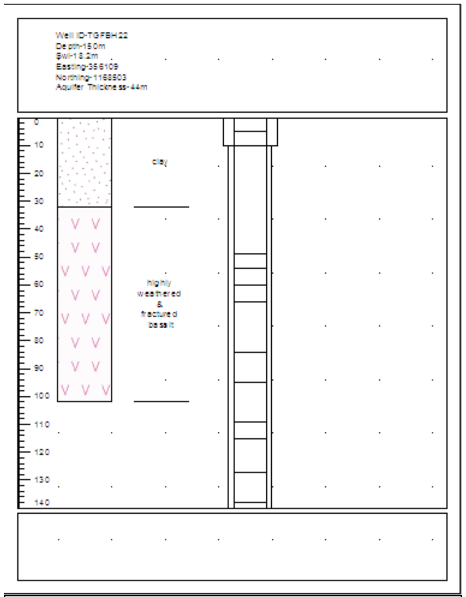

Well ID-TGFBH9-Dry
Depth-100m
Easting;411267
Northing-1156231
Aquifer Thickness-42m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
clay
tuff
pyroclastic rocks
highly weathered & fractured scoracious basalt

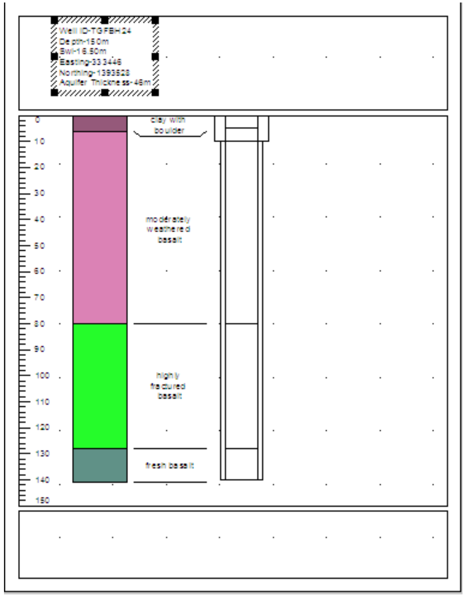

Well ID-TGFBH18
Depth-82m
Swl-2.5m
Easting-334333
Northing-1170001
Aquifer Thickness-18m
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
clay
tuff
highly weathered & fractured scoracious basalt
massive basalt

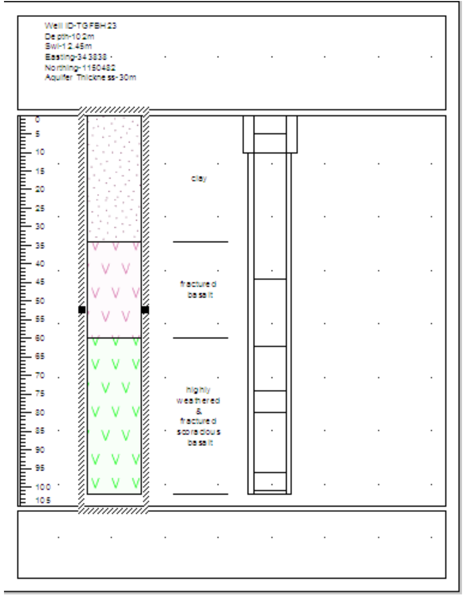

Well ID-TGFBH20
Depth-150m
Swl-9m
Easting-352113
Northing-1143960
Aquifer Thickness-42m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
clay
slightly fractured basalt
highly weathered & fractured scpracious basalt

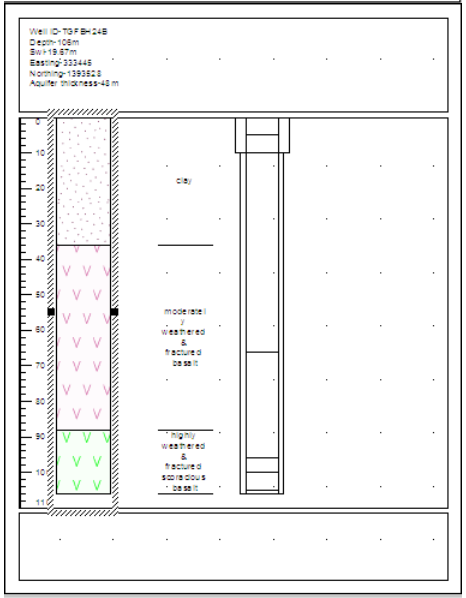

Well ID-TGFBH19
Depth-104m
Swl-3 m
Easting-356378
Northing-113709
Aquifer Thickness-42m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
clay
highly weathered & fractured scoracious basalt
massive basalt
highly weathered & fractured scoracious basalt
massive basalt

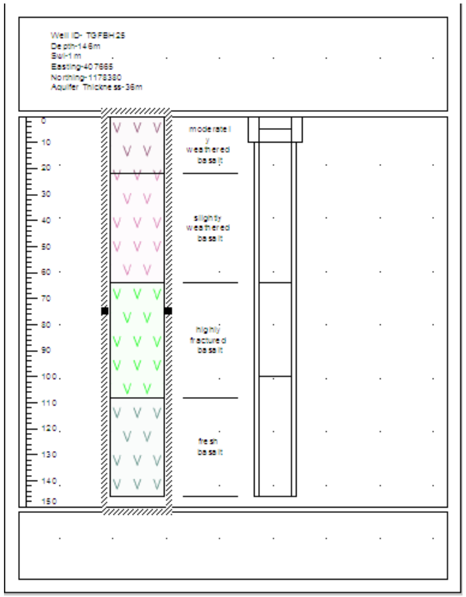

Well ID-TGFBH21
Depth-106m
Swl-16.58m
Easting-353830
Northing-1163944
Aquifer thickness-36 m
clay
weathered & fractured basalt
massive basalt
highly weathered & fractured scoracious basalt

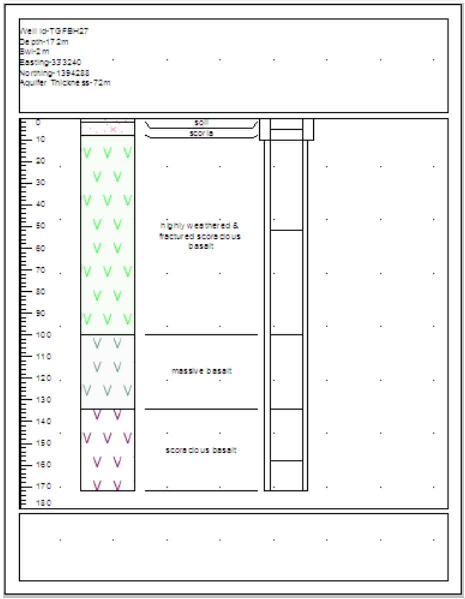

Well ID-TGFBH22
Depth-150m
Swl-18.2m
Easting-356109
Northing-1168503
Aquifer Thickness-44m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
clay
highly weathered & fractured basalt

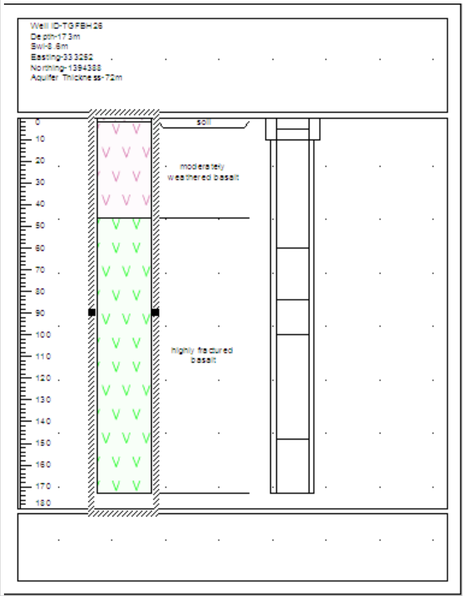

Well ID-TGFBH24
Depth-150m
Swl-16.50m
Easting-333446
Northing-1393528
Aquifer Thickness-46m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
clay with boulder
moderately weathered basalt
highly fractured basalt
fresh basalt

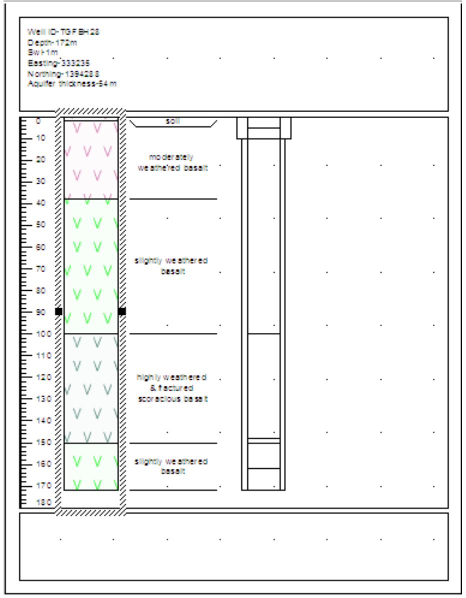

Well ID-TGFBH23
Depth-102m
Swl-12.45m
Easting-343838
Northing-1150482
Aquifer Thickness-30m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
clay
fractured basalt
highly weathered & fractured scoracious basalt

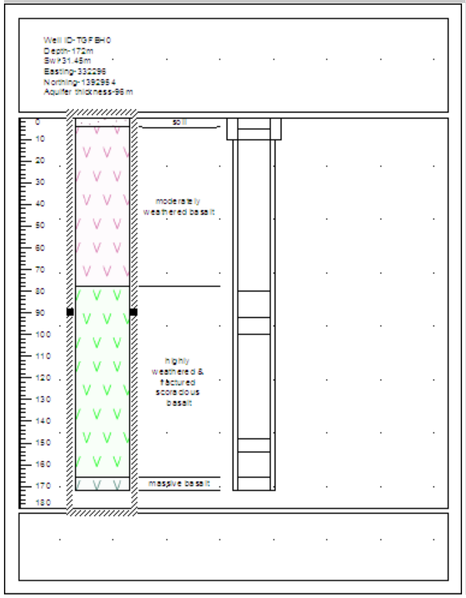

Well ID-TGFBH24B
Depth-106m
Swl-19.67m
Easting-333445
Northing-1393528
Aquifer thickness-48 m
0
10
20
30
40
50
60
70
80
90
10
11
clay
moderately weathered & fractured basalt
highly weathered & fractured scoracious basalt

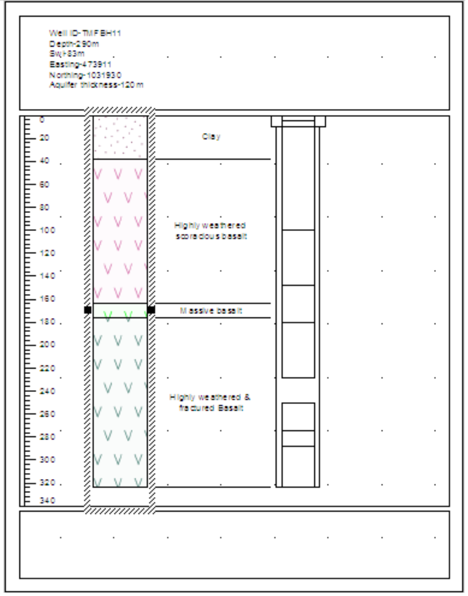

Well ID- TGFBH25
Depth-146m
Swl-1m
Easting-407665
Northing-1178380
Aquifer Thickness-36m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
moderatel y weathered basalt
slightly weathered basalt
highly fractured basalt
fresh basalt

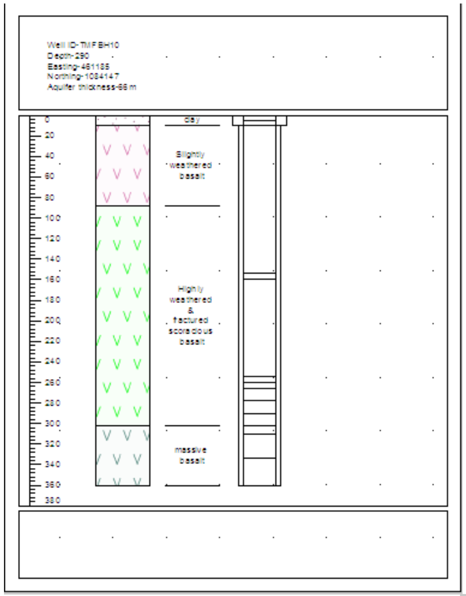

Well Id-TGFBH27
Depth-172m
Swl-2m
Easting-333240
Northing-1394288
Aquifer Thickness-72m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
soil
scoria
highly weathered & fractured scoracious basalt
massive basalt
scoracious basalt

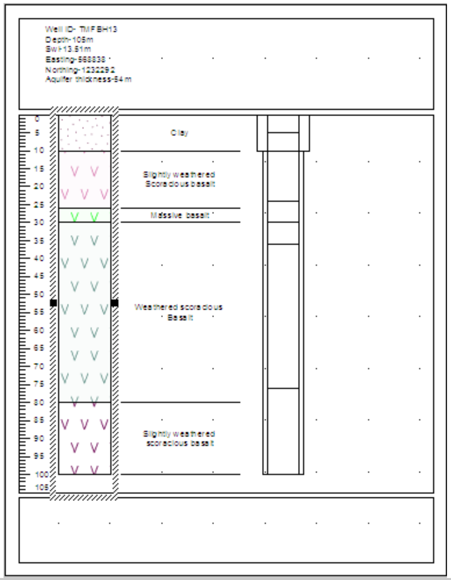

Well ID-TGFBH26
Depth-173m
Swl-8.6m
Easting-333252
Northing-1394388
Aquifer Thickness-72m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
soil
moderately weathered basalt
highly fractured basalt

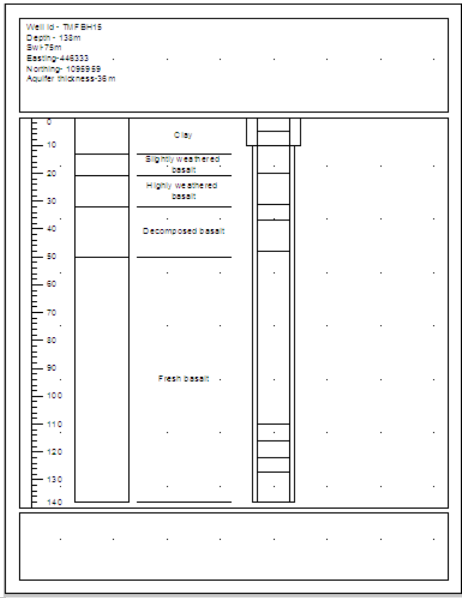

Well ID- TGFBH28
Depth-172m
Swl-1m
Easting-333235
Northing-1394288
Aquifer thickness-54m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
soil
moderately weathered basalt
slightly weathered basalt
highly weathered & fractured scoracious basalt
slightly weathered basalt

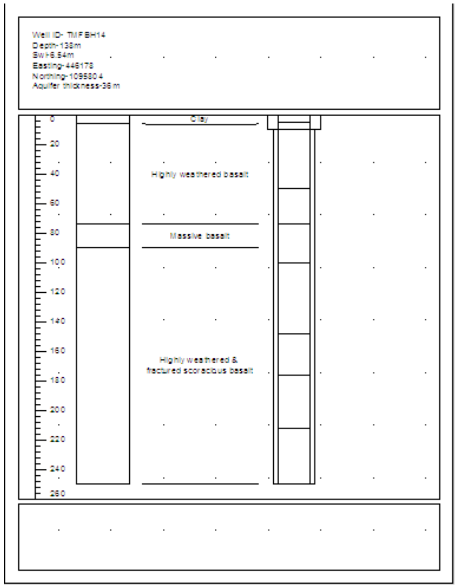

Well ID- TGFBH0
Depth-172m
Swl-31.45m
Easting-332296
Northing-1392954
Aquifer thickness-96m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
soil
moderately weathered basalt
highly weathered & fractured scoracious basalt
massive basalt

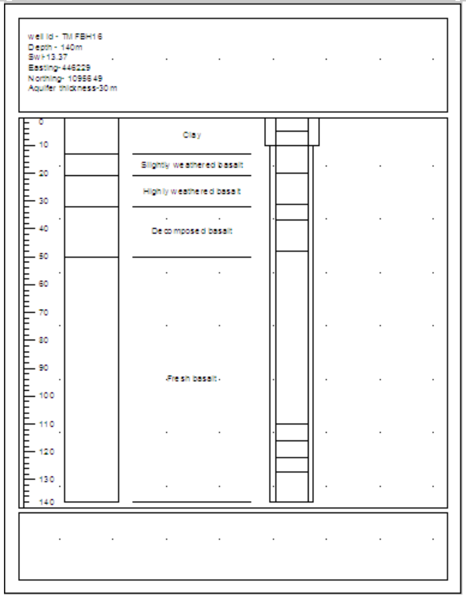

Well ID- TMFBH11
Depth-290m
Swl-83m
Easting-473911
Northing-1031930
Aquifer thickness-120m
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
Clay
Highly weathered scoracious basalt
Massive basalt
Highly weathered & fractured Basalt

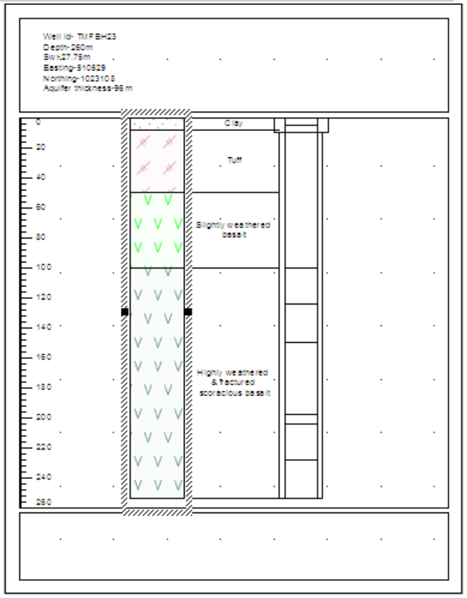

Well ID- TMFBH10
Depth-290
Easting-461185
Northing-1084147
Aquifer thickness-66 m
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
clay
Slightly weathered basalt
Highly weathered & fractured scoracious basalt
massive basalt

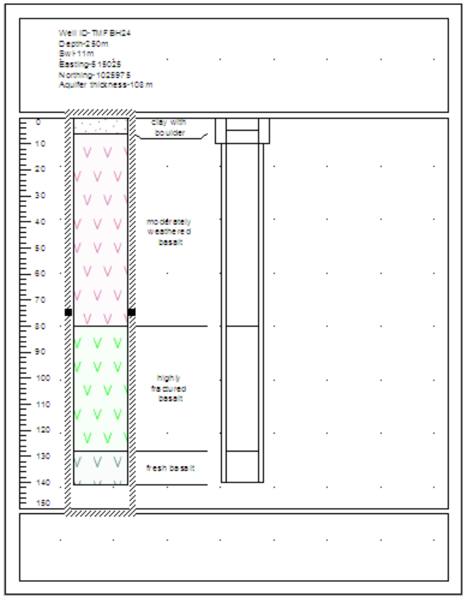

Well ID- TMFBH13
Depth-105m
Sw-13.51m
Easting-568838
Northing-1232292
Aquifer thickness-54 m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
Clay
Slightly weathered Scoracious basalt
Massive basalt
Weathered scoracious Basalt
Slightly weathered scoracious basalt

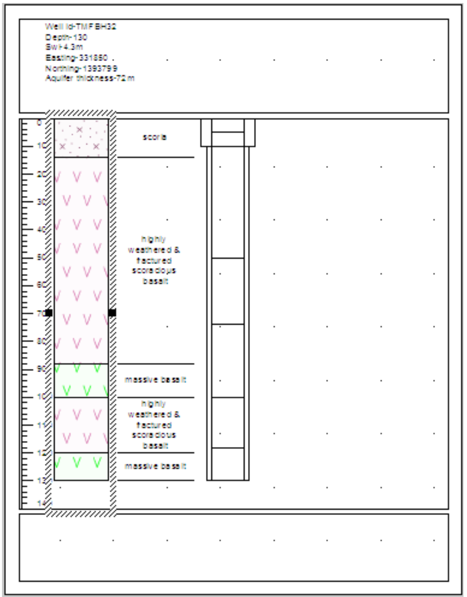

Well Id - TMFBH15
Depth - 138m
Sw-75m
Easting-446333
Northing- 1095959
Aquifer thickness-36 m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Clay
Slightly weathered basalt
Highly weathered basalt
Decomposed basalt
Fresh basalt

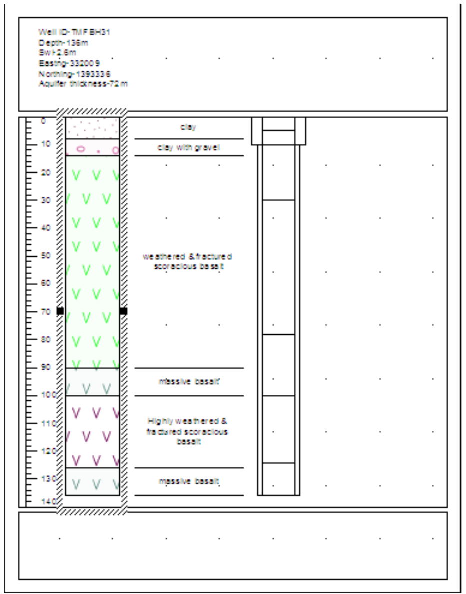

Well ID- TMFBH14
Depth-138m
Sw-6.54m
Easting-446178
Northing-1095804
Aquifer thickness-36 m
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Clay
Highly weathered basalt
Massive basalt
Highly weathered & fractured scoracious basalt

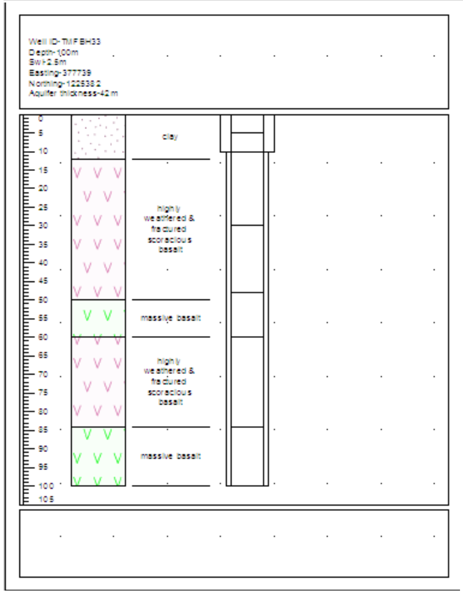

well id - TMFBH16
Depth - 140m
Sw-13.37
Easting-446229
Northing- 1095649
Aquifer thickness-30 m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Clay
Slightly weathered basalt
Highly weathered basalt
Decomposed basalt
Fresh basalt

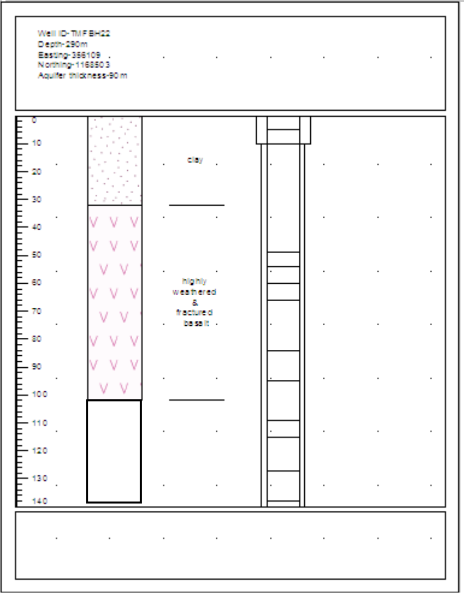

Well Id- TMFBH23
Depth-260m
Sw-27.75m
Easting-510529
Northing-1023108
Aquifer thickness-96 m
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Clay
Tuff
Slightly weathered basalt
Highly weathered & fractured scoracious basalt

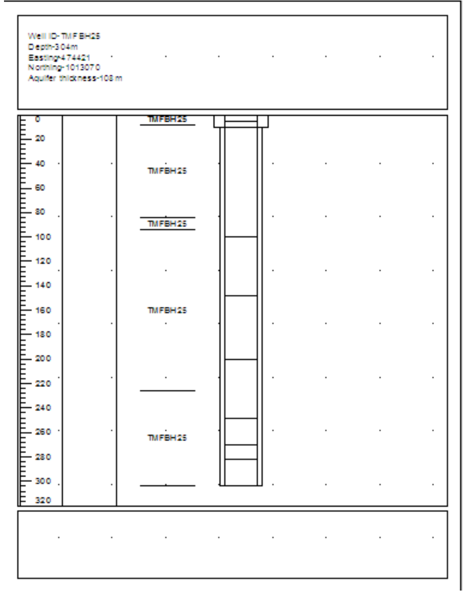

Well ID- TMFBH24
Depth-250m
Swl-11m
Easting-515025
Northing-1025975
Aquifer thickness-108 m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
clay with boulder
moderately weathered basalt
highly fractured basalt
fresh basalt

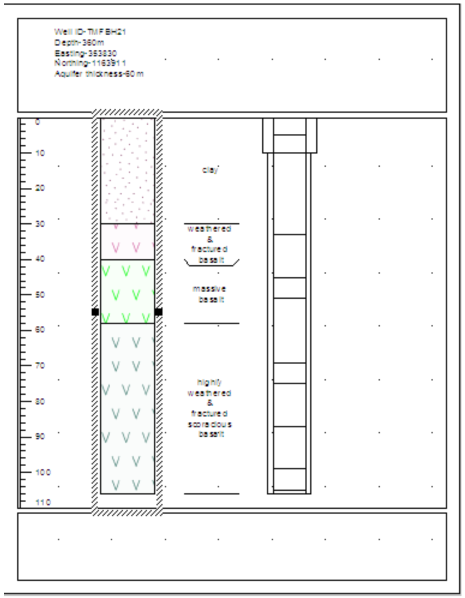

Well Id-TMFBH32
Depth-130
Swl-4.3m
Easting-331850
Northing-1393799
Aquifer thickness-72 m
0
10
20
30
40
50
60
70
80
90
scoria
highly weathered & fractured scoracious basalt
massive basalt
highly weathered & fractured scoracious basalt
massive basalt


Well ID- TMFBH31
Depth-136m
Swl-2.6m
Easting-332009
Northing-1393336
Aquifer thickness-72 m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
clay
clay with gravel
weathered & fractured scoracious basalt
massive basalt
Highly weathered & fractured scoracious basalt
massive basalt


Well ID- TMFBH33
Depth-100m
Swl-2.5m
Easting-377739
Northing-1225382
Aquifer thickness-42 m
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
clay
highly weathered & fractured scoracious basalt
massive basalt
highly weathered & fractured scoracious basalt
massive basalt


Well ID- TMFBH22
Depth-290m
Easting-356109
Northing-1168503
Aquifer thickness-90 m
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
clay
highly weathered & fractured basalt


Well ID- TMFBH25
Depth-304m
Easting-474421
Northing-1013070
Aquifer thickness-108 m
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
TMFBH25
TMFBH25
TMFBH25
TMFBH25
TMFBH25


Well ID- TMF BH21
Depth- 360m
Easting- 353830
Northing- 1163911
Aquifer thickness-60 m
0
10
20
30
40
50
60
70
80
90
100
110
clay
weathered & fractured basalt
massive basalt
highly weathered & fractured scoracious basalt