SCHOOL OF ENVIRONMENTAL SCIENCES

HYDROGEOLOGICAL CHARACTERISATION AND WATER SUPPLY POTENTIAL OF LEBALELO SOUTH, LIMPOPO PROVINCE OF SOUTH AFRICA

By

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DECLARATION

I, Rudzani Vincent Rambuwani, hereby declare that this dissertation for Masters of Earth Science in Hydrology and Water Resources at the University of Venda, hereby submitted by me, has not been previously submitted for a degree at this or any other institution. This is my work in design and execution, all reference materials contained herein have been duly acknowledged**.**

Signature RV Date: 8/26/2020

DEDICATION

This work is dedicated to God who is the beginning and the end, and to my family members. I love you all.

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I also want to say a big thank you to my late parent for giving me the platform to become who I am today. To my sisters, brother, wife and children I want to say a big thank you and I want you to know that I love you so dearly.

ABSTRACT

Lebalelo area of Sekhukhune district is one of many areas in South Africa experiencing portable water scarcity, especially during prolonged dry season. Due to the dominance of low yielding aquifers in South Africa, it is essential to manage groundwater resources in these low yielding aquifers. However, the management of low yielding aquifer is difficult in areas like Labelelo where the hydrogeological characteristics of the aquifers are understudied. This study investigated the hydrogeological characteristics of the aquifers in the area using combined geophysical method and analytical groundwater models. Four newly drilled borehole and five existing boreholes were used for this study. Geophysical survey was carried out using magnetic and electromagnetic methods. The magnetic survey was used to locate the position of magnetic bodies such as dolerite dykes and different lithologies with different magnetic properties. The electromagnetic survey however, was used to determine zones of high permeability associated with the intrusive bodies as well as high permeability zones in fault planes. Step test, constant discharge test and recovery tests were conducted on all the boreholes to stress the borehole. This was used to determine a suitable and sustainable pumping rate of the aquifer. Pumping test data from the pumping period and recovery was evaluated and interpreted using AQTESOLVE. Aquifer transmissivity, storativity, internal and external hydraulic boundaries were determined from the data. The transmissivity in the area ranges from 0.08 to 124.7 m2/day. The aquifer types in the area are double porosity aquifer, radial flow aquifer with single porosity. Inductive Coupled Plasma (ICP-MS) was used to measure heavy metals, trace metals and cations while Ion Chromatography (IC) was used to determine anions in groundwater of the study area. The groundwater in the area is dominated by calcium carbonate as a result of long residence time with dolomite. The hydrochemistry of the water indicates that the chemistry of the groundwater in the area is mainly controlled by rock-water interaction.

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1. INTRODUCTION

1.1 Background

Groundwater is of economic importance in both developing and developed nations of the world. An estimated 1.5 billion people worldwide rely on groundwater for sustainability (Clarke *et al*., 1996), with 50% of United States population depending on groundwater for their daily drinking purposes (Solley *et al*., 1998). Groundwater accounts for 15% of Africa's renewable water resources and is a source of drinking water in nearly all African rural areas, especially during the dry seasons as well as in the continent's main arid zones (UN, 2000; WWC, 2006). Groundwater has become a major contributor to the total water supply in arid and semi-arid rural regions (Van Camp *et al*., 2013), because it contributes over 70% of the total domestic water supply in these rural areas (du Toit *et al*., 2012). The pressure on water resources is increasing at an alarming rate due to world population growth, urbanization and economic development.

Groundwater is suitable for demand responsiveness especially in rural areas because of its easy accessibility, cheap cost of development and closeness to demand (McDonalds and Davies, 2000). Where groundwater is promptly accessible, wells and boreholes can be sited utilizing principally social criteria qualified by straightforward hydrogeological examination (McDonalds and Davies, 2000). However, challenges like limited groundwater storage, poor technical knowhow and difficulty in locating groundwater can arise in areas with complex structural and hydro geology (McDonalds and Davies, 2000). Hydrogeological investigation is important in achieving a successful and sustainable exploration and exploitation of groundwater for domestic and economic use. Natural groundwater chemically constitutes 99% of major chemical constituent (sodium (Na), calcium (Ca), magnesium (Mg), potassium (K), bi-carbornate (HCO_3), chlorine (Cl), sulphate (SO_4), nitrate (NO_3) and silicon (Si)) and 1% of trace elements (McDonalds and Davies, 2000). The abundance of the nine-major chemical constituent, constituting 99% of the solute content of natural groundwater reflects the geology of the aquifer and the history of the groundwater (Foster *et al*., 2000).

South Africa is located in a semi-arid region; therefore, it is considered a water stressed nation. Although attempts have been made to improve access to clean water and proper sanitation, but the daily demand for water still outweighs the amount supplied. The increasing daily demand of water has called for more hydrogeological investigation into sustainable groundwater exploration and abstraction. In many provinces in South Africa, hydrogeological characterisation has been carried out for various reasons. These include minimization of saline water intrusion, groundwater quality, aquifer characterisation, groundwater modelling, vadose-zone infiltration, determination of flow of groundwater scheme, recharge quantity and quality and declination of water table. This has brought much knowledge and understanding of the aquifer systems, which has led to optimised abstractions, abatement, informed groundwater planning development and allocation.

1.2 Statement of problem

There is lack of information regarding groundwater resources in South Africa (Nkondo *et al.*, 2012) because the quantity of groundwater in most rural areas are unknown. The growing demand for water and the limited capacity of surface water supply has resulted in groundwater being increasingly developed to augment surface water. The study area is dominantly rural, and the rate of evaporation supersedes the rate of precipitation thus most surface water sources are seasonal and may not flow in prolonged period of dryness and drought. Due to this factor, the area relies dominantly on groundwater resources (DWA, 2011). At national level, the main aquifer types in South Africa are dominantly low yielding fractured aquifers. Thus, utilisation of groundwater resources from these aquifers needs to be managed. This is difficult to achieve in areas where hydrogeological characteristics of aquifers are unknown. According to DWA (2011), the current known sustainable yield in the study area is insufficient to meet the present demand and the projected future demands.

Many studies (Mouton, 2011; Wright, 1992; Holland, 2011; du Toit, 2012) have been done on hydrogeological and hydro-geochemical characterization of fractured aquifers in South Africa. A typical example is a regional study done by Holland (2011) on the hydrogeological characterization of basement aquifers in Limpopo province. However, in all these studies, Lebalelo South areas have all been left out of these studies. Thus, no published work exists on the hydrogeochemical characterization of Lebelelo South, which is one of the water stressed areas in Limpopo province of South Africa.

Most aquifers in South Africa are basement fractured aquifers and they are being structurally controlled (Sami, 2009). Groundwater development in fractured basement aquifers of South

Africa is complex and more often have undependable spatial reliability (Banks and Robins, 2002). Due to the inherently low primary porosity and permeability of fractured aquifer, groundwater exploration techniques vary from aquifer to aquifer, thus most rural areas of South Africa, have failed boreholes as a result of poor understanding of structural hydrogeology and the hydraulic characteristics of most fractured crystalline aquifers. In Lebalelo South, a large number of the drilled boreholes lack basic hydrogeological information or has a wrong information to make an informed geological review about future groundwater exploration (DWA, 2011), due to lack of proper hydrogeological knowledge by most hydrogeologists.

Sustainable groundwater abstraction over the years depends on accurate determination of the hydraulic properties of the aquifer in question. The best hydrogeological tool for prediction of sustainable abstraction of groundwater resources is the groundwater model (Robins *et al*., 2006). However, the reliability of the groundwater model depends greatly on different basic conceptual models (theoretical models) and aquifer hydraulics which are obtained during borehole pumping test (Holland, 2011). Therefore, poor understanding of the pumping test data leads to poor interpretation of aquifer hydraulic properties and thus leading to the use of wrong conceptual models. Lack of understanding of the occurrence, movement and recharge of groundwater in basement terrain has frequently contributed to the unsustainable use of this resource (Chilton and Foster, 1995). The lack of information as a result of poor expertise in groundwater sustainable abstraction determination has led to failure of so many groundwater schemes in the study area.

A significant majority of water related deformation and deaths occur in developing countries while ninety percent of such deaths occur in children (Ashbolt, 2004). It has been a general misconception that groundwater is safe for drinking and does not need any treatment probably due to its location far away from surface source contaminants especially anthropogenic contamination. Over the last few decades in South Africa, many epidemics have been reported and investigation points to poor groundwater quality (Bessong *et al.*, 2009; Edokpayi, 2017). According to Levite *et al*. (2013), Steelport river is the main river supplying the study area and it is currently assessed to be in a poor state due to high concentration of heavy metals and toxins thus village communities depend mostly on water from boreholes and it is being consumed without any prior treatment. In Lebalelo South region, clean portable water is either lacking or inadequate (Obi *et al*., 2004).

1.3 Motivation

To make informed strategic future planning of groundwater allocation for economic development, there is a need to understand its quantity and quality. Better understanding of the way an aquifer functions and the ability to assess its capacity is essential also because it will result in optimum and sustainable use of groundwater.

Limited concrete geohydrological information on existing groundwater resources in rural areas of South Africa and misrepresentation and misinformation on some of the existing geohydrological investigation is a looming problem in South Africa. Lebalelo South is one of such areas where improper geophysical and structural investigation, misrepresentative aquifer characterization and poor water quality analysis have caused failure of most production boreholes, thus increasing the stress on the available groundwater resources. Identifying hydrological processes which control groundwater chemistry and evolution is critical to sustainable groundwater development. Lebalelo South is an area where groundwater development will be much beneficial yet, very little work on groundwater assessment has been done. This study will form the foundation on which further hydrogeological studies in the area can be developed especially with regards to fractured aquifer.

1.4 Objectives of the study

1.4.1 Main objective

To determine the hydrogeological and hydro-chemical characteristics of groundwater resources in Lebalelo South in Limpopo province of South Africa and its suitability for sustainable use.

1.4.2 Specific objectives

- To delineate groundwater occurrence using magnetic survey.
- To estimate aquifer parameters from borehole pumping tests.
- To determine the sustainable groundwater abstraction rate.
- To determine the hydro-chemistry of groundwater and its suitability for use.

1.5 Research questions

- Where is it suitable to drill water supply boreholes in Lebalelo South?
- What are the hydraulic characteristics of the aquifer(s) in Lebalelo South?
- What is the suitable discharge rate that would not lead to permanent dewatering of the boreholes?
- What is the groundwater quality status in Lebalelo South?

1.6 Study area

1.6.1 Location

The study area lies about 15 km North-West of Burgersfort Town in Greater Tubatse Local Municipality in Sekhukhune District of Limpopo Province, South Africa. This area is located within the geographical boundaries of 30˚00’ E, 24˚20’S and 30˚20E, 24˚40’S (Figure 1.1). The study area covers six (6) villages namely: Mandela, Ragapola, Magologolo, Ga-Riba, Riba-cross, Driekop

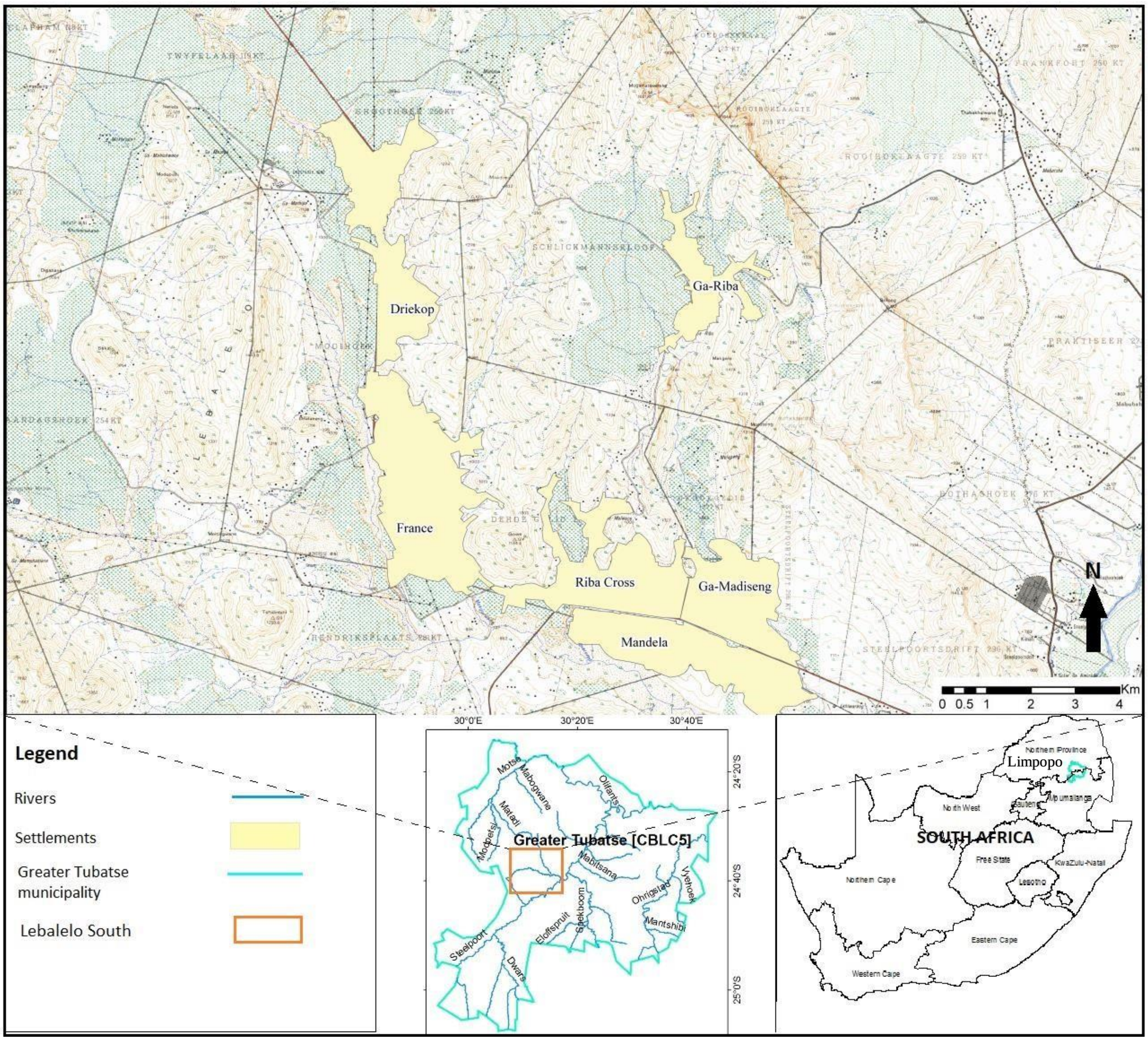

Figure 1.1: Locality map of the study area

1.6.2 Geology of the study area

Lebalelo South is mainly underlain by the Transvaal Sequence and Bushveld Complex rocks. The Transvaal Sequence consists of volcano-sedimentary rocks. These rocks were intruded by mafic igneous rocks which form the Bushveld Complex. The resultant rocks include quartzites, siltstones, shales, limestones and hornfels. Occasional north trending diabase dykes have also been identified during field reconnaissance. The valley flows are covered with relatively thick layers of sand, pebbles and boulders. The geological map is presented in Figure 1.2.

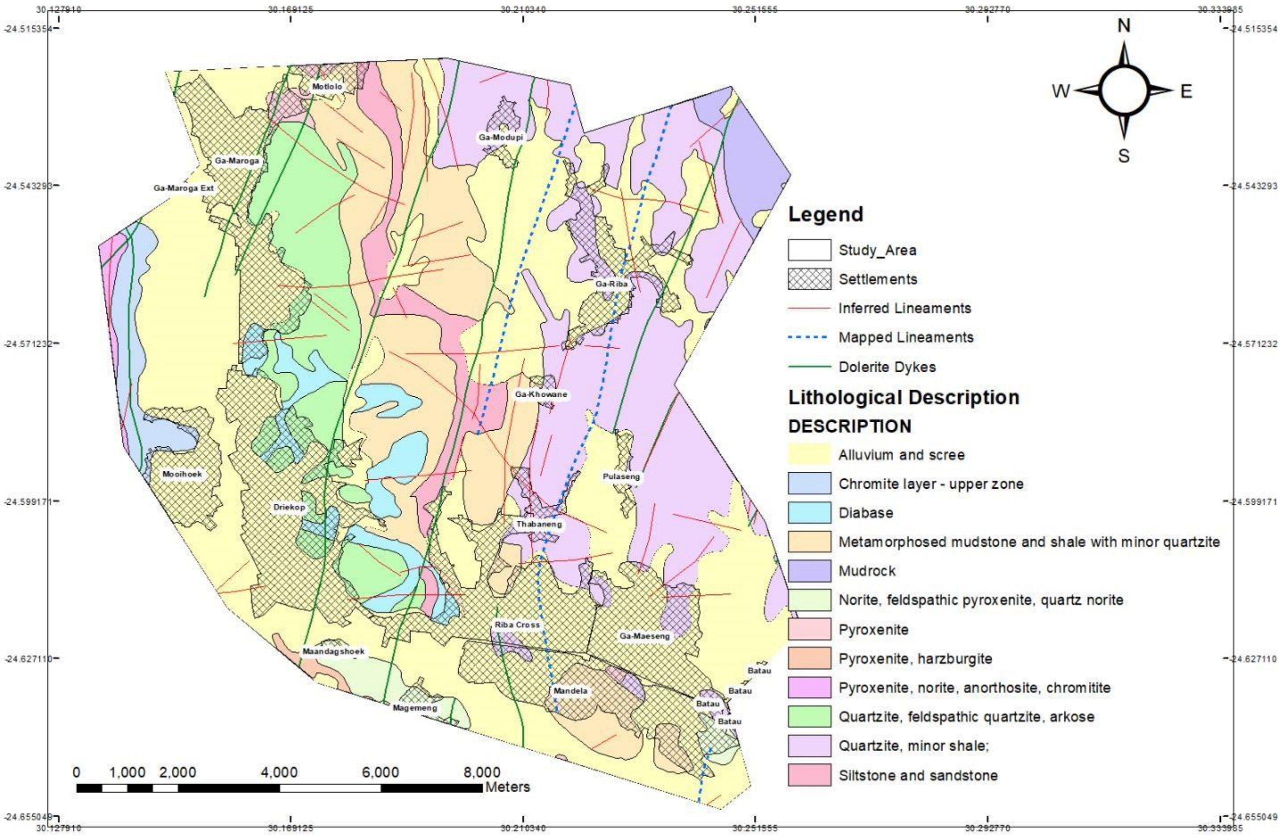

Figure 1.2: Geological map of Lebalelo South area.

1.6.3 Climate

According to the Tubatse Integrated Resource Information Report (2005), the average rainfall for this area fluctuates between 500mm and 800mm per year. Sekhukhune is located in the summer rainfall zone of the country, and receives more than 80% of its rainfall between November and March. The Sekhukhune area is characterised by a hot climate in the Olifants River Valley. The average temperature shows moderate fluctuation with average summer temperatures of 23°C, as well as a maximum of 28°C and a minimum of 18°C. In winter, the average is 13.5°C with a maximum of 20°C and a minimum of 7°C.

1.6.4 Topography and drainage System

There is quite a marked difference topographically within the investigated area. The topographical setting of the investigated areas is relatively flat south of the R37 Road. North of the road, the terrain is characterised by mountain ranges separated by relatively flat narrow valleys. The altitude ranges from about 800 m above sea level south of road R37 to about 1400 m above sea level in the mountain ranges north of the road R37. The area is drained by small seasonal stream which flow to Moopetsi River south of the scheme or Hoduopong River to the east. These rivers flow east and south-east respect to the Steelpoort River.

1.6.4 Geohydrology

The main River in the area is the Olifants/Elephants. Catchments areas include the Blyde River, Steelpoort and Watervals River. The Greater Tubatse Municipality gets water from the Olifants/Elephant River and the main catchment area (50%) is the Steelpoort River. According to the Hydrogeological Map of Phalaborwa (Sheet 2330, 1: 500 000 scale) covering Lebalelo South villages, the aquifer is regarded as intergranular and fractured aquifer. It is composed mainly of undifferentiated rocks and various mixed lithologies resulting from the tectonic activity that was experienced in the area. Groundwater is expected to occur in the fractured transitional zone between the weathered and fresh bedrock.

2. LITERATURE REVIEW

2.0 Preamble

Hydrogeological characterisation is consequential to sustainability of groundwater resource because it encompasses critical aspects of groundwater exploration and exploitation. Hydrogeological investigations are carried out to determine available groundwater resources and to determine a non-depletive way of abstraction and exploitation. This chapter elucidates on different aquifer parameters, exploration methods and analytical methods in groundwater quality and quantity analysis. This chapter also reviews different related studies that has been done in South Africa. Literature review on hydrogeological characterization is explained in details.

2.1 Previous studies

In South Africa, groundwater occurrence is structurally controlled, and successful groundwater exploration depends on accurate and reliable mapping of these structures. Sami (2009) in his work titled "Groundwater exploration and development" noted that South Africa's groundwater aquifers are mostly classified as fractured rock aquifer thus, successful groundwater exploration in South Africa should be based on reliable hydrogeological investigation and mapping of these five structures; faults, shears, dykes, contacts and fractured zones visually in the field. However, one of the biggest challenges faced by groundwater development in South Africa is poor exploration expertise of many hydrogeologists.

The relationship between the geology and geohydrology of South Africa was investigated by Lourens (2013). The study emphasised on the importance of understanding the geohydrological properties of fractured aquifer systems because, over 90% of the aquifers in South Africa are regarded as fractured aquifer and are controlled by secondary porosity and permeability. The work highlighted that the geological groups (Transvaal supergroup and the Bushveld igneous complex) underlying Lebalelo South are mainly dominated by interangular, fractured and karst aquifer system. Groundwater yields below 2 l/s are common although groundwater yields greater than 5l/s are obtainable given that groundwater siting is done accurately by targeting the karst aquifer systems. Groundwater recharge mostly occur in weathered zones.

A study carried out by Holland (2011) on the hydrogeological characterization of crystalline fractured aquifers in selected parts of Limpopo Province highlighted that the major challenge in groundwater exploration is understanding the factors responsible for secondary permeability in weathered – fractured rock aquifers. It was also highlighted that the basic assumptions underlying porous aquifers do not work for fractured aquifers because their heterogeneity has to be considered in the interpretation of groundwater hydraulic properties and also the choice of the conceptual modelling framework to be used. High borehole yields are associated with geological structure's depth and angle of dipping (dyke intrusion) and partially on the thickness of the regolith or overburden. Although, bedrock type, topographic and lithological setting, distance to surface water, all affected aquifer properties; the presence of transmissive heterogeneities such as dykes and lineaments was considered the most important factor. Alluvial deposits have high groundwater supply potential; however, they are limited in their lateral extent and easy movement of pollutants. Despite the apparent influence of regional factors on groundwater occurrence, the complexity of the weathered-fractured aquifer system suggests an over-riding influence of local features, which results in significant variations in yield and response to abstraction.

Groundwater storativity and transmissivity per unit area may be influenced by geologic factors such as enhanced fracturing and faulting, weathering enhanced permeability, coarse saprolite or presence of coarse sediments overlying the fractured crystalline aquifer system (Perrin *et al*., 2011; Roques *et al*., 2014; Lachassagne *et al*., 2011; Chilton and Foster 1995; Taylor and Howard 2000; Deyassa *et al*., 2014). Maurice *et al*., (2019) suggested that sustainability of high intensity abstraction of groundwater from fractured aquifer is dependent in part on whether there is groundwater recharge replenishing the high intensity abstraction. Therefore, in semi-arid areas like South Africa, this becomes a major challenge because recharge is relatively low in most areas. Alluvial overburden covering saprolites are important recharge pathway and a source of additional groundwater storage, and increase the saturated thickness of the underlying crystalline bedrock aquifer (Maurice *et al*., 2019).

Due to high cost and complexity of operation, most information on fractured aquifers in South Africa is obtained from single well as compared to the theoretical production and monitoring borehole. Dana and Jwan (2016) noted that transmissivity estimation is highly possible but specific storage is always overestimated in single borehole test due to well loss in the production borehole and this results in high drawdown value of the Cooper Jacobs plot of time against drawdown. Storativity depends on the radial distance from the observation borehole to the production borehole. However, in the absence of a monitoring borehole, the radial distance is interpolated from the well radius thus causing the specific storage to go out of standard range.

2.2 Basic Groundwater Exploration Approaches

Groundwater exploration in fractured aquifer system is a complex process due to hydrogeological complexity associated with it. Inadequacy in geomorphological, structural geological, topographical maps and review of previous reports in an area can add to the complexity of groundwater exploration in fractured aquifers. Therefore, assessment of the groundwater potential for groundwater exploration is mostly done through thorough review of historical data, geological maps, topographical maps, lineament mapping from satellite imagery, field observation and geophysical surveys. Geological maps are capable of revealing groundwater potential as geology influences the movement and storage of groundwater (Krishnamurthy *et al*., 1996). In recent years, with faster processing computers, GIS and Remote sensing techniques have been used to site borehole drilling areas by the use of thematic maps. The GIS overlay method has a benefit of including other factors which influence groundwater potential. However, for successful high yielding boreholes in South Africa, Sami (2009) placed special emphasis on a comprehensive geodynamic / strain analysis of the structural control of groundwater flow in the fractured aquifer. Figure 3 highlights basic pre-drilling groundwater exploration techniques.

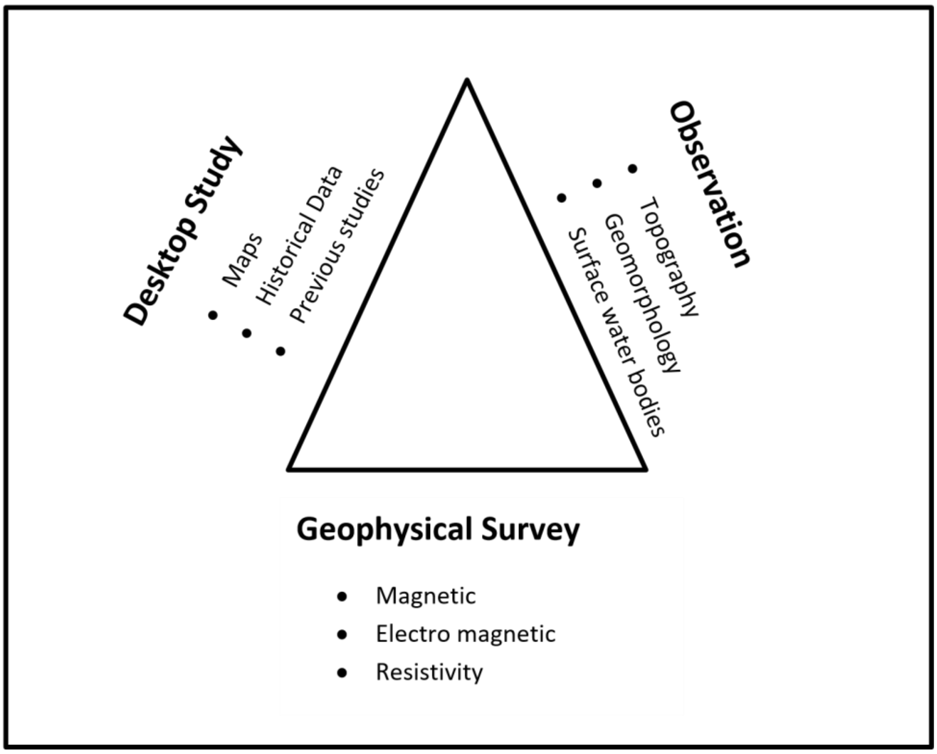

Figure 2.1: Methods of siting a borehole modified after MacDonald et al. (2005)

2.3 Geophysical methods

Geophysical investigations are performed to identify potential drilling targets for water supply. Surface geophysical methods such as magnetic, resistivity and electromagnetic can be used to reveal certain features about underlying geological structures and their potential to allow storage and preferential movement of the groundwater. For instance, weathered intrusions can act as preferential flow path for groundwater, the same can be said for faults and contacts such as bedding plane fractures. Identification of suitable drilling positions is important because production boreholes have to be placed in formations of high hydraulic conductivity formations in order to improve the potential yield.

2.3.1 Magnetic survey

The surface magnetic geophysics are conducted using magnetometers. The instrument directly measures the strength of the total magnetic field in nanotesla (nT) at a given locality. In general, every rock formation has its own magnetic properties depending on the mineral composition of that particular rock (Roux, 1980). The magnetic susceptibilities of the different rock types result in contrasting magnetic magnitudes. Thus, magnetic anomalies identified during the surveys can be interpreted to represent intrusive structures (such as dykes), geological contacts and faults which may have a bearing on the occurrence, storage and movement of groundwater. These geological structures are deemed to be primary targets in the selection of drilling sites for groundwater exploration. Traverses are conducted at right angles to geologic intrusions. The number of traverses vary depending on site conditions.

2.3.2 Resistivity method

The resistivity method is based on the fact that different geological units are more or less resistive to electrical current flow. A direct current (DC) or slowly varying alternating current (AC) current is injected into the earth by means of a pair of grounded current electrodes. The voltage drop between a pair of grounded potential electrodes is then measured at a selected position.

The resistivity method measures the apparent resistivity of soils and rock as a function of depth or lateral position. The apparent resistivity is the bulk average resistivity of all soils and rock influencing the current. It is calculated by dividing the measured potential difference by the input current and multiplying by a geometric factor specific to the array being used and electrode spacing. The resistivity of soils is mainly dependent on porosity, permeability, ionic content of the pore fluids, and clay mineralization.

Sounding resistivity method is also used to identify thick weathered regolith that has great potential for groundwater storage and flow properties. In general, electrical sounding is whereby the distribution of electrical resistivity with depth is studied progressively increasing the depth of investigation. On the other hand, resistivity profiling whereby the lateral distribution of electrical resistivity is studied by an electrode array for which the depth of investigation remains relatively constant. Profiling is most effective when lateral changes in resistivity are large. Traverses are conducted at right angles to geologic intrusions. The number of traverses varies depending on site conditions.

2.3.3 Electromagnetic (EM) methods

Electromagnetic methods provide a means to measure subsurface electrical conductivity and to identify subsurface metal objects. Electrical conductivity is a function of soil and rock type, porosity and permeability, as well as the composition of fluids that fill the pore spaces (McNeill, 1980). EM methods can be classified according to the:

- Source type being employed;
- Domain in which measurements are made (time or frequency domain)
- Source-receiver configurations employed (Vertical dipole and horizontal dipole) location in which measurements are made.

The EM do not require galvanic contact; hence, no electrodes have to be installed, implying less labour to do the survey in comparison to resistivity methods. EM techniques are not as sensitive to minor conductivity variations at surface as resistivity methods. The techniques are also not detrimentally influenced by the presence of low conductivity zones at shallow depths (such as the dry surface material). EM methods can be carried out in two different types of domain based on the type of instrument used. According to Balasubramanian (2007), Time-Domain Electromagnetic (TDEM) methods are based on the principle of using electromagnetic induction to generate measurable responses from sub-surface features. When a steady current in a cable loop is terminated, a time varying magnetic field is generated. As a result of this magnetic field, eddy currents are induced in underground conductive materials. The decay of the eddy currents in these materials is directly related to their conductive properties, and may be measured by a suitable receiver coil on the surface. The TDEM-Primary field is applied in pulses (20-40 ms) then switched off and the secondary field measured (same coil can be transmitter and receiver, more often large coil on ground and move small coil around).

The second method is the FDEM –Frequency-domain (FDEM) EM surveys. It is related to the measurements at one or more frequencies. The FDEM Transmitter produces continuous EM field. The secondary field is determined by nulling the primary field (need two coils).

EM methods are useful to locate saturated formations and features such as fractures and faults which potentially have high hydraulic conductivity. Faults and fractures can also act as preferential flow paths for contaminants and pollutants. Deep weathered regolith can also be identified using EM methods. Traverses are conducted at right angles to geologic intrusions whenever possible. The number of traverses also varies depending on site conditions. The source-receiver configuration can be classified as Vertical dipole and horizontal dipole, each with its unique advantages. One of the most common EM equipment used mostly in South Africa is the EM-34 Electromagnetic.

2.4 Pumping tests

2.4.1 Slug test

A slug test involves a sudden lowering or raising of the static water level in a borehole. This shifts equilibrium in the borehole by either increasing or decreasing pressure. By measuring the rate of recovery of the borehole, hydraulic conductivity (K) and transmissivity (T) can be estimated.

Despite the rapidness, with a slug test one can only determine the characteristics of a small volume of aquifer material surrounding the well and this volume may have been disturbed during drilling and well construction (Krusemann and De Ridder, 1990). In other words, it can only determine the effects of skin around the borehole. van Tonder and Vermeulen (2005) suggested that in South Africa, slug tests are carried out to estimate K in the close vicinity of the borehole and to get the first rough estimate of borehole yield. However, their findings were that it is problematic to estimate K and T using slug tests in fractured aquifers.

2.4.2 Step test

The purpose of step testing is to stress the borehole across its yield range for short intervals in order to select an appropriate abstraction rate for the constant discharge test. The final step should approach the estimated maximum yield of the borehole (Dross, 2011). A step-drawdown test is a single-well test in which the well is pumped at several successively higher pumping rates, drawdown for each discharge rate (step) is recorded with time. The duration (e.g. 1 - 2 hours) for each step is kept constant.

The main objective of the step test is to identify fracture positions and to choose a suitable rate for the constant rate test (Van Tonder *et al.*, 2001). The yield must be chosen so that the main water strike will be reached during the constant discharge rate test (Van Tonder *et al.*, 2001).

2.4.3 Constant discharge test

After the selection of the abstraction rate for the constant discharge test, the constant discharge tests are usually conducted for at least 24 hours in each borehole. The constant discharge test is conducted to fully stress the borehole but without exceeding the main water strike. Where there are existing boreholes within the vicinity of the pumping well, the drawdown is measured in observation boreholes for the purposes of estimating aquifer transmissivity.

2.4.4 Recovery test

After pumping is stopped in the step test or the constant discharge test, the water levels in the borehole and aquifer start to rise again which is called recovery or residual drawdown (Freeze and Cherry, 1979). The recovery of the water levels will be monitored until 95 % is achieved. Aquifer parameters can be estimated from the rate and pattern of recovery (Hiscock, 2005). The recovery test is more reliable than the other two because recovery takes place at a constant rate while on the other hand, it is very difficult to maintain a constant pumping rate in the real field. The recovery test is also usually used to verify the aquifer parameters estimated in the constant rate test (ICRC), 2011).

In the case of pumping wells, the Cooper and the Jacob (1946), has been found by Halford *et al*. (2006) to be the best method which can correctly estimate aquifer transmissivity from the pumping well drawdown data

$$T = \frac{2.3Q}{4\pi\Delta s} \quad \text{……………………………………………………………….Equation 2.1}$$

Where: Δs = the gradient of the straight

2.5 Pumping test analysis based on curve fitting

Pumping test analysis is usually done using curve matching techniques with different solutions developed for the various types of aquifers. Depending on the boundary conditions an appropriate theoretical solution must be used. Using an inappropriate theoretical solution is equivalent to comparing apples and oranges (Wu *et al*., 2005). No single analytical method can be applied to all crystalline basement aquifers when analysing pumping test data. Theis (1935) and Cooper and Jacob (1946) solutions are best applicable in homogeneous/uniformly fractured aquifers, Hantush and Jacob (1955) solution for leakage through the confining layer, while Neuman (1974) solution works well for unconfined aquifers and Moench (1984) solution for the double porosity model.

2.5.1 Aquifer parameters

Aquifer parameters such as hydraulic conductivity (K), transmissivity (T) and storativity (S) are the basic information required for aquifer investigation (Mondal *et al*., 2008). Storativity is the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer. Transmissivity is the rate at which groundwater flows horizontally through an aquifer. Hydraulic conductivity is the constant of proportionality that defines fluid flows through a porous media, which is dependent on permeability and the physical properties of the media. It describes the ease with which water can move through the fractures and pores. To estimate hydraulic conductivity, an empirical or experimental approach can be taken. Empirically, the study area's soil texture, grain size and pore size distribution and soil mapping units are correlated with areas with known values of hydraulic conductivity. Experimental techniques are constant-head method, falling-head method and auger-hole method.

2.5.2 Aquifer conceptual models

Characterizing hydraulic properties of an aquifer involve subjecting the borehole to a perturbation process such as pumping test, in order to study the aquifer response to such imposed stress (Renard et al., 2009). These data are interpreted through the help of numerical and analytical models to infer various hydraulic properties of the aquifer in question.

When dealing with fractured aquifers, the three main methods used to model groundwater flow are the equivalent porous media, the discrete fracture network and the dual porosity methods (Kröhn,1990). The equivalent porous media approach assumes that hydraulic properties can be described with a representative elementary volume (REV) concept. This approach is applicable to homogenous, densely fractured rocks or matrix blocks. Discrete fracture network approach is relevant for fractured rocks whose matrix is impermeable. Hence it accounts for the geometry of the flow path and properties of the fractures. The approach is suitable for smaller-scale groundwater modelling. In this approach is applicable when diffusion and storage in the matrix must be negligible. Dual porosity approach is a combination of the equivalent porous media and the discrete fracture network approaches. It is applicable to most types of fractured aquifers.

Homogeneously fractured aquifer

This type of aquifer is uniform and is considered to be the ideal. The assumptions are that:

- The aquifer is infinite in its lateral extent
- The aquifer is fully confined meaning that there is no leakage and/or recharge
- The aquifer is two dimensional
- The aquifer has homogeneous aquifer parameters such as transmissivity and storativity (Figure 2.2 left)

Under these assumptions, at the scale of interest the aquifer behaves identically to an unconsolidated aquifer as described by Theis (1935) and Cooper and Jacob (1946). In reality, these assumptions will be valid if a there is a dense network of uniform fractures intersecting the rock.

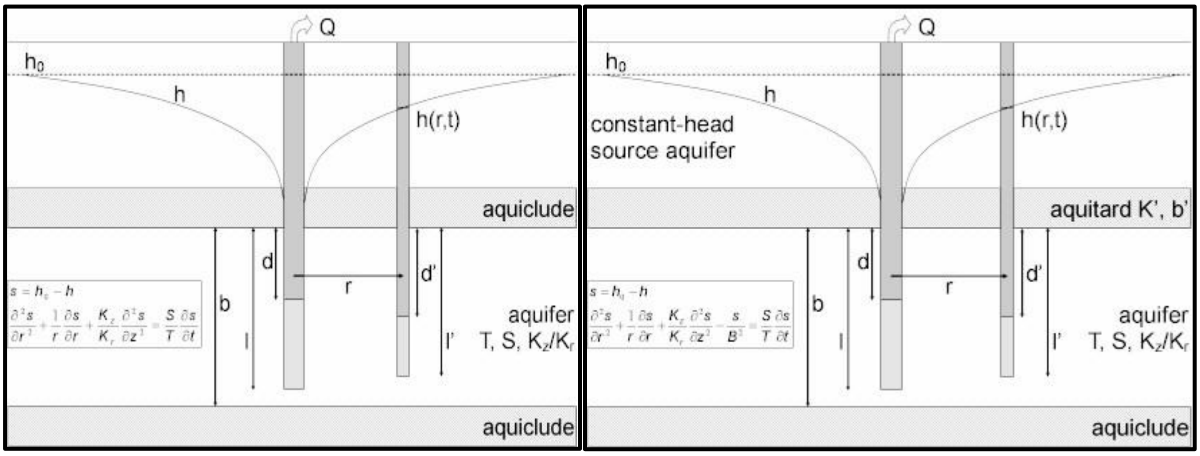

Figure 2.2: Illustration of an ideal confined aquifer (left) and a leaky aquifer (right) adopted from Holland (2011)

Leaky

This type of aquifer consists of a confined aquifer overlain by another aquifer on top of the aquitard (Figure 2.2 right). The assumptions are that:

- Recharge to the pumped aquifer comes from the overlain aquifer via the aquitard.
- The pumped aquifer is a homogeneous, isotropic aquifer.
- The flow is vertical in the aquitard.
- The aquitard only transmits and does not store water
- The head is constant in the overlain, unpumped aquifer
- The flow is constantly horizontal in the pumped aquifer

Hantush and Jacob (1955) describe the analytical solution for this situation and Moench (1985) has included wellbore storage and wellbore skin for simulating a leaky confined aquifer with aquitard storage.

Unconfined aquifer

This type of aquifer is underlain by an aquiclude, but is not restricted by any aquiclude or aquitard above it (Figure 2.3). Therefore, the phreatic (saturated) zone is in direct hydraulic relation with the vadose (unsaturated zone). The water table directly falls and rises according to any pumping and recharge, respectively. The approach most often used is based on the concept of a delayed water-table response. The solution to this aquifer type is described by Boulton (1954) and then Neuman (1974).

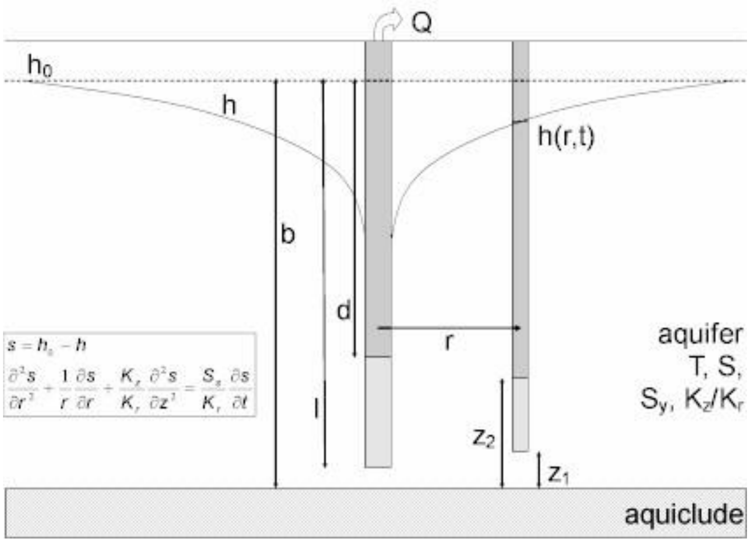

Figure 2.3: Illustration of an ideal unconfined aquifer

Aquifer with double porosity

This type of aquifer contains a combination of homogenous distributed conductive fractures and homogenous distributed matrix (Figure 2.4) (Barenblatt *et al*., 1960). Fractures and the matrix, both possess different storage and conductivity parameters. The matrix blocks are highly porous and have high storage capacity but low permeability. Direct flow to the well comes from the fractures only, which is radial. This becomes a homogeneous and continuous network of fractures in which the matrix blocks feed fractures with water.

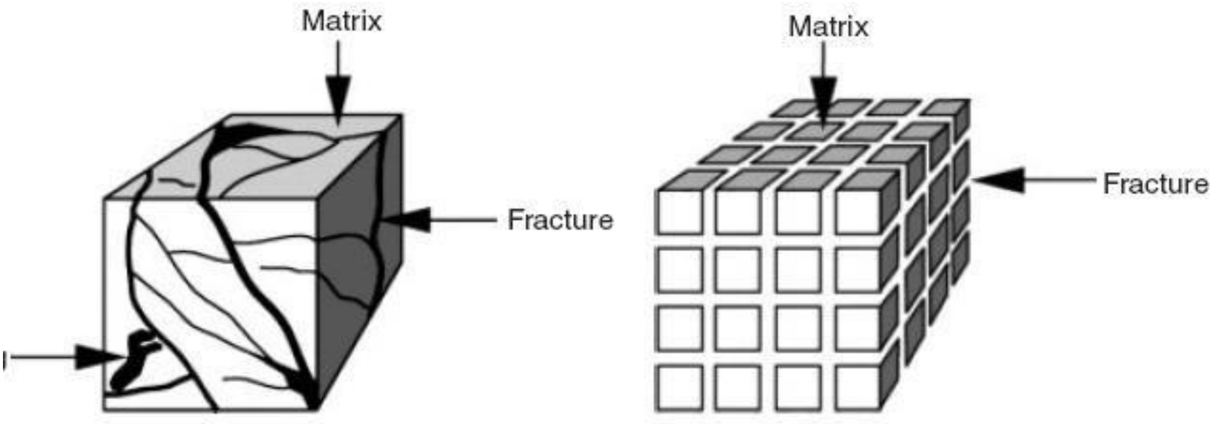

Figure 2.4: Illustration of double porosity (Cinco-Ley, 1996; Renard, 2005b).

Moench (1984) developed from Warren and Root (1963), Kazemi (1969) and presented the most complete solution for an aquifer with double porosity including wellbore storage, well skin and fracture skin. The typical time-drawdown curve observed is s-shaped and similar to that from an unconfined aquifer. Water is pumped from storage in the fractures during early-time and the matrix is passive. Water is the released from the matrix at intermediate-time. At this stage however, matrix drawdown is smaller than fractures drawdown. In late-time, matrix drawdown approaches fracture drawdown and the behaviour of the aquifer becomes similar to that of a single porosity aquifer.

Aquifer with individual fractures

This type of aquifer is a result of an individual fracture intersected by the well and acting as a drain in a larger porous aquifer. The approach assumes that a set of vertical fractures or a dyke can be represented by one vertical fracture which fully penetrates the confined aquifer (Bäumle, 2003). The unsteady-state flow to the well follows distinct flow phases (linear fracture flow, bilinear flow, radial flow and spherical flow).

2.5.3 Derivative plots

A diagnostic plot is a simultaneous plot of the drawdown and, the logarithmic derivative of the drawdown as a function of time in log–log scale (Bourdet *et al*., 1983). Derivative plots are used to identify the appropriate conceptual model that best interprets the data (Figure 2.5). The main advantage of using derivative plots is that they introduce unified approach of interpreting data from pumping tests. The other advantages of a derivative plot are that:

- It can detect behaviours that can be unseen from drawdown curves alone because of high sensitivity to changes in the drawdown curve.
- It enables the selection of conceptual model.
- The value of the derivative can be used to directly estimate aquifer parameters for certain conceptual models.

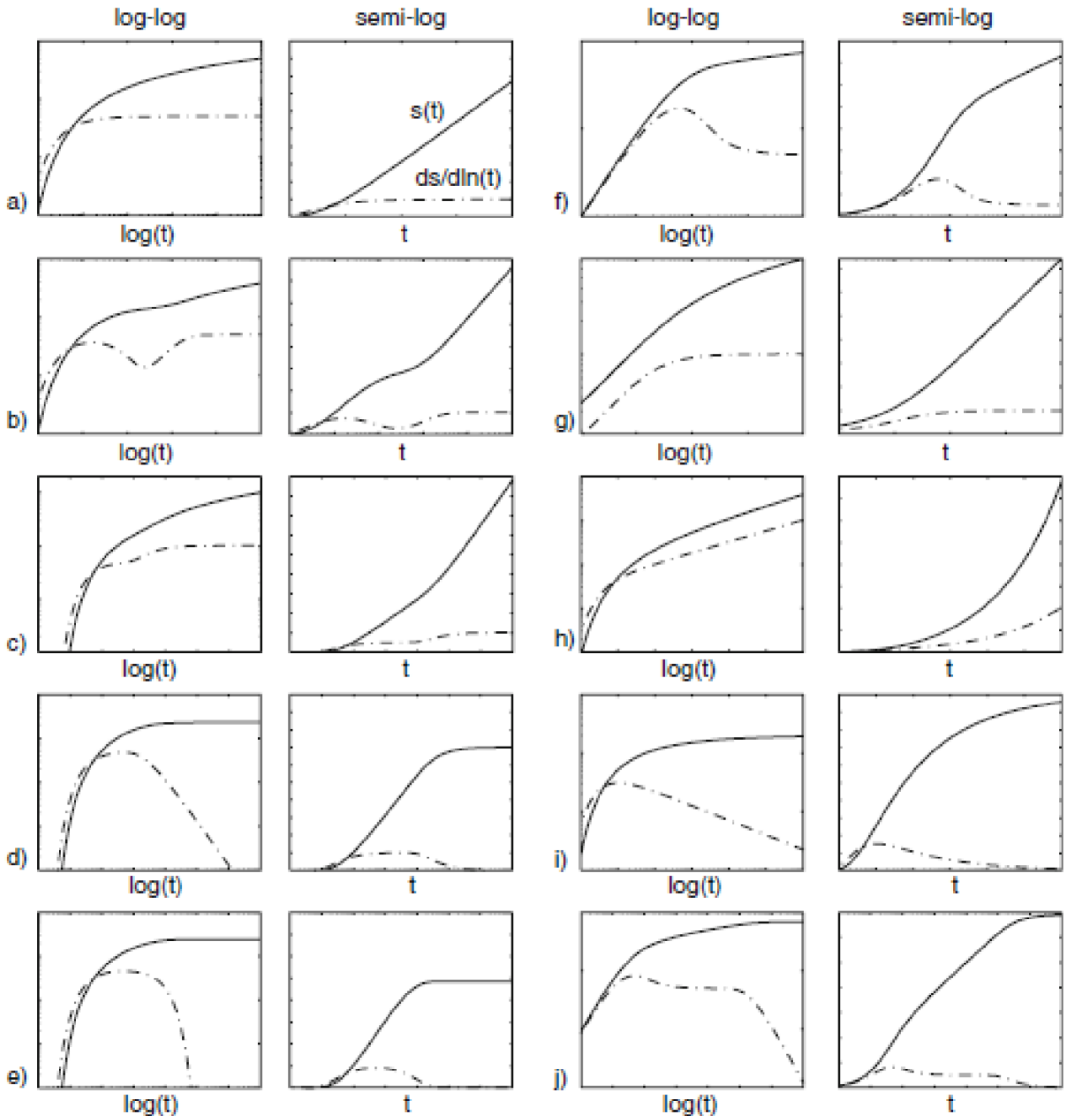

Figure 2.5: The typical derivative plot found in pumping tests data analysis (Renard et al., 2009).

- Theis model: infinite two-dimensional confined aquifer;
- double porosity or unconfined aquifer;
- infinite linear no-flow boundary;
- infinite linear constant head boundary;
- leaky aquifer;
- well-bore storage and skin effect;
- infinite conductivity vertical fracture.;
- general radial flow—non-integer flow dimension smaller than 2;
- general radial flow model—non-integer flow dimension larger than 2;
- combined effect of well bore storage and infinite linear constant head boundary

2.5.4 Interpretation of derivative Plots

Interpretation of derivative plots is usually done by analysing the pumping test data in different time phases. The early-data enables for detection of well bore storage. Intermediate-time data enables for the identification of the type of aquifer conceptual model that best suits the data. Late-time data enables the identification of boundaries (Renard *et al.*, 2009). A practical tool to use is the flow regime identification tool (Ehlig-Economides *et al.*, 1994) (Figure 2.6). By superimposing the diagram on the data and shifting, the type of flow in each phase of time during the test (early, intermediate and late) can be identified.

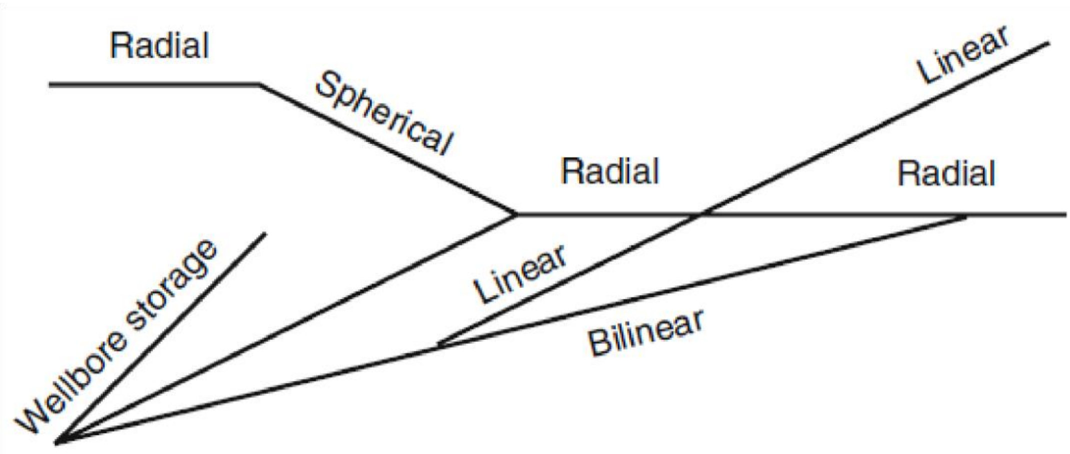

Figure 2.6: Flow regime identification tool (Ehlig-Economides et al., 1994)

Table 2.1: Theoretical solutions for different types of aquifers (Adapted from Holland, 2011)

Aquifer Type/*Characteristic*	Flow regime	Diagnostic plots			Typical theoretical model
		Semi-log	*Log-log*	*Derivative {special }*	
Homogenous, isotropic	radial	straight	(Theis-type)	stabilises	Theis (1935) / Cooper and Jacob (1946)
Leaky				decrease	Hantush and Jacob (1955) Moench (1985)
Unconfined			typical S-shape	slight dip (early times) stabilises	Neuman (1972, 1974).
Double porosity	linear or Bi-linear (early times) radial	two parallel straight-line sections	typical S-shape	characteristic dip stabilises	Warren & Root (1963) Moench (1984)
Single vertical fracture or dyke	linear flow (fracture)	reverse C-shape	straight line, slope 0.5	straight line, slope 0.5	Cinco-Ley and Samaniego (1981) Boonstra & Boehmer (1986)
	bilinear		straight line, slope 0.25	straight line, slope 0.25 {s vs $t^{1/4}$: straight}	
	linear (formation)		straight line, slope 0.5	straight line, slope 0.5 {s vs $t^{1/2}$: straight}	Gringarten et al. (1974)
	pseudo-radial	straight line		stabilises	Theis (1935) / Cooper & Jacob (1946)
Single horizontal fracture	storage		straight line with 1 slope		Gringarten and Ramey (1974)
	linear		straight line with 0.5 slope	straight line with 0.5 slope	
	pseudo-radial	straight line		stabilises	
General radial flow	n < 2 (linear)			positive slope	Barker (1988)
	n > 2 (spherical)			negative slope	
Fracture dewatering	-	flattening at fracture position		characteristic hump(s) (intermediate to late)	
Closed no flow boundary		tripling of slope	-		Kruseman and de Ridder (1990)
Recharge boundary		Decrease in slope		strong downward trend	

2.6 Boundary conditions

Pumping test data curves of drawdown usually deviate from the theoretical curves of the main types of aquifer. The cause of the deviation is the existence of specific boundary conditions for example. These boundary conditions may exist individually, but often exist in combination. Below are some conditions which occur in unconsolidated, confined aquifers (Kruseman and De Ridder, 2000).

2.6.1 Partial penetration of the well

The assumption that the pumped well fully penetrates the aquifer is made when modelling groundwater flow towards the well using theoretical models. Under this assumption, water flows horizontally to the well. However, in reality, if the well is not fully penetrating the aquifer then the assumption becomes invalid. Thus, the flow of groundwater towards the well will no longer be horizontal and will possess a vertical component. Such vertical components of groundwater flow result in extra head losses in the vicinity of the well (Figure 2.7a).

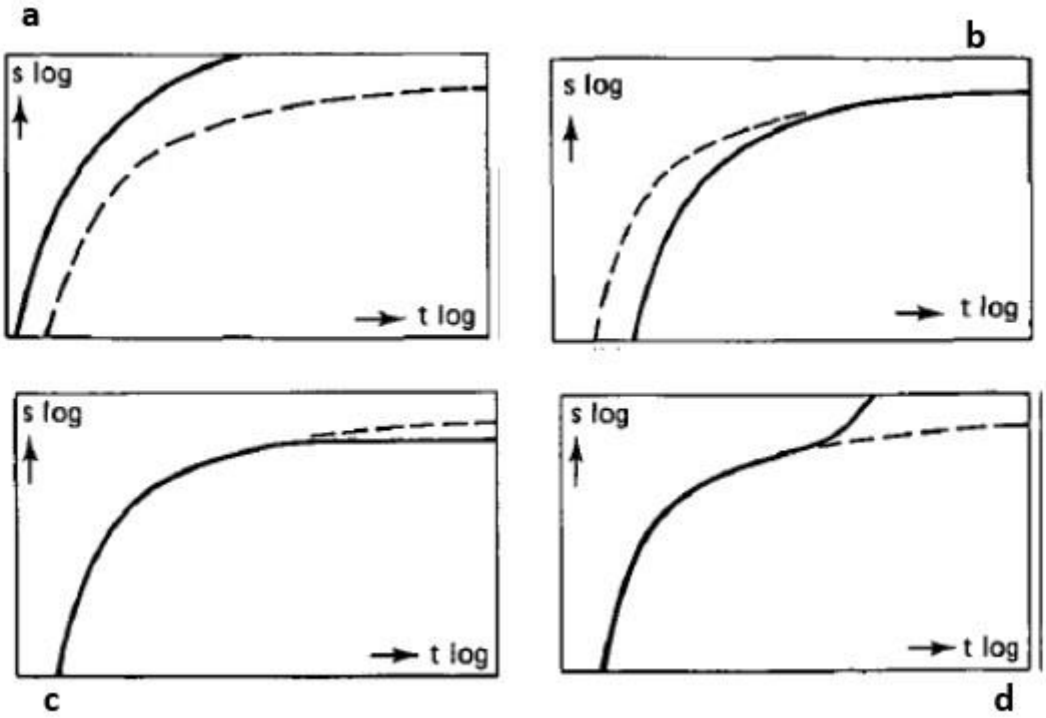

Figure 2.7: Showing deviations from theoretical curves caused by a) partial penetration, b) wellbore storage, c) recharge boundary and d) impermeable (no-flow) boundary

2.6.2 Well-bore storage

The assumption that well-bore storage in a pumped well aquifer is negligible is made on the basis that there is a theoretical sink. However, in reality, all wells have a certain dimension which inevitably stores some water. This well-bore storage must first be removed when at the beginning of pumping. This effect increases directly with the diameter of the well. Clearly, well-bore storage will appear at early-time phase of the pumping test. Well-bore storage is revealed by a straight-line with a slope of one at the early-time in a log-log plot of drawdown against time (Figure 2.7b).

2.6.3 Recharge or impermeable (no-flow) boundaries

Presence of recharge boundaries and impermeable boundaries also do cause the drawdown curve to deviate from the theoretical curves. Figure 2.7c shows the effect of presence of a recharge boundary to the cone of depression. The effect of impermeable boundaries on the drawdown is contrasting the effect of a recharge boundary. Drawdown doubles when the cone of depression reaches a no-flow boundary (Figure 2.7d) (Kruseman and De Ridder, 2000).

2.7 Sustainable yield

Borehole sustainable yield can be defined as the discharge rate at which a borehole must be pumped in such a way that the water level must not drop below a specified level (for example, main water strikes such as fractures and other flow zones) in the borehole after abstracting water from the borehole for a long time (for example, 2 years) without any recharge taking place (van Tonder *et al.*, 2001). Determination of the sustainable yield allows is important in that it highlights the abstraction rates which are applicable to an aquifer in order to avoid overexploitation. The FC method for estimating borehole yield (van Tonder *et al.*, 2001) that was specifically developed for single borehole is proposed for this investigation.

2.8 Groundwater quality

The quality aspect is equally important to the quantity aspect in groundwater assessment. Water quality determines the uses to which groundwater can be allocated. For domestic supply purposes groundwater usually has a natural good quality (Chilton and Foster, 1995). There is a general notion that groundwater is portable, but this is not always the case. Groundwater quality can be affected by pollution from both natural and anthropogenic processes such as mining and agriculture. Depending on the recharge scheme of the aquifer, groundwater quality can also vary due to seasons. The major problems found in groundwater quality are hardness of water, iron, nitrogen, fluorine, silica, sulphur and total dissolved substances. In more general terms, these are referred to as heavy metals and mineral nutrients.

Fractured crystalline basement aquifers exhibit secondary porosity thus, groundwater movement as well as pollutant movement is easy within the flow pathways (fractures). This implies that, the Lebalelo South aquifer is likely to have high risk of pollution. Presence of natural arsenic in water in Bangladesh and fluoride in India are examples where consumers of water with exceeding concentrations suffered toxic effects (Marais, 1999). The western parts of South Africa have been found to have high fluoride concentrations in groundwater (Stats SA, 2005). McCaffrey and Willis (1993), Fayazi (1994), McCaffrey and Willis (2001), Odiyo and Makungo (2012), amongst others, have reported that the major cause of dental fluorosis in South Africa is high fluoride content in groundwater. In many rural areas, groundwater is used without treatment. Samie *et al*. (2011) reported that groundwater supply to schools in Greater Giyani municipality had counts of harmful organisms which were higher than the Department of Water and Sanitation (DWS) standards for domestic use. Potgieter *et al*. (2007) and Bessong *et al*. (2009) also reported diarrhoea outbreaks in Limpopo Province as a result of microbial contamination of groundwater. This brings out the need to determine the quality of the water regularly and to compare with national standards (Ncube and Schutte, 2005).

There are three main classes of groundwater quality variables. These are physical, chemical and microbiological variables. The choice of groundwater quality variables to assess depends on various factors. The main factors are objectives of assessment, feasibility and cost of assessment (Chapman, 1996). In this study groundwater quality variables are chosen with the knowledge that groundwater characterisation is done for domestic water supply purposes.

With regards to domestic water supply, water colour, odour, suspended solids, turbidity, pH and hardness should be assessed. The colour of water can indicate pollution, although transparency of water does not confirm purity. For example, presence of blue-green algae or diatoms can cause blueish-green and yellowish-brown water colours, respectively. Again, presence of zooplankton can result in colours such as purple and red. Odour and turbidity are a result of dead microorganisms in the water (Chapman, 1996). pH anomalies can be an indication of industrial pollution by acids or alkalis. Polluted water produces significant and lethal consequences to human health. Water hardness makes it difficult to wash clothes and produces scales in electric appliances. Most of these variables are measured at the field using portable instruments. Chemical variables are mainly metals such as Ca, K, Mg, Na and trace metals which include arsenic (As), cadmium (Cd), iron (Fe), lead (Pb), selenium (Se), zinc (Zn), mercury (Hg); anions such as nitrate (NO_3) and fluoride (F), cyanide (CN), chloride (Cl) and Sulphates (SO_4) (Feldman *et al*., 2007).

2.8.1 Water quality analytical methods

Ions can be determined by a variety of techniques, of which many recent studies on chemical quality of water focused on ion chromatography (IC), flame and graphite furnace atomic absorption spectrometry (F-AAS and GF-AAS), mass and optical emission inductively coupled plasma spectrometry (ICP-MS and ICP-OES) (PerkinElmer, 2011). Table 2.2 shows the factors that influence choice of analysis technique.

Table 2.2: Factors affecting choice of analytical techniques (PerkinElmer, 2011)

	Flame AAS	GF AAS	ICP-OES	ICP-MS
Number of elements: Single	▪			
Few		▪		
Many			▪	▪
Levels: High ppb	▪		▪	
Sub ppb		▪	▪	▪
High ppt				▪
Sub ppt				▪
Number of samples: Very few	▪	▪		
Few	▪	▪	▪	▪
Many			▪	▪
Amount of sample: >5ml	▪	▪	▪	▪
<2ml		▪		

F-AAS and GF-AAS both make use of electromagnetic spectra produced after light is passed through a sample. In F-AAS the sample is introduced into the flame as a fine spray by the aerosol chamber.

A very minute portion of the sample actually reaches the flame and the retention period for the sample is very small. This inefficiency in sampling has been countered in the GF-AAS by introducing the sample into a graphite tube, where all the sample is atomized. This improves detection and sensitivity limits but also increases analysis period. AAS methods can only analyse one element at a time. This makes AAS most useful when there is a large number of samples and a single or few elements are being analysed (PerkinElmer, 2011).

An ICP is a plasma of argon which can produce very high temperatures, as high as 10 000 ˚C. At such temperatures, total atomization of the elements takes place in a sample. This greatly reduces occurrence of interferences (Chapman, 1996). An OES measures the light emitted by the elements in a sample introduced into an ICP. Comparison of observed intensities with the standard intensities of known concentration gives the concentrations of elements in the sample. An MS classifies and quantifies number of atomized ions from the ICP, according to mass-charge ratio to get concentrations. Both OES and MS use the same ICP for sample introduction but different quantifying techniques (APHA, 2005)

Ion chromatography can also be used to measure concentrations of anions and cations, with detection limits of parts per billion (ppb). It is the standard method used to analyse for anions, with advantages of multi-species analysis at a single sample run and ability to analyse solutions. The principle of ion chromatography is used to separate ions in the liquid sample and measure the concentrations. The liquid sample is passed through a chromatographic column which contains an electromagnetically charged resin. The resin attracts the ions and they adsorb on it. Eluent, a liquid which extracts the ions from the resin, is then run through the column, causing the ions to separate from the resin. Ions separate at different times because of the differences in attraction to the resin caused by type and size of the ions. As the ions separate from the resin, they gravitate to the chamber where they are detected and quantified. The eluted ions form peaks on the dictator, which can be identified by the retention times (APHA, 2005; Chapman, 1996).

Physical water quality parameters are mostly measured onsite using mobile specialized meter (e.g. turbidity meter) or combined multimeter (pH/EC/Temp multimeter). In-situ measurement of physical water quality parameters is important because some of the parameters are affected by atmospheric exposure. Such parameter includes temperature. However, not all physical parameters are affected as parameters such as Electrical conductivity (EC) and Total Dissolve Solids (TDS) can be measured in the laboratory using more sophisticated equipment like Ion Chromatograph and ion selective electrodes.

2.7.2 Water types

In the subsurface many, complex hydrochemical processes occur. Determination of hydrochemical facies is very useful in the characterisation of an aquifer. Hydrochemical facies have been used in chemical assessment of groundwater for decades. Hydrochemical facies give information on the origin of the chemical quality of groundwater. The methods have undergone sizeable modifications but underlying principles did not change. The effort of Hill (1940) was improved by Piper (1944) and subsequently modified by Durov (1948).

Piper diagrams are made in such a way that the milliequivalents percentages of the major cations and anions are plotted in separate triangle. These plotted points in the triangular fields are then projected further into the central diamond field. The central diamond field shows the general character of the groundwater. In Chadha´s diagram, however, the difference in milliequivalent percentage between alkaline earths (calcium + magnesium) and alkali metals (sodium + potassium), is expressed as percentage reacting values. This is then plotted on the X axis, and the difference in milliequivalent percentage between weak acidic anions (carbonate + bicarbonate) and strong acidic anions (chloride + sulphate) is plotted on the Y axis. The resulting field of study is a square or rectangle, depending upon the size of the scales chosen for X and Y co-ordinates. The milliequivalent percentage differences between alkaline earths and alkali metals, and between weak acidic anions and strong acidic anions, would plot in one of the four possible sub-fields. The major advantage of this diagram is that it can be drawn in any spreadsheet software packages (Chadha, 1999). Groundwater types were used by many researchers in their studies to understand the controlling factors of the water chemistry (Aris *et al*., 2009; Martos *et al*., 2002; Mondal et al., 2010; Ramesh and Elango 2012).

3. RESEARCH METHODOLOGY

3.0 Preamble

This chapter covers the scientific groundwater exploration approach, as well as the quantitative analysis of the hydraulic properties of the aquifer under investigation for long-term sustainable yield estimation. Methods for hydrochemical investigation as well as the quality of the groundwater in the study area is also covered in this chapter. This chapter provides a systematic approach in the determination of the hydrogeochemical and aquifer properties of groundwater in Lebalelo South.

3.1 Geophysical exploration

3.1.1 Magnetic Survey

Magnetic Survey was conducted using a Geotron model G5 Proton-precession magnetometer. The instrument directly measures the strength of the total magnetic field in nanotesla (nT) at a given locality. In general, every rock formation has its own magnetic properties depending on the mineral composition of that particular rock (Le Roux, 1980). The magnetic susceptibilities of the different rock types result in contrasting magnetic magnitudes. Thus, magnetic anomalies identified during the surveys can be interpreted to represent intrusive structures (such as dykes), geological contacts and faults which may have a bearing on the occurrence, storage and movement of groundwater. These geological structures were primary targets in the selection of drilling sites for groundwater exploration in Lebalelo South. Dolerite dykes and sill are ferromagnetic rock which are primary targets for groundwater exploration. Dolerite dykes are formed at great temperature during magmatic crystallization, therefore when dolerite dykes intrude parent rock at great temperature, contact metamorphism occur (Van der Westhuizen *et al*., 2000). These regions of contact metamorphism are called baked zones and they can be detected by the use of magnetometer.

Single traverses were constructed for each target structures. Traverses were conducted to intersect target structures at angle. Station spacing of 5m was used on all magnetic survey traverse. This station spacing was used in order to obtain maximum resolution and representation of the subsurface configuration. The length of the traverses varied depending on site conditions. During magnetic data acquisition, prominent features such as fences, metallic structures, and railroads that act as potential sources of noise and spurious spikes in the collected data were noted and corrected following Philip *et al*. 2002. Corrections (smoothing, removal of regional magnetic anomaly and establishment of zero line) were done similarly to the method of Roux et al, (1980). The G5 proton magnetometer used during the survey measures both regional and residual magnetic data as total magnetic field intensity. The regional and residual separation technique employed by Oldham and Sutherland (1955) was used in this study. The regional magnetic removal was done by Least Square fitting a low-order polynomial to the observed field data in Excel spread sheet. Smoothing was done by using simple 3-point running average method, while zero line was established by drawing E-line (a straight line connecting the highest and the lowest point of the anomaly) according to Werner (1953).

$$|B| = \frac{A + B + C}{3}$$

……….Equation 3.1

After processing, magnetic data were presented in the form of profiles from which interpretations of the subsurface characteristics were done. Magnetic Storm was not encountered during magnetic data acquisition as most of the survey was carried out very early in the morning.

Magnetic Susceptibility of the causative body was calculated using

$$K = \frac{0.5 \times 4\pi \times 2 \times \overline{T}}{W \times Ht}$$

……….Equation 3.2

Where K= susceptibility in SI unit

Z= Depth to top

$\overline{T}$= Amplitude of the anomaly

W= Width of the causative body

Ht= The earth's magnetic field

The estimated depth to top (depth of burial of dykes) was calculated using the ½ width rule.

The values obtained were curve fitted on a thin dyke anomaly for Dip estimation (Figure 3.1). The values were then plotted on Pdyke software for forward TMI modelling of the anomaly obtained. The Pdyke forward modelling was used to validate the result obtained from the thin dyke anomaly model.

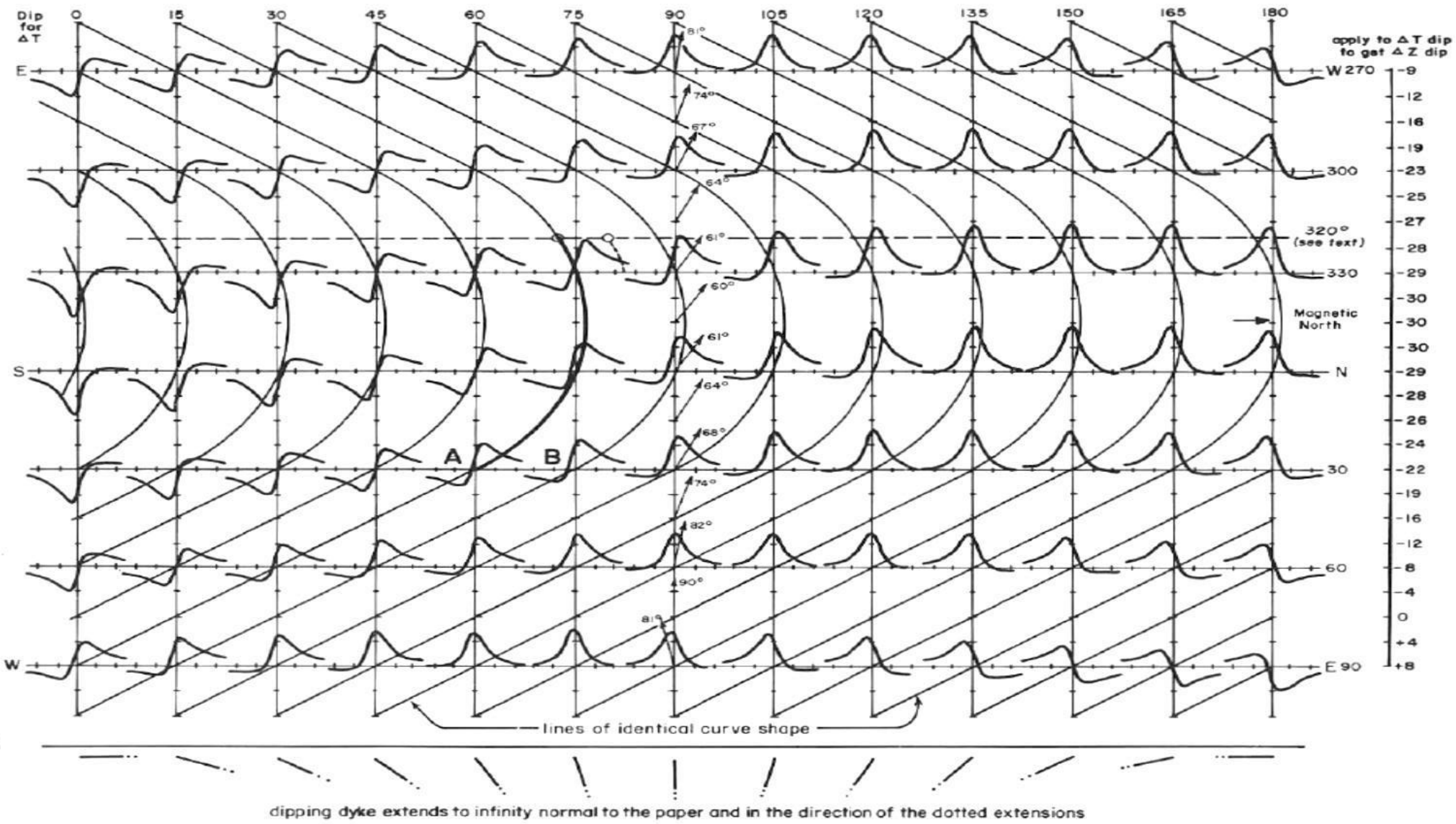

Figure 3.1: A thin dyke anomaly curve (Roux et al., 1980)

3.1.2 Electromagnetic survey

Electromagnetic survey was carried out to further compliment and investigate the anomalies obtained during magnetic survey. The electromagnetic survey was carried out on the same traverse laid out during the magnetic survey in order to investigate sub-surface geologic structures influencing groundwater storage. The EM survey was conducted using the FDEM 8BT instrument. This instrument is an active, frequency domain system (Very-Low Frequency Electromagnetic Method) that calculates an apparent conductivity of the earth by measuring the quadrature (out-of-phase) component of the secondary magnetic field at low induction numbers. According to Sundararajan, *et al*. (2007), VLF-EM are good for detecting fractured and weathered zones especially in crystalline basement rocks and also perfect for locating vertical intrusions like dykes (Payne, 2004). A station spacing of 10m and coil spacing of 40m was used. Maximum coil spacing was used in order to have the maximum depth of investigation. Only vertical dipole configuration was used because FDEM-8BT only supports vertical dipole. Vertical dipole is good for the detection of geological structures like vertical dykes (Payne, 2004).

3.2 Borehole drilling and testing

Four (4) boreholes were drilled between the summer months of October and December 2015. The drilling was carried out using rotary air percussion drilling machine powered by Doosan XHP1170 compressor. Three (3) types of drilling bits were used during drilling. The 10-inch (254 mm) drilling bit was used for reaming purpose, while the 6½ inch (165 mm) drilling bit was used for normal downhole drilling. However, in geological formations prone to collapse, a 4-blade PDC hole opening drilling bit was used to open up the alluvial formation for easy access by other drilling bits. Plain and perforated steel casing with a diameter of 171 mm was used for all the drilled boreholes. The perforated casing was used in formation where water strikes occurred while the plain steel casing was used for incompetent formations prone to collapse (clay). The 254 mm drilling bit was used until solid rock formations are encountered and the 165 mm was used to complete the boreholes to depth. Borehole logs are presented in chapter 4.

3.2.1 Step test

The test was carried out using a positive displacement pump (PD) also known as a mono-pump. This pump operates by mechanically inducing a vacuum in a chamber and then draws water out of the borehole by mechanical force. This type of pump is advantageous because it can pump water at high pressure and can work in wide pressure range. The pump head is driven by a motor fitted with an accelerator, gearbox and clutch. The pump was installed below the main water strike. This was done because in order to successfully determine a sustainable discharge rate, the main fracture or main water strike needs to be dewatered (van Tonder, 2001). A single well test was carried out for all the drilled boreholes in the study area. Each borehole was pumped at several successively higher pumping rates (steps), drawdown for each discharge rate (step) was recorded with time using Solnist model 101 dip meter. The step test consisted of four (4) steps, with each step lasting for about sixty (60) minutes. The step test was used to evaluate well performance and in choosing a suitable discharge rate for the constant rate test. The discharge rate was measured using a bucket and stopwatch. The discharge rate was calculated by dividing the volume of the bucket by the time it takes to fill it up.

3.2.2 Constant discharge test

A single-well constant discharge test was carried out after the selection of the abstraction rate for the constant discharge test. The constant discharge testing was conducted for 24 hours for each borehole. During pumping, drawdown was measured using Solnist model 101 dip meter, and the method for calculating the discharge rate is the same as the one used during step test.

The borehole was allowed to fully recover before the start of the constant discharge test.

3.2.3 Recovery test

After pumping was stopped, the water levels in the borehole and aquifer start to rise again which is called recovery or residual drawdown (Freeze and Cherry, 1979). The recovery of the water level was monitored until 95 % recovery was achieved using Solnist model 101 dip meter.

3.2.4 Pumping test analysis

Pumping test data from the pumping period and recovery tests was evaluated and interpreted to determine aquifer parameters. Groundwater flow regimes during the pumping period were characterised using diagnostic plots (log-log, semi-log and derivative plots) in order to identify the best analytical model that matched the data. Internal and external hydraulic boundaries were also identified.

AQTESOLVE version 4.50.002 software for analysing pumping test data was used to analyse and visualise the drawdown data. AQTESOLVE is a powerful software which has solutions for most of the typical conceptual models for aquifers. Solutions for confined, leaky, unconfined and fractured aquifers are available for the user. The procedure illustrated in the literature of the software involves:

- Plotting the drawdown versus time on log-log and semi-log sheets
- Plotting the derivative of drawdown vs time log-log and semi-log on the same sheet

The drawdown derivative is calculated using equation 3.3

$$\left(\frac{\partial s}{\partial \mathrm{InT}}\right)_i = \frac{(\Delta s_{i-1}/\Delta \mathrm{InT}_{i-1})\Delta \mathrm{InT}_{i+1} + (\Delta s_{i+1}/\Delta \mathrm{InT}_{i+1})\Delta \mathrm{InT}_{i-1}}{\Delta \mathrm{InT}_{i-1} + \Delta \mathrm{InT}_{i+1}} \quad \text{............................Equation 3.3}$$

Noise can distort the shape of the derivative curve and thus lead to misinterpretation of results. To remove the noise effect on the derivative plots, the smoothing differentiation was applied with a factor of 2.

From the semi-log and the log-log plots of drawdown and the derivative versus time, visual inspection was made in order to determine the most appropriate conceptual (Figure 2.5) model to apply for the calculation of hydraulic parameters. Categorically, early time of the curves was used to determine if there were significant well bore storage effects. Intermediate-time data was used to identify the type of aquifer conceptual model that best suited the data. Late-time data was used to identify existing boundaries. Since it is usual that there is no unique conceptual model to describe the prevailing field conditions, attention was given to the geology and other data available for each borehole site in order to single out a solution to apply.

3.3 Groundwater quality assessment

3.3.1 Sampling

Groundwater samples were collected after constant pumping of at least four (4) hours. This was done to ensure sampling of the representative groundwater from the aquifer matrix or fracture(s) as the case may be, rather than sampling of the well bore storage. The samples were pre-rinsed with the sample water as illustrated in water sampling guide by Weaver *et al.* (2007). The samples were collected in the summer months of December, 2015. The samples were collected in a 1L sterile plastic bottle as illustrated by Harvey (2000). The samples were placed under ice-cubes in a cooler box, and transported to the laboratory within hours of collection.

3.3.2 Sample preparation

Sample preparation was done at Capricorn Veterinary Laboratories, which is South African National Accreditation System (SANAS) certified for chemical analysis. The samples were stored in a refrigerator at a temperature of 4˚C and analysed within seven (7) days of collection. However, prior to the analysis, the samples and reagents were subjected to room temperature of 25˚C because temperature changes above normal room temperature affects the reliability of the result. The pH meter was calibrated using pH buffer 4.01 and 6.00. The calibration was carried out according to the manufacturer's specification and the calibration slope was 98%, which falls within the recommended limit. The samples were analysed for drinking and domestic water quality parameters (physical and chemical) in line with SANS (2006, 2011).

3.3.3 Sample analysis

The physical properties such as hardness, EC, turbidity and pH of the groundwater were evaluated to determine its suitability for use. Hand-held pH meter was used to measure the pH. EC was determined by titration while turbidity was determined using a Spectioquant pharo 300 spectrophotometer.

The chemical analysis incorporated major and trace chemical constituents as well as heavy and trace metals. In order to assess the quality of the groundwater in terms of its suitability for drinking and domestic, the measured concentrations of various parameters were compared to the target water quality limits given in DWAF (1996), SANS (2011) and also WHO (2011). The metals and non-metals selected for analysis were the selected in accordance to with drinking water requirement of SANS 2006.

In the laboratory analytical equipment were calibrated according to the manufacturer's procedures. ICAP 6000 series (ICP-OES) was used for chemical analysis of metals, which included Ca, K, Mg, Mn, Na and the trace metals which include Fe, Zn, Hg (United States Environmental Protection Agency (USEPA), 1994; APHA, 2005). The ICP-OES method was preferred because it can measure the concentrations of several cations and anions on a single run. Another advantage is that ICP-OES is more accurate up to sub parts-per-billion (PerkinElmer, 2011). Wet acid digestion was carried out according to USEPA method 3005 (USEPA, 1992). A well-shaken sample of aliquot was poured into a 50 ml centrifuge tube. There after 2 ml of concentrated HNO_3 and 1 ml of concentrated HCl was added. The sample was covered with a ribbed watch glass (plastic) and heated to reduce volume to 30 ml. After cooling, the tube walls and watch glass were washed down using water. The sample was filtered into 50 ml volumetric flask. Water was then added for the volume to reach 50 ml.

Ion Chromatography (IC) instrument Dionex ICS 2000 was used to analyse for anions. It is the standard preferred method of analysing for anions in water samples. Chemical parameters analysed using IC include major anions such as nitrate (NO_3) and fluoride (F), cyanide (CN^-), chloride (Cl) and Sulphates (SO_4). Dionex AS22 (45mM Na_2CO_3 and 1.4mM $NaHCO_3$) eluent was used. The Ion chromatograph was allowed to stabilize for like 20 min before the actual sample analysis was started. Some of the samples were diluted using standard addition method because the conductivity of the samples exceeded 500µs/cm. Dilution was necessary because the conductivity above 500µs/cm causes interference to the retention time, retention area and peak height of the analyte from the matrix element from the sample (Shimizu *et al*., 2006). The samples were loaded into the auto sampler and the samples were analyzed automatically and the readings recorded.

3.3.4 Quality assurance

During sampling, sterile sampling bottles were pre-rinsed with the samples to avoid cross contamination that could have occurred during post-production and transportation of the sampling bottles to the sampling point.

The samples were properly tightened to avoid leakage and placed under ice cubes, in an air-tight cooler box during transportation to the laboratory.

To avoid mis-identification of samples, the sterile sampling bottles were marked with a permanent marker for easy identification.

The analytical equipment was calibrated to the manufacturer's specification and recommendation

The samples were analysed in triplicates to ensure maximum accuracy and precision

Laboratory cross-contamination was avoided by pre-rinsing the apparatus with deionized water.

The laboratory temperature was kept between 20 - 25˚C

Analytical results were validated to ensure accuracy in the results. The validation was done using charge balance. The charge balance is founded on the theory that every solution must maintain neutrality.

The charge balance error was kept within the recommended limit of ±5%

During drilling, the borehole chippings were logged per every 5m and in case of lithology change, they were logged per change of lithology and change in colour. This was done to ensure full representation.

During step test and constant discharge test, borehole yields were measured in triplicate to ensure accuracy and precision.

The boreholes were purged for at least 4 hours before groundwater sampling was carried out. This is to ensure that water from well bore storage is flushed out and fresh water from the aquifer matrix and fracture(s) are sampled.

3.3.5 Groundwater mineralization

A hypothesis has been postulated earlier about the possible dominant mineralisation process of the groundwater in the study area. The mineralisation has been inferred to be caused by the residency of groundwater in the dolomitic and alluvium/scree aquifers. However, Gibbs plot was used to determine the major geological process responsible for the mineralisation of groundwater in the study area. The TDS of the groundwater samples collected was plotted against Equation 3.4

$$\boldsymbol{\frac{Na + k}{Na + k + ca}}$$

…..Equation 3.4

4. RESULTS AND DISCUSSIONS

4.1 Preamble

This chapter contains the results and discussions of experimental work done in Lebalelo South, Limpopo province of South Africa. The results of the ground geophysical surveys conducted across major mapped geological structures, identified during reconnaissance investigation are presented in this chapter. This chapter also encompasses the behaviour of the existing and newly sited and drilled boreholes in terms of aquifer characterization for effective groundwater yield estimation. The hydrochemistry and the chemical signature of the boreholes in the study area were discussed in this chapter.

4.2 Identification of drilling targets from geophysical investigations

Traverse lines were laid out to confirm the geological structures such as geological contact and lineaments identified during desktop study. The zones of higher permeability such as weathered and fractured zone associated with groundwater were also targeted. For borehole BH9 located at Mandela village, the hydrogeological structure targeted is a North – South striking dolerite dyke. Figure 4.1 shows the magnetic field data prior to correction by removal of regional and anthropogenic noise.

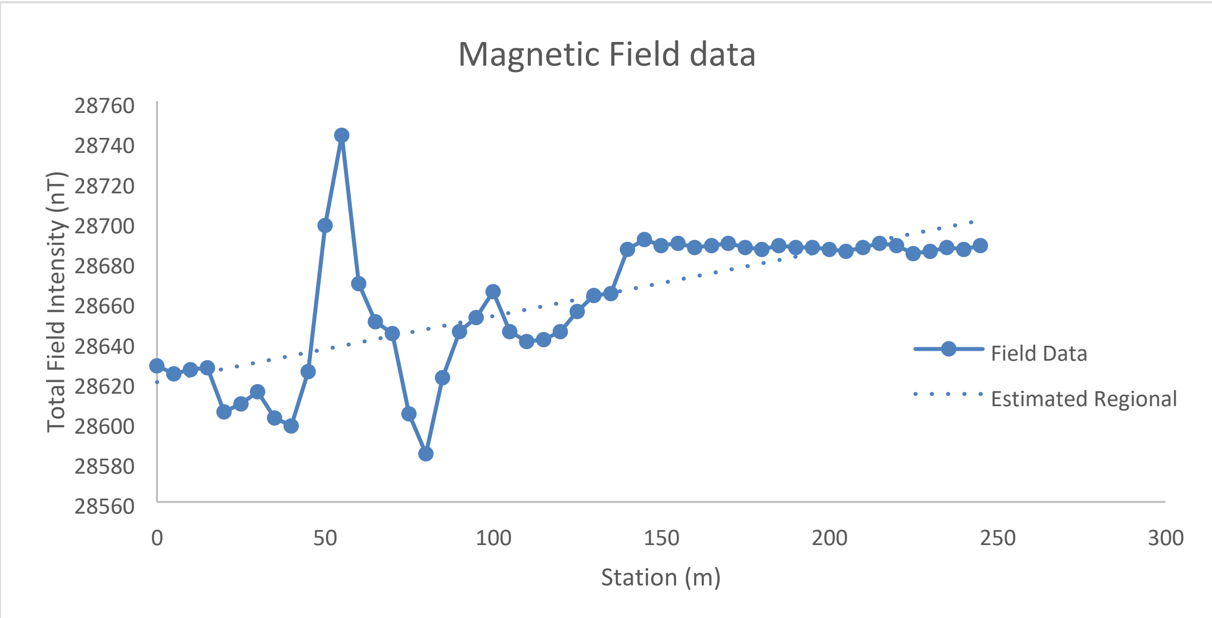

Figure 4.1: Magnetic field profile of BH9

According to Paver *et al.* (1943) this anomaly shape (Figure 4.1) is typical of a normal magnetic dyke anomaly with mostly positive amplitude. Steep slope is a typical characteristic of a normal anomaly associated with shallow buried magnetic body. The estimated regional anomaly was removed Least Square fitting of low-order polynomial. Figure 4.2 shows the field data for the traverse line laid at borehole BH9 in Mandela 2. The total field intensity is the combination of the earth's regional magnetics and the residual magnetic data produced by the rocks in the subsurface.

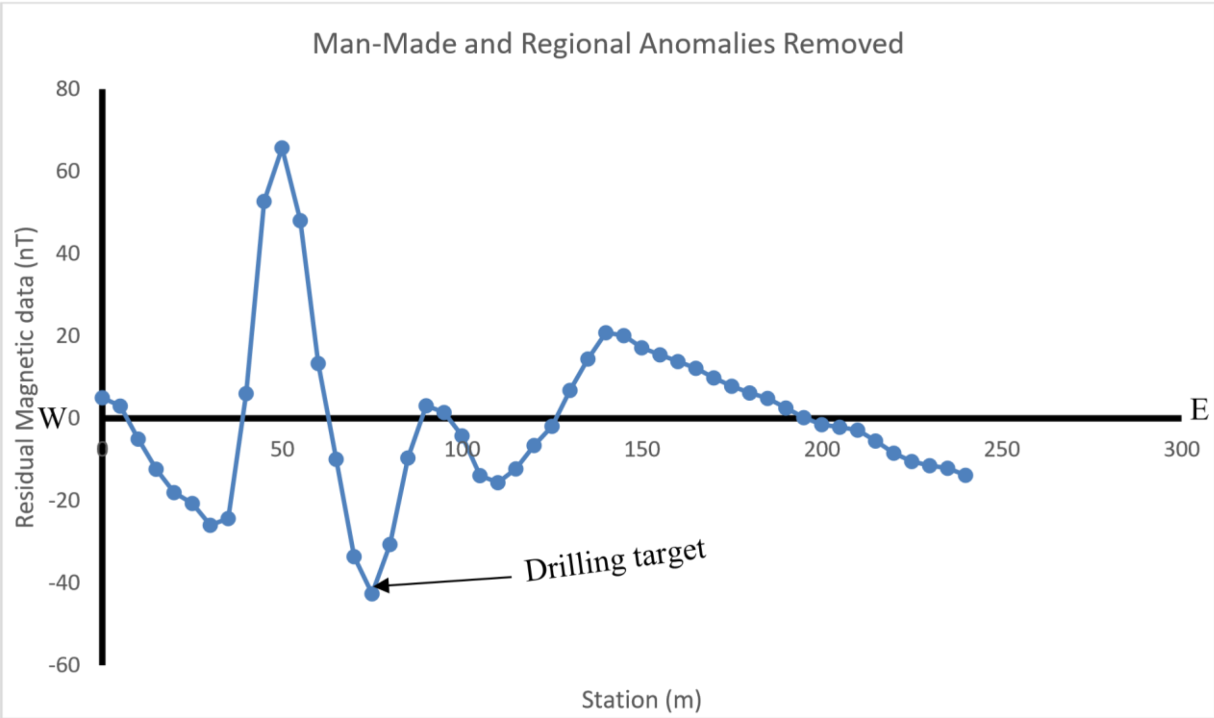

Figure 4.2: Residual magnetic profile of BH9 after smoothing and noise correction

From Figure 4.2, the estimated regional earth's magnetic data have been removed and the plotted data is from the residual magnetic data of the local rocks in the subsurface of the area. The traverse was carried out in a West to east direction across the North to South striking dyke. High linear magnetic anomaly is associated with the presence of dolerite dyke while the low or decreasing magnetic anomaly is often associated with fractures (Chandra, 2015). The magnetic lows are caused by hydration and alteration of magnetite to hematite (Chandra, 2015). Therefore, the region of negative anomaly is always targeted as it is referred to as a fractured zone associated with the intrusion of the country rock by dolerite. This denote that the dolerite dyke occurs between 40m and 65m, although the fracturing is perceived to occur at 35m and 70m as denoted by the green line. However, the dip direction of an intrusion plays an important role in its water-bearing capabilities. From the thin dyke anomaly, the dip direction was 80˚.

This denotes that the dyke is presumably dipping towards the East. Figure 4.3 shows the conductivity profile of the traverse. Lowest conductivity anomaly occurred at about 60 m from the start of the survey line.

Anomaly increase is noticeable from 70 m to 80m (Figure 4.2). According to Jones (2007) and MacDonalds *et al.* (2003), highly resistive magnetic body such as dolerite and diabase dykes are associated with very low apparent conductivity values. Increase in conductivity value denotes fracturing, weathering, hydration or reduced resistivity. Resistivity is inversely proportional to conductivity thus; a lower conductivity values denotes the presence and position of the dolerite dyke mapped on the map and magnetic profile. The first fracture position around 35 m (Figure 4.2) is not well defined on the electromagnetic profile. However, the second fracture position around 75 m is well defined with an increase in the apparent conductivity value (Figures 4.2 and 4.3). This profile results are in agreement with those of other studies such as Payne (2004), Jones (2007) and MacDonalds *et al.* (2003) thus, station 80 m was chosen for drilling.

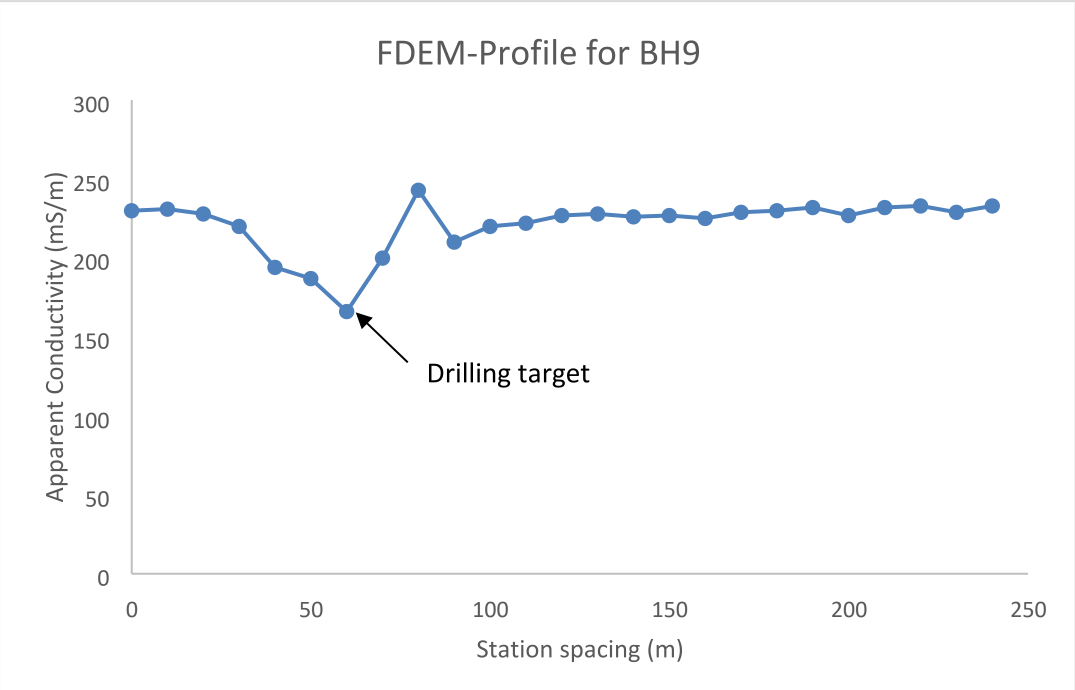

Figure 4.3: Electromagnetic profile of BH9

Magnetic data was plotted on Pdyke software for forward modelling of the intrusive body. Figure 14 shows the dipping direction of the intrusive body. The dipping direction coincides with the one given by the thin dyke curve fitting initially used in the interpretation of the magnetic data. As initially interpolated, the dyke is steeply dipping towards the South East. From figure 1.2, the geological structure with hydrogeological importance is the lineament mapped from LANDSAT imagery

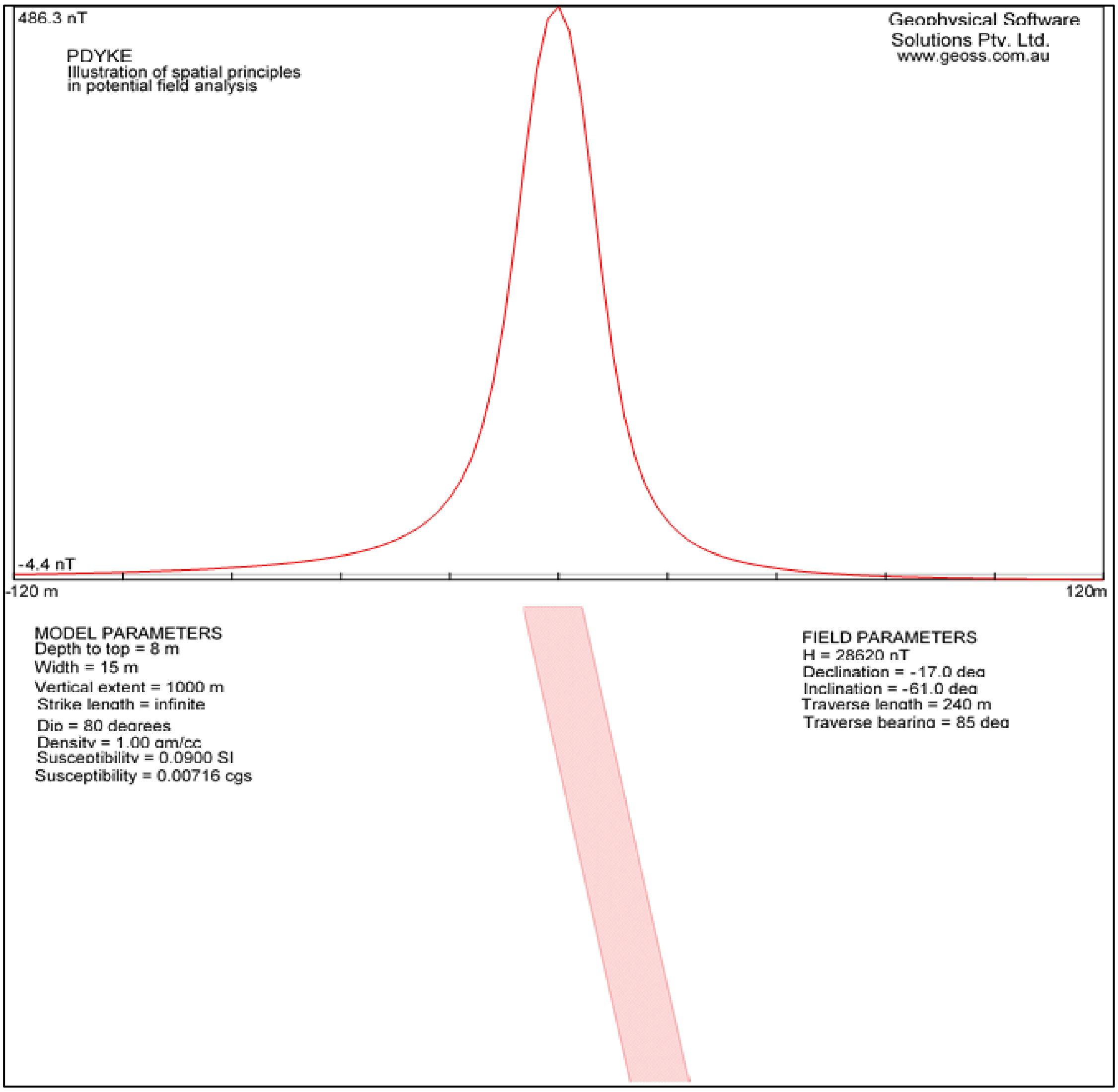

Figure 4.4: Forward modelling Dyke anomaly

These lineaments could be anything from fault to magmatic intrusion such as dyke and other volcanic rocks. A geophysical traverse was constructed from North to South to intersect the East to West striking lineament at an angle. The geometry of the lineament was investigated using magnetic and Electromagnetic geophysical method. The magnetic profiles are presented in Figures 4.5 and 4.6.

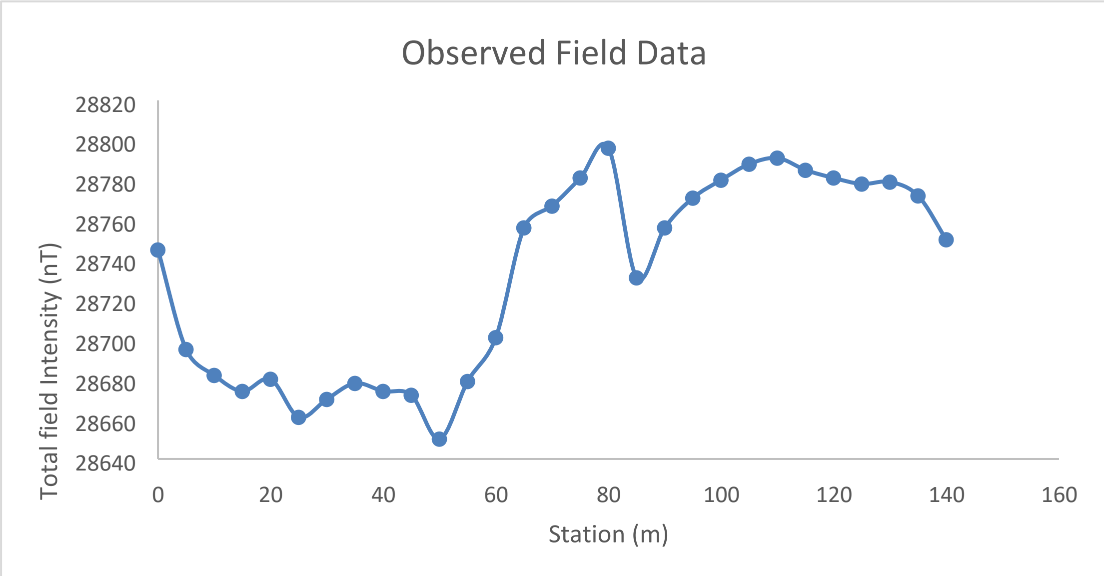

Figure 4.5: Observed field magnetic data for BH8

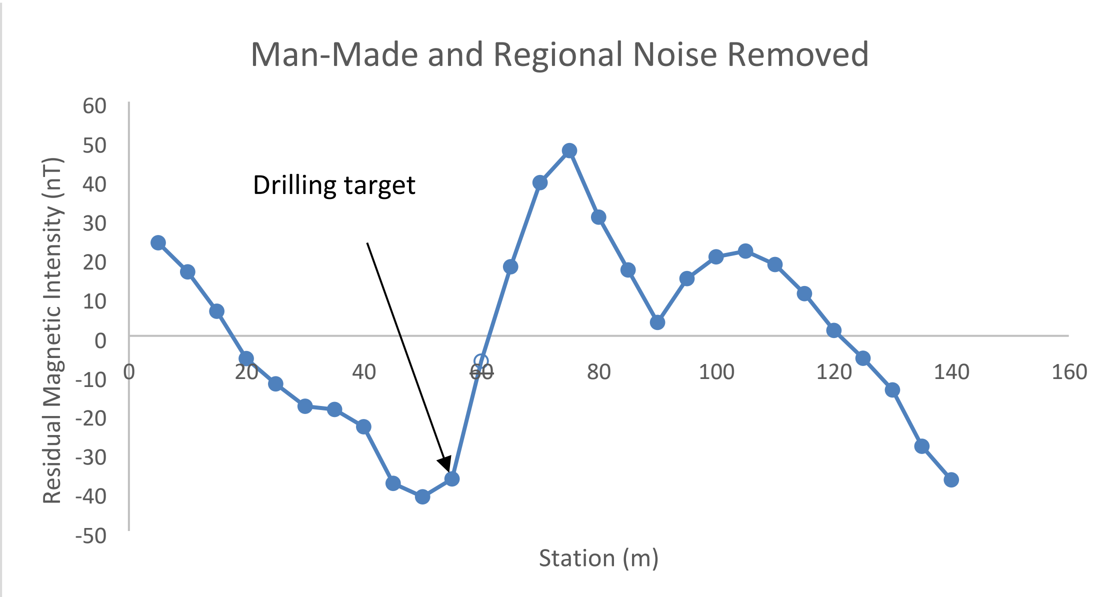

Figure 4.6: Corrected residual magnetic profile of BH8

From Figure 4.6, the shape of the anomaly is typical of an asymmetrical magnetic dyke anomaly (Paver *et al.*, 1943). The starting point on the profile was removed due to the presence of noise caused by a rusted car therefore, it was accounted for and removed from the profile. However, the anomaly prior to 40m station could not be interpreted due to an undefined anomaly. This is may be due to the fact that the traverse was started too close to the magnetic body. However, a magnetic decline occurred at 40m and was followed by a linear magnetic high up until 75 m after which the magnetic high was followed by a steep decline in magnetic susceptibility.

Another surge in magnetic linear value was encountered between 90m and 120m (Figure 4.6), but the anomaly was not well defined towards the end so no meaningful interpretation could be done towards the end. It is to be noted however, that double peaked anomaly could be as a result of a thick dyke (Paver *et al*., 1943). The double peak is caused by the concentration of magnetite towards the flanks of the thick dyke (Lourens, 2013). The fractured zone associated with the intrusion occur between 20 and 60 m with the peak around 50m. The thin dyke anomaly estimates the dipping angle to be approximately 10° due East. Visualization of the anomaly on a forward Pdyke model shows that the body is a massive gently dipping magmatic intrusion which somewhat resembles a sill due to the low angle of dipping (Figure 4.7).

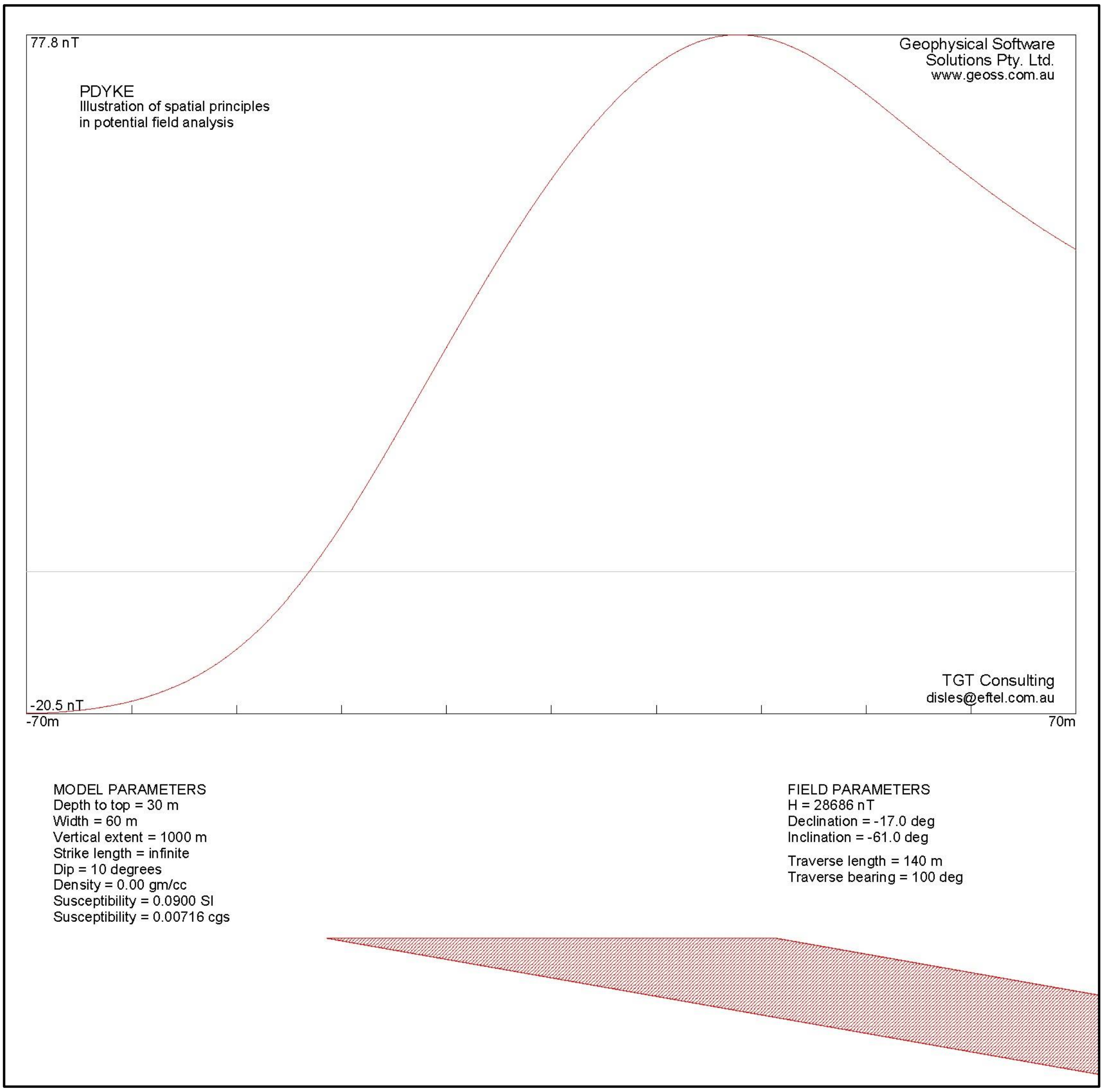

Figure 4.7: Forward Modelling of Dyke at BH8

Figure 4.8 shows the electromagnetic profile on the same traverse initially laid out. There is an increase in the conductivity value from 10m to 40 m. These positions conform to the position of the supposed fracture of the dyke. However, from 50 m, there is a decrease in the apparent conductivity and this coincides with the middle of the dyke (highest point of the dyke). The magnetic low at 50 m (Figure 16) coincides with the apparent conductivity high between 40 m and 50 m (Figure 4.8). However, the conductivity value looks to be higher at 40 m, interpolation was made to drill at 50 m since the apparent conductivity at 50 m is still higher than the surrounding conductivity.

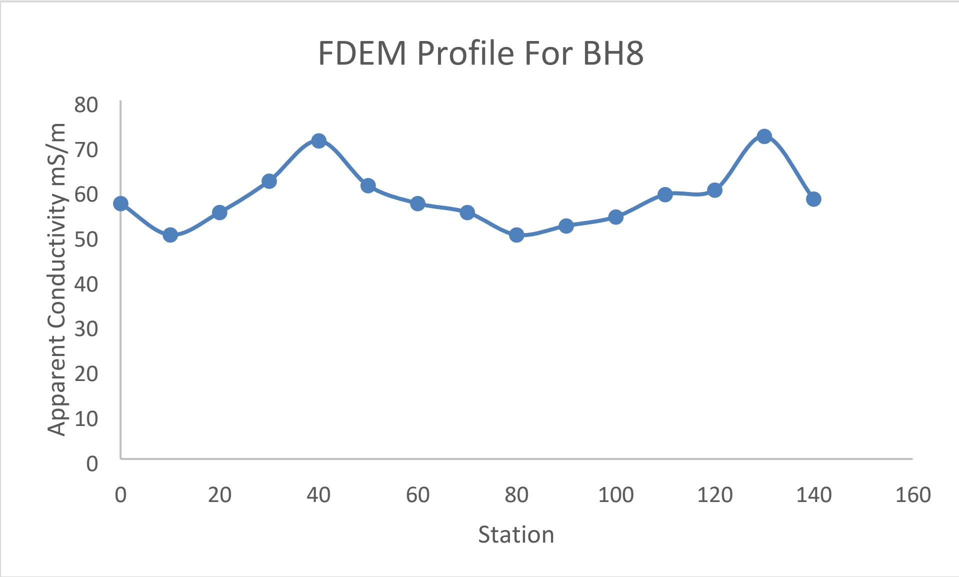

Figure 4.8: EM profile of BH8

From the geology map of the area (Figure 4.9), the traverse was laid out to intersect the geologic contact between alluvium and diabase, as well as West to East striking the LANDSAT imagery mapped lineament. Figure 4.10 shows the raw field data of the magnetic profile for BH7. The traverse was laid out in a South West – North East direction.

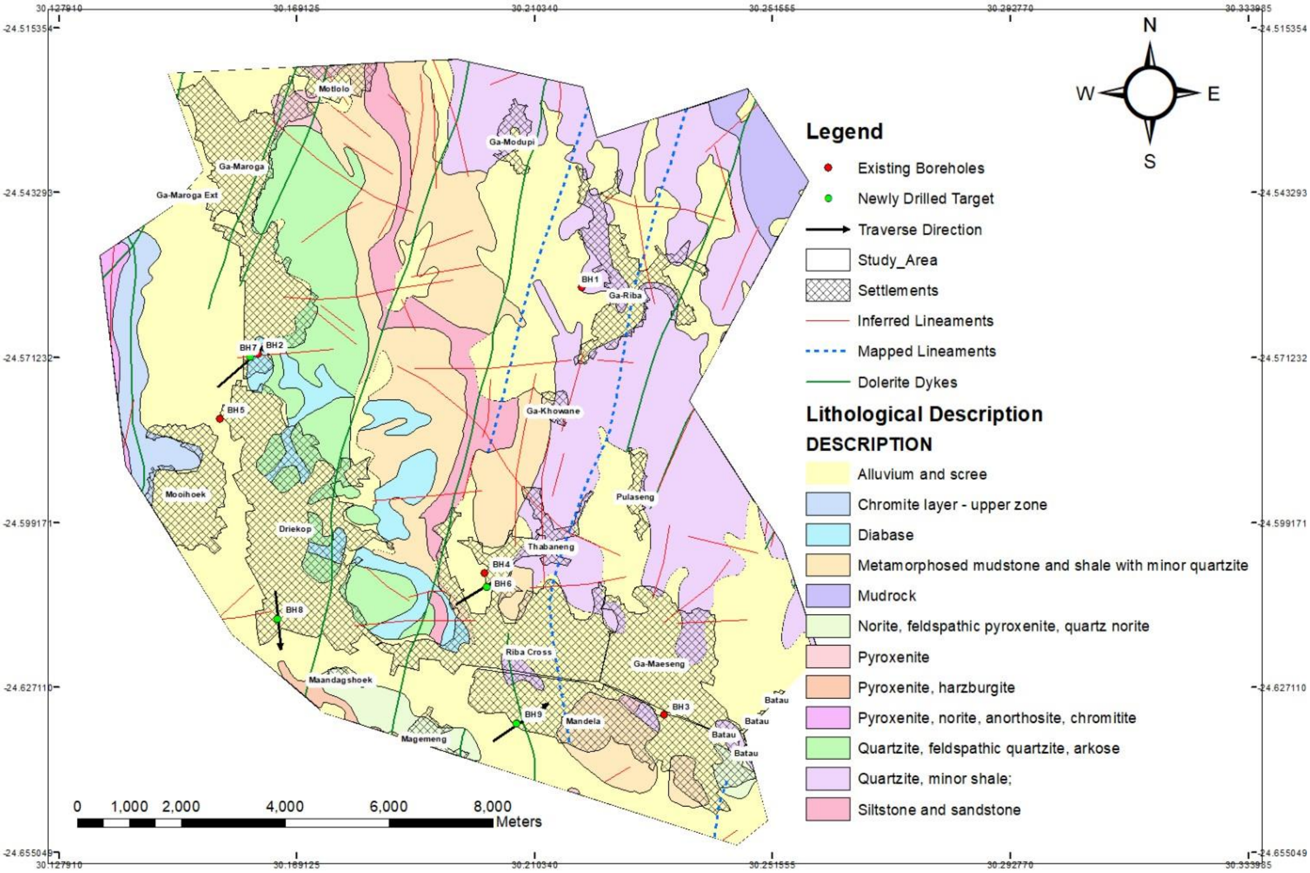

Figure 4.9: Map showing newly drilled and existing boreholes

However, from the profiles (Figures 4.10 and 4.11), two prominent features are noticeable between 60 – 90 m as well as 100 – 150 m. After the necessary corrections and smoothing, the inferred geological targets were well defined (Figure 4.11). A decrease in the magnetic intensity at 60 m signifies a change in lithology. Geological contact can also be of significant importance in hydrogeological context especially between sedimentary deposit and impermeable rock such as diabase and dolerite. Towards the end of the profile the presence of an east to west striking dyke was observed.

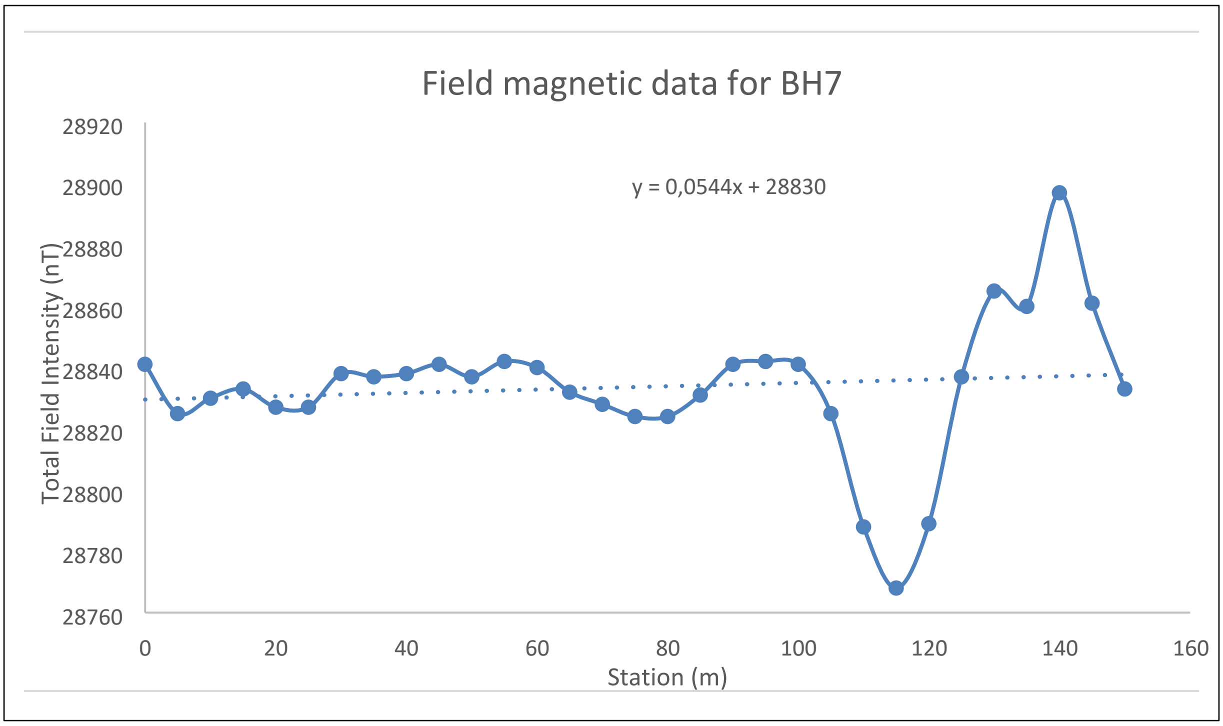

Figure 4.10: Observed field magnetic data for BH7

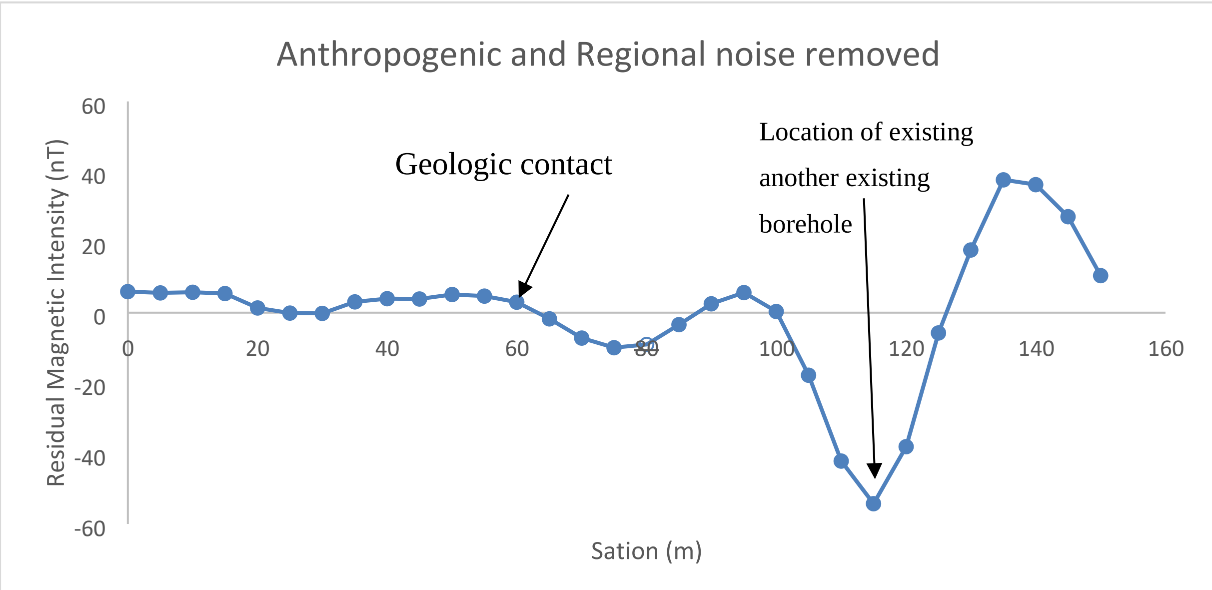

Figure 4.11: Corrected residual magnetic field data for BH7

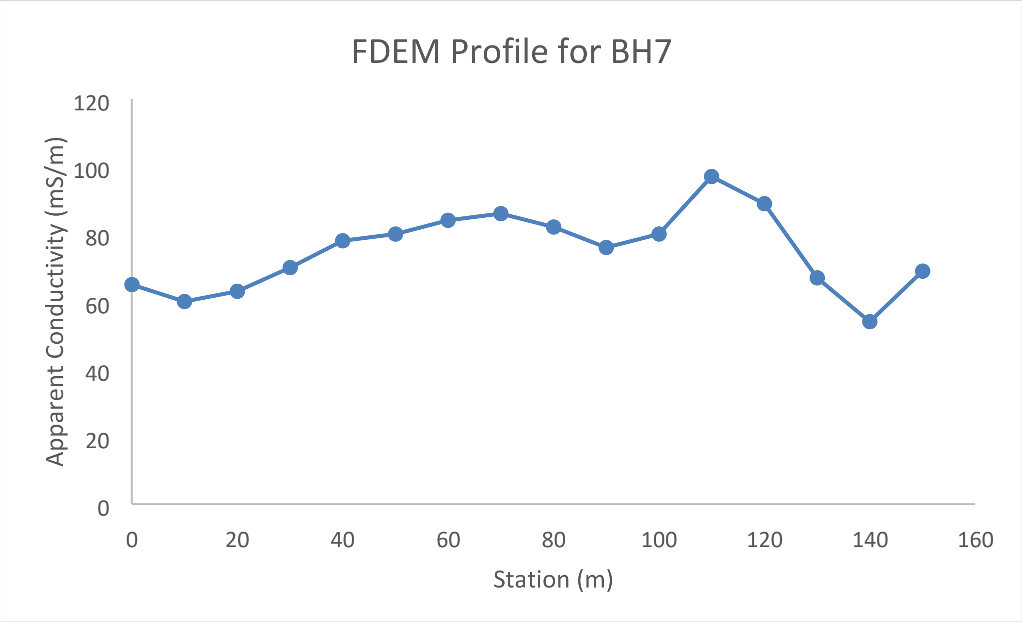

Figure 4.12: EM Profile of BH7

The EM profile for BH7 do not really show much but however, an increase in the apparent conductivity is noticeable at 20m up to 70m and this is followed by a decline and then another sharp increase in the conductivity values. The steep increase at 100m coincided with the negative magnetic anomaly on the magnetic profile which signifies a fracture position. However, the position of BH7 picked for drilling is not well defined on the anomaly but there seem to be a general increased conductivity as compared to the beginning of the line.

The magnetic profile of target BH6 is presented in Figure 4.13. The magnetic profile shows no essentially distinctive magnetic anomaly; therefore, no meaningful interpretation could be done. This is probably due to the fact that the profile was carried out on the same lithology without any magmatic difference. Figure 4.14 shows the EM profile for BH6. Interpretations could not be made from the magnetic profile therefore, target BH6 was picked from the EM profile. The point with the highest conductivity value was picked. The apparent conductivity increased at 30m and reached a maximum conductivity at 60m. This point was picked for drilling because higher conductivity values are associated with weathered zone. This zone is categorized as a weathered zone.

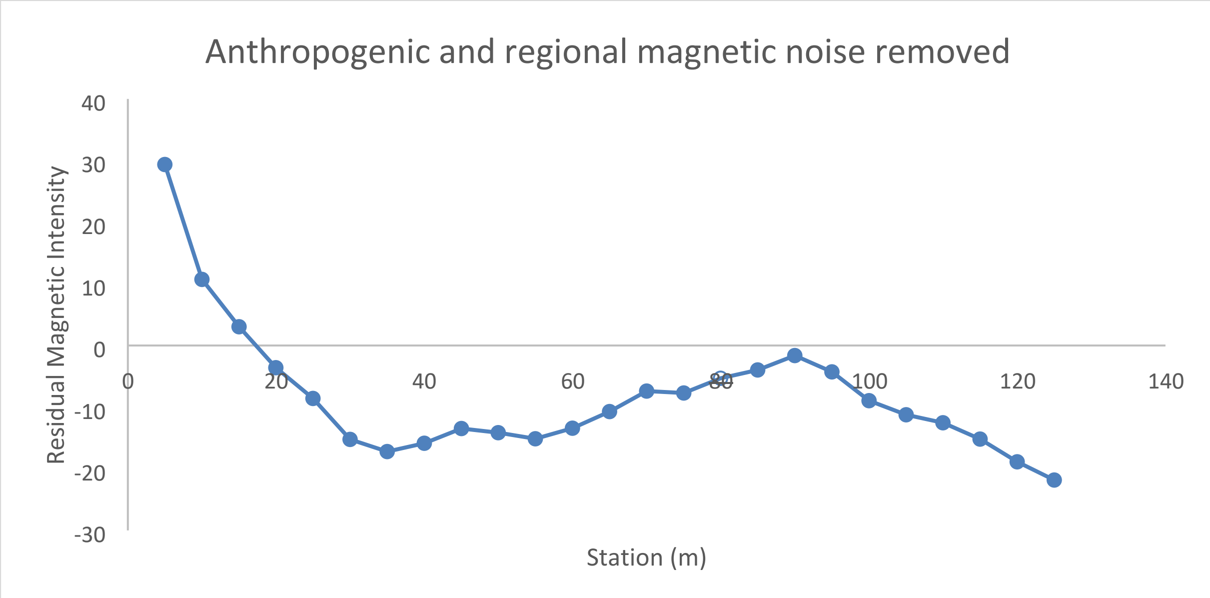

Figure 4.13: Residual magnetic profile of BH6

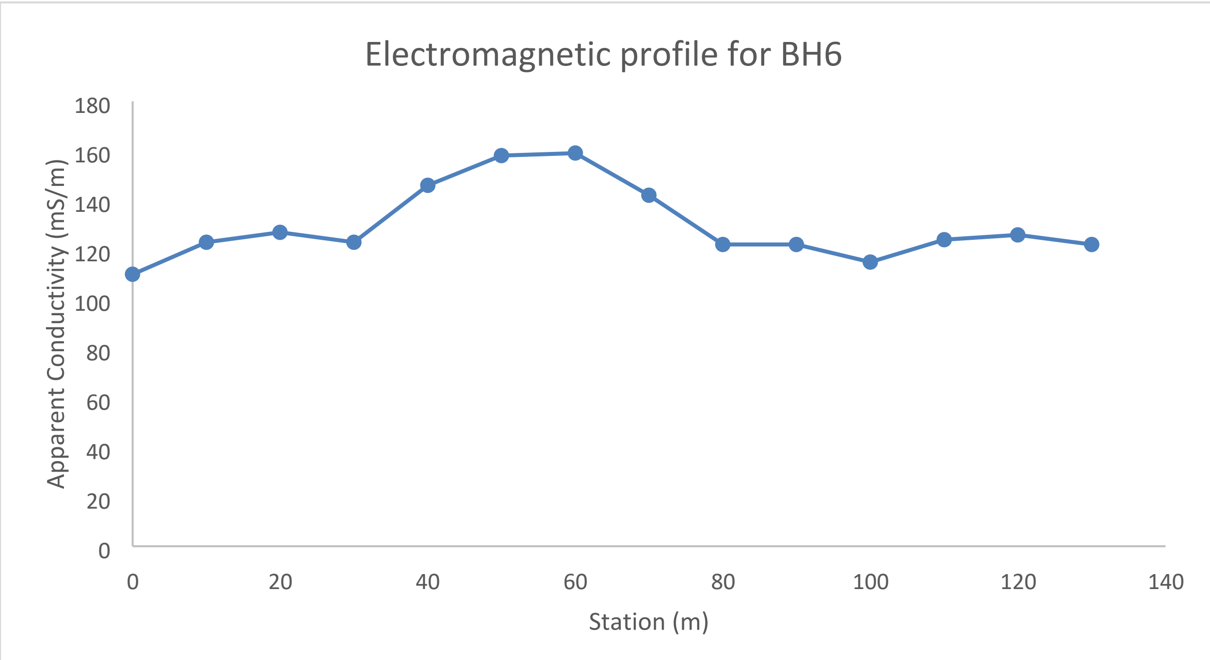

Figure 4.14: EM profile for BH6

In summary, a total of four (4) boreholes were newly sited and drilled and the other five (5) boreholes are pre-existing boreholes. BH3, BH4, BH5, BH6 and BH8 were all located on alluvium. Alluvium is well known for good groundwater potential. However, the alluvium in some places, acts as an overburden for the bedrocks. Contacts of lithologies are well known for groundwater potential. BH1 was sited at the contact between alluvium and quartzite. East to West striking lineament in the alluvial deposit was targeted for siting and drilling of BH7.

However, existing BH2 was also sited and drilled on the same lineament. North to South striking dolerite dyke was targeted for siting and drilling of BH9

4.3 Estimation of aquifer parameters

The rates and duration used in the borehole pumping tests are listed in Table 4.1. The static water levels (SWL) were from 6.97 m for BH3 to 20.95 m for BH9.

Table 4.1: Pumping tests rates and duration

Village Name	**BH No.**	**SWL (m)**	**SDT (l/s) per Hr**				**CDT (l/s)**
			Step 1	**Step 2**	**Step 3**	**Step 4**	
Ga-Riba	BH1	13.89	0.63	2.05	4.92	11.45	9.86
Ragapola	BH2	17.92	0.33	0.85	2.78 1	5.01	5.65
Mandela 1	BH3	6.97	0.88	2.09	5.23	9.74	5.12
Riba Cross 1	BH4	20.95	0.52	1.63	2.66	--	1.58
Magologolo	BH5	14.69	0.34	0.79	3.54	5.12	4.47
Riba Cross 2	BH6	14.94	0.46	1.06	2.26	--	0.86
Driekop	BH7	14.4	0.57	1.23	3.52	6.11	4.53
France	BH8	12.86	0.88	1.83	3.95	6.5	5.66
Mandela 2	BH9	20.24	0.56	0.88	--	--	0.53

Before an abstraction rate can be regarded as sustainable, groundwater abstraction must be balanced. The balancing can be done by either increasing the recharge or by decreasing the discharge (Holland, 2011). This is because in an undisturbed series of event, aquifers are in the state of natural long term equilibrium prior to pumping. Therefore, sustainable abstraction must consider the recovery behavior of the aquifer, and must also be lower than the discharge rate during pumping test. The typical solutions available for fractured aquifer environments are enumerated in Moench (1984), Barker (1988) and Gringarten-Witherspoon (1972). The diagnostic plots used to identify aquifer and flow conditions were semi-log plots and log-log plots of drawdown. In addition, drawdown derivative plots were also used. The visual inspection of the derivative plots showed the types of aquifer behaviour could be grouped into three groups i.e. double porosity only, double porosity with fracture dewatering and general radial flow model.

Early-time (0-100 min) drawdown data of BH1, BH2, BH5 and BH8 showed linear flow behaviour (Figures. 4.15, 4.16, 4.17 and 4.18). Linear flow is associated with vertically fractured aquifers (Ehlig-Economides et al., 1994). The intermediate time data had a dip in both the drawdown derivative log-log and semi-log plots. A dip in the drawdown derivative typically is associated with either a confined aquifer with double-porosity or an unconfined aquifer (Renard *et al.*, 2009). Double porosity is a characteristic of confined aquifers which have porosity due to fractures and aquifer matrix. Data for the boreholes BH1, BH2 and BH3 was fitted with the Moench (1984) solution for fractured aquifers with double porosity.

BH5 and BH8 shows infinite acting radial flow in the late-time derivative plot (Figures 4.17 and 4.18). BH1 and BH2, on the other hand did not have enough length of data to allow for identifying the behaviour or existence of boundary conditions.

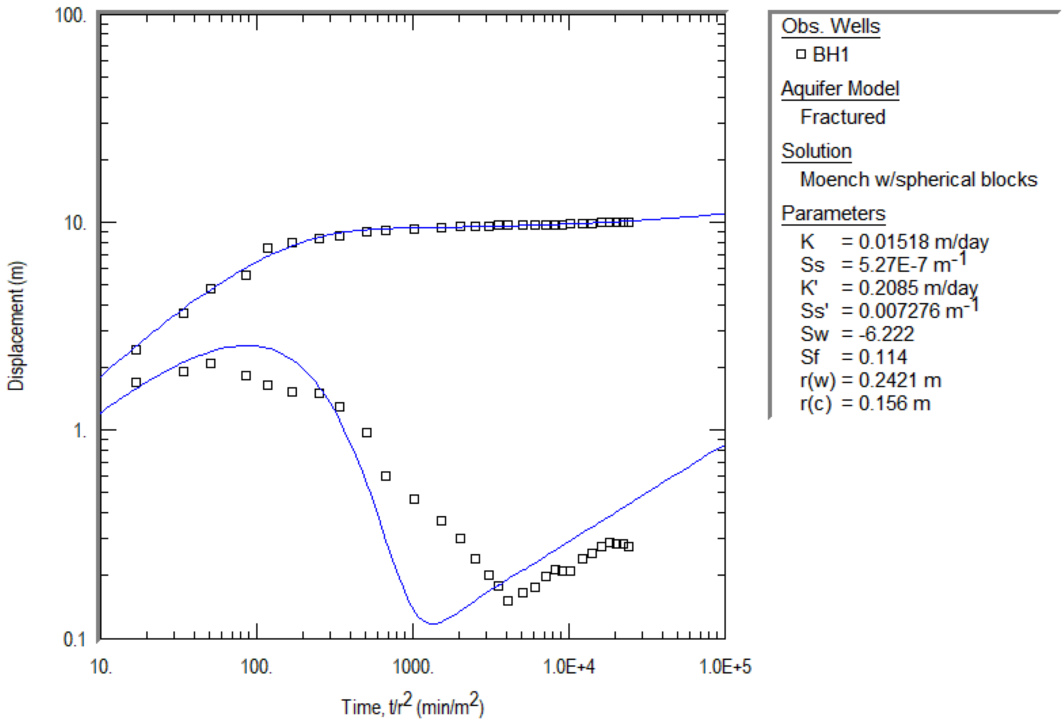

Figure 4.15: Drawdown and the derivative versus time for BH1

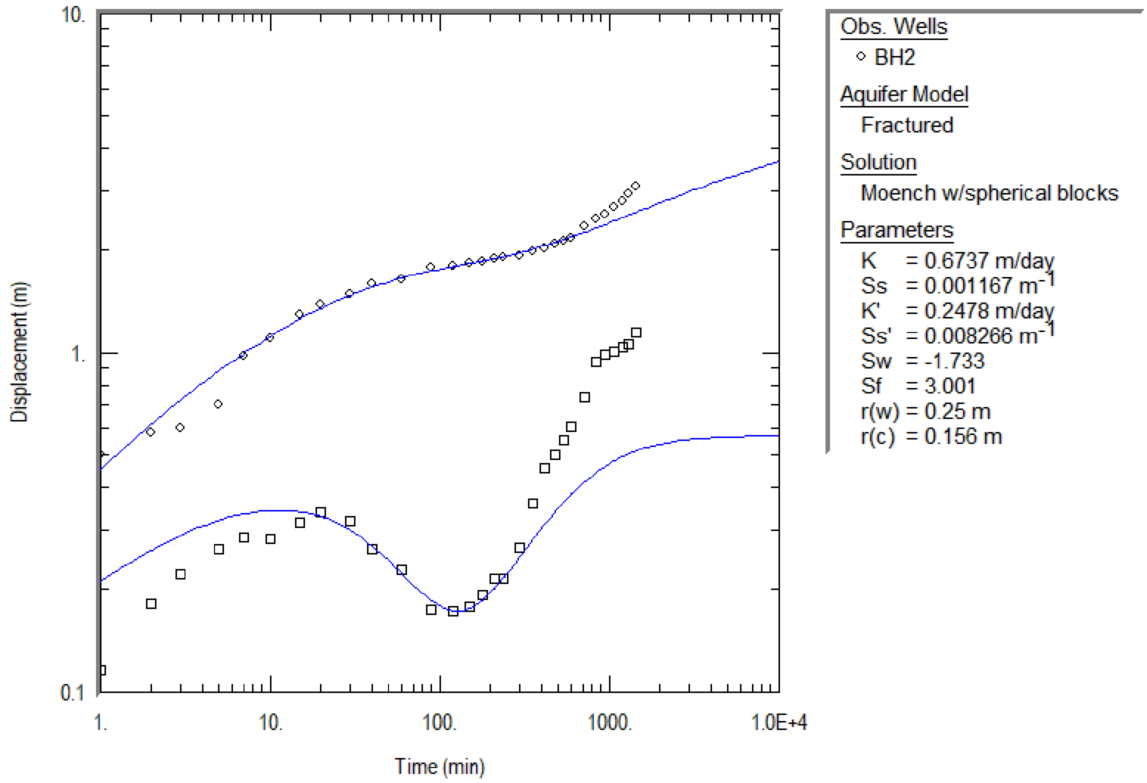

Figure 4.16: Drawdown and the derivative versus time for BH2

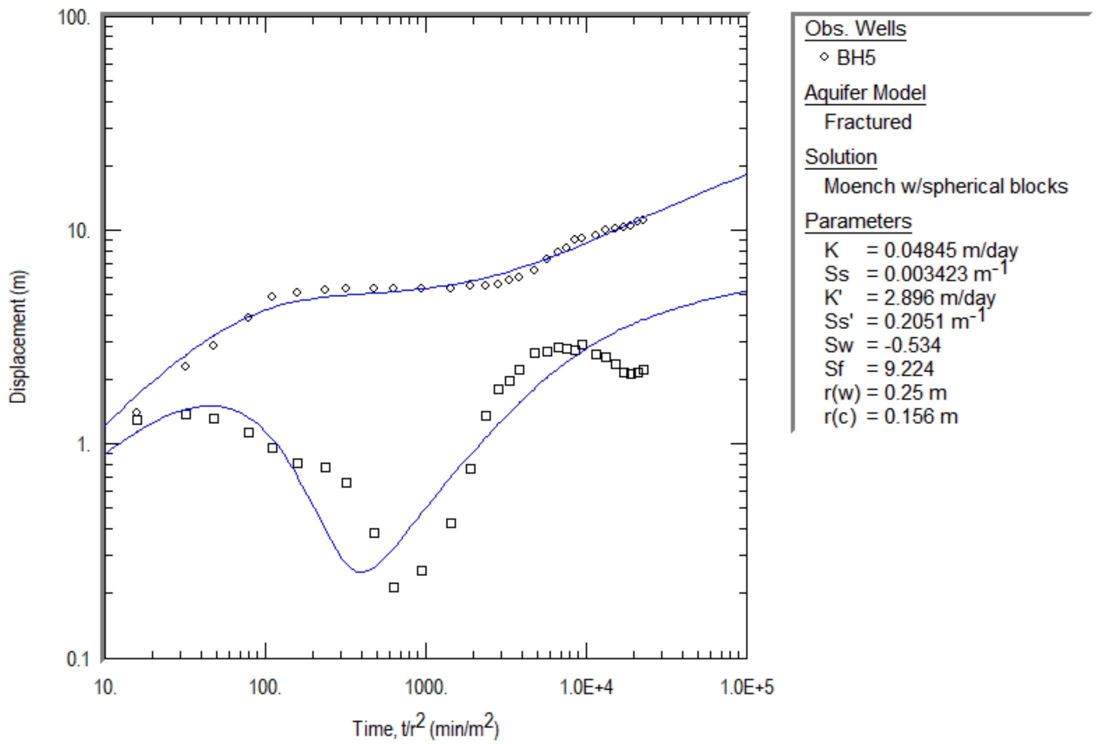

Figure 4.17: Drawdown and the derivative versus time for BH5

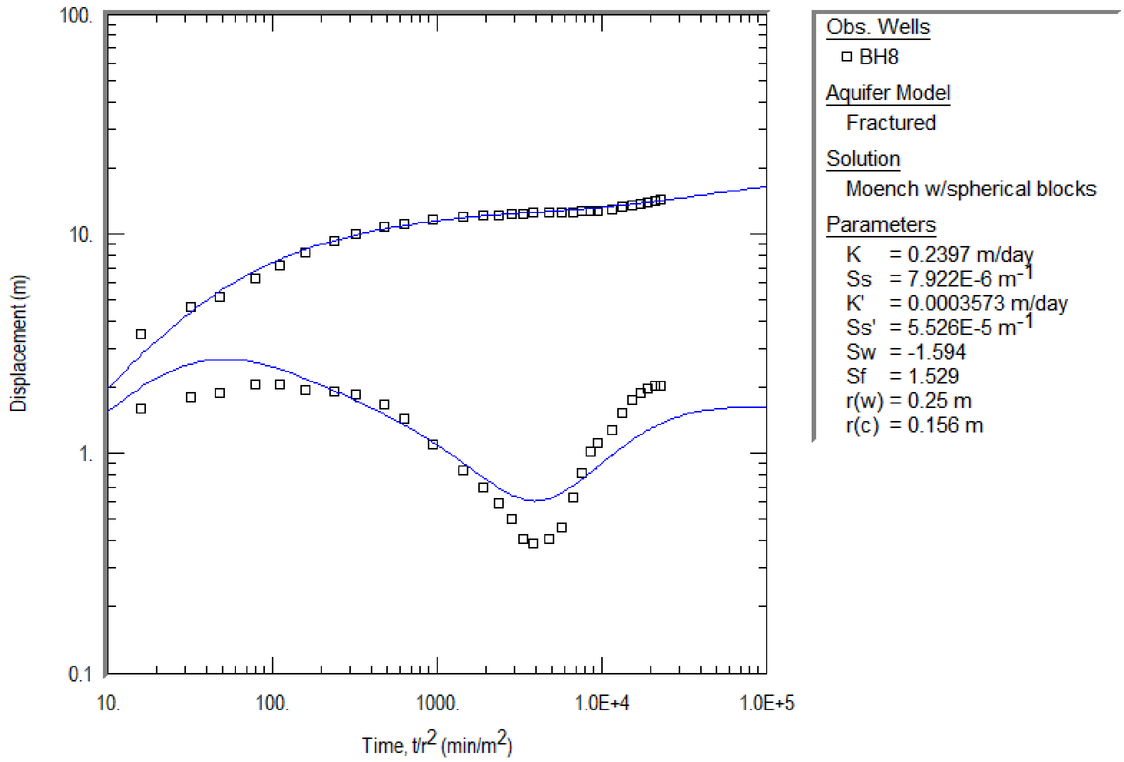

Figure 4.18: Drawdown and the derivative versus time for BH8

BH3, BH4, BH6 and BH7 data showed early-time linear behaviour and intermediate-time double porosity (Figures. 4.19, 4.20, 4.21 and 4.22). Dips were visible which occurred in the derivative data during the late-time phase of the pumping test. These showed the possibility of fracture dewatering (Holland and Witthuser, 2009). As the fracture is dewatered/drained, drawdown derivative dips and afterwards it rises again as before the fracture was encountered. This aquifer model suggests that in the early-time stages, water in the well comes from the fracture storage and from the aquifer rock matrix in the intermediate time then followed by a combination of both fracture and rock matrix flow. Borehole data for these boreholes was fitted with the Moench (1984) solution for fractured aquifers with double porosity.

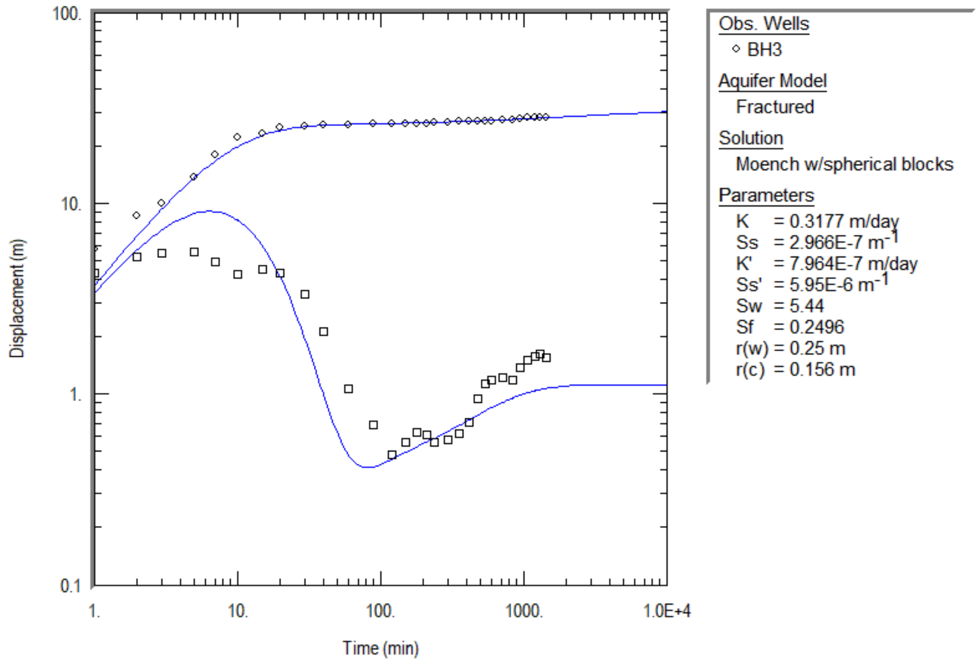

Figure 4.19: Drawdown and the derivative versus time for BH3

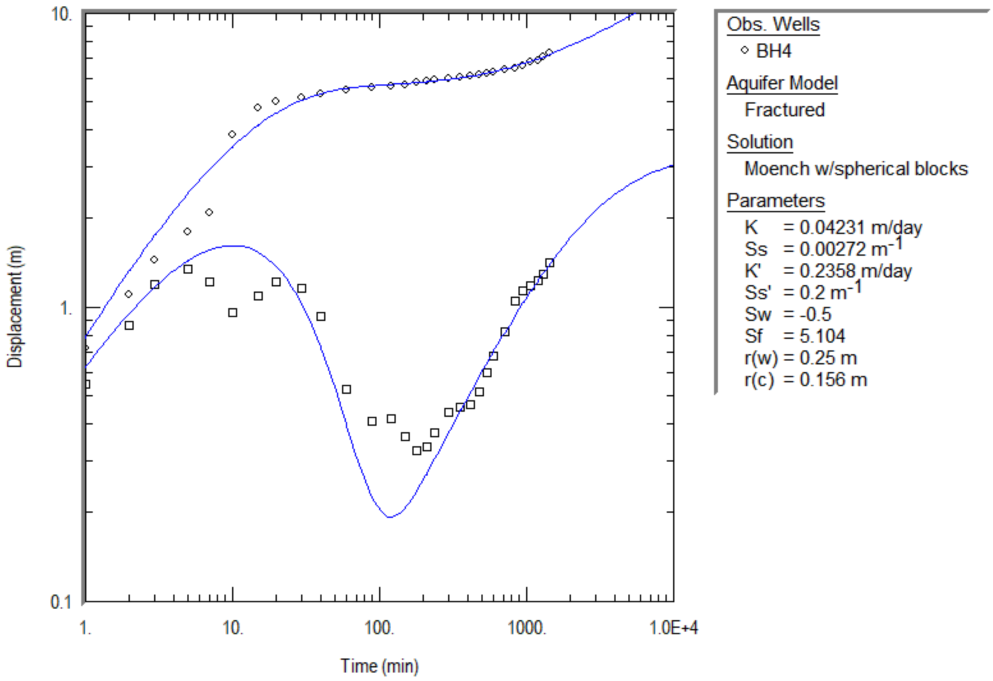

Figure 4.20: Drawdown and the derivative versus time for BH4

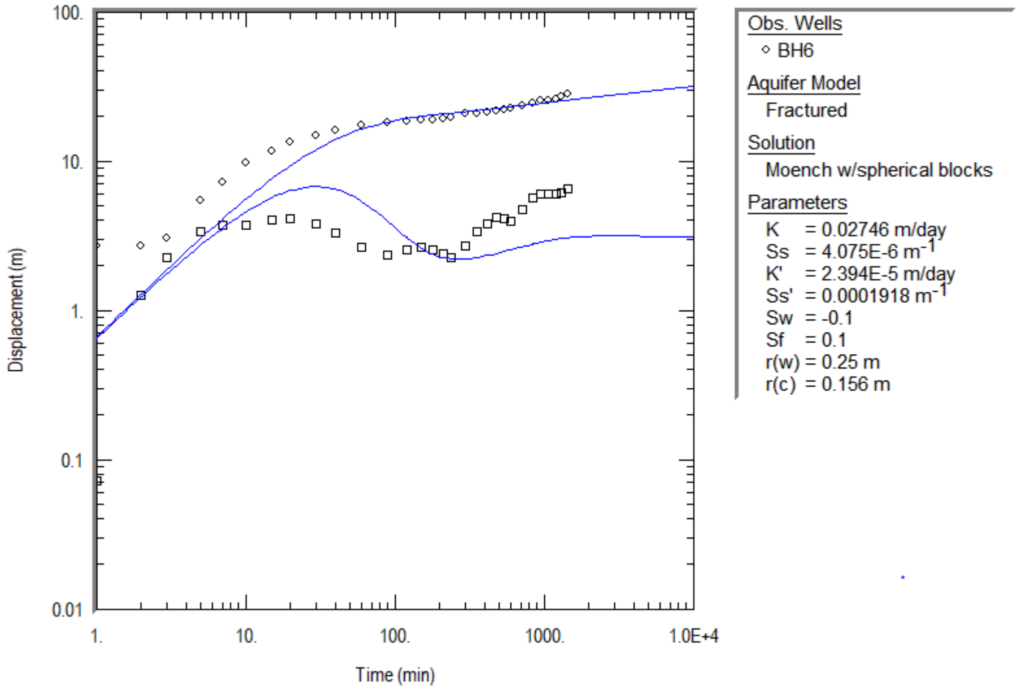

Figure 4.21: Drawdown and the derivative versus time for BH6

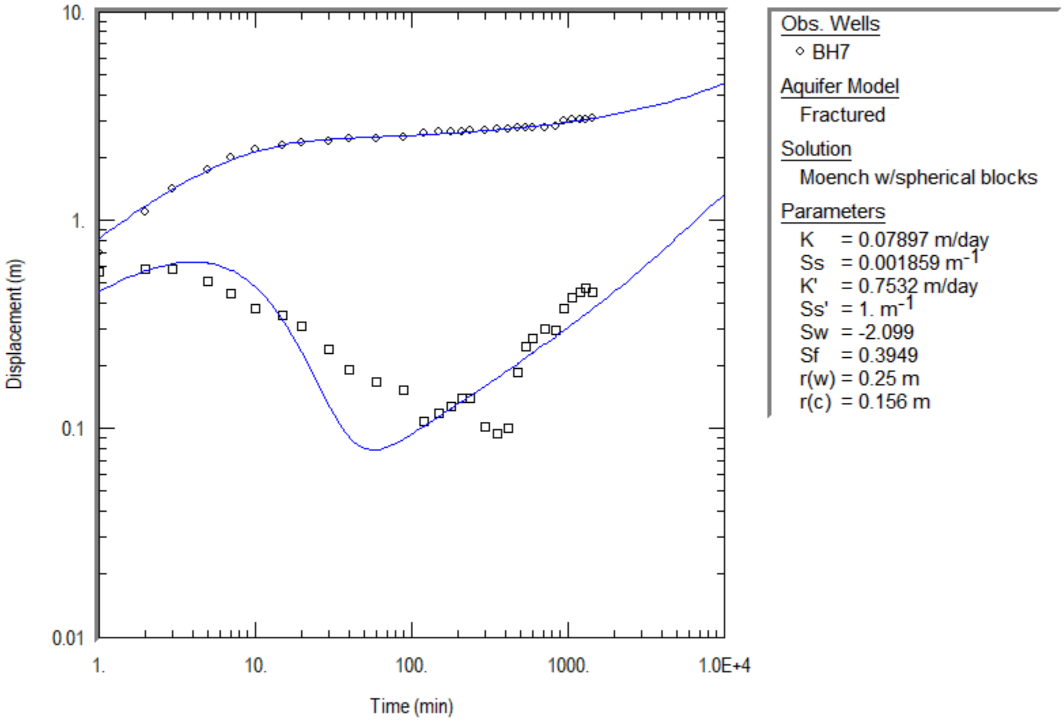

Figure 4.22: Drawdown and the derivative versus time for BH7

BH9 showed different behaviour from all the other boreholes (Figures 4.23). The drawdown derivative curve showed that general radial flow behaviour. This model is used when single fracture system is detected, where water flows to the well from the fracture in early time and then from both aquifer matrix and fracture storage. The Barker (1988) solution was fit to the log-log and the semi log data of the borehole.

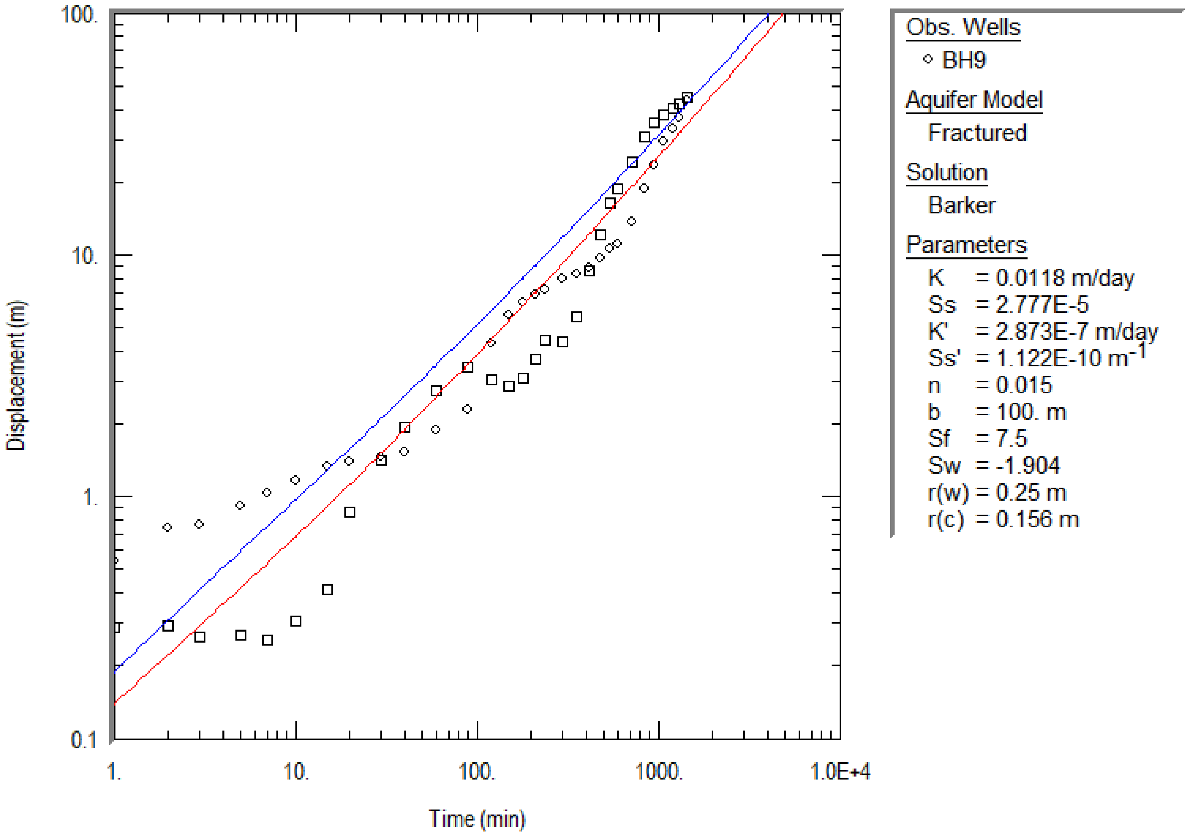

Figure 4.23: Log-log plot of drawdown and the derivative for BH9

Aquifer parameters that were obtained from the analysis of pumping tests are given in Table 4.2. The conceptual aquifer models were identified, under which the aquifer parameters were estimated by automatic curve fitting. Estimates of transmissivity and storativity were determined using the Cooper-Jacob solution for confined aquifers. Hydraulic conductivity was estimated using the diagnostic solutions that were identified to best analyse the data

Table 4.2: Estimated aquifer parameters

Village Name	**BH No.**	**Aquifer Type**	**T (m^2/day)** (Cooper-J)	**S** (Cooper-J)	**K (m/day)** (Diognostic solution)
Ga-Riba	BH1	Double porosity	82.67	0.005256	0.01518
Ragapola	BH2	Double porosity	123.1	1.08	0.6737
Mandela 1	BH3	Double porosity and fracture dewatering	13.94	0.00296	0.3177
Riba Cross 1	BH4	Double porosity and fracture dewatering	13.22	0.0645	0.04231
Magologolo	BH5	Double porosity	27.37	0.02041	0.04845
Riba Cross 2	BH6	Double porosity and fracture dewatering	1.714	0.02872	0.02540
Driekop	BH7	Double porosity and fracture dewatering	124.7	0.01719	0.07897
Frans	BH8	Double porosity	29.07	0.01994	0.2397
Mandela 2	BH9	general radial flow, single porosity	0.08953	0.2028	0.01180

Transmissivity was high in boreholes BH1, BH2 and BH7 where it was 82.67, 123.1 and 124.7 m^2/day, respectively. The rest of the transmissivities were from 0.08953 to 29.07 m^2/day. Storativity was in the range of 0.005256 and 1.08. BH2 and BH9 had abnormally high values. Generally, the values of transmissivity and storativity were high when compared to those of Holland (2011), whose study was in the Limpopo Plateau. The transmissivity value calculated by Holland (2011) was from 4 to 330 m^2/day for boreholes in fractured aquifers. These differences could be as a result of hydraulic gradient and the hydraulic conductivities in the regolith and underlying fractured bedrock. Also the differing transmissivity range could be as a result of more inter-connected secondary fracture system which increases the smooth flow of groundwater.

However, storativity values ranged from 0.005 to 1.08. Typical range for storativity values is between 0.0001 and 0.001 (Domenico and Schwartz, 1990). The storativity values in this study are within the range of values obtained by Holland (2011).

4.4 Hydrochemistry

4.4.1 Physical and aggregate properties

The pH of the groundwater in the study area ranged from 6.8 – 7.7 (Figure 4.24). This pH range fell within the accepted permissible range of 6 – 9 set by DWS (DWAF, 1996). According to DWAF (1996), pH value less than 7 indicates acidity while pH values above 7 indicates alkalinity. Therefore, the pH value of 6.8 shows that BH3 is slightly acidic while other samples showed a slightly alkaline pH. Although, pH does not have adverse effect on human health except when consumed at extremes, it could however indirectly catalyse other complex processes that are harmful to the body. pH indirectly enhances the solubility of toxic heavy metals and alteration (protonation and deprotonation) of other ions in the chemical structure of water (DWAF, 1996). In hydrogeology, pH is important because it shows the extent of geological influence on the groundwater of an area.

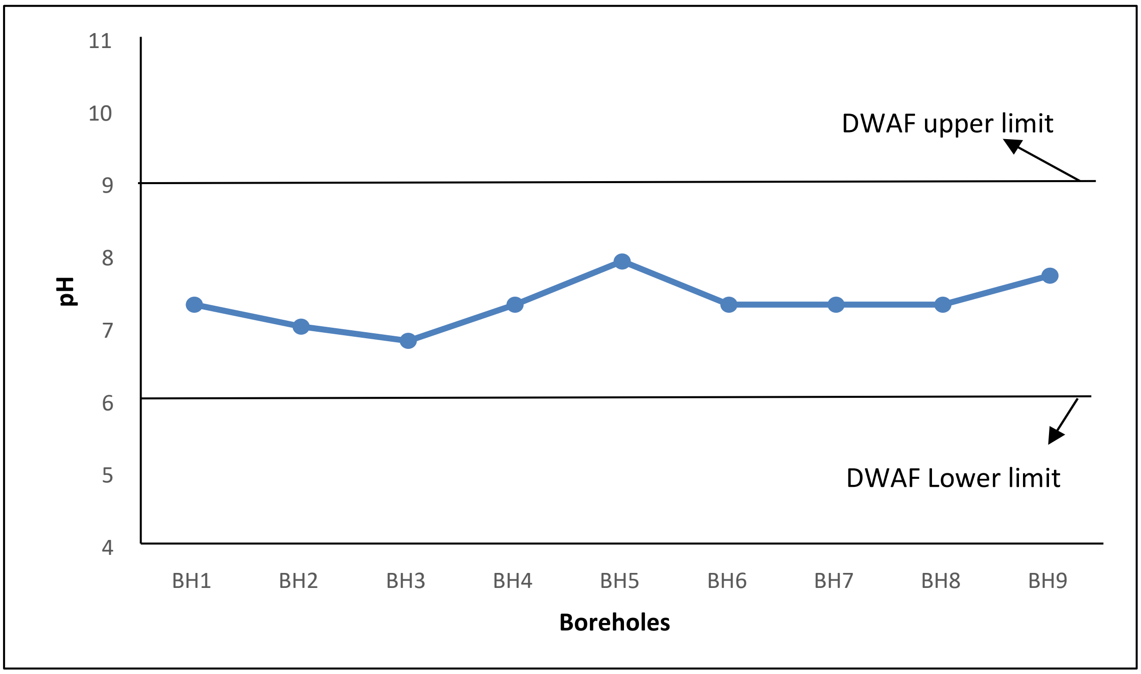

Figure 4.24: Plot showing pH values of samples collected

TDS is the amount of inorganic salts present in solution of the water and EC is a measure of the amount electrical current that the water can transmit (DWAF, 1996). EC gives an estimate of the total dissolved substance in the water (Yilmaz and Koc, 2014). The TDS value ranges from 293 mg/L to 896 mg/L. Sample BH9 has the highest TDS value of 896 mg/L while sample BH1 records the lowest TDS value of 293 mg/L. All the TDS values fell within the SANS 241 (2015) recommended limit of <1200 mg/L but most of the samples failed to meet the DWAF (1996) recommended TDS limit of <450 mg/L. However, DWAF (1996) noted that the TDS range between 450 – 1000mg/L are likely not to have any negative effect other than seldom salty taste.

Table 4.3 shows the correlation between TDS and EC of the groundwater samples.

Table 4.3: Correlation between TDS and EC

	TDS	*EC*
TDS	1	
EC	0.999998	1

There is a strong positive correlation between TDS and EC thus they are directly proportional to each other. Therefore, Because of the direct proportionality between EC and TDS, the conductivity value of all the samples also fell within SANS 241 (2015) recommended value of <170mS/m but BH1 and BH5 exceeded DWAF (1996) recommended limit of <70 mS/m (Figures 4.25). The conductivity and TDS value of groundwater are proxy indicators of the chronostratigraphy and the lithostratigraphy of the associated geology (Oyem *et al*., 2014; DWAF, 1996). According to DWAF (1996), groundwater TDS value between 195 mg/L – 1100 mg/L has been in contact with sedimentary rocks of mid-early Phanerozoic eon. The dominant alluvial and dolomitic deposit in the area is of Phanerozoic era, thus; TDS values are influenced by the dolomitic and alluvial lithology in the area.

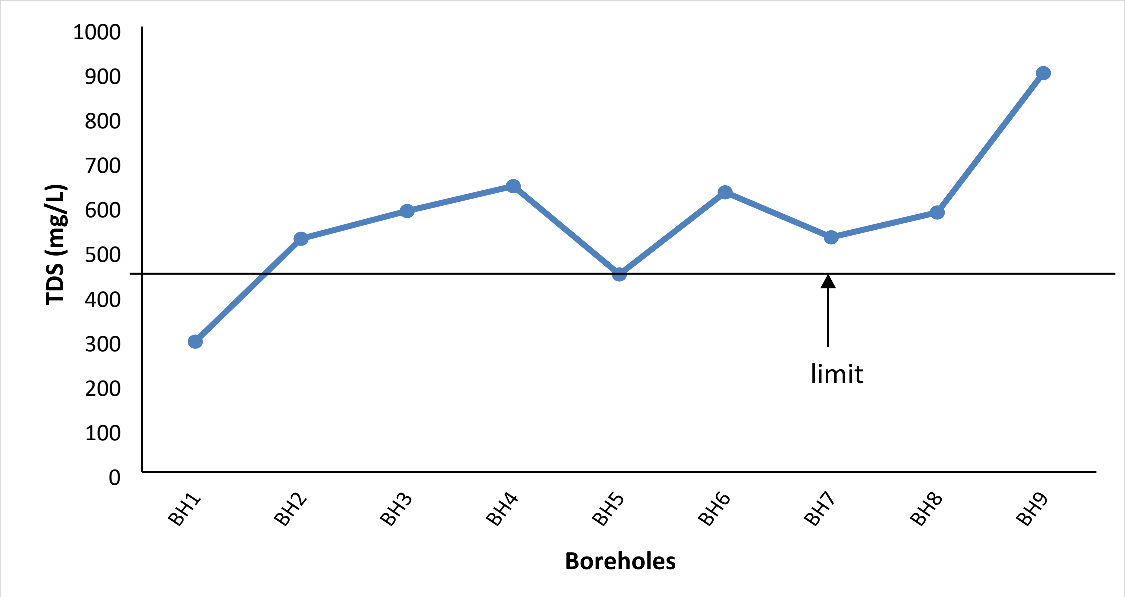

Figure 4.25: TDS of water from the boreholes

Total hardness is the sum of magnesium and calcium concentration expressed as $CaCO_3$. The geology of an area mainly influences the hardness of water. Hence the underlying geology can be inferred from the level of hardness of groundwater. Total hardness ranged from 157.84 – 598.49 (mg $CaCO_3$/l). According to the classification of water hardness by Kunim (1972) (Table 4.4), all the boreholes in the study area vary from moderately hard to very hard.

Table 4.4: Classification of hardness by Kunim (1972)

Hardness (mg $CaCO_3$/l)	0 - 50	50 – 100	100 - 150	150 - 200	200 - 300	> 300
Description	Soft	Moderately soft	Slightly hard	Moderately hard	Hard	Very hard

Seven out of the nine (9) boreholes have moderately hard water. The excessive hardness is reflective of the abundant dolomite in the area. Dolomites are anhydrous carbonate mineral composed of calcium magnesium carbonate. Turbidity of the groundwater ranged from 0.11 – 1.66 NTU (Figure 4.26). Turbidity of most (7 boreholes) of the boreholes were below the limit of DWAF. Two boreholes, BH5 and BH7 were above the limit with turbidity values of 1.62 and 1.66 NTU respectively. Turbidity has no direct health risk but the suspended particles associated with turbidity can be capitalised on by microbial organism as breeding ground (DWAF, 1996). However, the turbidity values of 1.62 and 1.66 NTU of borehole BH5 and BH7, respectively had a slight chance of contamination because it is less than 5 NTU. Therefore, the water is still fit for consumption with little or no treatment.

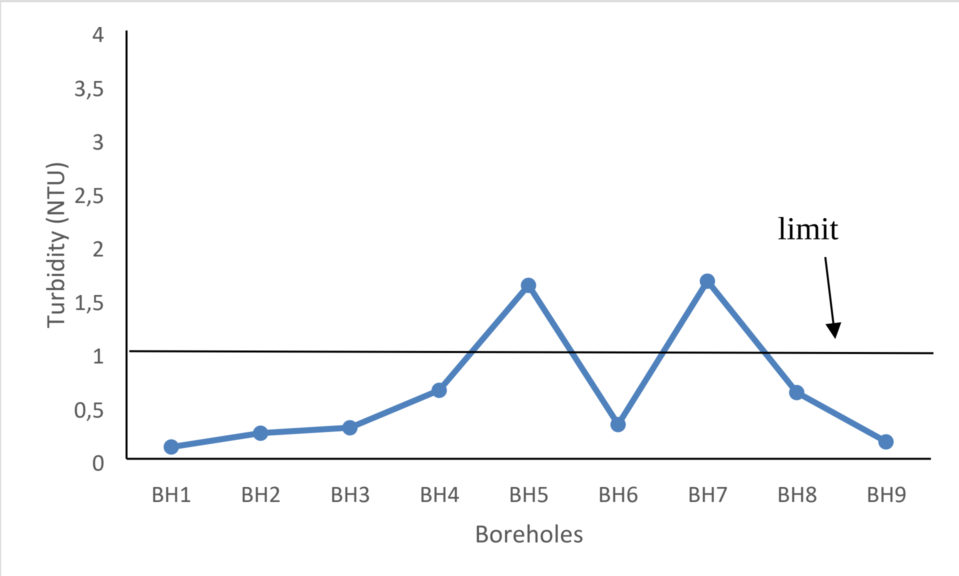

Figure 4.26: Turbidity of water from the boreholes

4.4.2 Chemical water quality parameters

Metals

Groundwater chemistry shows that most of the sample (BH2, BH3, BH6, BH7, BH8 and BH9) had concentrations of calcium (Ca) greater than 30 mg/L. Although concentration of Ca above 32 mg/L has no health effect, it has a scaling effect (DWAF, 1996). The result also indicated that the groundwater samples are dominated by magnesium (Mg). This high concentration of Mg elucidates more on the aforementioned fact about the dolomitic influence on the groundwater in the area. Magnesium concentration ranged from 39.23 to 122.62 mg/L. According to DWAF (1996) the targeted water quality value is 30 mg/L, although concentrations up to 70 mg/L are still expected to have no adverse health effects other than scaling. However, Mg concentration between 70 and 100 mg/L causes taste and low possibility of diarrhoea. Concentrations above 100 mg/L are critically unacceptable because they cause bitter taste, diarrhoea and increased scaling problems. Figure 4.27 shows the concentration of Mg and Ca against the permissible thresholds set by DWAF (1996) for domestic use.

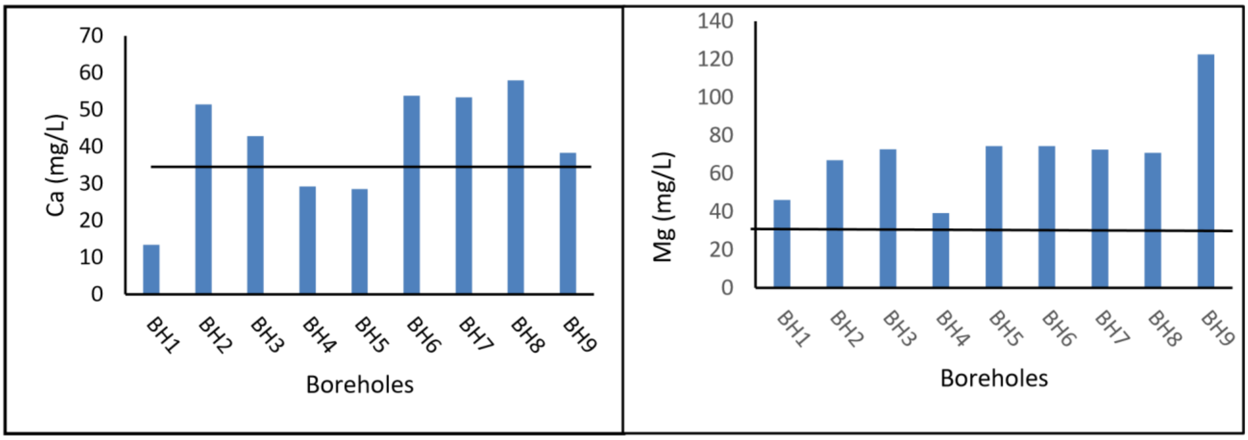

Figure 4.27: Calcium and magnesium concentrations

The rest of the metal constituents (Fe, K, Na, Mn and Zn) of the groundwater samples in Lebalelo South were mostly compliant with the DWAF (1996) guidelines for domestic water supply (Figure 4.28).

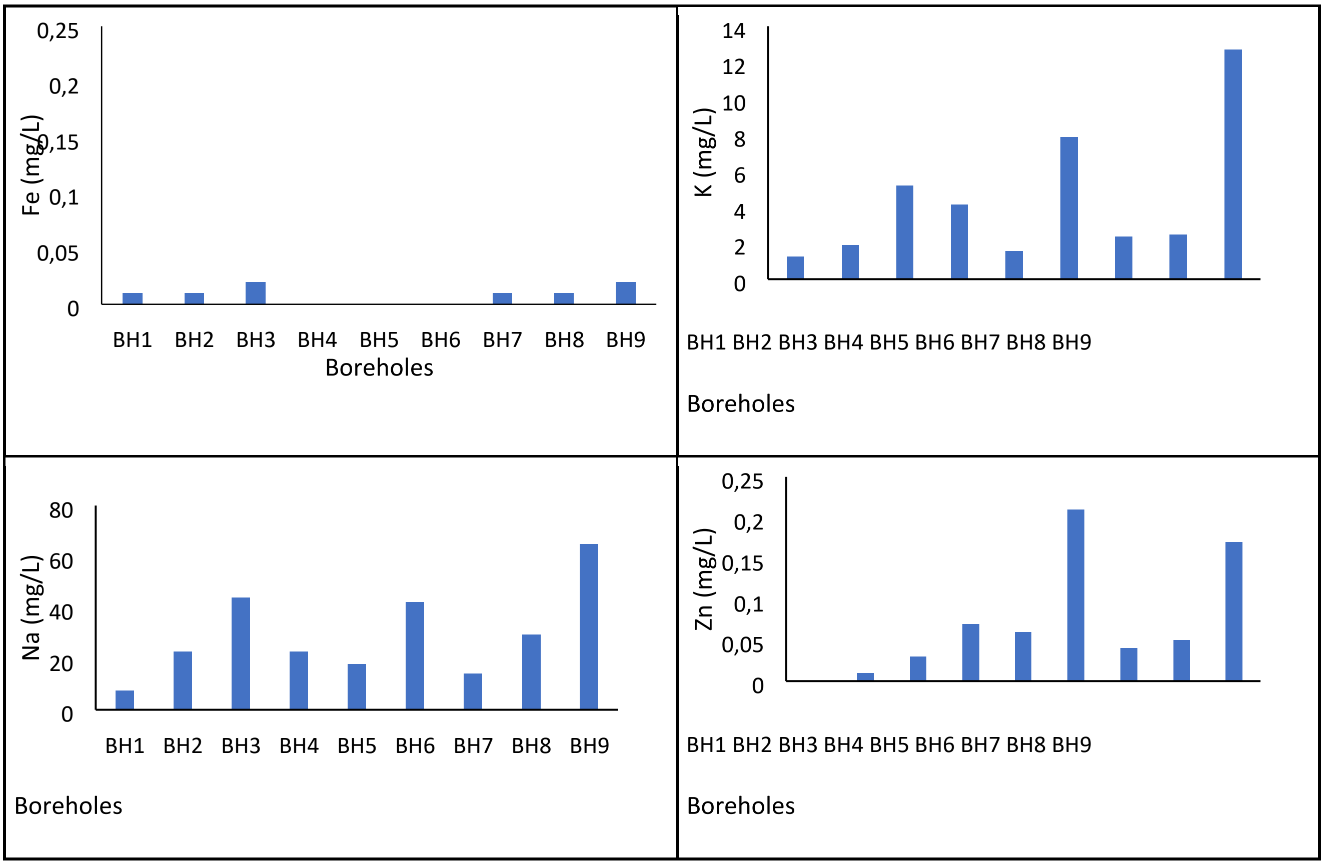

Figure 4.28: The concentrations of Fe, K, Na and Zn

Inorganic non-metallic constituents

Chloride was less dominant in the study area because it fell within the permissible DWAF (1996) limit with exception of BH9. Chloride concentration at BH9 was above the 100 mg/L permissible quality threshold, although at this concentration, no adverse health implication is noticeable but corrosion can occur in domestic appliances (Makungo and Odiyo, 2018). Typical sources of nitrates in groundwater are seeped sewage and agricultural fertilisers. Nitrites at concentrations higher than 10 mg/L are known to cause *methemoglobinemia* in infants, where they combine with the oxygen-carrying red blood pigment (haemoglobin). At concentrations higher than 20 mg/L nitrates may cause mucous membrane irritation in adults. Nitrates also form carcinogenic nitrosamines when they react with secondary and tertiary amines and amides (DWAF, 1996). BH9 shows the highest concentration of both nitrate and chloride (Figure 4.29).

This according to Makungo and Odiyo (2018) is indicative of an anthropogenic contamination from the combination of fertilizers and pit latrine seepage. This is evident by the presence of pit latrine in almost every household and the practice of small-scale subsistence farming on almost every plot in the study area. The presence of alluvium also enhances the flow of contaminant in the subsurface due to its effective porosity and permeability. Fluoride (F) is essential to the development of dental and skeletal framework of the body. The concentrations of fluoride in the study area ranges from <0.01 to 0.48 mg/L. These fluoride concentrations generally fell below the permissible limit of fluoride consumption by regulatory bodies like DWAF (1996) (1mg/L) and WHO (2003) (1.5 mg/L). However, the lower limit of DWAF (1996) is 0 mg/L while the lower limit of consumption set by WHO (2003) is 0.5 mg/L. Therefore, based on DWAF (1996) classification, BH1, BH4 and BH5 had extremely low to undetectable concentration of fluoride. Consumption of low concentration of fluoride is also detrimental to the body because it causes osteoporosis and dental caries in infants (Thompson, 2012; Ncube and Shutte, 2002). According to DWAF (1996), the lower permissible limit as compared to WHO (2003) limit was due to the consideration of climatic factor in South Africa which influences the daily consumption rate of water. Figure 4.29 shows the plots of chloride, fluoride, nitrate and sulphate in the study area.

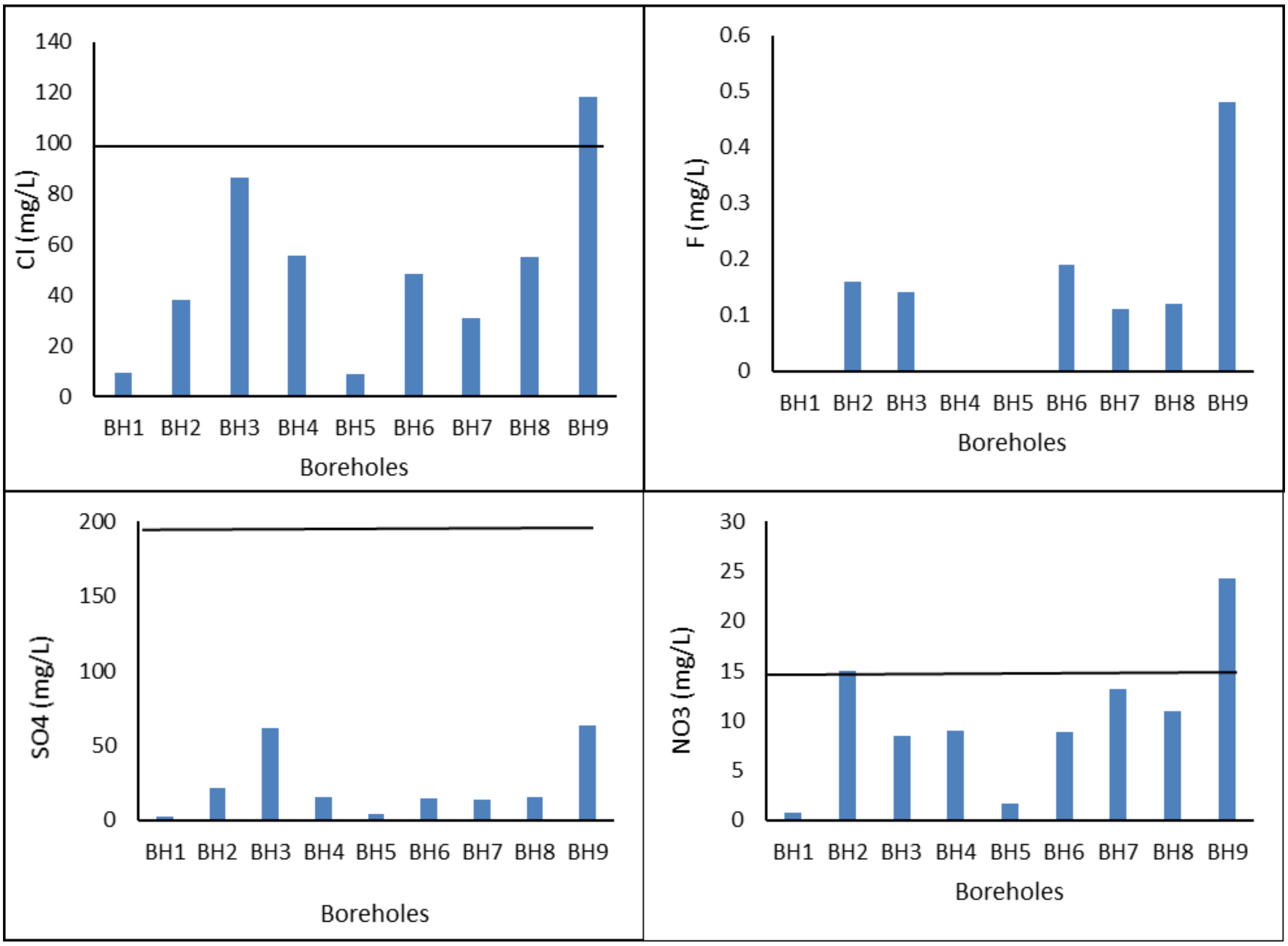

Figure 4.29: The concentrations of Cl, F, NO3 and SO4

Groundwater mineralization

Gibbs diagram (Figure 4.30) clearly showed that the chemistry of groundwater at Lebalelo south is mainly mineralised and enriched by rock-water interaction process and weathering. This explains the high concentration of Mg and Ca because the study area is dominated by dolomite.

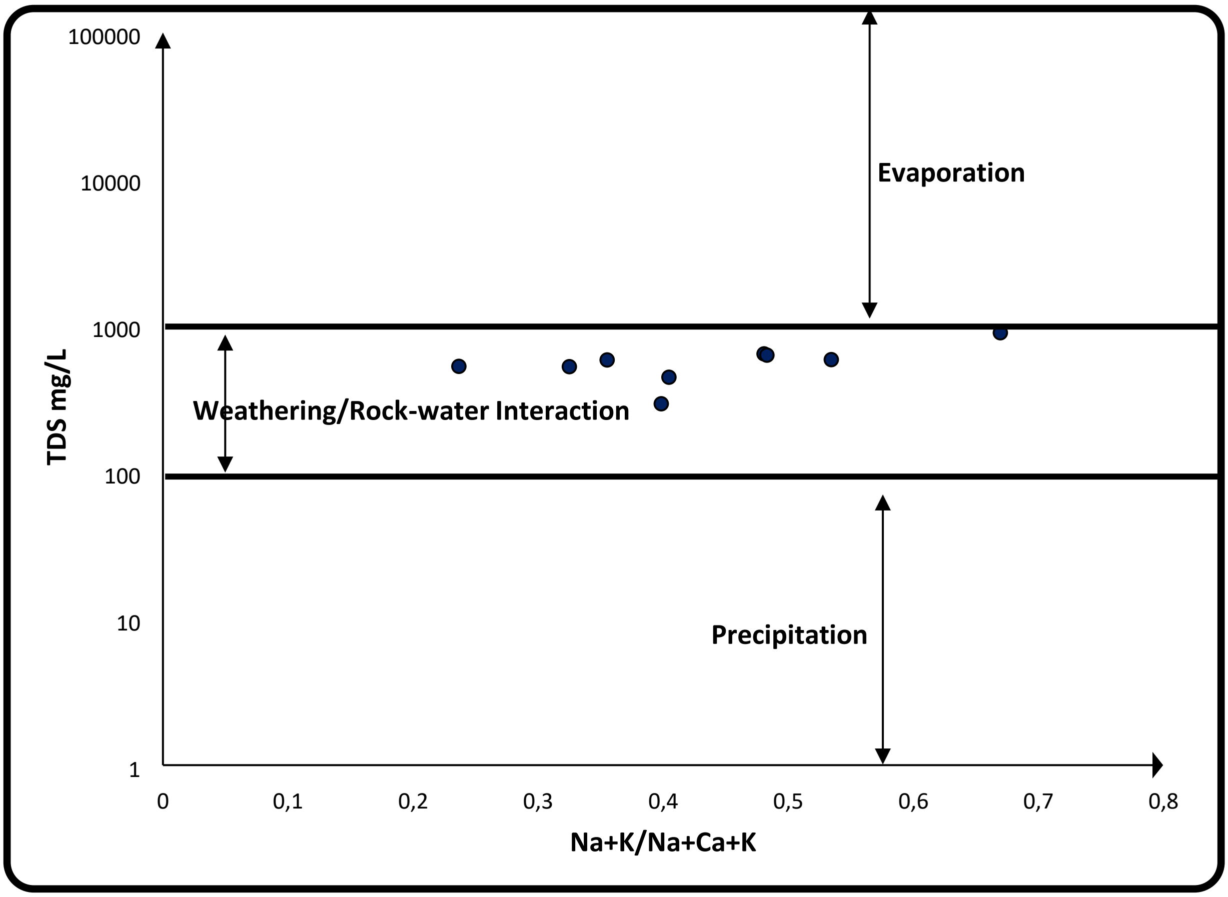

Figure 4.30: Gibbs diagram showing the mineralization process

Therefore, the residence time of groundwater and the lithostratigraphy plays an important role in the enrichment process of the groundwater in the area.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The aim of this study was to characterise the hydrogeology and hydrochemistry of Lebalelo South area. Geophysical surveys were carried out to determine the appropriate drilling position. The results indicated that the boreholes were sited in fractured zones associated with magnetic intrusion and lineament fracturing. The combination of magnetic and electromagnetic geophysical methods proved effective because the fractured zones associated with magnetic intrusion (dykes) and other magnetic structures (lineaments) showed higher conductivity values than the surrounding country rocks. Pumping tests were carried out on both the newly drilled boreholes and some existing boreholes in the study area, and the results were analysed using diagnostic plots, drawdown derivative plots and flow conditions. Most of the boreholes BH1 to BH8 showed double porosity behaviour and they were fitted with the Moench (1984) solution. In addition to that, BH3, BH4, BH6 and BH7 showed numerous instances of fracture dewatering. BH9 was peculiar displaying a general radial flow behaviour with single porosity which was fitted by Barker (1988) solution. Aquifer parameters were estimated from automatic curve matching. Transmissivity was high in boreholes BH1, BH2 and BH7 where it was 82.67, 123.1 and 124.7 m^2/day, respectively. The rest of the transmissivities were from 0.08953 to 29.07 m^2/day. The storativity of the tested boreholes ranges from 0.005256 to 1.08, whereas the transmissivity ranges from 0.01180 to 0.6737 m/day.

Water samples were collected from all the boreholes and were analysed in order to determine its suitability for domestic consumption and to determine its chemical history. The physicochemical parameters were mostly within the acceptable limit except for the hardness of the water which was the first indicator to the dominance of dolomite on the groundwater chemistry. Hydrochemical investigation shows that the chemistry of the groundwater is controlled by the interaction between the rocks in the area (alluvium/scree and dolomite) and the groundwater. The dominance of Mg and Ca as well as $CaCO_3$ proved that the dolomite in the area has a major influence on the groundwater chemistry. The groundwater samples were mostly suitable for consumption except for few excluded cases of high turbidity in boreholes BH5 and BH7, high Cl and NO_3 in BH9 as well as few cases of increased Ca and Mg.

The preceding paragraphs indicate that the objectives and research questions of the study were achieved.

5.2 RECOMMENDATIONS

The following recommendations are drawn from the outcome of this study:

Hydrogeochemical investigation which involves rock and soil sampling should be carried out in the area to establish a link between the geology and the groundwater

Leaching experiment should be carried out to determine the actual movement of ions from rock to groundwater.

More chemical parameters are needed to fully understand the extent and complexity of the geochemistry in the area.

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APPENDICES

APPENDIX 1: Tables

Physical and aggregate properties of groundwater

	BH1 GaRiba	BH2 Ragapola	BH3 Mandela 1	BH4 Riba Cross1	BH5 Mogologolo	BH6 Riba Cross2	BH7 Driekop	BH8 Frans	BH9 Mandela2	DWS guidelines
pH	7.3	7.0	6.8	7.3	7.9	7.3	7.3	7.3	7.7	6-9
Turbidity (NTU)	0.11	0.24	0.29	0.64	***1.62***	**0.32**	***1.66***	0.62	0.16	1
Conductivity (mS/m)	45.0	*80.7*	*90.1*	*98.8*	68.3	*96.6*	*81.1*	*89.7*	*137.8*	<70
TDS (mg/l)	293	*524*	*586*	*642*	444	*628*	*527*	*583*	*896*	<450
Total Hardness (mg/l)	222.53	403.49	405.68	233.87	376.86	439.23	430.85	435.26	598.49	

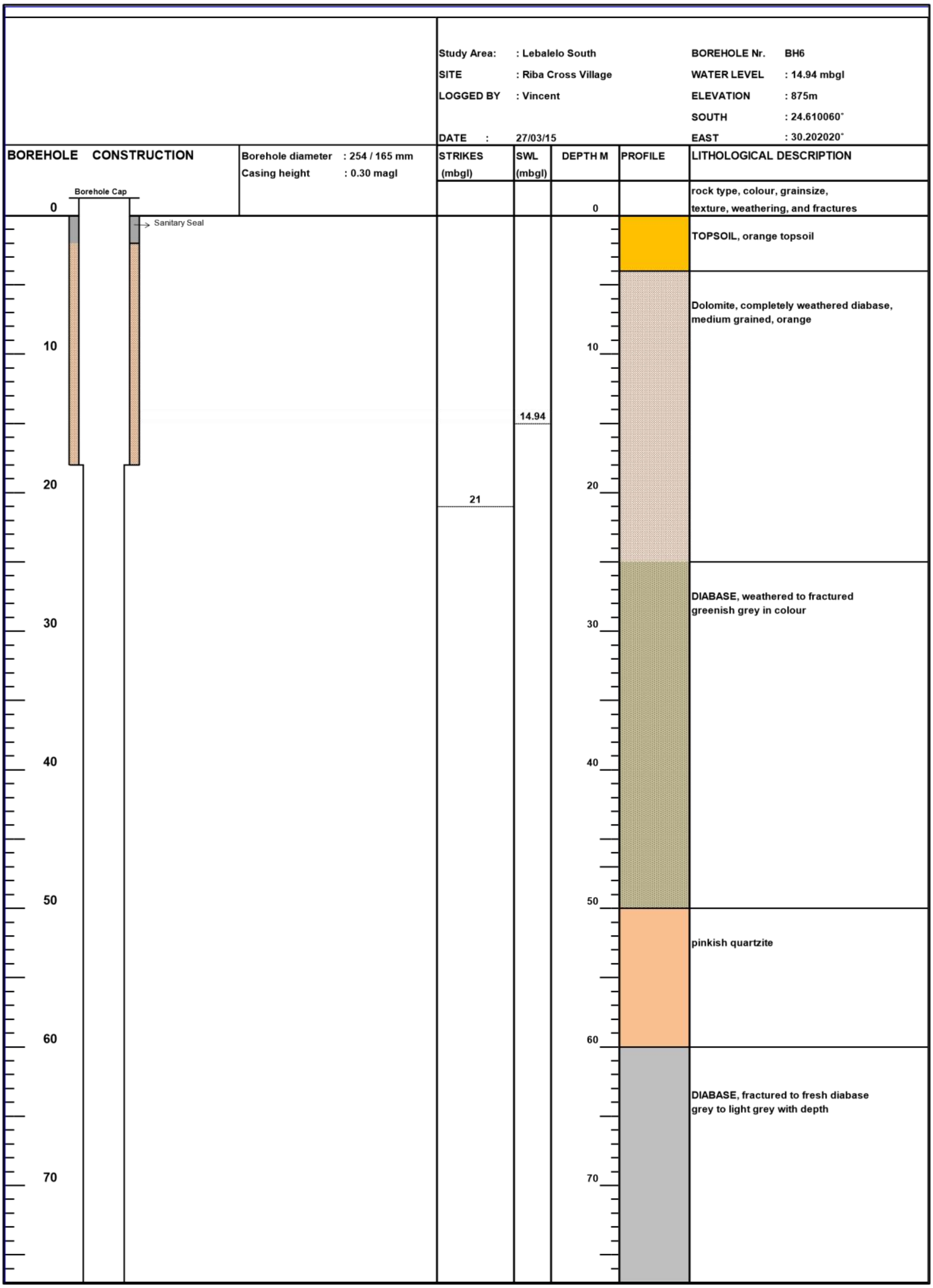
Metal constituents of groundwater in Lebalelo South

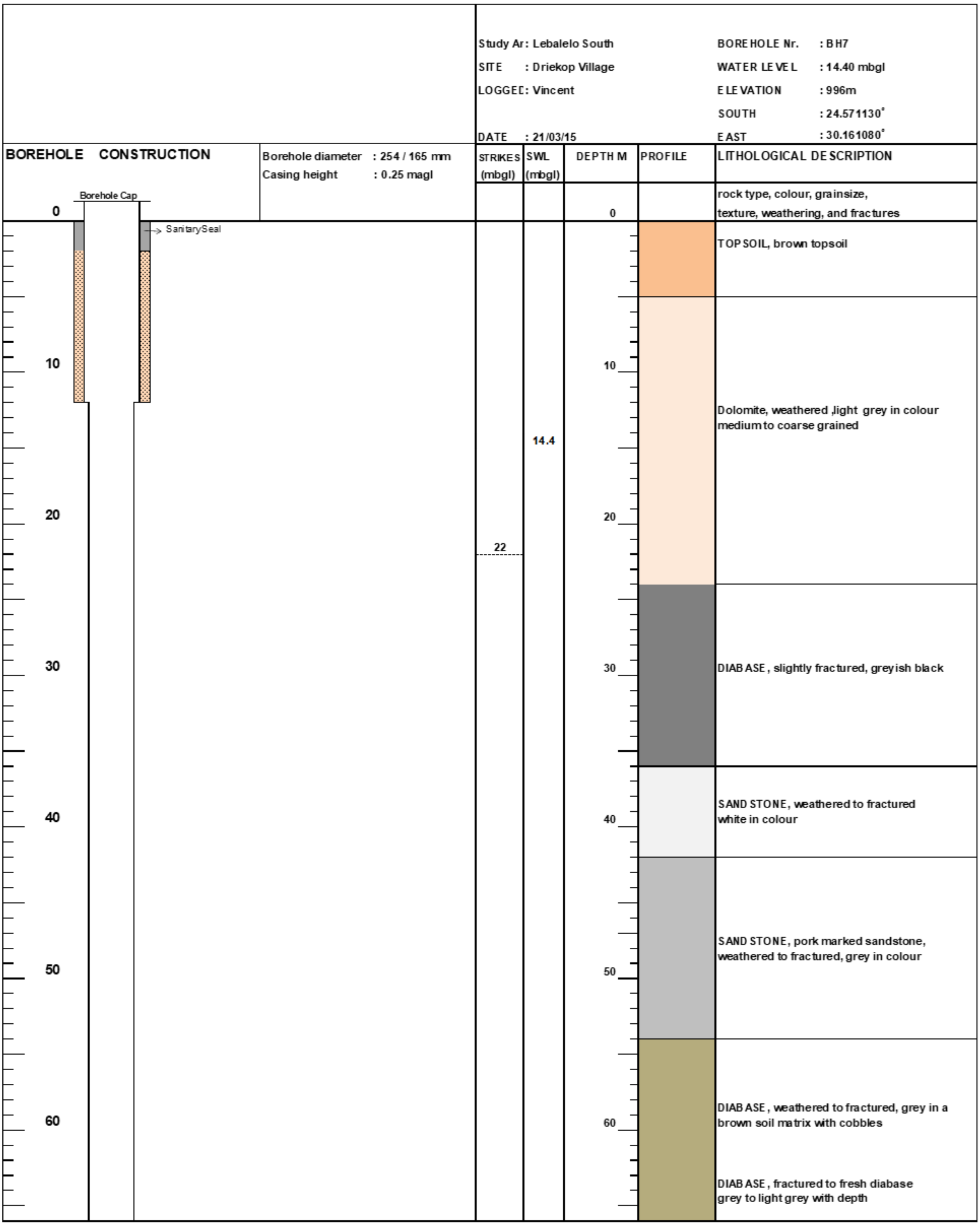
	BH1 GaRiba	BH2 Ragapola	BH3 Mandela 1	BH4 Riba Cross1	BH5 Mogologolo	BH6 Riba Cross2	BH7 Driekop	BH8 Frans	BH9 Mandela 2	DWS guidelines
Ca	13.44	***51.45***	***42.88***	29.21	28.51	***53.74***	***53.34***	***57.96***	***38.30***	<32
Mg	***46.08***	***67.04***	***72.80***	***39.23***	***74.41***	***74.36***	***72.56***	***70.82***	***122.62***	<30
Total Fe	0.01	0.01	0.02	<0.01	<0.01	<0.01	0.01	0.01	0.02	<0.1
Mn	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.02	<0.01	<0.01	0.05
K	1.26	1.90	5.18	4.14	1.55	7.88	2.35	2.46	12.72	<50
Na	7.64	22.86	44.04	22.91	17.83	42.32	14.19	29.46	64.96	<100
Zn	<0.01	0.01	0.03	0.07	0.06	0.21	0.04	0.05	0.17	<3

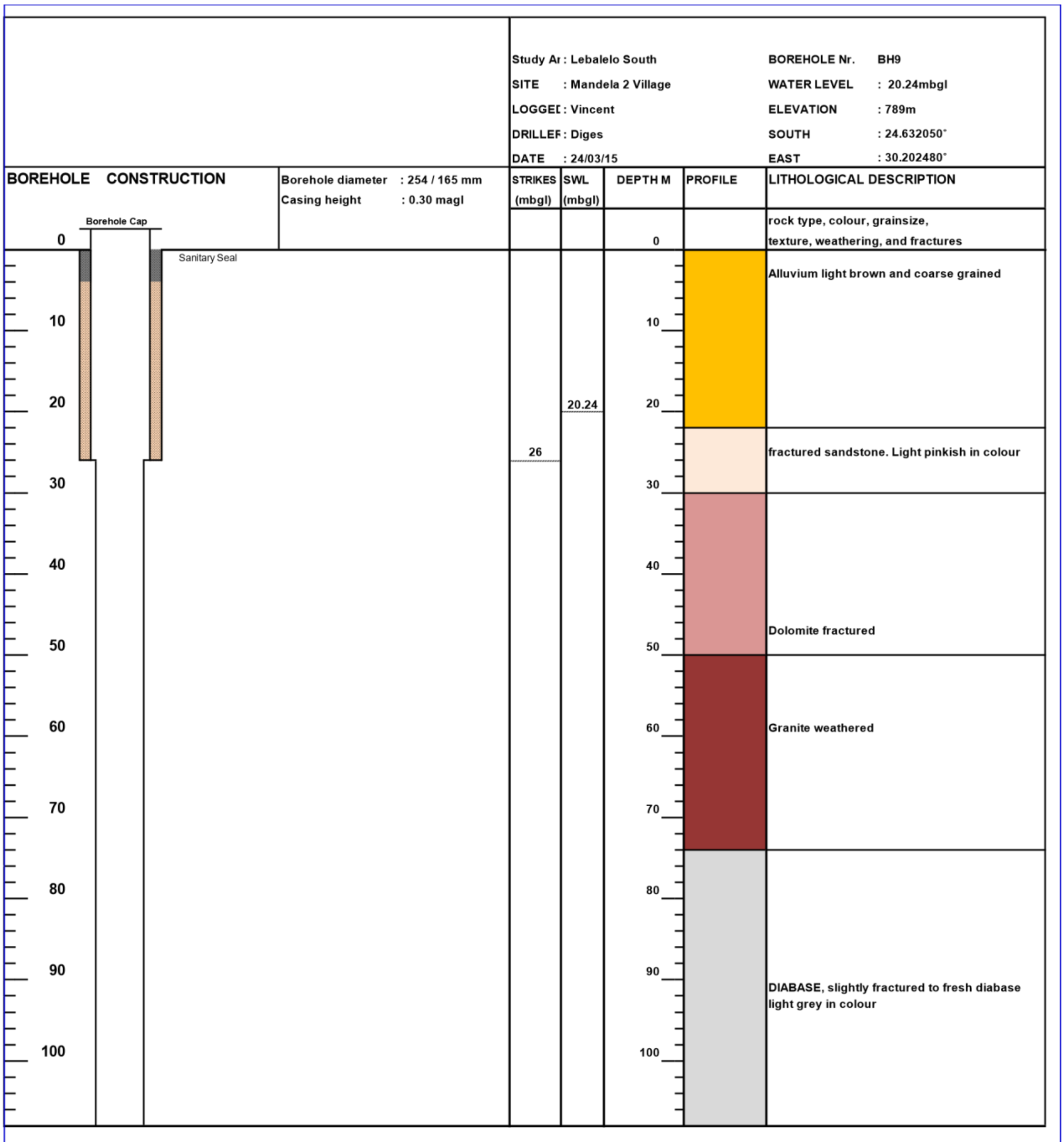
Inorganic non-metallic constituents of groundwater in Lebalelo South

	BH1 GaRiba	BH2 Ragapola	BH3 Mandela 1	BH4 Riba Cross1	BH5 Mogologolo	BH6 Riba Cross2	BH7 Driekop	BH8 Frans	BH9 Mandela 2	DWS guidelines
Cl	9.5	38.2	86.3	55.5	9.0	48.3	30.9	55.0	***118.3***	<100
F	<0.01	0.16	0.14	<0.01	<0.10	0.19	0.11	0.12	0.48	<1
NO3 (N)	0.78	***14.94***	***8.46***	***9.01***	1.68	***8.93***	***13.12***	***10.90***	***24.20***	<6
SO4	2.73	21.98	61.34	15.38	4.62	15.01	14.07	15.40	63.54	<200

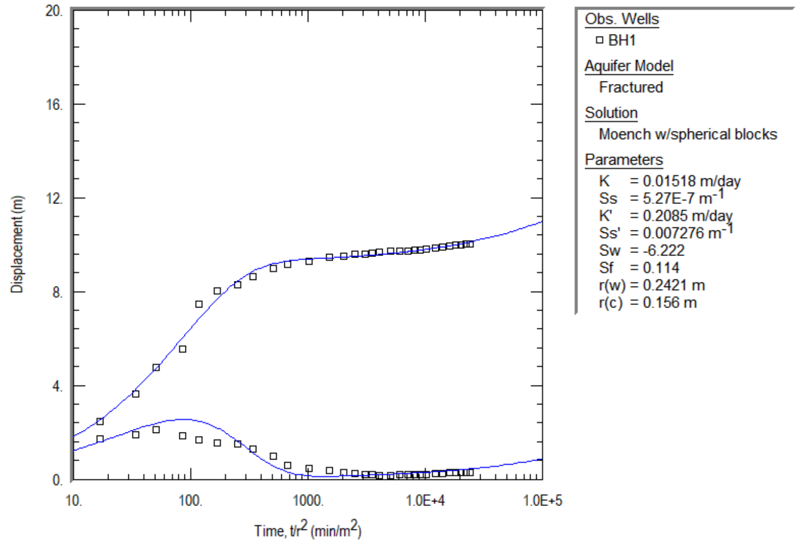
APPENDIX 2: Borehole logs

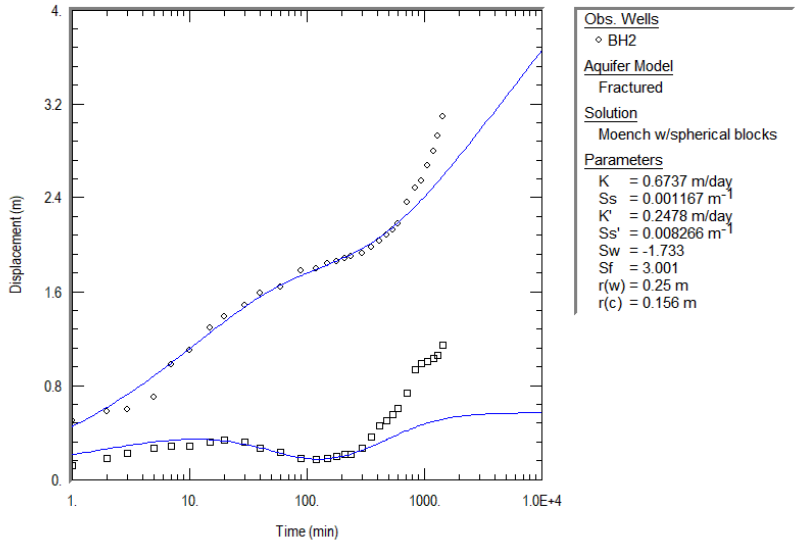


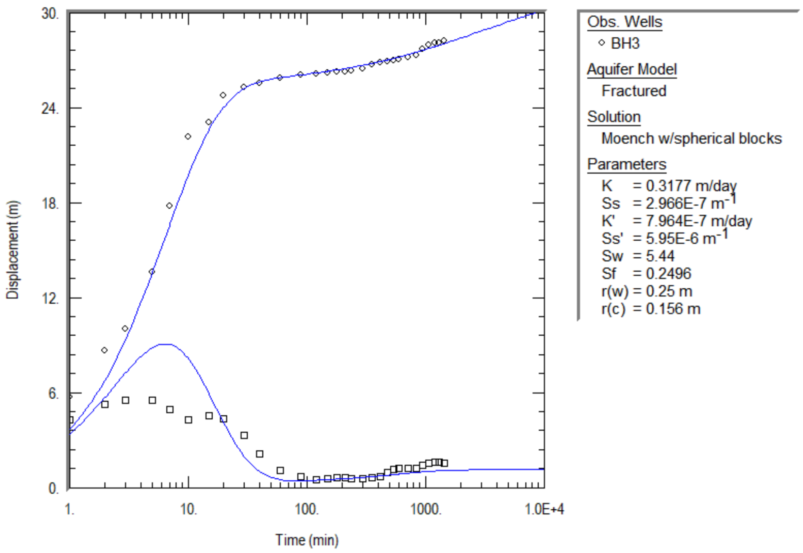

Study Ar: Lebalelo South
SITE : Driekop Village
LOGGED: Vincent
DATE : 21/03/15
BOREHOLE Nr. : BH7
WATER LEVEL : 14.40 mbgl
ELEVATION : 996m
SOUTH : 24.571130°
EAST : 30.161080°
BOREHOLE CONSTRUCTION
Borehole diameter : 254 / 165 mm
Casing height : 0.25 magl
Borehole Cap
Sanitary Seal
STRIKES (mbgl)
SWL (mbgl)
DEPTH M
PROFILE
LITHOLOGICAL DESCRIPTION
rock type, colour, grainsize, texture, weathering, and fractures
0
10
20
30
40
50
60
14.4
22
TOPSOIL, brown topsoil
Dolomite, weathered ,light grey in colour medium to coarse grained
DIABASE, slightly fractured, greyish black
SAND STONE, weathered to fractured white in colour
SAND STONE, pork marked sandstone, weathered to fractured, grey in colour
DIABASE, weathered to fractured, grey in a brown soil matrix with cobbles
DIABASE, fractured to fresh diabase grey to light grey with depth

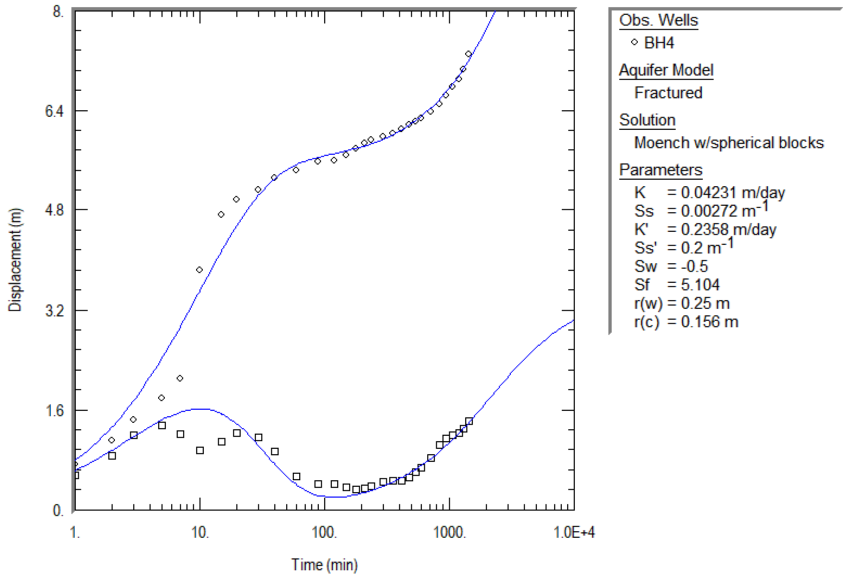

Study Ar : Lebalelo South
SITE : Mandela 2 Village
LOGGEI : Vincent
DRILLEF : Diges
DATE : 24/03/15
BOREHOLE Nr. BH9
WATER LEVEL : 20.24mbgl
ELEVATION : 789m
SOUTH : 24.632050°
EAST : 30.202480°
BOREHOLE CONSTRUCTION
Borehole diameter : 254 / 165 mm
Casing height : 0.30 magl
Borehole Cap
Sanitary Seal
STRIKES (mbgl)
SWL (mbgl)
DEPTH M
PROFILE
LITHOLOGICAL DESCRIPTION
rock type, colour, grainsize, texture, weathering, and fractures
0
10
20
30
40
50
60
70
80
90
100
20.24
26
Alluvium light brown and coarse grained
fractured sandstone. Light pinkish in colour
Dolomite fractured
Granite weathered
DIABASE, slightly fractured to fresh diabase light grey in colour

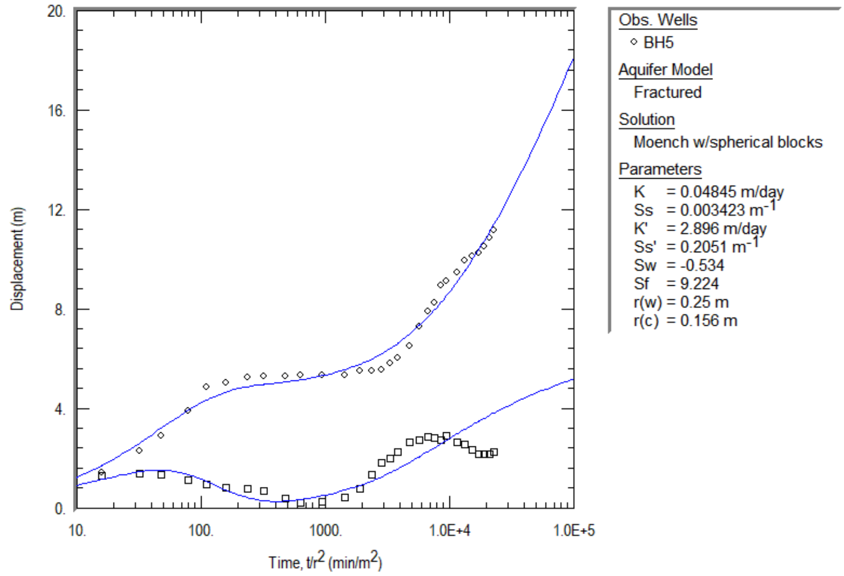
APPENDIX 3: Semi-log plots

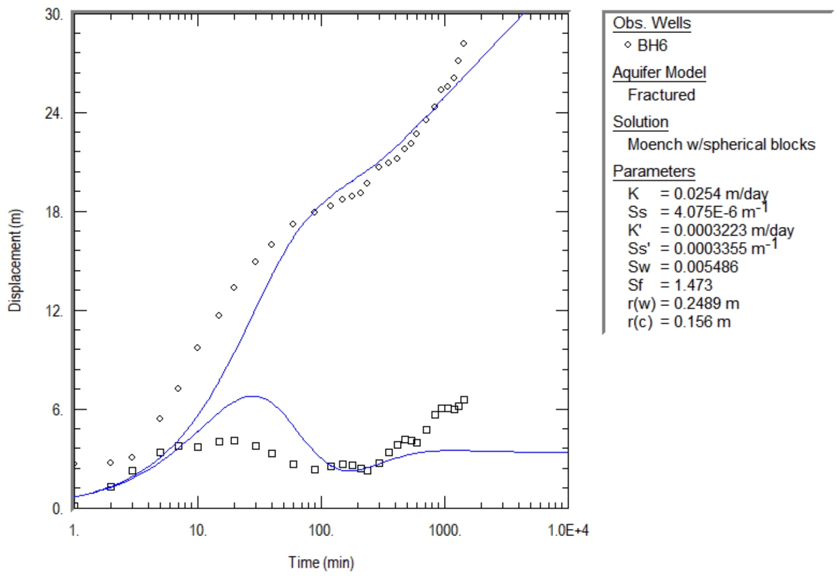


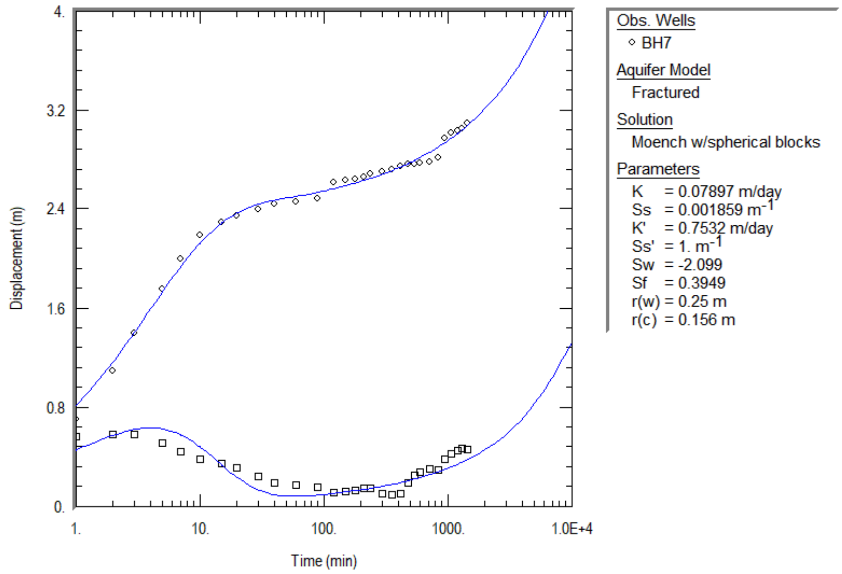


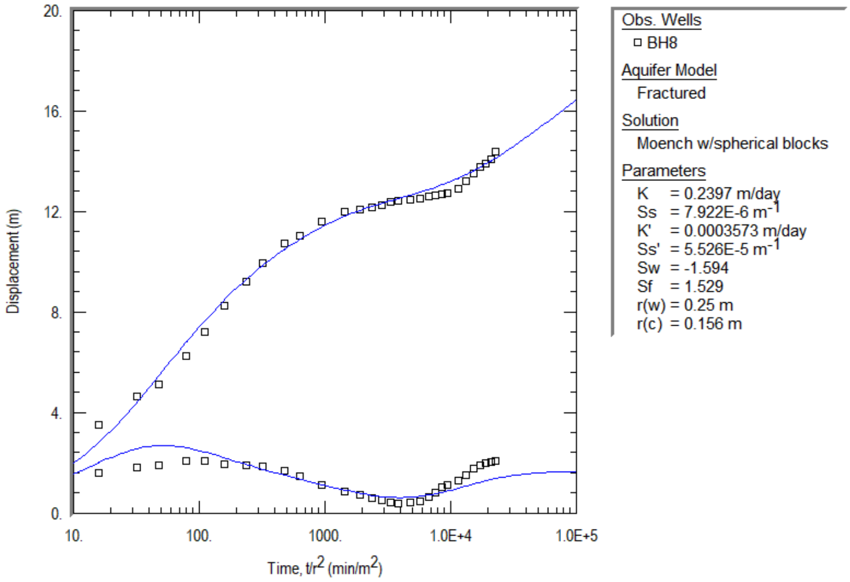


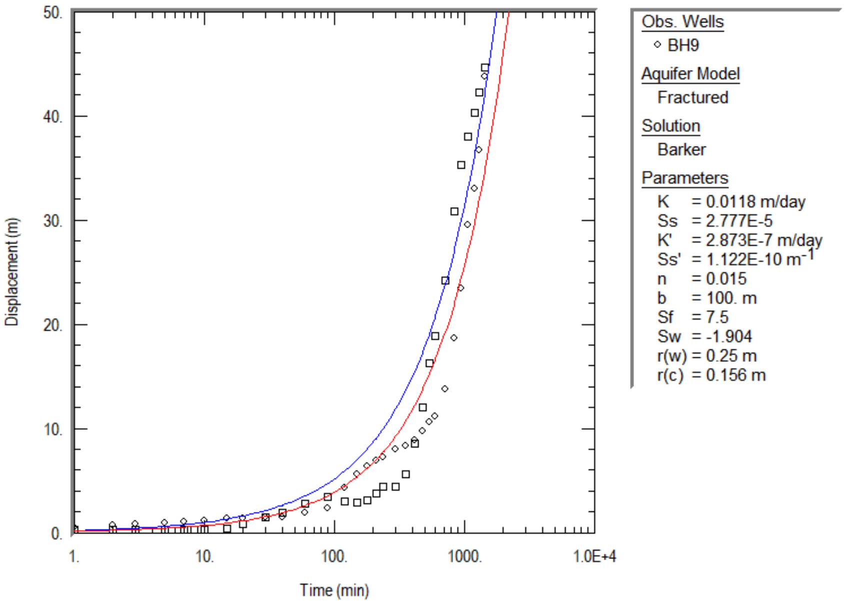

Obs. Wells
BH4
Aquifer Model
Fractured
Solution
Moench w/spherical blocks
Parameters
K = 0.04231 m/day
Ss = 0.00272 m-1
K' = 0.2358 m/day
Ss' = 0.2 m-1
Sw = -0.5
Sf = 5.104
r(w) = 0.25 m
r(c) = 0.156 m
Displacement (m)
Time (min)


Obs. Wells
BH5
Aquifer Model
Fractured
Solution
Moench w/spherical blocks
Parameters
K = 0.04845 m/day
Ss = 0.003423 m-1
K' = 2.896 m/day
Ss' = 0.2051 m-1
Sw = -0.534
Sf = 9.224
r(w) = 0.25 m
r(c) = 0.156 m
Displacement (m)
Time, t/r2 (min/m2)

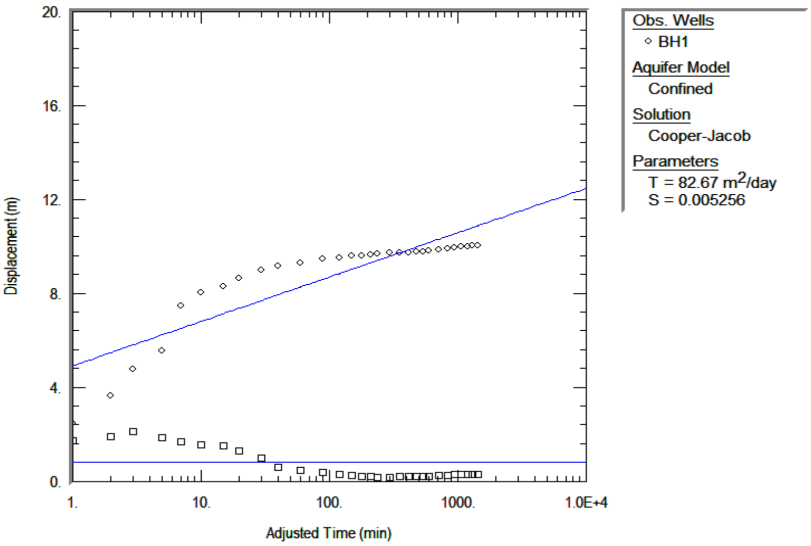

Obs. Wells
BH6
Aquifer Model
Fractured
Solution
Moench w/spherical blocks
Parameters
K = 0.0254 m/day
Ss = 4.075E-6 m-1
K' = 0.0003223 m/day
Ss' = 0.0003355 m-1
Sw = 0.005486
Sf = 1.473
r(w) = 0.2489 m
r(c) = 0.156 m
Displacement (m)
Time (min)

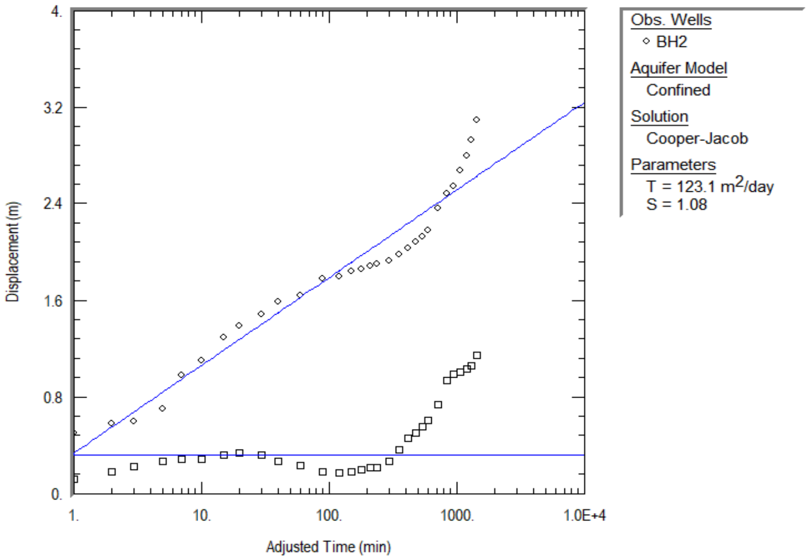

Displacement (m)
Time (min)
Obs. Wells
BH7
Aquifer Model
Fractured
Solution
Moench w/spherical blocks
Parameters
K = 0.07897 m/day
Ss = 0.001859 m-1
K' = 0.7532 m/day
Ss' = 1. m-1
Sw = -2.099
Sf = 0.3949
r(w) = 0.25 m
r(c) = 0.156 m

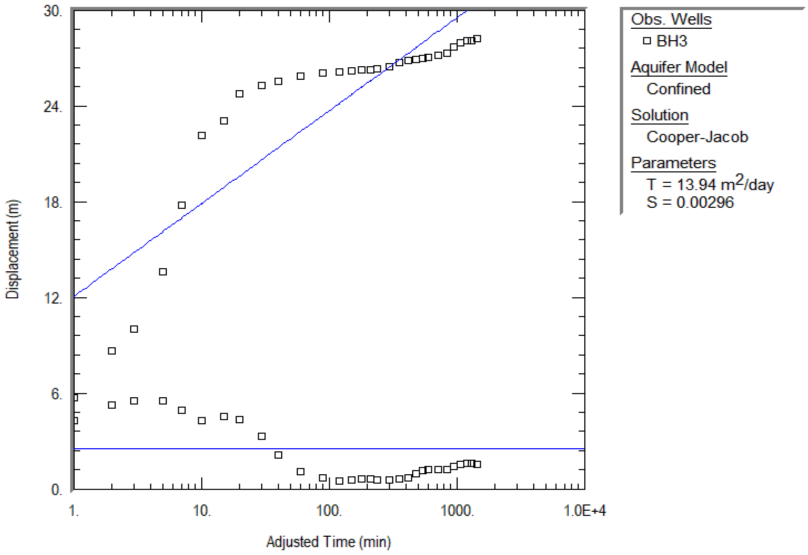

Displacement (m)
Time, t/r2 (min/m2)
Obs. Wells
BH8
Aquifer Model
Fractured
Solution
Moench w/spherical blocks
Parameters
K = 0.2397 m/day
Ss = 7.922E-6 m-1
K' = 0.0003573 m/day
Ss' = 5.526E-5 m-1
Sw = -1.594
Sf = 1.529
r(w) = 0.25 m
r(c) = 0.156 m

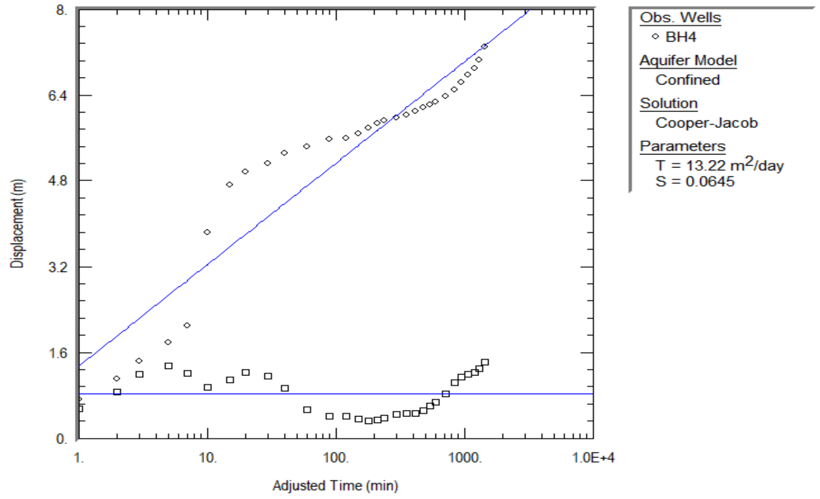

Displacement (m)
Time (min)
Obs. Wells
BH9
Aquifer Model
Fractured
Solution
Barker
Parameters
K = 0.0118 m/day
Ss = 2.777E-5
K' = 2.873E-7 m/day
Ss' = 1.122E-10 m-1
n = 0.015
b = 100. m
Sf = 7.5
Sw = -1.904
r(w) = 0.25 m
r(c) = 0.156 m

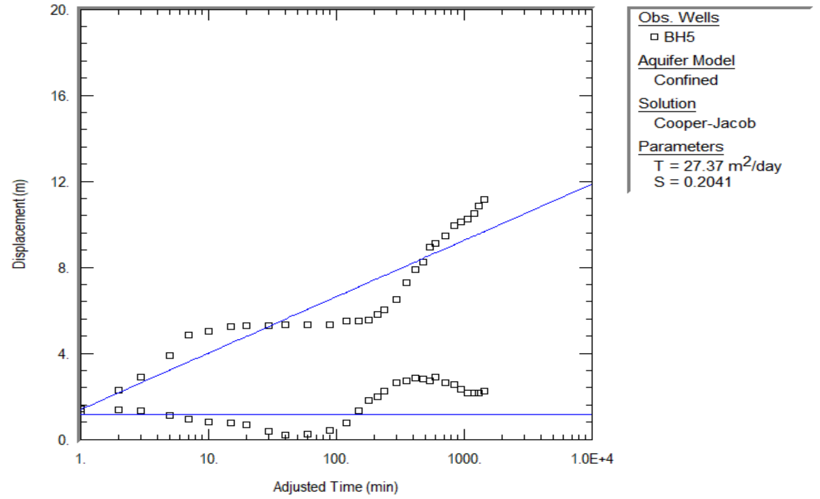
APPENDIX 4: Cooper-Jacob graphs

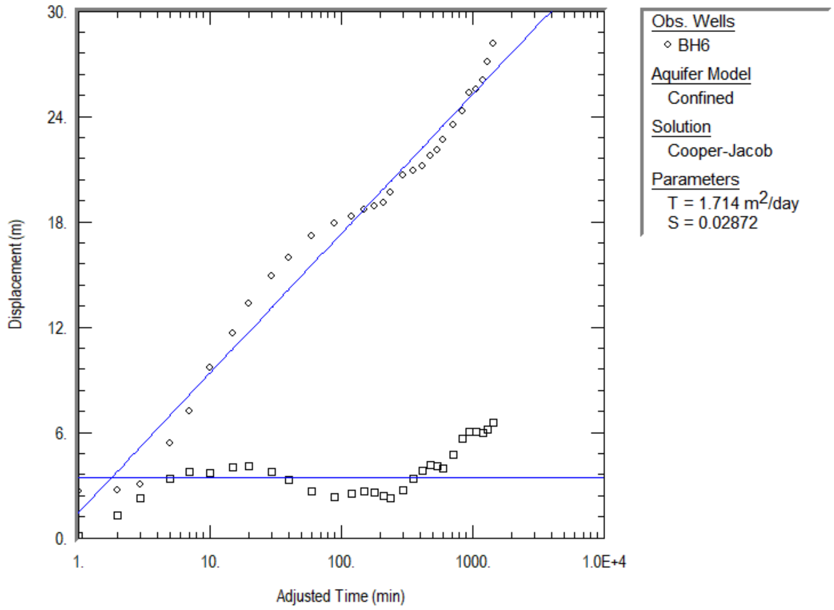


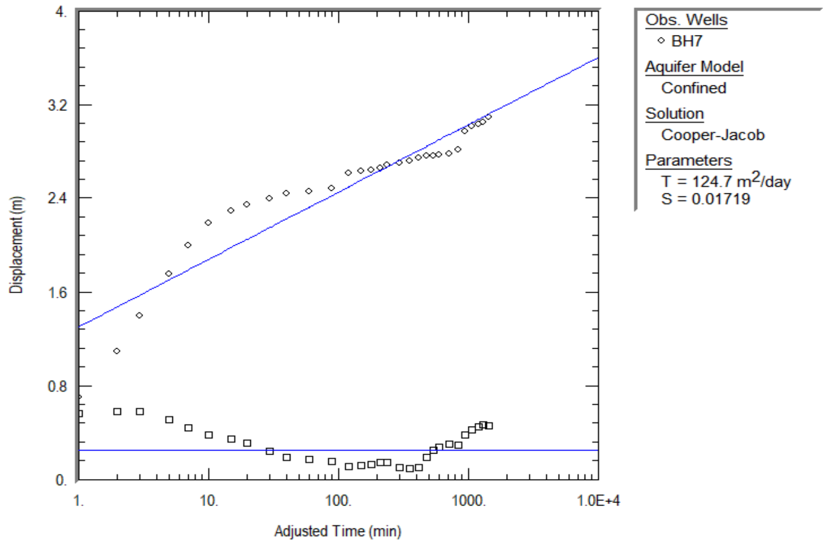


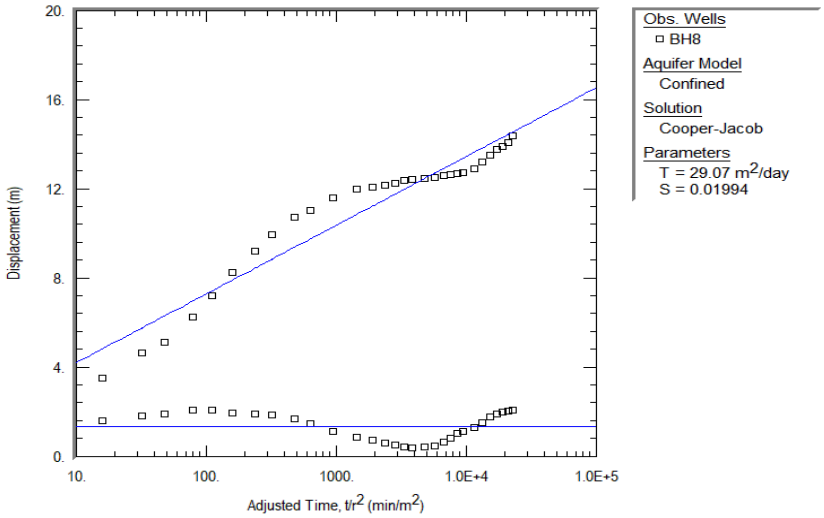


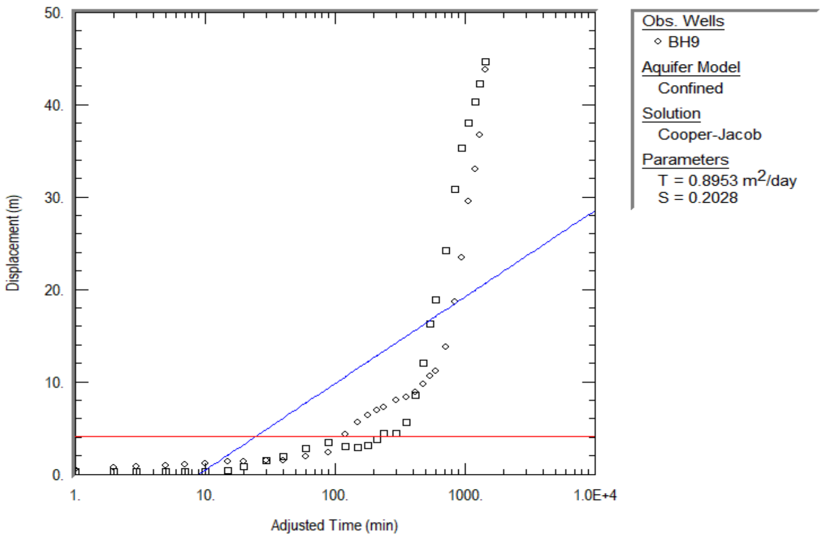

Obs. Wells
BH4
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 13.22 m2/day
S = 0.0645
Displacement (m)
Adjusted Time (min)


Obs. Wells
BH5
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 27.37 m2/day
S = 0.2041
Displacement (m)
Adjusted Time (min)


Obs. Wells
BH6
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 1.714 m2/day
S = 0.02872
Displacement (m)
Adjusted Time (min)


Obs. Wells
BH7
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 124.7 m2/day
S = 0.01719
Displacement (m)
Adjusted Time (min)
4.
3.2
2.4
1.6
0.8
0.
1.
10.
100.
1000.
1.0E+4


Obs. Wells
BH8
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 29.07 m2/day
S = 0.01994
Displacement (m)
Adjusted Time, t/r2 (min/m2)
20.
16.
12.
8.
4.
0.
10.
100.
1000.
1.0E+4
1.0E+5


Obs. Wells
BH9
Aquifer Model
Confined
Solution
Cooper-Jacob
Parameters
T = 0.8953 m2/day
S = 0.2028
Displacement (m)
Adjusted Time (min)
50.
40.
30.
20.
10.
0.
1.
10.
100.
1000.
1.0E+4