GROUNDWATER RESOURCE ASSESSMENT FOR TOWN WATER SUPPLY IN STEYNSRUS IN THE FREE STATE PROVINCE OF SOUTH AFRICA

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29 January 2016

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LIST OF ABBREVIATIONS

ARS	Above Recommended Standard
CMB	Chloride Mass Balance Method
DEAT	Department of Environment and Tourism
DM	District municipality
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
GHT	Geo-Hydro Technologies
GRAI	Groundwater Resources Assessment
GRAII	Groundwater Resources Assessment Project Two
IDP	Integrated Development Plan

LM	Local municipality
MAP	Mean Annual Precipitation
mbgl	metres below ground level
SADC	Southern African Development Community
SAR	Sodium Adsorption Ratio
SAWS	South African Weather Services
SWL	Static Water Level
TDS	Total Dissolved Solids
WHO	World Health Organization
WMA	Water Management Area

CHAPTER 1 INTRODUCTION

1.1 RESEARCH FRAMEWORK

The water scarcity of the Moqhaka Local Municipality and its respective towns, especially Steynsrus, make the efficient use of available water resources a necessity. This groundwater project was initiated through a national intervention by the Department of Water Affairs (DWA). The purpose of the groundwater (project) investigations was to find alternate sources to supplement the existing water resources but only if the revision of the current and projected future water demands confirms the need for augmentation (DWA, 2011a). Improving living standards, social development needs, increased population and increased irrigation have been the main factors contributing to increased water demands in Steynsrus. The efficient use of water resources on municipal level is necessary for sustainable use.

Groundwater Resources Assessment (GRA) project was completed in 2003 after the publication of a series of 21 hydrologeological maps (at a scale of 1:500 000) were compiled during the project dealing with the classification of South African aquifers. The main objective of the Groundwater Resources Assessment Phase I project (GRAI) that was initiated in 2003 was to quantify South Africa's groundwater resources (DWAF, 2006). The project included the quantification of the aquifer storage, recharge, groundwater use, and aquifer classification in order to estimate the amount of groundwater that can be abstracted on a quaternary catchment scale.

Steynsrus was selected as the study area for the project; this decision was based on feasibility in terms of the logistics and size, as well as the availability of funds for the project and the need for water. DWA has a long record (the oldest is 19 years) of hydrological data through its gauging stations along the Vals River that feeds the town, and there are also geohydrological and geochemical data that have been produced through various water supply projects.

In recent times, i.e. from year 2005 to date, Steynsrus has relied on groundwater for its water supply, with surface water supplementing this resource. In the past, groundwater was used to supplement the surface water resource; however, the reliance on surface water as a primary water supply source has decreased due to low rainfall and inadequate river flow. The dissertation is therefore aimed at assessing groundwater resources for water supply to the town of Steynsrus. In doing so, the study seeks to improve understanding of the factors controlling groundwater occurrence, aquifer yield potential, hydraulics and storage parameters, recharge characteristics and groundwater quality of the aquifer.

1.2 WATER SUPPLY BACKGROUND

The town of Steynsrus obtains water from both surface water and groundwater. The surface water source is the Vals River situated approximately 20 km out of the town. Groundwater sources are boreholes located in the town and in its vicinity. The reliability and sustainability of both water resources have been evaluated directly and indirectly. The direct evaluation has been through observation of the water shortages the town has had, causing major services such as schools to be closed (City Press, 2010). The indirect evaluation of the water resources in Steynsrus, especially groundwater, has been done through exploration studies and hydrological assessments by Geo-Hydro Technologies (GHT) on behalf of Moqhaka Local Municipality.

Shortages of water to meet the water demands in the town have been a major challenge. Water demand is defined as the volume of water needed by users to satisfy their needs (Wallingford, 2003). An investigation was conducted by Geo Hydro Technologies (GHT) on behalf of Moqhaka Local Municipality on the groundwater resources to find out whether the current and available groundwater resources are sufficient to meet the current and future water demands of Steynsrus. The water demands were determined via the *Development of the reconciliation strategy for all towns in the central region* study prepared by Pula Consulting on behalf of DWA (DWA, 2011a). The all-towns study considered different population databases in order to determine the current and projected water demands in 2030; these include the sources listed in Table 1. The growth trends established from the historical information (1996 and 2001) were assessed in the context of projected population growth of the town, obtained from the Stats SA (2007) population projections (quoted by DWA, 2011a).

A groundwater project by Hough and Rudolf (2012a) of Geo-Hydro Technologies funded by DWA was intended to make clean, safe and sustainable water accessible to certain rural communities (Steynsrus being one of these communities), with the goal of improving their health and livelihoods. This geohydrological assessment project provided valuable geohydrological information and revealed that urgent attention to exploration of the water resources in and around the town is required. The main results of the latter project are that the current and projected future water demands in Steynsrus are and will constitute a major challenge to meet due to the limited yields of the available water resources (DWA, 2011a).

Table 1: Population datasets used in the study

Source	Name	Level of data	Year
Stats SA	Census 1996	[1]Sub-places revised based on new demarcation	1996
Stats SA	Census 2001	[1]Sub-places	2001
Stats SA	Community Survey	Local municipality	2007
DWA	National Settlements	Settlements	2007
Eskom	Satellite Based Community	Individual households based on satellite photos	2006

[1]Sub-place: locations determined by Statistics South Africa, which generally correspond to suburbs, villages, or localities

Source: DWA (2011a).

In the GHT report (project RVN645.1/1352), Hough and Rudolf (2012b) generated findings concerning the groundwater potential of the town. Knowledge generated by Hough and Rudolf (2012b) provided information about the geological features and structures in the study area, which may act as preferential pathways for groundwater flow and which are the target areas for groundwater exploration for water supply purposes. This study will therefore seek to investigate the activities conducted to assess the groundwater potential as a sustainable resource in order to meet the projected 2030 water demands. The study will also estimate the groundwater balance for the town of Steynsrus and seek to determine whether groundwater as a sole source of water supply is sufficient to meet the 2030 water demands.

1.3 PROBLEM STATEMENT

Water is a limiting resource for development in Southern Africa and a change in water supply could have major implications in most sectors of the economy (SADC, 2001). Water systems in Southern Africa in general are classified as vulnerable (SADC, 2001). Factors that contribute to vulnerability in water systems in Southern Africa include seasonal and inter-annual variations in rainfall and high evaporation rates (Mukheibir and Sparks, 2003). Countries that are affected by water scarcity are mainly located in arid and semi-arid regions, and these include South Africa. The natural availability of water across South Africa is variable, and rainfall displays strong seasonality variation. Stream flow in South

African rivers is at a relatively low level for most of the year. This feature limits the proportion of stream flow that can be relied upon for use. An estimated 9% of the rainfall reaches the rivers in South Africa, compared to a world average of 31% (Department of Water Affairs and Forestry [DWAF], 1996a). The sustainability of groundwater resources depends, amongst other things, on the amount of rainfall and the extent of the aquifer boundaries. The main problem the study seeks to investigate is to ascertain how much groundwater is available in the study area and how suitable the quality of the groundwater is for human consumption.

1.4 METHODOLOGY

In order to obtain the necessary data and information for the completion of the study, many different tools and applications used in geohydrology had to be implemented and employed. The study had to consider the use of information from previous projects. The data generated in the project for water supply consisted of the desktop studies, field investigation which includes the hydrocensus whereby the existing boreholes within the 20 Km of the town were determined, remote sensing information such as aeromagnetic data and geological maps. Geophysics was conducted during field investigations by using a Magnetometer instrument. Drilling was also conducted upon the identified targets from geophysics and geological observation. Aquifer testing was conducted on the boreholes identified to have blow yield above 1.5 L/s, in order to determine flow regimes and estimate aquifer parameters. Water samples for chemical analysis were collected during aquifer pump testing, by taking a pumped sample from the borehole at the end of the tests.

Recharge for the study area was estimated using the Chloride Mass Balance method and Guess estimate method; the estimations indicated low recharge in accordance with maps constructed by Vegter (1995). All the parameters estimated and calculated would later be used for estimating sustainable yields and groundwater balance for Steynsrus.

1.5 AIMS AND OBJECTIVES

The aim of the project is to investigate the potential of the groundwater resources, and to determine if the resources will be sufficient for the current and future water demands. Effectively, the study will assess the sustainable yield, aquifer parameters and groundwater quality, and estimate the groundwater balance of the study area. The sub-aims of this research study and their respective objectives are as follows:

- Assessment of groundwater occurrence
    - Identify geological structures favourable to groundwater flow.
    - Use magnetic surface geophysics methods to identify drilling targets.
- Geological characterisation of aquifer
    - Collect and interpret data from the drilling logs.
    - Identify characteristics of the aquifer systems based on analysis of lithology.
    - Develop a conceptual understanding of aquifer geology.
- Characterisation of aquifer hydraulic and storage properties
    - Conduct aquifer pump testing.
    - Interpret the pump test data.
- Determination of the exploitable groundwater resource
    - Determine the sustainable yields of the boreholes.
    - Estimate groundwater recharge.
    - Determine the groundwater balance for the study area.
- Assessment of groundwater quality
    - Collect groundwater samples and submit these samples to a recognised laboratory for analysis.
    - Identify the hydro-geochemical processes controlling the groundwater chemistry.
    - Classify the water quality in terms of suitability use.

1.6 STRUCTURE OF DISSERTATION

This dissertation comprises nine chapters, and the various chapters are planned as follows:

Chapter 1 gives an introduction to the background of the research, problem statement, methodology, and aims and objectives of the study.

Chapter 2 provides a literature review, discussing the concepts and methods used to in groundwater assessment and development.

Chapter 3 provides a description of the study area in terms its location, surface and drainage, climate, geology and geohydrological aspects.

Chapter 4 deals with the desktop studies conducted, including the geological maps, map interpretation and the hydrocensus conducted to collect borehole information.

Chapter 5 deals with the geophysical surveys, results obtained from the magnetic method, and the quality of the magnetic data is also discussed critically.

Chapter 6 deals with the exploration drilling, the percussion geological logs description and bedding plane fractures encountered during the drilling exercise.

Chapter 7 discusses the aquifer pump testing results and characterises the hydraulic characteristics of the aquifers.

Chapter 8 provides the estimation of the groundwater recharge and the sustainable yields of the boreholes in the study area. The groundwater balance is discussed with an emphasis on the current and future water demands.

Chapter 9 deals with the groundwater chemistry of the study area and the results obtained of the inorganic chemistry analysis received from the laboratory of the Institute for Groundwater Studies (IGS).

Chapter 10 presents the conclusions of the study and the recommendations that have been made.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

The literature review was aimed at understanding the general methods and basic concepts when a groundwater assessment is conducted for water supply to a town. Understanding of these methods and basic concepts is important in estimating the sustainability of the groundwater resources, thus ensuring effective use of groundwater and preservation of groundwater quality that is suitable, particularly for domestic use.

Groundwater occurrence, groundwater flow and groundwater storage are some of the basic concepts which should be understood for planning of groundwater development and will be discussed in this chapter. The ultimate goal in understanding and using the above concepts and methods for groundwater resource assessment is to ensure sustainable development is reached. Since sustainable development of a community is dependent on the local population and the projected population in the future, it is often difficult to compute in a semi-arid country such as South Africa (SADC, 2001). In later sections, sustainable development is unpacked to understand how important it is for future water use.

2.2 OVERVIEW OF GROUNDWATER RESOURCE ASSESSMENT

Groundwater Resource Assessment in South Africa has been described as a model used to estimate groundwater allocation scenarios. It has been used to provide an introduction to the world of groundwater quantification on local and regional levels (DWAF, 2006).

GRAII was initiated to model a distinct geohydrological or hydro-lithological unit (such as a groundwater flow basin), and to provide a rough, desk-top estimate of the status of the groundwater resource and what volume might be abstracted without damaging local surface aquatic ecosystems over the long term. The project came about as a result of a need for a tool to regulate groundwater and surface water use by DWA. The project utilised the available data to make conclusions on a large scale (quaternary catchment scale). The idea was to use the geohydrological data (aquifer thickness, saturated thickness, hydraulic conductivity, and other aquifer parameters) and recharge data as the inputs. A series of algorithms were used to quantify the groundwater potential; the methodology generated water balance data for each cell (i.e. quaternary catchment), including the groundwater use and surface water flow data.

Alley *et al.* (1999) conducted a groundwater resource assessment study in the United States of America following concerns about the sustainability of the groundwater resources. In their study, the authors highlighted the depleting groundwater storage, reductions in stream flow, and changes in groundwater quality. The study highlighted the importance of understanding the basic hydraulic concepts when conducting a groundwater resource assessment. It makes it even more important in South African context for the complex nature of the Karoo fractured rocks. In a recent project, Monokofala (2010) conducted a groundwater assessment study for a town supply in the Mamusa Local Municipality. The study highlighted the need to understand and characterise the local aquifers.

To succeed in a groundwater assessment study, there is a need to understand the groundwater occurrence and types of aquifers in the area, describe the geological structures where the groundwater flows favourably, characterise the regional flow regime, estimate the aquifer parameters, estimate the sustainable yields of the local boreholes, analyse the water quality of the groundwater and estimate the water balance. The ultimate goal is to determine the water balance that presents an overview of the groundwater resource locally.

2.3 GROUNDWATER RESOURCE ASSESSMENT CONCEPTS

2.3.1 Groundwater Occurrence

Scientific methods have been used to determine groundwater occurrence, namely remote sensing, magnetic method, aeromagnetic imagery, electrical and electromagnetic methods, and the gravity method (Woodford and Chevallier, 2002).

Remote sensing has been mainly used as method to locate mapped dolerite intrusions and faults (Woodford and Chevallier, 2002). Remote sensing is ideally suited for Karoo conditions due to the relatively simple geology which mainly consists of undeformed sediments intruded by dolerite dykes and sills, the well-known relationship between the groundwater occurrence and dolerite intrusions, and the association of areas of dense vegetation with the shallow groundwater (Woodford and Chevallier, 2002). However, remote sensing is better used in conjunction with a geophysical method to explore for drilling high-yielding boreholes. Some of the commonly used methods are ground magnetic surveys, which measure the variations of the earth's magnetic field, electrical and electromagnetic methods, which determine the resistivity of various rock types with depth and lateral extent, and gravity methods, which involves measuring natural variations in the force of gravity.

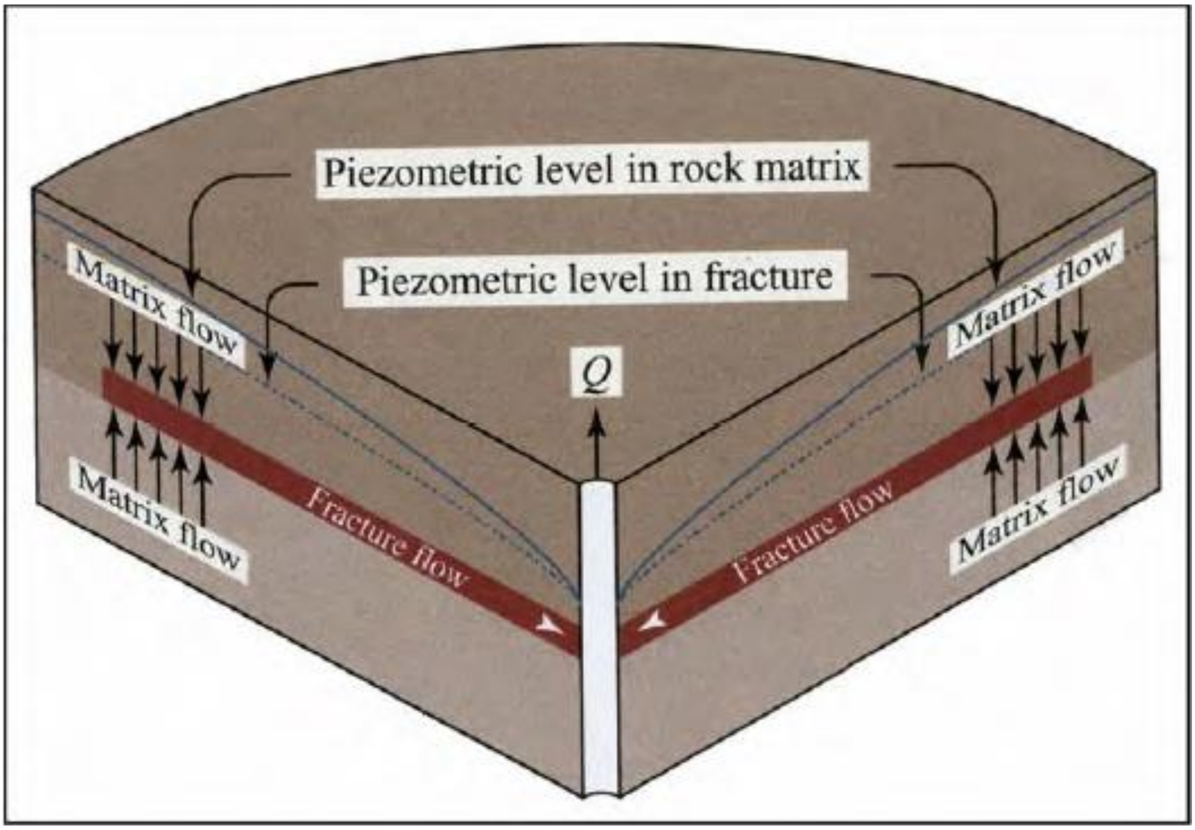
The magnetic method is one of the oldest methods of geophysical exploration. Magnetic anomalies in the earth's field are caused by two types of magnetism: induced and remnant magnetism. The induced magnetism of a body is in the same direction as the earth's present field (Roux, 1980). The modern magnetometers record the total magnetic field, while the earlier instruments measured either the horizontal or vertical components of the earth's magnetic field. Groundwater exploration in the Karoo Basin has been carried out using magnetic method measuring the vertical component of the earth's field, to trace the position and orientation of dolerite intrusions (Enslin, 1950).

Aeromagnetic imagery is also a method that is often used to trace large structural features, and especially dolerite intrusions into Karoo sediments. The aeromagnetic imagery, also known as the airborne magnetic surveys, covers a large area in a relatively short period of time, using helicopter or low-flying aircraft trailing a magnetometer. The Council of Geoscience has carried out aeromagnetic surveys for the entire Karoo Basin and these images are available in digital format or as printed maps (Woodford and Chevallier, 2002).

Electrical and electromagnetic methods are the second most commonly used method in groundwater exploration in the Karoo. The electrical method is used to determine the resistivity of various rock types and resistivity variations with depth and lateral extent. Generally, the Karoo sediments have lower resistivities than the crystalline rocks; and therefore seldom have resistivities greater than a thousand ohm metres (Woodford and Chevallier, 2002). Shale and mudstone successions are more conductive (less resistive) than sandstone units. Dolerite intrusions are highly resistive, with a high contrast between these rocks and the surrounding host rocks. Electromagnetic methods primarily involve placing a transmitter coil on the ground surface and energising it with alternating current at audio frequency. This generates a secondary magnetic field, which together with the primary field are sensed by the receiver coil, usually placed a short distance away (Woodford and Chevallier, 2002). Though the electromagnetic methods have been found to be successful in exploration (Botha *et al.*, 1992), their application in Karoo environments is often restricted because of the general conductive nature of the formations in the Karoo Basin; limiting the depth penetration unless relatively large transmitter coils are employed.

The gravity method involves measuring the natural variations in the force of gravity. These variations are primarily caused by density differences within different formations. Gravity prospecting is mainly used for locating zones of karst development, fractured dolomite or determination of the bedrock geometry beneath extensive alluvial-filled basins, where large density contrasts often exist between the unconsolidated sediments and the basement rocks (Woodford and Chevallier, 2002). The application of gravity method on Karoo geology has been found to be limited (Woodford and Chevallier, 2002).

Groundwater in the Karoo is most often associated with the contact zones between the dolerite intrusions and the sedimentary host rocks (which are the main targets for drilling), but successes have also been achieved in drilling into the centre of the dyke. Due to the fractures which act as conduits for groundwater, the dolerite intrusions become the primary geological formation target. The aperture and areal extent of these water-yielding fractures are limited, unable to store large quantities of water. Botha *et al.* (1998) pointed out that the formations and not the fractures act as the main storage units of water in Karoo aquifers. This is a contradicting assessment view as the formations in the Karoo are dense and relatively impermeable when compared to the unconsolidated sands and dolomite. This assessment of the Karoo aquifer systems has indicated that the flow in the formations resembles flow in porous medium and obeys Darcy's Law, and that the formations may contain large quantities of water, but may not be able to release it readily over small areas such as the circumference of a borehole (Woodford and Chevallier, 2002). The groundwater flow of the typical Karoo aquifer system is depicted below in Figure 1.



Source: Woodford and Chevallier (2002).

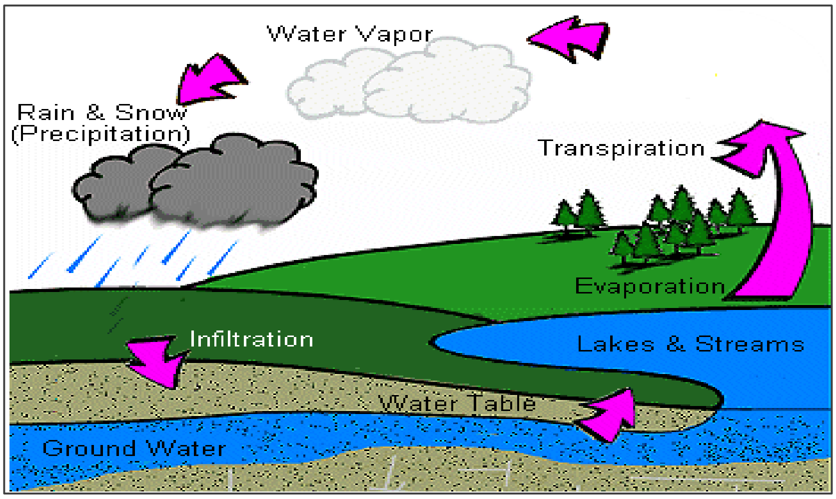
Figure 1: Typical groundwater flow towards a borehole in a Karoo aquifer

From the above depiction (Figure 1), the borehole in a dense Karoo formation will receive most of its water from the water-yielding fracture during pumping. This creates a drop in piezometric pressure within the fracture, and consequently water flows into the large water-yielding fractures from the rock matrix.

2.3.2 Groundwater Flow and Storage

The simplest approach to assess the physical behaviour of an aquifer is to perform a hydraulic test on the borehole drilled into the aquifer in question. There are other tests that can be performed to assess the aquifer (Botha *et al.,* 1998, Kruseman and De Ridder, 1994), but this study will be limited to the hydraulic testing as the method of assessing the aquifers. The physical behaviour of an aquifer system is determined by the interactions between the water and the rock matrix in which the aquifer occurs. Although there are other interactions that contribute to the behaviour of the aquifer, the adhesive force between the water molecules and the boundaries of the voids is the most basic interaction (Bear, 1972).

Groundwater systems consist of the mass of water flowing through pores and pathways below earth's surface, and water continuously flows from a point of recharge to a point of discharge (Woodford and Chevallier, 2002). Recharge is the mechanical way water is added into the groundwater system either through rainfall or inflow from another groundwater system. Discharge is the mechanical way water leaves the groundwater system to the surface. Figure 2 illustrates how water is infiltrated into the groundwater system.



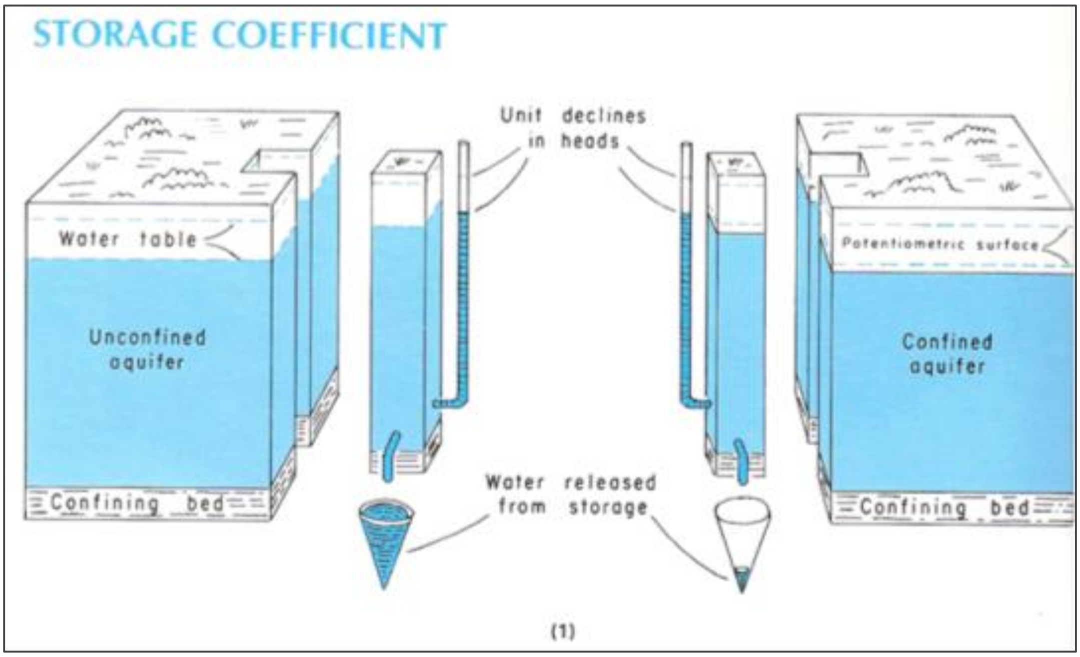
Source: European Environment Agency (EEA, 2003).

Figure 2: Typical Hydrological cycle, showing rainwater infiltration into the groundwater, evaporation and transpiration.

The above Figure 2 also shows how water leaves the system through natural processes such as evapotranspiration and evaporation and how some rain water can flow into lakes, rivers and the sea as part of runoff or baseflow. This can occur when the groundwater system is directly connected to a surface water system. It must be mentioned that groundwater also does leave the system by discharge initiated by man through a borehole or a well.

2.3.2.1 Borehole sustainability and aquifer parameters

Woodford and Chevallier (2002) highlighted the importance of understanding the basic hydraulic concepts when conducting groundwater assessments in fractured rock aquifers. In understanding the hydraulic concepts one needs to understand the types of aquifers, whether they are confined, semi-confined or unconfined, and also the location of these aquifers, see Figure 3.



Source: Heath (1983).

Figure 3: Confined and unconfined aquifers.

Different aquifers – confined and unconfined aquifers – have different characteristics and thus behave different to pumping, the same volume of water abstracted from the unconfined and confined aquifers, however, the water released from the aquifer storage is not the same, see Figure 3. Most of the aquifer parameters (such as transmissivity and hydraulic conductivity) of both the confined and unconfined aquifers in the same area can be more or less the same, with an exception of Storage Coefficient, also known as Storativity (S). The *Groundwater Dictionary* (DWA, 2011b) defines Storage Coefficient as *"the volume of water an aquifer releases from or takes into storage per unit surface area of* *the aquifer per unit change in head".* It is important to note that the volume of water stored and released in an aquifer and storativity (S) can be used to quantify the sustainable yield of a borehole and its hydraulics limits for sustainable use. Van Tonder *et al.* (2002) noted that to obtain accurate storativity values, an observation borehole is required during pump testing. For the purpose of the study – where it was feasible and practical – observation boreholes were located and monitored during pump testing of an adjacent borehole. Where there were no observation boreholes, theoretical S-values were used for reference guideline.

Murray *et al.* (2012) highlighted the importance of understanding basic concepts such as groundwater occurrence, groundwater flow and groundwater storage in planning for town/municipality water supply. One of the major parameters that are of importance in order to determine sustainable yield of the borehole is transmissivity (T). Transmissivity is defined by the *Groundwater Dictionary* (DWA, 2011b) as *"the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the average hydraulic conductivity and thickness of the saturated portion of an aquifer".*

Transmissivity provides an indication of the strength and limits (i.e. yield) of the borehole; it can be supplemented with the storativity (S) to estimate the sustainable yield. This is not to conclude that transmissivity and storativity are the only important parameters in estimating sustainable yield, however, both parameters are important in determining the flow regimes and estimating sustainable yield.

There are external factors that may influence the estimation of sustainable yield; some of these factors are precipitation, and rate of evapotranspiration. These make each groundwater system unique, with different possible factors which affect the sustainable yield. One of the major parameters or factors in sustainable yield estimation is recharge, which will be further discussed in the following section.

2.3.3 Groundwater Recharge

Recharge estimation provides the basis for efficient groundwater resource management. This is particularly important in regions with large demands for groundwater supplies, where such resources are the key to social and economic development. Estimating the rate of aquifer recharge is the most difficult of all measures in the evaluation of groundwater resources (Sun, 2005). Estimates of this kind are normally and almost inevitably subject to large errors. There is no single comprehensive estimation technique available for use and which does not give suspect results (Simmers, 1988). Aquifer recharge estimation can be done through many methods. Each of the methods has its own limitations in terms of applicability and accuracy. The techniques used to determine groundwater recharge in this study are the chloride mass balance and qualified guesses approaches.

Rainfall is the principal means for replenishment of moisture in the soil water system and recharge to groundwater. Moisture movement in the unsaturated zone is controlled by capillary pressure and hydraulic conductivity (Sun, 2005). As defined by the Food and Agricultural Organisation (FAO) (Jones *et al.*, 1981) as well as Lloyd (1986), there are two principal types of recharge: direct and indirect. **Direct recharge** is described as water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, through a direct vertical percolation of precipitation through the unsaturated zone (Lloyd, 1986). **Indirect recharge** results from percolation of rainfall to the water table following runoff and localisation in joints, as ponding in low lying areas and lakes, or through the beds of surface water (Lerner, Issar and Simmers, 1990). Indirect recharge includes surface water recharge, and a localised form of water from surface concentration of water in the absence of well-defined surface drainage is also defined as a type of recharge. In other publications this is known as *localised recharge*. Two distinct categories of indirect recharge are thus evident, i.e. that associated with surface water, and a second localised form resulting from surface concentration of water in the absence of well-defined surface drainage.

According to Kirchner *et al.* (1991), the main factors that affect the replenishment of the aquifer or the aquifer recharge are the following:

- **Rainfall**: magnitude, intensity, duration, spatial distribution.
- **Geological environment**: boundaries, hydraulic conductivity and storativity of formation.
- **Evapotranspiration**: the vegetation system, meteorological parameters.
- **Hydrology**: run-off, rivers.
- **Unsaturated zone**: thickness, hydraulic properties of the different soils, soil physical parameters, crust formation.
- **Flow mechanism**: soil matrix, flow along preferred pathways.

Further, Bredenkamp *et al.* (1995) stated that recharge is governed by the intricate balance between several components of the hydrologic cycle, each of which is a function of several controlling factors:

- **Rainfall**: intensity, frequency, variability, spatial distribution.

- **Evapotranspirative losses**: temperature, wind, humidity.
- **Discharge losses**: interflow, springs, base-flow, lateral flow and artificial discharge.
- **Catchment**: soil type, thickness, spatial distribution, topographical features, vegetation.
- **Geology**: rock types, structural geology and igneous intrusions.

Variations in geomorphology reflect differences in topography, vegetation, and soil type, which can affect recharge. Tóth (1963) demonstrated the impact of topography on local and regional groundwater flow paths. Recharge usually occurs in topographic highs, and discharge in topographic lows in humid regions, whereas in arid regions recharge is generally focused in topographic lows, such as valleys. Vegetation cover is important in assessing the recharge potential in any area. Recharge is generally greater in non-vegetated than in vegetated regions (Gee *et al.*, 1994), and greater in areas of annual crops and grasses than in areas of trees and shrubs (Prych, 1998). In irrigated areas return flow often contributes significant amounts of artificial recharge.

Estimation of recharge in the Karoo is not different from recharge estimation in other geological formations, except that the aquifer is normally only covered by a thin layer of soil, which limits the application of methods relating to the unsaturated zone. Recharge is very difficult to estimate reliably; more than one method is often used (Woodford and Chevallier, 2002). The most reliable and practical methods entail a mass balance approach.

2.3.3.1 The Chloride Mass Balance Method (CMB)

Chloride as an environmental tracer has been extensively used for the estimation of groundwater recharge. The Chloride Mass Balance (CMB) method developed by Eriksson and Khynakasem (1969) is simple to use, inexpensive and common in geohydrological investigations. Chloride is used for recharge estimation because of its conservative nature, it is highly soluble, it cannot be substantially taken up by vegetation (Sharma, 1997), and its relative abundance in rainfall and groundwater. CMB method assumes that the increase in chloride concentration has resulted from evapotranspiration losses and that no additional chloride has been added by contamination from, leaching of rocks, from the overburden, and from pollution. Description of the equation, if the assumption of chloride as a conservative ion is accepted, the groundwater recharge is simply given by Eriksson and Khynakasem (1969) and Houston (1987):

$$\text{Groundwater Recharge} = \frac{\text{Rainfall } (\frac{\text{mm}}{\text{a}}) \text{ x Chloride of rainfall } (\frac{\text{mg}}{\text{L}})}{\text{Chloride of groundwater } (\frac{\text{mg}}{\text{L}})} \ (\text{mm/a}) \tag{1}$$

The chloride method must be used with caution, as an accumulation of chloride near the soil surface due to evapotranspiration may override the assumption of a steady state chloride flux density throughout the unsaturated zone (Allison, Barnes and Leany, 1984).

Unfortunately, chloride concentrations of rainfall have only been measured at a few points in Southern Africa, but could be estimated from measurements of Botswana rainfall because of the good correlation of data. This indicates that the average chloride concentration is a function of the average precipitation. However, chloride concentrations decrease as mean annual rainfall increases, and conform to the concept of a higher percentage recharge for higher rainfall. The chloride method allows point measurements of recharge to be obtained from chloride concentrations of individual boreholes and spatial variability of recharge from monitoring points spread over the recharge area (Xu and Beekman, 2003).

2.3.3.2 Qualified guesses

A 'qualified guess' is a term used when general estimates are made through projections without sufficient data or information. These estimates are based on the knowledge of the area and its specifics, mathematical theories, and readily available data. The maps provided by Vegter (1995), the groundwater component of river base flow and harvest potential are used to determine the groundwater recharge rate in this study. The maps by Vegter (1995) detail the estimated recharge of the whole of South Africa, for an estimation of a local recharge value; the study area is located on these maps and its recharge value is determined from its position.

The qualified guesses for recharge from the soil/vegetation and geology are from expert opinions and general equations proposed by Bredenkamp *et al*. (1995) and Kirchner *et al*. (1991). This method is valuable for comparing with estimated values obtained through an analytical method (such as Chloride Mass Balance), as it will be discussed in this study.

2.3.4 Borehole Sustainable Yields

The manual by van Tonder *et al.* (2002) emphasises the importance of determining sustainable yield for a borehole to avoid overexploitation and drying of the borehole. This manual provides a detailed summary of pump testing types and the methods used to analyse the data from these tests. The manual will be used as a guideline when analysing and interpreting pump test data of the boreholes in the study area as it gives a guideline for fractured aquifers which are predominant in the study area. The emphasis will be on sustainable yield (Q) and transmissivity (T) and storativity (S) estimates.

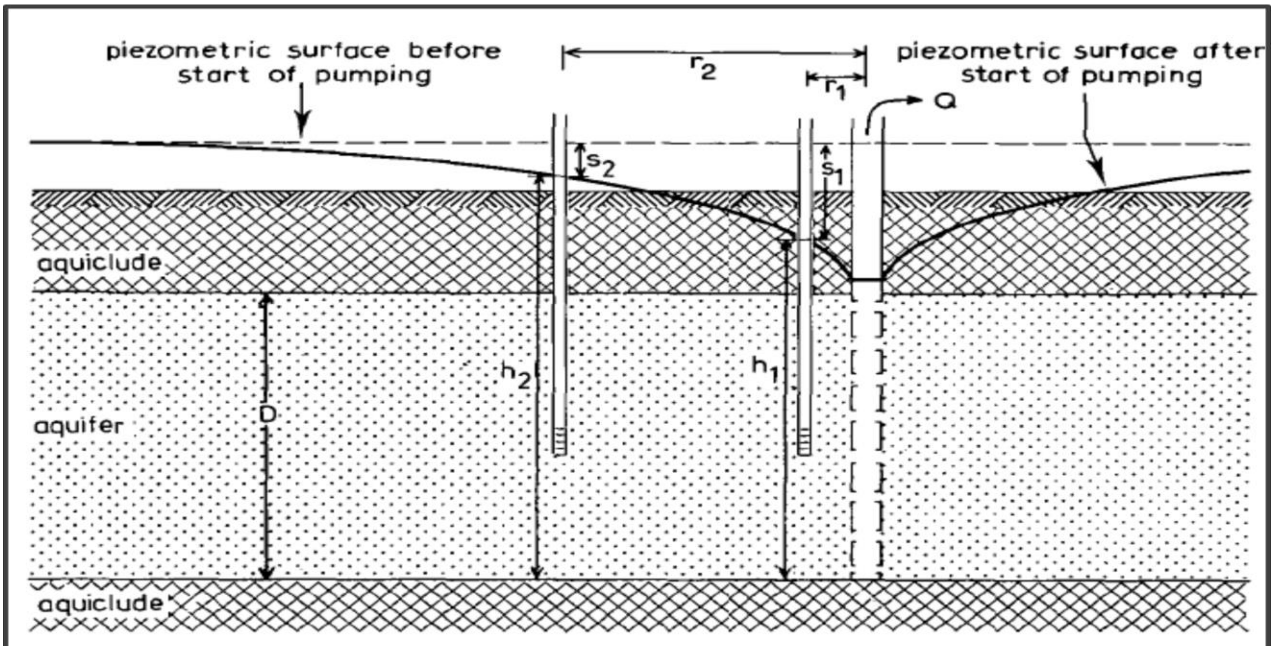
Sustainable yield can be defined as *"the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head or deterioration in water quality in the aquifer*" (DWA, 2011b). Sustainable yield estimation is of critical importance when dealing with areas such as Steynsrus, where the natural recharge is found to be low due to the lower mean annual precipitation (MAP = 565 mm/a) as estimated during the GRAII (DWAF, 2006). Understanding of abstraction patterns, aquifer characteristics and recharge is important to determining sustainable yields that do not only will lead to depletion of aquifer storage but also do not lead to underestimation of available groundwater.

The sustainable yields were calculated using the guidelines and methods described by Kruseman and De Ridder (1994). The authors emphasise the need to conduct aquifer pump testing to determine the aquifer parameters. In groundwater assessments, aquifer pump testing is one of the most important objectives; it allows characterising of the aquifer parameters and sustainable yields. Kruseman and de Ridder (1994) was referred to for equations such as the Cooper-Jacob, Theis, and other theoretical equations for the determination of the sustainable yields and aquifer parameters.

When interpreting and analysing the pump test data, certain assumptions are made, because the equations used to calculate these parameters are based on ideal conditions. Methods for evaluating pumping tests in confined aquifers are available for both predevelopment conditions (steady-state flow) and dynamic conditions (unsteady-state flow). For the purpose of this study, focus will be on the unsteady-state flow. The assumptions and conditions underlying the Theis, and Cooper-Jacob methods are as follows:

- The aquifer is confined.
- The aquifer has a seemingly infinite areal extent.
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area.
- Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area.
- The aquifer is pumped at a constant discharge rate.
- The well penetrates the entire thickness of the aquifer and the water pumped is influenced by the horizontal flow.
- The water removed from storage is discharged instantaneously with decline of the head (water level).
- The diameter of the well is small, i.e. the storage in the well can be neglected.

When a fully penetrating well pumps a confined aquifer (Figure 4), the influence of the pumping extends radially outwards from the well with time, and the pumped water is withdrawn entirely from the storage within the aquifer. In theory, because the pumped water must come from a reduction of storage within the aquifer, only unsteady-state flow can exist (Kruseman and De Ridder, 1994). In practice, however, the flow to the well is considered to be in a steady state if the change in drawdown has become negligibly small with time.



Key:
s: The drawdown in metres measured in a piezometer at a distance r in metres
Q: Constant discharge rate in m^3/day
D: Aquifer thickness in metres
t: Time in days since the pumping started
h: Steady state elevations of water levels in a piezometer in metres.

Source: Kruseman and De Ridder (1994).

Figure 4: Cross-section of a confined aquifer, showing change of water levels in a piezometer at constant discharge pumping rate.

2.3.5 Groundwater Quality

Guidelines from the South African National Standards for Drinking Water (SANS, 2006) will be used to determine water quality status. The availability of groundwater and suitability of its water quality for different uses are intertwined in a sense that some extreme concentrations in water can be beneficial for other use, and extremely bad for human health. The main focus will be the water quality that is suitable for domestic use such as drinking, cooking, washing, etc.

There are areas in the study area that already have been vulnerable to pollution, and this will be well highlighted. Identifying polluted areas and areas vulnerable to pollution will assist in the management of the water quality for domestic use, and this will also allow the establishment of a water quality management plan aimed at monitoring these sources and mitigate a plan when pollution plume ever migrates to other aquifer compartments. Groundwater quality remediation processes are generally expensive and commonly only partly successful. The main concern is the disposal of waste water in a manner that may be detrimental to the water resources. However, these kinds of disposals can be prevented and controlled.

The chemical composition of groundwater varies mostly due to the natural quality of the aquifer, and to a lesser extent, precipitation, recharge rate, meteorological aspects, saline water and flow patterns (Aastrup and Axelsson, 1984). The natural chemical composition of groundwater is mostly determined by the:

- Reaction velocity between water and minerals in sediment or rock;
- Residence time of water within the aquifer; and
- Contact area between water and minerals (Aastrup and Axelsson, 1984).

Understanding the above processes, and being able to make reliable quantitative statements about them, requires the application of theoretical analysis to develop tentative models and chemical characterisation. These hypotheses are often referred to as conceptual models (Aastrup and Axelsson, 1984). Essential data used in the determination of water quality in this study was obtained by the hydrochemical analysis of water samples in the laboratory.

2.3.5.1 Interpretation of chemical data

2.3.5.1.1 Piper and Durov diagrams

The major ionic species obtained from the hydrochemical analysis can be presented by various methods and diagrams, of which hydrochemical facies, the Piper (1944) trilinear diagram, is the most common and most often used. The Piper diagram is useful in sorting and filtering large volumes of chemical data by grouping ions. On this diagram the milliequivalent percentages of the cations and anions are plotted in left and right triangles as a single point. These points are then projected onto a central diamond-shaped area representing the total ionic distribution, see Figure 5. This makes chemical interpretation easier (Hem, 1985).

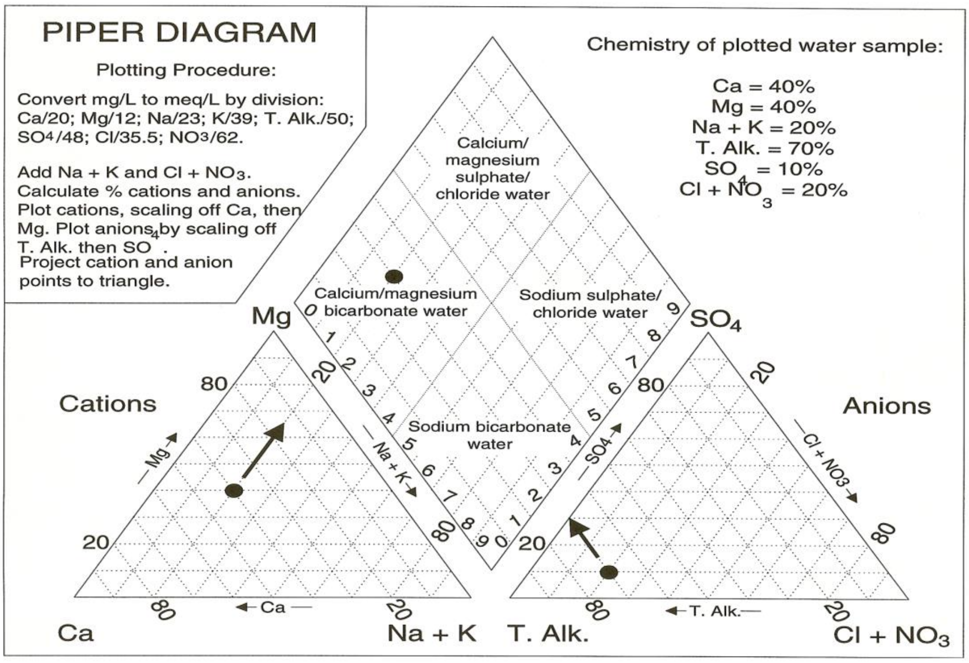


Figure 5: Illustration of a typical representation of water quality on a Piper diagram, also showing different types of water.

The Durov or Expanded Durov diagrams are similar to the Piper diagram in that the chemical analyses are plotted on the separate anion and cation triangles. In the expanded Durov diagram the three corners of each triangle are physically separated from one another, see Figure 6. The result is a square plot divided into nine areas, each characteristic of a different water type (Hounslow, 1995; Lloyd and Heathcote, 1985).

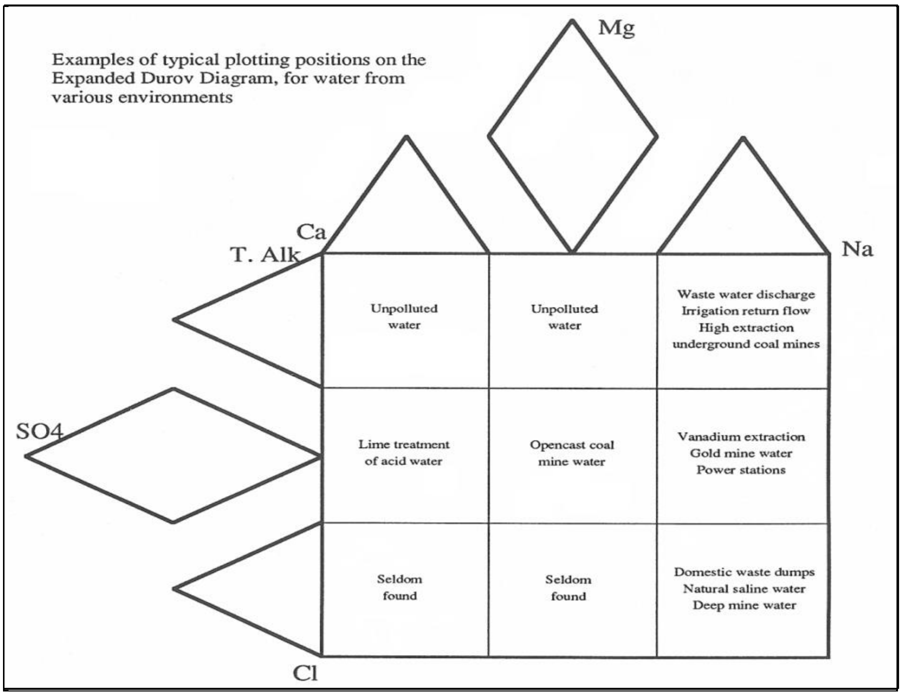


Figure 6: Illustration of plotting of macro ions on an Expanded Durov diagram, also showing different water types.

2.3.5.1.2 Schoeller diagram

The Schoeller diagram can also be used to present hydrochemical data. The Schoeller diagram is a semi logarithmic diagram which was developed to represent major ion analyses (SO_4^{2-}, HCO_3^-, Cl^-, Mg^{2+}, Ca^{2+}, Na^+/K^+) in milliequivalents (meq/L) and demonstrate the different hydrochemical water types on the same diagram (Hem, 1985). The axes on the diagram are displaced vertically so that the concentrations can be read in milliequivalents on the two outer scales (Hem, 1985). The diagram displays the ion ratios between points joined by straight lines, making interpretation easy. This type of graphical representation is advantageous in that, unlike the trilinear diagrams, actual sample concentrations are displayed and compared. The ratios of ions in samples are said to be equal if a line joining two points in a single sample is parallel to another line joining a second set of another sample (Hem, 1985).

2.3.5.1.3 Groundwater salinity

Salinity is used as a measurement to detect how concentrated the water and soils are with dissolved salts, which may be due to the local lithology and anthropogenic processes. The physical and chemical processes responsible for the development of saline soils involve the mineralisation of the groundwater, the physical transport of dissolved salts, the discharge of saline base flow into streams and lakes, and the precipitation of salts within the soil zone. Most of the salt in the groundwater system comes from input loading, which includes air-borne salts, salt dissolved in the water recharging the system, and salt contributed from mineral dissolution within the groundwater flow system (Salama, Otto and Fitzpatrick, 1999). The most important process that adds salt to groundwater is mineral dissolution reactions in the subsurface.

2.3.5.2 Statistical analysis

Geological and hydrogeological processes are generally complex; this can explain the random distributions of many field measurements. Physical and chemical data are prone to mathematical error due to the inability to follow a governing statistical trend, which makes interpretation of raw data difficult (Suk and Lee, 1999). Statistical analysis of chemical data is aimed to interpret and disclose the governing processes through data reduction and classification. Through classification achieved on the data set, interpretation is made easier (Suk and Lee, 1999).

2.4 SUSTAINABLE DEVELOPMENT

Sustainable water development and management is a critical component of development for all societies. Often, however, the geographic distribution of water resources does not correspond to the location of the demand population. South Africa, for example, is a semi-arid country (65% of the country) in which the average rainfall of 450 mm/year is well below the world average of about 860 mm/year. As a result, South Africa's water resources are in global terms, scarce and limited in extent (Otiono and Ochieng, 2004).

There are many challenges facing the sustainability of groundwater resource. Amongst others there are issues such as climate change, human errors in data handling, over-abstraction due to increasing water demand, damage of borehole infrastructures in remote areas, poor groundwater management systems and a total lack of groundwater monitoring and management at all.

Several studies (for example those by Edwin and Poyyamoli, 2012) have shown that climate change is likely to have a significant impact on the availability of freshwater resources. Freshwater-rich regions across Africa are projected to face water scarcity if current reserves are not managed effectively.

A groundwater monitoring and management plan constitutes an important part of achieving sustainability of water resources and providing important data that can be useful and optimising the use of the available water resources. Many boreholes often tend to get depleted due to over abstraction and disregard to pumping cycles (if there are any stipulated), and also the absence of groundwater management plan in place. Groundwater scientists often may draw up these groundwater management plans for municipalities for their use, but it has been found that the execution of the management plan is poor or neglected until there is major water level decrease and drying up of boreholes. It is understood that the decreased water levels and drying up of boreholes may be due to increased populations and demand for industries, agriculture and economic development. The need for groundwater scientists to refine the groundwater management plans and to address the obvious problems has never been greater for supporting local municipalities in ensuring that water resources are sustainable.

It is difficult to quantify sustainable use of water resources in an area where the water demands are already exceeding the exploitable water from the available water resources. Development of an integrated water resource strategy to reach sustainable development is necessary. This may include using available water resources other than local groundwater; if applicable, applying intermittent pumping patterns and rates, introduce artificial recharge into the groundwater system if the local geology is suitable, decreasing of unnecessary discharge of groundwater and application of water demand management and conservation measures.

On the other hand, solutions such as crop choice (salt- and drought-resistant crops), crop efficiency, biofertilisers, rainwater harvesting, flood proofing and retention measures, knowledge management, a decision support system and insurance by all involved should be worked upon to comprehensively address the challenges. This should be analysed under areas of physical, social and economic dimensions (Edwin and Poyyamoli, 2012).

2.5 GROUNDWATER ASSESSMENT CASE STUDIES

There have been several projects conducted in Free State that relate to assessment of groundwater. For the purpose of this study, a project in Marquard will be discussed to provide an example of such projects.

The town of Marquard is located in the eastern part of the Free State province, underlain by Adelaide and Tarkastad formations of the Beaufort Group. The project in Marquard included the remote sensing, geophysical surveys, exploration drilling, aquifer pump testing and recommendations of the sustainable yields using the Flow Characterisation program.

From the geological and aeromagnetic data contour maps there were no dolerite intrusions that were identified, except for on the western boundary of the study area, which is denoted by the reddish area on the geological map, see Figure 7. The green area on the aerial magnetic contour map denotes sedimentary rocks (Hough and Rudolf, 2011). Boreholes drilled were based magnetometer surveys which were conducted on potential dolerite intrusions and other structures based on the knowledge of the geology. Thirteen magnetic anomalies were identified from the magnetic data, these were associated with dolerite intrusion (DWA, 2011c). The negative magnetic anomalies detected were associated with the discontinuous magnetic intrusion (such as dolerite intrusion) which may have been caused by weathering, fracturing or faulting which was targeted for drilling of groundwater (DWA, 2011c). The positive magnetic anomalies were associated with the presence of the highly magnetic body such as the dolerite intrusion. Fourteen boreholes were drilled, the geological logs illustrated alternating layers of sandstone and shale formations and also presence of fractured dolerite intrusions in some boreholes. The alternating layers of sandstone and shale formations.

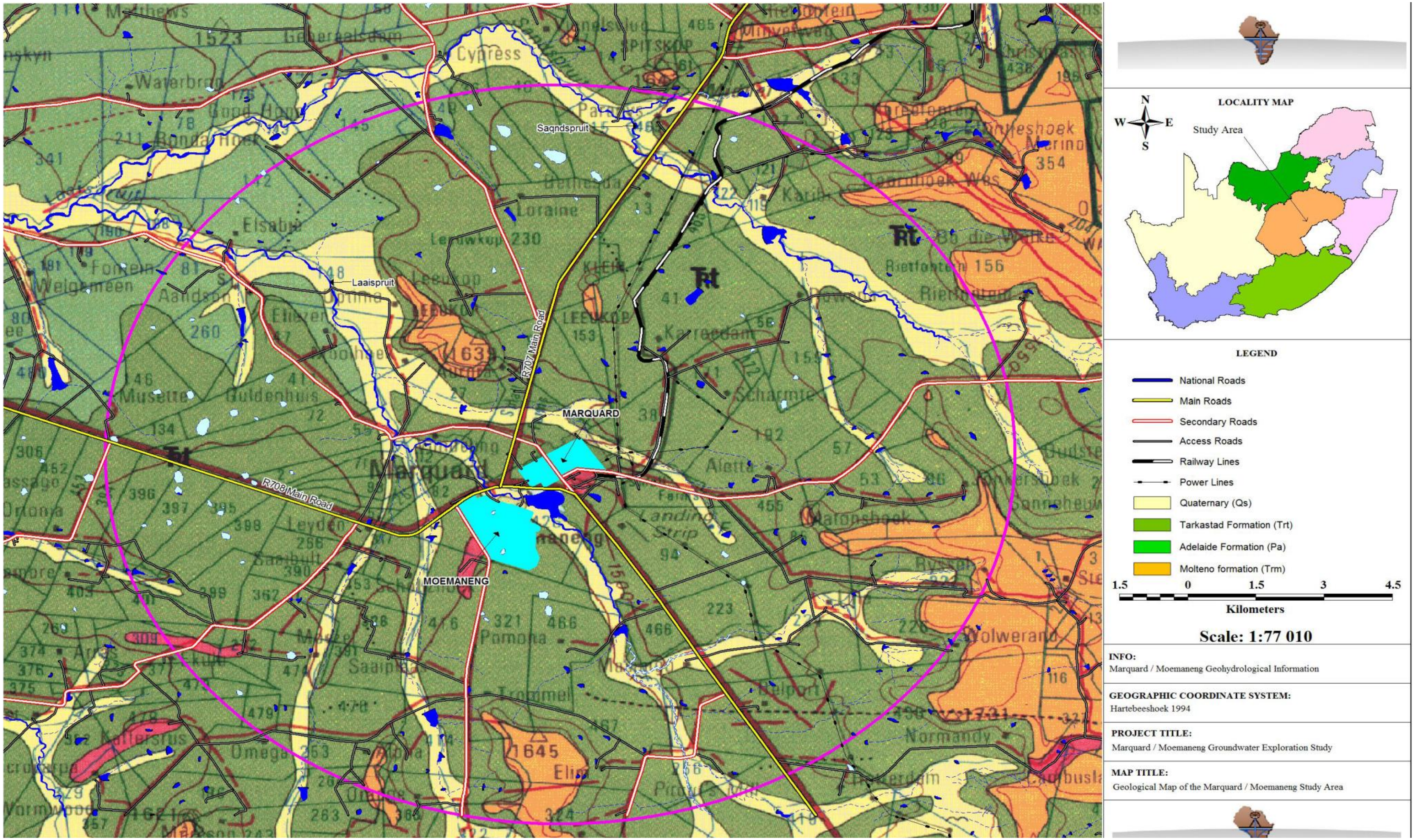


Figure 7: Geological map of Marquard (Hough and Rudolf, 2011).

Blow yields encountered during drilling ranged from 0.1-18.67 L/s, the higher blow yields were associated with fractured dolerite intrusion (Hough and Rudolf, 2011). Sedimentary rocks usually have low permeabilities and storativitity values, thus boreholes drilled into sedimentary rock formations had low yields with the exception where bedding plane fractures were encountered within the sedimentary rocks or fractured baked contacts zones between the sedimentary rocks and magmatic dolerite intrusions such as dykes and sills (Hough and Rudolf, 2011).

From the fourteen newly drilled boreholes, only seven boreholes were considered for 24-48 hours aquifer pump testing and appropriate sustainable yields were estimated, and recommended accordingly.

2.6 SUMMARY

Chapter 2 gives a review of literature of the basic concepts and methods which are important in groundwater resource assessment. A review of groundwater resource assessment study in South African is briefly discussed with the aim of highlighting the concepts and methods that are important in conducting such studies. The sustainable development was also discussed to highlight the importance of groundwater resources to the current and future population. Basic concepts and methods reviewed include the magnetic method, geohydrological and hydrochemical methods, aquifer parameters and sustainable yields. The next chapter provides description of the study area in terms of population, physiography, geology, geohydrology, etc.

CHAPTER 3 SITE DESCRIPTION

3.1 OVERVIEW AND ECONOMIC DEVELOPMENT

Steynsrus is a small town situated approximately 55 km east of Kroonstad under the Moqhaka Local Municipality. Moqhaka Local Municipality (LM) is located in the Fezile Dabi District Municipality (DM), formerly known as the Northern Free State DM. The Moqhaka LM area stretches from Viljoenskroon in the north to Steynsrus in the south. Besides these towns, the municipality is characterised by farming and rural settlements. Among other farming activities, cattle and maize farming are the most common in the area. According to the reconciliation strategies studies conducted on behalf of DWA (2011a), the population in the town is about 7 518. The study area falls within the Middle Vaal Water Management Area (WMA), specifically in quaternary catchment C60E (Figure 8); the WMA includes the Vals River draining into the Vaal River.

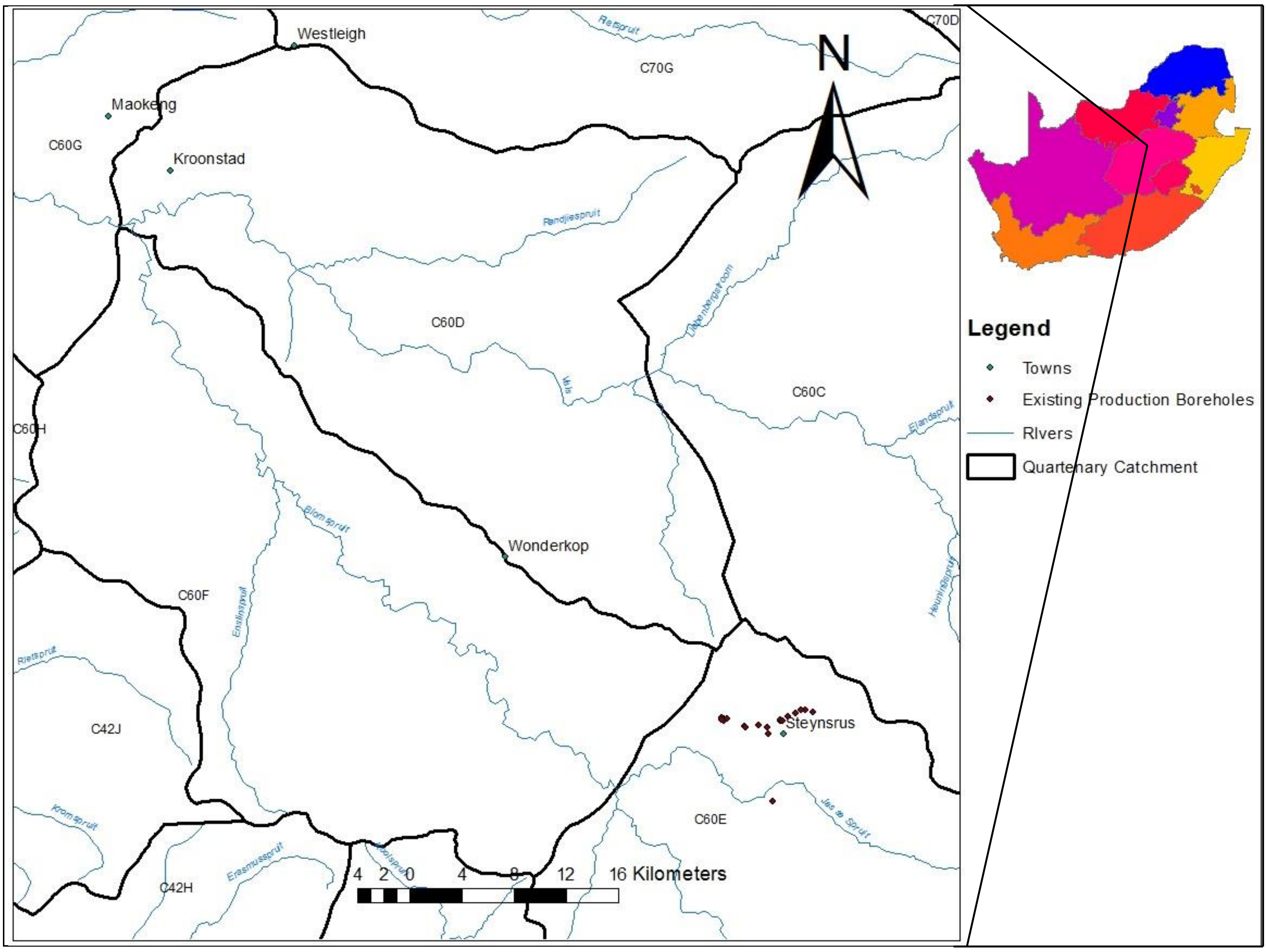


Figure 8: Map showing study area in Quaternary Catchment C60E (Map produced using Arc GIS 2012)

Some of the water is pumped and purified for domestic consumption along the Vals River course. A purification scheme at the local water treatment plant had been a major source of drinking water in the town of Steynsrus and it is fed by the Morgenzon Dam situated near the Vals River. The Morgenzon Dam is an off-channel storage dam and is owned by the Department of Water Affairs (DWA) and operated by Moqhaka LM. The Morgenzon Dam is approximately 400 m southwest of the Vals River. The dam is of strategic importance to rural and town development in Steynsrus and nearby township, Matlwangtlwang. Decreasing river flow has been recognised by the locals as a serious problem since the 1990s, but has hitherto largely been ascribed to low rainfall.

Steynsrus has a relatively low urban development. The town has a visible central business district, surrounded by urban free-standing houses and extensive low income housing, mainly in Matlwangtlwang. The municipality released statistics in its Integrated Development Plan (IDP) that approximately 90% of the population in Matlwangtlwang and Steynsrus are unemployed (Moqhaka LM, 2012).

Steynsrus is located in an area of agriculture significance and mainly provides services to this regard. Groundwater is used by the town and upstream farmers along the Vals River. The town tends to use both surface water and groundwater and relies more on the groundwater to supplement the surface water supply, and also as the main source when there is no or minimal flow in the river.

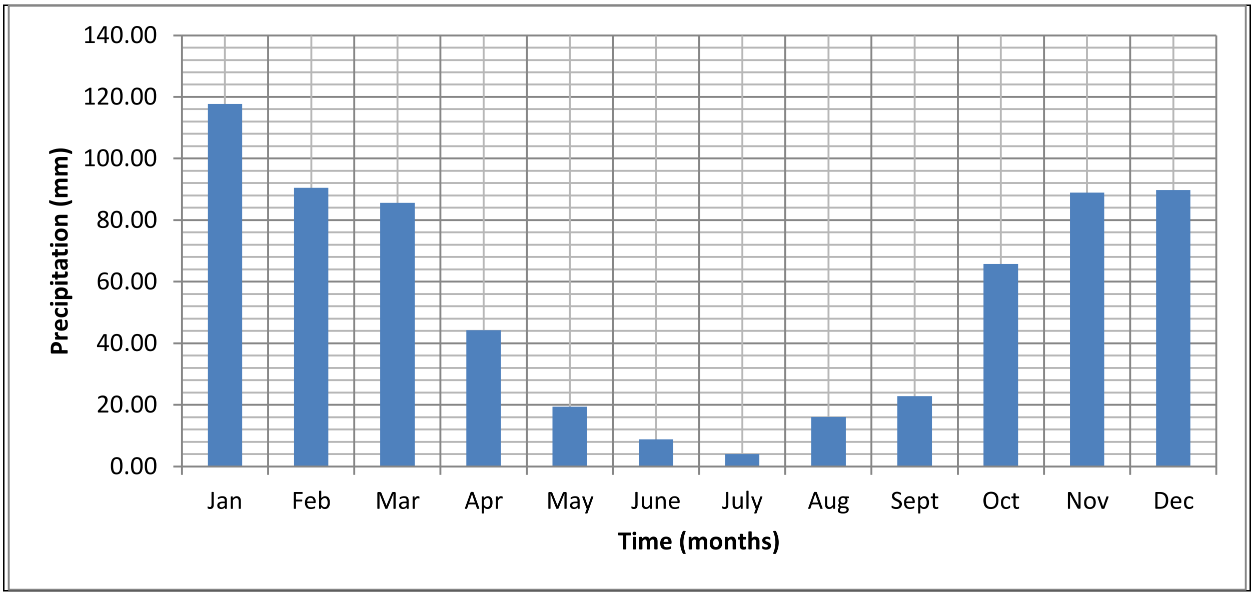
3.2 PHYSIOGRAPHY AND DRAINAGE

The topography is characterised by mainly flat areas and gradual elevations varying from 1 200 to 1 500 metres above mean sea level (mamsl). The area forms the south-eastern part of the Highveld region and straddles the Great Drakenberg Escarpment in the east (Schutte, 1983). The landscape is part of an undulating plain with generally few elevated areas, especially in the study area.

The primary river that drains the catchment where Steynsrus is situated is the Vaal River through its tributary, the Vals River. The tributary drains predominantly in north-westerly direction towards the Vaal River. The Vals River is a non-perennial river, which flows more frequently after periods of heavy rainfall. There are small dams built practically in and around the Vals River, mostly for farm water supply purposes. Their existence seriously reduces the surface water runoff of the area. No quantitative information thereof is, however, available. Drainage is topographically and geologically controlled, i.e. influenced by the folding and subsequent faulting of the underlying lithology (DWAF, 2003a).

3.3 RAINFALL AND CLIMATE

The climate is characterised by cold winters and very hot summers; maximum precipitation occurs as a result of thunderstorms in summer and autumn seasons. The temperature has large daily and seasonal variations. The mean surface temperature reaches maximum values during December and January, and minimum values during June and July. The period when frost can be expected lasts approximately 100 days (June to August). The mean annual temperature varies from 15.0 to 17.5 °C. The mean annual evaporation is in the range of 1 500–1 800 mm (DWAF, 2003b). The area experiences rainfall mostly during summer season, with precipitation mainly during December, January and February. Monthly rainfall records plotted in Figure 9 were obtained from the South African Weather Services (SAWS, 2013). The mean monthly rainfall indicates a summer rainfall climate with most of its rainfall patterns (65-117 mm/month) occurring during the months of October to March. As a result, the Vals River represents a non-perennial stream which only flows during the summer to autumn seasons between October and March.

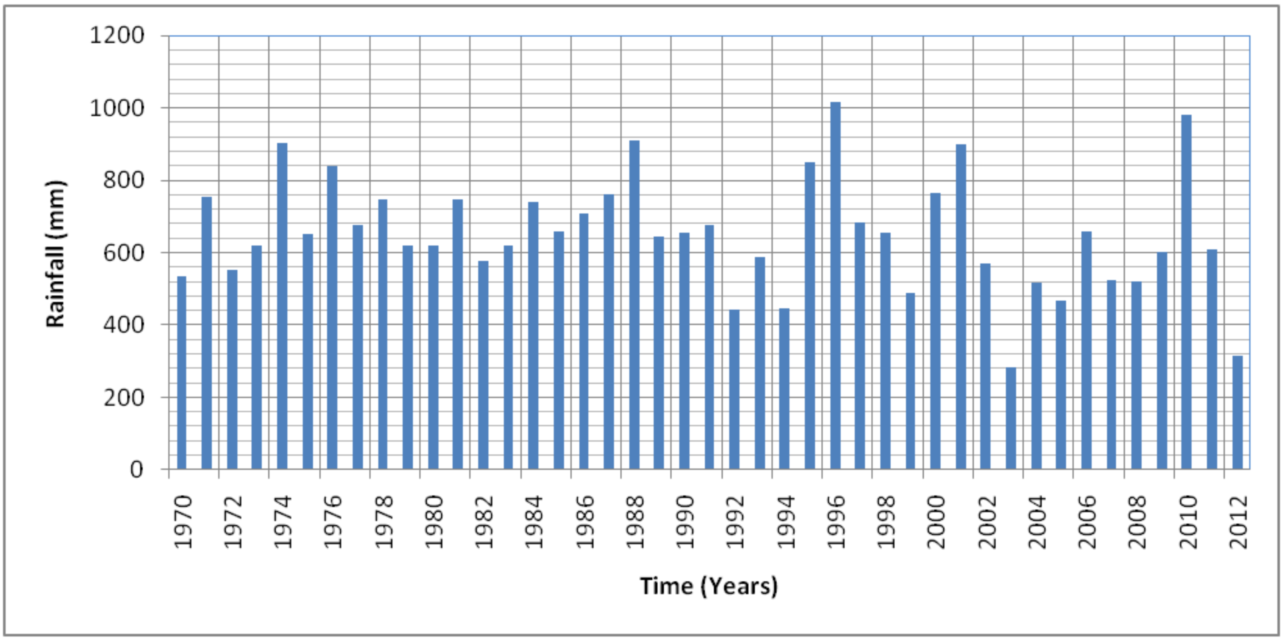


Source: SAWS (2013).

Figure 9: Study area mean monthly rainfall; showing rainfall trend.

The annual precipitation is erratic with wet and very dry cycles evident (Figure 10). The Mean Annual Precipitation (MAP) for the study area is 563-688 mm/annum. The estimated MAP in the GRAII project is a conservative 563 mm/annum. The highest MAP of 1 017 mm was recorded in 1996. Above average precipitation has also been recorded during the years 1974, 1976, 1988, 1994, 2000, 2001, and recently in the year 2010. With an exception of the rainfall recorded in 2010, the last 12 years have been the driest in the area, with as low as 316 and 285 mm/annum recorded in 2003 and 2012, respectively.

The recent low rainfall records do not suggest any major meteorological change, but it is important to note because the town relies on the river that is dependent on the rainfall , thus the lower the rainfall, the less water available for water supply.



Source: SAWS (2013).

Figure 10: Mean annual precipitation for the study area.

3.4 VEGETATION AND LAND USE

Due to the arid climate in Steynsrus, the vegetation over the most of the Middle Vaal WMA is sparse, and consists of mainly grassland (Figure 11), shrubs and some alien vegetation (Figure 12). According to Acocks (1952), vegetation in Steynsrus and other surrounding areas are classified as *pure grassland*, regarded as the natural vegetation typical of the Highveld.

The study area, however, is covered mostly by very dry grasslands; there is also livestock and some crop farming in the area. The occurrence of shrubs and natural vegetation can be explained by shallow and deeper soil moisture for more extensive root systems. Presence of termite hills and thorn shrubs are normally associated with the presence of rock outcrops, particularly dolerite dykes, which are the primary drilling target for groundwater in the area. Surface water and groundwater (Figure 13) are the source of farming in areas around the study area and along the Vals River.

Figure 11: Typical grassland in the study area

Figure 12: Typical alien vegetation in the study area

The irrigation of crops, such as maize, and sunflowers, occurs mainly downstream of the dams and along the Vals River. Livestock farming consists mainly of beef, dairy and sheep farming enterprises, as well as some game farming. There is no mining near the study area. The Voorspoed Diamond mine is located approximately 80 km north of the study area.

Figure 13: Wind pump used primarily for live stock watering

3.5 WATER RESOURCES

3.5.1 Surface Water

The main open surface water source available for the area is the Vals River; water is abstracted and stored in the nearby Morgenzon Dam for town water supply. DWA has river flow monitoring points along the Vals River, upstream in Lindley (on the R707 road bridge) and downstream towards Kroonstad (on the N1 road bridge) of the point where Steynsrus abstracts water. For the purpose of the study, the Lindley monitoring point was seen as the most important to the water of Steynsrus. According to the audited monitoring flow rate data DWA has made available on its website, the average monthly flow peaks (Figure 14) are in correlation to the rainfall period (October to March) which was described in the previous section. The peak in May can be explained by the frost which occurs around that period; although this statement is not based on any literature which has been produced for this subject. DWA obtains water quality samples for analysis at the same monitoring points mentioned above; the overall water quality status of the Vals River is fair to good with an expected exception of high *Escherichia coli* (*E. coli*) coliforms.

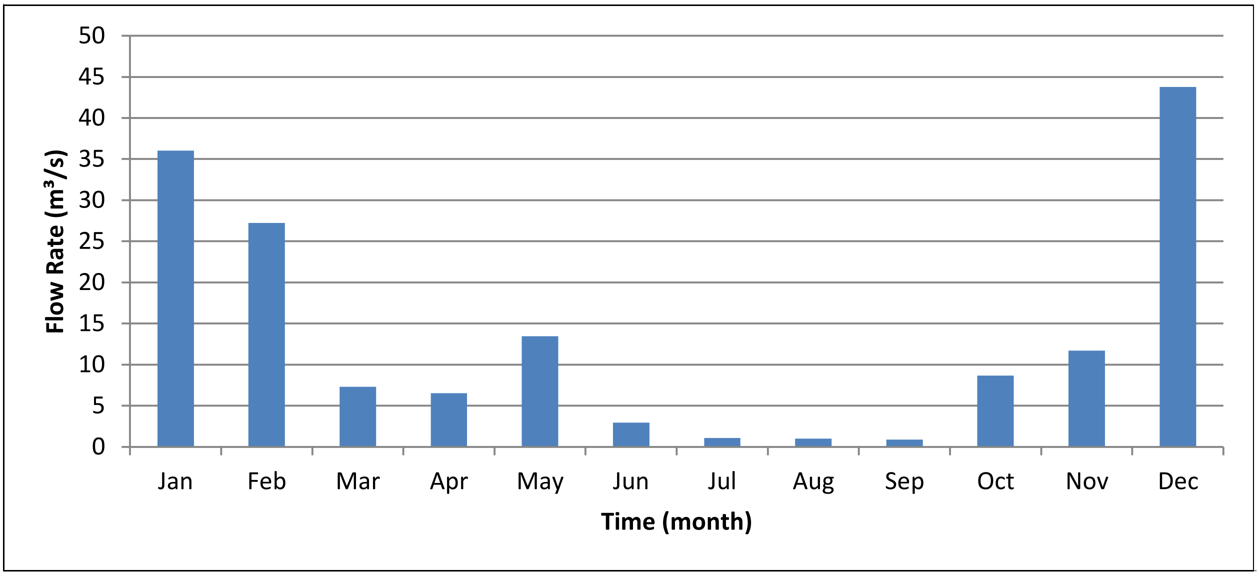


Figure 14: Graph showing mean monthly Vals River flow rate peaks at the Lindley C6H009 station (DWA, 2014).

The annual trends of the river flow were plotted to further highlight the change and condition of the flow in the Vals River (Figure 15). The lowest mean annual flow rate in almost 8 years was recorded in 2012 at the C6H009 Lindley station; this can be explained by the low rainfall experienced during 2012 as shown in Figure 10.

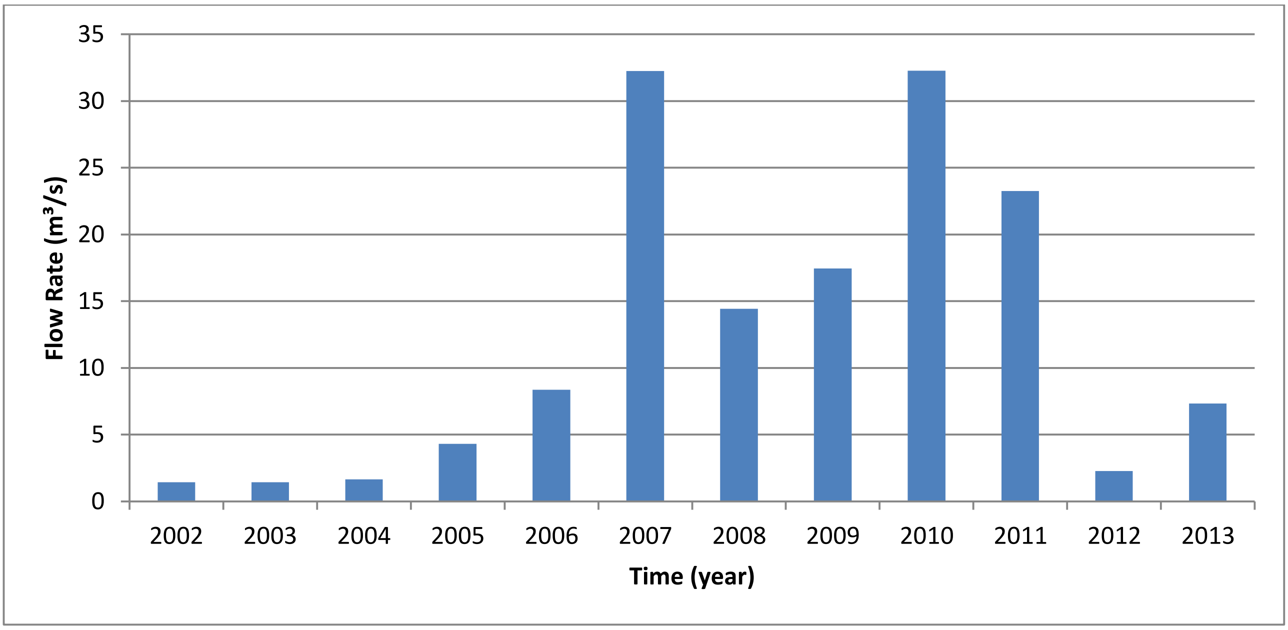


Figure 15: Mean annual flow rate along the Vals River at Station C6H009 in Lindley (DWA, 2014).

3.5.2 Local Groundwater

Groundwater is exploited through boreholes in the quaternary catchment C60E. Dolerite dykes and contact zones in Steynsrus represent the major groundwater resources within the study area. Others are the localised weathered formations and small faults have also been targeted for groundwater drilling.

The depth to the solid rock associated with dolerite intrusions is in the depth range of 45-60 m. No evidence of the existence of deeper aquifers (150 m or greater) within the area has been found to be of significant yields (DWAF, 2003a).

3.5.3 Groundwater Potential

Groundwater resource potential established from the DWA project data indicates that boreholes drilled in Steynsrus and surrounding areas have yields that range between 0.1 and 5.0 L/s yields. In general, irrespective of the lithology and presence or absence of dolerite, with exception of small isolated areas, the boreholes in Steynsrus are low-yielding with the median of 0.1-0.5 L/s (DWAF, 2003a). This was also observed from pump testing data of existing borehole conducted by Gombar (1977). A successful borehole is defined by van Copenhagen (1949) as a borehole that yields at least 0.1 L/s. The groundwater resource potential and allocable volume at catchment scale is summarised from the GRAII project data (Task 2C: GW Planning Potential) as presented in Table 2.

It is important to note that the Groundwater Resource Assessment Phase II (GRAII) entries were estimated for a quaternary catchment scale; these values may have limitations when utilised on a town scale. There is no readily available comprehensive information to quantify most of the geohydrological variables for the study area. However, some of the GRAII variables were utilised as reference for estimation of aquifer parameters and other variables.

Table 2: GRAII entries for quaternary catchment C60E

GRA II Variable	Information
Quaternary Catchment	C60E
Area (km²)	664
MAP (mm/a)	564
Mean annual potential recharge – Dry season (Mm³/a)	7.54
Mean contribution to river base flow (Mm³/a)	3.49
Average water level depth (metres below ground level)	15.1
5 m drawdown aquifer storage volume (Mm³/a)	3.37
Exploitability factor	0.40
Potability factor	1.00
Estimated groundwater use – 2004 (Mm³/a)	0.6
Average groundwater resource potential Mm³/a)	7.45

Source: DWAF (2004)

3.5.4 Water Use in the Moqhaka Local Municipality

The Water Use Registration was obtained from DWA Free State Regional Office. Three Water Use Authorisations, which include abstraction from surface water source (Vals River), abstraction from groundwater and storage of raw water at a Vals River off-channel storage dam (Morgenzon Dam) were granted to the municipality. The Local Municipality water use registration information is given in Table 3.

Table 3: Water use license information for Steynsrus

Variable	Surface Water Use	Groundwater Use
Registration Number	23002625	23002625
Town	Steynsrus	Steynsrus
Water Source	Vals River	Multiple groundwater boreholes
Dam storage capacity	401 000 m^3 (Morgenzon Dam)	401 000 m^3 (Morgenzon Dam)
Registered volumes	1 000 000 m^3/annum	407 040 m^3/annum

Source: WARMS (2013).

The total registered urban water use for the municipality is less than the current water requirements, resulting in no non-compliance issues with regards to abstraction and storage of water from Vals River. Table 4 gives a summary of the surface water source and allocation information.

Table 4: Water allocation information for Steynsrus Town Area

Raw Water Source	Storage Capacity (m^3)	Average abstraction (m^3/annum)	Registered Water Use (m^3/annum)
Morgenzon dam (Vals River Off Channel Storage Dam)	401 000	690 000	1 000 000

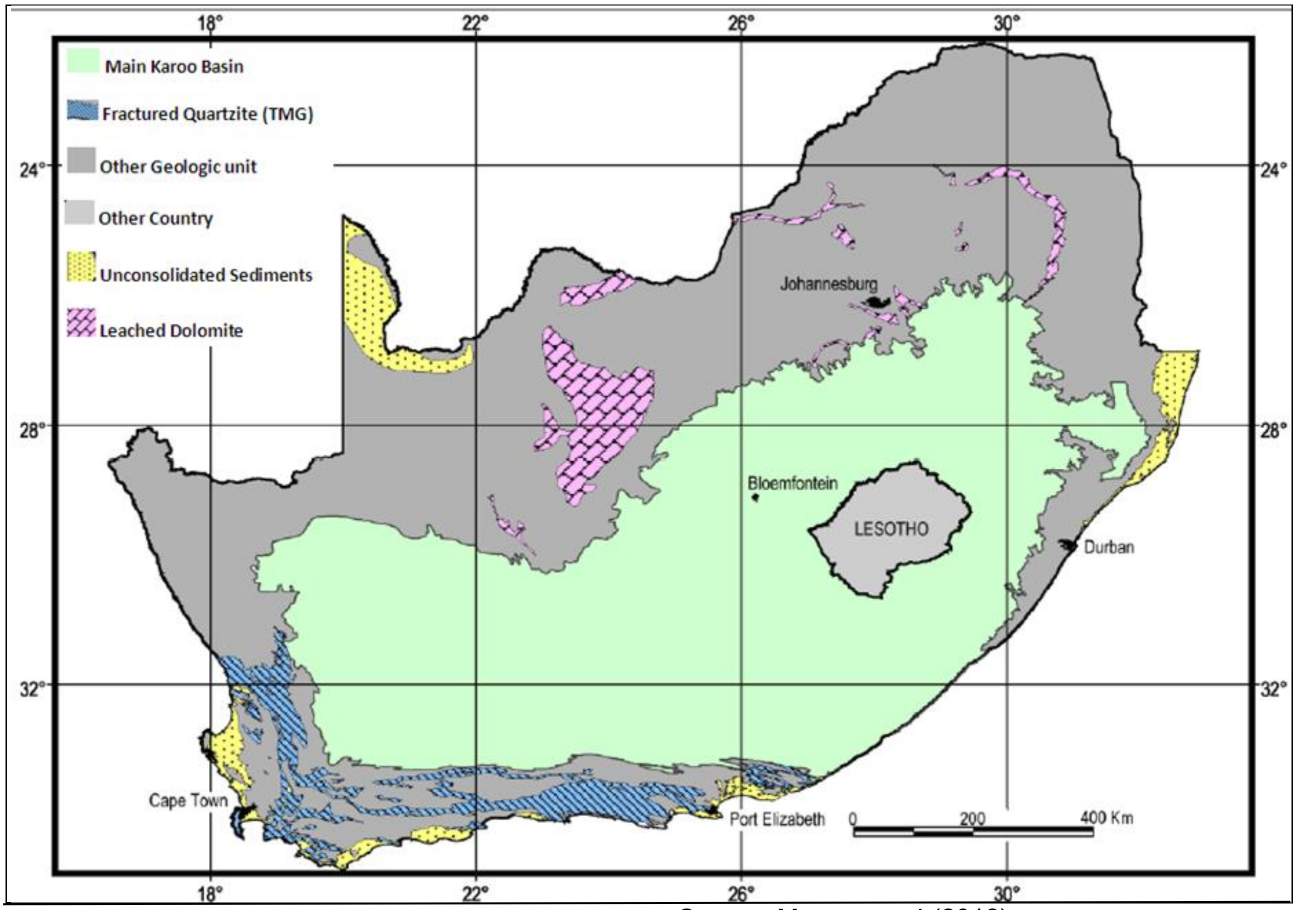
The water use information of other water users in and around Steynsrus was made available through the DWA Free State Region office. The areas of interest also included the upstream users of the Vals river who use the water predominantly for irrigation; the total allocation for the other Vals River water users registered with Department of Water Affairs is 3.41 Mm^3/a. Although there are various groundwater users in and around the study area, there were no records of major users of groundwater in the information that DWA provided. With the exception of one user registered, the amount of water authorised is 2 500 m^3/a for irrigation purposes.

3.6 GEOLOGY AND GEOHYDROLOGY

3.6.1 General Geology

Regionally, the study area is entirely underlain by rocks of the Karoo Supergroup (Figure 16), mainly comprising rocks of fluvial and deltaic origin of the Permian Beaufort Group (SACS, 1980). In South Africa, the Beaufort Group (Figure 17) occurs between the lower undifferentiated Karoo rocks (Molteno, Clarens and Elliot Group) and the Permian late Ecca Group, shown in Figure 17.

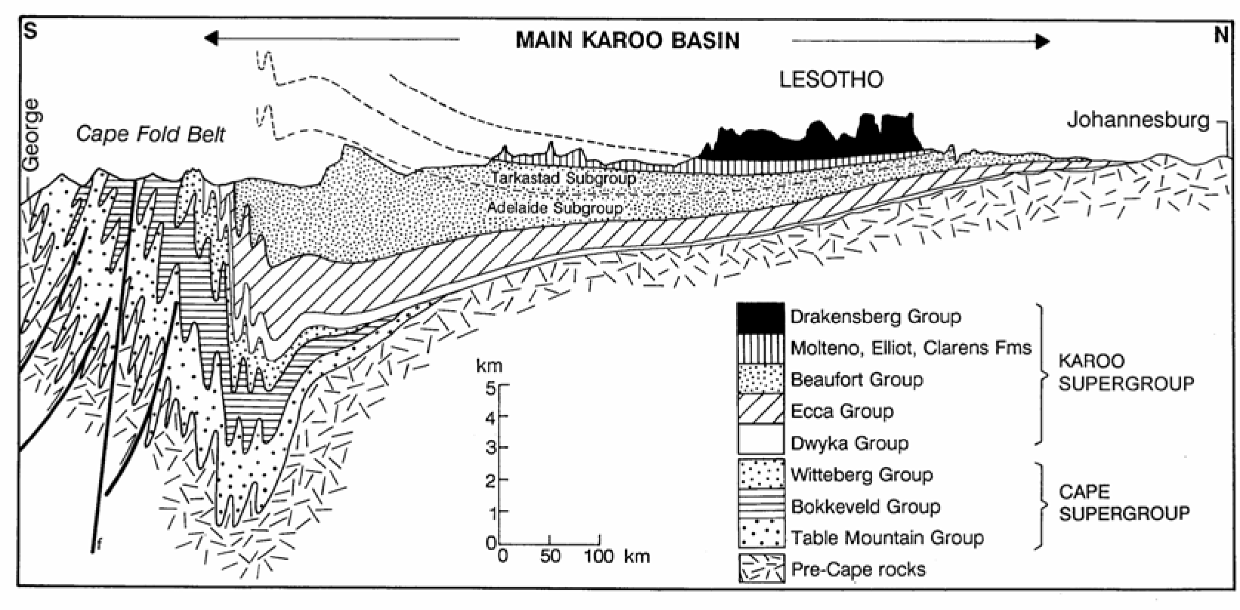
The Steynsrus area forms the northeastern part of the Central Karoo Basin. The area is predominantly underlain by rocks of the Adelaide and Tarkastad subgroups of the Beaufort Group. The Adelaide Subgroup consists of shale, siltstone and fine sandstone approximately 600 m in thickness (Johnson and Verster, 1994). The Tarkastad subgroup consists of an assemblage of sandstone and mudstone; the former is dominant in the area and approximately 200 m thick (Johnson and Verster, 1994).



Source: Murray *et al.* (2012).

Figure 16: Simplified geological map of South Africa indicating the distribution of the Karoo Supergroup.

Throughout South Africa, the Jurassic age dolerites intruded into the Karoo Supergroup and the underlying gneissic basement in the form of horizontal to subhorizontal transgressive sills and near vertical dykes in the region. The dolerites are also associated with argillaceous stratigraphically lower units of the Karoo Supergroup, namely the Dwyka to Beaufort Groups. The thickness of the dolerite sills ranges from 15 to 300 m and the dolerite dykes rangein thickness from 1 to 50 m. The undulating nature of the dolerite crossing the host rock bedding at a low angle causes their discontinuous occurrence on the land surface. Most sediment in the vicinity of intrusions were recrystallised during intrusion.



Source: Woodford and Chevallier (2002).

Figure 17: Cross-section of the Main Karoo Basin.

Quaternary deposits are found along the rivers and streams, consisting mainly of gravels that comprise cobbles and boulders.

3.6.2 Geohydrology

The Karoo Supergroup mainly consists of fractured-rock aquifers characterised by sediments with low permeability (Botha *et al.*, 1998). This implies that groundwater tends to flow mostly through secondary fractures, apertures and joints in the host rock. The Karoo aquifers make up more than half of South Africa's aquifers. The fractured-rock aquifers are directly recharged by rainfall infiltrating through the weathered zone until it reaches the underlying impermeable solid rock. Then groundwater flows on the contact zone between the weathered part of the underlying consolidated sediments following their shape. The contact zones are a result of the baking of the the sedimentary rocks by Jurassic age dolerite intrusion.

The two subgroups of the Beaufort Group, namely the Adelaide and Tarkastad Subgroups, make up the groundwater system in the study area. The Adelaide Subgroup consists predominantly of argillaceous sediments while the Tarkastad Subgroup consists of the large arenaceous content. The lithology of the Beaufort sediments appears to have little effect on the borehole yield and aquifer classification. The Beaufort Group, irrespective of the presence or absence of dolerite intrusions, with the exception of a few small isolated areas, is low-yielding with a median borehole yield range of 0.1–0.5 L/s (DWAF, 2003a). The depth to solid rock ranges from 30 to 40 m. However, as noted in an earlier section the boreholes associated with dolerite intrusions are usually drilled deeper (i.e. 45-60 m), depending on dolerite dip, shape and thickness. The regional flow through fractured Karoo rocks resembles flow in a porous medium (i.e. obeying Darcy's Law). Darcy's Law assumes laminar flow in saturated granular media, steady-state flow conditions, a homogeneous medium, isotherm and incompressible, and neglects the kinetic energy of the fluid (Fetter, 2001). The averaging character of Darcy's Law, based on the representative continuum and small influences of other factors, make it possible to use the macroscopic law of Darcy for situations that do not correspond to the basic assumptions (such as fractured rocks as is the case in this study, steady-state flow and transient flow, flow in aquitards, and flow in heterogenous systems) (Freeze and Cherry, 1979).

3.7 SUMMARY

Chapter 3 gives a description of the study area, in particular the physiography, climate, vegetation and land use, water resources, geology and geohydrology. Geohydrological and technical reports, data and available information were used for the compilation of the chapter. All the information gathered was used to describe the study area. The next chapter discusses the desktop study that was conducted and the analysis and interpretation of the geological, aerial ortho photo, and airborne magnetic data contour maps.

CHAPTER 4 DESKTOP STUDY

4.1 INTRODUCTION

The geohydrology and geology of the area has been studied by the Department of Water Affairs (DWA) and independent Consultants, and unpublished reports have been produced. Copies of reports pertaining to the area, together with DWA groundwater archive, geological and aerial magnetic maps from Council of Geosciences (CGS), and satellite images from Google Earth, were obtained and evaluated. This information and data provided the background for determining the geological and geohydrological characteristics of the study area. The following reports were used to gain an understanding of the geological and geohydrological characteristics of the study area:

- Feasibility study for the upgrading of the bulk water supply of Steynsrus in Moqhaka Local Municipality by Masetlaoka, Scott and Wilson Consulting (September 2011).
- Data, maps and information from the Groundwater Potential study by Hough and Rudolf (2012b).
- Data and information records from a hydrocensus and groundwater assessment in Steynsrus by Hough and Rudolf (2013) of Geo Hydro Technologies (GHT) Consulting.

4.2 REMOTE SENSING AND MAP ANALYSIS

Application of remote sensing in groundwater resource evaluation has been widely practiced. Remote sensing involves the use of air-photogrammetry, chiefly through visual interpretations. Apart from updating or refining geological maps, lineaments can be mapped and such information can be utilised to interpret the potential structures for drilling of groundwater. However, the concept of integrating remote sensing and Geographical Information Systems (GIS) is comparatively new (Saraf and Choudhury, 1997). Use of both the remote sensing and GIS has proved to be an efficient tool in groundwater studies (Saraf *et al.* 1994; Saraf and Jain, 1994). Occurrence of groundwater in the Karoo is confined to fractured hard rock terrains and weathered horizons (Woodford and Chevallier, 2002). Therefore, an extensive hydrogeological investigation is required for thorough understanding of Karoo groundwater conditions, Remote sensing provides the most accurate spatial information in this regard.

In this study, a geological map (Figure 18) and aerial ortho photos (Figure 19) were utilised to identify possible water bearing structures and lineaments within 20 Km of the study area. Ten potential dolerite intrusion structures were identified as shown in Figure 19; these potential structures can be verified further by geophysical methods and by use of percussion drilling.

Some of the identified dolerite intrusion structures can be seen intersecting nearby streams, as in Figure 18. In essence the edges of the dolerite intrusions are intersecting the alluvial aquifers (Hough and Rudolf, 2012). The use of the geological map was to identify water bearing structures (dolerite intrusions) through the aerial ortho photo maps. Note, the general geology of the study area is further discussed in Chapter 3 Section 3.6.

The dolerite structures are considered the primary targets for groundwater exploration in the Karoo Supergroup (Woodford and Chevallier, 2002); thus the identification of these structures is important. The contact between dolerite dykes and the host rock, within the weathered zone, remains the most important target for groundwater exploration (Vegter, 1995; Smart, 1998).

The aerial magnetic data as obtained from Council of Geoscience (CGS) were also used to further identify the highly magnetic dolerite intrusions in the study area. The airborne magnetic surveys are conducted using a low flying aircraft or helicopter trailing a magnetometer (Woodford and Chevallier, 2002). These surveys provide invaluable data for tracing the larger structural features. The entire Karoo basin has been surveyed aero-magnetically by the Council of Geoscience; the findings are available in digital format and printed maps. The high-resolution airborne magnetic surveys are commonly used to produce detailed maps of dolerite structures in the Karoo (Woodford and Chevallier, 2002).

The magnetic data are recorded continuously during the flight on a paper recorder or magnetic tape or electronically. The flight path of the aircraft is recorded by photographing the ground traversed with a special 35 mm camera (Woodford and Chevalier, 2002). An example of an aeromagnetic data contour map is shown in Figure 20.

The aerial magnetic map (Figure 20) shows that the study area is located on the sedimentary rocks (green and blue areas) of the Beaufort Group of the Karoo Supergroup which hosts extensive dolerite intrusions (red, pink/purple and yellow areas).

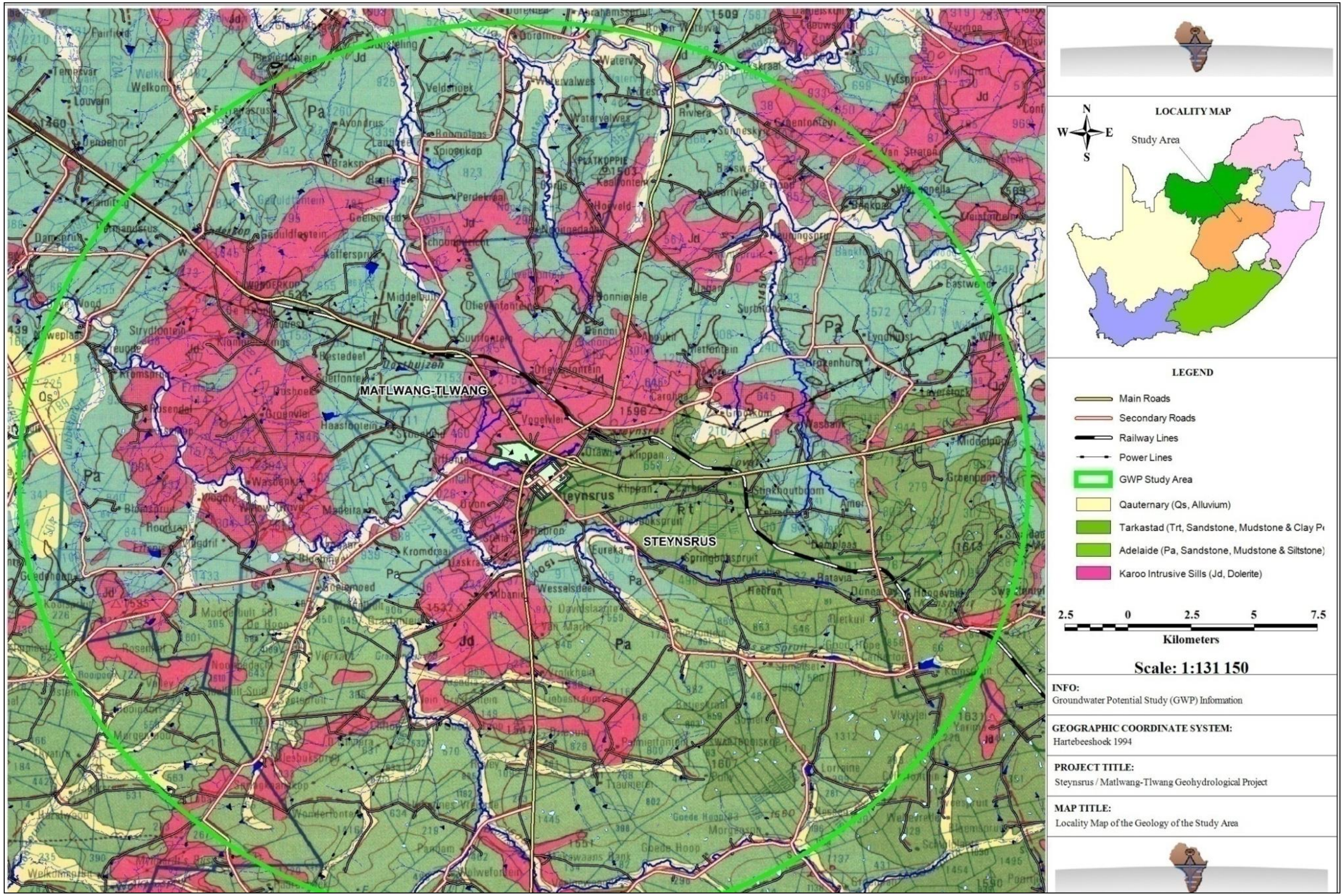


Figure 18: Geological Map of Steynsrus (Hough and Rudolf, 2012b).

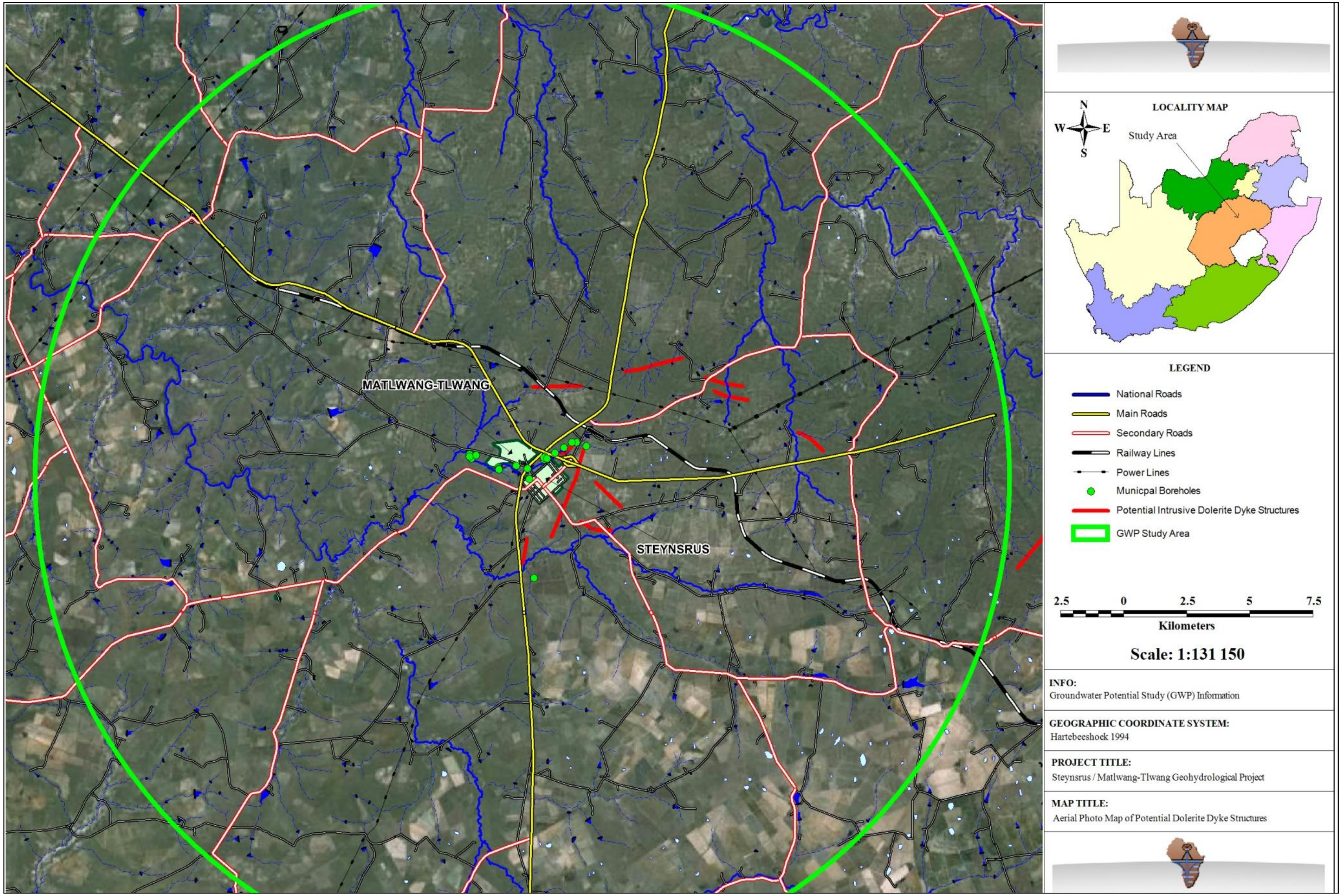


Figure 19: Locality map from the aerial photo (Hough and Rudolf, 2012b).

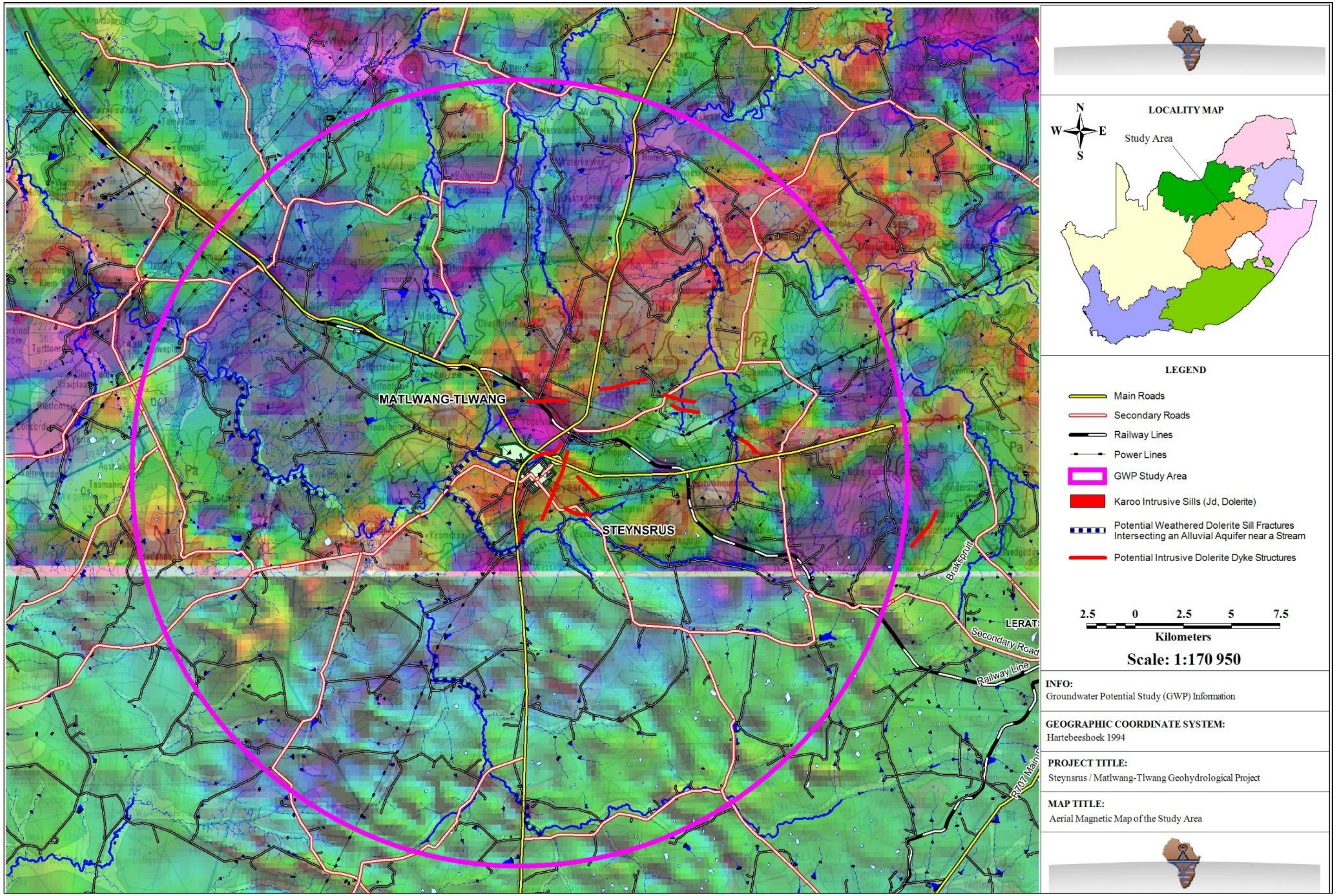


Figure 20: Aeromagnetic data contour map for Steynsrus (Hough and Rudolf, 2012b).

The aerial magnetic map (Figure 20) also depicts the identified dolerite intrusions intersecting an alluvial aquifer near streams that occur in the area. These identified structures can be verified through geophysical methods or percussion drilling as mentioned above.

4.2.1 Borehole Siting

Remote sensing and available geological maps and information were used to identify the primary drilling targets in the study area. The dolerite intrusions were identified as the primary drilling targets. As mentioned earlier, these identified targets can be further verified through geophysical methods, such as magnetometer surveys, and selected as drilling targets (as will be discussed in Chapter 5). The drilling targets were also sited on the identified areas based on the geological observations and knowledge of the area. The targets sited based on geological observations are listed in Table 5.

Table 5: List of the sited drilling targets based on the geology

Drilling Target Number	Latitude (°)	Longitude (°)
DT-05	-27.95564	27.57404
DT-06	-27.94588	27.56019
DT-07	-27.94709	27.55817
DT-08	-27.94537	27.53612
DT-09	-27.94519	27.53333
DT-10	-27.94156	27.52776
DT-11	-27.94156	27.52535
DT-12	-27.94203	27.52379
DT-14	-27.93008	27.54019
DT-15	-27.79327	27.53347
DT-17	-27.98742	27.55744

The above targets were identified from geological observations rather than geophysical methods, these targets include the weathered zone fractures and baked contact zone fractures that occur within or on the contact edges of dolerite structures (Hough and Rudolf, 2012b). For instance, DT-09 was sited on a visible highly weathered outcrop and DT-12 on joint structures to target the fractures that may be associated with the weathering and the contact areas associated with the dolerite intrusion, respectively.

4.3 BOREHOLE INFORMATION

No available data and information regarding the boreholes in Steynsrus could be sourced from the Department of Water Affairs (National Groundwater Archive). The existing borehole information was therefore obtained from the sources mentioned above; this information is summarised in Table 6.

Table 6: List of the existing boreholes and basic information

Name	Purpose of borehole	Longitude (°)	Latitude (°)	Casing Height (m)	Borehole Depth (m)	SWL (mbgl)	Reported Blow Yield (L/s)	Borehole Status
ST-OBH01	Observation	27.531	-27.9436	0.23	42.00		4.50	Unused.
ST-OBH02	Observation	27.5311	-27.9436	0.33	7.00		<0.10	Unused.
ST-OBH03	Observation	27.5304	-27.9428	0.3	30.00		0.50	Unused.
ST-OBH04	Observation	27.5307	-27.9438	0.9	42.00		10.00	Unused.
ST-OBH05	Observation	27.5313	-27.9443	0.37	42.00		20.00	Unused.
ST-OBH06	Observation	27.5331	-27.9431	0.32	48.00		<0.10	Unused.
ST-PBH07	Production	27.5305	-27.9437	0.18	60.87		5.00	Non-functional.
ST-PBH08	Production	27.5751	-27.9386	0.25	27.80	1.07		Non-functional.
ST-BH09		27.5731	-27.9386	0.5	83.08	3.47		Unused.
ST-BH10		27.5699	-27.9404	0.18	60.00			Unused.
ST-PBH11	Production	27.56608	-27.9424	0.13	77.60	2.38	3.00	Non-functional.
ST-PBH12	Production	27.55545	-27.9517	0.16	79.51	10.87		Non-functional.
ST-PBH13	Production	27.55459	-27.948	0.1	49.60	2.3		Non-functional.
ST-PBH14	Production	27.55005	-27.947	0.65	28.75	3.7		Non-functional.
ST-PBH15	Production	27.54288	-27.9478	0.25	25.15	2.25		Non-functional.
ST-BH16		27.54258	-27.9474					Unused.
ST-BH17		27.54284	-27.948					Unused.
ST-BH18		27.54281	-27.9483					Unused.
ST-BH19		27.56173	-27.9448	0.15	19.65	2.48		Unused.
ST-PBH20	Production	27.56187	-27.9438	0.25	40.82	5.45		Non-functional.
ST-BH21		27.56148	-27.944	0.1	42.80	5.43		Unused.
ST-BH22		27.56153	-27.9441	0.19	42.95	6.75		Unused.
ST-PBH23	Production	27.56285	-27.9444	0.27	51.00	2.27		Non-functional.
ST-PBH24	Production	27.57936	-27.9399	0.19	29.75	2.14		Non-functional.
ST-PBH25	Production	27.55738	-27.9876	0.29	39.30	13.57		Non-functional.

*Note: blank spaces indicate no available information.

A total of 25 boreholes were identified and verified as either existing production boreholes or potential and observation boreholes in the study area as listed in Table 6.

4.4 SUMMARY

Chapter 4 gives details of the desktop study that included remote sensing, GIS and map interpretations; thereby providing a presentation that includes the geological map, aerial ortho photo map and an airborne magnetic data contour map obtained from the Council of Geosciences. It also includes a section listing the borehole information collected during a hydrocensus that was conducted. The information gathered was used to determine the primary groundwater targets, i.e. dolerite intrusions that could be verified or explored through geophysical methods and/or percussion drilling. Moreover ten (10) potential dolerite structures were determined. On the identified dolerite intrusions, eleven drilling targets were sited based on the geological observations.

The existing borehole information gathered was used to indicate the extent of groundwater use in the study area and to identify boreholes that could be assessed through aquifer pump testing. The next chapter discusses the geophysical investigations that were conducted and the analysis and interpretation of the magnetic data produced.

CHAPTER 5 GEOPHYSICAL INVESTIGATIONS

5.1 INTRODUCTION

Various techniques have been developed and shown to locate favourable positions and targets for the exploitation of groundwater resources within Karoo rocks. These techniques include remote sensing, limited to geological mapping (Woodford and Chevallier, 2002); and geophysical methods. Electromagnetic and magnetic techniques were identified by Woodford and Chevallier (2002) as the most commonly and widely used techniques for exploring and drilling in the Karoo. Magnetic surveys have also proven themselves over the years to be the most efficient way to trace dolerite intrusions and have been applied successfully in South Africa for more than 60 years (Campbell, 1975; Enslin, 1950; Enslin, 1955; Gombar, 1977; Vandoolaeghe, 1979; Vandoolaeghe, 1980, van Eeden and Enslin, 1948; Woodford, 1984).

In this study the magnetic method was preferred over the electromagnetic technique that determines the resistivity of rock types. Electromagnetic techniques also determine the resistivity of variations with depth and the lateral extent of geological structures; these variations are then interpreted to identifying drilling targets. The preference for the magnetic method is supported by the fact that it is easy to operate and it is also easy to analyse and interpret the anomalies from a possible structure such as a dolerite intrusion, using standard anomaly curves by Roux (1980) (Appendix 1). These standard curves may clearly show the strike of the profile line on anomaly shape, and dip of the dyke for a magnetic inclination of 60° in the southern hemisphere. The standard curves have been devised to provide a rapid reference for the shape of a thin dyke anomaly for various dips and for various traverse line directions for the case of an inclination of 60˚ in the Southern Hemisphere and with a magnetic declination of 16˚ west of true north (Roux, 1980).

5.2 MAGNETIC SURVEY

The magnetic method has long been used to map regional geologic structures and to carry out mineral exploration (Reford, 1980). The method is used to map the intensity of the earth's magnetic field and interpret the intensity variations at different locations. Earth possesses vast quantities of minerals which contain iron and nickel, and which demonstrate the properties of ferromagnetism. The rocks, soils and structures (e.g. dykes, sills, fault zones) which contain these minerals have strong magnetic properties, and hence act as magnetic features. These magnetic features behave like magnets within the earth's crust, adding to the earth's main magnetic field. The change observed between the latter and former is a property of a rock called magnetic anomaly.

Geophysical surveys with the G5 Proton magnetometer were conducted in the area to delineate any subsurface structures that were identified in remote sensing in Section 4.2. The traverse lines (Figure 21) were selected based on remote sensing that was conducted to locate the dolerite intrusions. A station spacing of 5 m was used during the survey for all traverses, except Traverse S-TV04 and S-TV05 which had a station spacing of 2 m. The profiles were aimed at delineating the structures, preferably dolerite dyke and sill intrusions and geological contact zones in the study area. Additional magnetic surveys were conducted to compare with magnetic data used for drilling and to ascertain the magnetic field intensity relative to the local geology and the quality of the magnetic data.

The magnetic data were plotted in Excel to produce the profiles. All Traverse lines (see Figure 21) will be discussed below. Before interpretation was done it was necessary to smooth the magnetic data, remove the regional magnetic anomalies, determine the true zero line, and determine the depth, centre and thickness of the geological structures in question. A 3-point running average method was used for smoothing and to get the smoothed values of the magnetic field intensity.

For the data used for drilling removal of the regional field, which is usually caused by deep-seated effects (Roux, 1980), was done by obtaining the difference between the smoothed data and the field anomaly. The removal of the regional field on the magnetic data of the additional surveys conducted was done by estimating the regional field manually for the profile data. This was done based on the interpreter's understanding of the geology and the related field distribution and the use of a least-squares fitting of a low order polynomial to the observed data. The centre of the anomaly was determined by using the Logochev (1960) method; which uses the distance from the zero line determined to the minimum of the trend line. A parallel line with same distance as estimated from the zero line to the minimum distance is drawn from the middle of the anomaly, a parallel line to zero line is drawn where it intercepts the curve. The point at which the curve is intercepted is the centre of the dyke or geological structure, see Figure 22.

The depth of the dolerite structures were determined using the Horizontal Slope Distance (HSD) method which uses the horizontal distance between the points where the curve deviates from the maximum slope of the anomaly. Figure 23 provides a description of how the depth was determined for each anomaly (Roux, 1980).

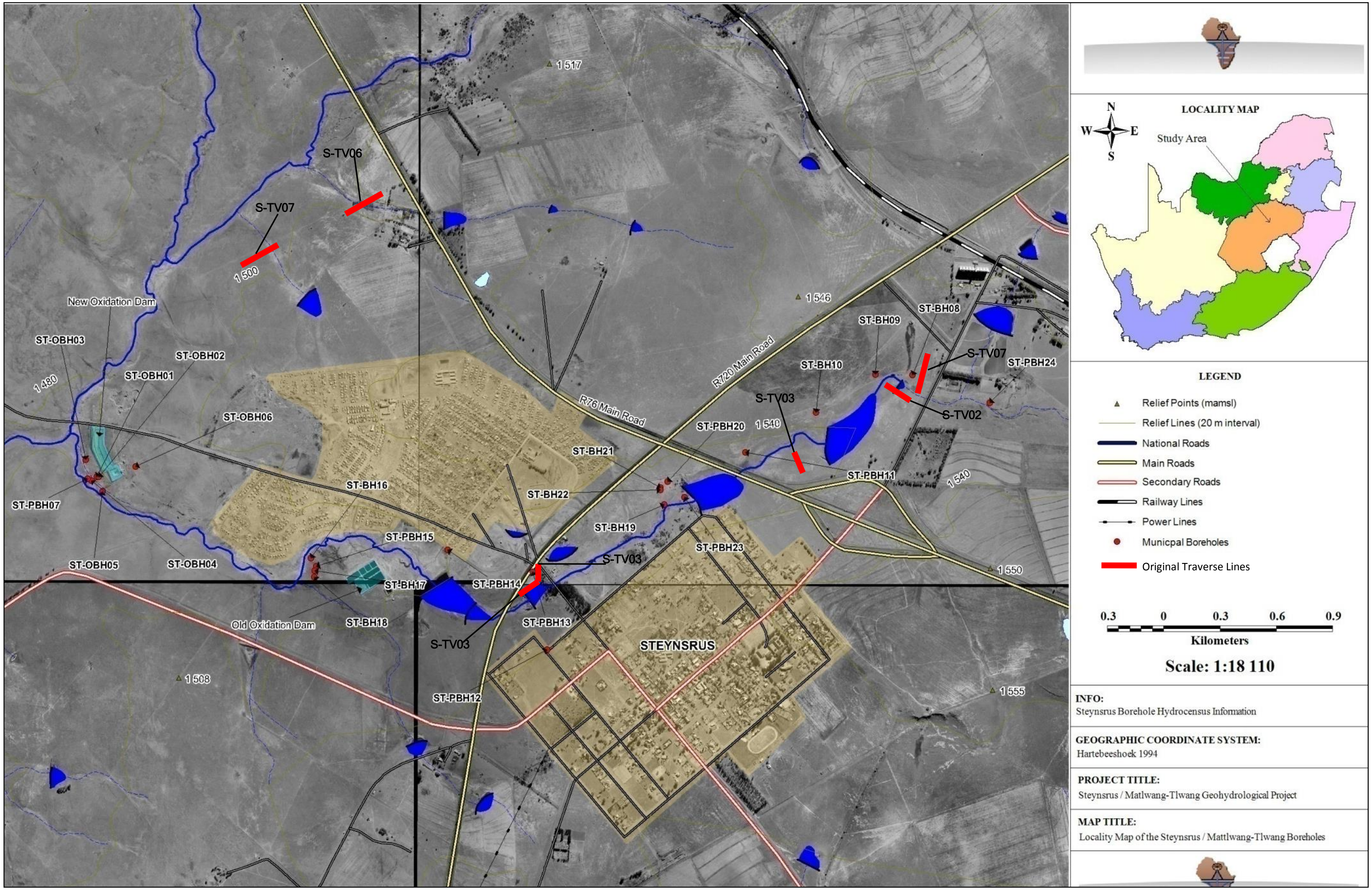


Figure 21: Location of the geophysical traverses in the study area (Hough and Rudolf, 2013).

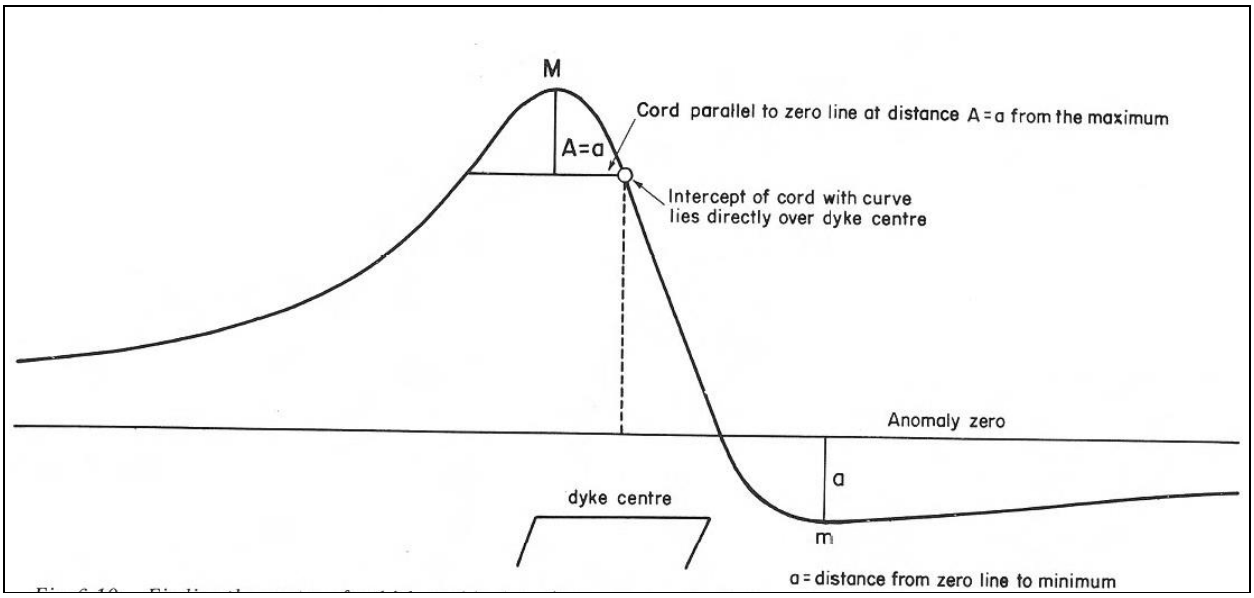


Figure 22: Finding the centre of a thick or thin dyke using Logochev method (Logochev, 1961).

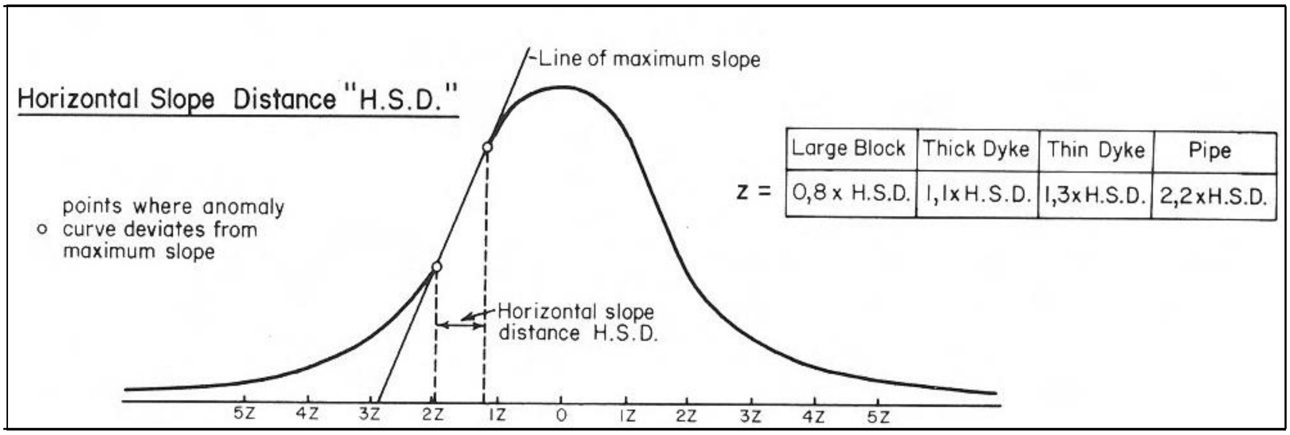


Figure 23: Determining depth of the dyke using Horizontal Slope Distance ("HSD") (Roux, 1980).

5.2.1 Results and Discussion

The magnetic data were recorded during the geophysics survey that was conducted by external consultants who were appointed for drilling of boreholes for the town water supply. The interpretations of these traverse profiles and the locations of the subsequent drilling target sites selected have been deduced with the available data and knowledge of the geology of the area. There were also additional traverses that were conducted to allow a comparison with the data presented by the external consultant and to validate the arguments and evaluation in this chapter. The interpretation and explanation of the magnetic data will also seek to assess the quality of the data; i.e. whether the data is typical of the expected magnetic field intensity in the area, or whether the shape of the anomaly and length of the traverses are sufficient for making of any conclusive deductions.

Traverse S-TV01

The traverse (Figure 24 and 25) is 250 m long from north to south; its magnetic field signature shows a sharp decrease near the centre with the lowest magnetic field intensity reached between station 70 and 90 m. The magnetic anomaly has an amplitude of approximately 2500 nano Tesla (nT) (after removal of regional magnetic field intensity). One drilling target (DT-01) was sited at 80 m along the traverse line to explore if the negative anomaly represents the discontinuity of an intrusion or contact zones or any underlying feature.

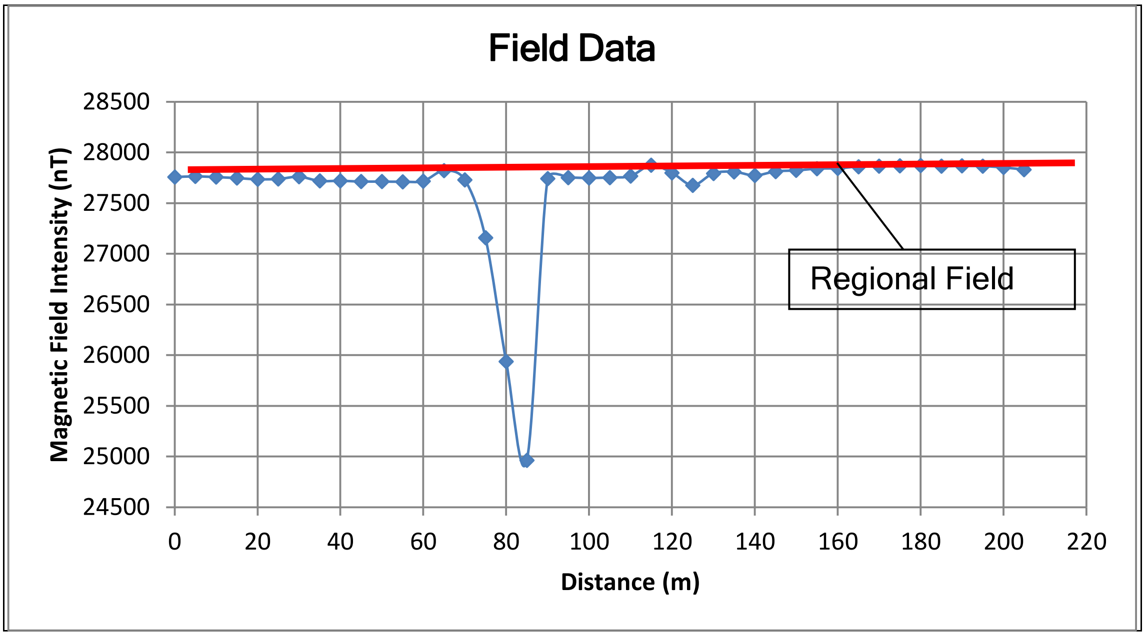


Figure 24: Traverse profile for S-TV01, field magnetic data.

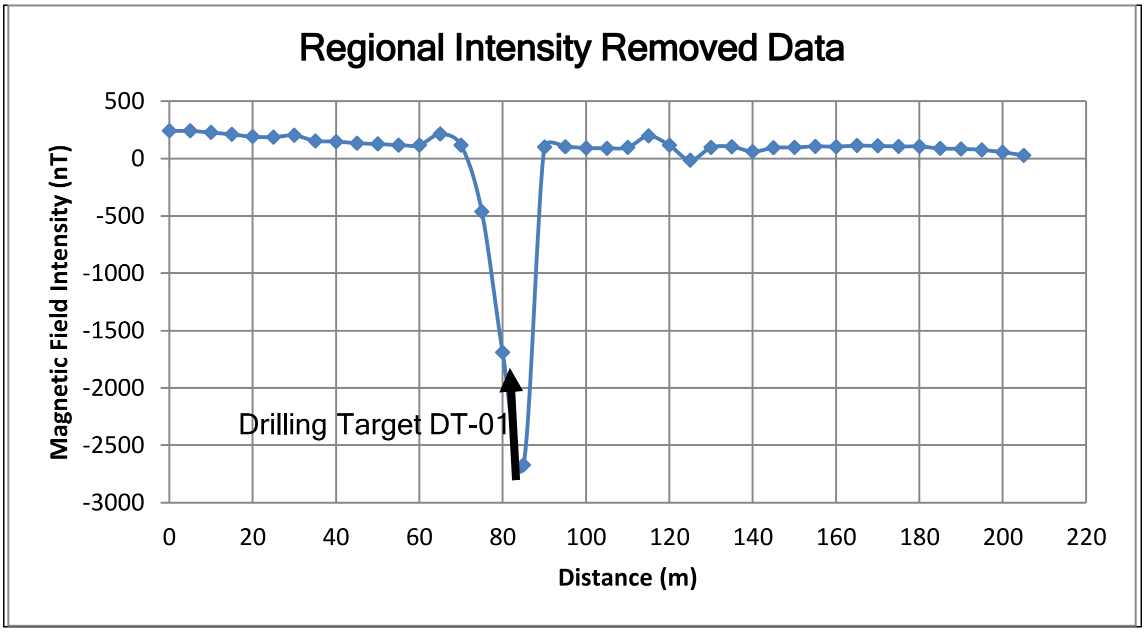


Figure 25: Traverse profile for S-TV01, showing the regional intensity removed data.

The large negative magnetic intensity at the anomaly can be attributed to zones where the intrusion discontinues, which could be due to features such as weathering, fracturing and or faulting. In an intrusive rock, these features can become a preferential flow path for groundwater and could thus can be good target for borehole siting.

Due to the absence of cultural effects such as the buried pipes or fences which could possibly have caused the positive anomaly, the resulting negative anomaly was considered to be triggered by the discontinuity of the possible geological feature , thus a drilling target was sited at 80 m to target the edges of the discontinuous geological feature. The geological structure triggers the magnetic anomaly due to the deviation of the magnetic field intensity from the normal value at the earth's surface caused by magnetic field intensity differences. The drilling target was sited to target the fractures that are associated with the center of the possible geologic feature which could be a preferential pathway for groundwater flow; where success has been found by Vandoolaeghe (1980). During the intrusion of dolerites, intensive fracturing forms in the older Karoo Supergroup sediments, thus the subsequent fractures are often targeted (Vandoolaeghe, 1980). Although the groundwater bearing fractures are mostly associated with the contact zones on the dolerite sheets/sills, other water-bearing fractures have also been found at the centre of the dolerite intrusion and at the geological features such as faults (Vandoolaeghe, 1980).

However, the magnetic field intensity of the anomaly was recorded with amplitude of above 2000 nT; this anomaly would be regarded as a single station anomaly according to Roux's (1980) guidelines for recognizing 'bad data'. For an appropriate recording of the reading in the field, it was supposed to be repeated to verify its accuracy. According to guidelines by Roux (1980) for recording magnetic data, a reading can be discarded if it is verified and it was found to still be significant. However, in this instance the anomaly could not be discarded as it was found to be related to the dolerite intrusion based on the remote sensing.

A new magnetic survey along the Traverse S-TV01 was conducted adjacent to the line done by the external consultant to further evaluate and compare to the magnetic data that was presented. The new magnetic data are shown as profile plots in Figure 26 and Figure 27. Ideally, the magnetic survey for Traverse S-TV01 would have been redone but due to the significant influence that would be caused by the drilled borehole from the identified drilling target (DT-01), it was decided to conduct the survey 10 m away from the original magnetic survey for traverse S-TV01. The new survey (Figure 26) conducted is also 250 m long from north to south; here the magnetic field signature shows an increase with an anomaly with an amplitude of about 30 nT.

In summary, the new traverse profile (Figure 26 and Figure 27) shows a negative anomaly from 65 m to about 130 m which could be attributed to the presence of the discontinuous geological feature such as a fault or a weathered formation. In comparison to the magnetic survey conducted by the external consultant (shown in Figure 25); the traverse profile in Figure 24 showed an acceptable amplitude for the magnetic anomaly of -157 nT. This is based on the Roux (1980) guidelines for typical reading triggered by a magnetic geological body, with acceptable amplitude of 300 nT.

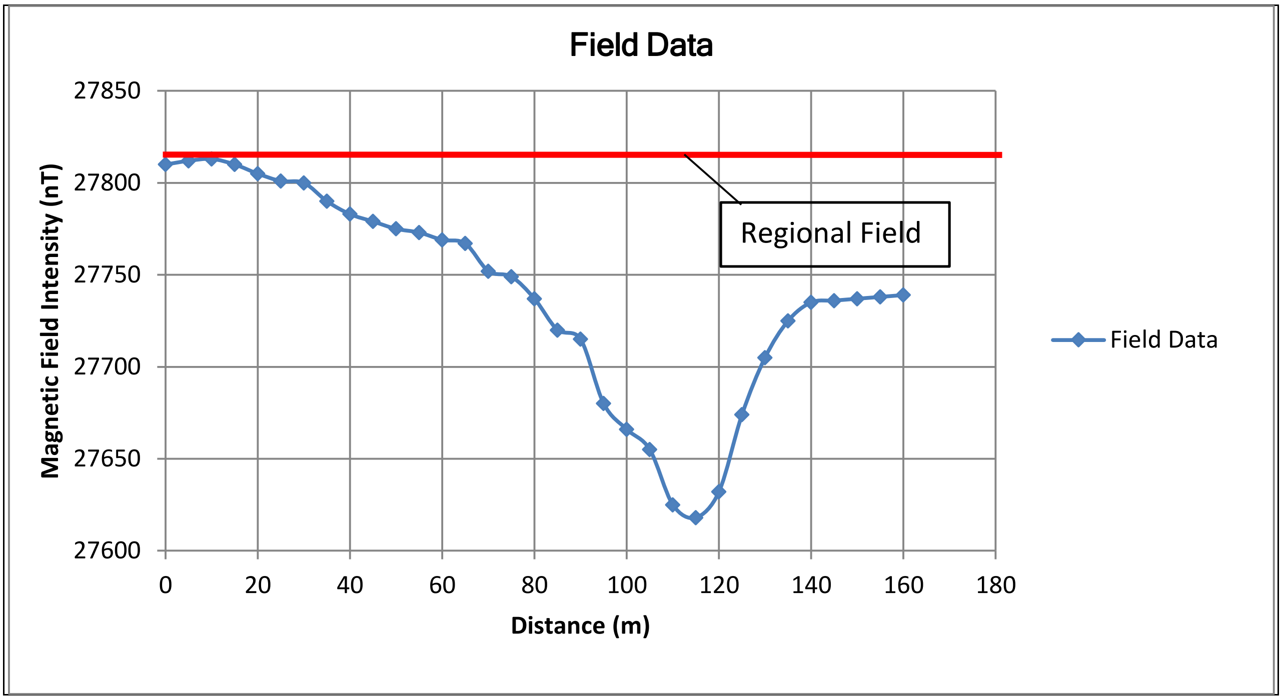


Figure 26: New magnetic survey profile for Traverse S-TV01, showing field data.

The estimated centre of the magnetic body using the Logochev's method is at 104 m relative to the anomaly zero, and the edge of the magnetic geological body is 25 m from the centre effectively at 122 m along the traverse (Appendix 2). The drilling target along this line was identified at 118 m, to target the edges of the magnetic geologic body. The depth of the magnetic body was estimated at 39 m below ground surface using the HSD method (See Appendix 2). The HSD method is applicable to dykes, it was used to calculate the depth of the dolerite which was identified through interpretation of the geological map and the magnetic data.

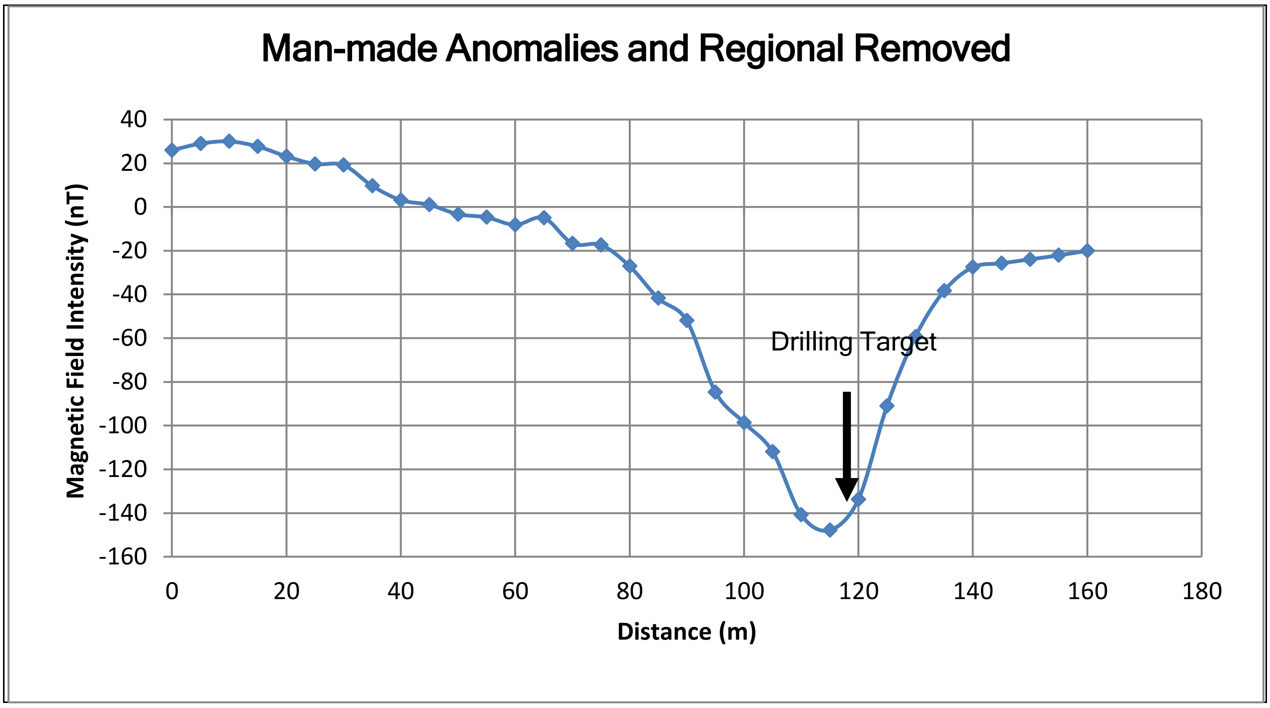


Figure 27: New Magnetic survey profile for Traverse S-TV01, showing field data and man-made anomalies after regional removal.

Traverse S-TV02

The traverse (Figure 28 and Figure 29) was 130 m long from southeast to north-west; between 40-60 m the magnetic signature decreased at a rapid gradient reaching a magnetic intensity field of 24 000 nT at 60 m. A relatively sharp increase of magnetic intensity was observed after a significantly large anomaly is recorded at 65 m; this suggested a presence of a discontinuous magnetic body which could be due to weathering or faulting according to the external consultant, as there were no cultural effects observed. One drilling target was sited at 55 m along the traverse line, namely DT-02. The below traverse profile (Figure 28) showed a one-step anomaly according to Roux (1980) guidelines for bad magnetic data; this will be discussed further below.

Although the drilling target was sited to target for the edges of the dolerite intrusion; the proof for targeting the edges of the dolerite will be discussed below using guidelines and methods by Roux (1980) on the new magnetic survey that was conducted; shown in Figure 30. It is important to note that the magnetic field intensity scale for this particular traverse is very large (1 200-2 800 nT); too large to attribute the data to natural underlying magnetic structures.

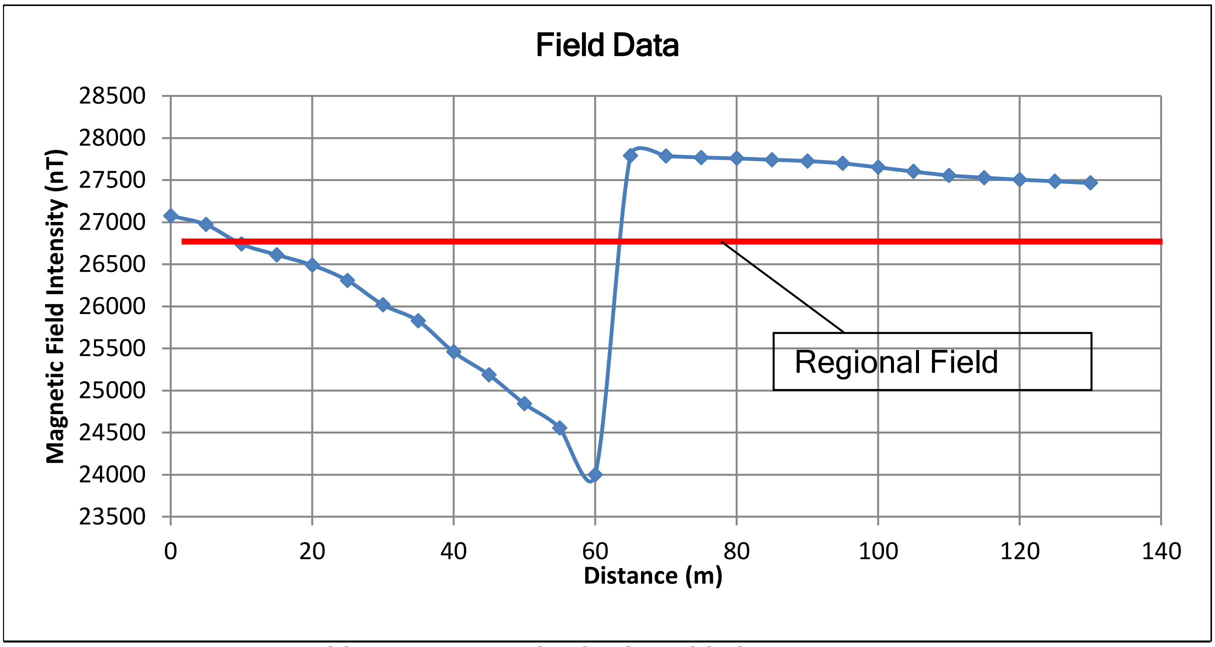


Figure 28: Traverse profile for S-TV02, field magnetic data.

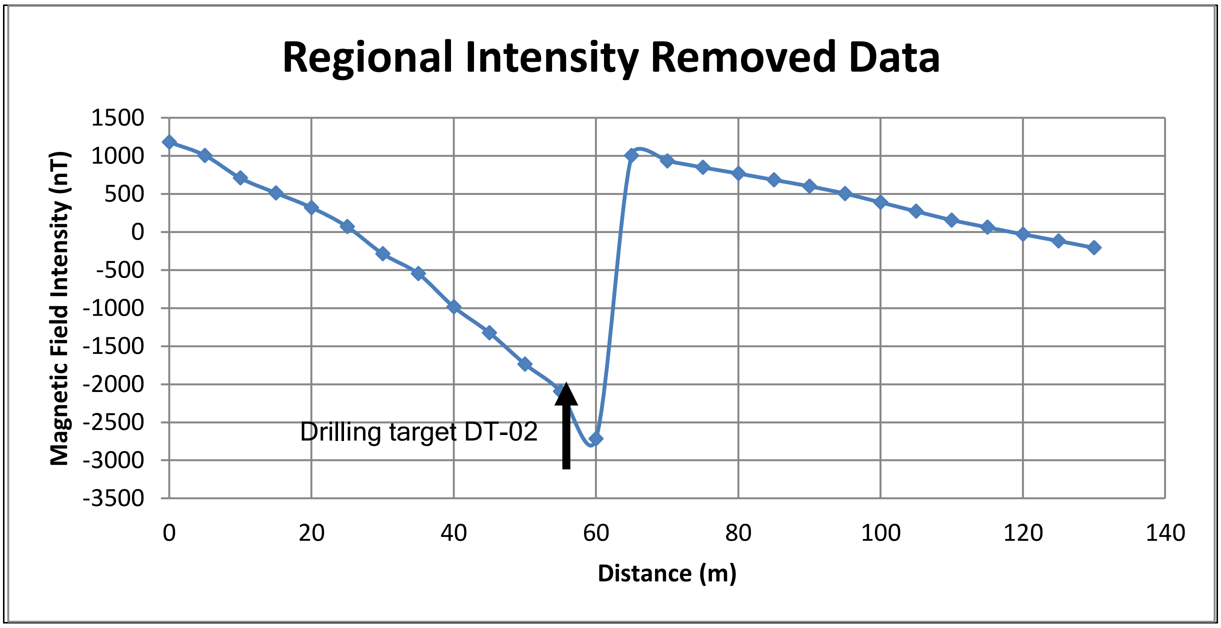


Figure 29: Traverse profile for S-TV02, showing regional intensity removed data.

The rapid magnetic field intensity increase over a very short distance (from 60-65 m) also suggests an unusual magnetic anomaly; this can be regarded as a single point anomaly according to guidelines by Roux (1980) for bad data as alluded earlier. Except for the cultural effects which could have been observed and attributed to this anomaly, a suggestion could be made that the magnetic survey was conducted inappropriately or the instrument that was used malfunctioned during the survey. The operator could have carried a magnetic object close to the sensing element or may have taken insufficient care in levelling the instrument (fluxgate) or may have incorrectly set the tuning dial.

The new magnetic survey, shown in Figure 30 and Figure 31, was conducted along the identified dolerite intrusion to verify the magnetic data recorded by the external consultant, shown in Figure 28 and Figure 29. Ideally, the magnetic survey for Traverse S-TV02 would also have been redone but due to the significant influence that would be caused by the drilled borehole from the identified drilling target (DT-02), it was decided to conduct the survey 10 m adjacent to the original survey for S-TV02. The new survey (Figure 30 and Figure 31) conducted is 160 m long from southeast to north-west; the magnetic field signature shows an increase with an anomaly with amplitude of about 600 nT was recorded.

In summary, the new traverse profile (Figure 31) shows the increasing anomaly from 110 m to about 125 m which could be attributed to the presence of the identified dolerite intrusion. Based on the guidelines by Roux (1980) for rapid reference of the shape of the anomaly, the positive anomaly was estimated at a dip of 135°. In comparison to the traverse profile in Figure 29, the traverse profile in Figure 31 showed an amplitude of the anomaly of magnetic field intensity of 414 nT relative to the anomaly zero. The estimated centre of the dolerite intrusion using the Logochev's method is at 113 m, and the edge of the dolerite is 9 m from the centre; effectively at 103 m. The drilling target along this line was identified at 103 m, to target to edges of the possible dolerite intrusion (See Appendix 2). The depth of the dolerite was estimated at 19.5 m below the ground surface using the horizontal slope distance method (See Appendix 2).

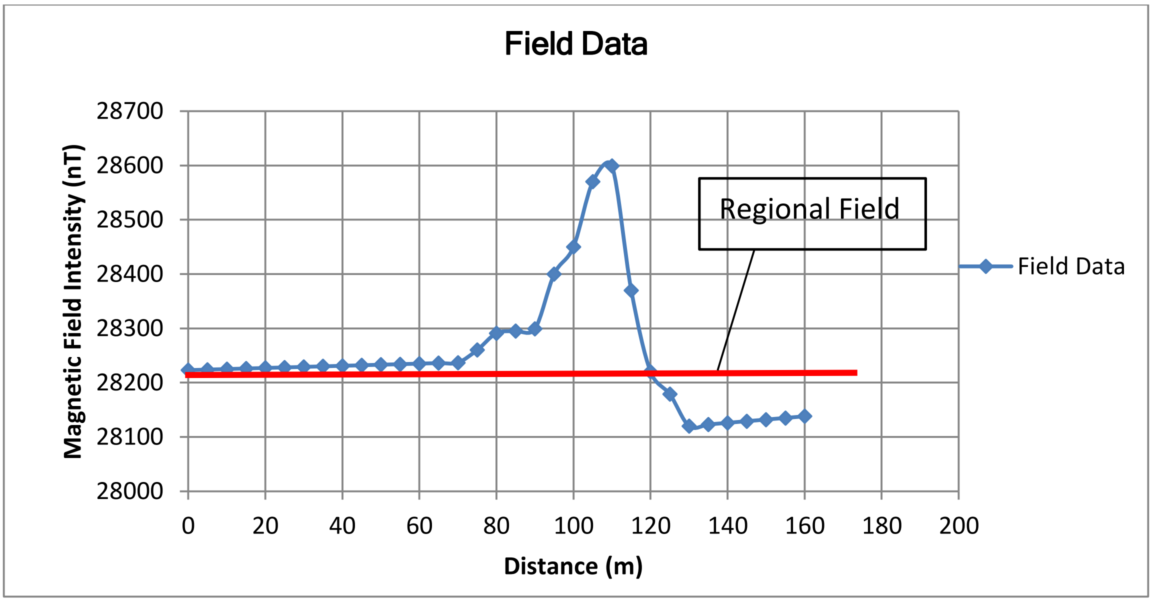


Figure 30: New magnetic survey profile for Traverse profile for S-TV02, showing field data.

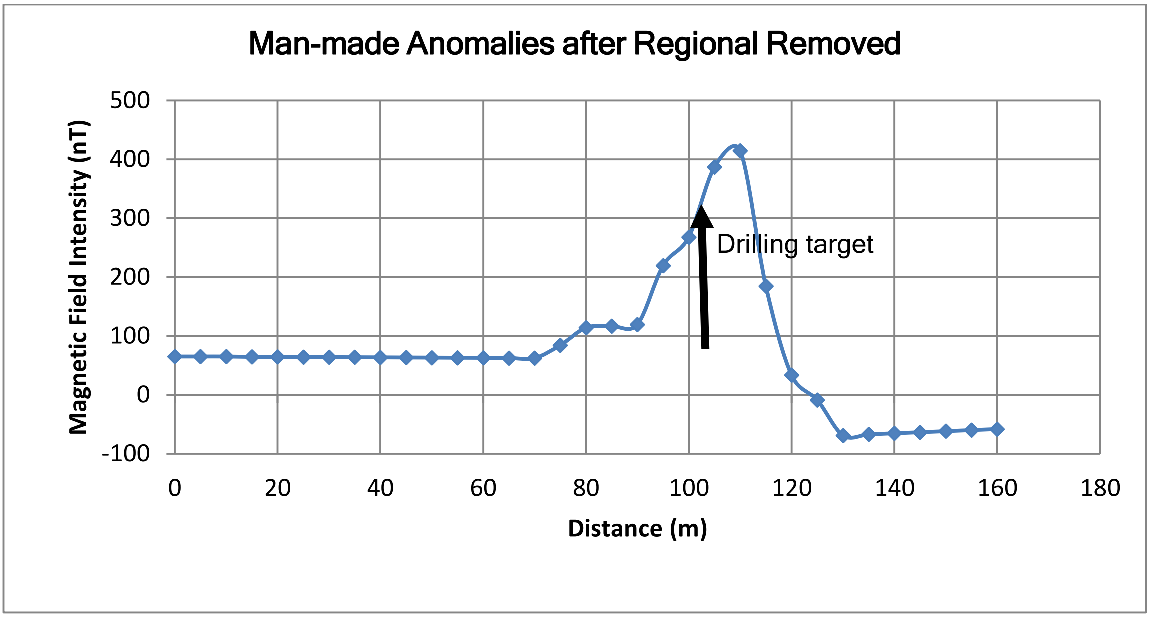


Figure 31: New magnetic survey profile for Traverse profile for S-TV02, showing man-made anomalies after removal of regional intensity.

Traverse S-TV03

The traverse (Figure 32 and Figure 31) is 70 m long from northwest to southeast direction. The magnetic field shows a gentle straight slope up to station at 20 m, there is an immediate magnetic signature decrease from 25 m resulting in a very large negative magnetic anomaly of at 35 m station, followed by a sharp increase in magnetic field intensity. A drilling target at 33 m was sited to target the discontinuous zone which may have been detected from 25-35 m; namely DT-03. The discontinuous zone could be due to faulting or weathering of the suspected intrusion along the traverse. The edges of the suspected dolerite intrusion were targeted for drilling without sufficient evidence such as the centre and depth of the dolerite intrusion; these parameters will be discussed below.

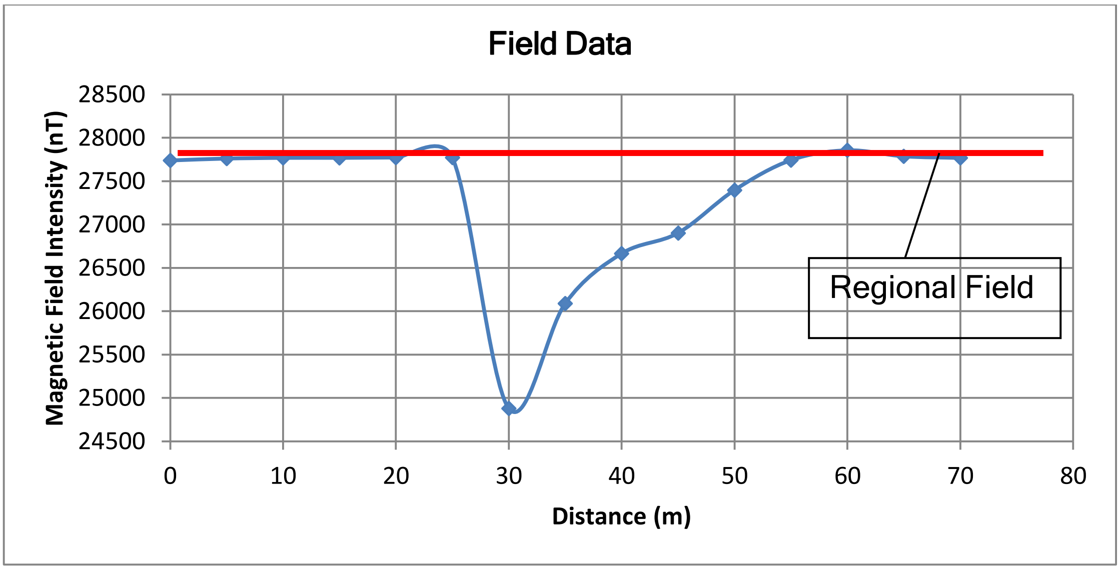


Figure 32: Traverse profile for S-TV03, showing field data.

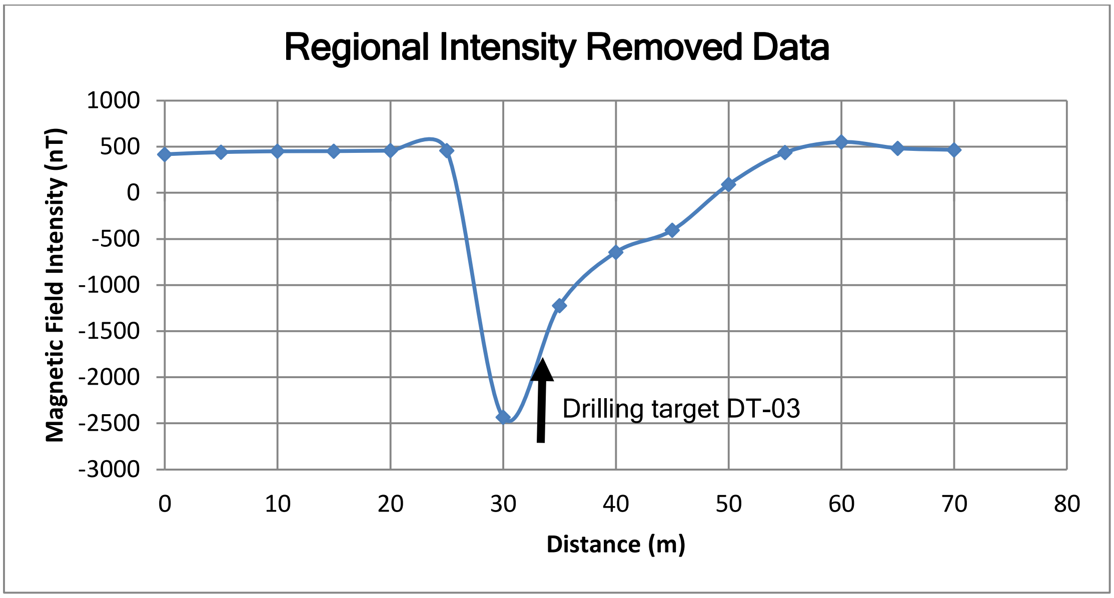


Figure 33: Traverse profile for S-TV03, showing regional intensity removed data.

The assumption was that the large anomaly was caused by a potential underlying structure (faulted or weathered) as there were no transparent cultural effects that could cause such an anomaly. However, the magnetic field intensity of the anomaly (Figure 32 and Figure 32) is very high (amplitude of 1843 nT) to be related to the magnetic underlying structures and what one normally expects in the Karoo. The data also shows a single-point anomaly at 30 m, hence the recorded reading is significantly smaller than the preceding reading by over 2000 nT. The operator needed to verify this recording because of its significance in terms of the identified dolerite intrusion in question; this prompted the suspicion that the magnetic data may be 'bad data'. However, the drilling target was sited by the external consultant based on this apparently erratic data without any reasonable explanation. The outcome of the drilled borehole based on this target (DT-03) will be discussed in Chapter 6. Ideally, magnetic survey for Traverse S-TV03 was supposed to be redone to verify the significant anomaly of several thousands nano Tesla, however the presence of a drilled borehole from the identified drilling target DT-03 made it difficult due to the influence the borehole (magnetic object) would have on the survey. It was decided that another line of survey be conducted adjacent (10 m away from the original survey line) to the original survey. The new traverse profile (Figure 33 and Figure 34) is 250 m long from southeast to northwest. The magnetic field signature (Figure 33 and Figure 34) shows a sharp increase with an anomaly of 41.50 nT after removal of the regional magnetic field intensity recorded at 115 m.

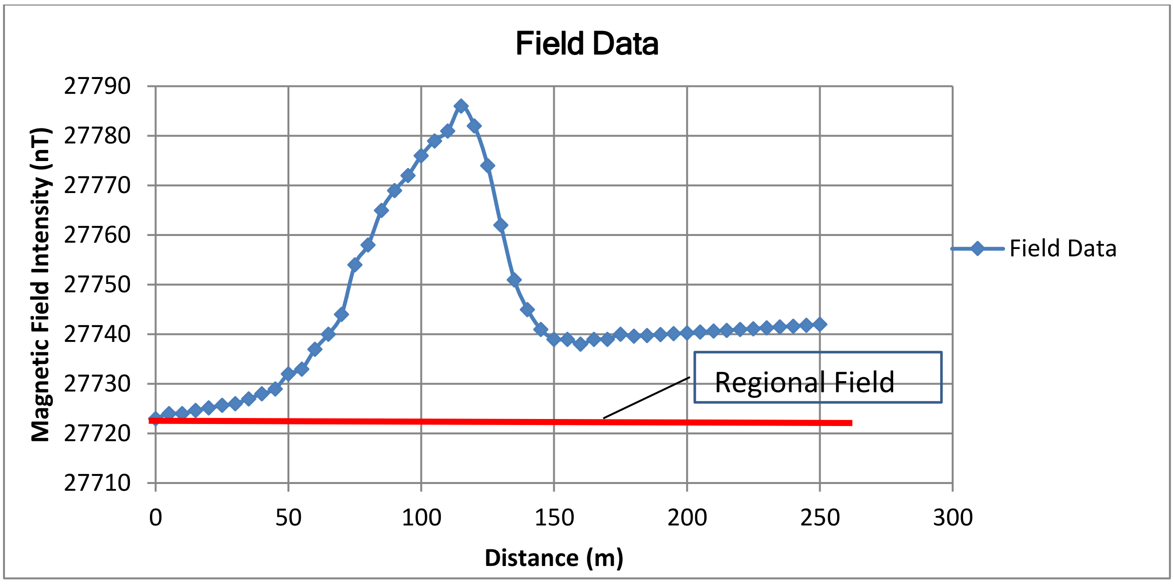


Figure 34: New magnetic survey profile for Traverse S-TV03, showing field data.

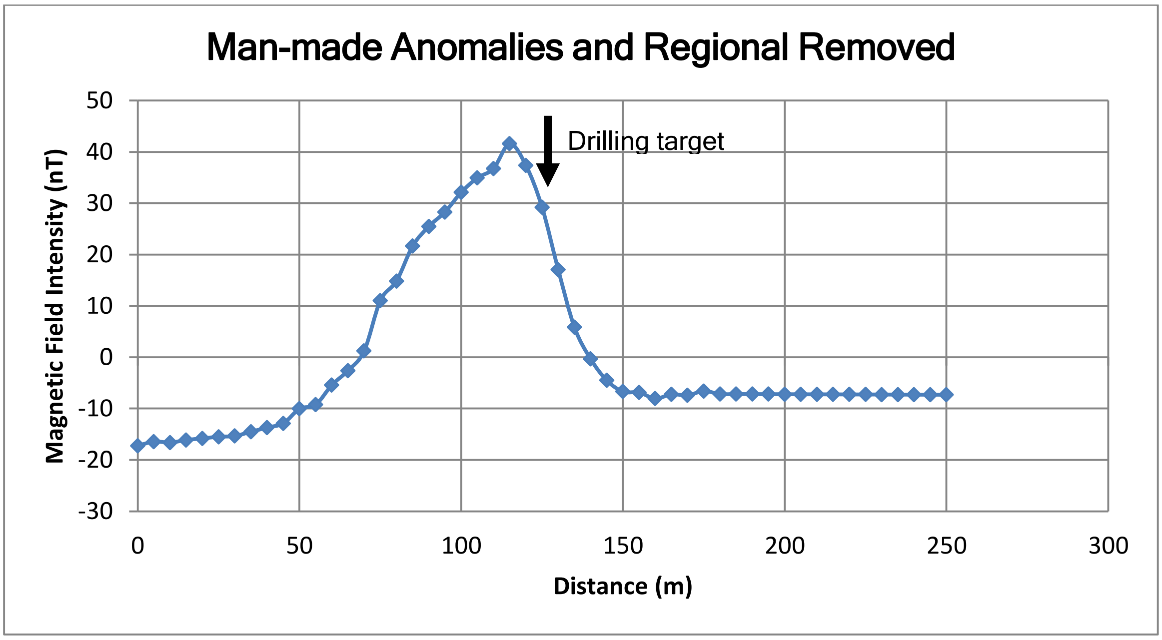


Figure 35: New magnetic survey profile for Traverse S-TV03, showing man-made anomalies after removal of regional.

Relative to the magnetic field intensity (2000 nT) of the anomaly recorded initially (Figure 32), the magnetic field intensity (41.5 nT) of the anomaly recorded in the new survey (Figure 34) would be more acceptable as an anomaly caused by an underlying geological structure based on the guidelines for typical reading triggered by a magnetic geological body (with an amplitude of approximately 400 nT). The traverse profile (Figure 34) shows a rapid increasing magnetic signature from 50 m to about 115 m and an immediate decrease until 150 m, this anomaly can be attributed to the presence of the identified dolerite intrusion. The centre of the dolerite intrusion at 85 m was estimated using Logochev's method relative to the set anomaly zero at -12.50 nT and the edge of the dolerite was estimated at 128 m. The drilling target along this profile (Figure 35) was identified at 125 m, to target the edges of the possible dolerite intrusion (See Appendix 2). The depth of the dolerite intrusion was estimated using the horizontal slope distance at 45.1 m below the ground level (See Appendix 2).

Traverse S-TV04

The traverse (Figure 36 and Figure 37) is 32 m from southwest to northeast. A significant magnetic anomaly was detected at 16 m, this showed a very large positive magnetic field intensity. The traverse lacked magnetic field variation and was too short to allow an accurate interpretation of any potential structures which could be explored for drilling. There were no observed cultural effects that could be attributed to the observed anomaly.

The traverse profiles (Figure 36 and Figure 37) also show a featureless data as observed from 0-6 m and 14-32 m. According to Roux (1980), a monotonously flat data can also be regarded as 'bad data' as they could be caused by the operator omitting to compensate for the earth's local magnetic field. It is also important to note that the observed magnetic field intensity of the anomaly was very large (up to 200 000 nT) relative to the magnetic field intensity of potential underlying structures normally found in the Karoo. The recorded reading for the anomaly is greater than the preceding reading by over 200 000 nT. The operator in this regard needed to verify diligently if this recording was correct. There was no drilling target sited based on this traverse (Figure 36 and Figure 37). Ideally, magnetic survey for S-TV04 needed to also be redone to verify the significant anomaly of several thousands recorded and investigate the featureless data recorded.

A new magnetic survey for Traverse S-TV04 was conducted to investigate the raised concerns with the magnetic data produced as discussed above. The traverse profile (Figure 38 and Figure 39) is also 32 m long from southeast to northwest. Relative to the amplitude doe the magnetic anomaly of 250 000 nT recorded in Figure 37, the amplitude for the magnetic anomaly of 200 nT in Figure 39 was recorded.

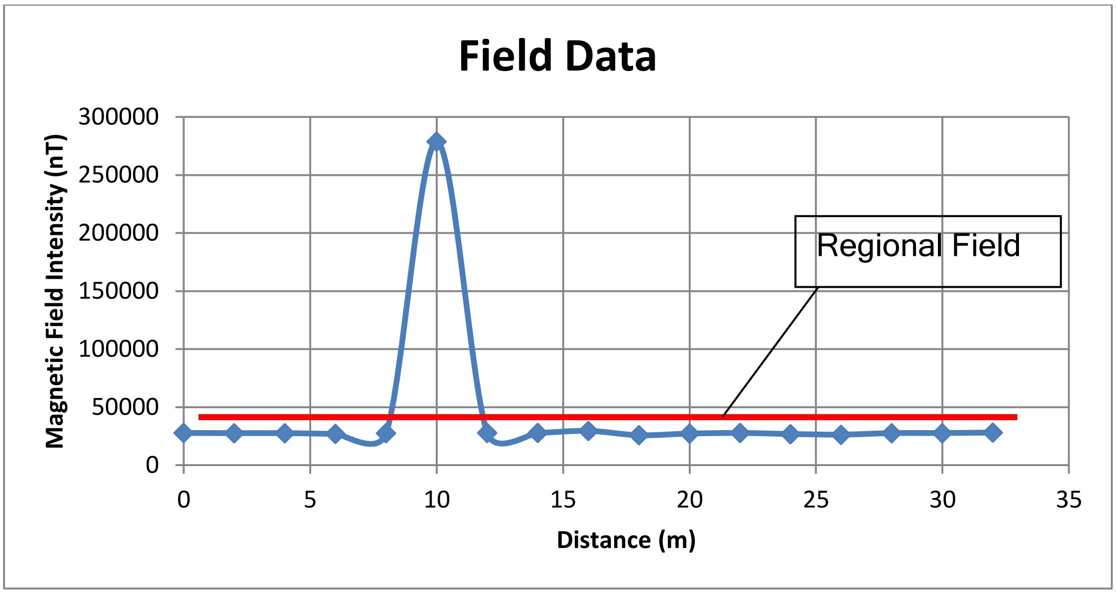


Figure 36: Traverse profile for S-TV04, showing field data.

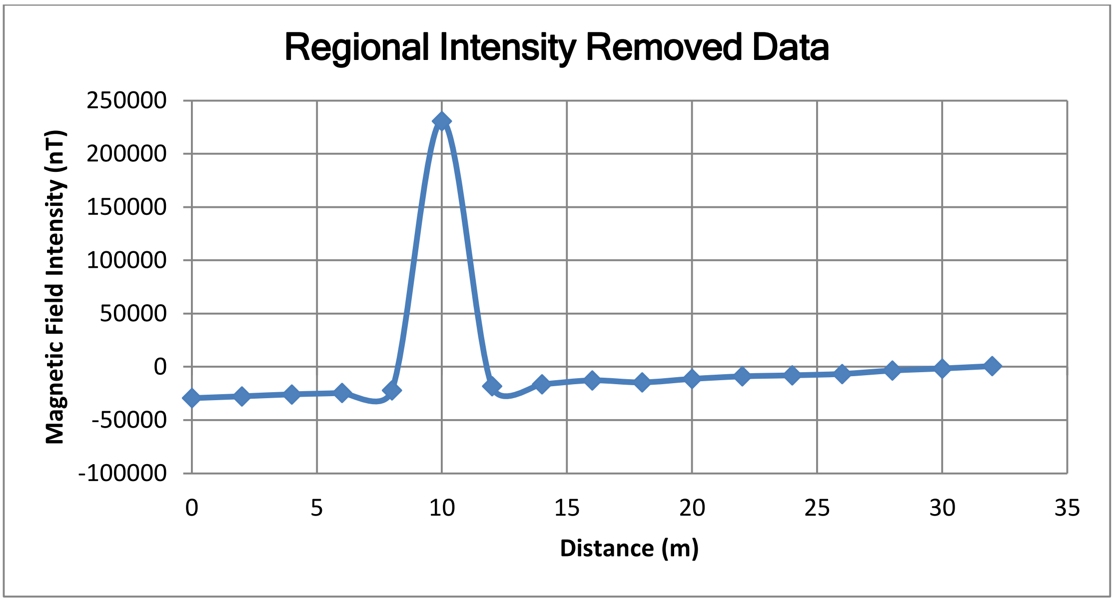


Figure 37: Traverse profile for S-TV04, showing regional intensity removed data.

The centre of the dolerite intrusion from the newly conducted magnetic survey data (Figure 39) was estimated using Logochev's method at 12.00 m along the traverse relative to the anomaly zero set at 1.00 nT (See Appendix 2). The edge of the dolerite was estimated at 9 m along the traverse, and the depth of the dolerite was estimated using the horizontal slope distance method at 7.80 m (See Appendix 2).

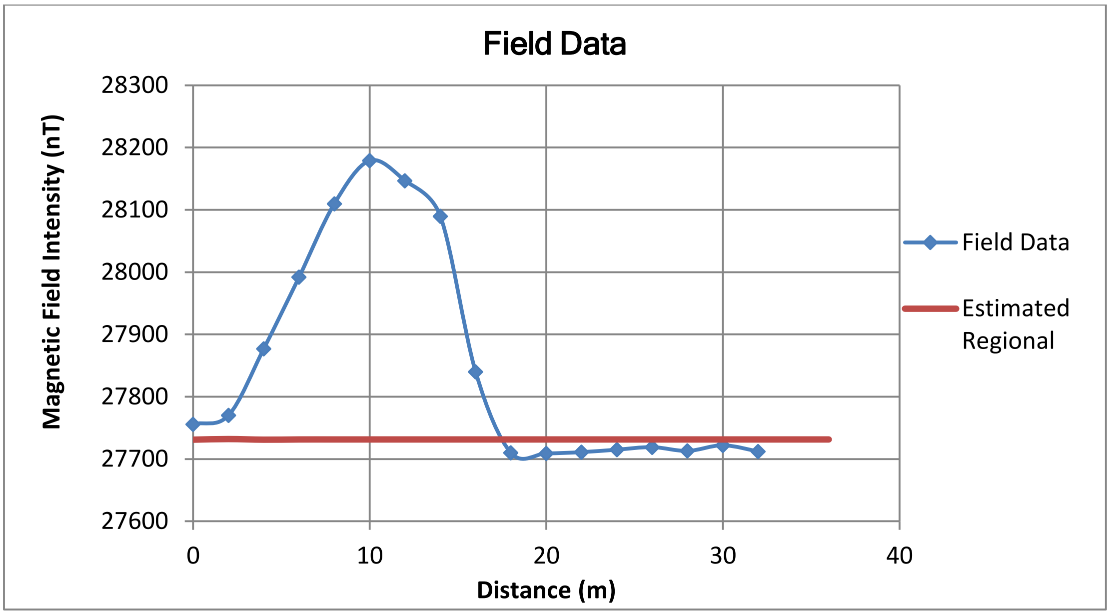


Figure 38: New magnetic survey profile for Traverse S-TV04, showing field data.

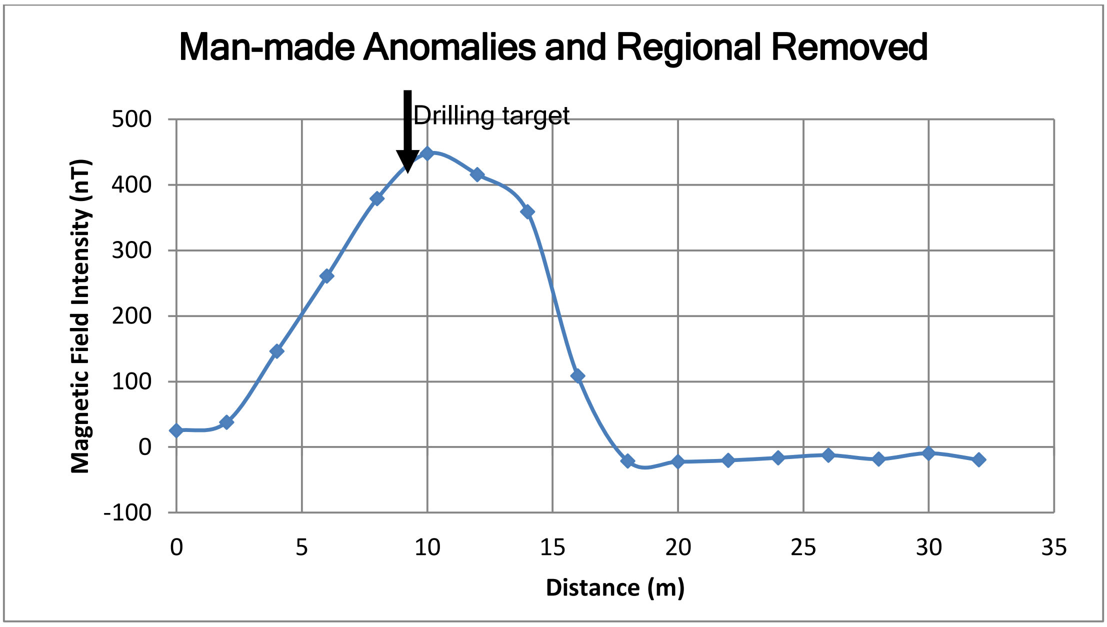


Figure 39: New magnetic survey profile for Traverse S-TV04, showing man-made anomalies after regional removal.

Traverse S-TV05

The traverse profile (Figure 40 and 41) is 25 m long from a north to south direction. The magnetic field shows a significant positive anomaly between stations 6 and 14m; with amplitude of 1896 nT at 12 m after the removal of the regional magnetic field intensity. The resulting anomaly was considered to be triggered by the geological structures, thus at 13 m a drilling target was sited, namely DT-04. The drilling target was sited to explore potential secondary fracture as well as targeting the edge of the possible dolerite observed. The proof to justify the position of the drilling target will be discussed and evaluated below.

It should be noted that the magnetic survey was conducted along a visible potential drilling structure (i.e. dolerite intrusion), making the siting of the drilling target easier. However, the observed amplitude of the magnetic anomaly of 1894 nT was found to be very large to attribute it to an underlying magnetic structure, shown in Figure 41. Although the dolerite intrusion in this regard was visible, the cause of the large magnetic field intensity observed may be explained as an error which could have been occurred during the survey.

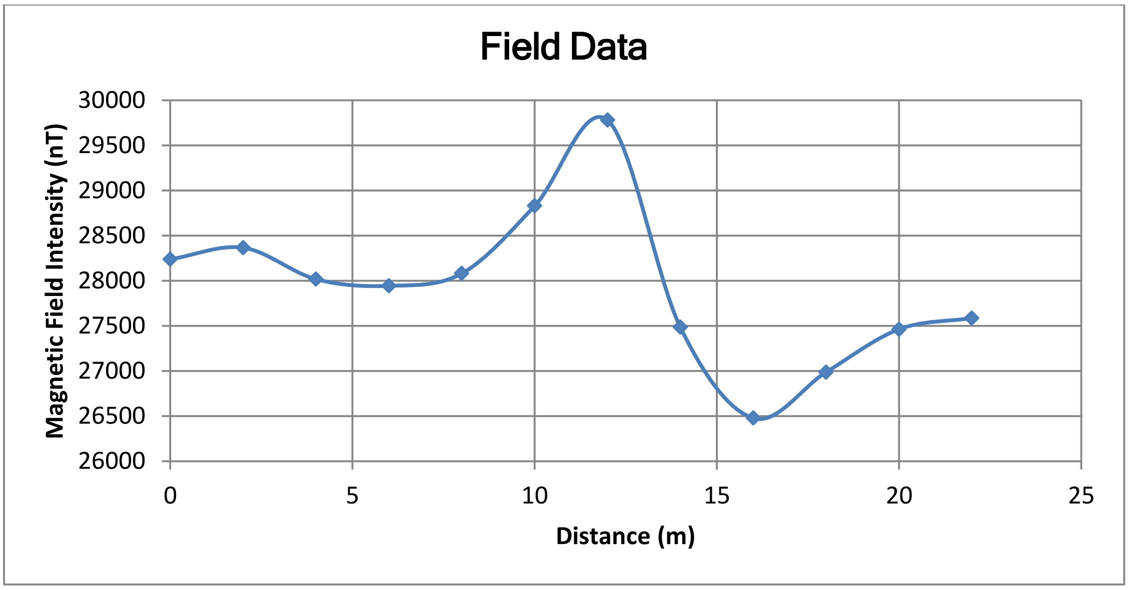


Figure 40: Traverse profile S-TV05, showing the field data.

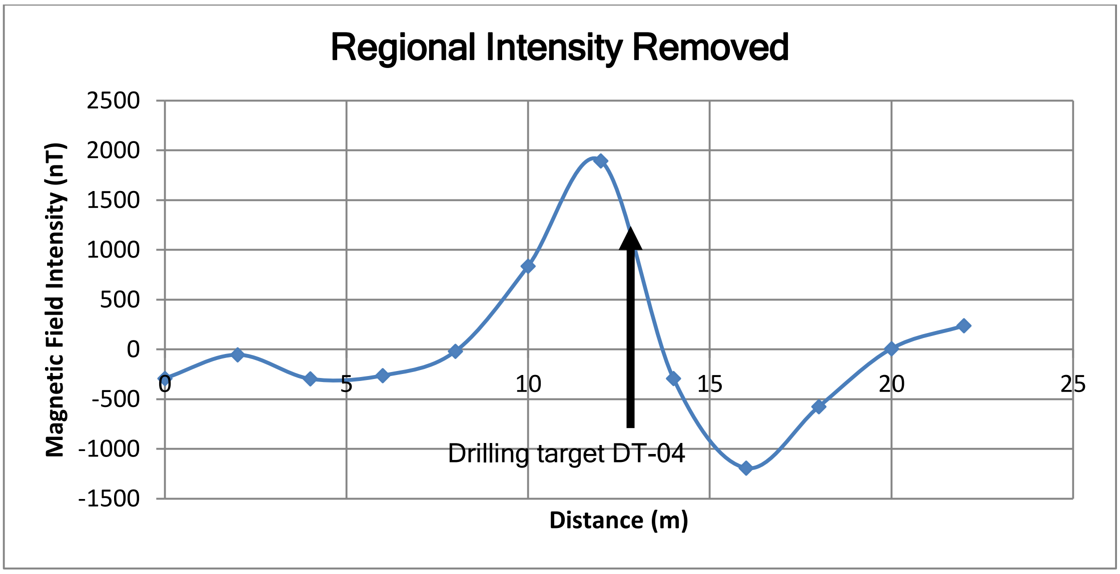


Figure 41: Traverse profile for S-TV05, showing regional intensity removed data.

A new magnetic survey (Figure 42 and Figure 43) along Traverse S-TV05 was conducted to investigate and verify the large anomaly observed in Figure 38. Due to the presence of a drilled borehole from the identified drilling target DT-04, the survey (Figure 42 and Figure 43) was conducted adjacent to the original magnetic survey (Figure 40) for Traverse S-TV05 (10 m away) to avoid the influence of the magnetic object (metal casings of the borehole).

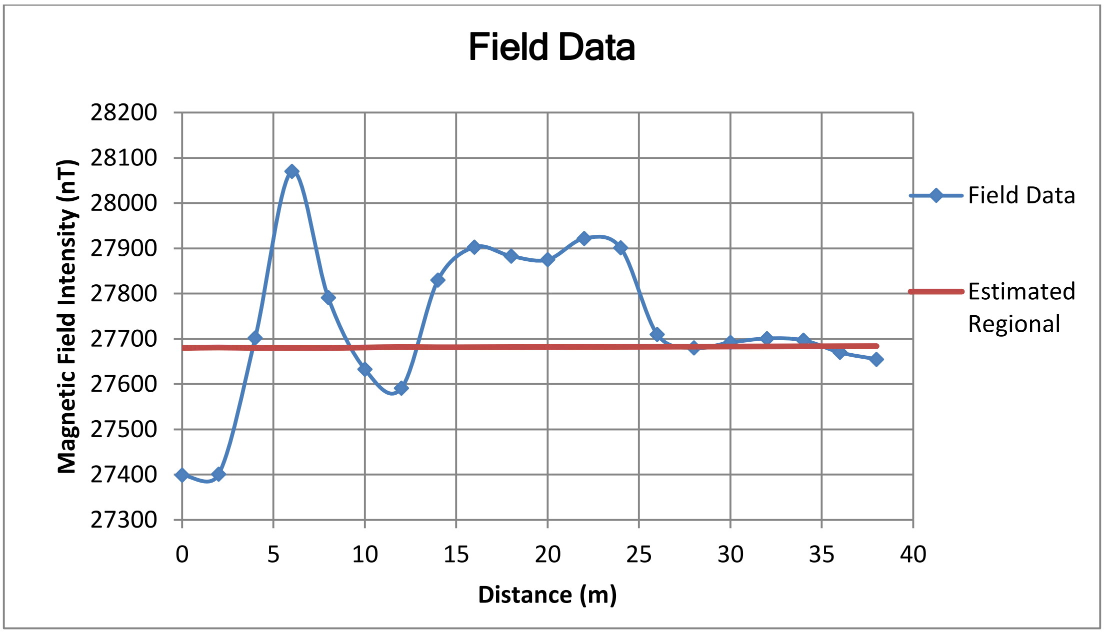


Figure 42: New magnetic survey profile for Traverse S-TV05, showing field data.

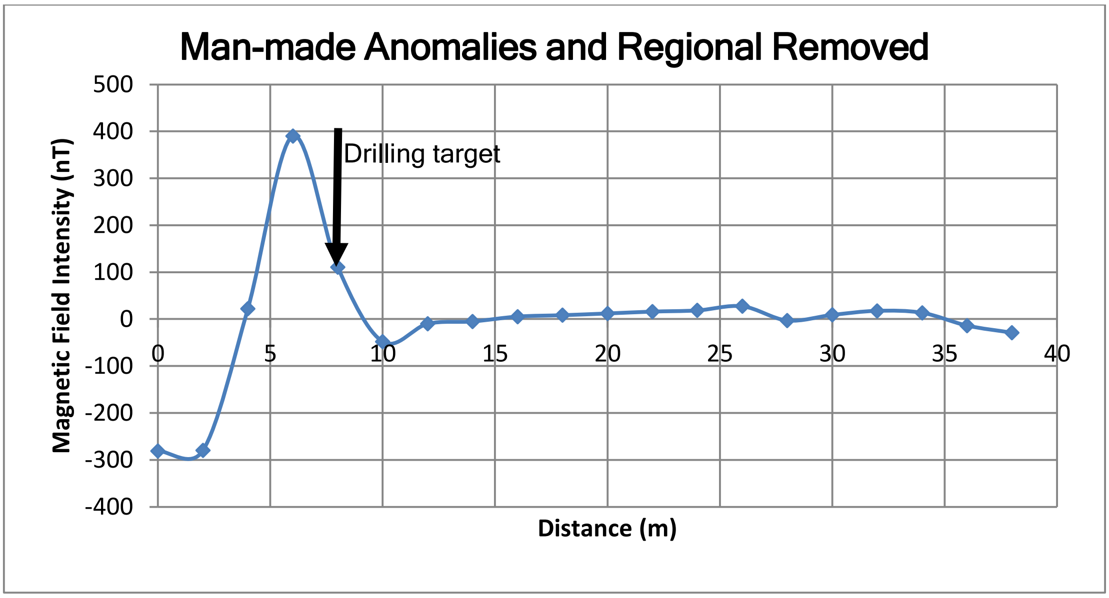


Figure 43: New magnetic survey profile for Traverse S-TV05, showing man-made anomalies after regional removal.

The new traverse profile (Figure 39 and Figure 40) is 38 m long from north to south. The magnetic field signature shows a steady increase from 2 m up to 6 m with amplitude of 380 nT; an immediate steady decrease from 6 m to12 m was observed; the segment (6-12 m) was accepted as the potential dolerite structure. The influence of the nearby fence which was noted from 14-20 m. Relative to the magnetic field intensity (1894 nT) of the anomaly recorded in Figure 38, the magnetic field intensity of 350 nT for the anomaly (Figure 40) was recorded. The centre of the dolerite intrusion was estimated at 4.5 m using the Logochev's method relative to the anomaly zero set at -150 nT and the edge of the dolerite intrusion was estimated at 8.0 m along the traverse (See Appendix 2). The depth of the dolerite intrusion was estimated at 3.9 m below ground surface using the horizontal slope distance method (See Appendix 2).

Traverse S-TV06

The magnetic survey (Figure 44) was 225 m long from southwest to north-east. Between 210-220 m the magnetic signature showed a significant anomaly with an amplitude of 104 nT at station 215 m. The significant anomaly at 215 m may be attributed to a discontinuous magnetic intrusion, which may be due to weathering or fracturing or faulting, thus can targeted as a preferential pathway for groundwater flow. One drilling target was sited at 210 m along the traverse line to explore the edges of the speculated discontinuous magnetic intrusion for subsequent drilling, namely DT-13, shown in Figure 45. The centre of the possible continuous magnetic intrusion was estimated at 216 m along the traverse using the Logochev's method, and the edge of the intrusion was estimated at 210 m, thus the drilling target selected at 210 m (See Appendix 2).

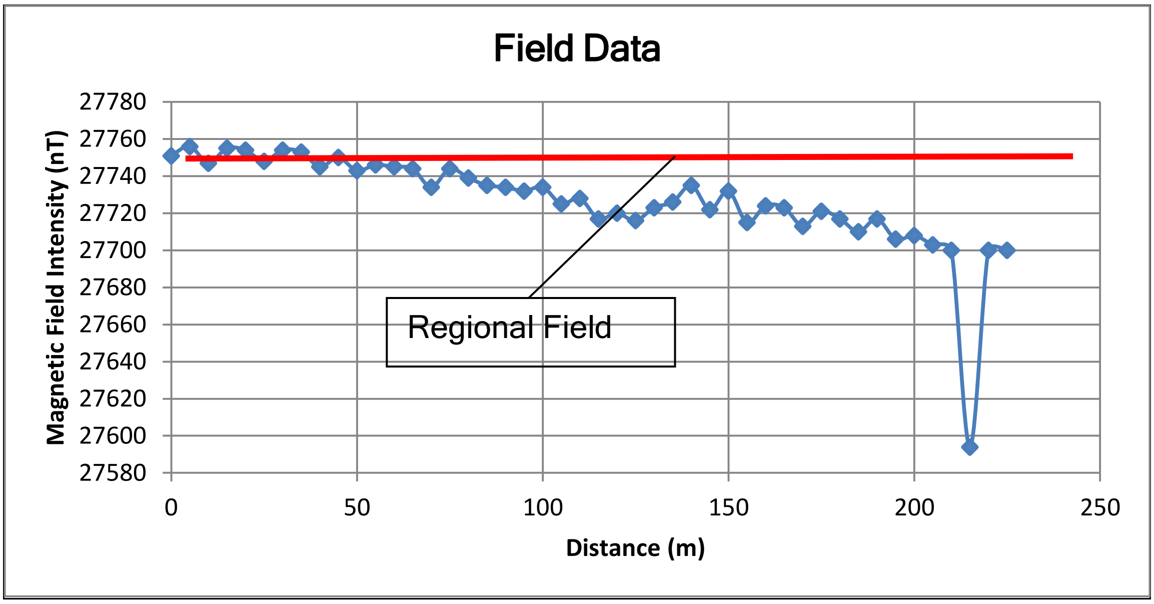


Figure 44: Traverse profile S-TV05, showing field data.

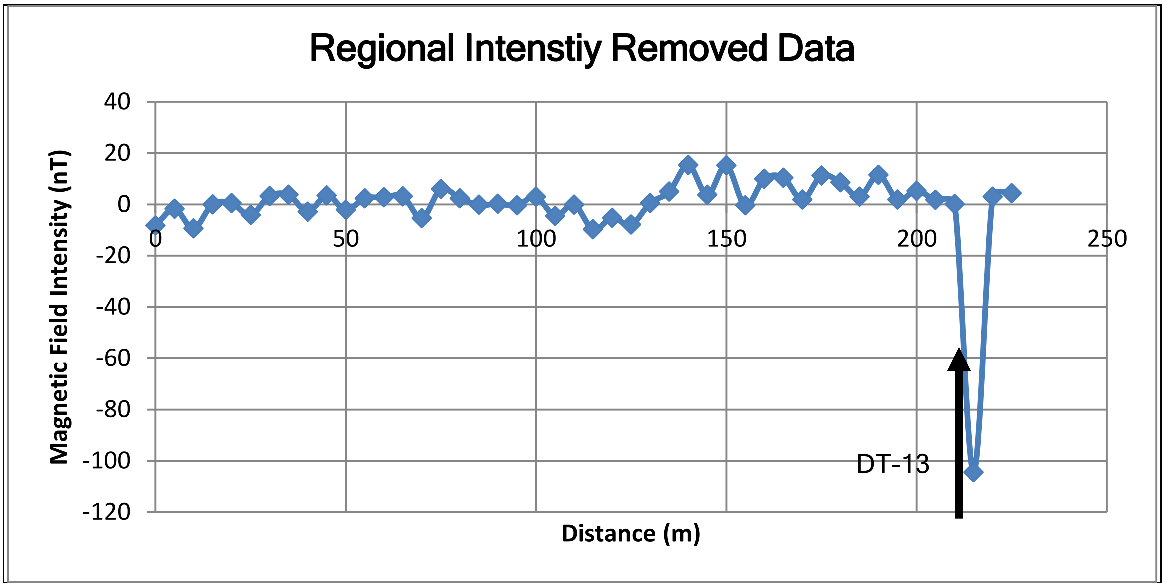


Figure 45: Traverse profile for S-TV06, showing regional intensity removed data.

The depth of the dolerite intrusion was estimated at 6.3 m below ground surface using the horizontal slope distance method (Appendix 2).

Traverse S-TV07

The traverse profile (Figure 46 and Figure 47) was 115 m long from south-west to north-east. The magnetic signature shows a significant negative anomaly of 969 nT between 100 and 115 m, this may be attributed to a discontinuous magnetic intrusion which could result due to weathering or fracturing or faulting; thus can be targeted for drilling as a preferential groundwater path. Noise effects recorded from 15-25 m can be attributed to the nearby fence which is located 6 m from the traverse line.

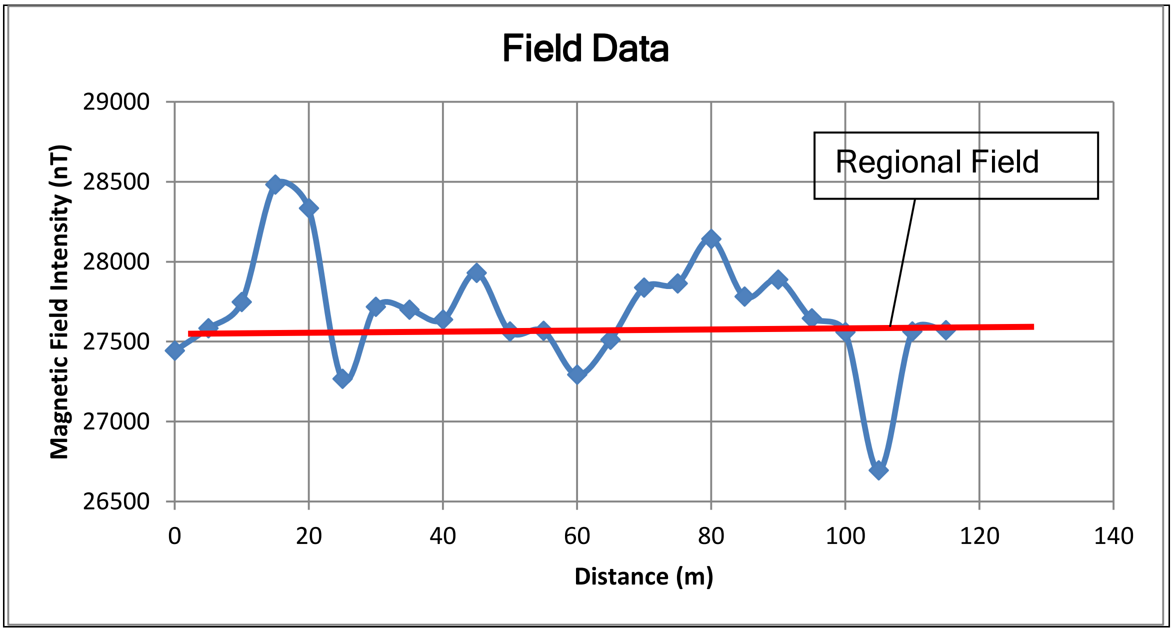


Figure 46: Traverse profile for S-TV07, showing field data.

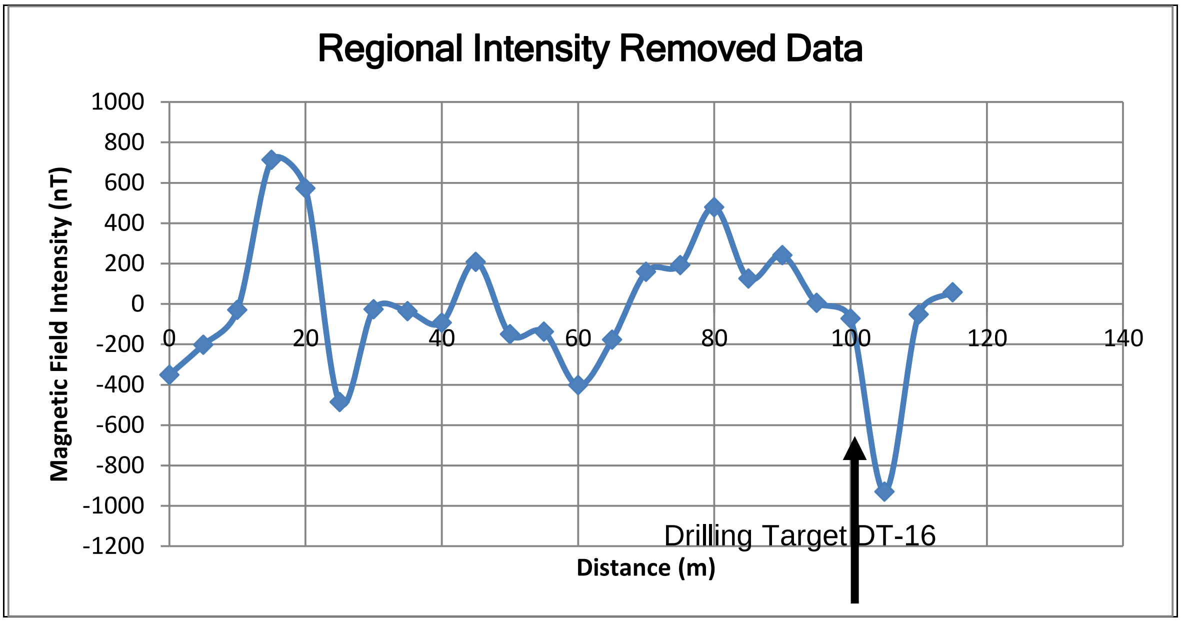


Figure 47: Traverse profile for S-TV07, showing the regional intensity removed data.

From the profile (Figure 46 and Figure 47) one drilling target was sited at 100 m along the traverse line, namely DT-16. The sited drilling target was aimed to explore the possible discontinuous magnetic intrusion. The justification of the position of the edges of the intrusion will be discussed below. The traverse was recorded until 115 m, no explanation was provided for stopping the survey at that distance. It is conceded that additional points would have given more information in justifying the sited drilling target.

Although a drilling target was sited; the magnetic field intensity of the anomaly was found to be very large (930 nT after the removal of the regional magnetic field intensity) to attribute it to an underlying magnetic geological structure.

A new magnetic survey (Figure 48 and Figure 49) was conducted to investigate and verify the large anomaly recorded in Figure 47. Due to the presence of a drilled borehole from the identified drilling target DT-16, the survey was not redone instead it was conducted adjacent to the original magnetic survey for Traverse S-TV07 (10 m away) to avoid the influence of the magnetic object (casings of the borehole). The new traverse profile (Figure 48 and Figure 49) is 135 m long from south-west to north-east. The magnetic field signature is generally gentle from 0-85 m with an exception of the influence of the near fence from 15-25 m; until a sharp decrease from 85-105 m is observed, and an increase is also observed from 105-120 m (Figure 48). The segment from 85-120 m can be regarded as the discontinuous zone of the possible magnetic intrusion with magnitude of -267 nT after the removal of regional magnetic field intensity. Relative to the amplitude for magnetic anomaly of -930 nT recorded in Figure 47, the amplitude for the magnetic anomaly of -267 nT was recorded f in Figure 49.

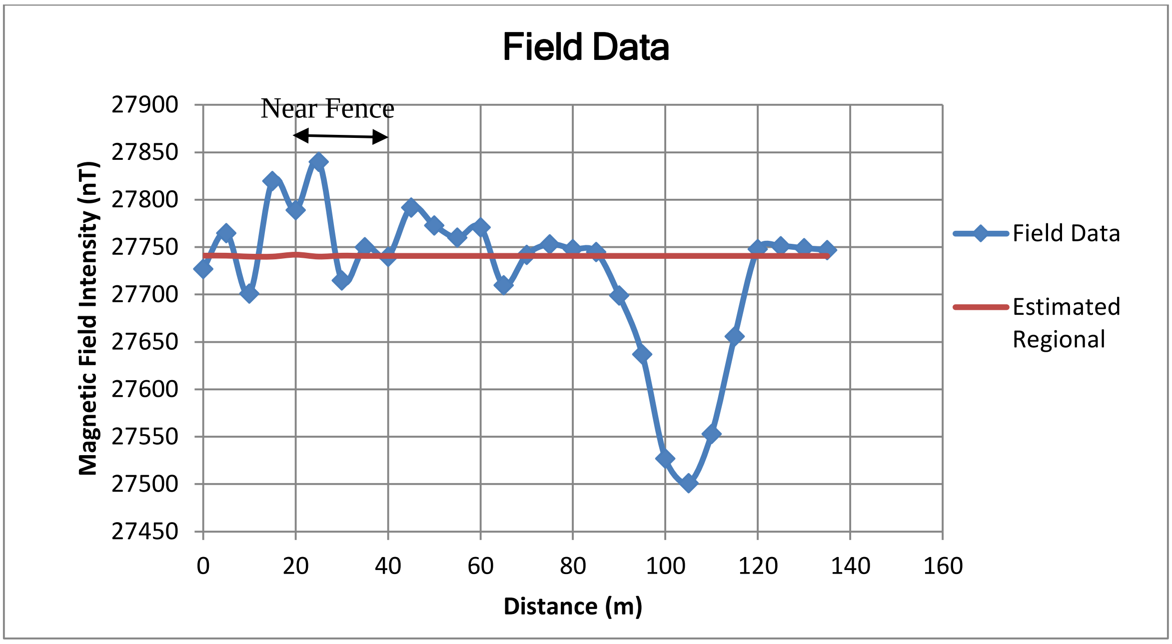


Figure 48: New magnetic survey profile for Traverse Profile S-TV07, showing field data.

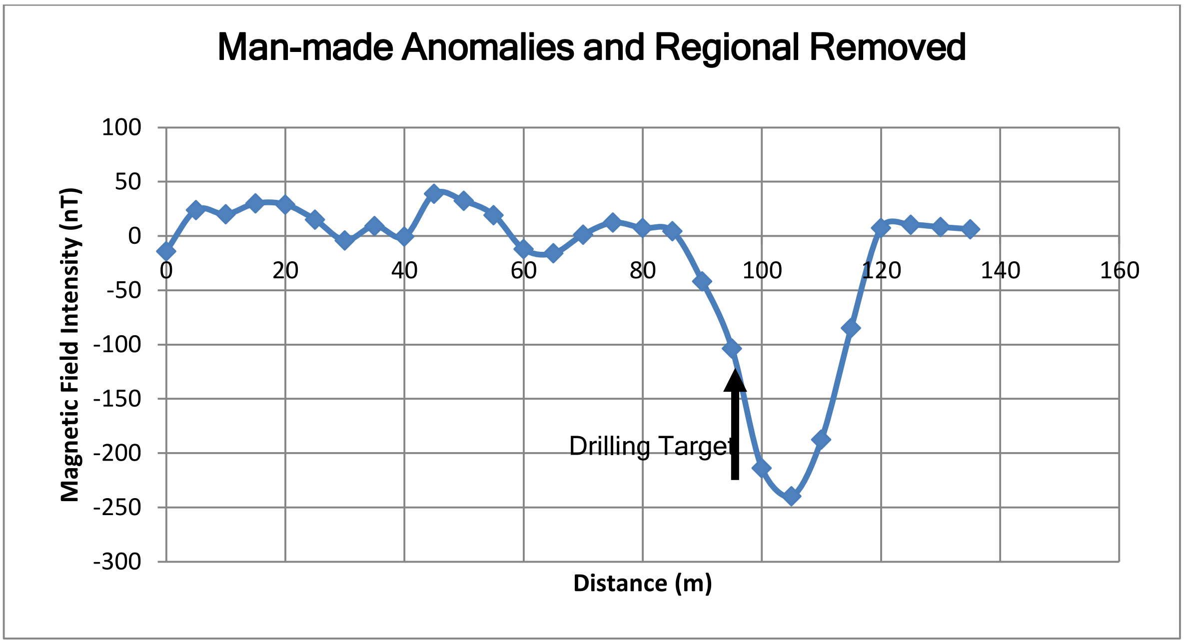


Figure 49: New magnetic survey profile for Traverse Profile S-TV07, showing man-made anomalies after regional removal.

The centre of the possible magnetic intrusion was estimated (using the Logochev's method) at 100 m along the traverse; relative to the anomaly zero, and the edges of the underlying discontinuous intrusion at 104 m (See Appendix 2). A drilling target could have been sited at 104 m to target the edges of the identified discontinuous intrusion from 85-120 m. The depth of the dolerite intrusion was estimated (using horizontal slope distance method) at 13 m below ground surface (See Appendix 2).

Traverse S-TV08

The traverse profile (Figure 50 and Figure 51) is 140 m long from south-west to northeast, between 90-105 m the magnetic signature shows a significant positive anomaly. This may indicate the presence of a highly magnetic geological body such as a dolerite intrusion in the area which can be explored for drilling. From the profile (Figure 51) one drilling target was sited at 97 m along the traverse line, namely DT-17. The drilling target was sited to explore the edges of the possible dolerite intrusion. The centre of the identified dolerite intrusion was estimated at 107 m using the Logochev's method relative to the anomaly zero, and the edges of the possible dolerite intrusion was estimated at 97 m along the traverse; thus the drilling target selected (See Appendix 2). The depth of the dolerite intrusion was estimated at 19.2 m using the horizontal slope distance method (Appendix 2).

Although a drilling target was sited at 97 m on a possible thin dolerite dyke, the end of the magnetic survey at 140 m was not explained, the survey could have been continued to record more points further (Figure 50 and Figure 51). This could have provided more information and justification of the segment. . From evaluation of the magnetic data; the magnetic survey for this traverse should have been redone; however, the owner of the farm did not permit access.

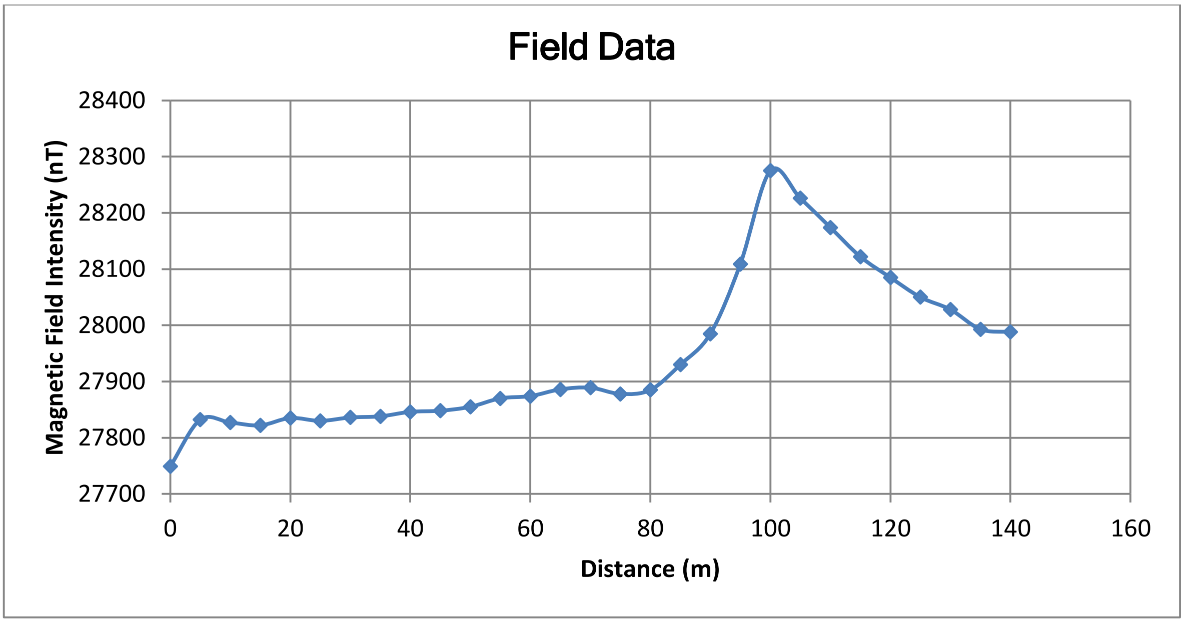


Figure 50: Traverse profile for S-TV08, showing field data.

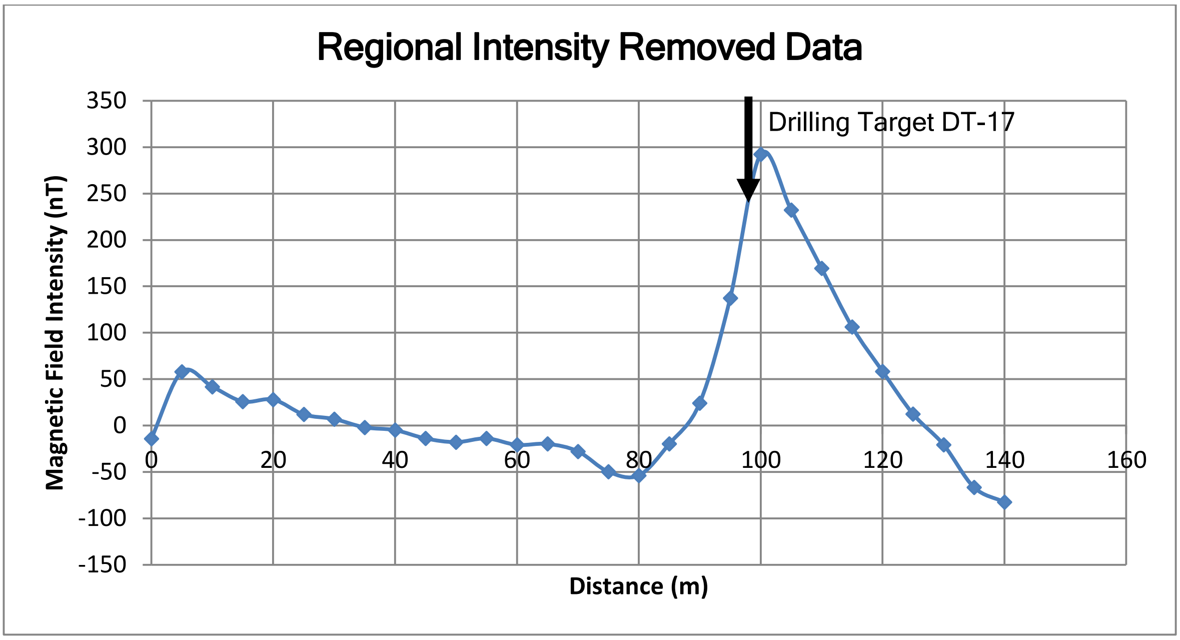


Figure 51: Traverse profile for S-TV08, showing the regional intensity removed data..

Additional Discussion

The Standard Anomaly Curves in the South African Geophysics Association (SAGA) Manual by Roux (1980) have been widely acknowledged as a robust method for interpreting magnetic anomaly data. The approach considers the anomaly to be caused by a relatively magnetic source in order to determine their average depth or length and dipping angle. One of the magnetic data (for Traverse S-TV07) above was smoothed by removing and correcting any suspected points. The correction of data can be quite a skilful operation; thus it is based on the experience. The purpose of correcting the suspect data is to eliminate possible contributions cultural effects such as the fence, wire, car, and borehole casing can have in the recorded data and most importantly to remove the regional magnetic field intensity for simple interpretation.

Generally, the above magnetic anomaly data with noted exceptions were found to have very high magnetic field intensity and the shape of the anomalies were difficult to interpret using the standard anomaly curve by Roux (1980). In previous studies that were conducted in Steynsrus, Gombar (1977) showed the expected shape of the anomalies and the range of the magnetic field intensities of the underlying structures, i.e. dolerite intrusions. The expected magnetic field intensity of the anomalies ranges from 50 to 400 nT; this range was accepted as the typical magnetic field intensity of highly magnetic underlying bodies in the area with exceptions noted above. Consequently, the magnetic field intensity of the anomalies in the study ranged between 400 and 2500 nT, except for the noted anomalies. However, bearing in mind the extent of the underlying magnetic bodies, the utilisation of such a very large magnetic field intensity of the anomalies may be a fundamental error in the application of standard anomaly curves and other interpretations intended for drilling exploration. Although there could be errors in the data, the positions of the expected anomalies would not change; hence it was decided this justifies the selection of the drilling targets which were sited based on this data. The new magnetic surveys for some of the above traverses were done to verify and compare with the magnetic data used for the drilling in the project.

The critical evaluation of the magnetic data and the ensuing interpretations aim to clarify and point out possible errors regarding the data. This would tremendously assist researchers and the Moqhaka Local Municipality (LM) in appropriate magnetic data interpretation using known standards and also data of an acceptable quality from consultants that conduct such exercises for the LM in the future. The magnetic data may have had errors, but it is important to further highlight that the positions of the anomalies and effectively the inferred position of the dolerite structures (identified in remote sensing) would not change.

5.3 SUMMARY

Chapter 5 provides the relevant details on the geophysics; in particular there is a focus on the magnetic method which was conducted for locating the drilling targets by the external consultant and also the surveys conducted to further evaluate and compare the previously conducted surveys from which drilling targets were sited. The geophysics survey identified seven drilling targets with alternative targets identified on the newly conducted traverses (see Appendix 2). Table 7 lists exploration sites; however the targets were not named in any priority order; these targets are inclusive of the sites identified for drilling only. The drilling targets and their justifications were based on the explanations ensuing from the magnetic data that were discussed. It should be noted that the negative anomalies were recorded as the vertical intensity parallel the magnetic bodies identified in remote sensing, thus negative anomalies were deduced; thus the negative anomaly is displaced from the recorded magnetic data.

There are always implications in siting of drilling targets using geophysics profiles. A successfully drilled borehole depends on the distances; angle and depth the field expert would have deduced following the interpretation of the traverse profile, on consideration of the knowledge of the geology outside the information generally known, and most importantly the experience of the operator and interpreter.

Table 7: Summary of geophysics data and selected sites

Traverse Line	Target	Station (m)	Longitude (°)	Latitude (°)	Comments
S-TV01	DT-01	80	27.57493	-27.9396	Negative anomaly, Sited to target the possible discontinuous magnetic intrusion.
S-TV02	DT-02	55	27.57351	-27.9411	Negative anomaly, Sited to target the possible discontinuous magnetic intrusion.
S-TV03	DT-03	33	27.5689	-27.943	Negative anomaly, Sited to target the possible discontinuous magnetic intrusion.
S-TV05	DT-04	13	27.55374	-27.9503	Positive anomaly, Edges of the possible dolerite intrusion were targeted.
S-TV06	DT-13	210	27.53347	-27.9301	Negative anomaly, Sited to target the possible discontinuous magnetic intrusion.
S-TV07	DT-16	96	27.53429	-27.9399	Negative anomaly, Sited to target the possible discontinuous magnetic intrusion.
S-TV08	DT-17	97	27.55744	-27.9874	Positive anomaly, Edges of the possible dolerite intrusion were targeted.

Although drilling targets are prescribed based upon expert guesses and interpretation; unsuccessful drilled boreholes could be drilled. The audience must understand that an expert opinion though it is based on experience and knowledge of the science may yield unsuccessful drilled boreholes due to the complex and unpredictable nature of groundwater science. The next Chapter gives the description of the geology of based on the drilling results obtained.

CHAPTER 6 DRILLING AND GEOLOGICAL CHARACTERISATION

6.1 INTRODUCTION

Drilling was conducted to further explore the detected and observed magnetic anomalies. Percussion drilling method was utilised to drill the boreholes for water supply. From the information obtained about the geology (soil type, lithology, rock types, etc.), geological characterisation of the area was done. The following sections will take the reader through the method of drilling that was used, the drill cuttings which were evaluated using geological knowledge, followed by a brief discussion of the drilled boreholes.

6.2 PERCUSSION DRILLING

Percussion drilling is the most economical and frequently used method of drilling for groundwater, especially into hard rock and semi-consolidated formations (Woodford and Chevallier, 2002). This drilling process produces drill cuttings that are removed from the borehole via the annulus between the drill-stem and the wall of the hole by circulating air at high pressure. Geological logging of the borehole can be conducted from the cuttings. Although percussion drilling avails the cuttings, the cuttings are not as easy to interpret like the core logs produced through a core drilling method. The latter method is often used in mines and it is more expensive. The other advantage of using this method is that the water is blown to the surface as soon as a water-bearing zone is encountered. This can provide an indication of the available supply; referred to as the blow-yield; however this can provide only the cumulative indication the yield from an individual fracture during drilling. The drilled boreholes were intended to be used for production for a town water supply.

Seventeen (17) new boreholes intended for production were drilled in the study area, of which seven (7) were drilled based on the geophysical interpretation as explained in Chapter 5, and ten (10) boreholes were drilled based on geological observation and map interpretation without geophysical surveys as explained in Chapter 4. The positions of all the newly drilled boreholes are shown in Figure 52. The water strikes were recorded for all drilled boreholes. The deepest drilled borehole was 118.38 m deep, and the shallowest of the drilled boreholes was 56.81 m. Twelve (12) showed low blow yields of <1.00 L/s and/or were found to be dry boreholes (Table 8); these boreholes were declared unsuccessful and were not pump tested for sustainable yield.

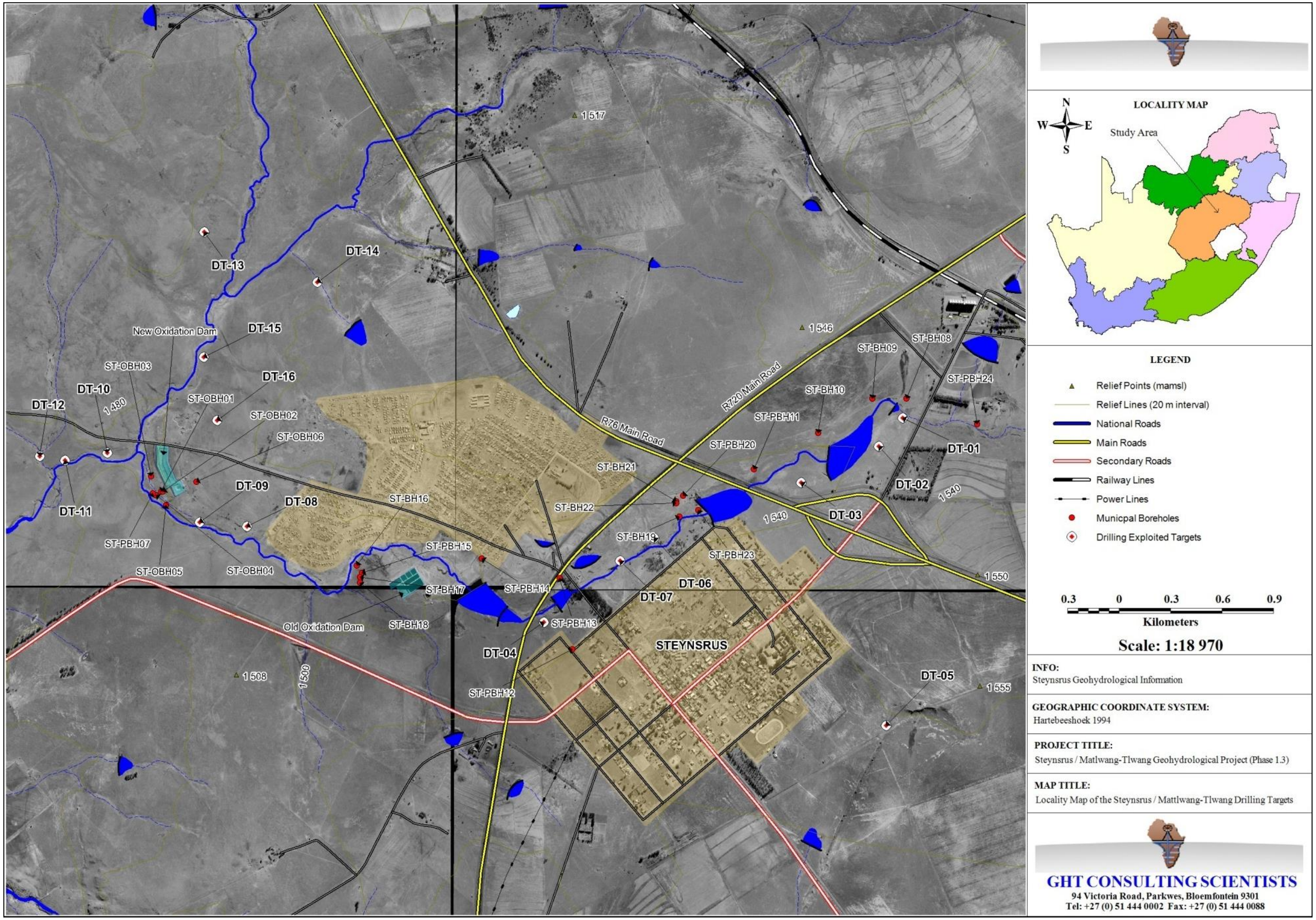


Figure 52: Map showing drilling targets sited and existing boreholes in the study area, (Hough and Rudolf, 2013).

6.2.1 Lithology

The general lithology obtained from the borehole drilling in the study area consisted mainly of layers of alternating or predominant sandstone and/or shale below the upper soil profile (see Figures 53 to 57), which are typical Karoo Supergroup attributes. The dolerite dyke and sill intrusions were intercepted in all the boreholes. Dolerite intrusions, particularly the dykes, are one of the more important targets for high-yielding boreholes in the Karoo rocks (Woodford and Chevallier, 2002), may host sedimentary deposit contact zones which act as preferential flow paths for groundwater. Therefore geological logs were recorded for most of the boreholes as the drilling progressed. The water strikes were recorded with the subsequent blow yields as the drilling progressed (see Table 8). It is important to correlate the observed water strikes, water levels, blow yields and the geological logs with aquifer behaviour which will be determined from aquifer pump testing data.

Boreholes drilled at sited drilling targets DT-03, DT-06, DT-07, DT-14 and DT-17 were estimated to have blow yields greater than 1.00 L/s during drilling. Hence these newly drilled boreholes with a recorded blow yield greater than 1.00 L/s (DT-03, DT-06, DT-07, DT-14 and DT-17), were recommended for aquifer pump testing. In cases where the newly drilled boreholes showed blow yields greater than 1.00 L/s during drilling, certain possibilities were suggested such as a high-yielding dolerite fracture being intersected or a bedding plane fracture in existence at a sandstone and/or shale contact area. It should be noted that the magnetic data available were for DT03 and DT-17 as presented in the previous chapter, and magnetic data were unavailable for DT-06, DT-07, and DT-14; as the latter were drilled based on only geological observation and remote sensing. There may be many factors that affect the measured blow yields determined during drilling, such as the capacity of the compressor depth of the water strike below the water level, the annulus between the drill stem and wall of the hole, emplacement of casing and screens, and fracture permeability (Woodford and Chevallier, 2002). For instance, the emplacement of casing during drilling may inhibit the yield that could be estimated from possible fractures unless the casing is perforated along the water strikes observed. Blow yields provide good information about the potential yield of the borehole and consequently the local aquifer, but the measurement must be treated as a guide only. Below the geological logs of the drilled boreholes will be discussed.

DT-03 Geological logs

Figure 53 shows the geological logs, water strikes with depth and respective blow yields of DT-03. DT-03 geological logs show shale and dolerite intrusion contact area at about 58 mbgl and 87 mbgl. Sedimentary deposit contact areas are important in that they can host bedding plane fractures that can act as preferential pathways for groundwater flow (Gomo, 2009). Sandstone and shale contact areas associated with water strikes are observed at 21 and 48 mbgl; with blow yields of 0.31 and 0.23 L/s, respectively. In total there were four water strikes intersected during the drilling at 21, 48, 52 and 85 mbgl. Considering that the subsequent borehole DT-03 drilled was sited on the basis of a magnetic data (Figure 32 and Figure 33) deduced to be 'bad data', a cumulative blow yield of 4.30 L/s makes it difficult to arrive at any conclusive explanations with regards to the result of such a yielding borehole. However, it should be noted that the edges of the discontinuous geological intrusion were targeted; and were intersected as shown in the geological logs (Figure 53). The alternating layers of dolerite intrusion and shale formation may be an error in recording the geological logs. At the time of analysing the data; the actual geological drill cuttings were not available to verify this phenomenon. The evidence is provided in the preceding Chapter 5 in Figure 32 and Figure 33, the depth and the edges of the dolerite was estimated at 51 m below ground surface and 125 m along the Traverse line. The dolerite intrusion upon drilling was intersected at 54 m; a comparable depth to the 51 estimated using horizontal distance method.

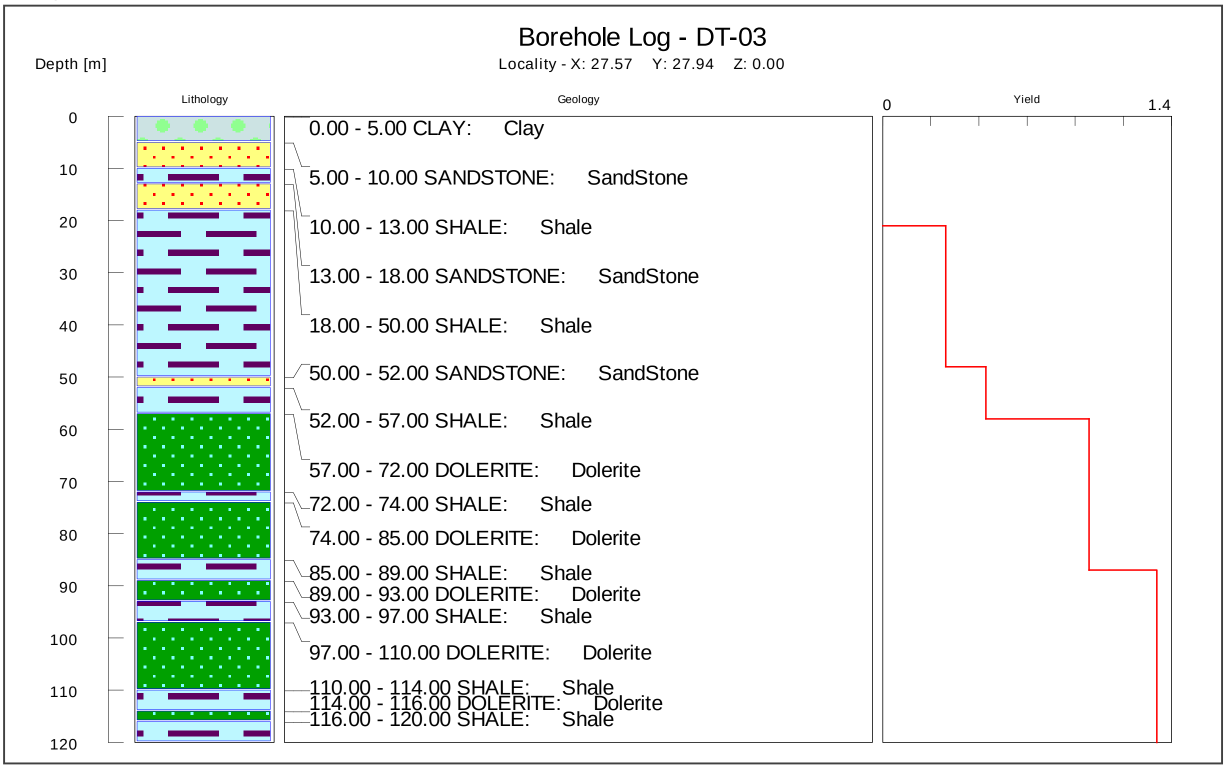


Figure 53: Descriptive borehole geological logs for Target DT-03 shown in depth below ground level and the respective blow yields in L/s.

Although the borehole was drilled upon the erroneous magnetic data as explained in Chapter 5, the main structural body for groundwater dolerite intrusion was still detected during drilling. The amount of the accumulated blow yield measured is attributed to formation contact areas and the dolerite intrusion fractures which can be seen above (Figure 53).

DT-06 Geological logs

Figure 54 shows geological logs of DT-06, which is a drilled borehole based on the geological observation and map interpretation as explained in Chapter 4. The geological logs (Figure 54) for DT-06 show alternating layers of shale and sandstone sedimentary rocks. The main water strike of DT-06 is located along the shale formation at 40 mbgl with a blow yield of 1.00 L/s. The sandstone and dolerite intrusion contact area was also intersected at 18 mbgl as shown in Figure 54, with a blow yield of 0.5 L/s. A cumulative blow yield of 1.5 L/s (Figure 54) was measured suggesting the possibility of a high-yielding fractures being intersected along the dolerite intrusion and the shale formation. The cumulative blow yield from the graph (Figure 54) was calculated by adding all the blow yields for the respective water strikes encountered.

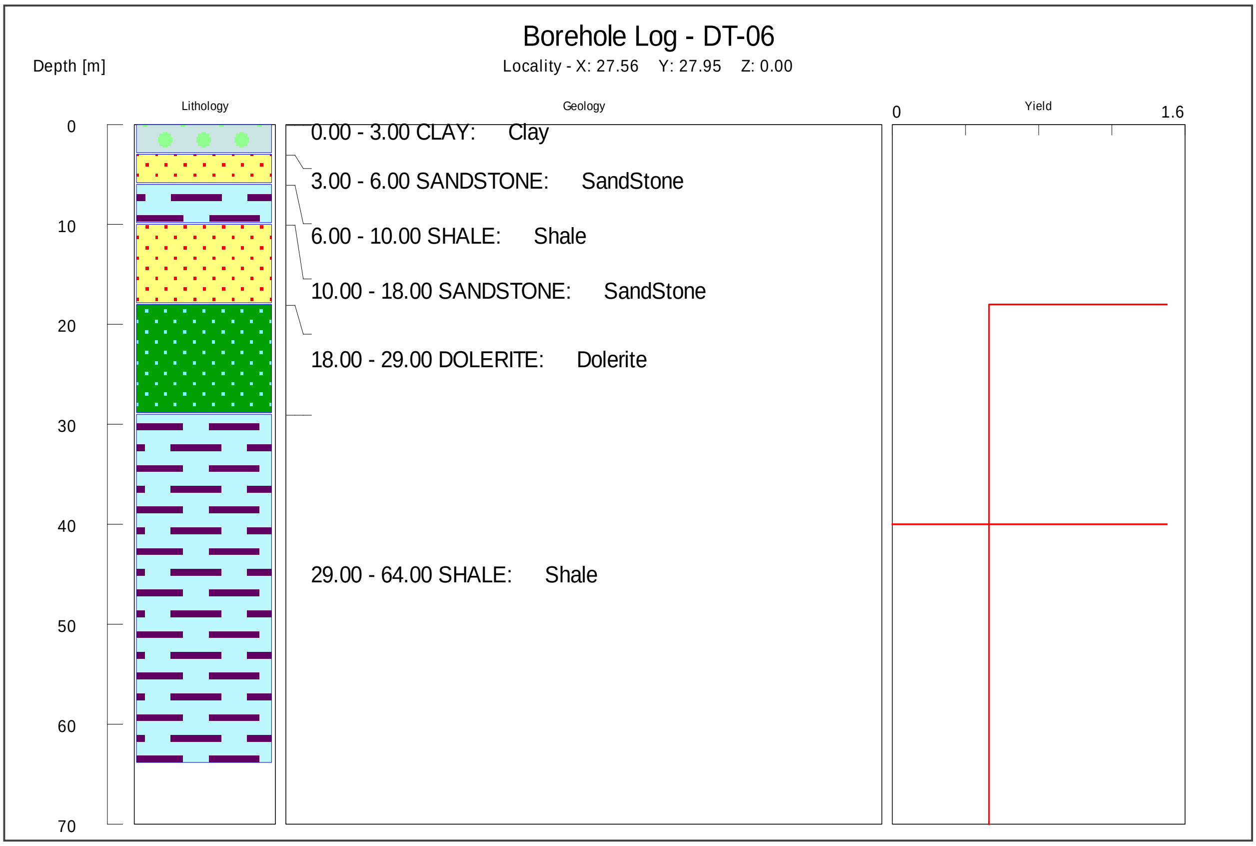


Figure 54: Descriptive borehole geological logs for target DT-06 shown in depth below ground level and the respective blow yields in L/s.

DT-07 Geological logs

The geological logs of the borehole target DT-07 is shown in Figure 55, the borehole was drilled based on the geological observation and map interpretation as explained in Chapter 4. The geological logs for DT-07 (Figure 55) shows predominant alternating layers of shale and sandstone with a thin dolerite intrusion intersected. The geological logs (Figure 55) also shows the water strikes which are located close to the shale and sandstone contact area with the sandstone and dolerite intrusion at about 11 mbgl and 34 mbgl, respectively.

A cumulative blow yield of 5.5 L/s (Figure 55) was measured suggesting the possibility of a high-yielding fracture being intersected along the shale and sandstone contact area (11 mbgl) and the shale and dolerite intrusion contact area (34 mbgl).

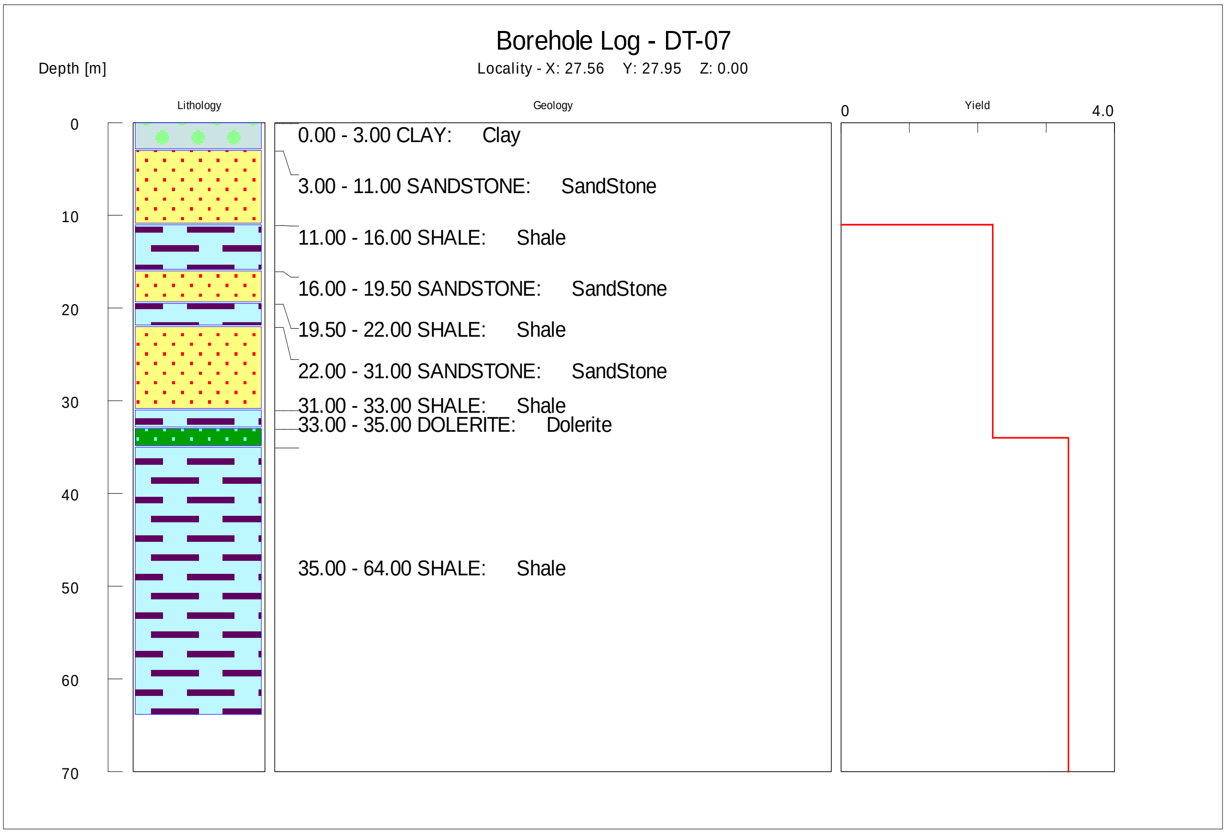


Figure 55: Descriptive borehole geological logs for target DT-07 shown in depth below ground level and the respective blow yields in L/s.

DT-14 Geological logs

Figure 56 shows geological logs of DT-14, the drilled borehole was based on geological observation and map interpretation as explained in Chapter 4. The geological logs for DT-14 is typical of the sedimentary deposits - shale and sandstone - of the Karoo Main Basin. Figure 53 also shows the water strikes at 29 and 38 mbgl on the sandstone contact area;

with the respective yields indicated. The cumulative blow yield of the borehole of 1.9 L/s (Figure 55=6) was measured, the main water strike intersected at 38 mbgl measured a blow yield of 1.7 L/s. The measured blow yield suggested the possibility of high-yielding fractures being intersected along the sandstone and shale contact areas.

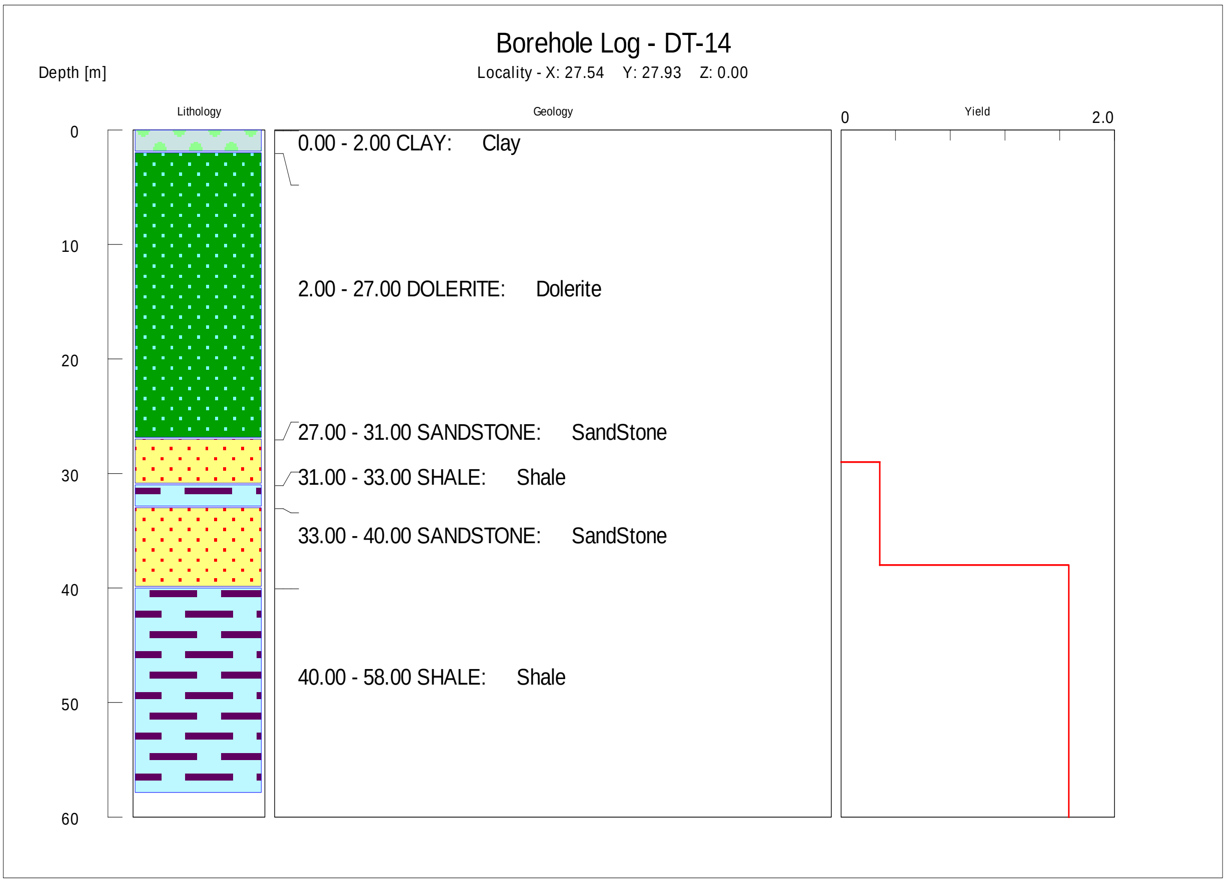


Figure 56: Descriptive borehole geological logs for target DT-14 shown in depth below ground level and the respective blow yields in L/s.

DT-17 Geological logs

Figure 57 shows geological logs of DT-17, the borehole was drilled based on the geophysical survey and interpretation. The geological logs show a very thin sandstone deposit and a predominant dolerite intrusion. From the geophysics data interpretation (Figure 50 and Figure 50) used the edges of the dolerite intrusion were targeted, the targeted dolerite intrusion was estimated at a depth of 19.20 m. The dolerite intrusion was intersected at 12 m, this is not comparable to the estimated 19.20 m based on the horizontal distance method (HSM). The lack of comparison of the actual depth at which the dolerite intrusion was intersected with the estimated depth based on HSM can be attributed to the erratic measurements which were highlighted. The geophysics data used for drilling DT-17 was regarded as ‘suspect data’ according to guidelines of Roux (1980) for recording of magnetic data. Figure 57 also shows the main water strike at about 36 mbgl associated with the dolerite intrusion, and another water strike is indicated at 19 mbgl. The cumulative blow yield of 24 L/s was measured, the main water strike intersected at 36 mbgl with a blow yield of 20 L/s (Figure 57). The measured blow yield suggested the possibility of very high-yielding fractures being intersected along the dolerite intrusion.

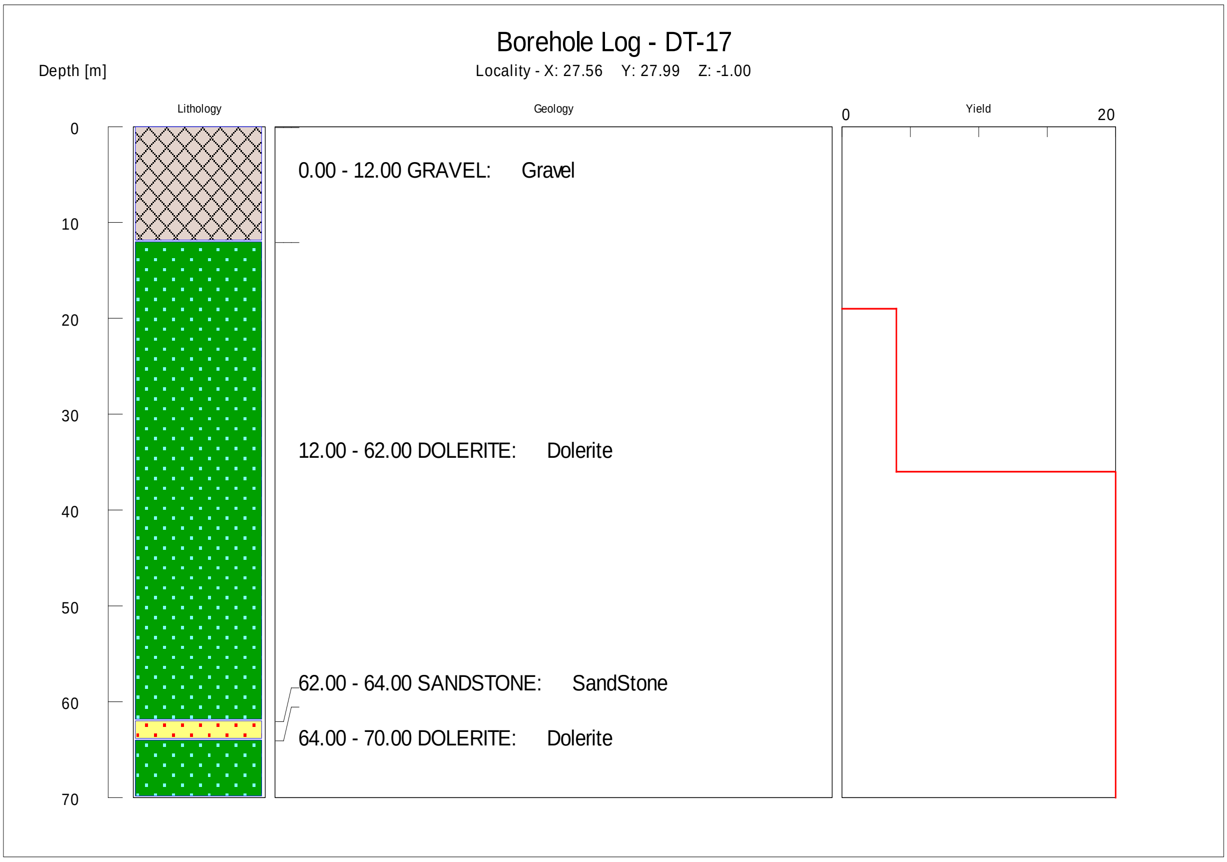


Figure 57: Descriptive borehole geological logs for target DT-17 shown in depth below ground level and the respective blow yields in L/s.

6.2.2 Unsuccessfully Drilled Boreholes

There were also unsuccessfully drilled boreholes which were sited via geophysics and based on geological observations. These boreholes were deemed 'unsuccessful' due to the insufficient blow yields (<1.00 L/s) (see Table 8) which were measured. Hence these boreholes were not considered for aquifer pump testing. Borehole drilling relies on the scientific predictions based on the knowledge of the area, geology, and analysis of the geophysical data if any.

Of particular interest among the unsuccessfully drilled boreholes are those which were sited through a geophysics surveys, the geological logs are shown in Appendix 3. In the previous chapter, the magnetic data that were used for drilling of some of the boreholes in the study were explained. However, other than for the few exceptions mentioned, these were generally found to be 'bad data' in terms of guidelines by Roux (1980) as was explained in Chapter 5. Drilling exercises rely on the predetermined sites to be explored upon the geophysics or geological interpretation of the area, the functioning of the machinery and the experience in the field. This suggests that there may be various explanations of drilling 'unsuccessful' boreholes; in this study some of the explanations may include dried aquifers due to over abstraction in the area (Dry Borehole ST-PBH25 reported to DWA (2012), generally low-yielding area as had been assessed in DWAF (2003), poor geological and/or geophysical interpretation and poor borehole siting. For the purpose of the argument of the quality of the magnetic data used to drill some of the boreholes in this study, one could suggest that the unsuccessfully drilled boreholes may be due to the error data and incorrect interpretation. The geological logs of DT-01, DT-02, DT-04 and DT-16 (Appendix 3) showed typical sedimentary deposits with the dolerite intrusion intersected. As it was explained in the previous chapter, the magnetic data used was found to be erroneous; the position of the anomalies and effectively the position of the dolerite intrusion would not change. This can explain the correct drilling through the dolerite intrusion. It was suggested that the boreholes may have been correctly drilled into and/or through the dolerite intrusion. However, the positioning of the drilling targets from the erroneous magnetic data may have affected the success of the drilled boreholes. An exception was realised on the DT-13 percussion geological logs (Appendix 3), the target was intended to drill through the edges of a possible dolerite intrusion.

Table 8: Drilled unsuccessful boreholes in the study area

Name	Latitude (°)	Longitude (°)	Cumulative Blow Yields (L/s)
DT-01	-27.93957	27.57493	0.44
DT-02	-27.94108	27.57351	0.01
DT-04	-27.95032	27.55374	0.17
DT-05	-27.95564	27.57404	0.08
DT-08	-27.94537	27.53612	0.01
DT-09	-27.94519	27.53333	0.01
DT-10	-27.94156	27.52776	0.01
DT-11	-27.94156	27.52535	0.80
DT-12	-27.94203	27.52379	0.08
DT-13	-27.94183	27.53347	0.01
DT-15	-27.79327	27.53347	0.17
DT-16	-27.93988	27.53429	0.01

According to the DT-13 geological logs (Appendix 3), the dolerite intrusion which was predicted was missed completely; this can further support the erroneous magnetic data and interpretation.

6.3 SUMMARY

Chapter 6 gives detailed descriptions of the drilling and geology of the boreholes. Percussion drilling of seventeen (17) boreholes was conducted of which only seven had magnetic data available, all of the boreholes are located within 20 Km of the town Steynsrus. The drilling was carried out on the prescribed drilling targets from the geophysics and geological siting. The deepest drilled borehole was 118.38 m deep, and the shallowest of the drilled boreholes was 56.81 m. As the drilling progressed, drill cuttings were made available for interpretation and geological logging, this allowed further knowledge of the geology of the borehole. The respective blow yields and water strikes were also recorded as the drilling progressed. The estimated blow yields were used to indicate the potential yield from the fractures encountered.

There were twelve borehole drilled which showed very low blow yields (<1.00 L/s), these boreholes were declared 'unsuccessful' based on the guideline used by DWAF (2003a) for considering boreholes for aquifer test pumping for water supply and were not subjected to sustainable yields for town water supply. The cumulative blow yields of the 'unsuccessful' drilled boreholes ranged from 0.01 to 0.80 L/s. The general lithology from the geological logs consists mainly of layers of alternating or predominant sandstone and/or shale formations below the upper soil profile. The dolerite intrusions were intercepted in all the boreholes. The next Chapter will give pump testing details of the four successfully drilled boreholes (DT-06, DT-07, DT-14 and DT-17, with exclusion of DT-03) and the estimation of the aquifer parameters in the study area based on the respective pump testing data.

CHAPTER 7 PUMP TESTING AND AQUIFER PARAMETERS

7.1 INTRODUCTION

Aquifer pump testing has been described by Kruseman and De Ridder (1994) as the simplest approach for an understanding of the physical behaviour of the aquifers and for determining the aquifer parameters. Information and details from the geological descriptions in chapter 6 were used to correlate the physical behaviour of the aquifer.

The key objective in the study was to determine the sustainable yield of the boreholes in the area through pump testing. However, the pump testing data was also used to determine other aquifer parameters such as the storativity and transmissivity values of the aquifers. The following Guidelines by van Tonder *et al.* (2002) were used to conduct the constant discharge tests:

- Choosing of pump size with high discharge rate.
- Calibration test.
- Determining length of constant discharge test.
- Measuring of drawdown during the pumping period.
- Measuring of recovery upon stopping the pumping.
- Identifying any errors or events during the constant test.

7.2 AQUIFER TESTING

7.2.1 Blow Yields

Blow yields' information was not available for most of the existing boreholes. Of the seventeen drilled boreholes in the area, only five boreholes with measured blow yields greater than 1.0 L/s were identified during the drilling. Table 9 (see below) shows the recorded blow yields of the five boreholes. In DWAF (2003a), blow yields greater than 1.0 L/s were considered as the threshold for assessing whether it is feasible and warranted to perform other tests such as constant discharge on the borehole.

Table 9: List of boreholes with blow yields above 1.0 L/s and the respective depth of the main water strikes

Borehole name	Latitude (°)	Longitude (°)	Borehole depth (m)	Cumulative blow yields (L/s)	Main water strike (mbgl)
DT-03	-27.943	27.5689	121	4.3	87
DT-06	-27.946	27.5602	64	1.5	40
DT-07	-27.947	27.5582	64	5.5	34
DT-14	-27.93	27.5402	58	1.9	39
DT-17	-27.987	27.5574	70	24	37

From the successfully drilled boreholes, the blow yields ranged from 1.5 to 24 L/s, and the main water strikes ranged from 34-87 mbgl.

7.2.2 Step Discharge Test

Sixty minutes step discharge tests were performed on 20 boreholes (including the existing boreholes and the newly drilled boreholes) for up to four steps as per requirement for an exploration and town water supply boreholes (DWAF, 1997). The four-step discharge tests over time were conducted to determine the proper discharge rate for a subsequent aquifer test referred to as the constant discharge test. The yield used for constant discharge testing is determined from the step discharge test by establishing the most stabilised (flattening) slope of the four steps. The most stabilised slope of the four steps is regarded as the rate that can be used stress the borehole while not depleting or collapsing the preferential pathways of the aquifer such as fractures.

From the step discharge test (Figure 58) for borehole DT-06, well stabilised flow conditions can be observed during the first and second step tests at 10-60 and 127-180 minutes; respectively. The pumping rate during those periods ranged between 0.79-1.04 L/s and 2.02-2.22 L/s; respectively for first and second step tests (Figure 58). The subsequent constant discharge rate used for this borehole was 2.22 L/s. Although the first step test rate of 1.04 L/s could have been used; the second step test rate was preferred as to enable full stressing of the aquifer. Other step discharge tests for the other boreholes were analysed using the same interpretation as the test for DT-06 to determine the constant discharge rate used, the relevant step discharge test graphs for other boreholes (i.e. DT-03, DT-07, DT-14 and DT-17) are shown in Appendix 4.

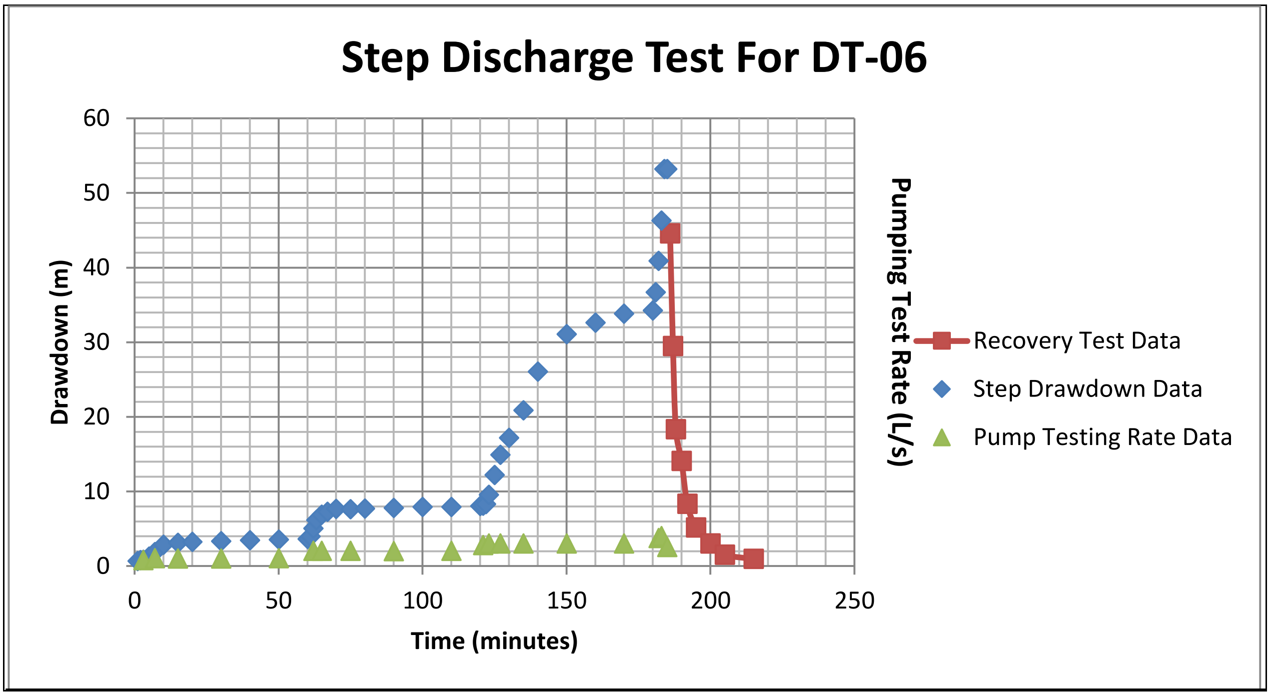


Figure 58: Graph showing drawdown behaviour through step discharge tests for borehole DT-06.

7.2.3 Constant Discharge Test

Constant discharge rate testing was conducted to estimate sustainable yields of the boreholes in Steynsrus for a town water supply. The data obtained from the pump testing were used to also estimate hydraulic parameters such as transmissivity, storativity, and as also the development of a general conceptual model of the aquifer. Different types of models and corresponding methods of analysis have been developed and used to estimate hydraulic parameters in primary aquifer systems, however; the application of these methods for secondary (fractured) aquifer systems generally leads to ambiguous results (Pacome, 2010). This is mainly because most developed models for interpreting hydraulics tests assume a homogeneous, isotropic porous medium, and one of three basic flow geometries (spherical, radial and linear) described by the NCR (1996).

The analytical models developed by Theis (1935) and Cooper-Jacob (1946), have been shown to estimate hydraulic parameters (transmissivity and storativity values) that represent, a mixture of the matrix and fracture properties. Studies by Botha *et al.* (1998) and van Tonder *et al.* (2001) illustrated the use of these analytical models in Karoo fractured rocks. Because the geometry of the fracture network is not initially known, usually three kinds of analytical models are applied in fractured-rock aquifers for the analysis of the constant discharge hydraulics test data as described by Kruseman and De Ridder (1994): (1) the double porosity model, (2) the single fracture model, and (3) the generalised radial acting flow models.

In a double porosity model; a confined densely fractured and consolidated system is assumed. In an aquifer like this, two systems are recognised: the fractures of high permeability and low storage capacity, and the matrix blocks of low permeability and high storage capacity (Kruseman and De Ridder, 1994). The fractures tends to control the flow of the aquifer for a certain period, followed by a second period during which the matrix blocks feeds water to the fractures and the head in fractures stabilises, and then in the last period the water pumped comes from both the fractures and the porous matrix (Kruseman and De Ridder, 1994). These subsequent periods can be plotted on the diagnostic plots to ascertain the flow as explained.

In a single fracture model; the aquifer is assumed to be homogenous, isotropic, and large lateral extent, and is confined above and below by impermeable beds. A pump well is also assumed to intersect an embedded major fracture, fault or dyke (with infinite length). The fracture is also assumed to have an infinite hydraulic conductivity. This means that the drawdown in the fracture is uniform over its entire length at any instant of time; this implies that there is no hydraulic gradient in the fracture. This uniform drawdown induces a flow from the aquifer into the fracture. The time-drawdown response of the aquifer is predominantly influenced by the intersected fractures. The types of single fracture models used for groundwater studies are the infinite conductivity fracture model by Ramey and Gringarten (1976), uniform flux fracture model, the finite conductivity fracture and the dyke model. It is important to note that these methods have been developed primarily for a better understanding of the behaviour of hydraulically fractured geological formations in deep oil reservoirs. However, the approach of these methods has been successfully applied to many wells that intersect natural or hydraulic fractures (Kruseman and De Ridder, 1994). In particular, the assumption that the fracture has an infinite hydraulic conductivity was found 'unrealistic' by Kruseman and De Ridder (1994). This was found to be 'unrealistic' if the assumption of a plane fracture is made or if the fracture is mineral-filled. In reality, a certain hydraulic gradient will exist in the pumped fracture and the uniform flux solution (recognising that water from the aquifer enters the fracture at the same rate per unit area) must therefore be interpreted as giving the appearance of a fracture with high, but not infinite conductivity as the assumption suggested (Kruseman and De Ridder, 1994). This solution seems, indeed, to match drawdown behaviour of wells intersecting natural fractures better than the infinite-conductivity solution does. It is also important to note that the dyke model as a single fracture model has been successfully applied in the Karoo aquifers by Chiang and Riemann (2001).

In the generalised radial acting flow models, a confined, homogenous and isotropic fractured medium, with Darcian flow, finite storage, infinite matrix and negligible fracture skin are assumed. As pumping continues the flow pattern tends to change from parallel flow to pseudo-radial flow; regardless of the hydraulic conductivity of the fracture (Kruseman and De Ridder, 1994). During this period most of the pumped water originates from areas farther removed from the fracture. Barker (1988) proposed a type curve method to determine the hydraulic conductivity and the specific storage of the fracture system, if the fracture thickness is known. This method can only be applied if the well storage and well bore skin are negligible, if not; the method can be applied to observation borehole data. The manual for pump testing analysis in fractured rock aquifers by van Tonder *et al.,* (2002) was used for estimating the sustainable yields and the aquifer parameters. The constant discharge test involved monitoring of the drawdown of the pumped borehole and adjacent boreholes, while the discharge rate was kept constant (Kruseman and De Ridder, 1994; Ohio Environmental Protection Agency, 1995; Stallman, 1971; van Tonder *et al.*, 2002; Woodford and Chevallier, 2002). Prior to the start of the pump test, water levels of the pumping and observation boreholes were recorded to determine existing trends of water levels of the boreholes without any pumping. The recorded water levels were evaluated to determine any unusual behaviour of the borehole without pumping so as to consider it when interpreting the pump test data. The pump tests duration lasted for at least 24 hours, the longest pump test was 72 hours long (Table 10). Twenty boreholes were considered for pump testing in the whole project; however for a detailed geohydrological analysis and interpretation for (4) boreholes were used (i.e. DT-06, DT-07, DT-14 and DT-17) (Table 10). The newly drilled boreholes (DT-03, DT-06, DT-07, DT-14 and DT-17) were given other names which are listed in Table 10.

In some tests, steady state occurs a few hours in some others it never occurs. However, DWAF (1997) guidelines recommend 24-72 hours pump testing to produce diagnostic data. For community water supply it is a requirement to conduct pump test longer than 24 hours (DWAF, 1997).

The time interval for water level measurements varied from frequent at the beginning of the test, when water levels were changing rapidly, to long at the end of the test when the water levels change is slow (Table 11). The constant discharge test with the respective recovery test was conducted on 20 boreholes (Figure 59). (See Table 10 for the details of the constant discharge tests).

It is important to note that pump tests were conducted on fifteen existing boreholes (ST-PBH11, STPBH14, ST-PBH12, ST-PBH23, ST-PBH08, ST-PBH09, ST-PBH22, ST-

PBH25, ST-PBH15, ST-PBH20, ST-PBH24, ST-PBH33, ST-PBH30, ST-PBH07, ST-PBH13) without drilling details such as water strikes, geological logs, borehole depth and date of drilling (See Table 10).

Table 10: Constant discharge test information for 20 boreholes tested

Name	Drilling Target Number	Borehole depth (m)	Duration (h)	Date of test	Static water level (mbgl)	Dynamic water level (mbgl)	Residual drawdown (mbgl)
ST-PBH11		77.60	24	2012-04-01	2.73	7.00	0.63
ST-PBH14		28.75	24	2012-03-26	5.80	10.89	10.89
ST-PBH12		79.51	48	2013-08-06	15.74	10.90	5.82
ST-PBH23		51.00	48	2012-04-30	2.29	6.50	0.31
ST-PBH08		27.80	24	2012-03-20	0.89	10.11	0.48
ST-BH09		83.08	24	2012-03-17	3.17	37.30	1.65
ST-BH22		42.95	48	2012-04-20	6.81	15.80	0.74
ST-PBH25		39.30	24	2012-03-27	16.45	21.98	5.28
ST-PBH15		25.15	24	2012-03-29	1.97	12.90	0.78
ST-PBH26	DT-03	118.38	24	2013-04-06	3.94	66.46	2.32
ST-PBH27	DT-06	62.95	48	2013-01-05	3.67	14.36	1.20
ST-PBH29	DT-14	56.81	48	2013-06-17	9.31	28.54	2.70
ST-PBH20		40.82	24	2012-04-16	6.15	5.54	0.90
ST-PBH24		29.75	48	2012-03-30	1.80	13.52	0.64
ST-PBH33		76.58	12	2013-04-07	0.56	54.64	11.49
ST-PBH28	DT-07	62.05	48	2013-05-28	3.50	39.96	0.84
ST-PBH30		58.20	48	2013-06-17	0.90	21.21	1.54
ST-PBH32	DT-17	58.00	28	2013-06-28	8.70	37.85	7.38
ST-PBH07		60.87	72	2012-03-23	2.87	12.70	1.77
ST-PBH13		49.60	48	2012-04-16	1.75	5.20	0.56

The geohydrological information (i.e. water strikes, geological logs, borehole depth and date of drilling) were not available, and the subsequent boreholes were reported to have been drilled a long time ago (no records). A detailed geohydrological interpretation and analysis was conducted on the newly drilled boreholes (DT-06, DT-07, DT-14 and DT-17) which have such geohydrological information. This is worth pointing out as such information is important for interpreting and analysing the observed pump test data; this is because the relevance and value of such information goes beyond the aquifer testing exercise to data analysis and interpretation of the drawdown trends (van Tonder *et al.,* 2002). However, lack of geohydrological information (such as the geological logs) on most of the existing boreholes can affect the degree of confidence with which the pumping test data can be interpreted and explained.

Table 11: Range of interval between water-level measurements in the pumping well

Time since start of pumping	Time interval per recording
0–0 minutes	1 minute
10–20 minutes	5 minutes
20–60 minutes	10 minutes
60–240 minutes	30 minutes
240–600 minutes	60 minutes
600 to shutdown	120 minutes

Source: van Tonder *et al*. (2002)

Attributes such as the geology and water strikes are important for precise and confident interpretation of the pump test data. Bearing in mind that the Steynsrus area is characterised by an arid to semi-arid climates with long periods of dry weather, the community relies much on groundwater supply. It was important to conduct pump testing on the existing boreholes without geohydrological information; cautiously neglecting the ideal guidelines by van Tonder *et al.* (2002) for conducting pump tests on boreholes with sufficient information.

For the purpose of this study, the recently drilled boreholes (DT-06, DT-07, DT-14 and DT-17) with geohydrological information (i.e. water strikes, borehole depth, geological logs, etc.) will be discussed in characterising the hydraulic behaviour in the area as alluded earlier.

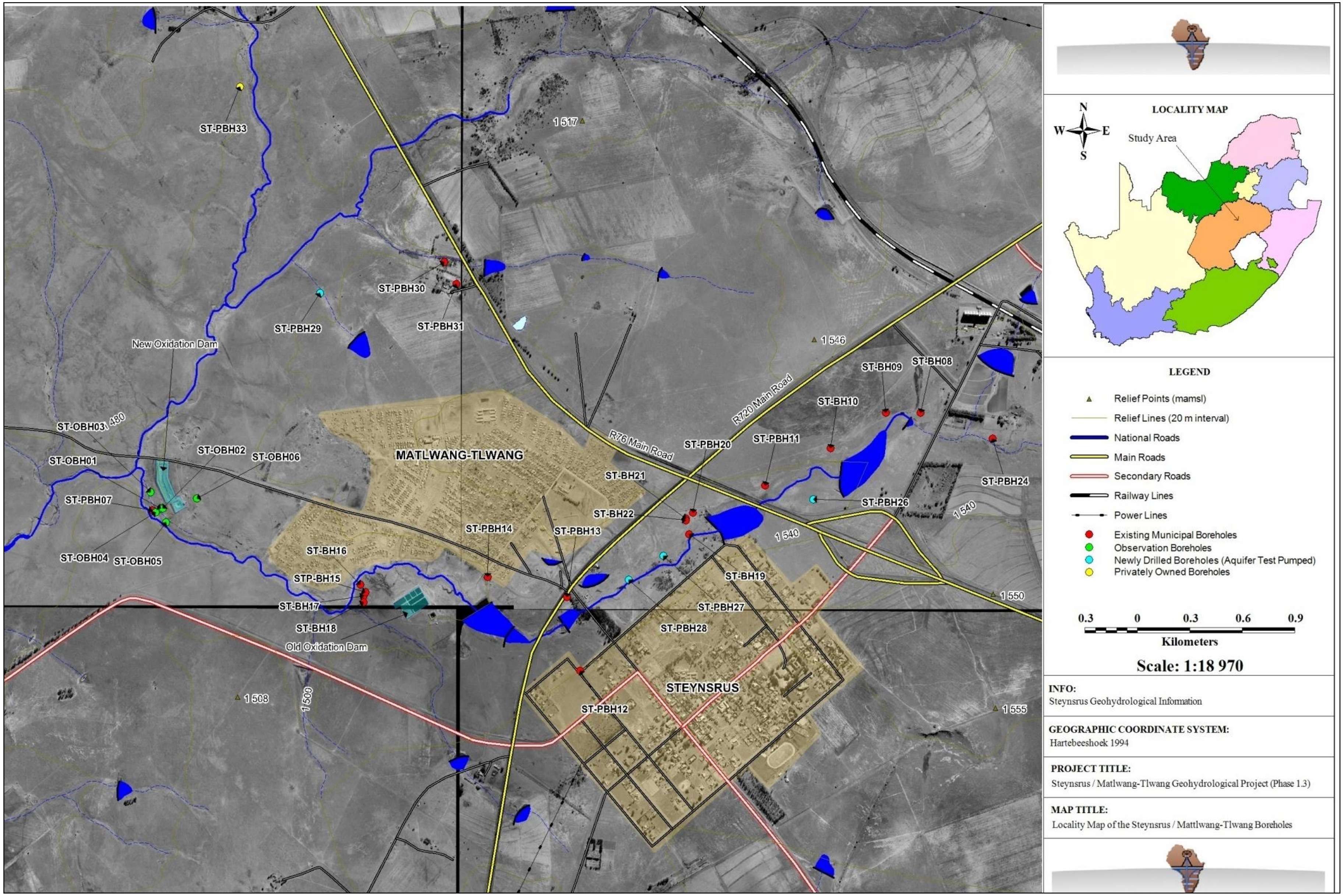
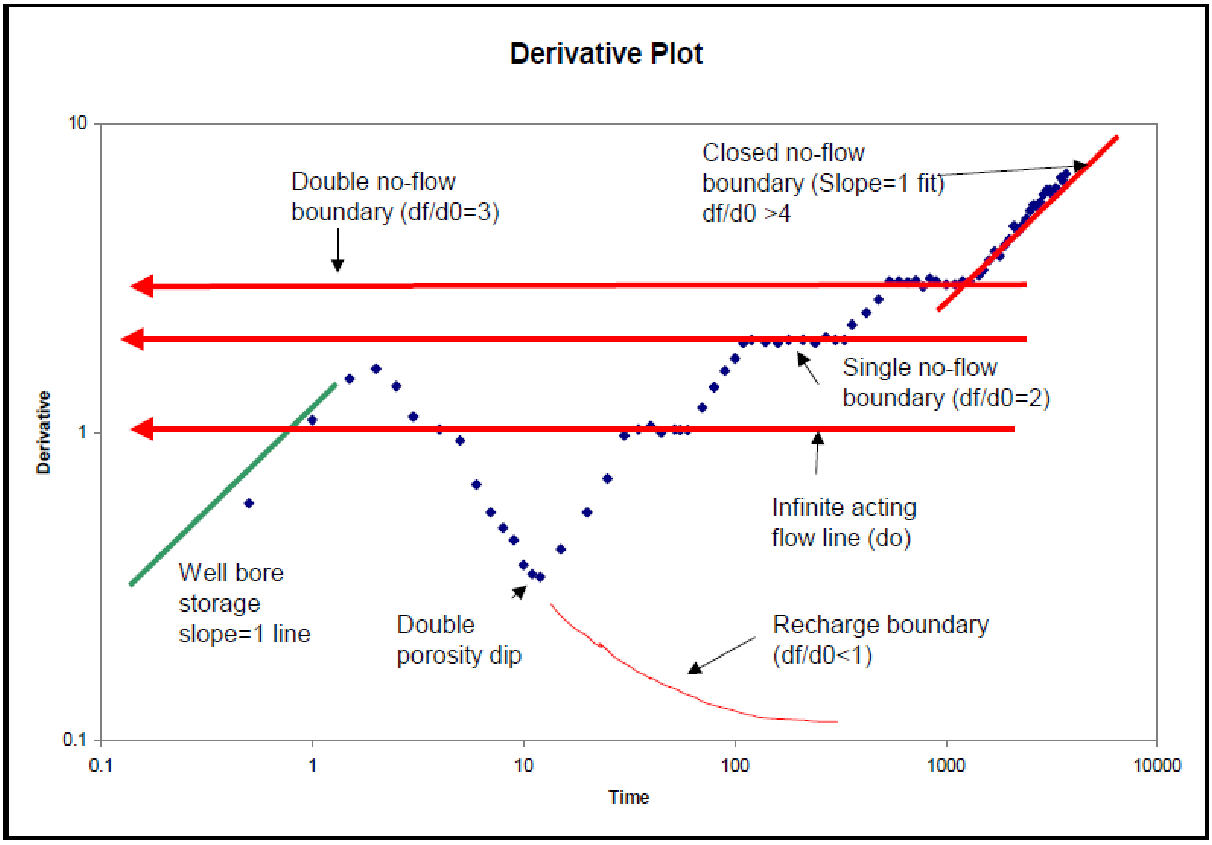


Figure 59: Location of boreholes in Steynsrus evaluated by constant discharge test (Hough and Rudolf, 2013).

7.2.3.1 Diagnostic plots

The diagnostic plots are used in this study to determine the aquifer characteristics of the pump tested boreholes; i.e. to ascertain the conceptual model of the hydraulic scenario. A diagnostic plot allows the dominating flow regimes to be identified; these yield straight lines on specialised plots (Kruseman and de Ridder, 1994). There are diagnostic plots for confined, unconfined and leaky aquifers of unconsolidated nature and for confined, consolidated aquifers. The diagnostic plots used in this study are for the confined fractured aquifers including the confined fractured aquifer (double porosity type), a single plane vertical fracture, and a permeable dyke in poorly permeable aquifer.

The Log-log plot of drawdown versus time of pumping, semi-log plot of drawdown versus time, and log-log plot of derivative of drawdown and time are carefully used to identify the inner and outer boundary conditions; thereby determining the aquifer characteristics. There may be instances whereby the aquifer's response to pumping cannot be discerned from drawdown log-log plot, however, this can be observed on the derivative of drawdown plot (Woodford and Chevallier, 2002). Figure 60 and Table 12 illustrates the different slope responses and related characteristics on a log-log plot of the derivative of drawdown and time plot versus time.



Source: van Tonder *et al.* (1999)

Figure 60: Typical derivative graph for various boundary conditions.

Table 12: Characteristics of a derivative drawdown plot (Woodford and Chevallier, 2002)

Feature	Characteristic
Slope = 1 at early time	Well Bore Storage.
Slope = 0.5 at early time	Long fracture (usually factor 2 difference between drawdown and derivative. Limited fracture network.
Slope = 0.25	Finite fracture with factor 4 difference between drawdown and C-J derivative. Well connected fracture network.
Slope = 1 at late time (upwards)	Closed boundary.
Slope = downward and then updward	Position of fracture reached, whereafter the fracture is dewatered.
Strong downward trend	Recharge boundary.
Dip in derivative	Dual porosity aquifer response.

The characteristics of the log-log plot of drawdown and semi-log plot of drawdown versus time are listed in Table 13 and 14, respectively.

Table 13: Characteristics of a log-log plot of drawdown (Woodford and Chevallier, 2002)

Feature	Characteristic
Slope = 1 at early time	Well Bore Storage.
Slope = 0.5 at early time	Linear flow in fracture, water derived from fracture only.
Slope = 0.25 at early time	Bi-linear flow dominant, where water is leaking from the matrix into the fracture.
Horizontal line	Recharge boundary or leakage from matrix = abstraction rate or position of fracture is reached.

Table 14: Characteristics of a semi-log plot of drawdown (Woodford and Chevallier, 2002)

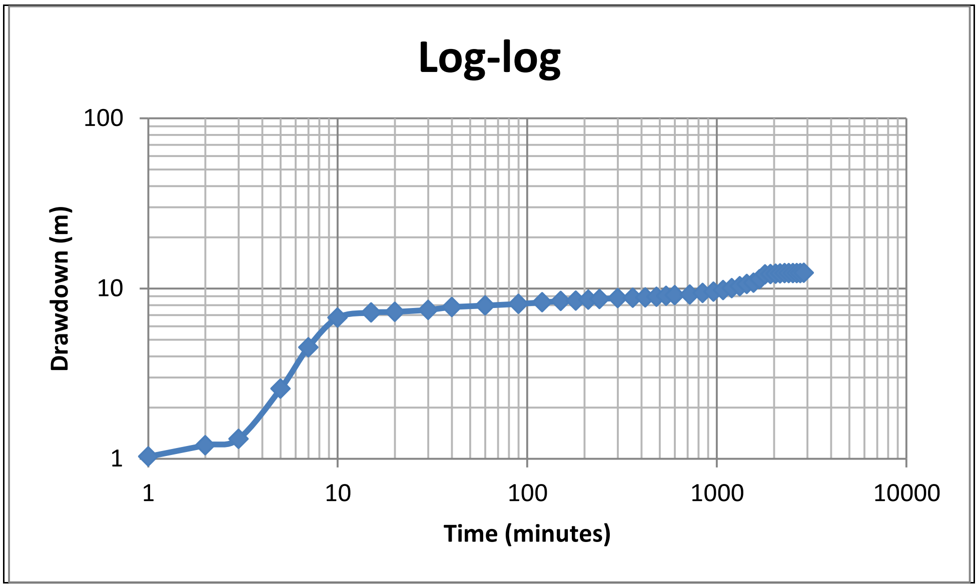
Feature	Characteristic
Straight line segment	Indication of radial flow.
Two parallel lines	Dual porosity.
Horizontal line	Recharge boundary or period where leakage from matrix = abstraction rate or water level has reached position of a fracture.
Steepening segment during late times	Boundary reached or matrix flow becomes dominant.

Semi-log plot is very useful for showing a straight line that is characteristic of infinite acting radial flow, and also for recognising certain boundary types and positions of fractures (Woodford and Chevallier, 2002). The most generally used plot is the log-log plot of drawdown; the aquifer responses are easily identified on this plot with a log-log derivative plot used to confirm the identified responses. The following flow characterisation was done through FC Program by van Tonder *et al.* (1998), particularly with plotting of the derivative curve.

Pump Test for DT-06

During the pumping test for DT-06 (also named ST-PBH27), a constant discharge rate of 2.20 L/s was used (Appendix 4). Observation boreholes for this particular aquifer test were borehole ST-PBH22 and ST-PBH28, with distances of 150 and 300 m away from the pumping borehole, respectively. The observation boreholes were monitored during the constant discharge test to determine any changes and influences. There were no changes of drawdown observed in the observation borehole ST-PBH28, and borehole ST-PBH22 showed a change of drawdown of 0.20 m after 2880 minutes. Boreholes ST-PBH27 and ST-PBH22 were suggested to be drawing water from similar aquifer. The geological logs for existing borehole ST-PBH22 (also observation borehole in this regard) were not available to compare to the newly drilled borehole DT-06.

From the pumping test data, the log-log plot (Figure 61) is indicative of an unconfined aquifer, although at early time from 0-90 minutes the curve is indicative of a confined aquifer behaviour. This is evidenced and supported by the semi-log plot (Figure 61), there is a non-linear relationship between the time and drawdown at time 0-5 minutes and then a linear with slope of 1, indicative of radial acting flow from 5-10 minutes. According to Kruseman and De Ridder (1994) such behaviour as observed in Figure 61, it is indicative of an unconfined aquifer. A slope of 1 is also observed from 5-10 minutes on the log-derivative plot in Figure 62; and a sudden decrease in slope from 10-30 minutes indicates radial flow with boundary effects according to van Tonder *et al.* (1998) as the slope flattens due to the boundary identified by an increasing slope of 1 from 360-960 minutes. At medium pumping times (30-1080 minutes), log-log plot shows a gentle slope with the drawdown stabilising; caused by the rechaging from the overlying formation into the sandstone formation (Figure 61).



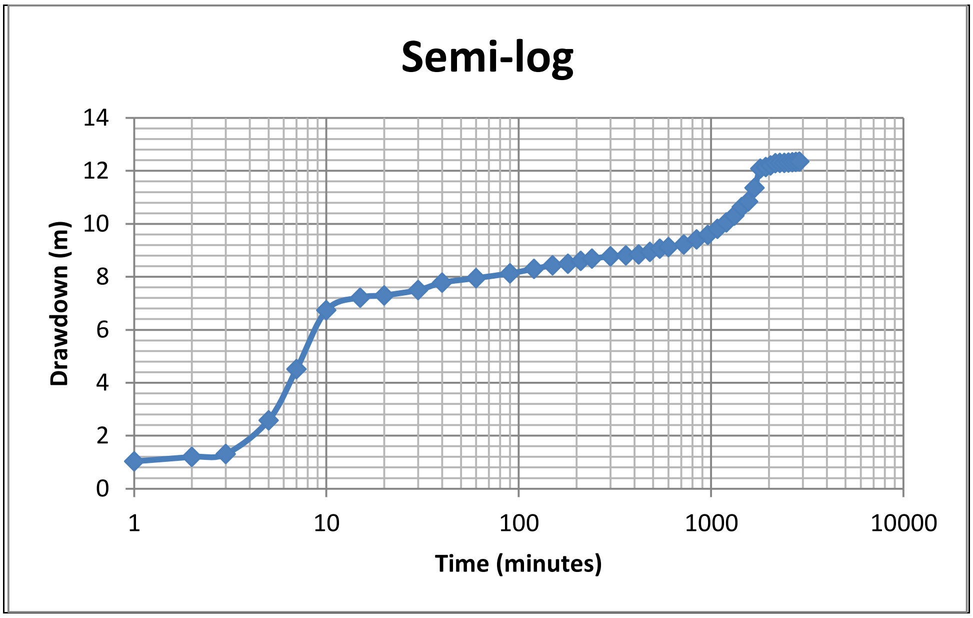


Figure 61: Log-log and semi-log drawdown and time plots for DT-06.

At late times (1080-1440 minutes), there is steepening segment of the curve observed on the semi-log plot (Figure 61) indicating that the boundary has been reached (no-flow boundary) on the log-derivative plot in Figure 62). The no flow boundary can be associated with the dolerite intrusion observed on the geological logs for DT-06 in Figure 54 from 10-13.20 m below static water level.

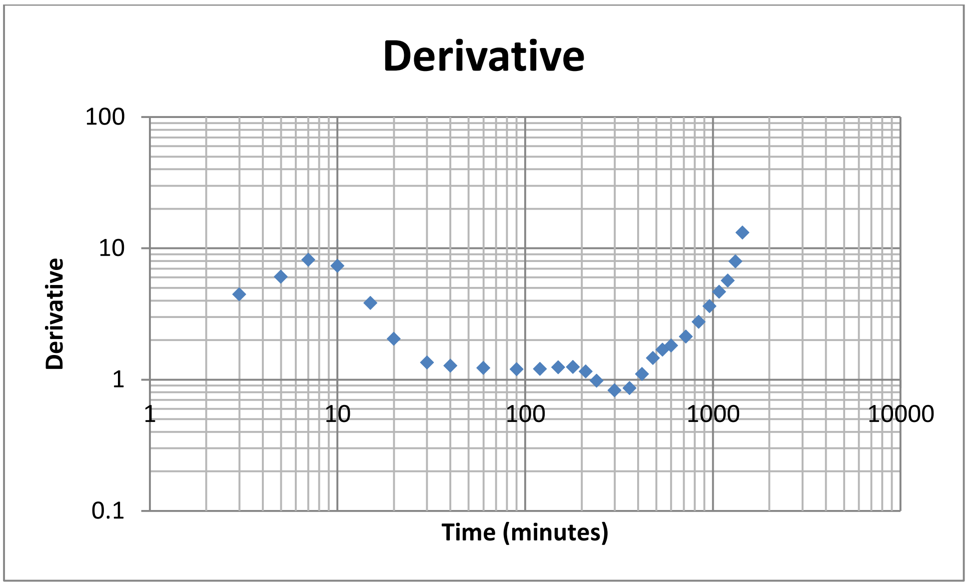
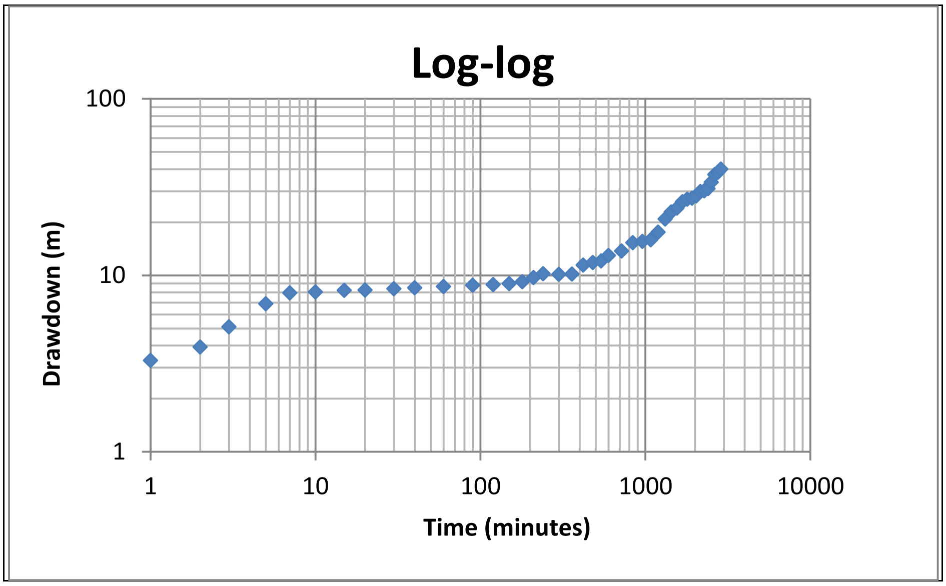


Figure 62: Log-log of derivative and time plot for DT-06.

Pump Test for DT-07

During the pumping test for DT-07 (also named ST-PBH28); an average abstraction rate of 6.00 L/s was used (Appendix 4). Observation boreholes for this particular aquifer test were borehole ST-PBH22 and ST-PBH27, with distance of 450 m and 352 m away from the pumping borehole, respectively. The observation boreholes water levels were monitored during the constant discharge. The change in drawdown observed in the observation boreholes were measured at 0.22 m and 0.15 m after 2880 minutes, respectively, the change in drawdown in the adjacent boreholes may suggest that these boreholes draw water from the same aquifer.

From the pumping test data the plots are indicative of the linear flow from 1-7 minutes (Figure 63). This can be explained by the estimated slope of 0.5 for the early time of 1-7 minutes from the log-log plot (Figure 63). Water is suggested to be coming from the fractures. The geological logs (Figure 55) of DT-07 indicated a water strike along the shale formation at about 8 m below static water level; this position was reached after seven minutes. The water being pumped at the early time is suggested to be coming from this fracture. At medium time from 7-300 minutes, there is a flattening of the gradient on the log-log drawdown plot which can be explained as the rock matrix feeding water to the fractures (Figure 63). This can be confirmed by the dipping of the derivative gradient on the log-log derivative plot (Figure 64). At late time (300-2 880 minutes) there is the increasing steep gradient (with a slope of 0.5) on the semi-log drawdown plot indicative of dominant rock matrix flow. This can be confirmed by the gradual increase of the derivative gradient on the log-log derivative plot (Figure 64).



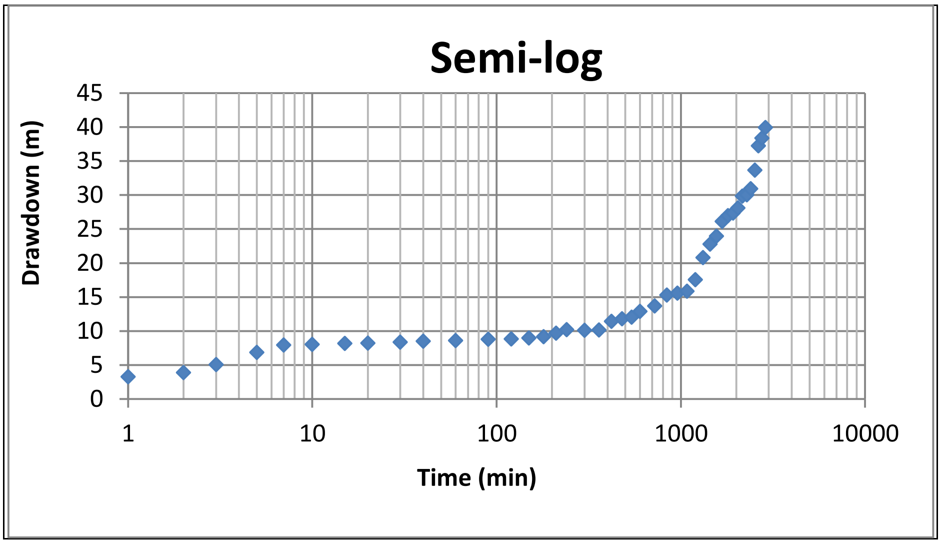


Figure 63: Log-log and semi-log drawdown and time plots for DT-07.

The flattening of the log-log derivative curve (Figure 64) at time intervals 20-60, 240-300, and 720-840 minutes are indicative of the infinite acting flow, single no-flow boundary with a derivative of 2, and a double no-flow boundary with a derivative of 3, respectively. The decrease in slope at time 1440-1880 minutes may suggest a dual porosity or recharge boundary. The steepening at the late time 1880-2400 may suggest that the no-flow boundary has been reached at depth of 28 m below static water level (this is the position of the dolerite intrusion observed in Figure 55 for DT-07).

Although, the dolerite intrusion were targeted in drilling as the preferential pathway for groundwater occurrence in the study, for this borehole in particular, the fracture on the shale and sandstone formation for a certain period (1-7 minutes) in Figure 63) controlled the flow of water being pumped and the fracture associated with dolerite intrusion was observed as the main water strike.

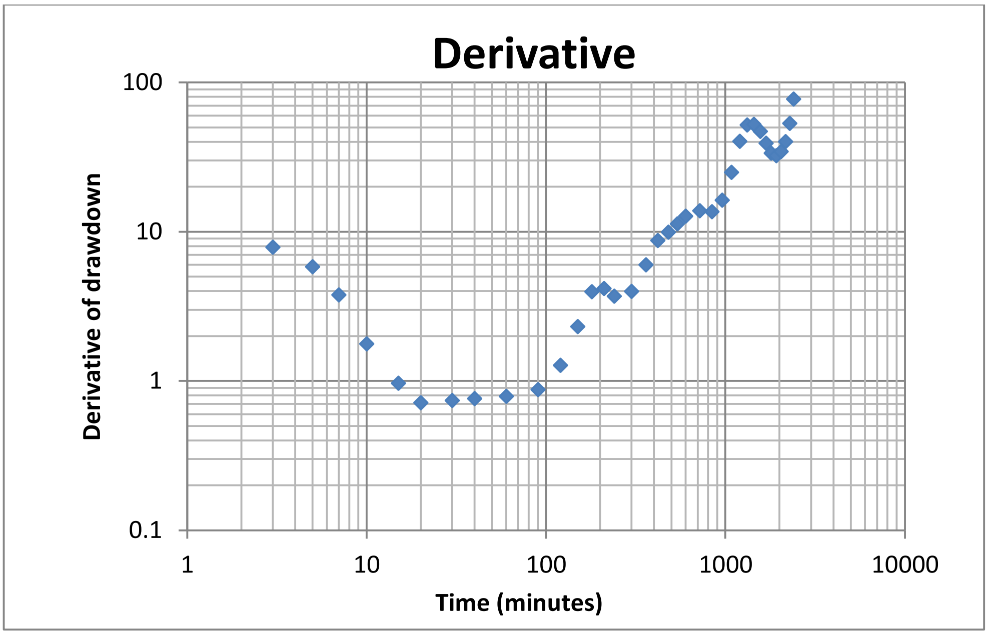
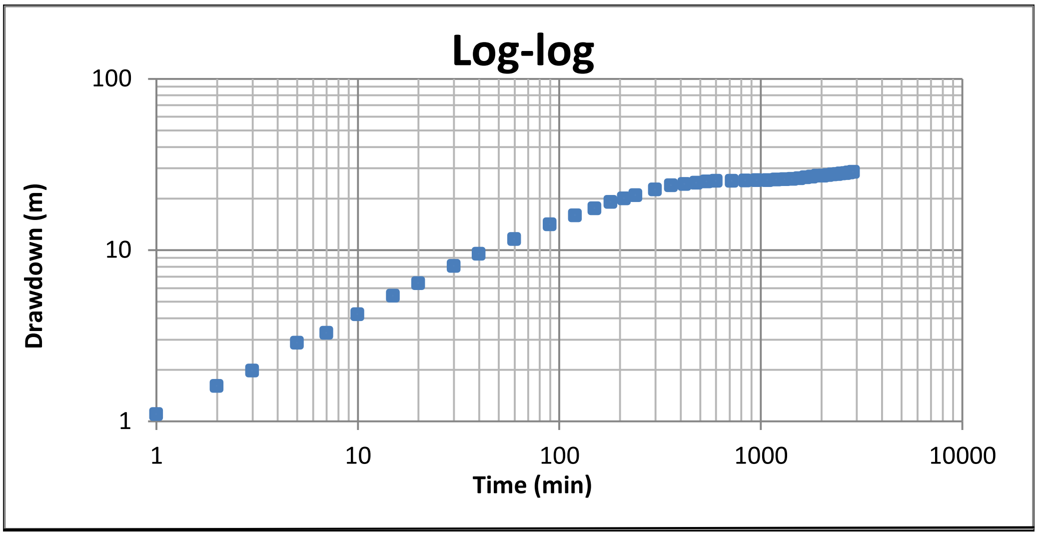


Figure 64: Log-log of derivative and time plot for ST-PBH28.

Pump Test for DT-14

During the pumping test for DT-14 (also named ST-PBH29); an average abstraction rate of 2.04 L/s was used (Appendix 4). There were no observation boreholes for this particular aquifer test, and no boreholes were found in the vicinity of 500 m of the pumping borehole.

From the pumping test data, the log-log drawdown plot is indicative of the linear flow (with a slope of 0.5) from early time of 1-210 minutes (Figure 65). The water flow is suggested to be coming from fractures with a high hydraulic conductivity. The sandstone formation fracture indicated as a water strike on the geological logs (Figure 56) of DT-14 at about 14 m below the static water level, can be attributed to the linear flow. The log-log derivative plot (Figure 66) can confirm the flow coming from fractures, showing a slope of 0.5 at early time. From 210-840 minutes there is a gradual flattening of the gradient on the log-log drawdown plot (Figure 65) suggesting an approach of the main water strike thus increasing the flow into the borehole. This can be confirmed on the log-log derivative plot (Figure 66), there is downward dipping slope at time 15-840 and 1680-2160 to suggest more inflow of water into the borehole. At late time (840-2 520 minutes), there is the increasing gradient on the semi-log drawdown plot (Figure 66) indicative of retarding flow boundary.



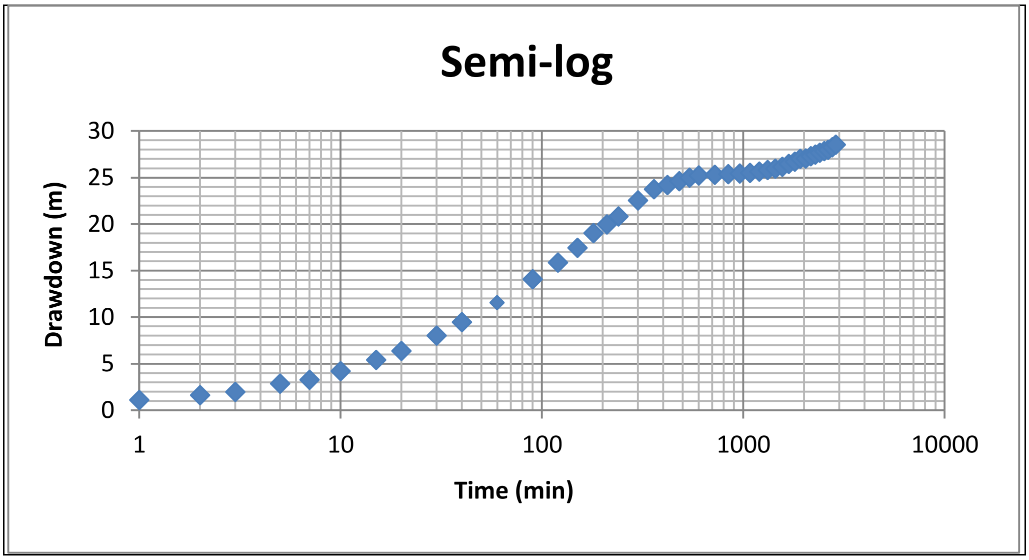


Figure 65: Log-log and semi-log drawdown and time plots for DT-14.

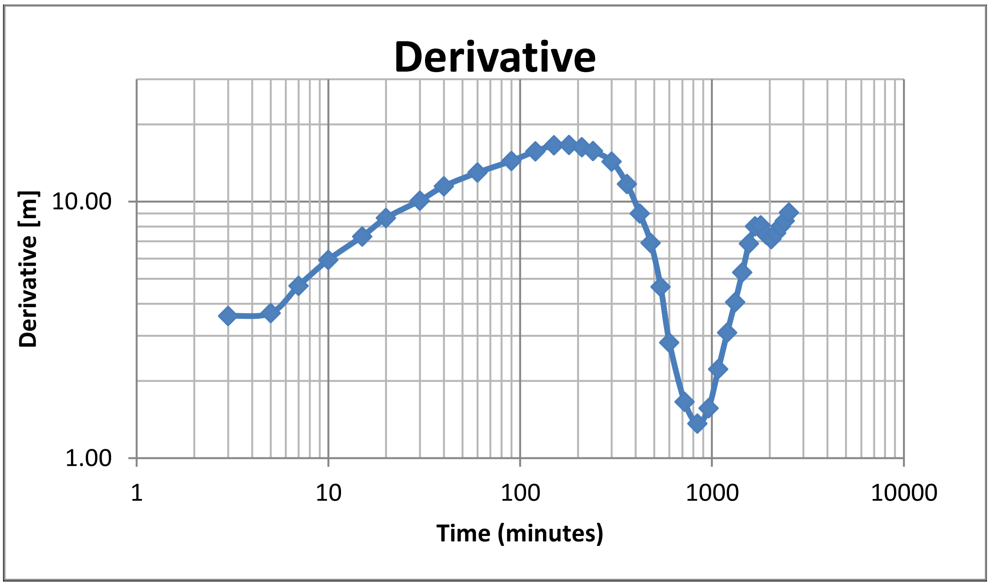


Figure 66: Log-log derivative and time plot for DT-14.

Pump Test for DT-17

During the pumping test for DT-17 (also named ST-PBH32), an average abstraction rate of 9.05 L/s was used (Appendix 4). There were no observation boreholes for this particular aquifer test, and no boreholes found in the vicinity of 500 m of the pumping borehole.

From the pumping test data, the log-log drawdown plot is indicative of the linear flow from 0-90 minutes (Figure 67), the slope of 0.5 along the log-log drawdown confirms the linear flow. The water is said to be exclusively flowing from the dolerite fracture. The geological logs (Figure 57) of DT-17 (ST-PBH32) indicated a water strike along the dolerite intrusion at about 19 and 36 mbgl. At medium to late time (90-180 minutes) there is a decrease in the gradient along the log-log drawdown plot (Figure 67), suggesting a bilinear flow with an estimated slope of 0.25 thus an indication of bilinear flow from the matrix into the fracture.

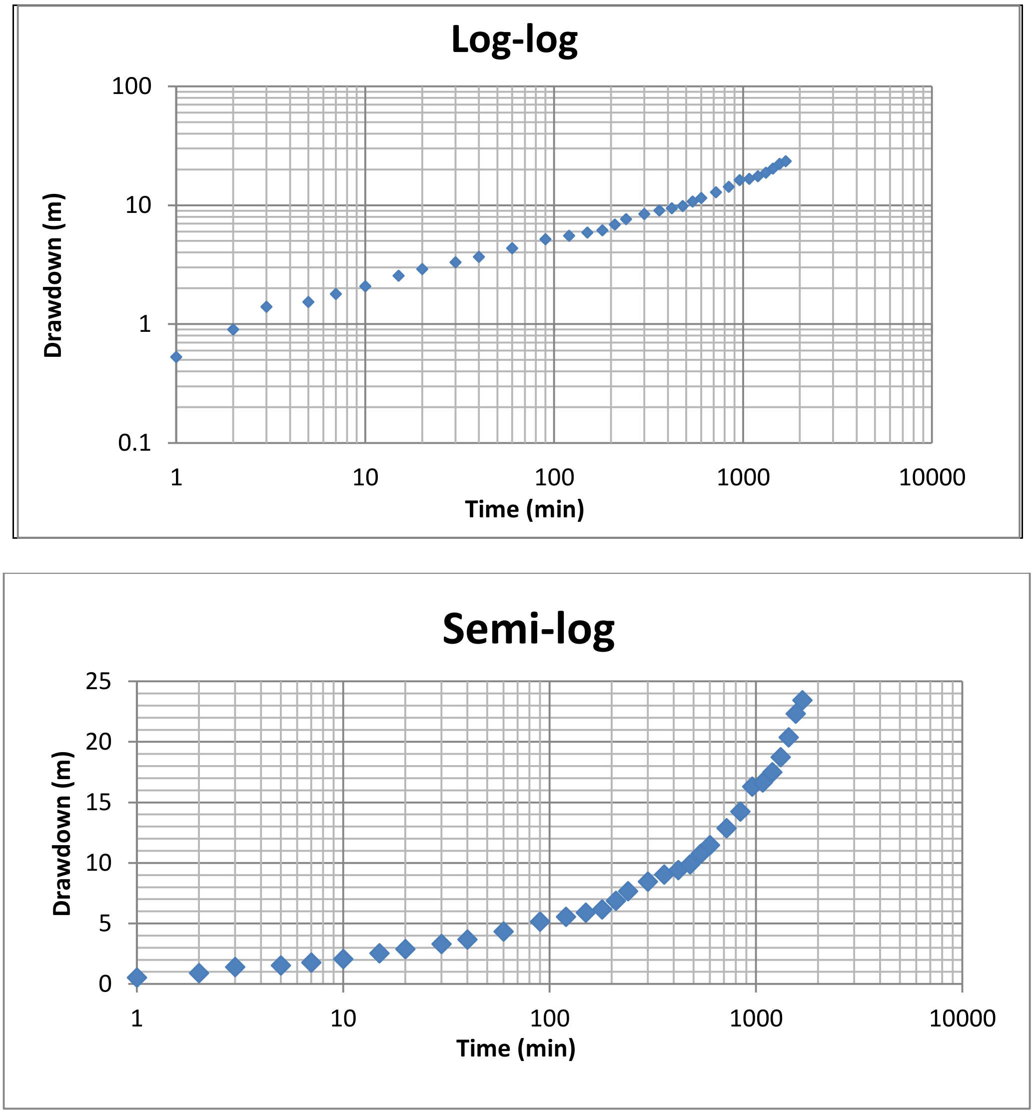


Figure 67: Log-log and semi-log drawdown and time plots for DT-32.

The adjacent aquifer (rock matrix) is suggested to be yielding water to the dolerite fractured. The semi-log plot (Figure 67) also indicates the steeping of the gradient, this is associated with the dominant rock matrix flow. The sharp upward trend at the end of the semi-log plot (Figure 67) at time 960-1680 minutes can be suggested as the no-flow boundary; with less water flowing into the borehole. This can be attributed to the the fracture observed (Figure 57) at 19 mbgl, as it may be dewatered.

The log-log derivative plot (Figure 68) is indicative of the downward and then upward slope at about 8 and 21 m below the static water level at time 360 and 960 minutes, respectively. This is suggested to be dewatering of the fractures which were intersected, these fractures are indicated on the geological logs (Figure 57) for DT-17 to at about 8 and 22 m below static water level and a corresponding 19 and 36 mbgl on the geological logs in Figure 54, respectively.

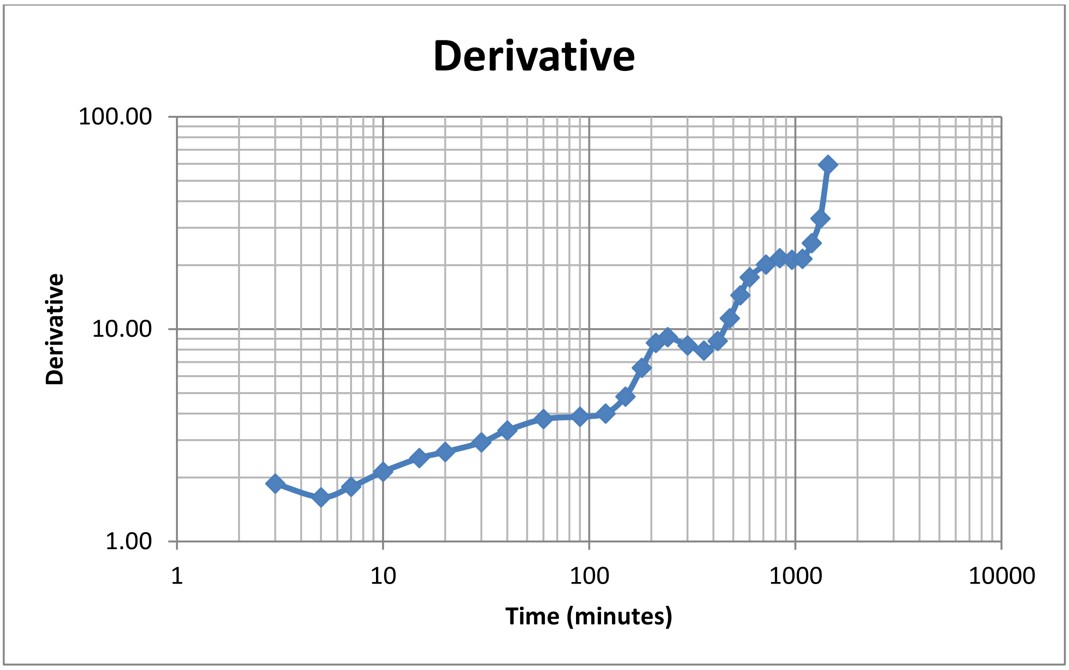


Figure 68: Log-log derivative and time plot for DT-17.

7.2.4 Recovery Test

Upon switching off the pump after the constant discharge test, all the boreholes were allowed to recover during the monitored period. The water levels in the pumping boreholes as well as the observation boreholes start to rise following shut down of the pump. This was done to get the extent of the aquifer and connectiveness of the fractures, and to determine the aquifer parameters such as transmissivity of the formation by applying analytical methods (Cooper-Jacob or Theis method) to the radial acting flow phase of the recovery data (Driscoll, 1986). The recovery inside the abstraction borehole was measured until the water level recovered to 95% of the original static water level or measured for duration equal to the pumping test; whichever occurs first (van Tonder *et al.*, 2002). If the borehole is considered to have recovered completely; a horizontal flattening at a late time indicates that the fracture system acts like a semi-closed boundary (i.e. low formation transmissivity value). The aquifer parameters determined from recovery test data are usually compared to the parameters determined from pump test data (van Tonder et al., 2002).

Establishing and understanding of the influence on water levels during recovery period have an important value when analysing the behaviour of water level changes. Table 15 shows the estimated recovery percentages of the water levels to the initial static water level, duration of the recovery test and coordinates of the boreholes.

Table 15: Recovery test informaiton; including duration of test, initial static water level, and recovery percentage

Name	Longitude (^{0})	Latitude (^{0})	Duration of Test (Hours)	SWL (mbgl)	%Recovery
ST-PBH12	27.55545	-27.95169	48.00	15.74	90.56
ST-BH22	27.56153	-27.94413	22.00	6.81	90.67
ST-PBH25	27.55738	-27.98764	36.00	16.45	75.98
ST-PBH15	27.54288	-27.94780	8.00	1.97	90.31
ST-PBH26	27.56890	-27.94304	0.25	3.94	96.91
ST-PBH27	27.56019	-27.94588	1.00	3.67	91.61
ST-PBH29	27.54019	-27.93269	34.00	9.31	90.54
ST-PBH20	27.56187	-27.94375	48.00	6.15	83.75
ST-PBH24	27.57936	-27.93991	48.00	1.80	90.46
ST-PBH33	27.53548	-27.92228	48.00	0.56	78.97
ST-PBH28	27.55817	-27.94709	0.05	3.50	91.37
ST-PBH30	27.54738	-27.93110	24.00	0.90	92.74
ST-PBH32	27.55744	-27.98742	48.00	8.70	90.26
ST-PBH07	27.53050	-27.94370	72.00	2.87	86.06
ST-PBH13	27.55459	-27.94796	48.00	1.75	89.21

7.2.5 Aquifer Parameters

The transmissivity values (T-values) were estimated by means of the Cooper-Jacob (1946) method, as discussed by Kruseman and De Ridder (1994), with S-values obtained by RPTSOLV software (Verwey *et al.*, 1995).

7.2.5.1 Cooper-Jacob method

The Cooper-Jacob (1946) analytical method assumes the aquifer in question and the confining layer are homogenous, isotropic and of uniform thickness in estimating the transmissivity values. However in most of the real conditions, most of these assumptions are not valid. At the study site, the aquifer is heterogenous due to its complex geology, the flow through the aquifer is not isotropic and the thickness of the aquifer varies relative to the geology. In such cases, assumptions to simplify complex heterogenous conditions can be made. Such assumptions can simplify the complex structure of real heterogenous formations in order to provide insight into the behaviour of drawdown in heterogenous formations. Butler and Liu (1993) conceptualised the non-uniform aquifer as a uniform matrix into which a disk of anomalous properties had been placed. The study found that Cooper-Jacob method can be used in any laterally non-uniform system to estimate matrix transmissivity if the flow to the pumping well is approximately radial during the period of analysis.

7.2.5.1.1 Validity of Assumptions of Cooper-Jacob method

The Cooper-Jacob method is also easy to apply in comparison to the methods that were developed to describe aquifer response to pumping in fractured media. The Cooper-Jacob method was preferred over other analytical methods due to its easy applicability to determine the hydraulic properties (transmissivity and storativity) of non-leaky confined aquifers. The analysis of the method involves matching a straight line to drawdown data plotted on a semi-log plot. Although not conceptually correct in many fractured rock environments, Phillips (1994) showed that the Cooper-Jacob analysis could provide acceptable estimates of transmissivity in a wide range of geological environments.

In a fractured aquifer, there are two systems, i.e. fracture and matrix. During a pumping test, groundwater is released from matrix, flows vertically to the fracture and then along the fractured zone towards the abstraction borehole. However, neither the Theis nor Cooper-Jacob methods consider this situation (van Tonder *et al.*, 2002). When applying these methods, only the portion of groundwater, which is released outside of the radius of the observation borehole, is considered by the analytical solution. This portion is decreasing with the increasing distance of the observation borehole. This explains the decreasing of the determined S-values with the distance (van Tonder *et al.*, 2002). As a result of applying Theis or Cooper-Jacob methods, the estimated T and S-values represent a mixture of the matrix and fracture properties (Chiang and Riemann, 2001).

Table 16 summarises the comparison of the analytical method assumptions and the real situation in the study area. Assumptions of Cooper-Jacob method relative to the study:

- **Aquifer with an infinite areal extent**

  All aquifers in the study have limited extent due to no-flow and recharge boundaries.

- **Aquifer is confined**

With an exception of borehole ST-PBH27, the aquifers are characterised as fractured-rocks; the fractures that control the flow of the water in the aquifer are under pressure thus confined.

- **Aquifer pumped at constant discharge rate**

All the aquifers as indicated in Table 10 were pumped for 24-72 hours.

- **Well penetrates the entire thickness of the aquifer**

The drilled boreholes do not penetrate the entire aquifer; casing was installed especially on the weathered and unconsolidated layers.

- **Aquifer has a seemingly infinite areal extent.**

All of the aquifers in the study have limited extent due to no-flow boundaries and recharge boundaries identified under discussion for the flow regime diagnostics in subsection 7.2.3.1.

- **The aquifer is homogeneous, and uniform thickness over the area.**

From Chapter 6; all boreholes discussed showed different geological layers; characterised by alternating layers of shale and sandstone, and dolerite intrusions.

- **The water removed from storage is discharged instantaneously with decline of the head (water level).**

- As the boreholes were pumped at constant rate, water levels were recorded and indicated decreases, increases and stabilized levels per respective geological conditions.

- **Aquifer is porous media**

Fractured rock mass can be considered a mutli-porous medium consisting of the matrix and fracture components (van Tonder et al., 1998)

Although, some of the assumptions of Cooper-Jacob are not adhered to by the conditions in the study area, Jacobson (1978) reported that all models for fractured aquifers may lead to drawdown behaviour that can also be found under other conditions than those assumed. In many cases boundaries, differing hydraulic conductivity distributions, leaky aquifers, fault and stratification can all lead to drawdown that may resemble the curves found for the given models of fractured formations. The drawdown behaviour produced by both the delated gravity response and heterogenous non-fractured aquifers are the same as some observed in fractured formations. Jacobson (1978) concluded that additional information from core samples and drilling logs from an aquifer is needed to help decide which model will best describe the aquifer.

7.2.5.1.2 Estimation of Transmissivity using Cooper-Jacob method

The FC spreadsheets developed by van Tonder *et al.* (1998) was used for the Copper and Jacob; Figure 69 (semi-log drawdown plot) shows the Cooper-Jacob fit at late time for the pumping borehole ST-PBH15 (an existing borehole). The fitted graph yielded a transmissivity value of 19.90 m^2/day. The sudden rapid increase in drawdown from 9.8-12.0 meter below static water level at time 540-600 minutes was considered unusual behaviour. The cause of this behaviour was not explained, the most likely reason may be incorrect recording by the data collector. The graph was fitted at the late time of the semi-log curve; this is in accordance with Kirchner and van Tonder (1995) and Kruseman and De Ridder (1994) for determining transmissivity values for estimation of the sustainable yield. The late time transmissivity is referred to as the matrix transmissivity, and the early time transmissivity as the fracture transmissivity (Kirchner and van Tonder, 1995). The matrix storativity is usually greater than fracture storativity in a fractured aquifer, thus the matrix has a greater influence on the long term exploitation potential of the aquifer (Vegter, 1995). The late time segment of the curve represents the average transmissivity that incorporates the influence of the boundaries and zones of lower transmissivity values.

For the purpose of illustrating; existing boreholes (ST-PBH15 and ST-PBH07) and one newly drilled borehole DT-14 (also ST-PBH29) were also used. Plots for borehole (DT-14 and ST-PBH07 were also fitted to further estimate the transmissivity values; shown in Figures 70 and 71, respectively. The fitted graph plots for both DT-14 and ST-PBH07 yielded transmissivity values of 4.30 and 36.40 m^2/day, respectively. Other transmissivity values for other boreholes determined by the Cooper-Jacob Method are shown in Table 16. The transmissivity values estimated from pump testing data ranged between 2.5 and 92.10 m^2/day, these estimates are within the expected range (5-100 m^2/day) determined by Rosewarne (2008) maps.

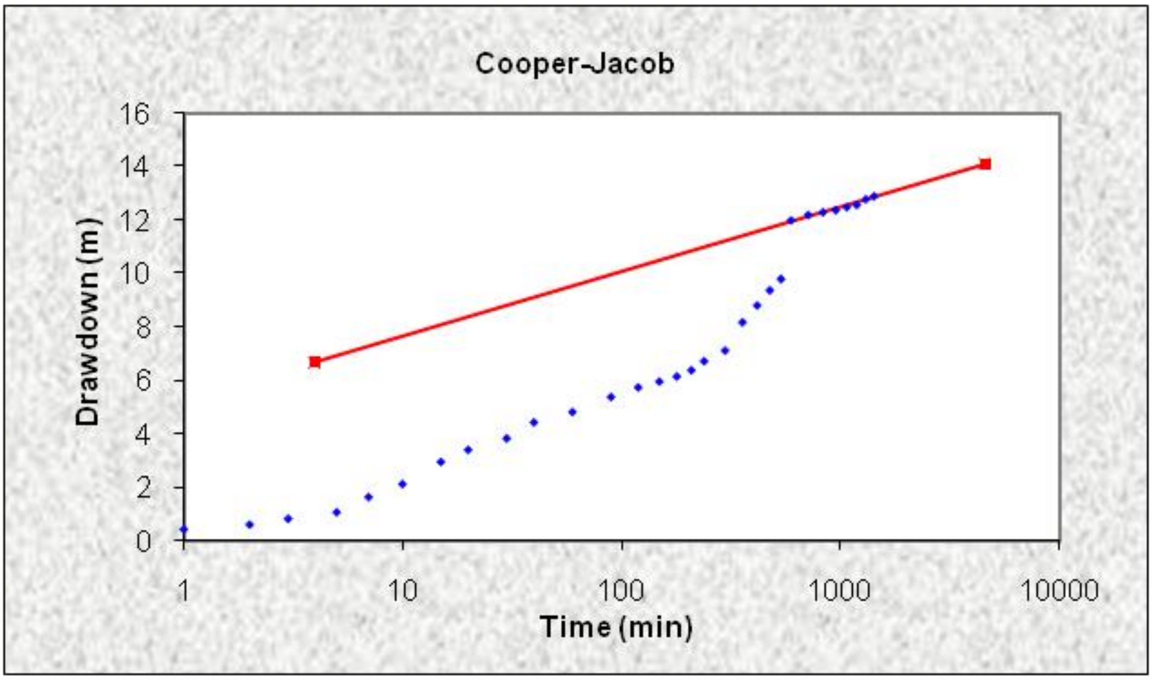


Figure 69: Cooper-Jacob fit for ST-PBH15 pumping borehole

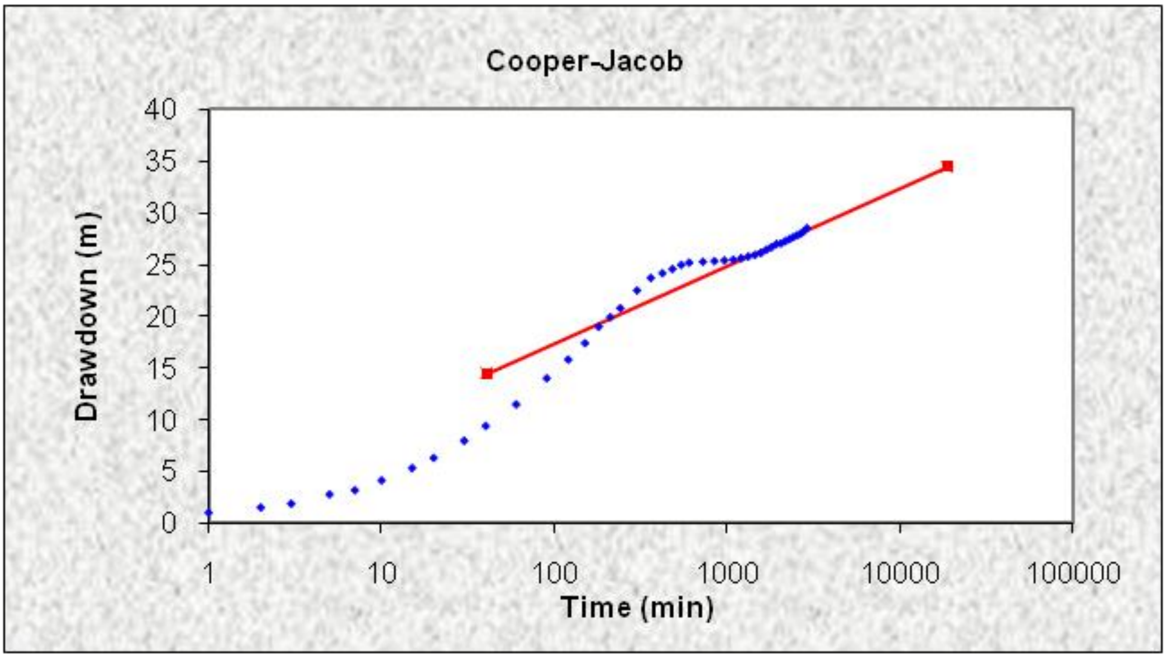


Figure 70: Cooper-Jacob fit for DT-14 pumping borehole.

The range of transimissivity from 5-100 m^2/day can be adopted as the expected transmissivity values for the aquifers in the study area. From the generalised transmissivity map there were areas indicated with an expected transmissivity values between 100-200 m^2/day (Rosewarne, 2008). From Table 16, transmissivity values estimated from the recovery test data ranged from 3.3-185.40 m^2/day.

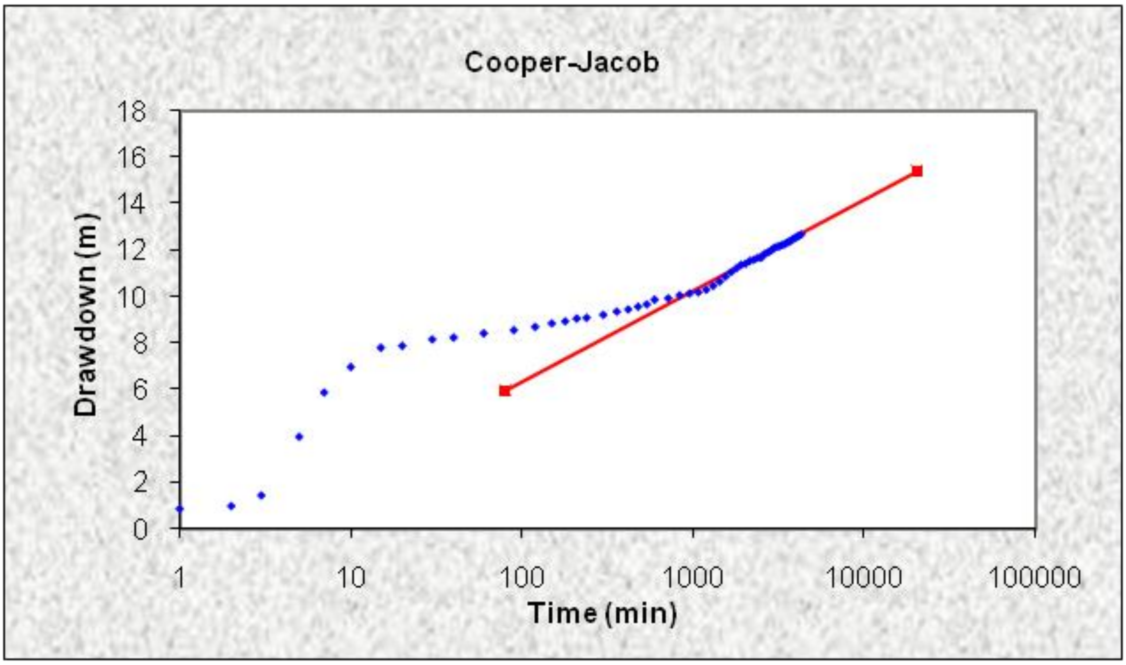


Figure 71: Cooper-Jacob fit for ST-BH07 pumping borehole.

As shown in Table 16; some T-values from recovery test are higher than those estimated from pump testing data; latter values are for the formation of the aquifer.

Table 16: Information of the aquifer parameters (Transmissivity values) estimated using Cooper-Jacob method

Name	Transmissivity (m²/d) (From Pump Test)	Recovery Test based Transmissivity (m²/d)
ST-PBH12	2.50	3.30
ST-PBH26	2.50	3.60
ST-BH09	3.60	14.02
ST-PBH33	4.20	1.30
ST-PBH28	90.10	160.50
ST-PBH29	4.30	3.20
ST-PBH32	18.50	20.2
ST-PBH11	11.10	12.30
ST-BH22	30.60	40.65
ST-PBH30	8.60	4.20
ST-PBH25	4.10	12.50
ST-PBH27	11.10	2.30
ST-PBH23	19.40	22.20
ST-PBH24	15.40	21.25
ST-PBH07	36.40	180.10
ST-PBH14	23.30	15.00
ST-PBH08	23.30	17.80
ST-PBH15	19.90	48.40
ST-PBH20	33.50	33.20
ST-PBH13	92.10	185.40

Storativity values were estimated using Cooper Jacob method (derived Equation 3 below):

$$S = \frac{2.30Q}{4\pi KD} \log \frac{2.25KDt}{r^2 S} \tag{2}$$

Where s is the drawdown in the borehole, Q is the abstraction rate of the pumping borehole, K is the hydraulic conductivity of the aquifer, D is the thickness of the aquifer or fracture, t is the time, S is the storativity of the aquifer and r is the distance from pumping borehole to adjacent borehole. For a fixed time t, a plot of drawdown versus the logarithm forms a straight line; if this line is extended until it intercepts the time-axis where s=0 m, the interception point has the coordinates s=0 and t=h. Substituting these values into Equation 2 gives Equation 3; which was used to calculate storativity values (Table 17) for some boreholes.

$$S = \frac{2.25KDt}{r^2} \tag{3}$$

7.2.5.2 RPTSOLV program

The RPTSOLV program (Verwey *et al.*, 1995) avoids the dependency of storativity on distance and homogeneity of the aquifer system in estimating storativity values. Particularly, the RPTSOLV program was used to avoid using the analytical method which do not cater for fractured porous mediums. Assumptions for analytical methods include a homogenous medium, especially on the scale of a pumping test; the fractured rock system violate this due to the horizontal movement in fractures and vertical leakage in the surrounding matrix which cannot be accounted for in analytical solutions.

ST-BH09, as the pumping borehole, was used to estimate the aquifer parameters. Observation borehole ST-BH08 was affected by the abstraction effects from the pumping of borehole ST-BH09. In the RPTSOLV program, the pump was assumed to be set at matrix and fracture position. The fracture was adopted as the observation position. The distance of 196 m from the observation borehole ST-BH08 to the pumping borehole ST-BH09 was used in the exercise. Table 17 shows aquifer parameters estimated using the RPTSOLV program and parameters estimated using the Cooper-Jacob method from the FC program.

Pumping boreholes ST-PBH15 and ST-PBH07 were also used to estimate aquifer parameters. The observation boreholes BH01 (privately owned borehole to which access was allowed for use), as well as ST-PBH06 and ST-PBH01 were affected by the abstraction effects from pumping boreholes ST-PBH15 and ST-PBH07, respectively.

Table 17: Aquifer parameters estimated using the RPTSOLV program and Cooper-Jacob method from the FC program

Site Name	T-Formation (m²/d)	S-Matrix	T-Formation (m²/d)	S-value
	RPTSOLV Parameters		Cooper-Jacob Method Parameters	
ST-BH08	4.21	9.32E-07	5.5	2.54E-05
BH01	9.87	3.60E-04	4.2	8.20E-05
ST-PBH06	35.19	2.01E-04	110.2	4.62E-04
ST-PBH01	30.86	8.81E-05	42.2	4.12E-04

The fractures were adopted as the observation position in both cases. The distance from the pumping boreholes ST-PBH15 and ST-PBH07 to the observation boreholes BH01, ST-PBH06 and ST-PBH01 are 60 m, 30 m and 54 m, respectively. These distances were used in the exercise. Table 17 above shows the aquifer parameters estimated.

The aquifer parameters estimated using both the RPTSOLV and the Cooper-Jacob method were compared. The estimated parameters (Table 17) for borehole ST-BH08, BH01 and ST-PBH01 were found to be close; particularly the transmissivity values suggested to be similar, with the exception of the aquifer parameters for borehole ST-PBH06 which were found to be different. The storativity estimated using the Cooper-Jacob method were found to be very higher than those estimated using RPTSOLV. It is important to note that the RPTSOLV program estimated for the storativity of the rock matrix, the fracture and rock matrix influence is different. In general, the storativity values estimated using RPTSOLV were found to be less than the values estimated using the Cooper-Jacob Method. The Cooper-Jacob method does not cater for the fractured porous aquifers in the study area, whereas the RPTSOLV program caters for the fractured rocks. The values estimated using the RPTSOLV program can be accepted as the more accurate values for storativity based on the limitation of the Cooper-Jacob method. However, both methods can be used for estimating aquifer parameters as they provide valuable information.

Figures 72 and Figure 73 illustrate the fitted models for exercise conducted using data from observation boreholes BH01 and ST-PBH06; respectively. It should be noted for the RPTSOLV program to accurately estimate aquifer parameters, storativity values particularly; it requires fitting of the model on the drawdown data for an observation borehole during an aquifer test.

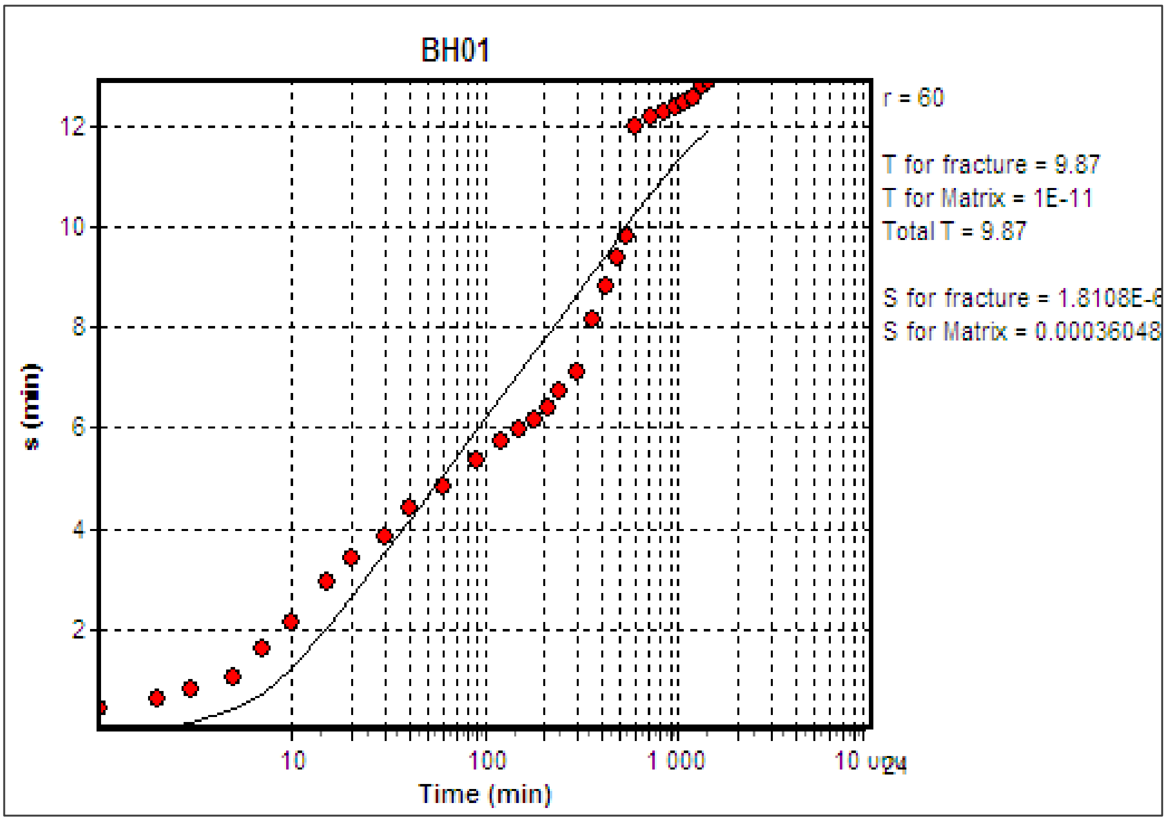


Figure 72: Graph fitted by the RPTSOLV program for observation borehole BH01.

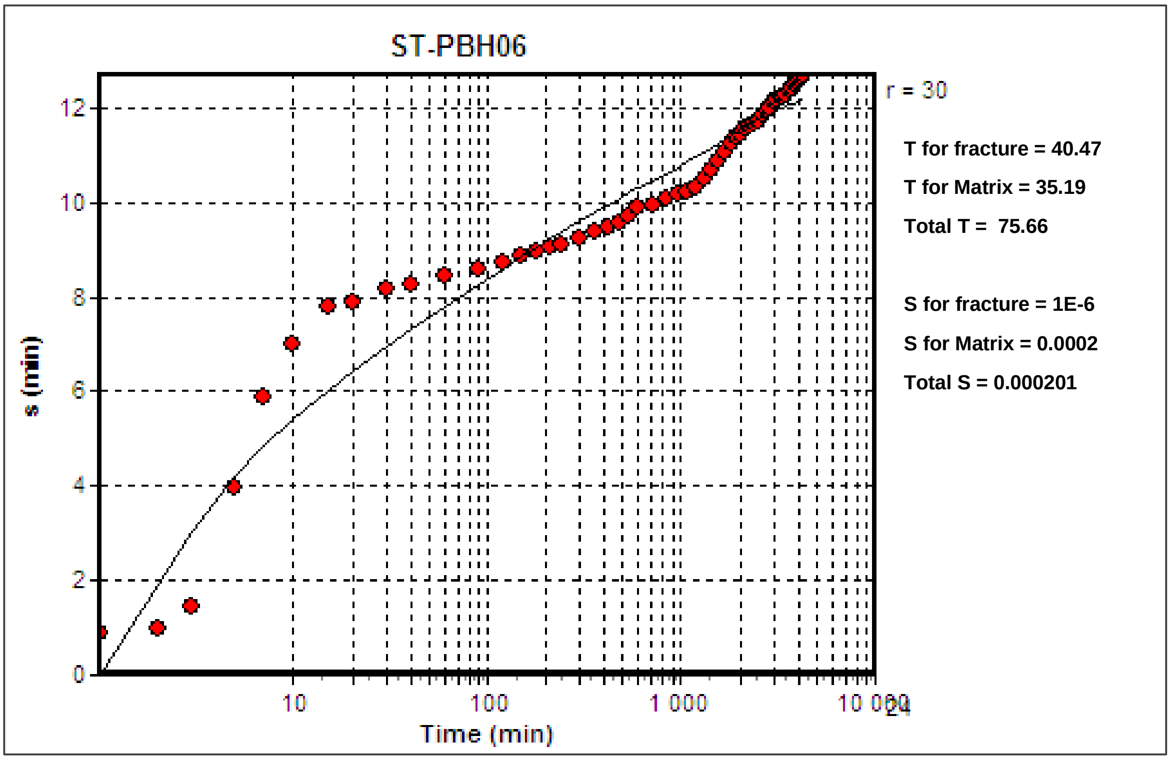


Figure 73: Graph fitted by RPTSOLV program for observation borehole ST-PBH06

The fitting of the drawdown data for estimating the storativity values on RPTSOLV is based on the program iterations and scenarios put in the program. The graphs presented (Figure 72 and Figure 73) were the best fitted on an evaluation of all the output the program generated.

7.3 SUMMARY

Chapter 7 describes the step drawdown, constant discharge rate and recovery tests conducted on the boreholes in Steynsrus. The pump test was used to estimate the sustainable yields of the boreholes, the aquifer parameters of the aquifers were also estimated.

Pumping tests were conducted for 20 boreholes; all of the boreholes are located within 15 km of the town Steynsrus. The aquifer test, which is referred to as the constant discharge test, was carried out. The aquifer test was preceded by the step discharge test to evaluate the borehole capacity (pump rate) at which the borehole could withstand without major fluctuation of water levels during pumping. Drawdown was also measured in adjacent observation boreholes during the constant discharge test. The influence on adjacent boreholes during aquifer testing was recorded for analysis.

The aquifers are generally characterised by fractures. The transmissivity values obtained from Cooper-Jacob were in the range of 2.5-92.10 m^2/day. This is an indication of very low to very high transmissivity values for fractured Karoo aquifers according to the maps by Murray *et al.* (2012).

Storativity values (S) obtained by the RPTSOLV program can be adopted as the expected values for a fractured rock system in the Karoo. The estimated S-values range from 9.32×10^{-7} to 3.60×10^{-4}. Fitting of the graph for determining of the storativity values was difficult; the reason could be attributed to the complex fractured aquifers and their behaviour which cannot be described by simplified analytical methods. The differences in the storativity and transmissivity values may signify that these boreholes do not withdraw water from the same aquifer, indicating the presence of different aquifer systems in the area and/or could also be due to variation of the fracture extend and different properties of the fracture networks. The next Chapter will discuss the estimation of the groundwater recharge and water balance of the study area.

CHAPTER 8 EXPLOITABLE GROUNDWATER RESOURCE

8.1 INTRODUCTION

Geohydrologists tend to combine the aquifer parameters and local geological information to determine the sustainable yield of the borehole. This includes an assessment of the pump test data, geological data, and climatic data. The aquifer pump test information is usually obtained from the step drawdown test, a constant discharge and a recovery test; these are used in correlation with the geological data to obtain the sustainable yield of the borehole.

This chapter will seek to estimate the groundwater recharge and sustainable yields of the boreholes, and further determine the water balance. The chapter will also look to highlight some of the challenges of using groundwater for water supply in the Steynsrus area.

8.2 RECHARGE ESTIMATION

Recharge is a phenomenon that can be influenced by meteorological and hydrogeological factors which may change spatially and temporally. These factors are important to understand and relate to determining the quantity of the groundwater recharge with confidence (Tóth, 1963). Recharge processes tend to be more complex in folded and fractured rock areas where effective recharge may tend to occur in the area with high density of fractures and percolate through fracture networks (Woodford and Chevallier, 2002). Recharge estimation for the purpose of this study was done using chloride mass balance and qualified guesses methods, in section 8.2.1 and 8.2.2, respectively.

8.2.1 Chloride Mass Balance Method

Aquifer recharge estimation in the Karoo is not different from other geological formations; except that the aquifers are typically covered by a thin layer of soil. This characteristic of Karoo aquifers limits the application of methods which relate to the unsaturated zone (Woodford and Chevallier, 2002). Woodford and Chevallier (2002) also stated that the fractured rocks and dolerite outcrops are regarded as preferential areas of recharge. The water quality balance using the chloride method (also known as the Chloride Mass Balance Method) was preferred to estimate the recharge in the study area over other methods due to the obtained data for this study. The Chloride Mass Balance Method (CMB) is easy to use and does not require storativity value (S-value) of the aquifer to estimate the recharge. The other mass balance method (groundwater balance method) can only be used to estimate groundwater recharge where long records on water level trends and abstraction rates are available (Woodford and Chevallier, 2002). These records were not available for this study.

Groundwater abstraction from an aquifer is considered to be a mixture of recent recharge and water stored in the aquifer. For this study, the mean rainfall chloride concentrations are 1.3 mg/L and 0.8 mg/L for winter (May) and summer (December) sampling regimes, respectively (DWAF, 2006). For the purpose of this study the former value was used as the samples were collected during the dry months. The mean annual precipitation used in this study is 563.8 mm/a (DWAF, 2006). The minimum recharge rate calculated using Equation 1 is 4.75 mm/a, and percentage recharge of 0.62% associated with sample ST-PBH14, the maximum recharge rate of 47.90 mm/a and a corresponding 8.50% is associated with sample ST-PBH29. The harmonic mean recharge rate is 16.95 mm/a corresponding to a percentage 3.00% (Table 18). The harmonic mean recharge was calculated using all the samples in the area; this was done to estimate recharge on a town scale.

It should be noted that the CMB method assumes the sole source of chloride is from precipitation; this makes the method easy to use for the study area. The other natural sources of chloride, such as rock weathering, irrigation and pollution, were assumed to be negligible. The CMB-method also assumes precipitation contributes to recharge; this tends to depend on the geological characteristic of the area. Mean annual precipitation values most closely estimate potential recharge for unconsolidated sediments; where infiltration varies depending on soil porosity and permeability, topography, storm intensity, and antecedent-moisture conditions (Allison and Hughes, 1978). Fracture flow and runoff become increasingly important, and in some cases flow along contact zones or fractures accounts for the bulk of infiltrating waters (Allison and Hughes, 1978; Stone, 1985; Gifford, 1985; Sharma, 1988).

The estimated recharge percentage using CMB method of 4.01% compares particularly well with the values of Vegter (1995) (5.67%), the first qualified guess estimate that can be used in the study area according to Woodford and Chevallier (2002). The qualified guess estimates for recharge will be discussed further in section 8.2.2.

Table 18: Estimated recharge values using Chloride Mass Balance Method

Borehole Name	Cl_{gw} (mg/L)	Cl_{rain} (mg/L)	Precipitation (mm/a)	Recharge (mm/a)	%Recharge
ST-PBH29	15.30	1.30	563.8	47.90	8.50
ST-PBH30	21.40	1.30	563.8	34.25	6.07
ST-PBH33	23.40	1.30	563.8	31.32	5.56
ST-PBH13	26.27	1.30	563.8	27.90	4.95
ST-PBH20	27.90	1.30	563.8	26.27	4.66
ST-PBH28	28.70	1.30	563.8	25.54	4.53
ST-BH22	29.00	1.30	563.8	25.27	4.48
ST-PBH27	30.10	1.30	563.8	24.35	4.32
ST-PBH23	32.01	1.30	563.8	22.90	4.06
ST-PBH08	32.13	1.30	563.8	22.81	4.05
ST-PBH24	33.06	1.30	563.8	22.17	3.93
ST-PBH32	34.50	1.30	563.8	21.24	3.77
ST-PBH11	36.35	1.30	563.8	20.16	3.58
ST-PBH26	37.30	1.30	563.8	19.65	3.49
ST-PBH25	40.19	1.30	563.8	18.24	3.23
ST-PBH12	40.37	1.30	563.8	18.16	3.22
ST-PBH07	45.20	1.30	563.8	16.22	2.88
ST-BH09	57.60	1.30	563.8	12.72	2.26
ST-PBH15	65.11	1.30	563.8	11.26	2.00
ST-PBH14	209.05	1.30	563.8	3.51	0.62
Recharge minimum (mm/a)	**3.51**				
Recharge maximum (mm/a)	**47.90**				
Harmonic Mean recharge (mm/a)	**16.95**				
%Harmonic Mean Recharge	**3.00**				

8.2.2 Qualified Guesses

The maps of Vegter (1995), Agrohydrological Model (ACRU: Agricultural Catchments Research Unit) and Harvest Potential were consulted to estimate area annual recharge rate; this method is referred to as qualified guesses estimations of recharge. Maps by Vegter (1995) were published by WRC; these maps were based on statistical analysis of data from approximately 120 000 borehole records. The maps included representations of the borehole prospects, saturated interstices, depth of groundwater level, mean annual groundwater recharge (shown in Appendix 5), groundwater component of river flow, groundwater quality, and hydrochemical types. Information that was collected from all these maps was later used to compile Groundwater Harvest Potential map by Baron et al., 1998); which is one of the maps used in Qualified Guess. The Groundwater Harvest Potential map estimated the total sustainable volume of groundwater that could be extracted annually for different areas in South Africa (Appendix 5). The ACRU map used as part of Qualified Guess were produced to determine the mean annual recharge based on the different soil profiles that the groundwater percolates and flow through into the vadose zone (Schulze, 2003).

Based on these maps (Appendix 5) and the position of the study area on these maps; estimates were determined. The qualified guesses for recharge values are shown in Table 19. The Vegter Method yields a much higher rate of 32 mm/a than the other methods. The average recharge from the methods in Table 19 is 22.3 mm/a corresponding to a recharge percentage of 3.96%.

Table 19: Recharge estimation using qualified guesses

Method	Recharge (mm/a)	Recharge as % of Precipitation
Vegter[1]	32.0	5.67
ACRU[2]	10.0	1.77
Harvest Potential[3]	25.0	4.43

[1]Vegter (1995); [2]Schulze (1995), and [3]Baron *et.al.* (1998)

The above estimated groundwater recharge (section 8.2.1) using the Chloride Mass Balance method suggests several constraints to the chloride method. First, the uncertainty in precipitation and chloride inputs limits the precision of long-term recharge-rates calculations because the calculations are highly sensitive to precipitation and chloride inputs. Therefore, these parameters should be assigned a range in values rather than a single, modern average; although the range in values may tend to underestimate or overestimate the recharge over the large area in question, however, it may be useful to provide a general recharge threshold for the particular area (Woodford and Chevallier, 2002). The range for the recharge estimated using the CMB method is 0.62-8.50% (corresponding 3.51-47.90 mm/a) of the precipitation of the area, and qualified guess recharge estimate is 1.77-5.67% (corresponding 10.00-32.00 mm/a).

Despite the constraints discussed, recharge rates calculated using chloride mass balance and qualified guess are comparable; the qualified guess estimates are more conservative in comparison to the CMB estimates. This may be due to the limited information that the maps used to estimate the recharge have. It should be noted that the validity of the assumption that all precipitation infiltrates into the sediments varies considerably with permeability and porosity, topography, and antecedent-moisture conditions. While limitations to both methods exist, recharge rates can be assumed to represent range of averages, based on the available information in this study.

8.3 GROUNDWATER RESOURCE SUSTAINABLE YIELD ESTIMATES

8.3.1 Borehole Recommended Yields

Sustanable yield is a phenomenon that has many different and at times ambiguous definitions. Kalf and Woolley (2005) reviewed the definitions and concepts of sustanable yields and evaluated if all groundwater systems can be made sustainable or not. However, for the purpose of this study sustainable yield definition explained by van Tonder *et al*. (2002) as the discharge rate that will not cause the water level in a pumping and adjacent boreholes to drop below a prescribed limit of importance to the aquifer. Determining the sustainable yield of a borehole is important for the overall management of the aquifer. Sustanable yield can be influenced by factors such as recharge, aquifer parameters and geological setting. These factors are very important in estimating, and validating the sustainable yield.

For the purpose of this study, the FC program developed by van Tonder *et al.* (1998) was used. It is easy to use, incorporates the effects of well-losses, the rate of water level recovery is considered, incorporates various other characteristic flow regimes and methods and the influence of adjacent boreholes.

Sustainable yield is estimated as the ratio of the pumping and available drawdown s if pumping rate Q is a constant for a well, as defined below in Equation 4. The available drawdown could be the position of the main water strike in the borehole; if the drawdown reached this point; a drastic decrease in the yield of the borehole would occur (van Tonder *et al.,* 1998).

$$Q_{\text{sustainable}} = Q_{\text{Pumping Test}} \frac{s_{\text{Available}}(t=t_{\text{long}})}{s_{\text{Pump Test}}(t=t_{\text{long}})} \quad (4)$$

There exist a problem of extrapolating the drawdown measured during the pumping test from the end of the test to a time (t_{long}) of two to five years. The extrapolation of the measured pumping test drawdown if t_{long} describes the maximum operation time in which the drawdown s shall not exceed a maximum drawdown $s_{Available}$ to determine the sustainable yield $Q_{sustainable}$, as defined in Equation 4 (van Tonder *et al.*, 1998). The extrapolation of the pumping test drawdown is traditionally applied through Theis solution which assumes an aquifer of a infinite extent (van Tonder *et.al.*, 1998). The drawdown measured during pumping test is the sum of the drawdowns due to the production well, s_{well}, and the boundaries, $s_{boundary}$; decribed in equation (5).

$$s(t = t_{long}) = s_{well} + s_{boundary} \qquad (5)$$

An extrapolation of the pumping test drawdown beyond the time of the end of the measurement is obtained by using a Taylor series expansion in Equation 6 around the late measurement points (at $t = t_{EOP}$) based on the measured drawdown curve of the production well (s_{well}) including drawdown derivatives, and by accounting for boundaries (van Tonder *et.al.*, 1998).

$$s_{Well}(t = t_{long}) \approx s(t = t_{EOP}) + \frac{\partial s}{\partial \log t}\Big|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP}) + \frac{1}{2}\frac{\partial^2 s}{\partial(\log t)^2}\Big|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP})^2 \qquad (6)$$

The effects of the boundaries can only be deduced at the late times of the pumping test; extrapolation of s (t) therefore does not in general include boundary information. For the effects of the boundaries of the ($s_{Boundary}$); an image well theory is applied (van Tonder *et.al.*, 1998). Table 20 lists the variables that are inserted into FC program and how they are determined for estimating sustainable yield of a borehole.

Table 20: List of the variables in estimating sustainable yield of a borehole on FC program

Variables	Description
Extrapolation time in years	The time of the pumping.
Effective borehole radius (r_e)	Determined using the derivative values and the thickness of the fracture zone.
Q (l/s) from pumping test	Pumping rate used during the pumping test
s_a (available drawdown),	The distance from the Rest Water Level to the Main Water strike.
Annual effective recharge (mm)	The mean annual recharge is inserted if known.
t(end) and s(end) of pumping test	The end time t and drawdown s after pumping test.
Average maximum derivative	Determined using mathematical expansions integrated on FC.
Average second derivative	Determined on FC. If the value is a negative.
Derivative at radial flow period	Determined from derivative plot on FC program where s' is horizontal.
Transmissivity and Storativity estimates from derivatives	Early T-value estimated from the derivative at radial flow period, and the late T-value from the average maximum derivative. S-values can be determined from RPTSOLV program.

For a basic solution in FC Program, sustainable yield is estimated using the derivatives and subjective information about the boundaries. If valuable information exists about the boundaries, an "Advanced Solution" for estimating sustainable yield is proposed in FC program; using the derivatives, knowledge on the boundaries and influence of other boreholes (Van Tonder et al., 1998; Van Tonder et al., 1999).

Table 21 shows the estimated sustainable yields using the FC Method for a pumping cycle of 24 hours. The sustainable yields estimated by the FC program range from 0.47–2.42 L/s per 24 hour pumping cycle. Some of the parameters which affect the sustainable yield which was estimated using the FC Method, are listed in Table 21.

Table 21: Estimated sustainable yields using the FC Method, and other FC Method parameters

Name	FC Average sustainable yield (L/s)	FC_Method parameters				
		Extrapolation time (years)	Available drawdown (m)	Average maximum derivative (m)	Average second derivative (m)	Derivative at Radial Flow Period (m)
ST-PBH12	0.47	2	16.9	16	0.1	4.7
ST-BH22	0.76	2	15.8	40.2	0	0.85
ST-PBH25	0.82	2	22	25.3	0.1	3.48
ST-PBH15	0.88	2	12.9	15.4	0	2.92
ST-PBH26	0.5	2	32.3	16	0	7.1
ST-PBH27	0.5	2	14.1	5	0	2.38
ST-PBH29	0.5	2	23.7	8	0	8.89
ST-PBH20	0.91	2	5.5	4.4	0	1.17
ST-PBH24	1.06	2	13.5	5.3	0	3.07
ST-PBH33	0.6	2	25.6	12	0	10.68
ST-PBH28	0.75	2	26.1	20	0.2	1.7
ST-PBH30	0.9	2	19	6.9	0	5.48
ST-PBH32	1	2	21.8	20	0.1	2.96
ST-PBH07	2.42	2	12.7	8.9	0.1	2.29
ST-PBH13	3	2	5.2	3.4	0	0.83
Total (L/s)	15.07					
Amount of water (L/day)	1302048					

8.3.2 Water Balance

The saturated water balance method which is often used by geohydrologists (Woodford and Chevallier, 2002) for determining aquifer recharge for Karoo fractured aquifers was used to obtain the exploitable groundwater resource and the shortfall in Steynsrus. Monokofala (2010) found the method useful for assessing the available groundwater resources in his study. The method is described by the following equation:

$$\text{Inflow} - \text{Outflow} + \text{Re} - \text{Q} = \text{S}.\frac{\text{dV}}{\text{dt}} = \text{Balance}\ (\text{Q}_{\text{balance}}) \qquad (7)$$

Where:

dV (Groundwater Volume of the area) = A.dh where A is the aquifer area and dh is the change in the hydraulic head,

dh (Change in hydraulic head) = the fluctuation in saturated volume of the aquifer based on groundwater. Level fluctuations (dh) integrated for points spread over the aquifer (m).

S (Storativity) = Storativity of the aquifer

Re (Re is Recharge of groundwater) = represents the effective recharge; groundwater recharge with the evapotranspiration losses accounted for (ML/day).

Q = represents the abstraction of groundwater from boreholes (ML/day).

Inflow and Outflow = represents groundwater from other natural factors such as evapotranspiration and frost and springs (in ML/day)

For the purpose of this study from Equation 7, the information of the inflow that could arise in the form of dew and/or frost was unavailable and was considered to be negligible to attempt to justify the determined water balance with the available information. The natural discharge or outflow in the form of groundwater evaporation was obtained from DWAF (2006), with an estimated value of 0.11 mm/a for quaternary catchment C60E with an area extent of 664 Km^2. The system tends to undergo a water level decrease due to abstraction; if the decrease persists to the extent of exceeding the recharge; the aquifer would be mined out. Water balance gives an overview of how much water is available for use in a system; thus it was important to determine for the study area.

It should be noted that the mean recharge for the area was used as the effective recharge value in the area. Effective recharge takes into consideration the infiltration of rainfall into the local ground water table. The area extent of the Steynsrus was obtained from Google Maps; Table 22 gives a summary of the water balance estimated in the study area; with surface area extent of 16 Km^2. The current shortfall of 0.60 ML/day was estimated based on the exploitable amount of groundwater that could be abstracted from the recommended sustainable yields (1.30 ML/day) (Appendix 9).

Table 22: Summary of water balance in Steynsrus study area

Unit area	[1]Evapo. Rate (ML/day)	Recharge (ML/day)	Recommended sustainable yields (ML/day)	Water demands (ML/day) (DWA, 2011a)		Shortfall (ML/day) (DWA, 2011a)		Exploitable balance (ML/day)
Year				2013	2030	2013	2030	2030
Steynsrus & Matlwangtlwang	0.0048	1.4	1.30	2.00	2.20	0.7	0.90	-0.80

[1]Evapo. Rate: represents the mean groundwater evaporation of the area by DWAF (2006).

This implies that currently there is a deficit of 0.70 ML/day to supply the town water demands if the available water sources (boreholes) were used as recommended.

It is important to note that the recommended sustainable yields were based on the estimates made in section 8.3. The water demands used in this study were obtained from DWA (2011a); using the estimated and projected population. Based on the water demands estimated and projected for 2013 and 2030, the shortfall of the amount of water Steynsrus requires in meeting the water demands are 0.70 ML/day and 0.90 ML/day for the year 2013 and 2030 (Appendix 9), respectively. This means Steynsrus does not meet its water demands in 2013 and would not meet the projected future water demands if the available groundwater resource were exploited for water supply.

The exploitable groundwater resource in the study area was estimated to be in deficit of 0.60 and 0.80 ML/day for current and future (2030) water demands (Appendix 9). In other words if the available resources were exploited to meet the current and 2030 water demands, the decrease in the available aquifer storage would be 0.60 and 0.80 ML/day; respectively. These calculations were based on the groundwater recharge of 1.34 ML/day, bearing in mind that the estimation was done based on the groundwater recharge of the Steynsrus area of 16 km^2. This is a preliminary guidance that the groundwater resources in Steynsrus may not be sufficient to meet the current and future demands.

8.4 SUMMARY

Chapter 8 provides a detailed description of the recharge estimated using different methods, in particular Chloride Mass Balance method and the Guess Estimate method by Vegter (1995). This was done using the groundwater quality and available hydrogeological information of the study area. The water balance of the study area was also estimated using the population of town; to assess the water demands in the town. Recharge guess estimates by CMB method ranged from 1.77 to 5.67%. These estimates are comparable to previous studies in the Karoo with a similar semi-arid climate and geological setting; studies in Trompsburg and Dewetsdorp were estimated at 2.35–4.5% (Woodford and Chevallier, 2002) based on the mean annual precipitation of 400-470 mm/a, which is less than the mean annual precipitation (MAP) of 584 mm/a.

Sustainable yields estimated from the FC program ranged from 0.47 to 3.00 L/s. These are relative yields expected in the Karoo with limited recharge; expected range is 0.1–5.00 L/s for the Beaufort Group (DWAF, 2003a). The approach used in recommending municipal production and standby boreholes considered a borehole with sustainable yields less than 1.0 L/s for a 12-hour pumping cycle per day as interim use only; boreholes with at least 1.0 L/s for a 12-hour pumping cycle were considered suitable for long-term production; and 24-hour pumping cycles were used to avoid the intermittent pumping of boreholes which has been found to lead to over-abstraction of boreholes in poorly managed well-fields in the Karoo (Murray *et al.*, 2012).

The 2030 exploitable groundwater resource in the area according to the water balance using the area extent of Steynsrus (of 16 km^2) is in deficit of 0.80 ML/day. The next Chapter gives details on the groundwater quality assessment of the study area; recommendations on the drinking water will also be discussed.

CHAPTER 9 HYDROCHEMISTRY

9.1 INTRODUCTION

Water samples were collected during the hydrocensus and pump testing of the existing and newly drilled boreholes, by taking a pumped sample from the borehole outlet and taps. The majority of the boreholes had pump equipment installed which are only accessible via pumping. Purging was conducted before collection of samples as it is general protocol in collection of samples (Weaver *et al.,* 2007). The samples were preserved by storing the samples in cooler box with ice at a temperature of 4˚C before they were submitted to the Institute for Groundwater Studies Laboratory at the University of Free State in Bloemfontein for analysis.

The major and minor ions analyses were performed. The chemical variables analysed were based on the understanding of domestic water use guidelines and the historical chemical data of the area. The sampling and chemical analyses of groundwater in the area were conducted to assess and evaluate the general groundwater quality and identify any emanating issues with the groundwater quality and recommend accordingly for the domestic water use. A total of 25 samples were analysed for the study area, samples were collected once per season in March-April in 2012 and June-July in 2013.

9.2 STATISTICAL ANALYSIS

9.2.1 Univariate Statistics

A univariate statistical overview of the groundwater dataset is presented in Table 23. The concentrations of Na^{+} in the samples are in the range of 37.15 to 161.00 mg/L. The highest Na^{+} concentration was observed in ST-PBH33, newly drilled borehole also named DT-17, and the lowest Na^{+} concentration was observed in ST-PBH07, formerly used production borehole near the waste water treatment works. The concentrations of Cl^{-} are in the range of 15.30 to 209.05 mg/L. The highest concentration was observed in ST-PBH14 and the lowest was observed in the newly drilled borehole ST-PBH29 (also named DT-14).

Table 23 shows pH between 6.89 and 9.20 and Total Alkalinity of 404.00 mg/L; the high Total Alkalinity implications will be discussed further below. The Total Dissolved Solids concentration is between 405.30 and 1225.70 mg/L, the samples will be classified by TDS concentration in subsection 9.3.1.

This section was important to determine the range and other statistical variables to ascertain the quality of the chemistry dataset.

Table 23: Univariate statistical overview of the groundwater chemistry data set

Variable	N	Mean	Standard deviation	Minimum	Median	Maximum
pH	25	7.47	0.48	6.89	7.38	9.20
EC	25	75.49	23.22	47.40	70.70	175.10
TDS	25	536.00	157.33	405.30	494.90	1225.70
Ca^{2+}	25	56.89	29.38	1.52	57.56	163.00
Mg^{+}	25	26.26	14.30	0.42	26.22	73.90
Na^{+}	25	72.94	30.82	37.15	64.08	161.00
K^{+}	25	2.71	1.60	0.42	2.32	7.62
Cl^{-}	25	41.33	36.54	15.30	32.60	209.05
SO_4^{2-}	25	54.54	37.31	3.42	40.90	185.64
F^{-}	25	0.67	1.19	0.00	0.30	5.87
NO_2-N	25	0.01	0.00	0.01	0.01	0.02
NO_3-N	25	3.72	12.14	0.05	1.32	61.61
NH_4-N	25	0.15	0.09	0.04	0.12	0.41
PO_4^{-}	25	0.33	0.41	0.10	0.10	1.00
Alkalinity	25	299.92	32.24	250.00	295.00	404.00
Fe^{2+}	25	0.04	0.06	0.01	0.02	0.30
B	25	0.88	3.78	0.04	0.10	19.00
Mn^{2+}	25	0.20	0.79	0.00	0.03	4.00
As	52	0.01	0.00	0.01	0.01	0.01
Total hardness	25	249.91	130.22	5.52	256.32	710.50

*All values in mg/l except for pH values and depth to water level as indicated as meters below ground level.

9.2.2 Quality of Inorganic Chemistry Data

It was important to ascertain the data quality before any manipulation and projections was done on the chemical data. The reliability of chemical data can be checked by computation of ionic charge balance error (Mandel and Shiftan, 1981 and Lloyd and Heathcote, 1985). If the ionic charge balance error of a chemical data-set is more than 5% it makes the quality of analysis questionable. If the ionic balance error is more than 5% then the analytical analysis for the individual ions may be in error or an important constituent of the solution may not have been included in the Reaction Error calculation (Mandel and Shiftan, 1981). In the present study, the ionic balance error criteria were applied to chemical analyses of each dataset. Reaction errors are shown in Appendix 6, with a range between -4.88 and 4.64%. The chemical data for all the samples were of acceptable quality; within the 5% ionic charge balance.

9.3 GROUNDWATER QUALITY

Drinking water quality guidelines are aimed at protecting public health and preventing any possible water related health issues. The guidelines for South Africa (DWAF, 1996b) provide the limits of variables which should be accepted for domestic, industry and agriculture water use. However, these limits do not necessarily imply that there would be health risks if the values were exceeded. The World Health Organization (WHO) Guidelines for Drinking-Water Quality (2011) provide the limits of elements and adverse health effects associated with exceeding the limits. The WHO guidelines were aimed at providing recommendations for managing the risk from hazards that may compromise the safety of drinking water.

Samples indicated as suitable and unsuitable for human consumption are listed in Table 18 according to the WHO (2011) guidelines, as well as the guidelines set by DWAF (1996b), SANS (2006), and SANS, 2011), which are listed below as well as in Appendix 7 and 8. The categorising of the samples according to classes was conducted through SANS241: 2006 and SANS241-1: 2011. Class 1 category implies that the water quality is recommended for lifetime use, Class 2 category implies that the water quality is marginal, Class 3 category is poor water quality and Class 4 category is unacceptable water quality. The described ARS (Above Recommended Standard) class water quality implies that the water quality is above the recommended standards limit of SANS241-1:2011, and are thus not recommended for domestic use without treatment.

Poor to unacceptable water quality limit (>1 mg/L) for Fluoride ions concentration were detected in samples ST-BH09, ST-PBH26, ST-PBH29 and ST-PBH33; in Table 24. ST-PBH33 showed the highest concentration of Fluoride ions of 5.87 mg/L; Class 4 water quality. Fluoride is a common constituent in groundwater; it is associated with natural sources such as rocks and volcanic activity, and agricultural use of phosphatic fertilizers and industrial activities such as burning of coal (WRC, 2001). Continued consumption of higher fluoride concentrations in water can cause dental fluorosis and in extreme cases even skeletal fluorosis. The high fluoride concentrations in the above samples were considered to be brought by the contamination of a natural source i.e. the dolerite intrusion (WRC, 2001).

Table 24: Water quality classes according to SANS241:2011

Site Name	pH	EC	TDS	Total Alk	Na	Ca	Mg	K	Cl	SO4	F	NO3-N	NH4-N	Fe	Mn	Tot. Hard
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/l	mg/L	mg/L	mg/L
ST-BH08	7.18	67.90	475.30	293.00	59.31	68.97	28.42	2.55	32.13	38.29	0.26	1.99	0.14	0.01	0.00	288.94
ST-BH09	7.54	65.50	458.50	255.00	72.87	49.08	20.77	1.68	57.60	20.65	2.19	0.44	0.17	0.01	0.00	207.84
ST-BH11	7.19	72.50	507.50	307.00	49.50	64.00	28.70	3.75	36.35	38.26	0.41	1.32	0.06	0.02	0.03	277.67
ST-BH19	7.48	79.40	555.80	358.00	52.69	71.09	34.64	2.14	23.00	65.00	0.26	0.75	0.36	0.03	0.04	319.76
ST-BH21	7.34	70.70	494.90	314.00	43.02	62.61	32.02	2.28	32.00	35.00	0.28	1.53	0.41	0.02	0.02	287.82
ST-BH22	7.37	69.50	486.50	312.00	41.70	57.56	28.84	2.11	29.00	34.00	0.21	1.47	0.04	0.02	0.02	262.15
ST-PBH07	7.25	70.70	494.90	273.00	45.40	58.89	38.22	1.32	39.14	74.00	0.16	0.08	0.16	0.02	0.19	303.92
ST-PBH12	7.57	74.40	520.80	292.00	87.11	55.23	23.57	2.18	40.37	69.20	0.40	0.05	0.20	0.01	0.05	234.73
ST-PBH13	7.06	73.80	516.60	319.00	50.50	65.90	29.40	3.86	26.27	48.89	0.24	2.19	0.07	0.02	0.04	285.29
ST-PBH14	7.15	175.10	1225.70	276.00	86.16	163.00	73.90	4.07	209.05	185.64	0.00	61.61	0.09	0.02	0.01	710.50
ST-PBH15	7.30	107.10	749.70	404.00	92.87	84.30	41.15	1.70	65.11	79.26	0.07	3.04	0.08	0.02	0.03	379.45
ST-PBH20	7.23	69.80	488.60	303.00	41.04	63.50	29.50	2.98	27.90	33.96	0.18	1.50	0.07	0.02	0.03	279.71
ST-PBH23	7.24	75.50	528.50	326.00	61.59	63.70	27.03	3.39	32.01	40.48	0.30	1.93	0.05	0.03	0.01	270.09
ST-PBH24	7.39	70.60	494.20	285.00	63.90	57.30	22.33	2.44	33.06	49.63	0.39	1.77	0.11	0.02	0.02	234.81
ST-PBH25	7.43	85.50	598.50	301.00	89.46	66.80	21.78	4.55	40.19	114.80	0.29	0.05	0.09	0.01	0.07	256.32
ST-PBH07	7.47	73.70	515.90	288.00	37.15	55.06	40.35	1.26	45.20	70.30	0.13	0.05	0.14	0.30	0.10	303.09
ST-PBH12	7.67	73.70	515.90	280.00	91.62	39.87	17.73	1.13	41.20	66.90	0.34	0.05	0.20	0.03	0.07	172.37
ST-PBH26	7.41	72.10	504.70	295.00	82.73	40.58	17.47	7.62	37.30	32.30	1.06	4.24	0.12	0.17	0.02	173.08
ST-PBH27	7.26	77.90	545.30	324.00	64.08	59.25	26.22	5.04	30.10	65.30	0.37	1.67	0.11	0.02	0.01	255.63
ST-PBH28	7.38	67.90	475.30	297.00	49.60	54.23	25.70	2.32	28.70	38.80	0.30	1.25	0.09	0.02	0.01	240.95
ST-PBH29	8.61	57.90	405.30	287.00	141.83	1.52	0.42	0.61	15.30	3.42	1.71	0.05	0.25	0.05	0.01	5.52
ST-PBH30	7.63	60.30	422.10	277.00	108.76	21.70	7.74	1.45	21.40	26.30	0.38	0.08	0.21	0.02	0.05	85.98
ST-PBH31	7.47	67.30	471.10	267.00	67.66	43.27	21.04	2.66	32.60	40.90	0.55	5.65	0.09	0.02	0.04	194.44
ST-PBH32	6.89	67.90	475.30	250.00	81.83	51.29	17.95	4.21	34.50	87.70	0.29	0.08	0.14	0.06	0.12	201.82
ST-PBH33	9.20	67.60	473.20	315.00	161.00	3.60	1.70	0.42	23.40	10.51	5.87	0.07	0.21	0.12	0.00	15.97
Class 0	5.0-9.5	<70	<450		<100	<80	<70	<25	<100	<200	<0.7	<6	<1.0	<0.5	0 - 0.1	0 - 200
Class 1	4.5 - 5 & 9.5 - 10	70 - 150	450 - 1000		100-200	80-150	70 - 100	25-50	100-200	200-400	0.7 - 1.0	6.0-10	1.0 - 1.5	0.5 - 1.0	<1.5	200 - 300
Class 2	4.0 - 4.5 & 10 - 10.5	150 - 370	1000 - 2400		200-400	150-300	100 - 200	50-100	200-600	400-600	1.0 - 1.5	10.0-20.0	>1.5	1.0 - 5.0	1.5 - 4	300 - 600
Class 3	3 - 4 & 10.5 - 11	370 - 520	2400 - 3400		400 - 1000	>300	200 - 400	100 - 500	600 - 1200	600 - 1000	1.5 - 3.5	20 - 40		5.0 - 10	4.0 - 10	>600
Class 4	< 3 & >11	>520	>3400		>1000		>400	>500	>1200	>1000	>3.5	>40		>10	>10	

Key:

Class 0	Very Good Water Quality
Class 1	Good Water Quality
Class 2	Permissible Water Quality
Class 3	Unacceptable Water Quality
Class 4	Unacceptable Water Quality

There were no anthropogenic activities that were reported nearby the boreholes to suggest as the cause for the contamination of fluorides. Borehole logs for DT-03 and DT-14 in Figure 53 and Figure 54, respectively, show the dolerite intrusion intersected during the drilling of the boreholes; this is supports the suggestion that the contamination of fluoride in the boreholes may have been caused by natural source.

Dolerite deposits consist of mineral called fluorapatite which contains fluoride in the form of CaF_2. In groundwater, the ionic compounds of fluoride dissolve (WRC, 2001). The concentrations of fluoride in the groundwater have been shown to be limited by the mineral's solubility. In the absence of calcium in solution, allows high concentrations of fluoride (Edmunds and Smedley, 1996); this can be proven with the results for ST-PBH29 (also named DT-14) and ST-PBH33, the fluoride concentrations were 2.19, 1.17, and 5.87 mg/L; respectively. The high fluoride concentrations (for ST-BH09, ST-PBH29 and ST-PBH33) correspond with the low calcium concentration of 1.52 and 3.60 mg/L

Table 24 also shows high (>40 mg/L) nitrate ions (NO_3^-) concentration in sample ST-PBH14; which is classified as Class 4 (unacceptable water quality). The elevated nitrate concentration in ST-PBH14 is suggested to be due to the nearby sewage line and Waste Water Treatment Works (WWTW); disposal of the effluents by spreading of the sludge on the field. The elevated Total Dissolved Solids (TDS) in sample ST-PBH14 is also attributed to the sewage sludge. High Total Hardness concentration of 710.50 mg/L was also detected in sample ST-PBH14, the concentration is above the SANS241 (2011) limit of 600 mg/L deeming the water quality "Unacceptable" as mentioned above. The geological logs were unavailable for borehole ST-PBH14 to provide guide as to what could have caused the high concentration of Total Hardness.

Ferrous (Fe) ion and Manganese (Mn) ion are present as trace elements (Table 24). Manganese is relatively low in all samples except for ST-PBH07 and ST-PBH32 in which 0.189 and 0.122 mg/L were measured, respectively; slightly exceeding the SANS241-1: 2011 limit of 0.1 mg/L. Manganese is the only aesthetic parameter which contributes significantly to the taste, smell and colour of the water. The nitrates as nitrogen concentrations are generally low, except in municipal borehole ST-PBH14 where 61.61 mg/L was measured, and is well above the SANS241: 2006 of 10 mg/L.

Total Dissolved Solids (TDS) concentration in the study area is predominantly classified as drinkable water. Based on the TDS classification by Davis and De Wiest (1996) shown in Table 25, 94.12% of the groundwater sites sampled in June-July 2012 are suitable for drinking, whilst 5.88% can be useful for irrigation. For the samples analysed in June-July

2013 in Table 26; all of the groundwater sites are suitable for drinking according to TDS classification by Davis and De Wiest (1996). Groundwater temperatures vary from 14.20 to 23.00 ˚C with lower temperatures associated with winter season, i.e. sampling was done in March-April 2012 and June-July 2013. The pH in the area ranges from 6.89 to 9.20 with a mean of 7.47 pH value showing that the groundwater is slightly alkaline; an indication that the dissolved carbonates are predominantly in the HCO_3^- form.

Table 25: Classification of water quality based on total dissolved solids for samples collected in March-April 2012.

TDS (ppm)	Water Type	Percentage (%)
Up to 500	Desirable for drinking	41.18
500 to1 000	Permissible for drinking	52.94
<3 000	Useful for irrigation	4.88
>3 000	Unfit for drinking and irrigation	0

Source: Davis and De Wiest (1996).

Table 26: Classification of water quality based on total dissolved solids for samples collected in June-July 2012.

TDS (ppm)	Water Type	Percentage (%)
Up to 500	Desirable for drinking	75.00
500 to1 000	Permissible for drinking	25.00
<3 000	Useful for irrigation	0
>3 000	Unfit for drinking and irrigation	0

The total hardness of the groundwater ranges between 5.52 and 710.50 mg/L (Table 27). The total hardness measurements thus are classified as very ‘soft’ to ‘ very hard’, based on the criteria by Durfer and Becker (1964). The water quality is predominantly (56% of the samples) classified as good quality based on the total hardness. There was a sample with concentration above >600 mg/L as discussed earlier.

Table 27: Total hardness classification of water quality based on DWAF (1998) for all samples collected.

Total Hardness (mg/L)	Water Type	Percentage (%)
0-200	Ideal water quality	24
200 to 300	Good water quality	56
300 to 600	Marginal water quality	16
600	poor water quality	4

9.3.1 Irrigation suitability

Fipps (2003) indicated in his standards for irrigation water quality that water samples containing high Na^+ concentration tend to have a pH above 8.5. Sodium content (%Na) is expressed in terms of the following, Equation 9:

$$\%\mathrm{Na} = \frac{(\mathrm{Na}^{+}+\mathrm{K}^{+})}{(\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}+\mathrm{Na}^{+}+\mathrm{K}^{+})} \mathrm{x}\ 100 \qquad (8)$$

All ionic concentrations are expressed in mg/L.

The sodium percentage method (Equation 8) is used to determine the soluble sodium content with respect to other major ions. Samples are classified into four categories based on restriction on water use; first category is deemed ‘low’ with %Na below 20, second category is ‘moderate’ with %Na between 20-40, third category is ‘high’ with %Na between 40-80, and fourth category is ‘very high’ with %Na above 80.

When the concentration of sodium ion is high in irrigation water, Na^+ ions tend to be absorbed by clay particles, displacing Mg^{2+} and Ca^{2+} ions. This exchange process in soil reduces the permeability and eventually results in soil with poor internal drainage.

Sodium %Na values estimated (Appendix 6) indicate more than 46% of the groundwater samples analysed are suitable for irrigation, with the exception of samples ST-PBH29 and ST-PBH33, with $\%Na^+$ concentrations of 98.66 and 96.82%, respectively; category 4 with very high degree of restriction of the water use. This is supported by the pH above 8.5; for samples ST-PBH29 and ST-PBH33 pH values are 8.61 and 9.20, respectively.

The suitability for irrigation of the water in the study area is further assessed through the salinity hazard (also known as the Sodium Adsorption Ratio) in Figure 74. The Sodium Adsorption Ratio (SAR) ranges from 0.51 to 103.3 (Appendix 4); with a low of 0–10 SAR, medium of 10-18 SAR, high of 18-26 SAR and a very high of SAR above 26 (Khodapanah, Sulaiman and Khodapanah*,* 2009) (Figure 74). The groundwater that falls within the medium SAR and lower (Class 2) can be used in most cases without any special practices for salinity control (Khodopanah *et al.*, 2009). Consequently, water samples that fall in the high salinity hazard class (Class 3) may be detrimental to sensitive crops. If these samples were used for irrigation of crops, careful management practices would be required. The very high salinity water (Class 4) is not suitable for irrigation for crops, except for salt tolerant crops. The SAR mean of 7.01 for the study area generalise the water quality in the study area suitable for irrigational purposes with the exceptions mentioned above.

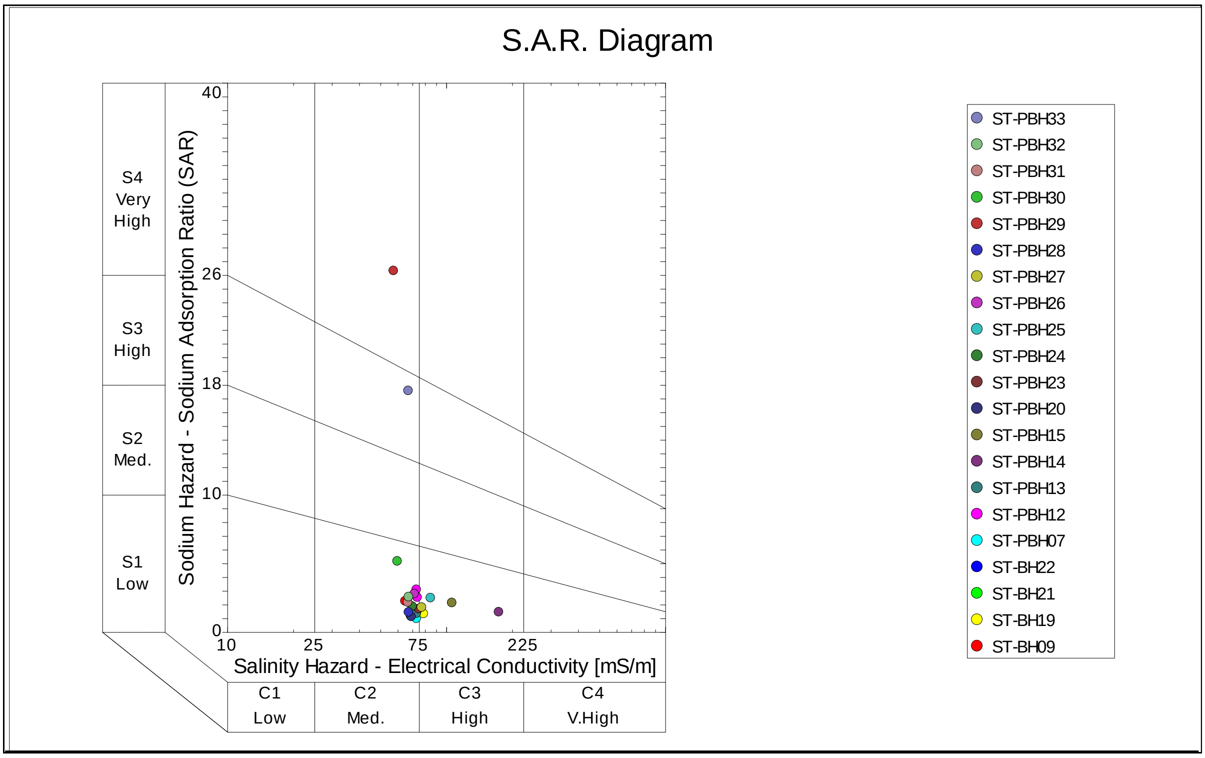


Figure 74: SAR diagram showing the classes of water in the study area.

9.4 HYDROGEOCHEMICAL CHARACTERISTICS

Hydrogeochemical characteristics of groundwater are evaluated using (i) the Durov diagram (Durov, 1948), (ii) the Piper trilinear diagram (Piper, 1944), (iii) the Schoeller diagram (Schoeller, 1964) and (iv) the Wilcox diagram (Wilcox, 1955) These diagrams shows chemical distribution of groundwater based on data collected in March-April 2012 and June-July 2013. Windows Interpretation Systems for Hydro-geologists (WISH) was used to plot the chemistry on Piper and Expanded Durov diagrams, Schoeller diagram and SAR diagram.

From the plots in Figures 75-77, the Na^+ represent the dominant cations in samples ST-PBH29 and ST-PBH31, there is no dominant cation in other samples as, whilst HCO_3^- in the form of Total Alkalinity represents the dominant anion in all samples. The water type can be termed Na-HCO_3 for ST-PBH 29 and ST-PBH31 (Figure 75 and Figure 76). Water samples from Borehole ST-PBH28, ST-PBH27, ST-PBH07, ST-PBH30 and ST-PBH32 can be regarded as 'unpolluted water' according to Expanded Durov diagram (Figure 77) for water types (Durov, 1948).

The bicarbonate as the major ion is also supported by the pH values 6.89-9.20; suggesting neutral hydrogenation of the carbonate in the water. The elevated Na^+ concentrations (Figure 77) are in the range of 37.15 to 161 mg/L. The dominant sodium ions shown in expanded Durov, Piper and Schoeller diagrams in Figure 77-79 may be attributed to the cation exchange of calcium (Ca) and magnesium (Mg) ions in an aqueous solution, with sodium (Na) ions on clay laminating the shale and sandstone geological formations in the study area.

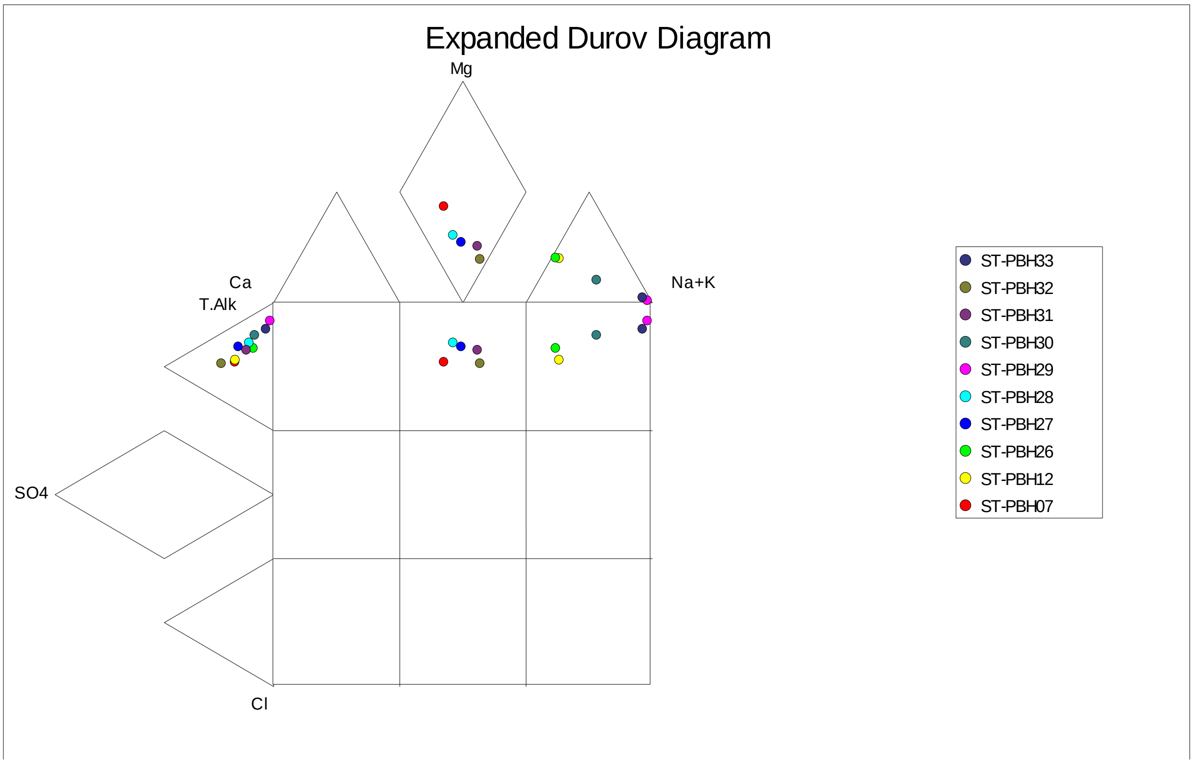


Figure 75: Expanded Durov diagram for characterising major ions for samples collected in June-July 2012.

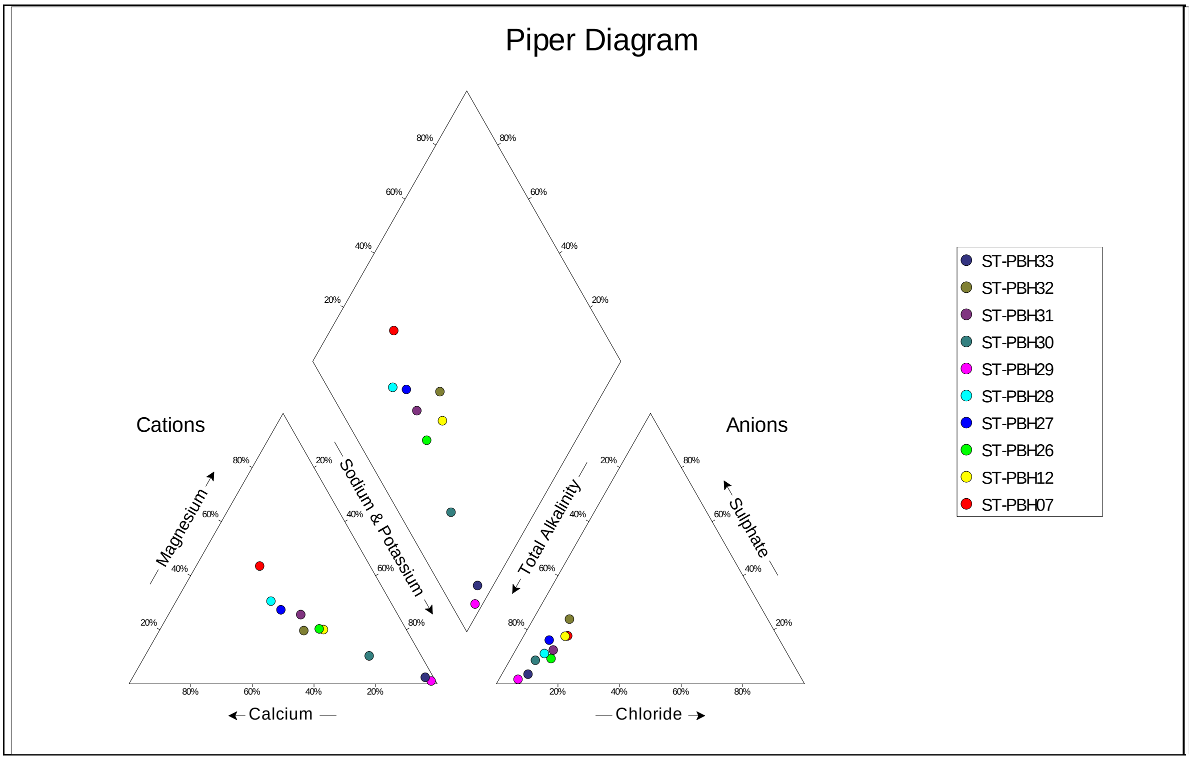


Figure 76: Piper diagram showing the major ions for samples collected in March-April 2012.

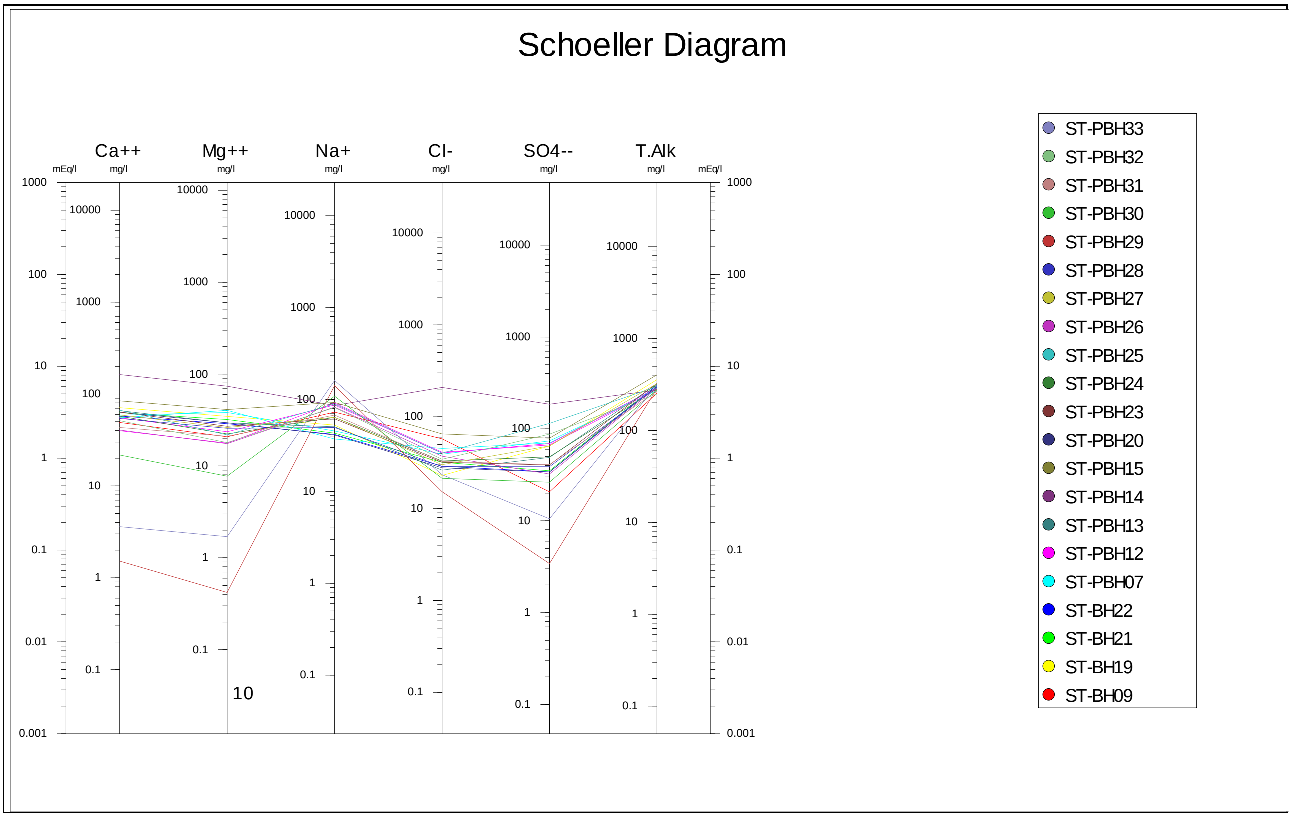


Figure 77: Schoeller diagram showing the distribution of ions in the study area.

The Schoeller diagrams (Figure 77) shows ST-PBH14 municipal borehole with elevated chloride concentrations; classified as type II water according to Rimawi (1992). Rimawi (1992) described the four types of water; the first two types of water as fresh groundwater which originates as contemporary recharge and sometimes fresh water that percolates over a short distance within the aquifer. The third and fourth types are related with fresh-brackish water of non-contemporary or old recharge (Salameh and Rimawi, 1984). The latter ascends from deep aquifers along major faults, or originates through fresh water mixing with saline water that flows through evaporites (Rimawi and Udluft, 1985). The geological logs were unavailable for the existing borehole ST-PBH14 to assess the cause of the elevated chloride levels. There was also no notable source on the surface that could suggest that the elevated chloride levels are due to man-made deposits. The sample for ST-PBH14 is characterised as Na-HCO3; as the dominant anion is bicarbonate evidenced from the Piper diagram in Figure 78. The rest of the samples as shown in Figure 78 and Figure 79 are characterised as by high bicarbonate concentrations with no dominant cation, the groundwater from these boreholes is categorised as Type I water by Rimawi (1992). The latter water is regarded as 'unpolluted water' by Durov (1948) for classifying water types, shown in Figure 79.

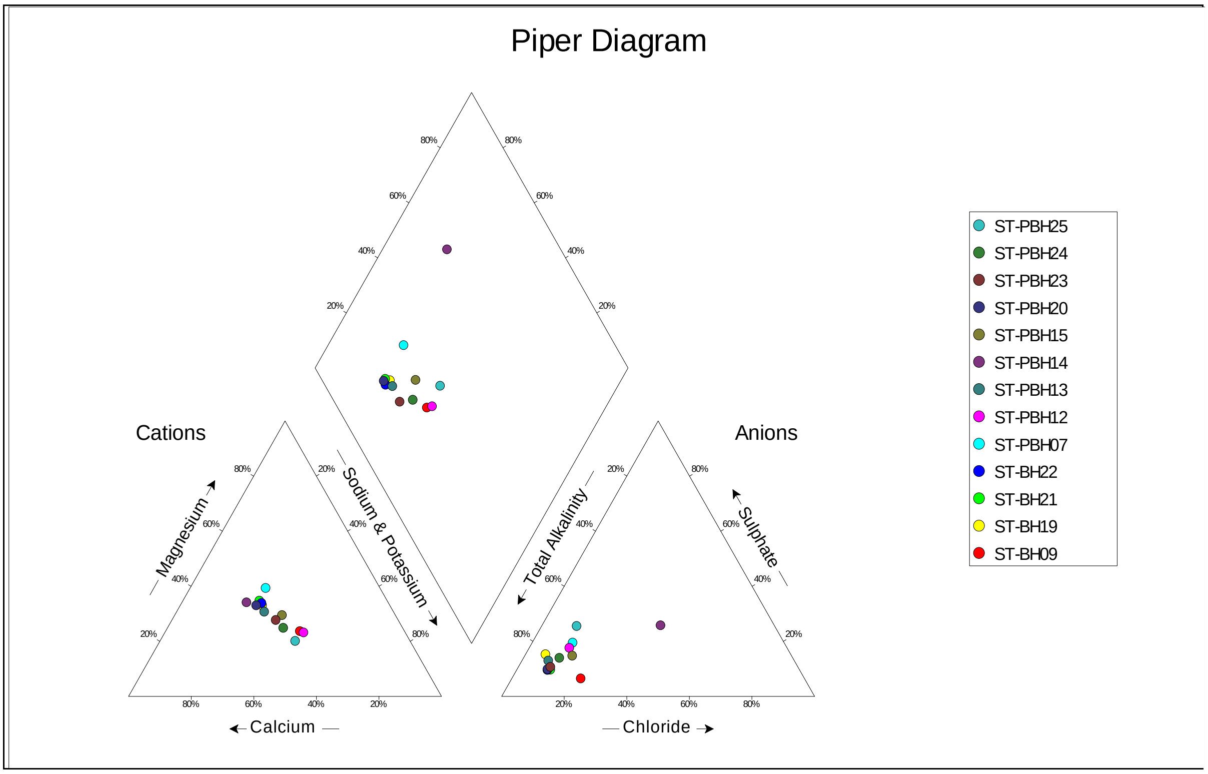


Figure 78: Piper diagram showing the major ions for samples collected in June-July 2013.

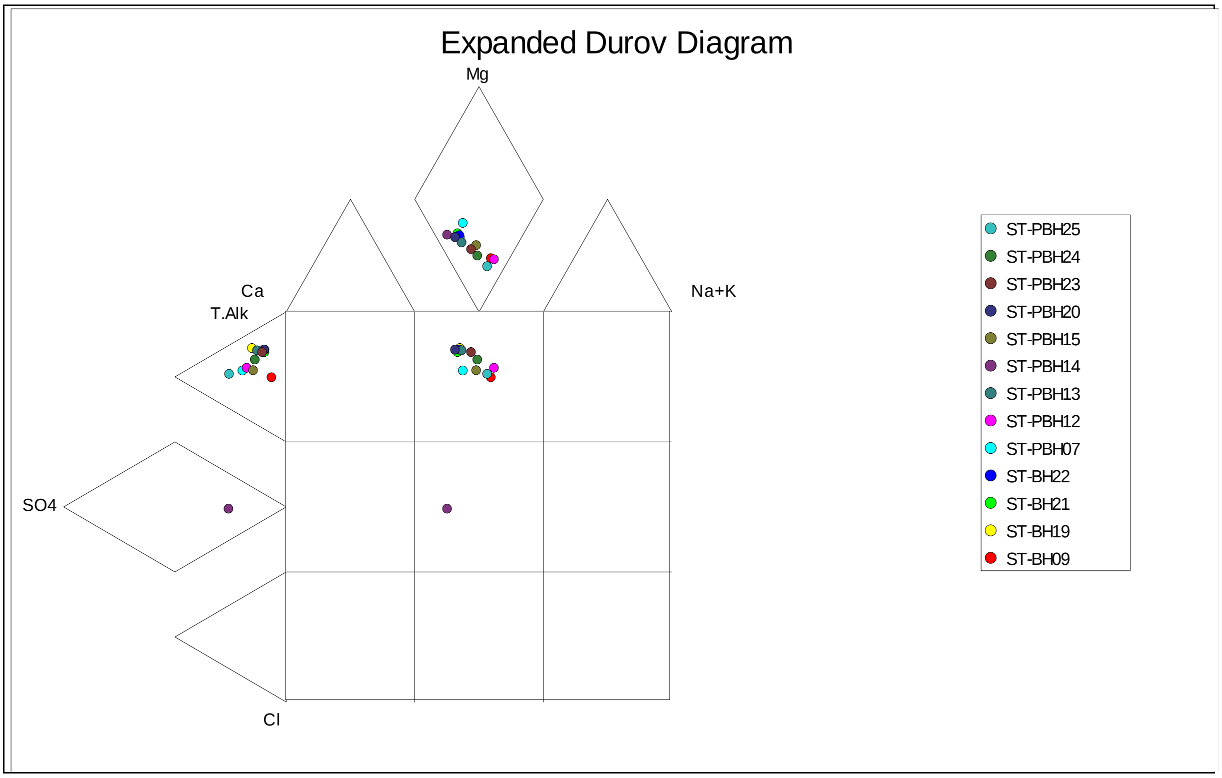


Figure 79: Expanded Durov diagram for characterising major ions for samples collected in June-July 2012.

9.5 SUMMARY

Chapter 9 gives details of the groundwater quality assessment and interpretation. This was done through the analysis of the water quality samples and interpretation of the results. The statistical analysis of the groundwater quality results is also explained. The hydrochemical data for all the samples were of acceptable quality according to the estimated ionic charge balance of the samples. The groundwater quality in the study area is predominantly Class 1 according to the DWAF (1996b), SANS241: 2006 and SANS241-1: 2011 water quality standards. The water quality data were also analysed using Piper, Expanded Durov, Schoeller and Salinity Adsorption Ratio. From the diagrams, Na^+ represents the dominant cations in some samples and no dominant cation in other samples, whilst HCO_3^- represents the dominant anion in all samples. The water type can be termed Na-HCO_3 for samples with sodium as dominant cation and Ca-K-Mg-Na-HCO_3. The SAR mean of 7.01 for the study area generalise the water quality in the study area suitable for irrigational purposes with the exceptions mentioned above. The next chapter discusses the conclusions and the recommendations from the study.

CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

This dissertation emanated from data gathered during work by Scott and Wilson Engineers on behalf of Moqhaka Local Municipality in 2013 to investigate and explore the groundwater resources for supplementing the town water supply in Steynsrus. The MSc study went an extra mile to comprehensively evaluate and interpret the data in the context of research in order to develop a better understanding of geohydrology properties and groundwater potential of the aquifer. In general, the primary aim of the study was to assess the groundwater resources of Steynsrus and also investigate whether the groundwater resources can meet the future water demands of the town. The aim was achieved by applying various field and laboratory experiments to collect, assess and interpret the data and information made available from the site in terms of the geophysics, geology, geohydrology and chemistry. Conclusions with respect to the findings on the study area will be presented.

10.1.1 Geophysics Survey

The Surface Magnetic Geophysics Method was used to locate drilling targets that have a direct bearing on groundwater occurrence. The modern proton magnetometers were also used to trace the position and dip of dolerite dykes. The magnetic method proved to be a good technique to use for locating of the dolerite intrusions.

Although the magnetic method was used for siting the drilling target, it must be highly noted that some of the geophysical data obtained were regarded as 'bad data'. The data showed suspicious magnetic field intensity relative to the local geology for naturally occurring bodies and some targets were sited on a one-step anomaly. The newly conducted magnetic surveys showed and proved that the drilling targets used in the project were based on erratic data. A success rate of 30% was achieved by drilling boreholes through the geophysics. It is believed that the success rate could have been improved if the geophysical survey were conducted appropriately according to conventional standards and were interpreted up to acceptable levels.

10.1.2 Geology and Geohydrology

Exploring for groundwater resources was done in the area through geophysics and drilling of boreholes. It was important to know factors controlling the occurrence of the groundwater at the study area in order to reach the goal of drilling successful boreholes for the town water supply.

The study area predominantly consists of alternating layers of sandstones and shale deposits with an extensive dolerite intrusion. In all the drilled boreholes, dolerite intrusion was intersected. The yield of the boreholes ranged from 0.1 to 3.0 L/s. Generally, the fractures were intercepted between 20 and 30 mbgl for successfully drilled boreholes (blow yield >1.0 L/s) and were intercepted between 40 and 50 mbgl for unsuccessfully drilled boreholes (blow yield <1.0 L/s).

10.1.3 Aquifer Parameters

The aquifer pump testing conducted in the study provided an understanding of the local groundwater flow and the hydraulic characteristics of the aquifers. It was important to characterise the flow through diagnostic and specialised plots in order to estimate aquifer parameters and sustainable yields of the boreholes; with improved knowledge. The groundwater flow in the study area is characterised by fractal flow behaviour, with an exception of borehole ST-PBH27 as it is indicated as an unconfined aquifer. The fractures in the aquifers control water flow and how the aquifers in the area behave to pumping. The transmissivity values estimated by the Cooper-Jacob method are in the range of 2.50-92.10 m^2/day and the storativity values ranged between 9.32×10^{-7} to 3.60×10^{-4} using the RPTSOLV program. The varying storativity values indicate that the water may not be withdrawn from the same aquifer storage.

10.1.4 Groundwater Quality

The water in the area is generally of good quality as assessed through SANS241:2006 and SANS241-1:2011. One of the existing boreholes (ST-PBH07) tested with a good sustainable yield estimated (>2.00 L/s) had elevated manganese concentrations of 0.10mg/L. The water type can be termed Na-HCO3 for samples with sodium as dominant cation and Ca-K-Mg-Na-HCO3. The boreholes with water quality issues, if treated or rehabilitated, would increase the sustainability of the aquifers.

10.1.5 Groundwater Sustainable Use

The existing sustainable yield from groundwater sources is only 15.07 L/s for a 24 hour pumping cycle per day (equivalent to 1.30 ML/day). The low borehole yields from both the existing and newly drilled boreholes may be due to various reasons: water quality issues, boreholes in close vicinity, lack of groundwater recharge, lack of groundwater management and, in some instances, a speculation of over-abstraction of boreholes. The limitation of geophysics work conducted for drilling of the boreholes could have also contributed in the lower sustainable yields of the newly drilled boreholes.

The town water demands for 2030 are at 2.20 ML/day; a very low shortfall of 0.90 ML/day is currently realised. However, this shortfall is still a major challenge for a small town with limited water resources options.

10.1.6 Additional Findings

The following findings were also concluded following the assessment and investigation of the groundwater resources of the area in Steynsrus:

- The confidence rating for the geophysical data used for siting of the newly drilled boreholes was low. The magnetic data showed significant errors which could have resulted in wrong interpretations and low-yielding boreholes. The most likely reason for bad data could be inappropriate survey and data processing for interpretation. However, the magnetic method when used appropriately must still be viewed as the preferred method for detecting groundwater targets in an area such as Steynsrus.
- The study concluded that the current sustainable borehole yields (per 24 hour duty cycle) are not sufficient for the current population and shortfall of meeting the 2030 water demands as projected.
- Lack of groundwater management, a monitoring plan and knowhow by the municipal officials makes it a major challenge for the Moqhaka Local Municipality to use the current groundwater resources efficiently and sustainably.
- Groundwater resources cannot be viewed as the only source for town water supply; thus can be used to augment the surface water supply.

10.2 RECOMMENDATIONS

The following recommendations were deduced from the study investigation, findings and conclusions:

- A geophysics survey with reasonable quality and interpretation must be conducted to explore for drilling targets that can be drilled for groundwater to meet the water demands in the town up to 2030. Preferably two geophysics methods can be used, namely the magnetic method and electromagnetic method.
- Currently, the groundwater resources in the town are not sufficient to meet the town water demands; other sources such as surface water should be explored to meet the 2030 water demands.
- Investigation should be conducted on Steynsrus upstream water users along the Vals River to verify the water authorisation as the limited Vals River flow at the Steynsrus outlet may also be due to over-exploitation of the source.
- A comprehensive groundwater monitoring and management plan must be initiated and implemented to ensure the available groundwater resources are preserved, conserved, protected, managed and controlled for sustainable use by the current community and for the future. It includes proper data collection, storage, analysis and archiving in a computer database such as DWA Hydstra. This document can be used as a guide for the groundwater monitoring and management plan Steynsrus.
- A groundwater monitoring and management plan training workshop must be conducted for equipping the officials for managing the Steynsrus groundwater resources.
- The Moqhaka Local Municipality must implement a project for water conservation and water demand management to ensure that water is used efficiently and effectively by the community and water pipelines are reported by the locals and fixed timely.
- In order to characterise and classify the water quality for town water supply, sampling is required for all seasons.
- Groundwater must be treated at the local water treatment plant prior to human consumption. This is particularly for samples that were classified as marginal water quality (Class 2) and have good sustainable yield estimates.

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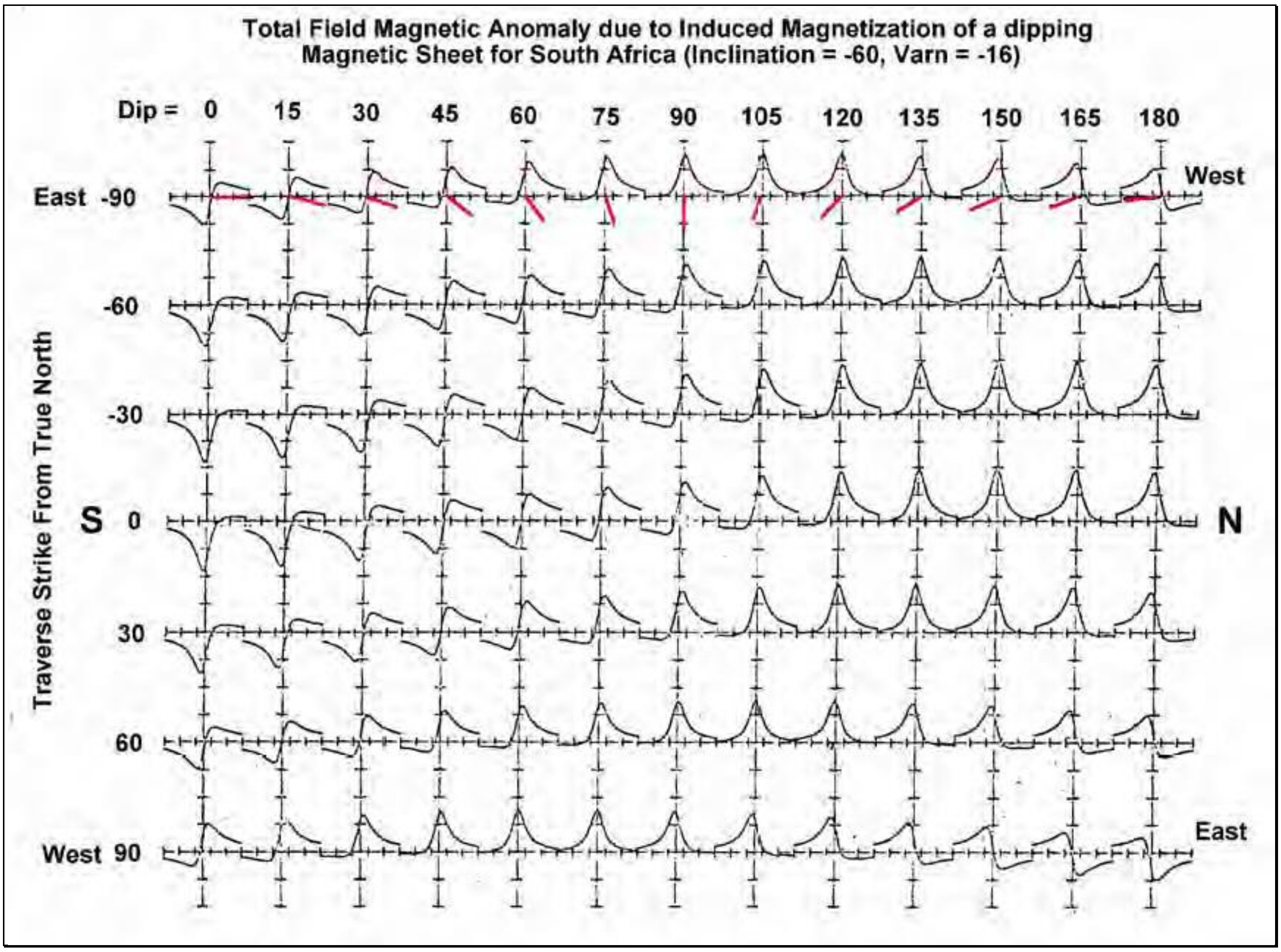
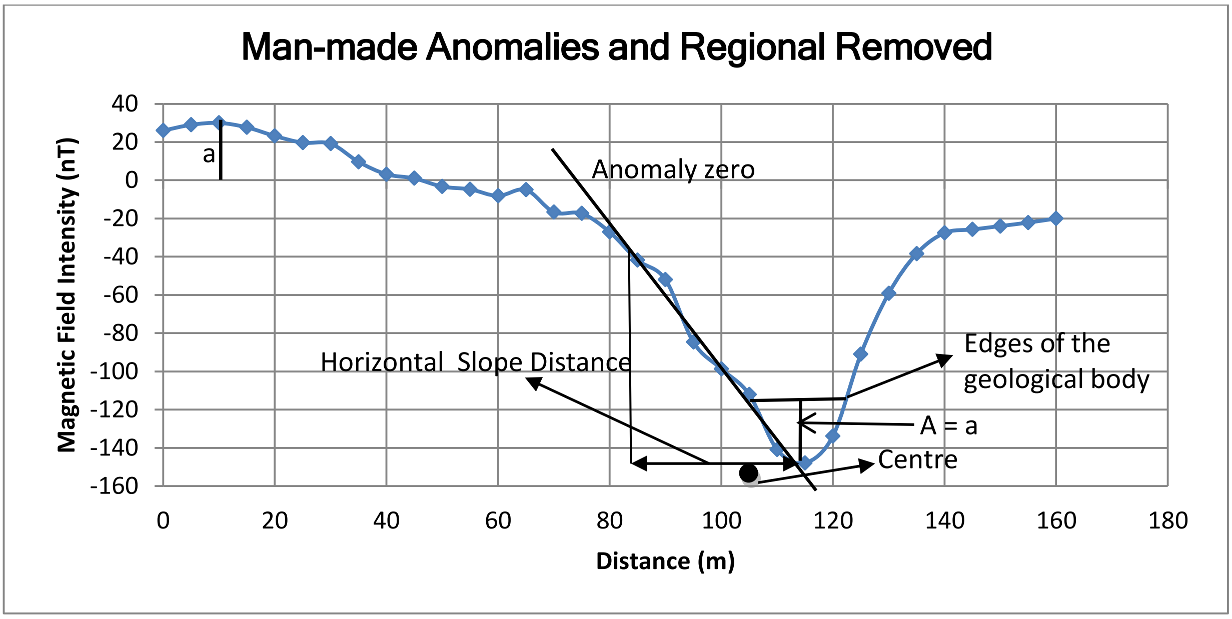
APPENDIX 1:
TYPE CURVES FOR MAGNETIC ANOMALIES OVER DIPPING DOLERITE DYKES IN SOUTH AFRICA



APPENDIX 2:

CALCULATIONS FOR DOLERITE INTRUSIONS PARAMETERS

1. Calculations for the centre and the depth of a possible magnetic body using Logochev's method and HSD, respectively, for Traverse S-TV01 (from the new magnetic survey):



a = distance from the zero line to maximum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 104 m along the traverse.

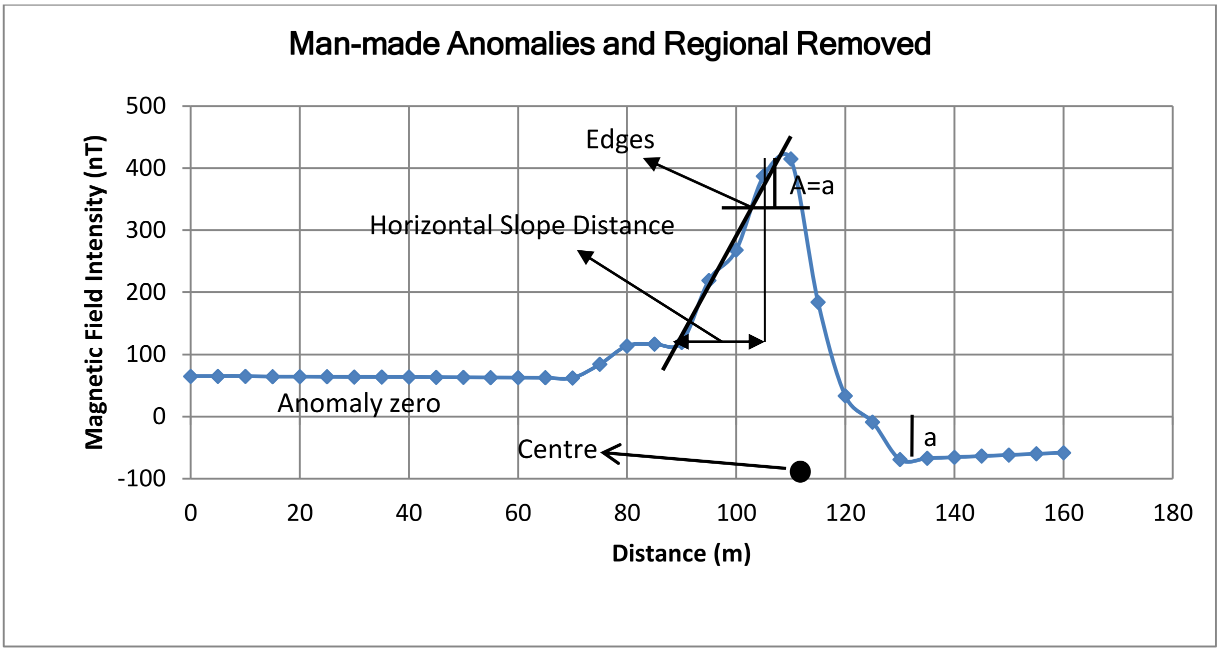
The edges of the geological body were estimated by drawing the line from centre across the curve at 122 m along the traverse.

The estimated Horizontal Slope Distance HSD = 30 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 30 = 39 m below ground surface

2. Calculations for Traverse S-TV02



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 113 m along the traverse.

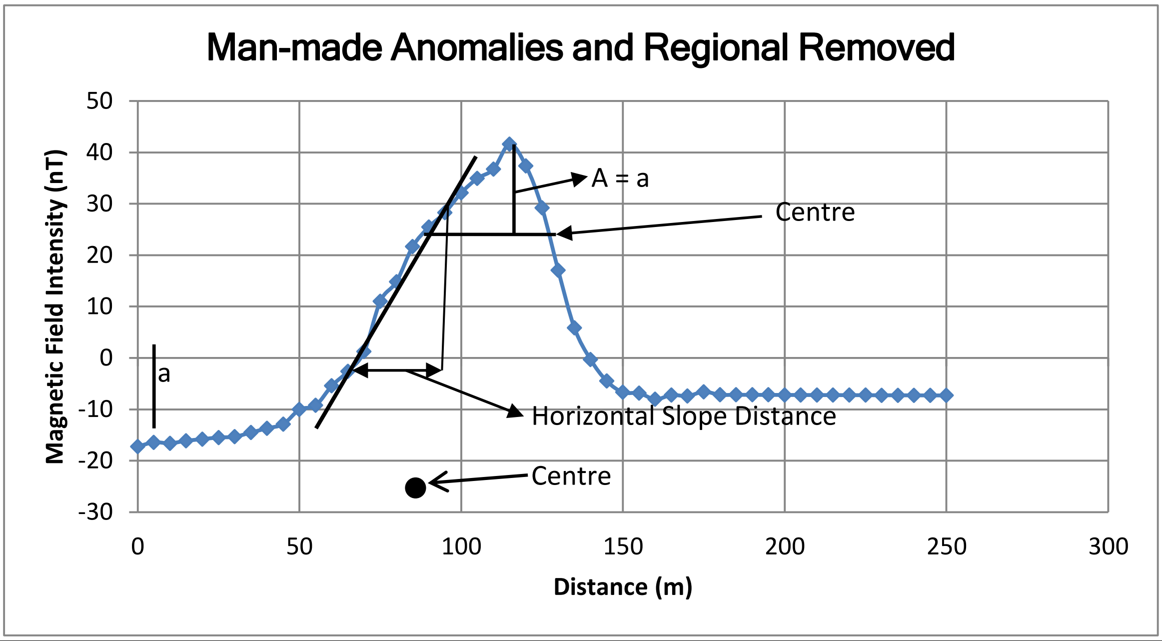
The edges of the geological body were estimated by drawing the line from the centre across the curve at 103 m along the traverse.

The estimated Horizontal Slope Distance HSD = 15 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 30 = 19.5 m below ground surface

3. Calculations for Traverse S-TV02



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 85 m along the traverse.

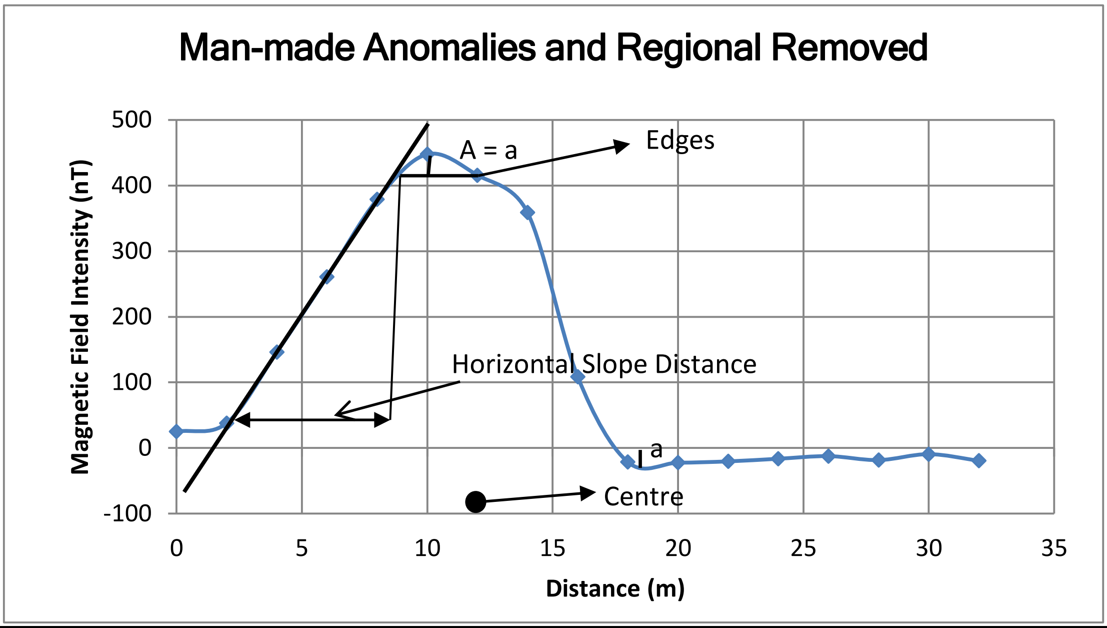
The edges of the geological body were estimated by drawing the line from centre across the curve at 128 m along the traverse.

The estimated Horizontal Slope Distance HSD = 41 m;

Using Thick Dyke formulae of 1.1 x HSD:

Depth of the magnetic body = 1.1 x 30 = 45.1 m below ground surface

4. Calculations for Traverse S-TV04



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 12 m along the traverse.

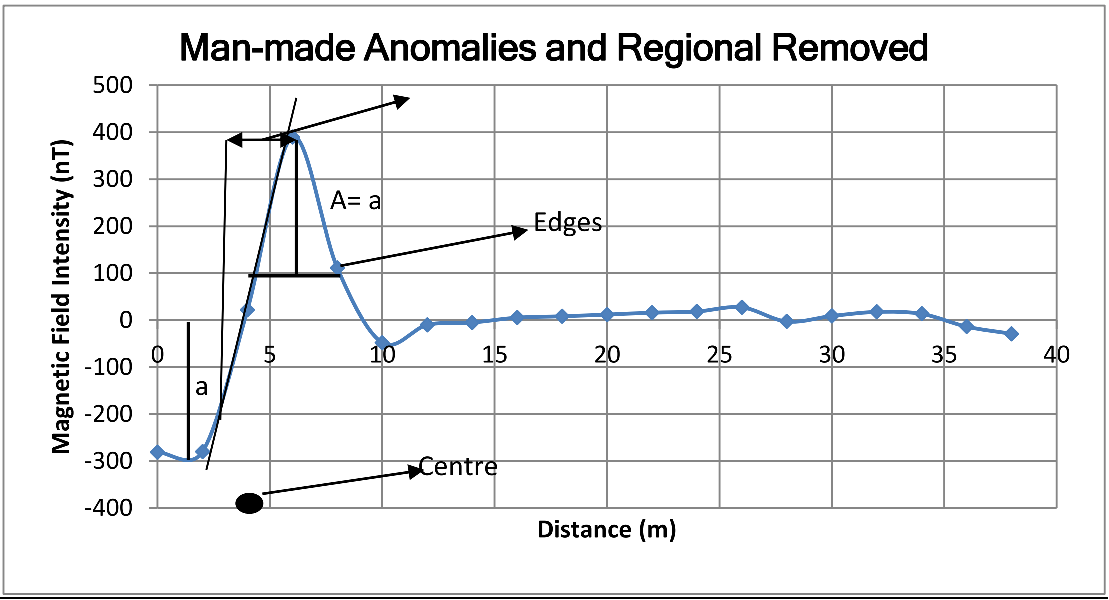
The edges of the geological body were estimated by drawing the line from centre across the curve at 9 m along the traverse.

The estimated Horizontal Slope Distance HSD = 6 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 6 = 7.8 m below ground surface

5. Calculations for Traverse S-TV05



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 4.5 m along the traverse.

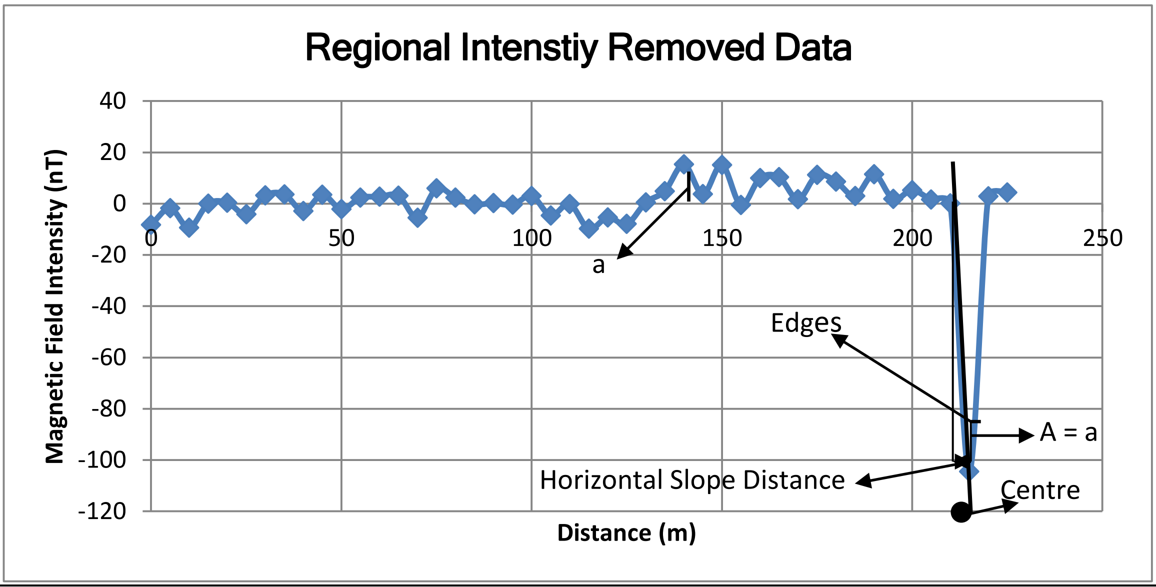
The edges of the geological body were estimated by drawing the line from centre across the curve at 8 m along the traverse.

The estimated Horizontal Slope Distance HSD = 3 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 3 = 3.9 m below ground surface

6. Calculations for Traverse S-TV06:



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 214 m along the traverse.

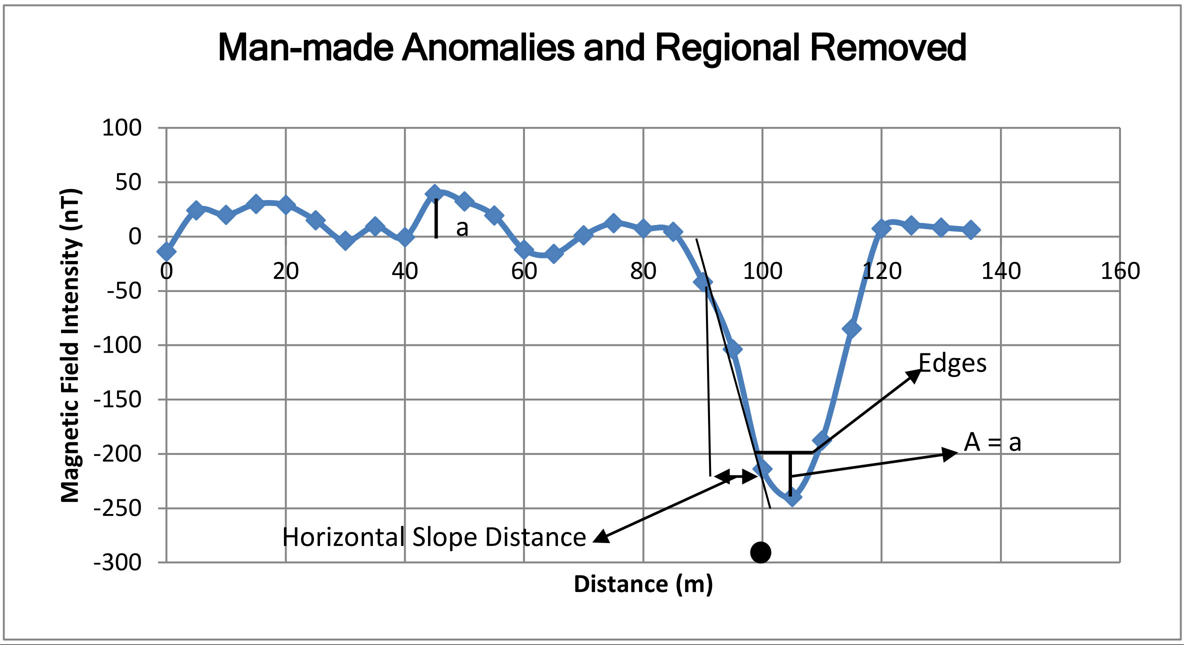
The edges of the geological body were estimated by drawing the line from centre across the curve at 217 m along the traverse.

The estimated Horizontal Slope Distance HSD = 4.8 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 4.8 = 6.3 m below ground surface

<u>7. Calculations for Traverse S-TV07:</u>



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 100 m along the traverse.

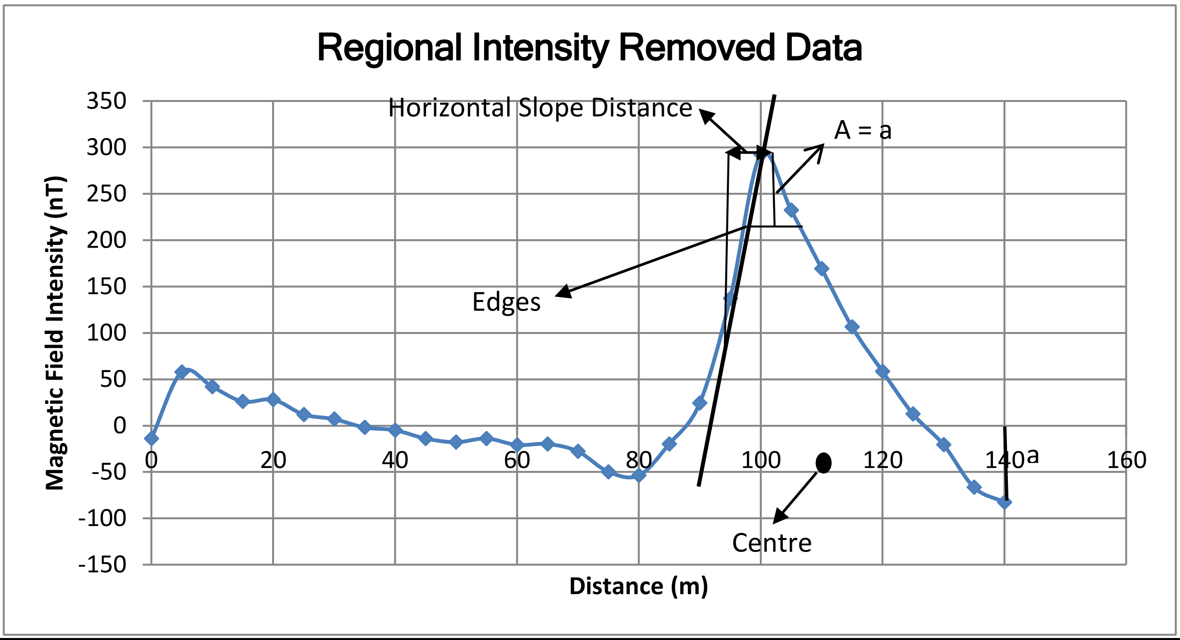
The edges of the geological body were estimated by drawing the line from centre across the curve at 104 m along the traverse.

The estimated Horizontal Slope Distance HSD = 10 m;

Using Thin Dyke formulae of 1.3 x HSD:

Depth of the magnetic body = 1.3 x 10 = 13 m below ground surface

8. Calculations for Traverse S-TV08



a = distance from the zero line to minimum

A = a when a cord parallel to zero line is drawn; then the intercept of cord drawn with the curve lies directly over the centre of the geological body.

The centre of the geological body is calculated at 107 m along the traverse.

The edges of the geological body were estimated by drawing the line from centre across the curve at 97 m along the traverse.

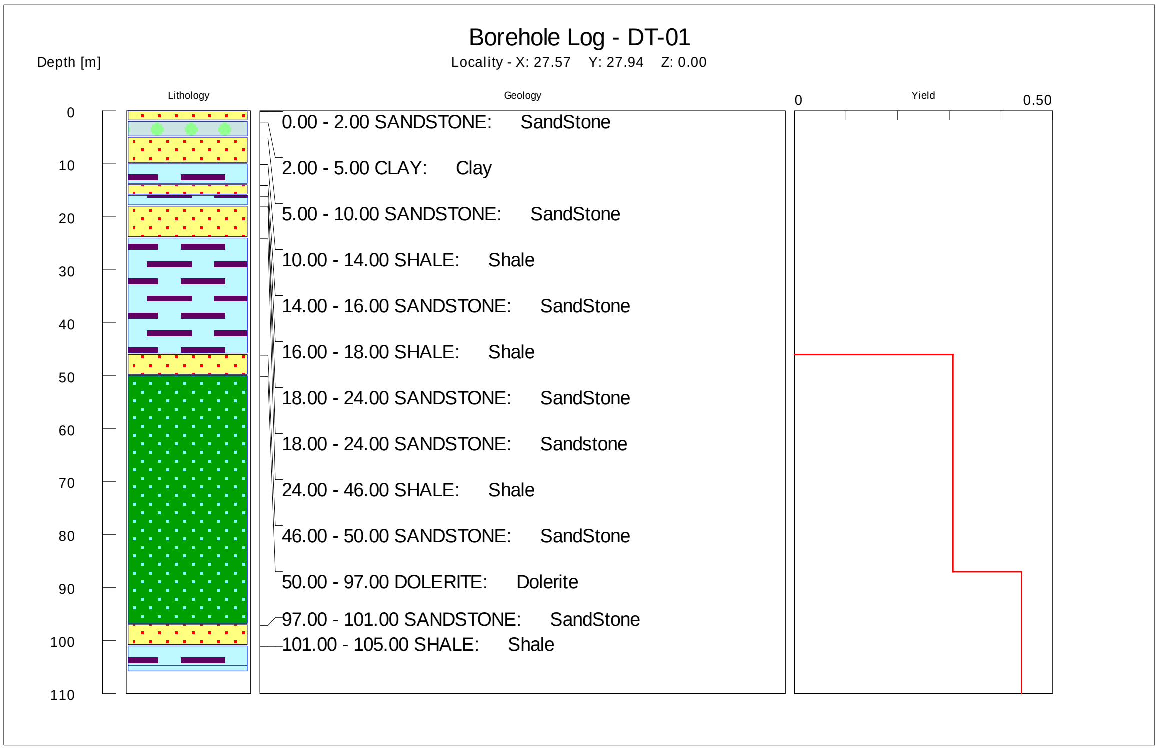
The estimated Horizontal Slope Distance HSD = 3 m;

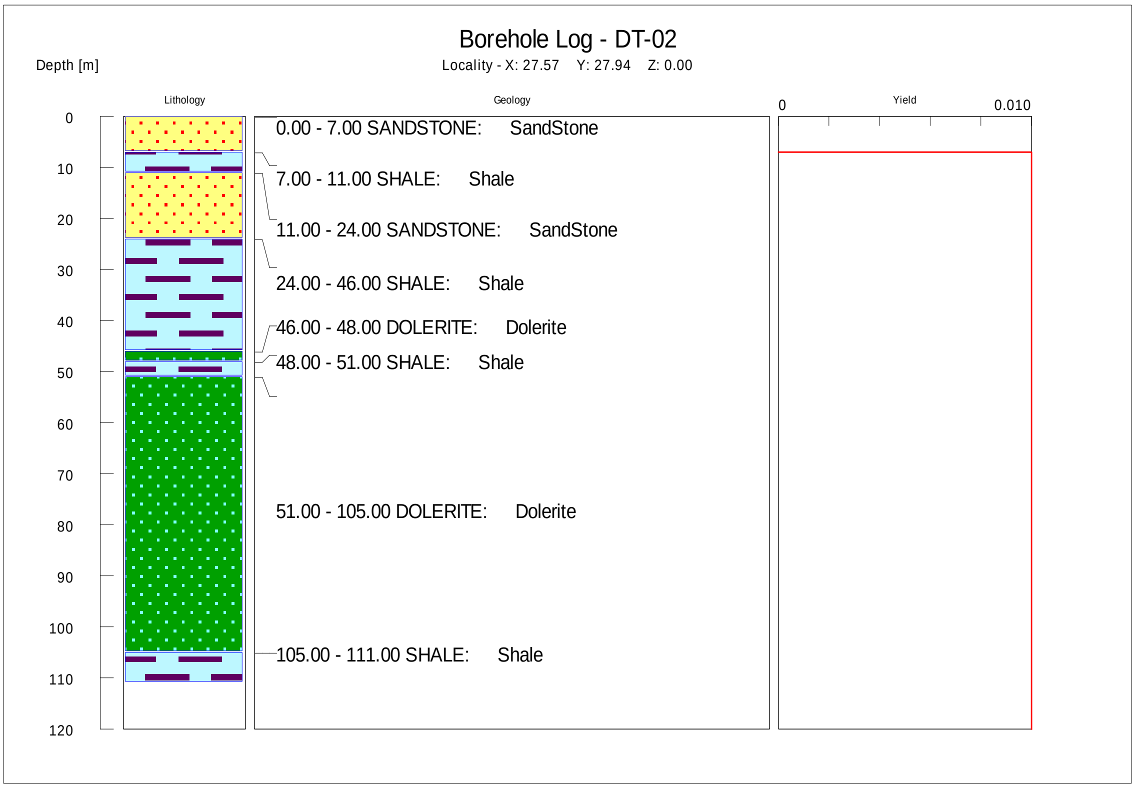
Using Thin Dyke formulae of 1.3 x HSD:

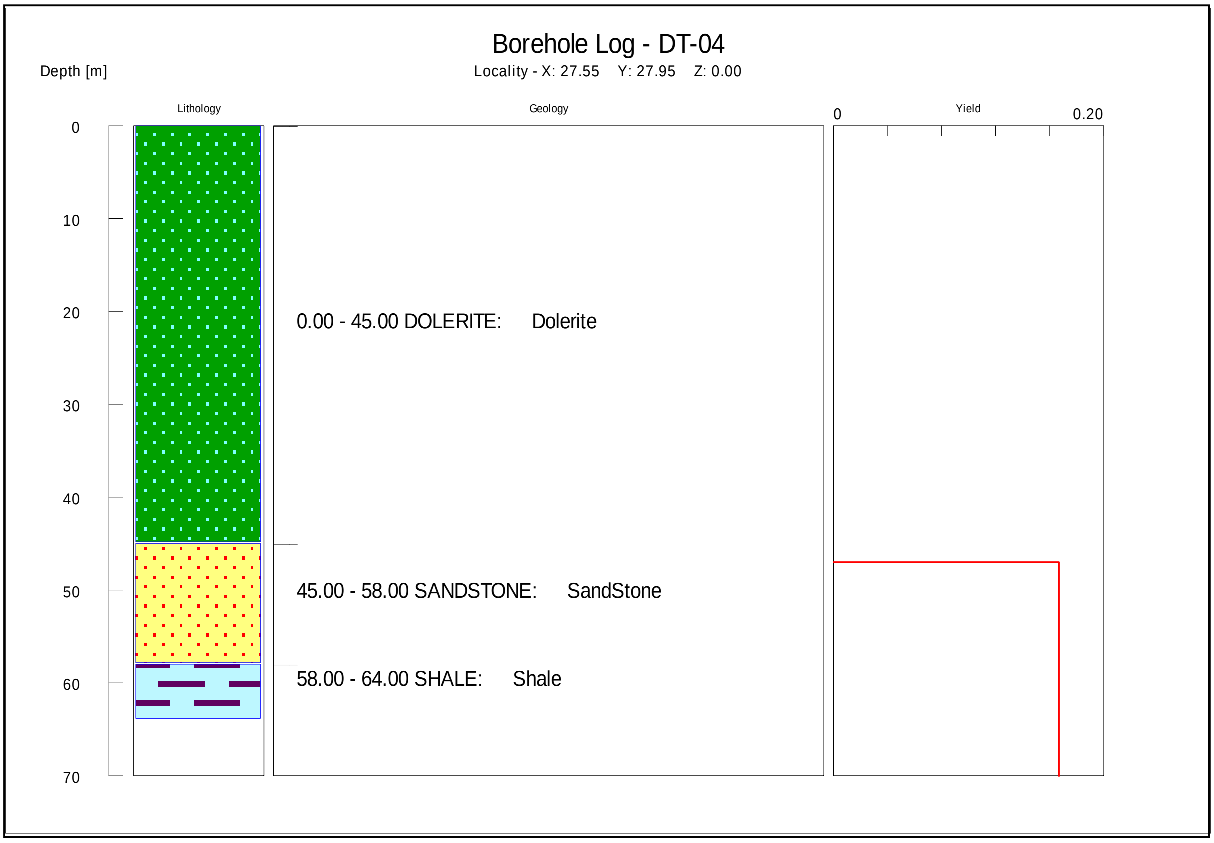
Depth of the magnetic body = 1.3 x 3 = 3.9 m below ground surface

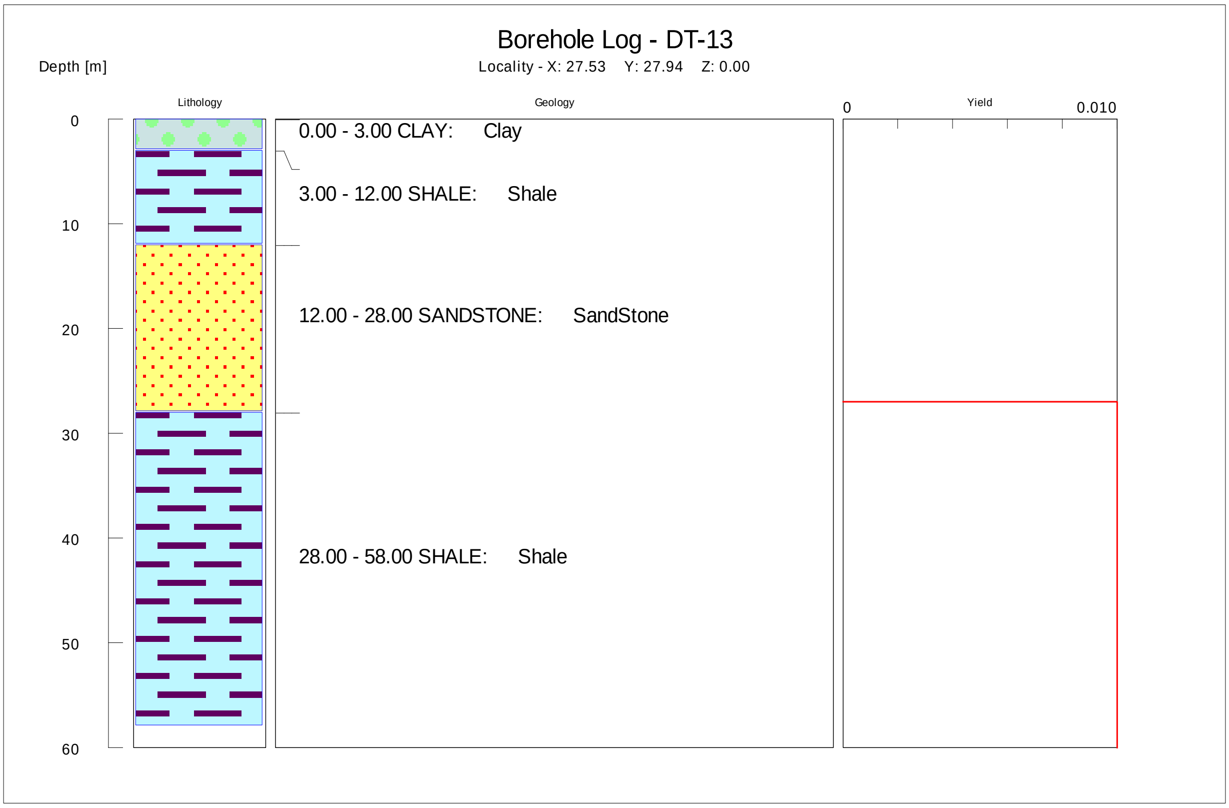
APPENDIX 3:

GEOLOGICAL LOGS OF THE UNSUCCESSFULLY DRILLED BOREHOLES.

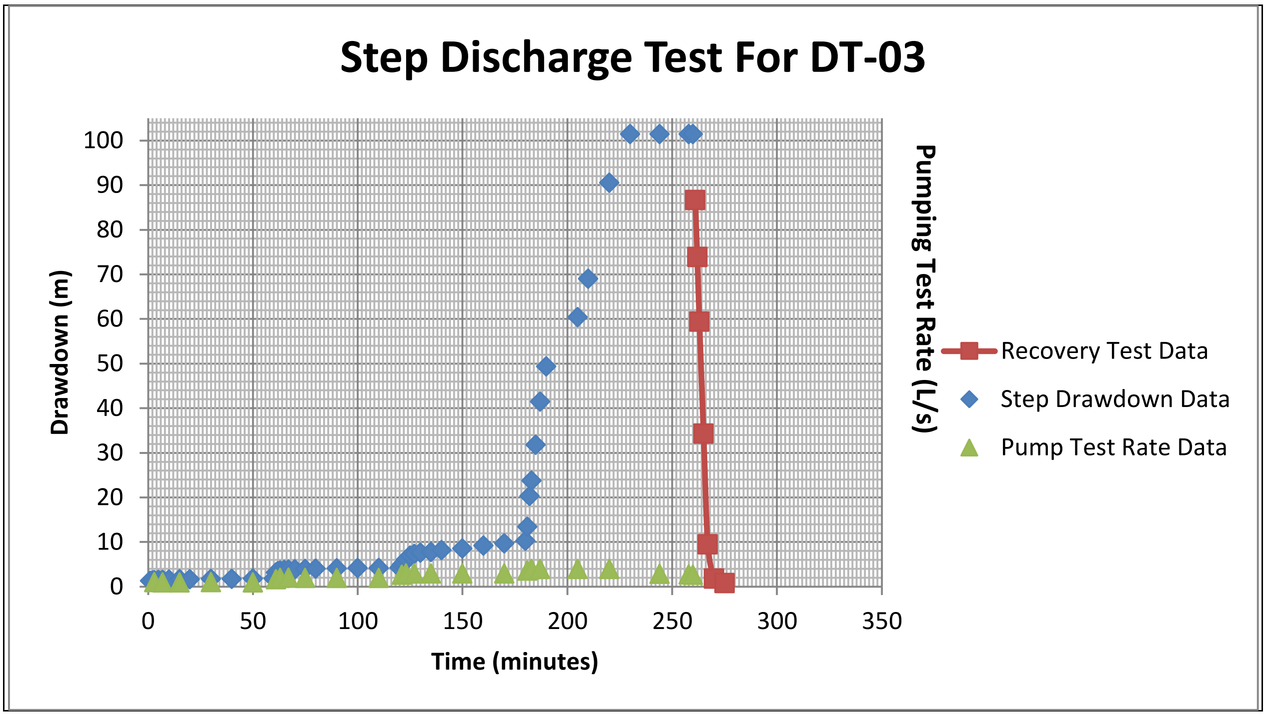


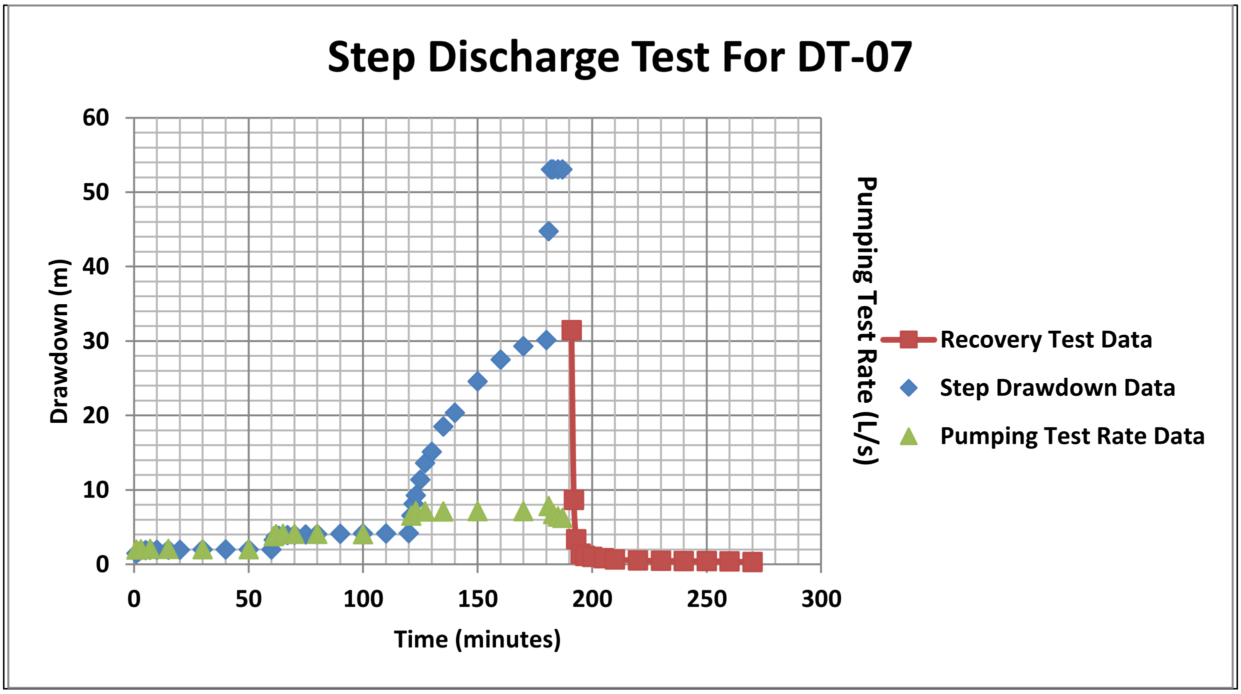


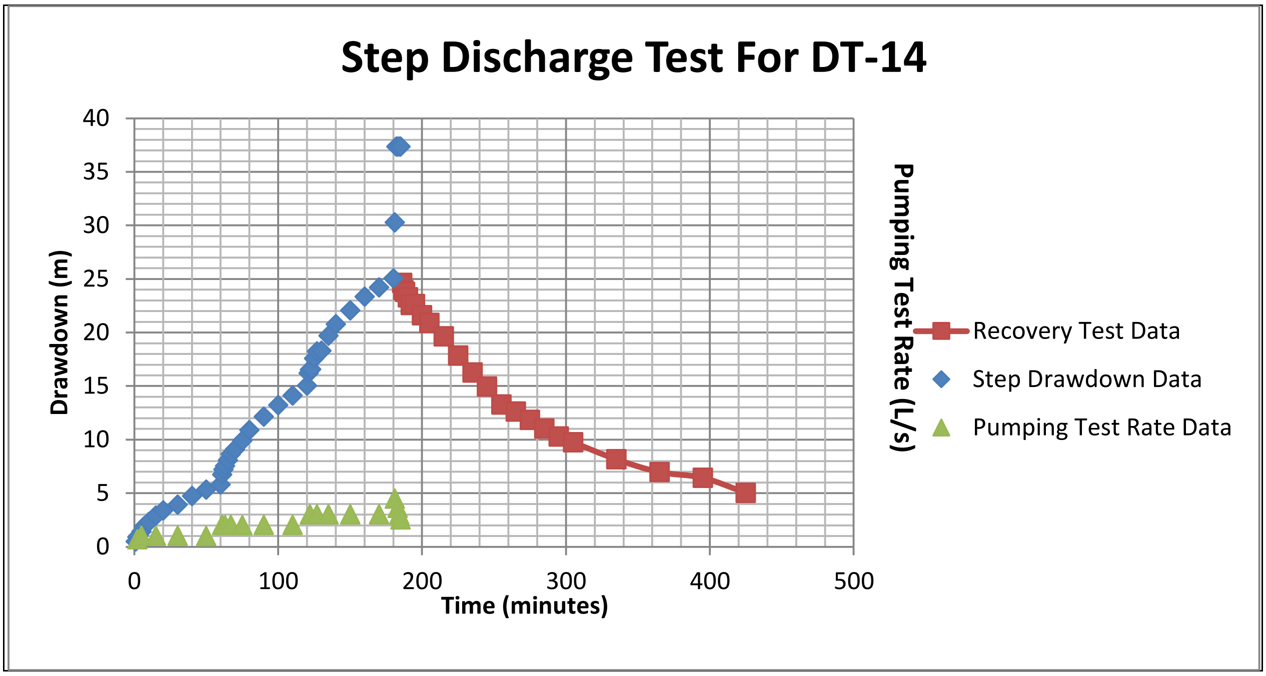

Borehole Log - DT-04
Locality - X: 27.55 Y: 27.95 Z: 0.00
Depth [m]
Lithology
Geology
Yield
0
0.20
0
10
20
30
40
50
60
70
0.00 - 45.00 DOLERITE: Dolerite
45.00 - 58.00 SANDSTONE: SandStone
58.00 - 64.00 SHALE: Shale

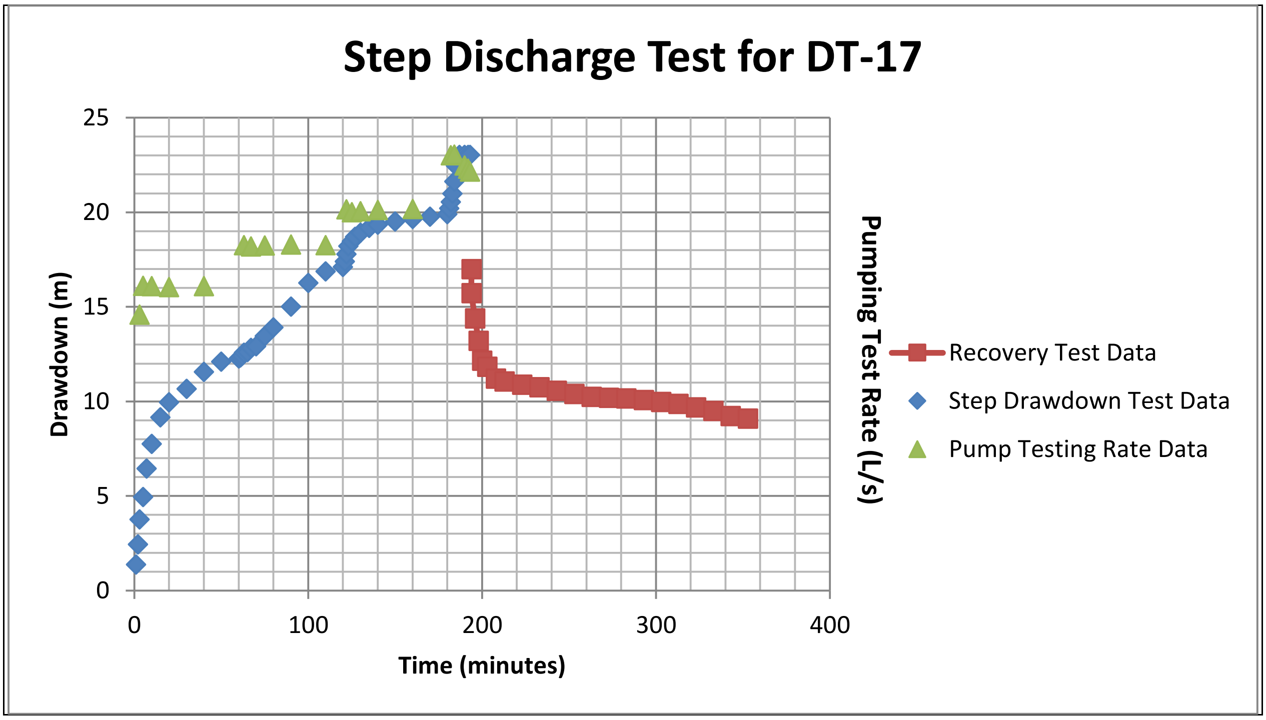

Borehole Log - DT-13
Locality - X: 27.53 Y: 27.94 Z: 0.00
Depth [m]
Lithology
Geology
Yield
0
0.010
0
10
20
30
40
50
60
0.00 - 3.00 CLAY: Clay
3.00 - 12.00 SHALE: Shale
12.00 - 28.00 SANDSTONE: SandStone
28.00 - 58.00 SHALE: Shale

Appendix 4: Step Discharge Test Data






Step Discharge Test For DT-14
Drawdown (m)
Time (minutes)
Pumping Test Rate (L/s)
Recovery Test Data
Step Drawdown Data
Pumping Test Rate Data
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500


Step Discharge Test for DT-17
Drawdown (m)
Time (minutes)
Pumping Test Rate (L/s)
Recovery Test Data
Step Drawdown Test Data
Pump Testing Rate Data
0
5
10
15
20
25
0
100
200
300
400

Appendix 5:
Qualified Guess Recharge Estimation

Qualified Guess of Recharge Kroonstad

Performed by using existing data, expert opinions and interpolation of known values

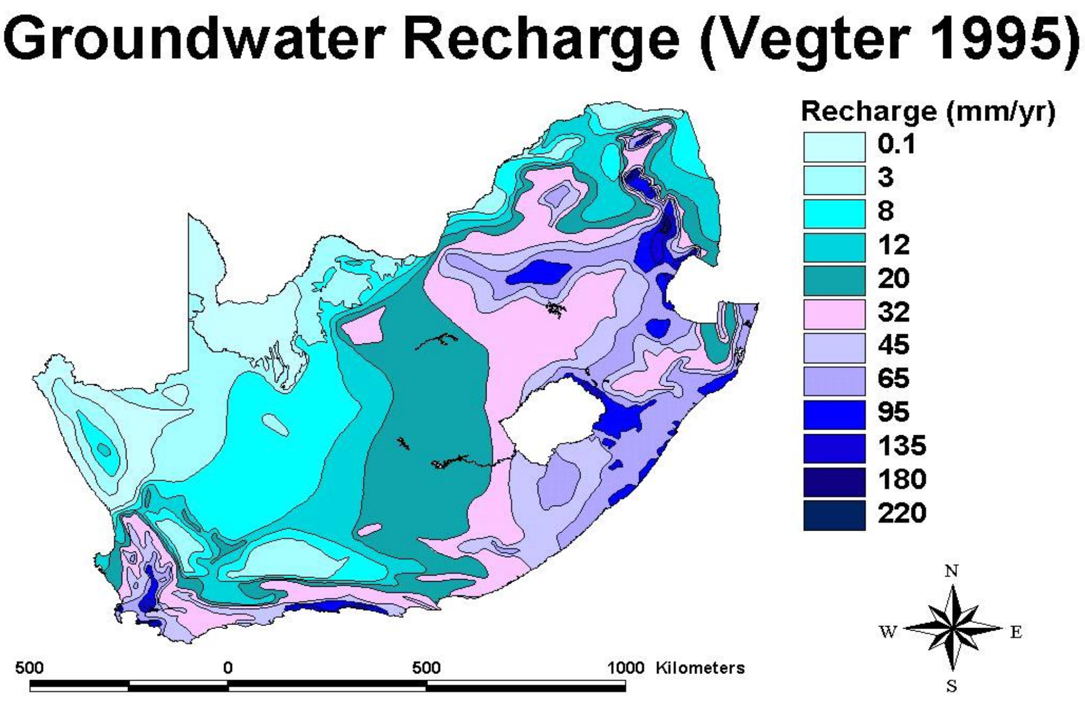
N

Summary

Method	Recharge (mm/a)	%
Vegter	32.0	5.7
Acru	10.0	1.8
Harvest Potential	25.0	4.4

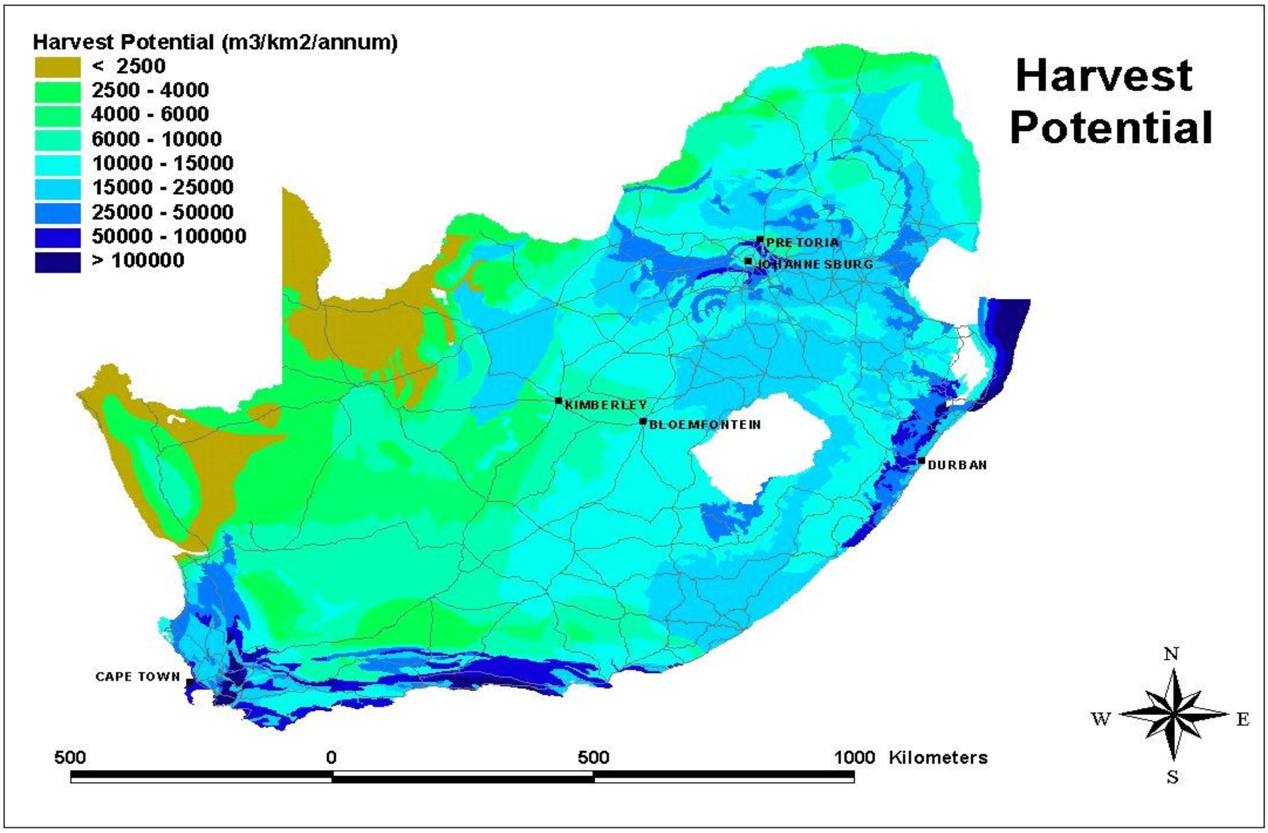
Vegters Map

Recharge from map =	32
Recharge (mm/a) =	32
Recharge (%) =	5.67



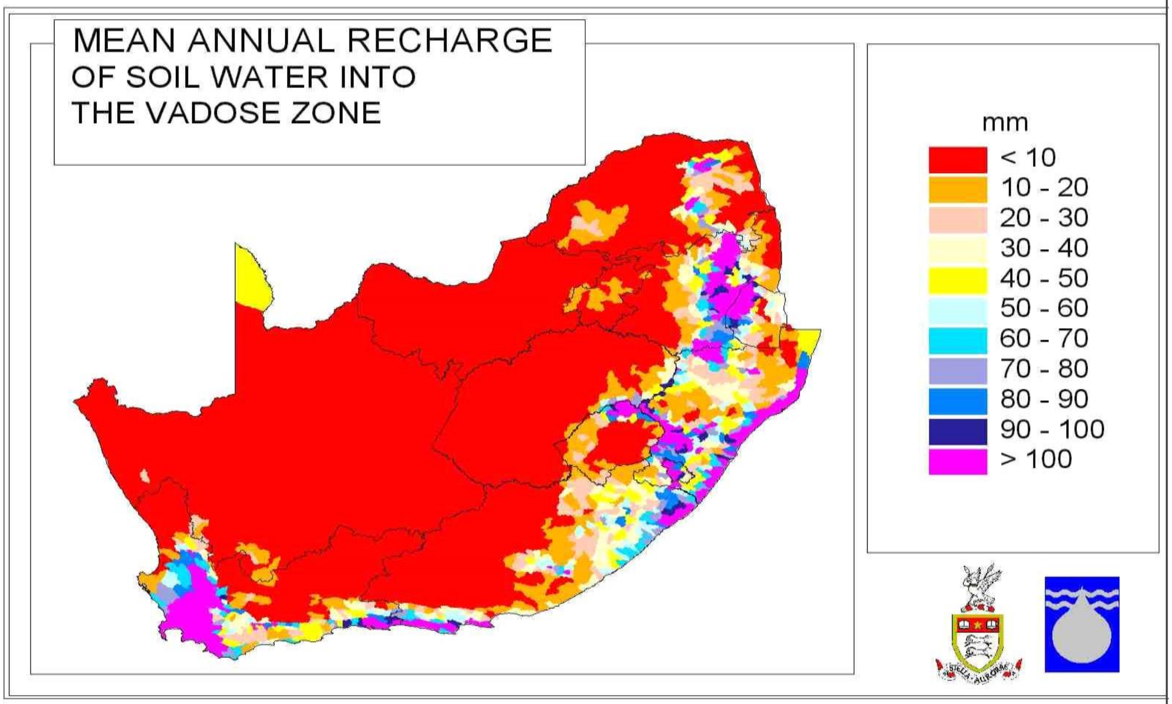
Harvest Potential Map

Recharge (mm/a)	25.00
% Recharge	4.43
HP from Map[m3/km2/a]=	25000



ACRU recharge by Roland Schulze

From map: **ACRU recharge**	10
Recharge (%) =	1.77



APPENDIX6:
Chemistry Data with Estimated Ionic Balance, %Na and SAR

Site Name	pH	EC	TDS	Na	Ca	Mg	K	Cl	Ionbal	%Na	SAR
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	%		
ST-BH08	7.18	67.90	475.30	59.31	68.97	28.42	2.55	32.13	4.64	38.84	0.86
ST-BH09	7.54	65.50	458.50	72.87	49.08	20.77	1.68	57.60	0.71	51.63	1.48
ST-BH11	7.19	72.50	507.50	49.50	64.00	28.70	3.75	36.35	-1.47	36.49	0.76
ST-BH19	7.48	79.40	555.80	52.69	71.09	34.64	2.14	23.00	-2.33	34.15	0.70
ST-BH21	7.34	70.70	494.90	43.02	62.61	32.02	2.28	32.00	-1.78	32.37	0.64
ST-BH22	7.37	69.50	486.50	41.70	57.56	28.84	2.11	29.00	-4.88	33.65	0.68
ST-PBH07	7.25	70.70	494.90	45.40	58.89	38.22	1.32	39.14	0.25	32.48	0.66
ST-PBH13	7.06	73.80	516.60	50.50	65.90	29.40	3.86	26.27	-1.60	36.32	0.75
ST-PBH14	7.15	175.10	1225.70	86.16	163.00	73.90	4.07	209.05	-3.95	27.58	0.51
ST-PBH15	7.30	107.10	749.70	92.87	84.30	41.15	1.70	65.11	-0.15	42.98	1.05
ST-PBH20	7.23	69.80	488.60	41.04	63.50	29.50	2.98	27.90	-1.11	32.13	0.62
ST-PBH23	7.24	75.50	528.50	61.59	63.70	27.03	3.39	32.01	-1.28	41.73	0.96
ST-PBH24	7.39	70.60	494.20	63.90	57.30	22.33	2.44	33.06	-1.54	45.45	1.13
ST-PBH25	7.43	85.50	598.50	89.46	66.80	21.78	4.55	40.19	-2.06	51.49	1.43
ST-PBH07	7.47	73.70	515.90	37.15	55.06	40.35	1.26	45.20	-4.85	28.70	0.55
ST-PBH12	7.67	73.70	515.90	91.62	39.87	17.73	1.13	41.20	-4.56	61.69	2.25
ST-PBH26	7.41	72.10	504.70	82.73	40.58	17.47	7.62	37.30	-4.75	60.88	2.02
ST-PBH27	7.26	77.90	545.30	64.08	59.25	26.22	5.04	30.10	-4.73	44.71	1.06
ST-PBH28	7.38	67.90	475.30	49.60	54.23	25.70	2.32	28.70	-4.25	39.38	0.88
ST-PBH29	8.61	57.90	405.30	141.83	1.52	0.42	0.61	15.30	-0.32	98.66	103.39
ST-PBH30	7.63	60.30	422.10	108.76	21.70	7.74	1.45	21.40	-1.74	78.92	5.22
ST-PBH31	7.47	67.30	471.10	67.66	43.27	21.04	2.66	32.60	-4.45	52.23	1.49
ST-PBH32	6.89	67.90	475.30	81.83	51.29	17.95	4.21	34.50	-0.74	55.41	1.67
ST-PBH33	9.20	67.60	473.20	161.00	3.60	1.70	0.42	23.40	-0.31	96.82	42.96

APPENDIX7:
Drinking Water Quality Standards by DWAF (1996b) and WHO (2011)

Variable	Domestic	Industry	Agriculture (Irrigation)	WHO (20110
Alkalinity ($CaCO_3$)		0-1200	0-5	
Aluminium	0-0.15		0-0.1	0.9
Arsenic	0-0.01		0-0.1	0.01
Cadmium	0-5		0-10	0.003
Calcium	0-32			
Chloride	0-100	0-500	0-100	
Chromium (IV)	0-0.05		0-0.1	0.05
Cobalt			0-0.005	
Copper	0-1		0-0.2	2
Fluoride	0-1		0-2	1.5
Iron	0-0.1	0-10	0-5	
Lead	0-0.01		0-0.2	0.01
Magnesium	0-30			
Manganese	0-0.05	0-10	0-10	
Mercury	0-0.001			0.006
Molybdenum			0-0.01	
Nickel			0-0.2	0.07
Nitrate+Nitrite	0-6		0-5	53
Potassium	0-50			
Silica			0-150	
Sodium	0-100		~70	
Sulphate	0-200	0-500		
Zinc	0-3		0.1	
pH	6-9	5-10	6.5-8.4	
TDS	0-450	0-1600	~40	
Barium				0.7
Selenium				0.04

APPENDIX 8:
Water Quality Classes Description for Drinking according to SANS241:2006

Variable	Units	Class I	Class II
Aluminium (Al)	mg/L	<300	300-500
Antimony (Sb)	mg/L	<10	10-50
Arsenic (As)	mg/L	<10	10-50
Cadmium (Cd)	mg/L	<5	5-10
Total Cromium (Cr)	mg/L	<100	100-500
Cobalt (Co)	mg/L	<500	500-1000
Copper (Cu)	mg/L	<1000	1000-2000
Cyanide (CW)	mg/L	<50	50-70
Iron (Fe)	mg/L	<200	200-2000
Lead (Pb)	mg/L	<20	20-50
Manganese (Mn)	mg/L	<100	100-1000
Mercury (Hg)	mg/L	<1	1-5
Nickel (Ni)	mg/L	<150	150-350
Selenium (Se)	mg/L	<20	20-50
Vanadium (V)	mg/L	<200	200-500

APPENDIX 9: CALCULATIONS FOR WATER BALANCE

$$Inflow - Outflow + Re - Q = S.\frac{dV}{dt} = Balance\ (Q_{balance}) \qquad (7)$$

Area Surface of C60E = 664 Km^2 = 66.4 x 107 m^2 (DWAF, 2006)

Area Surface of Steynsrus town = 16 Km^2 = 1.6 m^2

Recharge = 32 mm/a = 0.032 m/a (DWAF, 2006) = Re

Groundwater Evaporation = 0.11 mm/a = 0.00011 m/a = Outflow

Sustainable yield of boreholes in Steynsrus = 1.3 ML/day = Q (Estimates from Section 8.3)

Water Demands (in 2013) = 2.0 ML/day

Water Demands (in 2030) = 2.2 ML/day

Conversion of Re and Groundwater Evaporation SI units into ML/day:

(i) Re = Area (in m^2) x Re (in m/a)

Re = 66.4 m2 x 0.032 m/a

Re = 21 248 000 m^3/a

Therefore Re = 212.5 x 108 L/year = 212.5 x 102 ML/year (For the Quatenary catchement)

Re = 21 250 (ML/year) x 16 Km^2 ÷ 664 (km^2) (Effective recharge for Steynsrus)

Therefore, Re = 512 ML/year = 1.4 ML/day

(ii) Outflow = Groundwater Evaporation = 0.11 mm/a = 0.00011 m/a

Therefore, Outflow = 0.00011 (m/a) x 66.4 x 107 m^2 =73040 m^3/a = 73.04 ML/year

Outflow = 73.04 ML/year x 16 Km^2 ÷ 664 (km^2) (Effective groundwater evaporation for Steynsrus)

Therefore, Outflow = 1.76 ML/year = 0.0048 ML/day

(iii) $Inflow - Outflow + Re - Q = S.\frac{dV}{dt} = Balance\ (Q_{balance})$

0 – 0.0048 + 1.4 – 2.0 = Balance

Therefore, Groundwater Balance = 0.60 ML/day in 2013

0 – 0.0048 + 1.4 -2.2 = Balance

Therefore Groundwater Balance = 0.80 ML/day in 2030.

(iv) Water deficits based on Sustainable yields:

Water Deficits for 2013 = Sustainable yields – Water demands = 1.3 – 2.0 = -0.7 ML/day

Water Deficits for 2013 = Sustainable yields - Water demands = 1.3 – 2.2 = -0.9 ML/day

ABSTRACT

Groundwater resource assessment aims to obtain fundamental data and information needed to describe the hydraulic and chemical parameters in order to estimate the available groundwater resource which is suitable for drinking. This study was undertaken with the purpose of determining and estimating the groundwater occurrence, groundwater flow parameters, groundwater quality and storage in typical Karoo Main Basin aquifers such as in the Steynsrus study area in South Africa. The field investigations were designed to define and determine the sustainable yields and the properties of the aquifers and the exploitable volumes. The research places emphasis on the appropriate tools and their applications in order to understand the local aquifers so as to optimise the groundwater exploration for town water use and to determine the future water use.

The geophysical surveying methods, particularly the magnetic method, were utilised to investigate and determine borehole drilling targets, and to locate groundwater potential structures, which are often associated with high borehole yields. The quality of the magnetic data utilised for drilling by the external consultant was critically evaluated and was found to be 'bad data'. Percussion drilling played an important role in providing geological subsurface information; in particular locations of fractures which are often associated with favourable groundwater flow were identified. Seventeen (17) boreholes were drilled in the whole project, seven (7) of the boreholes were sited by magnetometer survey and interpretation, and ten (10) of the drilled boreholes were sited by geological mapping and map interpretation. Twelve of the drilled boreholes were declared 'unsuccessful' due to yielding a blow yield below 1.00 L/s; therefore these boreholes were not considered for aquifer pump testing. Blow yields of five (5) of the newly drilled boreholes were between 1.5 and 24 L/s. Hence aquifer pump testing was conducted to determine sustainable yields, and aquifer parameters were also estimated. Pump testing was conducted on twenty boreholes; including fifteen (15) existing boreholes and five (5) newly drilled boreholes. The groundwater flow regimes were described using the aquifer pump test data correlated with the percussion geological logs and determined aquifer parameters. The general groundwater flow in the study area is characterised or influenced by fractures. The amount of the groundwater than can be used to supplement the water supply in Steynsrus is 1.3 Mega Litres (ML) per day; provided that all the recommended sustainable yields are considered. The groundwater quality assessment of the study area was also conducted for hydrochemical analysis of the water samples collected during the study. The dominant water type in the study area was determined as Na/Mg-HCO_3.

Based on these findings, the aquifers in the study were concluded to be a fractured system of alternating layers of sandstone and shale formations, characterised by the favourable groundwater flow characteristics at the dolerite fractures, and in some cases bedding plane fractures of sandstone formations. The study demonstrates the value in the methods and concepts applied in geohydrological studies to understand the local aquifer properties and in order to estimate the sustainable yields and the groundwater balance.

Keywords: Borehole sustainable yield, Geohydrological characterisation, Groundwater assessment, Groundwater flow, Groundwater occurrence, Aquifer parameters, Karoo fractured-rock aquifers, Water balance, Water quality

OPSOMMING

Die assessering van grondwaterhulpbronne het ten doel om die fundamentele data en inligting te verkry wat nodig is om die hidrouliese en chemiese parameters te beskryf ten einde die beskikbare grondwaterhulpbron wat geskik is vir drinkwater te skat. Hierdie studie is onderneem met die doel om die voorkoms van grondwater, grondwatervloei parameters, grondwaterkwaliteit en stoor in tipiese Karoo Main Basin waterdraers soos in die Steynsrus studie area in Suid-Afrika te bepaal. Die veldondersoeke is ontwerp om die eienskappe van die waterdraers te definieer en die ontginbare volumes te bepaal. Die navorsing beklemtoon die toepaslike metodes en programme wat gebruik kan word om die plaaslike akwifere te verstaan om die eksplorasie van grondwater vir watergebruik in ‘n dorp te optimaliseer en die toekomstige watergebruik te bepaal.

Die geofisika opmeting, veral die magnetiese metode, was waardevol om boorgatteikens te ondersoek, die strukture wat die potensiaal het vir groundwater en wat dikwels geassosieer met 'n hoë boorgatopbrengste, op te spoor. Die perkussieboor was belangrik in die verskaffing van ondergrondse geologiese inligting, in die besonder die lokalisering van frakture wat dikwels geassosieer word met gunstige grondwatervloei. Waterdraerpomptoets is uitgevoer om volhoubare opbrengste te bepaal, en waterdraerparameters is ook beraam. Die plaaslike vloeiregimes is beskryf met behulp van die waterdraerpomptoetsdata gekorreleer met die perkussie geologiese logs en die bepaling van waterdraerparameters. Grondwaterkwaliteitbeoordeling van die studie-area is gedoen vir anorganiese veranderlikes (makro- en mikroparameters) van die watermonsters wat tydens die studie ingesamel is. Die tipe water in die studie-area is bepaal as die Na/Mg-HCO_3-tipe verkry van die metodes (naamlik die Durov- en Piper-diagramme) wat gebruik is om grondwater te klassifiseer.

Gebaseer op die bevindinge, is bevind dat die waterdraers in die studie bestaan uit 'n faktuurstelsel van afwisselende lae van sandsteen- en skalieformasies, wat gekenmerk word deur gunstige grondwatervloei weg van die dolerietfrakture, en in sommige gevalle beddingfrakture van sandsteenformasies. Die studie toon die waarde van die toepassing van metodes en konsepte in geohidrologiese studie om die lokale waterdraereienskappe te verstaan ten einde volhoubare opbrengs en die grondwaterbalans te skat.